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LONG-SHORT GRBS WITHIN THE HORIZON OF THE ADVANCED LIGO/VIRGO NETWORK AND TIME LAG BETWEEN COMPACT OBJECT COALESCENCE AND GRB ONSET

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ABSTRACT

Short duration GRBs (SGRBs) are widely believed to be powered by the mergers of compact binaries, like binary neutron stars or possibly neutron star-black hole binaries. Though the prospect of detecting SGRBs with gravitational wave (GW) signals by the advanced LIGO/VIRGO network is promising, no known SGRB has been found within the expected advanced LIGO/VIRGO sensitivity range. We argue, however, that the two long-short GRBs (GRB 060505 and GRB 060614) may be within the horizon of advanced GW detectors. In the upcoming era of GW astronomy, the merger origin of some long-short GRBs, as favored by the macronova signature displayed in GRB 060614, can be unambiguously tested. The model-dependent time-lags between the merger and the onset of the prompt emission of GRB are estimated. The comparison of such time-lags between model prediction to the real data expected in the era of the GW astronomy would be helpful in revealing the physical processes taking place at the central engine (including the launch of the relativistic outflow, the emergence of the outflow from the dense material ejected during the merger and the radiation of gamma-rays). The achievable accuracy of measuring the speed of GW in the advanced LIGO/VIRGO era is also examined.

Subject headings: gamma-ray burst: general—stars: black holes—stars: neutron—binaries: general

1. INTRODUCTION

The coalescence of a binary compact object system (either a neutron-star (NS) binary or a stellar-mass black hole (BH) and NS binary) has been widely suggested to account for short-duration gamma-ray burst (SGRB) events (Eichler et al. 1989; Narayan et al. 1992; Nakar 2007; Berger 2014) that lasted typically shorter than 2 seconds in soft $\gamma-$ray band (Kouveliotou et al. 1993). Since 2006, it had been suspected that the compact object mergers could also produce the so-called long-short GRBs (also known as the supernova-less long GRBs which are apparently long-lasting but do not show any signal of supernovae down to very stringent limits) which share some properties of both long- and short-duration GRBs (Gehrels et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Zhang et al. 2007). The compact binary coalescence (CBC) is generally expected to be strong gravitational wave (GW) radiation source and are prime target for some gravitational detectors like advanced LIGO/VIRGO (Abadie et al. 2015; Acernese et al. 2015, see also the latest LSC-Virgo white paper at https://dcc.ligo.org/LIGO-T1400054/public). In the absence of successful detection of the gravitational radiation triggered by SGRB(Abadie et al. 2012; Aasi et al. 2014a,b), a "smoking-gun" signature for the compact-binary origin of an SGRB would be the detection of the so-called Li-Paczynski macronova (also called a kilonova), which is a near-infrared/optical transient powered by the radioactive decay of $r-$process material synthesized in the ejecta that is launched during the merger event (e.g., Li & Paczynski 1998; Kulkarni 2005; Metzger et al. 2010; Barnes & Kasen 2013). The identification of macronova candidates in the afterglows of the canonical short event GRB 130603B (Tanvir et al. 2013; Berger et al. 2013) and the long-short burst GRB 060614 (Yang et al. 2015; Jin et al. 2015) are strongly in support of the CBC origin of some GRBs. A conservative estimate of the macronova rate favors a promising detection prospect of the GW radiation by the (upcoming) advanced LIGO detectors (Jin et al. 2015). We anticipate that in 2020s many compact-object-merger driven GW sources would be detected (Abadie et al. 2010) and a small fraction of such events would be accompanied by supernova-less GRBs (including both the short and long-short events).

The observation of a "nearby" supernova-less GRB provides a reliable estimate of the time, sky location and distance of a potential binary merger signal. This significantly reduces the parameter space of a follow-up GW search and consequently could be used to reduce the effective detection threshold and effectively increase the detectors' sensitivity and their detection rate (e.g., Kochanek & Piran 1993; Finn et al. 1999; Harry & Fairhurst 2011; Kelley et al. 2013; Nissanke et al. 2013; Dietz et al. 2013; Williamson et al. 2014; Clark et al. 2015). In this work we examine whether some SGRBs and/or long-short GRBs are within the horizon of the advanced LIGO/VIRGO network and discuss the model-dependent time lag between the coalescence and GRBs.

This work is structured as follows: In Sec. 2 we discuss/summarize the prospect of detecting GW-associated GRBs in the era of advanced LIGO/VIRGO and examine whether any recent GRBs (either SGRBs or long-short GRBs) are within the horizon of the advanced LIGO/VIRGO network. In Sec. 3 the model-dependent time lags between the merger and GRBs are presented and the possibility of revealing the nature of merger remnants with such time delays is discussed. The expected progress in measuring the speed of GW with the future data are investigated in Sec. 4. Our results and discussion are presented in Sec. 5.

2. THE PROSPECTS OF DETECTING GW SIGNAL ASSOCIATED SGRBS AND LONG-SHORT GRBS

2.1. *The prospect of detecting SGRBs with GW signals*

The strategy of the targeted search for GWs associated with short GRBs has been extensively discussed in Harry & Fairhurst (2011) and Williamson et al. (2014). Given the time and sky location of the GRB, the suggested search is restricted to a six second span of data around the GRB, allowing for a merger time 5 s before and 1 s after the time of the GRB (e.g. Clark et al. 2015). As we will demonstrate in Sec. 3 (see also Table 1 for a summary), such a time span likely allows for realistic delays between the merger and GRB signal[1]. Following Clark et al. (2015) in this work we do not consider the first GW detection but focus on later observations for which a specific false positive rate (i.e., a limit on the fraction GW observations are spurious) is required. Note that the possibility of a signal with a signal-to-noise ratio (SNR, ρ_*) being a background can be estimated as $P_{\rm BG}(\rho > \rho_*) = 10^{-[5+2(\rho_*-9)]}$ for $\rho_* \geq 6.5$ and otherwise $P_{\rm BG}(\rho > \rho_*) = 1$ (Williamson et al. 2014; Clark et al. 2015). Throughout this work we pay attention to the events with $\rho_* \geq 9$, i.e., $P_{\rm BG}(\rho > \rho_*) \leq 10^{-5}$.

While as mentioned above the targeted search strategy is "the suggested targeted search is restricted to a six second span of data around the GRB, allowing for a merger time 5 s before and 1 s after the time of the GRB ".

2.1.1. *BNS mergers*

The sky and binary orientation averaged sensitivity of the advanced LIGO/VIRGO network for binary neutron star (BNS) mergers is about 200 Mpc (Aasi et al. 2013). As found in numerical simulations the merger-powered GRB jets are beamed perpendicular to the plane of the binary's orbit (Faber & Rasio 2012). Along the direction of the GRB jet, the amplitude of the associated GW signal is a factor of 1.5 greater than the orientation averaged one. Consequently the nominal sensitivity for BNS-merger GRB signals in the advanced detector network is ≈ 300 Mpc for a $\rho_* = 12$. The sensitive distance scales inversely with the ρ_* threshold, which can be expressed as (Clark et al. 2015)

$$D_{*,\rm BNS} \approx 400~{\rm Mpc}~(9/\rho_*). \qquad (1)$$

When the advanced LIGO/VIRGO network has reached its full sensitivity, with the 'local' SGRB detection rate of $4 \pm 2~{\rm Gpc}^{-3}~{\rm yr}^{-1}$ (Wanderman & Piran 2015), the detection rate of the GW signal associated SGRB for a full sky $\gamma-$ray monitor is estimated as

$$\mathcal{R}_{\rm full~sky}(\rho_* = 9) \approx 1 \pm 0.5~{\rm yr}^{-1},$$

where all SGRBs are assumed to originate from BNS mergers. Such an assumption seems reasonable since the BH−NS merger rate is generally expected to be just $\sim 1/10$ times that of the BNS merger rate (Abadie et al. 2010).

For *Fermi*-GBM like detectors with a field of view of ~ 9 sr (Meegan et al. 2009), the GW-SGRB rate is hence expected to be

$$\mathcal{R}_{\rm GBM}(\rho_* = 9) \approx 0.7 \pm 0.35~{\rm yr}^{-1}.$$

The potential problem is that the Fermi-GBM localization is not accurate enough and the error of area is typically tens or hundreds of square degrees, making optical followup of these events very challenging and so far no afterglow from a Fermi-GBM only SGRB has been observed. Fortunately, the situation may change soon. In 2017 the Zwicky Transient Facility (ZTF) with an instantaneous field of view $\sim 47^0$ and a r-band sensitivity $\sim$ 21th mag will have first light at Palomar Observatory (http://www.ptf.caltech.edu/ztf). In one full night the survey field of viewis expected to be $\sim 2.4 \times 10^4$ square degrees, almost half of the sky. Therefore it is very likely that a good fraction of optical afterglows of "nearby" SGRBs would be detected in the survey mode of ZTF or other large area optical telescopes (see Metzger & Berger 2012, for detailed discussion).

Swift-BAT (Gehrels et al. 2004) and upcoming Chinese-French Space-based multi-band astronomical Variable Objects Monitor (SVOM, Paul et al. 2008) can localize GRBs very accurately and the optical followup observations are easier. With an instantaneous field of view of ~ 2 sr the detection rate of GRB-GW signal observations is expected to be

$$\mathcal{R}_{swift}(\rho_* \geq 9) \approx 0.16 \pm 0.08~{\rm yr}^{-1}. \qquad (2)$$

Recently, Bartos & Marka (2015) have shown that the LIGO/Virgo network can boost gravitational wave detection rates by exploiting the mass distribution of neutron stars. For searches with detected electromagnetic counterparts, the detection rate may increase of 60% (Bartos & Marka 2015). Hence our current estimate can be taken as conservative.

2.1.2. *NS-BH mergers*

Ten BNS binaries are known in the Galaxy (Lattimer 2012). The neutron star-black hole (NS-BH) binaries, however, have not been directly observed yet. Nevertheless, such binaries are believed to be formed as a result of two supernovae in a massive binary system and an NS-BH merger is likely needed in reproducing the macronova data of the long-short burst GRB 060614 (Yang et al. 2015; Jin et al. 2015). The masses of the black holes in the NS-BH binary systems, of course, can be just inferred indirectly and the merger rate of NS-BH binaries can be "reasonably" estimated (Abadie et al. 2010). Farr et al. (2011) considered separately a sample of 15 low-mass, Roche lobe filling systems and a sample of 20 systems containing the 15 low-mass systems and 5 high-mass, wind-fed X-ray binaries and used Markov chain Monte Carlo methods to sample the posterior distributions of the parameters implied by the data for five parametric models and five non-parametric (histogram) models for the mass distribution. Farr et al. (2011) found strong evidence for a mass gap between the most massive neutron stars and the least massive black holes, confirming the results of Bailyn et al. (1998) and Ozel et al. (2010). For the low-mass systems (combined sample of systems), they found a black hole mass distribution whose 1% quantile lies above $4.3~M_\odot$ ($4.5~M_\odot$) with 90% confidence. The typical NS-BH binary systems are expect to have a mass ratio of $\sim 1:4$, for which the sensitive distance of the aLIGO/AdV network can be estimated as

$$D_{*,\rm NS-BH} \approx 690~{\rm Mpc}~(9/\rho_*). \qquad (3)$$

If $\sim 1/5$ of short and long-short GRBs are produced by NS-BH mergers, while aLIGO/AdV are more sensitive to the

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[1] Note that in this work we adopt the most widely-adopted hypothesis that the SGRBs were powered quickly after the merger. One caution is that a small amount of SGRBs seem to have precursor emission and the precursors are likely from the same central engine activity as the main bursts (Charisi et al. 2015). In the binary merger scenario, the merger likely happened before the precursor. If so, the time-lag between the GW signal and the SGRB/long-short GRB can be long to ~ 100 s, which may label the lifetime of the supramassive neutron star formed in the merger or alternatively the fall-back accretion timescale of the fragmented part of the compact object.

heavier NS-BH system, we expect around half of the CBC events might have an EM counterpart has an origin of NS-BH mergers.

In summary, in 10 years of full run of aLIGO/AdV network about ten to twenty GW-associated SGRBs are expected and possibly one half of them may have an NS-BH merger origin (see Williamson et al. 2014; Wanderman & Piran 2015; Clark et al. 2015, for similar results). The statistical study of such a sample, though somewhat limited, may shed valuable light on the physical processes taking place at the central engine (see Sec. 3 for the details). Please also bear in mind that the above estimate has just taken into account the SGRBs. In reality, some supernova-less long GRBs may also have a compact object merger origin and the detection rate of merger events will increase.

2.2. *Swift "supernova-less" GRBs: within the sensitivity distance of advanced LIGO/VIRGO network*

As shown in last subsection, the detection prospect of GW-associated SGRBs is promising for the advanced LIGO/VIRGO network. Previously just the SGRBs or even the further selected events have been investigated (see e.g. Kelley et al. 2013; Wanderman & Piran 2015) and *no events are found within the averaged sensitive distance of the advanced LIGO/VIRGO network for BNS mergers with* $\rho_* \geq 9$. Such a result is somewhat disappointing though not in tension with the expectation (see eq.(2)).

Below we show that the real situation can be much more encouraging. The difference between this approach and the earlier ones is the adopted GRB sample. We do not restrict ourselves to the canonical SGRBs. Instead, we include also all "nearby" (i.e., $z < 0.3$) supernova-less long GRBs, including XRF 040701 (X-ray flash, Soderberg et al. 2005), GRB 060505 and GRB 060614 (Fynbo et al. 2006).

XRF 040701 was localized by the Wide-Field X-Ray Monitor on board the *High Energy Transient Explorer (HETE-2)* on 2004 July 1.542 UT. It is characterized by the very low peak frequency (i.e., < 6 keV) of the prompt emission. Soderberg et al. (2005)'s foreground extinction-corrected HST detection limit is $\simeq$ 6 mag fainter than SN 1998bw, the archetypal hypernova that accompanied long GRBs (Galama et al. 1998), at a redshift of $z = 0.21$. The analysis of the X-ray afterglow spectra reveals that the rest-frame host galaxy extinction is constrained to $A_{\rm V,host} \lesssim 2.8$ mag, suggesting that the associated supernova, if there was, should be at least ~3.2 mag fainter than SN 1998bw (Soderberg et al. 2005). Due to the lack of the sufficient multi-wavelength afterglow data, the "absence" of a bright supernova associated with XRF 040701 did not attract wide attention. The situation changed dramatically when the supernovae associated with GRB 060505 and GRB 060614 had not been detected down to limits hundreds of times fainter than SN 1998bw (Fynbo et al. 2006). Particularly, GRB 060614, a bright burst with a duration of ~ 102 s at a redshift of 0.125, had dense followup observations with Very Large Telescope and Hubble Space Telescope. The physical origin (either a peculiar collapsar or a compact object merger) of GRB 060614 was debated over years (e.g., Fynbo et al. 2006; Gehrels et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Zhang et al. 2007). The re-analysis of the optical afterglow emission of GRB 060614 found significant excess components in multi-wavelength photometric observations, which can be reasonably interpreted as a Li-Paczyński macronova that powered by the radioactive decay of debris following an NS-BH merger while the weak supernova model does not work (Yang et al. 2015; Jin et al. 2015). As summarized in Xu et al. (2009), the origin of GRB 060505 at a redshift of $z = 0.089$ is less clear. The properties of its host galaxy seems to be consistent with that expected for the long-duration GRBs (Thöne et al. 2008) but GRB 060505 is an outlier of the so-called Amati relation that holds for long GRBs (Amati et al. 2007). The HST observations at $t \sim 14.4$ days after the burst did not find optical emission down to a limiting AB magnitudes of 27.3$^{\rm th}$ in F814W band and 27.1$^{\rm th}$ in F475W band (Ofek et al. 2007). Such stringent limits are strongly at odds with the collapsar model but can be well consistent with the NS-NS merger model (Tanaka & Hotokezaka 2013).

It may be still a bit early to conclude that all "nearby supernova-less" long GRBs (i.e., "long-short GRBs") are from compact object binary mergers. The successful identification of a macronova signal in the long-short event GRB 060614, nevertheless, renders such a possibility more attractive than before. If the NS-BH merger model for GRB 060614 is correct, the luminosity distance of this event is $D_{\rm L} \approx 576$ Mpc, which is smaller than $D_{*,\rm NS-BH}$ as long as $\rho_* \leq 10.8$ (see eq.(3)). For GRB 060505, the redshift $z = 0.089$ corresponds to a luminosity distance $D_{\rm L} \approx 400$ Mpc, which almost equals to $D_{*,\rm BNS}$ for $\rho_* = 9$ (see eq.(1)). Intriguingly, among the supernova-less and short events detected so far, GRB 060505 and GRB 060614 consist of the "whole" sample that might yield detectable GW signal for the advanced LIGO/VIRGO network (see Fig.1).

Though it could be just a coincidence, the presence of two *Swift* GRB candidates within the averaged sensitivity distance of the advanced LIGO/VIRGO network for $\rho_* \geq 9$ is indeed very encouraging for the ongoing GW experiments. On the other hand, if the supernova-less long-duration XRFs/GRBs were from a peculiar kind of collapsar (though we believe it is very unlikely to be the case for GRB 060614), no GW signal is detectable for these distant cosmic sources. Therefore we suggest that the supernova-less long-duration XRFs/GRBs are one of prime targets for advanced LIGO/VIRGO network and the nature of such a kind of "mysterious" events would be unambiguously pinned down in the era of GW astronomy.

3. MODEL-DEPENDENT ESTIMATES OF TIME LAG BETWEEN BINARY COALESCENCE AND GRB ONSET

In this section we present our model-dependent estimates of time lag between GW coalescence time and GRB onset (i.e., $\Delta t_{\rm a}$) and discuss how a statistical study of $\Delta t_{\rm a}$ could help us to better understand the physical processes taking place at the central engine. In general, $\Delta t_{\rm a}$ can be divided into two parts. One is the time delay between the merger time, which could be estimated by analyzing the GW data (e.g., Fairhurst 2011; Veitch et al. 2015), and the successful launch of the ultra-relativistic ejecta (i.e., $\Delta t_{\rm laun}$). The other is the time delay between the successful launch of the ultra-relativistic ejecta and the onset of the gamma-ray emission (i.e., $\Delta t_{\rm em}$). Below we examine $\Delta t_{\rm laun}$ and $\Delta t_{\rm em}$ model-dependently and separately.

Notice that we are using the coalescence time, when the GW signal spikes, as a proxy to the merger moment. One might reasonably argue that these two are not identical, but as the binary system evolve very rapidly towards the merger, there's no physical motivation to believe they separate by more than ~ 10ms (Fairhurst 2011; Pürrer 2014).

3.1. $\Delta t_{\rm laun}$ *expected in different merger scenarios*

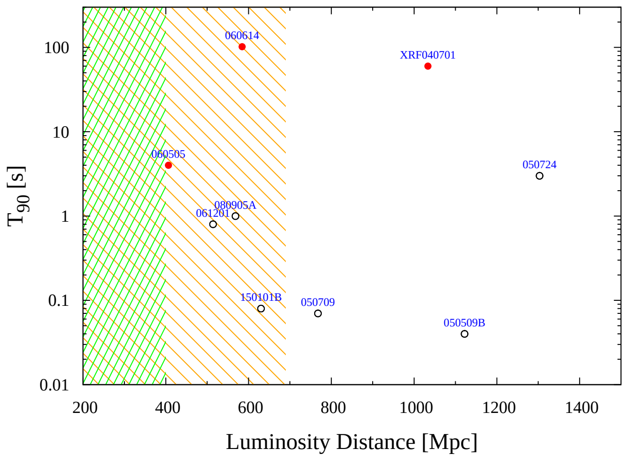

FIG. 1.— The "nearby" (i.e., $z \leq 0.3$) *supernova-less* GRBs, including the SGRBs and the long-short GRBs, and the averaged sensitivity distances of advanced LIGO/VIRGO network (i.e., $\rho_* \geq 9$) for binary neutron star mergers and neutron star-stellar black hole mergers. The open circles are the SGRBs discussed in the literature, including GRB 050724 with a duration $T_{90} = 3 \pm 1$ s (Fox et al. 2005). The red filled circles are the long-short GRBs. The data are taken from Berger (2014), Fynbo et al. (2006), Soderberg et al. (2005) and Levan et al. (2015). Interestingly, the long-short burst GRB 060505 is within $D_{*,\rm BNS}(\rho_* = 9)$. Three short bursts (including GRB 061211, GRB 080905A and GRB 150101B) and the long-short burst GRB 060614 are within $D_{*,\rm NS-BH}(\rho_* = 9)$. Though the NS-BH merger rate is expected to be one order of magnitude lower than that of the BNS mergers and hence most supernova-less GRBs should have a BNS merger origin, there is some evidence for an NS-BH merger origin of GRB 060614. Hence the GW signals of GRB 060614-like events taking place in the era of advanced LIGO/VIRGO would be detectable.

3.1.1. *NS-NS mergers*

The maximum gravitational mass of a cold non-rotating neutron star is known to be $M_{\rm max} > 2\ M_\odot$ (Antoniadis et al. 2013) and the threshold for collapse of the merger-formed remnants into black holes can be estimated roughly as $M_{\rm thres} \approx 1.35\ M_{\rm max}$ (Shibata & Taniguchi 2006). Hence a total gravitational mass greater than $\approx 2.7\ M_\odot$ is likely required for prompt collapse to a black hole. Such massive neutron star binaries should just account for a small fraction of merger events if the mass distribution of "cosmic" neutron star binaries resembles what people observed in the Galaxy (see Lattimer 2012, for a recent review). Hence usually we do not expect the prompt collapse of the merger-formed neutron stars. Instead the merger formed remnants are widely expected to be very massive neutron stars with strong differential rotation that can support against the collapse at least temporarily. Such remnants are called the hypermassive neutron stars (HMNSs). The fate of the post-merger HMNSs is however uncertain, and is contingent on the mass limit for support of a hot, differentially rotating configuration (e.g., Baumgarte et al. 2000; Hotokezaka et al. 2013a).

When $M_{\rm max} < M < M_{\rm thres}$, various mechanisms could act to dissipate and/or transport energy and angular momentum, possibly inducing collapse after a delay which could range from tens of milliseconds to a few seconds (see Faber & Rasio 2012, for a recent review). For instance, in the presence of strong magnetic field, the magnetic braking effect can effectively transfer the angular-momentum in a timescale $\tau_{\rm br} \sim R_{\rm s}/V_{\rm A} \sim 0.3\ {\rm s}\ (R_{\rm s}/10^6\ {\rm cm})(\rho/10^{15}\ {\rm g\ cm^{-3}})^{\frac{1}{2}}(\epsilon/0.3)(B_{\rm s}/10^{13}\ {\rm G})^{-1}$, where $V_{\rm A}$ is the Alfven's velocity, $R_{\rm s}$ is the radius of the neutron star and $\epsilon \sim 0.3$ is the expected strength ratio between the surface magnetic field $B_{\rm s}$ and the interior polorial magnetic field (Sharpiro 2000). Another mechanism is the magnetorotational instability (MRI), which generates turbulence in a magnetized rotating fluid body that amplifies the magnetic field and transfers angular momentum. In the presence of MRI, an effective viscosity is likely to be generated with the effective viscous parameter $\nu_{\rm vis} \sim \alpha_{\rm vis} c_{\rm s}^2/\Omega_{\rm c}$, where $\alpha_{\rm vis}$ is the so-called α-parameter, $c_{\rm s}$ is the sound velocity of the envelope of the HMNS and $\Omega_{\rm c}$ is the angular velocity of the core of the differentially-rotating neutron star (Balbus & Hawley 1991). Thus, the viscous angular momentum transport time scale can be estimated as $\tau_{\rm MRI} \sim R_{\rm s}^2/\nu_{\rm vis} \sim 0.1\ {\rm s}\ (R_{\rm s}/10^6\ {\rm cm})^2(\alpha_{\rm vis}/0.01)^{-1}(c_{\rm s}/0.1c)^{-2}(\Omega_{\rm c}/10^4\ {\rm rad\ s^{-1}})^{-1}$ (Hotokezaka et al. 2013a). A reasonable estimate of the termination timescale of the differential rotation is $\tau_{\rm diff} = \min\{\tau_{\rm br}, \tau_{\rm MRI}\} \sim 0.1$ s, after which the HMNS is expected to collapse.

The situation is even less uncertain when both finite-temperature effects in the equation of state and neutrino emission of the central compact object have been taken into account. In the numerical simulations of the merger of binary neutron stars performed in full general relativity incorporating the finite-temperature effect and neutrino cooling, Sekiguchi et al. (2011) found that the effect of the thermal energy is significant and can increase $M_{\rm max}$ by a factor of $20\% - 30\%$ for a high-temperature state with $T \geq 20$ MeV. Since they are not supported by differential rotation, the hypermassive remnants were predicted to be stable until neutrino cooling, with luminosity of $\sim 3{-}10\times10^{53}\ {\rm erg\ s^{-1}}$, has removed the pressure support in $\tau_{\rm thermal} \sim 1$ s (Sekiguchi et al. 2011).

For $t < \tau_{\rm w}$, a baryon-loaded wind is continuously ejected which would bound the bulk Lorentz factor of the jet to $\Gamma_{\rm w} \sim 5(L_{\rm jet}/10^{52}{\rm erg\ s^{-1}})(\dot{M}_{\rm w}/10^{-3}M_\odot\ {\rm s^{-1}})^{-1}$, where $L_{\rm jet}$ is the isotropic-equivalent luminosity of the jet and $\tau_{\rm w}$ is the wind duration (either $\tau_{\rm diff}$ or $\tau_{\rm thermal}$, depending on the mechanism that mainly supports against the collapse). Such a low $\Gamma_{\rm w}$ is too small to give rise to energetic GRB emission. Hence it is widely anticipated that no GRB is possible unless the neutrino-driven wind gets very weak or more realistically the neutron star has collapsed to a black hole. After the collapse of the HMNS, the earlier out-moving dense wind remains to hamper the advance of the jet, whose injection lifetime, $t_{\rm jet}$, is determined by the viscous timescale of the accretion disk (Lee et al. 2004). Murguia-Berthier et al. (2014) suggested that in the black hole central engine model for (short) GRBs, the black hole formation should occur promptly as any moderate delay at the hyper-massive neutron star stage would result in a choked jet. The argument that just the mergers with a remnant collapse within a timescale $\sim t_{\rm diff} \sim 0.1$ s can produce (short) GRBs may just hold in the scenario of energy extraction via neutrino mechanisms. The accretion timescale of the torus formed in binary neutron star mergers can be estimated as $t_{\rm acc} \sim 0.1\ {\rm s}\ (\alpha/0.1)^{-6/5}$, where α is the viscosity parameter (Narayan et al. 2001; Popham et al. 1999). Following Zalamea & Beloborodov (2011) and Fan & Wei (2011), it is straightforward to estimate the corresponding luminosity of the annihilated neutrinos/antineutrinos as $L_{\nu\bar{\nu}} \approx 10^{49}\ {\rm erg\ s^{-1}}(\dot{m}/0.1\ M_\odot\ {\rm s^{-1}})^{9/4}$, where $\dot{m}$ is the accretion rate and the spin of the black hole has been taken to be $a = 0.78$, a typical value for the black hole formed in binary neutron star mergers. The isotropic-equivalent luminosity of the ejecta is then $L_{\rm jet} \approx 2 \times 10^{51}$ erg s$^{-1}(\dot{m}/0.1\ M_{\odot}\ {\rm s}^{-1})^{9/4}(\theta_{\rm jet}/0.1)^{-2}$, which satisfies the condition of relativistic expansion of the jet head within the preceding neutrino-driven wind medium (i.e., eq.(8) of Murguia-Berthier et al. (2014)) as long as $\dot{m} > \dot{m}_{\rm jet} \approx 0.2\ M_{\odot}\ {\rm s}^{-1}$. The accretion disk mass is $M_{\rm disk} \sim \dot{m}_{\rm jet} t_{\rm acc} \sim 0.02\ M_{\odot}$. Such an accretion disk mass is consistent with that found in numerical simulations of binary neutron star mergers (Faber & Rasio 2012), which in turn suggests that short GRBs are likely for $t_{\rm jet} \approx t_{\rm acc} > \tau_{\rm w}$ if $\tau_{\rm w} < 0.1$ s, in agreement with Murguia-Berthier et al. (2014). If instead $\tau_{\rm w} \gg 0.1$ s, the required $M_{\rm disk}$ would be too massive to be realistic (Fan & Wei 2011; Liu et al. 2015).

The situation is significantly different for the magnetic process to launch the GRB ejecta. The huge amount of rotational energy of the black hole can be extracted efficiently via the Blandford−Znajek process and the luminosity of the electromagnetic outflow can be estimated by $L_{\rm BZ} \approx 6 \times 10^{49}\ {\rm erg\,s^{-1}}\ (a/0.75)^2(B_{\rm H}/10^{15}\ {\rm G})^2$, where $B_{\rm H} \sim 1.1 \times 10^{15}\ {\rm G}\ (\dot{m}/0.01\ M_{\odot}\ {\rm s}^{-1})^{1/2}(R_{\rm H}/10^6\ {\rm cm})^{-1}$ is the magnetic field strength on the horizon of the black hole (Blandford & Znajek 1977). Therefore $\dot{m} \sim 0.01\ M_{\odot}\ {\rm s}^{-1}$ is sufficient to launch energetic ejecta with $L_{\rm jet} \sim 10^{52}\ {\rm erg\,s^{-1}}(\theta_{\rm j}/0.1)^{-2}$. An $\alpha \leq 0.01$ is needed to get a $t_{\rm acc} \sim$ a few seconds. Such a "small" α is still possible (Narayan et al. 2001) and the required accretion disk mass is also in the reasonable range of $\sim 0.01\ M_{\odot}$. Please note that in these estimate the ejecta "breakout" criterion suggested in Murguia-Berthier et al. (2014) has been adopted. In reality, the Poynting-flux jet could break out from the "neutrino-driven wind" more easily than the hydrodynamic jet. This is because the reverse shock that slows down the hydrodynamic jet and the collimation shock that collimates it, cannot form within the Poynting-flux-dominated jet. As a result the Poynting-flux dominated jet moves much faster and dissipates much less energy while it crosses the preceding neutrino-driven wind (Bromberg et al. 2014). The latest time-dependent 3D relativistic magnetohydrodynamic simulations of relativistic, Poynting-flux dominated jets that propagate into medium with a spherically-symmetric power-law density distribution has found out that some instabilities can leads to efficient dissipation of the toroidal magnetic field component and hence the propagation of such a "headed" magnetized ejecta is likely similar to that of a hydrodynamic ejecta (Bromberg & Tchekhovskoy 2015). In such a case, the "breakout" criterion of Murguia-Berthier et al. (2014) applies. After the "breakout" of the "headed" magnetized ejecta, an evacuated funnel presents and the later ejecta moves freely without significant magnetic energy dissipation (i.e., it is within the phase of "headless" jet (Bromberg & Tchekhovskoy 2015)). Therefore, a $t_{\rm acc} \sim$ a few seconds may be sufficiently long to successfully produce GRBs for $\tau_{\rm w} \sim \tau_{\rm thermal} \sim 1$ s. The conclusion of this paragraph is that GRB is still possible in the case of $\tau_{\rm w} \sim \tau_{\rm thermal} \sim 1$ s but the outflow should be launched via magnetic processes.

The expected time delay between the merger of the binary neutron stars and the launch of the ultra-relativistic GRB outflow can thus be approximately summarized as $\Delta t_{\rm laun,BNS} \sim$ (0.01 s, 0.1 s, 1 s) for (the prompt formation of black hole, differential rotation supported HMNS, thermal pressure supported HMNS), respectively. The minimum $\Delta t_{\rm laun,BNS}$ is taken to be ~ 10 ms since the merger time is expected to be measured with an accuracy better than ~ 10 ms and the ultra-relativistic outflow may be launched promptly.

3.1.2. *NS-BH mergers*

In this case the central engine is a stellar mass black hole and the region along the spin axis of the black hole is likely cleaner than the case of NS-NS mergers. However, the joint effects of shocks during the disk circularization, instabilities at the disk/tail interface, and neutrino absorption unbinds a small amount ($\sim 10^{-4}\ M_{\odot}$) of material in the polar regions (Foucart et al. 2015). Over longer timescales, the neutrino-powered winds become active and eject material in the polar regions. Though the material is still negligible compared to the material ejected dynamically in the equatorial plane during the disruption of the neutron star, this ejecta could impact the formation of a relativistic jet (Foucart et al. 2015). Nevertheless, a few percents of the energy radiated in neutrinos is expected to be deposited in the region along the spin axis of the black hole through $\nu\bar{\nu}$ annihilations (Setiawan et al. 2006; Janka et al. 1999). The energy deposition at a rate $\sim 10^{51}\ {\rm erg\ s^{-1}}$ might also be able to power short γ-ray burst (Foucart et al. 2014; Lee & Ramirez-Ruiz 2007).

As in the BNS merger scenario, the magnetic mechanism may be more promising in launching ultra-relativistic outflows and then giving rise to GRBs. In the recent high-resolution numerical-relativity simulations for the merger of BH-NS binaries that are subject to tidal disruption and subsequent formation of a massive accretion torus, the accretion torus formed quickly and the magnetic-field was amplified significantly due to the non- axisymmetric magnetorotational instability and magnetic winding (Paschalidis et al. 2015; Kiuchi et al. 2015). The amplification can yield $B \sim 10^{15}$ G at the BH poles in ~ 20 milliseconds after the merger and the corresponding Blandford-Znajek luminosity can be sufficient high to power GRBs.

For the role of the magnetic process in extracting the energy for the GRBs, the data of GRB 060614 likely has shed valuable light on. Such a long-short event is most likely powered by the merger of a binary system of neutron star and stellar mass black hole (Yang et al. 2015; Jin et al. 2015). As found in various numerical simulations, the total mass of the accretion disk is expected to be not much more massive than $\sim 0.1\ M_{\odot}$. On the other hand, the duration of the "long-lasting" soft γ−ray emission is ~ 100 s. Hence the time averaged accretion rate is expected to be just in order of $\dot{m} \sim 10^{-3}\ M_{\odot}\ {\rm s}^{-1}$. For such a low accretion rate, the neutrino mechanism is expected to be unable to launch energetic GRB outflow (e.g., Fan et al. 2005; Liu et al. 2015). Instead, the Blandford−Znajek process can give rise to Poynting-flux dominated outflow with an "intrinsic" luminosity $L_{\rm BZ} \approx 6 \times 10^{47}\ {\rm erg\ s^{-1}}\ (a/0.75)^2(B_{\rm H}/10^{14}\ {\rm G})^2$ (Blandford & Znajek 1977), which is sufficient to explain the observed γ−ray luminosity of GRB 060614 after the correction of a jet opening angle of the outflow $\theta_{\rm j} \sim 0.1$ (see Xu et al. 2009). Therefore, the soft long-lasting gamma-ray "tail" emission of GRB 060614 likely has a moderate to high linear polarization (Fan et al. 2005).

In view of these facts, we suggest that ultra-relativistic outflows may be launched within $\Delta t_{\rm laun,BHNS} \sim$10s milliseconds after the BH-NS mergers via either the neutrino-antineutrino annihilation or magnetic process(es).

3.2. $\Delta t_{\rm em}$ *expected in baryonic and magnetic outflow models*

3.2.1. *The bayronic outflow*

The neutrino-antineutrino annihilation process will launch an extremely-hot fireball. For such a kind of baryonic outflow, the acceleration is well understood (Piran et al. 1993; Mészáros et al. 1993) and most of the initial thermal energy may have been converted into the kinetic energy of the baryons at the end of the acceleration (Shemi & Piran 1990). A quasi-thermal emission component, however, is likely inevitable (see Chhotray & Lazzati 2015, and the references therein for the resulting spectrum). The quasi-thermal emission is mainly from the photosphere at a radius $R_{\rm ph}$, which can be estimated as $R_{\rm ph} \approx 4.6 \times 10^{10}~{\rm cm}~(L/10^{51}~{\rm erg~s^{-1}})(\eta/200)^{-3}$, where L is the total isotropic-equivalent luminosity of the baryonic outflow and η is the initial dimensionless entropy (Paczynski 1990; Daigne & Mochkovitch 2002). Assuming an initial launch radius of the fireball $R_0 \approx 10^7$ cm, at $R_{\rm ph}$ the thermal radiation luminosity is expected to be $L_{\rm th} \approx 2.5\times10^{49}~{\rm erg~s^{-1}}(L/10^{51}~{\rm erg~s^{-1}})^{1/3}(\eta/200)^{8/3}(R_0/10^7~{\rm cm})^{2/3}$. And the quasi-thermal radiation peaks at a temperature $T_{\rm th} \sim 80~{\rm keV}~(L/10^{51}~{\rm erg~s^{-1}})^{1/4}(\eta/200)^{2/3}(R_0/10^7~{\rm cm})^{1/6}$. For the sources within the advanced LIGO/VIRGO detection ranges (i.e., $D \approx 300$ Mpc), the energy flux can be high up to $\mathcal{F} \sim 2\times10^{-6}~{\rm erg~s^{-1}}~(L/10^{51}~{\rm erg~s^{-1}})^{1/3}(\eta/200)^{8/3}(R_0/10^7~{\rm cm})^{2/3}$, which is detectable for *Swift* or *Fermi*-GBM. The acceleration timescale of the baryonic is $\sim (1+z)R_0/c$ and the delay between the termination of the acceleration and the emergence of the thermal photons can be estimated as $\sim (1+z)R_{\rm ph}/2\eta^2c$. For $\eta \geq 100$ the latter is significantly smaller than the former, hence $\Delta t_{\rm em} \sim (1+z)R_0/c \sim 0.3~{\rm ms}~(1+z)(R_0/10^7~{\rm cm})$, which is ignorably small.

If the photospheric quasi-thermal radiation is non-detectable (say, for the NS-BH mergers at $D \sim 1$ Gpc), more efficient emission may be cased by the collision between the baryonic shells ejected from the same central engine but with much different Lorentz factors. Strong internal shocks are generated and ultra-relativistic particles are accelerated. A fraction of internal shock energy has been converted into magnetic field and the electrons moving in the magnetic field produce energetic $\gamma-$ray emission (Rees & Mészáros 1994). In such a model, the variability of the prompt emission largely traces the behavior of the activity of the central engine and the onset of the "internal shock emission" is expected to be within the typical variability timescale of the prompt emission that can be $\sim 1-10$ ms (Piran 1999), i.e., $\Delta t_{\rm em} \sim 1-10$ ms.

3.2.2. *The magnetic outflow*

In the case of the magnetic outflow, both the acceleration and the subsequent energy-dissipation/radiation are more uncertain (see Kumar & Zhang 2015; Granot et al. 2015, for recent reviews). If the magnetic energy has been effectively converted into the kinetic energy of the outflow (Granot et al. 2015), the prompt emission of GRBs can be from the magnetized internal shocks (Fan et al. 2004) or the photosphere with internal dissipation of energy via gradual magnetic reconnection (Giannios 2008) and we expect $\Delta t_{\rm em} \sim 1-10$ ms. Note that in the latest time-dependent 3D relativistic magnetohydrodynamic simulations of relativistic, Poynting-flux dominated jets that propagate into medium with a spherically-symmetric power-law density distribution has found out that some instabilities can leads to efficient dissipation of the toroidal magnetic field component (Bromberg & Tchekhovskoy 2015), for which the onset of the prompt emission is likely dominated by the photospheric radiation and $\Delta t_{\rm em}$ is ignorably small.

If the photospheric radiation is too weak to be detectable for *Fermi*-GBM-like detectors due to either the absence of a dense wind-like medium in the direction of the black hole spin or the small luminosity of the breaking out material, the observed onset of the prompt emission is likely significantly delayed. In some models most of the initial magnetic energy has not been converted into the kinetic/thermal energy of the outflow and the prompt emission of GRBs is due to the magnetic energy dissipation at a rather large distance $R_{\rm pro} \sim 10^{16}$ cm [2] possibly due to the breakdown of magnetohydrodynamic approximation of the highly-magnetized outflow (Usov 1994; Zhang & Mészáros 2002; Fan et al. 2005), or the current-driven instabilities developed in the outflow shell (Lyutikov & Blandford 2003), or the internal collision-induced magnetic reconnection and turbulence (Zhang & Yan 2011). Correspondingly we expect $\Delta t_{\rm em} \sim (1+z)R_{\rm pro}/2\eta^2c \sim 2~{\rm s}~(1+z)~(R_{\rm pro}/10^{16}~{\rm cm})(\eta/300)^{-2}$, which may be comparable with but smaller than the duration of the short GRBs (i.e., T_{90}). Hence we have $\Delta t_{\rm em} \sim \min\{T_{90},~2~{\rm s}~(1+z)~(R_{\rm pro}/10^{16}~{\rm cm})(\eta/300)^{-2}\}$.

SGRB 050509B and SGRB 050709 have $T_{90} = 0.04$ s and 0.07 s, respectively (Fox et al. 2005). For such "brief" events, $R_{\rm pro} \sim 10^{16}$ cm is *disfavored* unless $\eta \gtrsim 2000$. The η as high as ~ 2000, however, would render them the outstanding outliers of the correlation $\eta \approx 250~(L_\gamma/10^{52}~{\rm erg~s^{-1}})^{0.3}$ holding for some long GRBs (Lü et al. 2012; Fan et al. 2012; Liang et al. 2015) and possibly also the short burst GRB 090510 if its $\eta \gtrsim 1200$, as argued in Ackermann et al. (2010), where L_γ is the $\gamma-$ray luminosity of the GRB. Moreover, unless there is the fine tuning that the central engine shut down almost at the same time as the outflow breaks out the dense material, the central engines of these two very-short bursts should be (promptly-formed) black holes and $\Delta t_{\rm a} < T_{90}$ is expected.

3.3. *Expected relationship between* $\Delta t_{\rm a}$ *and* T_{90}

We summarize in Table 1 the suspected $\Delta t_{\rm a}$ (i.e., the sum of $\Delta t_{\rm laun}$ and $\Delta t_{\rm em}$), where the case of $R_{\rm pro} \ll 10^{16}$ cm includes the scenarios of photospheric radiation and regular (magnetized) internal shock radiation. Clearly, the shortest delay is expected in the cases of prompt BH formation in the NS-NS mergers or the NS-BH mergers if the onset of the prompt emission is governed by the photosphere or regular internal shocks (i.e., $R_{\rm pro} \ll 10^{16}$ cm) and such events will be valuable in imposing very stringent constraint on the difference between the GW and the speed of light (see Sec.4 for the details).

In Sec.3.1.1 we have already mentioned that the prompt formation of BH in BNS mergers is likely uncommon. As long as $R_{\rm pro} \ll 10^{16}$ cm, one naturally expects that (1) for BNS mergers $\Delta t_{\rm a}$ is significantly longer than that of the NS-BH mergers, i.e., $\Delta t_{\rm a}({\rm NS-BH}) \ll \Delta t_{\rm a}({\rm BNS})$; (2) for NS-BH mergers, usually $\Delta t_{\rm a}$ is expected to be shorter than T_{90}, i.e., $\Delta t_{\rm a}({\rm NS-BH}) < T_{90}$. While for $R_{\rm pro} \sim 10^{16}$ cm, we expect that $\Delta t_{\rm a}$ should be comparable with T_{90} for both BNS and NS-BH merger powered SGRBs (Note that for some very-

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[2] The magnetized internal shocks with significant magnetic dissipation (Fan et al. 2004) can take place at a much smaller radius, say, $\sim 10^{14}-10^{15}$ cm.

TABLE 1

EXPECTED TIME DELAY BETWEEN THE COALESCENCE AND THE GRB ONSET (I.E., $\Delta t_{\rm a}$).

Mergers	Prompt Remnant	$R_{\rm pro} \ll 10^{16}$ cm	$R_{\rm pro} \sim 10^{16}$ cm
BNS	BH	~ 10 ms	$\sim \min\{T_{90},\ 2\ {\rm s}\}$
	DRS[a] HMNS	~ 100 ms	$\sim 0.1\ {\rm s} + \min\{T_{90},\ 2\ {\rm s}\}$
	TPS[a] HMNS	~ 1 s	$\sim 1\ {\rm s} + \min\{T_{90},\ 2\ {\rm s}\}$
NS−BH	BH	~ 10 ms	$\sim \min\{T_{90},\ 2\ {\rm s}\}$

[a] DRS is the abbreviation of “Differential rotation supported” and TPS is the abbreviation of “Thermal pressure supported”.

shortly lasting events such as SGRB 050509B and SGRB 050709, $R_{\rm pro} \sim 10^{16}$ cm is most-likely disfavored). Therefore, with reasonable large BNS merger GRB sample and NS-BH merger GRB sample, the statistical distribution of $\Delta t_{\rm a}$ and T_{90} for each sample or alternatively the distribution of $\Delta t_{\rm a}$ for the combined sample could shed valuable light on the central engine physics.

Are BNS mergers and NS-BH merger events distinguishable in the era of advanced LIGO/VIRGO? It is known that GW observations can efficiently measure the binary's chirp mass $\mathcal{M} \equiv (m_1 m_2)^{3/5}/(m_1 + m_2)^{1/5}$, which however leaves the individual masses undetermined, where m_1 and m_2 are the gravitational masses of the binary stars, respectively (Bartos et al. 2013; Hannam et al. 2013). Moreover, the accuracy of the reconstruction of the masses is decreased by the additional mass-ratio-spin degeneracy. Fortunately, in many cases the nature of the binary system can be determined. For instance, considering non-spinning compact objects and a $\rho_* \approx 10$, a $\mathcal{M} \gtrsim 2.8 M_\odot$ implies that one of the binary compact objects has to have a mass $> 3.2\ M_\odot$, above $M_{\rm max}$ for any reasonable NS models, while a $\mathcal{M} \lesssim 1.2 M_\odot$ suggest that the mass of both compact objects need to be $< 2M_\odot$ unless one of the NSs is smaller than $1M_\odot$, in which case the limit to the heavier object is $3M_\odot$ (Bartos et al. 2013; Hannam et al. 2013). Together with the expected detection rate of the GRBs with GW signals (see Sec.2.1), we think that in the era of the GW astronomy, reasonably large BNS merger GRB sample and NS-BH merger GRB sample will be available and our goals will be (at least partly) achievable.

4. MEASURING THE VELOCITY OF THE GRAVITATIONAL WAVE: EXPECTED PROGRESS

According to general relativity, in the limit in which the wavelength of gravitational waves is small compared to the radius of curvature of the background space-time, the waves propagate with the velocity of the light, i.e., c (see Will 1998, and the references). In other theories, the speed could differ from c and one interesting possibility is that the gravitation were propagated by a massive field. The non-zero graviton mass induces a modified gravitational-wave dispersion relation and hence a modified group velocity that can be parameterized as (Will 1998; Nishizawa & Nakamura 2014)

$$v_{\rm g}^2 = (1 - m_{\rm g}^2 c^4/E^2)c^2,$$

where $m_{\rm g}$ and E are the graviton rest mass and energy (usually associated to its frequency via the quantum mechanical relation $E = hf$, where h is Planck's constant and f is the frequency), respectively. In such a case, the gravitational wave signal is expected to arrive later than the simultaneously emitted photons and the observed time delay (i.e., the photons should arrive earlier) should be

$$\delta t_{\rm o} = \frac{1}{c}\int_0^{z_{\rm o}} (1+z)\left(\frac{c}{v_{\rm g}} - 1\right) {\rm d}l,$$

where ${\rm d}l = cdz/[(1+z)H_0 \sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda}]$ is the differential distance the photons have traveled. Note that in this work we take the flat cosmological model (i.e., $\Omega_{\rm M} + \Omega_\Lambda = 1$), $\Omega_{\rm M} = 0.315$ and $H_0 \approx 70$ km s^{-1} Mpc^{-1} is the Hubble's constant (Ade et al. 2014; Riess et al. 2011). The current astrophysical data has imposed a tight constraint on $v_{\rm g}$, which is found to be very close to c. Hence $v_{\rm g}$ can be approximated as $c/v_{\rm g} \approx 1 + m_{\rm g}^2 c^4/2h^2 f^2$. On the other hand, the observed frequency $f_{\rm o}$ has suffered from the redshift and hence $f = (1+z)f_{\rm o}$. We have $c/v_{\rm g} - 1 \approx m_{\rm g}^2 c^4/2(1+z)^2 h^2 f_{\rm o}^2$ and

$$\delta t_{\rm o} = \frac{1}{H_0}\frac{m_{\rm g}^2 c^4}{2h^2 f_{\rm o}^2}\int_0^{z_{\rm o}} \frac{{\rm d}z}{(1+z)^2\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda}},$$

with this equation one can constrain $m_{\rm g}$ and hence the difference between $v_{\rm g}$ and c that is of our interest (we define the parameter $\varsigma \equiv (c - v_{\rm g})/c$) as

$$\varsigma \approx \frac{H_0 \delta t_{\rm o}}{(1+z_{\rm o})^2} \Big/ \int_0^{z_{\rm o}} \frac{{\rm d}z}{(1+z)^2\sqrt{\Omega_{\rm M}(1+z)^3 + \Omega_\Lambda}}, \qquad (4)$$

it reduces to $\varsigma \approx H_0 \delta t_{\rm o} z_{\rm o}^{-1}[1 + (0.75\Omega_{\rm M} - 1)z_{\rm o}]$ for $z_{\rm o} \ll 1$ and $\varsigma \approx H_0 \delta t_{\rm o} \Omega_{\rm M}^{1/2} z_{\rm o}^{-2}$ for $z_{\rm o} \gg 1$. Obviously for $z_{\rm o} \ll 1$, the correction due to the redshift of the GW frequency is small and one nice approximation of ς is that given in Will (1998), i.e.,

$$\varsigma \approx 5 \times 10^{-17}\left(\frac{200\ {\rm Mpc}}{D}\right)\left(\frac{\delta t_{\rm o}}{1\ {\rm s}}\right).$$

Note that in reality usually the photons and the coalescence are not simultaneous and we have $\delta t_{\rm o} = (1+z)\Delta t_{\rm e} - \Delta T_{\rm a}$, where $\Delta T_{\rm a}$ and $\Delta t_{\rm e}$ are the differences in arrival time and emission time, respectively, of the photons and the GW signal. In most cases, it is rather hard to get a priori value for $\Delta t_{\rm e}$. As a conservative estimate of ς, one can set $\Delta t_{\rm e} = 0$ to constrain the absolute amplitude of ς as

$$|\varsigma| \leq 5 \times 10^{-17}\left(\frac{200\ {\rm Mpc}}{D}\right)\left(\frac{\Delta T_{\rm a}}{1\ {\rm s}}\right). \qquad (5)$$

Some widely discussed electromagnetic counterparts of compact object mergers include (Metzger & Berger 2012): (a) the (short) gamma-ray bursts and X-ray flares; (b) the afterglow emission of the (off-beam) gamma-ray burst outflows; (c) the macronova/kilonova emission of the sub-relativistic r-process material ejected during the merger; (d) the radio radiation of the forward shock driven by the sub-relativistic outflow launched during the merger. These scenarios hold for both NS-NS and NS-BH mergers (please note that for some very massive BHs, the NSs would be swallowed entirely and no bright electromagnetic counterparts are expected). For our purpose, the time delay between the merger and the “emergence” of the electromagnetic counterpart (i.e., $\Delta T_{\rm a}$) is needed.

The intense gamma-ray emission is expected to be within seconds after the merger (see Table 1 for the model-dependent estimate, where $\Delta t_{\rm a}$ is the same as $\Delta T_{\rm a}$ needed in eq.(5)). The X-ray flares may appear within tens seconds and sometimes may last $\sim 10^3$ s or even longer. The challenge of detecting the soft X-ray signal alone is the lack of X-ray detector(s) with a wide field of view. Such a situation will not change until the proposed Einstein Probe (http://ep.bao.ac.cn; Yuan et al. 2014), a soft X-ray detector with an instantaneous field of view $\sim$ 3600 square degrees, or similar X-ray observatories are in operation after 2022. Since advanced LIGO/VIRGO are expected in full run in 2019, here we just focus on the detectors that may (still) work at that time and hence will *not* discuss the X-ray signal any longer.

If the ultra-relativistic outflow is “on-beam”, the optical/radio afterglow are relatively long-lasting and the peak of the forward shock optical emission is expected to be within $10^2 - 10^3$ seconds after the merger, depending on the initial bulk Lorentz factor of the GRB outflow and the number density of the circum burst medium. The optical afterglow emission of a good fraction of on-beam but missed merger-origin GRBs are expected to be detectable for ZTF if the bursts are within the sensitivity distance of advanced LIGO/VIRGO network. The radio afterglow emission from SGRBs and long-short GRBs are actually very rare (see Fong et al. 2014, and the references) and the peak times were found to be < 1 day. If the ultra-relativistic outflow is “off-beam” with an angle separation $\Delta\theta$, the forward shock emission won’t “enter” the line of sight until its bulk Lorentz factor has dropped to $\approx 1/\Delta\theta$ (Janka et al. 2006). Note that the timescale measured in the off-beam case is related to that in the on-beam case as $dt_{\rm off} \approx (1+\Gamma^2\Delta\theta^2)dt_{\rm on}$ and the relation between $t_{\rm on}$ and Γ reads $\Gamma \approx 7\ E_{\rm k,51}^{1/8} n_{-2}^{-1/8} t_{\rm on,d}^{-3/8}$, where $E_{\rm k,51}$ is the kinetic energy of the GRB outflow in unit of 10^{51} erg s^{-1}, n_{-2} is the number density of the circum burst medium in unit of 10^{-2} cm^{-3} and $t_{\rm d}$ is the timescale in unit of day. Hence the peak time of the off-beam relativistic ejecta can be estimated as $t \sim 10$ day $E_{\rm k,51}^{1/3} n_{-2}^{-1/3} (\Delta\theta/0.2)^{8/3}$. At such a late time, the forward shock optical emission is likely (much) dimer than 22th mag for a source at a distance of ∼ 400 Mpc (We draw such a conclusion since the bright optical emission of GRB 060614, a burst likely has a merger origin, has such an optical emission if shifted to a distance of 400 Mpc) and the detection prospect is not very promising (see also Metzger & Berger 2012).

As for the macronova emission, in ultraviolet/optical band peak is likely in a few days while the infrared emission may peak in one or two weeks (see e.g. Li & Paczynski 1998; Barnes & Kasen 2013; Hotokezaka et al. 2013b, for the theoretical predictaions; Please see Jin et al. 2015 for the first observed multi-epoch/band macronova lightcurve). The radio emission caused by the sub-relativistic outflow is expected to peak in years after the merger (Nakar & Piran 2011). However, for the electromagnetic counterpart discovered in the optical/radio survey, it is not realistic to estimate when the signal can be discovered. The extensive discussion on the detection prospect of various signals with current on upcoming detectors/telescopes is beyond the scope of this work (one can instead see Metzger & Berger (2012) for detailed discussion). For the current purpose, we simply take the “expected peak” time of the late time signal (i.e., if the peak time is longer than 1 day) to estimate the prospect to constrain the difference between the gravitational wave speed and the speed of light.

Approximately we can conclude that if the photon signal associated with the GW radiation is (the prompt GRB emission, on-beam forward shock emission, macronova emission), $\Delta T_{\rm a}$ is expected to be in the orders of ($\sim 0.01 - 1$ s, $0.01 - 1$ day, $1 - 10$ days), respectively. The expected constraints on ς are illustrated in Fig.2.

As noticed by Metzger & Berger (2012), macronova emission may be the most frequently-detectable electromagnetic signal of the merger events. The detection of the macronova emission, say, at $t \sim 1$ day (i.e., $\Delta t_{\rm a} \sim 10^5$ s) after the merger will yield the constraint $|\varsigma| \leq 2.5\times10^{-12}(D/400~{\rm Mpc})$, which improves the constraint set by the Hulse-Taylor binary pulsar (Finn & Sutton 2002) by ~ 10 orders of magnitude.

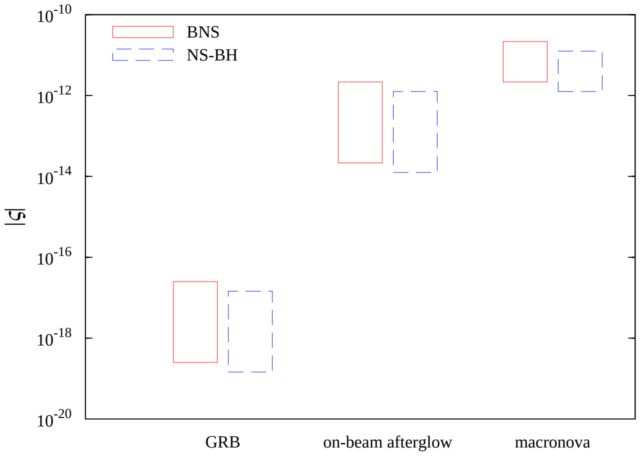

Fig. 2.— Expected constraints on the difference between the GW propagation velocity and the speed of light (i.e., $|\varsigma|$) in the cases of different kinds of electromagnetic counterparts. The solid and dashed rectangles are for binary neutron star mergers and neutron star-stellar-mass black hole mergers, respectively.

5. DISCUSSION

SGRBs are widely believed to be powered by the mergers of compact object binaries. Note that the BH−NS merger rate is generally expected to be $\sim 1/10$ times that of the NS−NS merger rate (Abadie et al. 2010). Hence most SGRBs are expected to be from NS−NS mergers and a small fraction of events may be due to NS−BH mergers. Though in the upcoming era of advanced LIGO/VIRGO network the prospect of detecting GW-associated SGRBs is promising, none of the nearby (i.e., $z < 0.2$) SGRBs are found within the sensitivity distance of the upcoming advanced LIGO/VIRGO network $D_{*,\rm BNS} \approx 400$ Mpc $(9/\rho_*)$ for $\rho_* \geq 9$. Such a non-identification, though still understandable (see eq.(3)), is somewhat disappointing. Interestingly, we find out that GRB 060505, one supernova-less long event (also known as long-short GRB), if powered by a NS-NS merger, is likely within the distance of $D_{*,\rm BNS}(\rho_* \approx 9)$. The other long-short burst GRB 060614, accompanied with a macronova signal that is plausibly powered by a NS−BH merger, is within the distance of $D_{*,\rm NS-BH}(\rho_* \approx 9)$. Therefore in the era of GW astronomy, the compact object binary merger origin of some long-short GRBs, as favored by the macronova signature displayed in GRB 060614, will be unambiguously tested. We hence suggest that both SGRBs and long-short GRBs are prime targets of the advanced LIGO/VIRGO network and $\gamma-$ray detectors with wide field of views are encouraged to monitor the sky continually to get the accurate information of the prompt emission properties.

In the era of the advanced LIGO/VIRGO, reasonably large NS-NS merger GRB sample and NS-BH merger GRB sample are establishable (see Sec.2). Motivated by such a fact, we have examined the possible distribution/relation of $\Delta t_{\rm a}$ and T_{90} for each sample or alternatively the distribution of $\Delta t_{\rm a}$, the delay between the binary coalescence and the onset of the associated GRB emission. As summarized in Tab. 1, in the case of $R_{\rm pro} \ll 10^{16}$ cm that represents the scenarios of photospheric radiation and regular (magnetized) internal shock radiation, it is expected that (1) for NS-NS mergers $\Delta t_{\rm a}$ is significantly longer than that of the NS-BH mergers, i.e., $\Delta t_{\rm a}({\rm NS-BH}) \ll \Delta t_{\rm a}({\rm NS-NS})$; (2) for NS-BH mergers, usually $\Delta t_{\rm a}$ is expected to be shorter than T_{90}, i.e., $\Delta t_{\rm a}({\rm NS-BH}) < T_{90}$. While for $R_{\rm pro} \sim 10^{16}$ cm, we expect that $\Delta t_{\rm a}$ should be comparable with T_{90} for both NS-NS and NS-BH merger powered SGRBs. The comparison with future real data will be helpful in revealing the central engine physics.

To tightly constrain the difference between the GW velocity and the speed of light, the shorter $\Delta T_{\rm a}$ the better (see Sec.4). If the electromagnetic counterpart of GW signal is GRB, we have $\Delta T_{\rm a} = \Delta t_{\rm a}$. The shortest $\Delta t_{\rm a}$ is expected for the prompt BH formation in the NS-NS mergers or the NS-BH mergers if the onset of the prompt GRB emission is governed by the photosphere or regular internal shocks (i.e., $R_{\rm pro} \ll 10^{16}$ cm). Due to the low detection rate of GRB accompanied GW signals, the first electromagnetic counterpart of GW signal is likely the macronova. The detection of the macronova emission at $t \sim 1$ day after the merger will yield the constraint $|\varsigma| \sim 10^{-12}$, which would be significantly tighter than the current constraint set by the Hulse-Taylor binary pulsar.

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