The merger-driven gamma-ray bursts (GRBs) and their associated gravitational-wave (GW) radiation, if both are successfully detected, have some far-reaching implications, including, for instance: (i) the statistical comparison of the physical properties of the short/long-short GRBs with and without GW detection can test the general origin model; (ii) revealing the physical processes taking place at the central engine; (iii) measuring the velocity of the gravitational wave directly/accurately. In this work, we discuss these implications in the case of a possible association of GW150914/Gamma-ray Burst Monitor (GBM) transient 150914. We compared GBM transient 150914 with other SGRBs and found that such an event may be a distinct outlier in some statistical diagrams, possibly due to its specific binary black hole merger origin. However, the presence of a “new” group of SGRBs with “unusual” physical parameters is also possible. If the outflow of GBM transient 150914 was launched by the accretion onto the nascent black hole, the magnetic activity rather than the neutrino process is likely responsible for the energy extraction, and the accretion disk mass is estimated to be \( \sim 10^{-5} M_\odot \). The GW150914/GBM transient 150914 association, if confirmed, would provide the first opportunity to directly measure the GW velocity, and its departure from the speed of the light should be within a factor of \( \sim 10^{-17} \).

Key words: binaries: close – gamma-ray burst: general – gravitation

1. INTRODUCTION

The mergers of compact object binaries are known to be promising gravitational-wave (GW) sources and are prime targets of the advanced Laser Interferometer Gravitational-wave Observatory (LIGO)/Virgo network (e.g., Clark & Eardley 1977; Abbott et al. 2016a). Such mergers involving neutron stars are also widely believed to be the physical origin of SGRBs (e.g., Eichler et al. 1989; Piran 2004; Kumar & Zhang 2015) that lasted typically shorter than 2 s in the soft \( \gamma \)-ray band (Kouveliotou et al. 1993). After the discovery of the so-called long-short events GRB 060505 and in particular GRB 060614 (both are apparently long-lasting but do not show any signal of supernovae down to very stringent limits; see Fynbo et al. 2006), it had been suspected that the compact object mergers could produce these peculiar events as well (Della Valle et al. 2006; Gal-Yam et al. 2006; Gehrels et al. 2006; Zhang et al. 2007). Before 2015 September due to the lack of direct detection of GWs, the evidence for the compact object merger origin of SGRBs are from the observations of their afterglows and host galaxies (Berger 2014). The most important indirect evidence may be the identification of Li-Paczynski macronovae/kilonovae (e.g., Li & Paczynski 1998; Metzger et al. 2010; Barnes & Kasen 2013), arising from the radioactive decay of \( r \)-process material synthesized in the ejecta that is launched during the mergers, in SGRB 130603B (Berger et al. 2013; Tanvir et al. 2013), long-short GRB 060614 (lsGRB 060614; Jin et al. 2015; Yang et al. 2015), and SGRB 050709 (Jin et al. 2016), which in turn suggests that compact object mergers do take place. Interestingly, the macronova/kilonova modeling of the signals in lsGRB 060614 and SGRB 050709 favors the mergers of neutron star–black hole binaries. The expected advanced LIGO/Virgo sensitivity range for neutron star–black hole merger events is about twice that of the binary neutron star merger events (Abbott et al. 2016a).

Benefiting from such an “improvement,” lsGRB 060614 and possibly also lsGRB 060505 are within the expected advanced LIGO/Virgo sensitivity range (Li et al. 2016). Such a finding is very encouraging for the people interested in establishing GRB/GW associations since no known SGRB has been found within the advanced LIGO/Virgo sensitivity range for a binary neutron star system (e.g., Clark et al. 2015). The detection rate of GRB/GW association by the advanced LIGO/Virgo network in its full performance is estimated to be \( R_{\text{GRB/GW}} \sim 1 \text{yr}^{-1} \) and that GRB/GW association is widely expected not to be formally established until 2020.

On 2015 September 14 at 09:50:45 UTC, the two detectors of the LIGO simultaneously detected a transient GW signal sweeping upward in frequency from 35 to 250 Hz with a peak GW strain of \( 1.0 \times 10^{-21} \) and matching the waveform predicted by general relativity for the inspiral and merger of a pair of \( \sim 30 M_\odot \) black holes and the ringdown of the single newly formed massive black hole (Abbott et al. 2016b). This great event is known as GW150914, which is the first direct detection of GWs and the first identification of a binary black hole merger (Abbott et al. 2016b). Surprisingly, the Fermi Gamma-ray Burst Monitor (GBM) observations at the time of GW150914 revealed the presence of a weak gamma-ray transient 0.4 s after the GW event was recorded (i.e., the delay between the GW signal and the GRB onset is \( \delta t \sim 0.4 \text{ s} \)), with a false-alarm probability of 0.0022 (Connaughton et al. 2016). This weak but hard gamma-ray transient lasted \( T_s \sim 1 \text{s} \) and its localization, though poorly constrained, is consistent with that of GW150914. With the luminosity distance \( D \sim 410 \text{ Mpc} \) of GW150914, the isotropic-equivalent energy of the gamma-ray transient released between 1 keV and 10 MeV is of \( L_e = 1.8^{+1.5}_{-1.0} \times 10^{49} \text{ erg} \text{s}^{-1} \), which is also typical for SGRBs (Connaughton et al. 2016). Nevertheless, we call the possible \( \gamma \)-ray event “GBM transient 150914” rather than “SGRB 150914” because the simultaneous observations by INTEGRAL...
Figure 1. Upper and lower panels are for the “correlation” between the rest-frame peak energy $E_{\text{p,rest}}$ and the isotropic total energy $E_{\text{iso}}$, and the luminosity $L_{\text{iso}}$ of SGRBs, respectively. The filled circles represent the short GRBs with measured redshifts and spectral parameters updated up to 2016 January 1, the open circles represent GRB 150906B at different redshifts (see also Zhang et al. 2015), and the red pentagram represents GBM transient 150914. The red dashed rectangle represents the possible distribution of spectral peak energy and isotropic energy/luminosity for GBM transient 150914. The solid and dashed lines are adopted from Figures 8 and 9 of Zhang et al. (2012), which mark the allowed regions inferred from these early data. Some data are taken from Zhang et al. (2012, 2015), Gruber (2012), and Gruber et al. (2014), and some are analyzed in this work.

(Savchenko et al. 2016) did not yield a similar signal (see Compton et al. 2016 for a possible solution of the tension between these observation results). In this work, we focus on the implications of the association between GW150914 and the possible GBM transient 150914.

2. SOME GENERAL IMPLICATIONS OF THE GRB/GW ASSOCIATION

The GRB/GW association, if established, has some far-reaching implications, including, for instance:

1. A test of the merger origin of the “old” or too far SGRBs/lSGRBs: The neutron star merger model for SGRBs/lSGRBs has been supported by host galaxy and afterglow observational data and in particular by the macronovae/kilonovae identified in SGRB 130603B, lSGRB 060614, and SGRB 050709. Nevertheless, this observational evidence is indirect. The GW signal associated with some SGRBs/lSGRBs, if detected in the future, will provide the direct evidence for neutron star merger scenario of these specific events. The comparison of these “new $\gamma$-ray events” with the previous SGRBs/lSGRBs can serve as a valid test of the merger origin of these (old) events without GW data. If these new $\gamma$-ray events with an accompanying advanced LIGO/Virgo GW signal are found to be similar to the (old) events without GW data in many aspects, the merger scenario for SGRBs/lSGRBs will be strongly supported (the same also holds for the events in the era of advanced LIGO/Virgo but beyond the sensitivity range of GW detectors). This implication, though it looks to be apparent, is non-trivial in view of the relatively low detection rate of the GRB/GW association in the full-performance stage of advanced LIGO/Virgo (i.e., $R_{\text{GRB/GW}} \sim 1 \text{ yr}^{-1}$, which is much smaller than the SGRB/lSGRB detection rate that is $\sim$40 per year for Fermi-GBM), with which the sample of GRB/GW associations is expected still to be small in the next decade and the universal connection between SGRBs/lSGRBs and mergers cannot be directly established.

2. Constraining the mass of the accretion disk of the GRB and revealing the energy extraction process of the central engine: The energy output of the GRB central engine (an accretion disk + central black hole system) depends on $M_{\text{BH}}$, the accretion rate ($\dot{M}$), the spin of the black hole ($a$), and possibly also the structure of the disk. With the electromagnetic observational data, the energy output of the central engine can be reasonably inferred, which, however, is not sufficient to break the degeneracies among parameters of $(M_{\text{BH}}, \dot{M}, a)$, as stressed in Fan & Wei (2011). Therefore, without additional assumptions, it is not possible to estimate the accretion disk mass ($M_{\text{disk}}$) with the electromagnetic data alone. Fortunately, the situation for neutron star merger-driven GRBs could be much better. For some relatively “nearby” SGRBs/lSGRBs with high-quality GW data, the masses of the binary stars (and sometimes even the mass of the formed accretion disk) can be inferred (Kiuchi et al. 2010), with which $M_{\text{BH}}$ and $a$ of the newly formed black hole can be reasonably evaluated (Lee et al. 2000). We can thus estimate $\dot{M}$ and $M_{\text{disk}}$ in the neutrino model and in the magnetic process model, respectively (see Section 3.2 for an illustration). If the GW data have been able to yield a reliable $M_{\text{disk}}$, we can compare it with the estimated one and then distinguish between the energy extraction process. Otherwise, if the $M_{\text{disk}}$ found in a given model is significantly more massive than $\sim 0.1 M_{\odot}$ (the upper limit of $M_{\text{disk}}$ found in current numerical simulations), it is reasonable to rule out such a scenario.

3. Directly measuring the velocity of the gravitational wave: In general relativity the velocity of GW ($v_{\gamma}$) is the speed of light ($c$). However, various gravity theories have been proposed in the literature and the GW velocity can be different from $c$ (see Will 1998 and the references therein). The subluminal movement of gravitons has been extremely tightly constrained (i.e., $\zeta \equiv (c - v_{\gamma})/c \lesssim 2 \times 10^{-15}$) by the absence of gravitational Cherenkov radiation of the ultrahigh-energy cosmic rays.
Figure 2. “Expected” afterglow emission of GBM transient 150914, which are “generated” from the R-band (upper panel) and X-ray (lower panel) afterglow emission of several nearby SGRBs. The modifications include the corrections of fluxes due to the distance and $z$ shifts and the factor of $\sim 2 \times 10^{49}$ erg/$E_{\text{iso}}$ to roughly correct the difference arising from different $E_{\text{iso}}$ (according to the afterglow model: Piran 2004; Kumar & Zhang 2015), where the subscript $i$ represents a given GRB presented in the figure. The X-ray and optical afterglow data are taken from Fong et al. (2015). The $3\sigma$ upper limit of X-ray emission following GW150914 (Serino et al. 2016) is also marked.

detected on the Earth (Moore & Nelson 2001). However, in the case of superluminal movement (i.e., $v_{\text{g}} > c)$, currently the constraint is still “loose,” i.e., $(v_{\text{g}}-c)/c < 4 \times 10^{-3}$ (Baskaran et al. 2008). The GRB/GW association, if established, can directly improve the constraint on the superluminal movement by many orders of magnitude.

3. IMPLICATIONS OF THE GRB/GW ASSOCIATION: THE CASE OF GW150914/GBM TRANSIENT 150914

3.1. Is GBM Transient 150914 Different from Other SGRBs?

An SGRB nature of the transient 150914 is favored in the Fermi-GBM data analysis (Connaughton et al. 2016; see, however, Savchenko et al. 2016). If indeed associated with GW150914, the luminosity \( L_{\gamma} \approx 1.8^{+0.5}_{-1.0} \times 10^{49} \text{ erg s}^{-1} \) is in the low end of the distribution (with a duration of $\sim 1$ s we have $E_{\text{iso}} \sim 2 \times 10^{49} \text{ erg}$) while the spectral peak energy $E_{\text{peak}} \sim 3 \text{ MeV}$, however, is very high (note that a Comptonized spectrum model yields $E_{\text{peak}} \sim 3.5^{+1.5}_{-1.1} \text{ MeV}$ and the single power-law spectrum fit to the data up to the energy $\sim 4$ MeV gives an index of $-1.4^{+0.12}_{-0.21}$). As already noted in Ruffini et al. (2015) and Zhang et al. (2015), the previous statistics of SGRBs (e.g., Zhang et al. 2012; Tsutsui et al. 2013; Berger 2014; D’Avanzo et al. 2014) found a typical $E_{\text{iso}} \sim 10^{51}$ erg and $L_{\gamma} \sim 10^{52}$ erg s$^{-1}$ for $E_{\text{peak}} \sim (1 + z)E_{\text{peak}} \sim 1 \text{ MeV}$. Then, the relatively low $L_{\gamma}$ and $E_{\text{iso}}$ of the GBM transient 150914 likely renders it to be a distinguished outlier. To better check whether it is indeed the case, we have updated our previous analysis (i.e., Zhang et al. 2012) with a significantly extended sample of SGRBs with well-measured $E_{\text{peak}}$ and redshift ($z$). Our new $E_{\text{p,rest}}-E_{\text{iso}}$ and $E_{\text{p,rest}}-L_{\gamma}$ diagrams are given in Figure 1, where a possible nearby event GRB 150906B (Golenetskii et al. 2015; Levan et al. 2015) is also included. Interestingly, we found that the current diagrams are not well consistent with the tight correlations of $E_{\text{p,rest}}-E_{\text{iso}}$ and $E_{\text{p,rest}}-L_{\gamma}$ reported in, for example, Zhang et al. (2012; i.e., see the previous allowed regions marked by dashed lines in Figure 1). In particular, there seems to be a new sub-group of low $L_{\gamma}$ ($E_{\text{iso}}$) but high $E_{\text{p,rest}}$ SGRBs,$^4$ such as GRB 080905A (Gruber 2012), GRB 150906B (if indeed at a distance of $\sim 52$ Mpc to the Galaxy; Ruffini et al. 2015; Zhang et al. 2015), and the GBM transient 150914. Among our current sample, GRB 090510 has the highest $E_{\text{p,rest}} \sim 8.4 \text{ MeV}$. Thanks to the very dense prompt emission, GRB 090510 is still marginally consistent with the $E_{\text{p,rest}}-E_{\text{iso}}$ and $E_{\text{p,rest}}-L_{\gamma}$ correlations (e.g., Zhang et al. 2012; Tsutsui et al. 2013; D’Avanzo et al. 2014). The GBM transient 150914 may have the second highest $E_{\text{p,rest}}$, but its $E_{\text{iso}}$ and $L_{\gamma}$ are in the low end of the distribution, rendering such a source the most outstanding outlier of the $E_{\text{p,rest}}-E_{\text{iso}}$ and $E_{\text{p,rest}}-L_{\gamma}$ correlations (even if GRB 150906B is at $z = 0.01$, GBM transient 150914 is a more distinct outlier).

There are however some cautions. The location of GW150914 is poorly constrained; for all 11 positions along the LIGO arc analyzed by Connaughton et al. (2016) a power law is adequate to fit the spectrum of the transient. The $E_{\text{peak}}$ reported in Connaughton et al. (2016) is from the Comptonized model fit assuming a source position at the northeastern tip of the southern lobe. Such a fit is not statistically preferred over the power law; and hence $E_{\text{peak}}$ is uncertain. Savchenko et al. (2016) analyzed the data of INTEGRAL/SPY-ACS and reported upper limits on the fluence at the time of the event ranging from $2 \times 10^{-8}$ erg cm$^{-2}$ to $10^{-9}$ erg cm$^{-2}$ in the 75 keV–2 MeV energy range for GRB spectral models (assuming two standard hard and soft GRB spectra with parameters $\alpha = -0.5$, $\beta = -1.5$, $E_{\text{peak}} = 1000 \text{ keV}$ and $\alpha = -1.5$, $\beta = -2.5$, $E_{\text{peak}} = 500 \text{ keV}$) and sky positions. Greiner et al. (2016) reanalyzed the GBM data with PGStat and suggested that the GBM transient 150914 may be not an astrophysical event and the spectrum (fluence) is likely softer (lower) in comparison with typical short-hard GRBs. The best-fit spectral indices for positions along the LIGO arc cover the range $-1.93$ to $-1.5$ (with large errors) and the fluence covers the range $8 \times 10^{-8}$ erg cm$^{-2}$ to $2.7 \times 10^{-7}$ erg cm$^{-2}$ in the 10–1000 keV energy range (see Table 1 of Greiner et al. 2016). Motivated by these results, we consider a soft spectrum with $E_{\text{peak}} \sim 500 \text{ keV}$ and $E_{\text{iso}} \sim 4 \times 10^{52}$ erg as the low end of the possible distribution. As shown in Figure 1, a transient with such parameters may still be “atypical” in the diagrams unless $E_{\text{peak}} \lesssim 100 \text{ keV}$.

GBM transient 150914, if indeed associated with GW150914, has a binary black hole merger origin different from other SGRBs that are believed to be powered by either double neutron star mergers or black hole–neutron star mergers. Therefore, the dissimilarities in the prompt emission may reflect the different underlying physical processes. The other non-trivial possibility is that there is a group of SGRBs with low $L_{\gamma}$ and $E_{\text{iso}}$ but high $E_{\text{p,rest}}$ that are hard to detect unless take place “nearby” (i.e., $z < 0.1$). The nearby GBMs are

$^4$ Indeed this possibility may be favored over the previous one since the chance to detect the first burst of a brand-new population in coincidence with the first GW event should be tiny.
rare in number, accounting for the rarity of such a group of “emerging” events. So far, GBM transient 150914 is the unique candidate from a double black hole merger. Its GRB 060614 and SGRB 050709 likely had a black hole–neutron star merger origin (Yang et al. 2015; Jin et al. 2016). For the rest of the SGRBs/lsGRBs, the progenitor stars are unknown, and statistical studies in different kinds of mergers are not possible.

In next decade when a reasonably large sample of GRBs with known origin is available, a statistical study of the prompt emission properties in different merger scenarios may better reveal the physical processes powering gamma-ray transients.

After the GRB there should be relatively long-lasting afterglow emission. Instead of numerically estimating the forward shock afterglow, we “generate” the expected emission with some nearby SGRBs, i.e., we collected the data of several nearby GRBs and converted them to the distance and roughly also the $E_{\text{iso}}$ of GBM transient 150914 to get an “overview” of the expected afterglow brightness (please see Figure 2). For optical telescopes with a sensitivity of ~24th mag, the optical afterglow of GBM transient 150914 might be detectable within ~1 day after the burst. Due to the lack of a wide-field sensitive X-ray monitor, with a very large location error, the detection of the forward shock X-ray afterglow emission is challenging. The prospect could be enhanced if there were X-ray flares, as observed in other GRB afterglows. The searches for optical and X-ray emission following GW150914 yielded null results, partly due to the inaccurate location (e.g., Serino et al. 2016; Smartt et al. 2016).

### 3.2. The Mass of the Accretion Disk Launching the Outflow of GBM Transient 150914

A SGRB-like electromagnetic signal from a stellar-mass black hole binary merger is unexpected, as noted in Connaughton et al. (2016). A speculative scenario is as follows: these two ~30 $M_\odot$ black holes had “massive” disks. Some disk material survived in the merger and accreted onto the nascent ~60 $M_\odot$ black hole in a few seconds. Hence ultra-relativistic outflow was launched and the subsequent energy dissipation produced soft gamma-ray emission, as in the case of normal GRBs (e.g., Piran 2004; Kumar & Zhang 2015). The other more speculative scenario is the reconnection of the magnetic fields confined in the two colliding disks. Alternative astrophysical scenarios giving rise to GW150914/GBM transient 150914 association can be found in the literature (e.g., Loeb 2016; Perna et al. 2016). Instead of figuring out a detailed physical model of the prompt emission, below we estimate the mass of the accretion disk launching the outflow of GBM event 150914 (in this work we do not discuss the charged black hole model and refer the readers to Zhang 2016 and Savchenko et al. 2016).

For the brief high-energy transients, like GRBs, it is rather hard to estimate $M_{\text{disk}}$ with the electromagnetic data alone since that the energy output of the central engine depends on ($M_{\text{BH}}$, $M$, $a$) while the electromagnetic observational data alone cannot break the degeneracies among these three parameters. For double neutron star mergers, the parameters of $M_{\text{BH}}$ and $a$ can be relatively reasonably speculated, with which $M$ and hence $M_{\text{disk}}$ can be inferred (Fan & Wei 2011; Liu et al. 2015). Nevertheless, these earlier approaches are based on the “hypothesized” $M_{\text{BH}}$ and $a$. For GBM transient 150914, such approximations are not needed any longer. With the GW data, the newly formed black hole of GW150914 is found to have a mass $M_{\text{BH}} \sim 62 M_\odot$ and a spin $a \sim 0.67$.

Below, we discuss the process(es) launching the outflow and then estimate $M_{\text{disk}}$.

In general, there are two kinds of physical processes that may launch ultra-relativistic energetic outflows. One invokes the neutrino/anti-neutrino annihilation (i.e., $\nu + \bar{\nu} \to e^+ e^-$; Eichler et al. 1989; Ruffert & Janka 1998). The other is the magnetic processes, for example, the Blandford & Znajek (1977) mechanism. We adopt an empirical relation of the neutrino/anti-neutrino annihilation luminosity proposed by Zalamea & Beloborodov (2011), for $a = 0.67$ which gives

$$L_{\nu, \bar{\nu}} \approx 1.4 \times 10^{49} \text{erg s}^{-1} \dot{m}^{5/4} \left(\frac{M_{\text{BH}}}{62 M_\odot}\right)^{-3/2},$$

where the accretion rate is defined as $\dot{m} = \dot{M} / M_{\text{BH}}$ s$^{-1}$. To account for the observed luminosity $L \sim 4 \times 10^{47}$– $2 \times 10^{49}$ erg s$^{-1}$ of GBM transient 150914, we need $\dot{m} \sim 0.2$–1.2, which is too high to be realistic. If the outflow of GBM transient 150914 is highly collimated with an opening angle of $\theta_{1/2} \sim 0.1$, we have $\dot{m} \sim 0.1 (L_{\gamma}/10^{49} \text{erg s}^{-1})^{1/3} (\theta_{1/2}/0.1)^{5/9}$ and hence an accretion disk mass

$$M_{\text{disk,\theta}} \approx 0.1 (L_{\gamma}/10^{49} \text{erg s}^{-1})^{1/3} (\theta_{1/2}/0.1)^{8/9} M_\odot,$$

which seems still be too high to be reasonable. We conclude that the neutrino/anti-neutrino annihilation process is disfavored.

The magnetic processes are known to be more efficient in launching relativistic outflow from hyper-accreting black holes (e.g., Fan et al. 2005; Liu et al. 2015 and the references therein) and hence may be favored for the current event. In the Blandford & Znajek (1977) mechanism, the outflow luminosity is estimated to be (see also Lee et al. 2000)

$$L_{\text{BZ}} \approx 4 \times 10^{47} (a/0.67)^2 (\dot{m}/10^{-4}) \text{ erg s}^{-1}.$$  

If collimated into a half-opening angle of $\theta_{1/2} \sim 0.1$, the observed luminosity will be $L \sim 2L_{\text{BZ}}/\theta_{1/2}^2 \sim 10^{50} (a/0.67)^2 (\dot{m}/10^{-4})(\theta_{1/2}/0.1)^{-2} \text{ erg s}^{-1}$, which can account for the observation of GBM transient 150914 if

$$M_{\text{disk,BZ}} \sim 10^{-5} (L_{\gamma}/10^{49} \text{ erg s}^{-1}) M_\odot.$$  

Such a massive transient accretion disk may suggest that the binary black holes were in a dense medium. For example, the double black hole binary system could be formed in a short distance capture (i.e., a black hole–star binary captures the other black hole) and the dense medium was ejected from the star when the black holes merged (T. Piran 2016, private communication; see also the talk at https://gw150914.aei.mpg.de/program/hsi-pirans-talk). The material fallback from the collapse when the black hole formed can produce massive disks, too (J. Katz 2016, private communication). However, the fallback accretion is not expected to last very long time. Hence, the merger should take place in a short time, which might be possible in some specific scenarios (e.g., Loeb 2016; Perna et al. 2016). As for the specific single-star model (Loeb 2016), the challenge is how to give rise to a $\delta t$ as short as 0.4 s (Woosley 2016).
Comparing with the bounds summarized in Table 1 of Li et al. 2016).

3.3. Measuring Gravitational-wave Velocity and Constraining the Graviton Mass

In general relativity theory, the speed of a GW is the same as c. In other theories, the speed of a GW however can differ from c, and one interesting possibility is that the gravitation was propagated by a massive field. The non-zero graviton mass induces a modified GW dispersion relation and hence a modified group velocity that can be parameterized as (e.g., Will 1998) \( v_g^2 = (1 - m_g^2 c^4/E^2)c^2 \), where \( m_g \) and \( E \) are the graviton rest mass and energy (usually associated with its frequency via the quantum mechanical relation \( E = hf \), where \( h \) is Planck’s constant and \( f \) is the frequency), respectively. In general, we define the parameter \( \zeta = (c - v_g)/c \) and a bound can be set by (e.g., Will 1998; Nishizawa & Nakamura 2014; Li et al. 2016)

\[
|\zeta| \leq 10^{-17} \left( \frac{410 \text{ Mpc}}{D} \right) \left( \frac{\delta t}{0.4 \text{ s}} \right)
\]

(3)

Previously, limits on the speed of GWs had been set indirectly in several model-dependent ways. The solar system bound on the graviton mass yields a \( |\zeta| \leq 10^{-8} \) (Larson & Hiscock 2000) and the bounds from pulsar timing is \( |\zeta| \leq 4 \times 10^{-3} \) (Baskaran et al. 2008). If the GW velocity is subluminal, then cosmic rays lose their energy via gravitational Cherenkov radiation and cannot reach the Earth. The observed ultrahigh-energy cosmic rays that have an extragalactic source also suggests a \( |\zeta| \leq 2 \times 10^{-19} \text{ or } \leq 2 \times 10^{-15} \), respectively (Caves 1980; Moore & Nelson 2001). Clearly our direct constraint on \( |\zeta| \) is much tighter than the solar system or the Galactic constraints. The full performance of the advanced LIGO/Virgo network in the 2020s is expected to be able to improve the constraint on \( |\zeta| \) by a factor of \( \sim 100 \), which can be comparable with the bound set by the extragalactic ultrahigh-energy cosmic rays.

The corresponding constraint on the mass of graviton is

\[
m_g \leq 8 \times 10^{-22} \text{ eV} \left( |\zeta|/10^{-17} \right)^{1/2} (f/50 \text{ Hz}),
\]

(4)

and the bound on graviton Compton wavelength \( \lambda_g = h/m_g c \) is

\[
\lambda_g \gtrsim 2 \times 10^{17} \text{ cm}.
\]

Comparing with the bounds summarized in Table 1 of Goldhaber & Martin Nieto (2010), our constraints on \( m_g \) and \( \lambda_g \) are weaker than some specific evaluation.

4. DISCUSSION AND CONCLUSION

Due to the (expected) low detection rate of GRB/GW association in the full-performance stage of advanced LIGO/Virgo, it was widely believed that the GRB/GW association would not be reliably established until 2020. The merger-driven GRBs and their associated GW radiation, if both successfully detected, have some far-reaching implications, including, for instance: (i) testing the merger origin of the “old” or too far short and long-short GRBs via the comparison of the physical properties of the events with and without GW detection; (ii) constraining the mass of the accretion disk of the GRB and then revealing the energy extraction process of the central engine; (iii) measuring the GW velocity directly/accurately.

On 2015 September 14, the two detectors of LIGO simultaneously detected a transient GW signal GW150914 from the merger of a pair of \( \sim 30 M_\odot \) black holes (Abbott et al. 2016b). Usually a double black hole merger is unexpected to give rise to gamma-ray transient. The Fermi-GBM observations, surprisingly, found a weak SGRB-like transient, and the time/location coincidences favor the association between GW150904 and GBM transient 150914 (Connaughton et al. 2016). If correct, this would be the first time an SGRB originating from a double black hole merger could be identified and suggests that the merger of much more massive black holes binaries may give rise to high-energy transients that can serve as the electromagnetic counterparts of the GW signals.

We have compared GBM transient 150914 with other SGRBs with known redshift and well-measured \( E_{\gamma, \text{peak}} \) and found that such an event may be a distinct outlier in the \( E_{p, \text{rest}} \) distribution. The 

\[
E_{p, \text{rest}} = E_{p, \text{iso}} - L_v \nu_d
\]

diagrams (see Figure 1). The dissimilarities of GBM transient 150914 with other SGRBs might be attributed to its specific binary black hole merger origin. However, together with GRB 080905A and possibly also GRB 150906B (if indeed very nearby with a \( z \sim 0.01 \)), there might be a “new” group of SGRBs with low \( L_v \) and \( E_{\text{iso}} \) but high \( E_{p, \text{rest}} \) that are hard to detect unless they took place “nearby.” With the current limited sample of (nearby) SGRBs, it is hard to conclude whether the “peculiarity” of prompt emission of GBM transient 150914 is “intrinsic” or not (see Section 3.1).

The physical origin of GBM transient 150914 is unclear. A speculative process is the hyper-accretion of the disk material that survived in the merger onto the nascent black hole. Within such a scenario, we show that the outflow powering GBM transient 150914 was likely launched via some magnetic progresses. The mass of the newly formed black hole as well as its spin parameter inferred from the GW data (Abbott et al. 2016b) provide the first chance to evaluate the accretion rate/accretion disk mass without making additional assumptions on the needed physical parameters. The estimated accretion disk mass is \( \sim 10^{-5} (L_v/10^{49} \text{ erg s}^{-1}) M_\odot \), implying that the binary black hole progenitors were in a dense medium (see Section 3.2).

If confirmed, the association between GBM transient 150914 and GW150914 would also provide the first opportunity to directly measure the velocity of the GW, and the difference between the GW velocity and the speed of the light should be within a factor of \( 10^{-17} \) (see Equation (3) in Section 3.3; see also Ellis et al. 2016), which is nicely in agreement with the prediction of general relativity. With the successful performance of the advanced LIGO/Virgo network in the 2020s, the bound on \( |\zeta| \) is expected to be tightened by a factor of \( \sim 100 \).

Finally, we would like to point out that though we focus on the implications of the GRB/GW association in the tentative case of GW150914/GBM transient 150914, the approaches are general and can be directly applied to future GRB/GW events.

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