Draft version February 16, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11



# IMPLICATION OF THE ASSOCIATION BETWEEN GBM TRANSIENT 150914 AND LIGO GRAVITATIONAL WAVE EVENT GW150914

Xiang Li[1,2], Fu-Wen Zhang[3], Qiang Yuan[1], Zhi-Ping Jin[1], Yi-Zhong Fan[1], Si-Ming Liu[1], and Da-Ming Wei[1]
[1] Key Laboratory of dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Science, Nanjing, 210008, China.
[2] University of Chinese Academy of Sciences, Yuquan Road 19, Beijing, 100049, China.
[3] College of Science, Guilin University of Technology, Guilin 541004, China.

*Draft version February 16, 2016*

## ABSTRACT

On September 14, 2015 the two detectors of LIGO simultaneously detected a transient gravitational-wave signal GW150914 and the Fermi GBM observations found a weak short gamma-ray burst (SGRB)-like transient (i.e., the GBM transient 150914). The time and location coincidences favor the association between GW150904 and GBM transient 150914. We compared GBM transient 150914 with other SGRBs and found that such an event is indeed a distinct outlier in the $E_{\rm p,rest} - E_{\rm iso}$ and $E_{\rm p,rest} - L_\gamma$ diagrams ($E_{\rm iso}$ is the isotropic-equivalent energy, $L_\gamma$ is the luminosity and $E_{\rm p,rest}$ is the rest frame peak energy of the prompt emission), possibly due to its specific binary-black-hole merger origin. However, the presence of a "new" group of SGRBs with "low" $L_\gamma$ and $E_{\rm iso}$ but high $E_{\rm p,rest}$ is also possible. If the outflow of GBM transient 150914 was launched by the accretion onto the nascent black hole, we estimate the accretion disk mass to be $\sim 10^{-5}\ M_\odot$, implying that the binary black hole progenitors were in dense medium. The association between GBM transient 150914 and GW150914 also provides the first opportunity to directly measure the velocity of the gravitational wave. The difference between the gravitational wave velocity and the speed of the light is found to be smaller than a factor of $10^{-17}$, nicely in agreement with the prediction of general relativity theory.

*Subject headings:* gamma-ray burst: general—binaries: close—gravitation

## 1. INTRODUCTION

The mergers of compact object binaries are known to be promising gravitational wave sources and are prime targets of advanced LIGO/Virgo network (e.g., Clark & Eardley 1977; Aasi et al. 2013). Such mergers are also widely believed to be the physical origin of short Gamma-ray Bursts (e.g., Eichler et al. 1989; Piran 2004; Berger 2014; Kumar & Zhang 2015) that lasted typically shorter than 2 seconds in 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 (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; see Fynbo et al. (2006)), it had been suspected that the compact object mergers could produce these peculiar events as well (Gehrels et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006; Zhang et al. 2007). Before Sept. 2015, due to the lack of direct detection of gravitational wave, the evidence for the compact object merger origin of the short GRBs (SGRBs) are from the observations of their afterglows as well as host galaxies (see Berger 2014, for a review). The most important indirect evidence may be the identification of the so-called Li-Paczyński macronovae (e.g., Li & Paczyński 1998; Metzger et al. 2010; Barnes & Kasen 2013) in SGRB 130603B (Tanvir et al. 2013; Berger et al. 2013) and long-short GRB 060614 (Yang et al. 2015; Jin et al. 2015), which in turn suggests that comapct object mergers do take place.

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory (i.e., LIGO) simultaneously detected a transient gravitational-wave signal sweeping upwards in frequency from 35 to 250 Hz with a peak gravitational-wave 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. 2016). This great event is known as GW 150914, which is the first direct detection of gravitational waves and the first identification of a binary black hole merger (Abbott et al. 2016). Interestingly, the Fermi Gamma-ray Burst Monitor (GBM) observations at the time of GW150914 reveal the presence of a weak gamma-ray transient 0.4 s after the gravitational wave event was recorded (i.e., the delay between the GW signal and the GRB onset is $\delta t \sim 0.4$ s), with a false alarm probability of 0.0022 (Connaughton et al. 2016). This weak but hard gamma-ray transient lasted $T_\gamma \sim 1$ s and its localization, though poorly-constrained, is consistent with that of GW150914. With the luminosity distance $D \sim 410$ Mpc of GW150914, the isotropic-equivalent energy of the gamma-ray transient released between 1 keV and 10 MeV is of $L_\gamma = 1.8^{+1.5}_{-1.0} \times 10^{49}$ erg s$^{-1}$, which is also typical for SGRBs (Connaughton et al. 2016). The remarkable association between GW150914 and the almost simultaneous GBM short-duration gamma-ray transient (hereafter GBM transient 150914) has some far-reaching implications, which are the focus of this work.

This work is structured as the following. In Sec. 2 we examine whether the GBM transient 150914 is significantly different from other SGRBs. In Sec. 3 we estimate the mass of the accretion disk launching the

fwzhang@glut.edu.cn (FWZ), yzfan@pmo.ac.cn (YZF)

outflow of GBM transient 150914. In Sec. 4 we measure the velocity of gravitational wave and then set the bound on the mass of graviton. We summary our results with some discussions in Sec. 5.

## 2. IS GBM TRANSIENT 150914 DIFFERENT FROM OTHER SGRBS?

A SGRB nature of the transient 150914 is favored in the Fermi GBM data analysis (Connaughton et al. 2016). If indeed associated with GW150914, the luminosity $L_\gamma = 1.8^{+1.5}_{-1.0}\times10^{49}$ erg s$^{-1}$ is in the low end of the distribution (with a duration of $\sim 1$ s we have $E_{\rm iso}\sim 2\times10^{49}$ erg) while the spectral peak energy $E_{\rm peak}\sim 3$ MeV, however, is very high (Note that a Comptonized spectrum model yields $E_{\rm peak}\sim 3.5^{+2.3}_{-1.1}$ MeV and the single power-law spectrum fit to the data up to the energy $\sim 4$ MeV gives an index of $-1.4^{+0.18}_{-0.24}$). As already noticed in Ruffini et al. (2015) and Zhang et al. (2015), the previous statistics of SGRBs (e.g., Zhang et al. 2012) found a typical $E_{\rm iso}\sim 10^{51}$ erg and $L_\gamma \sim 10^{52}$ erg s$^{-1}$ for $E_{\rm p,rest}=(1+z)E_{\rm peak}\sim 1$ MeV. Then the relatively low $L_\gamma$ and $E_{\rm iso}$ 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 $E_{\rm peak}$ and redshift ($z$). Our new $E_{\rm p,rest}-E_{\rm iso}$ and $E_{\rm p,rest}-L_\gamma$ diagrams are in Fig.1, where a possible nearby event GRB 150906B (Golenetskii et al. 2015; Levan et al. 2015) is also included. Interestingly we found that the updated diagrams are not well consistent with the tight-correlations of $E_{\rm p,rest}-E_{\rm iso}$ and $E_{\rm p,rest}-L_\gamma$ reported in for example Zhang et al. (2012, i.e., the fit lines in Fig.1). In particular, there seems to be a new sub-group of low $L_\gamma$ ($E_{\rm iso}$) but high $E_{\rm p,rest}$ SGRBs, such as GRB 080905A, GRB 150906B (if indeed at a distance of $\sim 52$ Mpc to the Galaxy) and the GBM transient 150914. Among our current sample GRB 090510 has the highest $E_{\rm p,rest}\sim 8.4$ MeV. Thanks to the very dense prompt emission, GRB 090510 is still marginally consistent with the $E_{\rm p,rest}-E_{\rm iso}$ and $E_{\rm p,rest}-L_\gamma$ correlations. The GBM transient 150914 likely has the second highest $E_{\rm p,rest}$ but its $E_{\rm iso}$ and $L_\gamma$ are in the low end of the distribution, rendering such a source the most outstanding outlier of the $E_{\rm p,rest}-E_{\rm iso}$ and $E_{\rm p,rest}-L_\gamma$ correlations (Even if GRB 150906B is at $z=0.01$, GBM transient 150914 is a more distinct outlier). 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 $E_{\rm iso}$ but high $E_{\rm p,rest}$ that are hard to detect unless take place "nearby" (i.e., $z<0.1$). The nearby GRBs are rare in number, accounting for the rarity of such a group of "emerging" events. So far, GBM transient 150914 is the unique candidate from double black hole merger. GRB 060614 likely has a black hole-neutron star merger origin (Yang et al. 2015). For the rest SGRBs and long-short GRBs, 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.

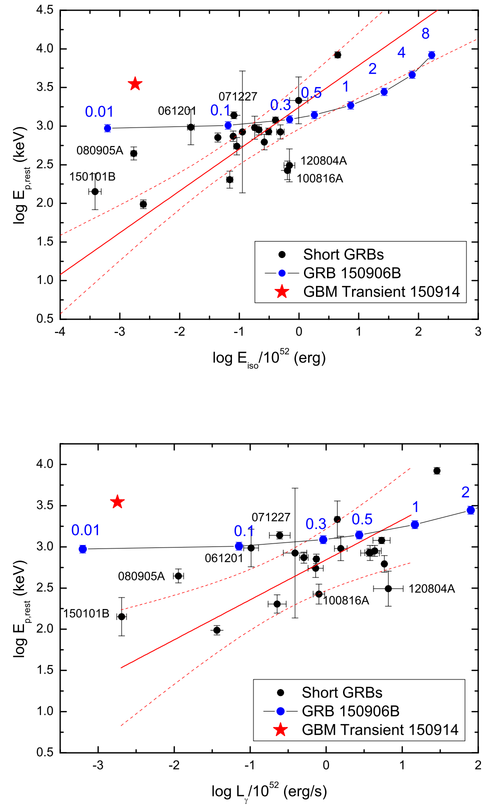


Fig. 1.— The Left and Right panels are for the "correlation" between the rest frame peak energy $E_{\rm p,rest}$ and the isotropic total energy $E_{\rm iso}$ and $L_\gamma$, respectively. The black circles represent the short GRBs with measured redshifts and spectral parameters updated up to Jan 1, 2016, the blue circles represent GRB 150906B at different redshifts (see also Zhang et al. 2015), and the red pentagram represents GBM transient 150914. The fit lines are taken from Fig.8 and Fig.9 of Zhang et al. (2012). Some data are taken from Zhang et al. (2012, 2015), Gruber (2012) and Gruber et al. (2014).

## 3. 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 noticed in Connaughton et al. (2016). A speculative scenario is the following: These two $\sim 30\ M_\odot$ black holes had "massive" disks. Some disk material survived in the merger and accreted onto the nascent $\sim 60\ M_\odot$ 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. 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.

For the brief high energy transients, like GRBs, it is rather hard to estimate the mass of the accretion disk ($M_{\rm disk}$) with the electromagnetic data alone. This is because usually the energy output of an accretion disk + central black hole system depends on $M_{\rm BH}$, 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 enough to break the degeneracies among parameters of ($M_{\rm BH}$, $\dot{M}$, $a$), as stressed in Fan & Wei (2011). For double neutron star mergers, the parameters of $M_{\rm BH}$ and $a$ can be relatively reasonably speculated, with which $\dot{M}$ and hence $M_{\rm disk}$ can be inferred (Fan & Wei 2011; Liu et al. 2015). Nevertheless, these earlier approaches are based on the "hypothesized" $M_{\rm BH}$ and $a$. For GBM transient 150914, such approximations are not needed any longer. With the gravitational wave data, the newly-formed black hole of GW150914 is fount to have a mass $M_{\rm BH} \sim 62~M_\odot$ and a spin $a \sim 0.67$. Below we discuss the process(es) launching the outflow and then estimate $M_{\rm disk}$.

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., $\nu\bar{\nu} \rightarrow e^+e^-$; 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

$$L_{\nu\bar{\nu}} \approx 1.4 \times 10^{49}~{\rm erg~s^{-1}}\dot{m}^{9/4}(\frac{M_{\rm BH}}{62 M_\odot})^{-3/2}, \qquad (1)$$

where the accretion rate is defined as $\dot{m} = \dot{M}/M_\odot~{\rm s^{-1}}$. To account for the observed luminosity $L_\gamma \sim 2 \times 10^{49}~{\rm erg~s^{-1}}$ of GBM transient 150914, we need $\dot{M} \sim 1~M_\odot~{\rm s^{-1}}$, which is too high to be realistic. If the outflow of GBM transient 150914 is highly collimated with an opening angle of $\theta_{\rm j} \sim 0.1$, we have $\dot{M} \sim 0.1(\theta_{\rm j}/0.1)^{8/9}~M_\odot~{\rm s^{-1}}$ and hence an accretion disk mass

$$M_{{\rm disk},\nu\bar{\nu}} \sim 0.1(\theta_{\rm j}/0.1)^{8/9}~M_\odot,$$

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 Blandford & Znajek (1977) mechanism, the outflow luminosity is estimated to be (see also Lee et al. 2000)

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

If collimated into an half-opening angle of $\theta_{\rm j} \sim 0.1$, the observed luminosity will be $L_{\rm obs} \sim 2L_{\rm BZ}/\theta_{\rm j}^2 \sim 10^{50}~(a/0.67)^2(\dot{m}/10^{-4})(\theta_{\rm j}/0.1)^{-2}~{\rm erg~s^{-1}}$, which can account for the observation of GBM transient 150914 if $\dot{m} > 10^{-5}$. Correspondingly, the accretion disk should have a mass

$$M_{\rm disk,BZ} \sim 10^{-5}~M_\odot.$$

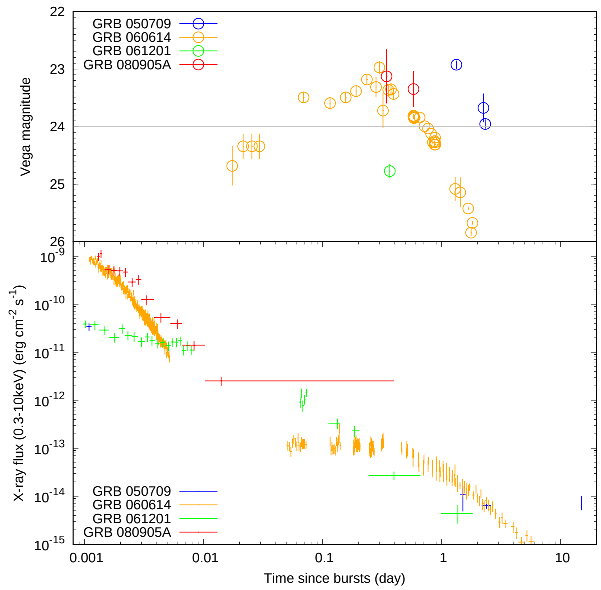


Fig. 2.— The R-band (upper panel) and X-ray (lower panel) afterglow emission of several nearby short GRBs after some modifications, including the corrections of fluxes due to the distance and $z$ shifts and the factor of $\sim 2 \times 10^{49}~{\rm erg}/E_{\rm iso,i}$ to roughly correct the difference arising from different $E_{\rm iso}$ (according to the afterglow model (Piran 2004; Kumar & Zhang 2015)), where the subscript $i$ represents a given GRB presented in the figure. The data are taken from Fong et al. (2015).

Such a massive transient accretion disk may suggest that the binary black holes were in dense medium. We would like to point out that $\delta t \sim 0.4$ s and $T_\gamma \sim 1$ s are indeed consistent with that expected in the scenario of "prompt" black hole formation + subsequent magnetic jet launching and energy dissipation for SGRBs (see Tab.1 of Li et al. 2016).

After the GRB there should be relatively long-lasting afterglow emission. Instead of numerically estimating the forward shock afterglow, we collected the data of several nearby GRB and converted them to the distance and roughly also the $E_{\rm iso}$ of GBM transient 150914 to get an "overview" of the expected afterglow brightness (please see Fig.2). One can see that for the optical telescopes with a sensitivity of $\sim$ 24th mag, the optical afterglow of GBM transient 150914 might be detectable within $\sim 1$ day after the burst. Due to the lack of wide-field sensitive X-ray monitor, with the 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.

## 4. MEASURING GRAVITATIONAL WAVE VELOCITY AND CONSTRAINING THE GRAVITON MASS

In general relativity theory, the speed of gravitational wave is the same as $c$. In other theories, the speed of gravitational wave however can 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 (e.g., Will 1998; Nishizawa & Nakamura 2014) $v_{\rm g}^2 = (1 - m_{\rm g}^2c^4/E^2)c^2$, 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, we define the parameter $\varsigma \equiv (c - v_{\rm g})/c$ and a bound can be set by (e.g., Will 1998; Li et al. 2016)

$$|\varsigma| \leq 10^{-17} \left(\frac{410 \text{ Mpc}}{D}\right)\left(\frac{\delta t}{0.4 \text{ s}}\right). \quad (3)$$

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

The corresponding constraint on the mass of graviton is

$$m_{\rm g} \leq 8 \times 10^{-22} \text{ eV } (|\varsigma|/10^{-17})^{1/2}(f/50 \text{ Hz}), \quad (4)$$

and the bound on graviton Compton wavelength $\lambda_{\rm g} = h/m_{\rm g}c$ is

$$\lambda_{\rm g} \geq 2 \times 10^{17} \text{ cm}. \quad (5)$$

Comparing with the bounds summarized in Table 1 of Goldhaber & Nieto (2010), our constraints on $m_{\rm g}$ and $\lambda_{\rm g}$ are weaker than some specific evaluation.

## 5. DISCUSSION AND CONCLUSION

On September 14, 2015 the two detectors of LIGO simultaneously detected a transient gravitational-wave signal GW150914 from the merger of a pair of $\sim 30M_\odot$ black holes (Abbott et al. 2016). 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 is the first time to identify a SGRB originated from a double black hole merger and in turn suggests that the merger of much more massive black hole binaries may give rise to high energy transients that can serve as the electromagnetic counterparts of the gravitational wave signals.

We have compared GBM transient 150914 to other SGRBs with known redshift and well measured $E_{\rm peak}$ and found that such an event is indeed a distinct outlier in the $E_{\rm p,rest} - E_{\rm iso}$ and $E_{\rm p,rest} - L_\gamma$ diagrams (see Fig.1). The dissimilarities of GBM transient 150914 with other SGRBs may 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 $L_\gamma$ and $E_{\rm iso}$ but high $E_{\rm p,rest}$ that are hard to detect unless they took place "nearby". With the current limited sample of (nearby) SGRBs, it is hard to conclude wether the "peculiarity" of prompt emission of GBM transient 150914 is "intrinsic" or not (see Sec.2).

The physical origin of GBM transient 150914 is unclear. A speculative process is the hyper accretion of the disk material 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 gravitational wave data (Abbott et al. 2016) 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 $\sim 10^{-5}\ M_\odot$, implying that the binary black hole progenitors were in dense medium (see Sec.3).

The association between GBM transient 150914 and GW150914 also provides the first opportunity to directly measure the velocity of the gravitational wave. The difference between the gravitational wave velocity and the speed of the light is found to be smaller than a factor of $10^{-17}$ (see eq.(3) in Sec.4), which is nicely in agreement with the prediction of the general relativity theory. With the successful performance of advanced LIGO/Virgo network in 2020s, the bound on $|\varsigma|$ is expected to be tightened by a factor of $\sim 100$.

## ACKNOWLEDGMENTS

This work was supported in part by National Basic Research Programme of China (No. 2013CB837000 and No. 2014CB845800), NSFC under grants No. 11525313 (i.e., the Funds for Distinguished Young Scholars), No. 11361140349, No. 11433009 and No. 11273063, the Foundation for Distinguished Young Scholars of Jiangsu Province, China (Grant No. BK2012047) and the Strategic Priority Research Program (Grant No. XDB09000000).

## REFERENCES

Aasi, J., Abadie, J., Abbott, B. P., et al. (LIGO Scientific Collaboration, Virgo Collaboration) 2013, arXiv:1304.0670
Abbott, B. P. et al. (LIGO Scientific Collaboration, Virgo Collaboration), 2016, Phys. Rev. Lett., 116, 061102
Baskaran, D., Polnarev, A. G., Pshirkov, M. S., and Postnov, K. A. 2008, Phys. Rev. D 78, 044018.
Bardeen, J. M., Press, W. H., & Teukolsky, S. A. 1972, ApJ, 178, 347
Barnes, J. & Kasen, D. 2013, ApJ, 773, 18.
Berger, E., Fong, W., & Chornock, R. 2013, ApJL, 744, L23
Berger, E., 2014, ARA&A, 52, 43
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Chen, W. X., & Beloborodov, A. M. 2007, ApJ, 657, 383
Clark, J. P. A., & Eardley, D. M., 1977, ApJ, 215, 311
Connaughton, V., et al. 2016, Nature submitted (http://gammaray.nsstc.nasa.gov/gbm/publications/preprints/gbm_ ligo_pre
Della Valle, M., Chincarini, G., Panagia, N., et al. 2006, Natur, 444, 1050
Eichler D., Livio M., Piran T., & Schramm D. N. 1989, Natur, 340, 126

Evans, P. A., Beardmore, A. P., Page, K. L., et al. 2009, MNRAS, 397, 1177
Fan, Y. Z., & Wei, D. M. 2011, ApJ, 739, 47
Fan, Y. Z., Zhang, B., & Proga, D. 2005, ApJL, 635, L129
Finn, L. S., & Sutton, P. J., 2002, Phys. Rev. D, 65, 044022
Fong, W. F. et al. 2015, ApJ, 815, 102
Fynbo, J. P. U., Watson, D., Thöne, C. C., et al. 2006, Natur, 444, 1047
Gal-Yam, A., Fox, D. B., Price, P. A., et al. 2006, Natur, 444, 1053
Gehrels, N., Norris, J. P., Barthelmy, S. D., et al. 2006, Natur, 444, 1044
Golenetskii, S. et al. 2015, GCN Circ. 18259 (http://gcn.gsfc.nasa.gov/gcn3/18259.gcn3)
Goldhaber, A. S., & Martin Nieto, M. M. 2010, Rev. Mod. Phys., 82, 939
Gruber, D., 2012, Proceedings of Science PoS (GRB 2012), 007 (http://arxiv.org/abs/1207.4620)
Gruber, D., et al. 2014, ApJS, 211, 12
Jin, Z. P., et al. 2015, ApJL, 811, L22
Kasen, D., Badnell, N. R. & Barnes, J. 2013, ApJ, 774, 25
Kouveliotou, C., C. A. Meegan, G. J. Fishman, N. P. Bhat, M. S. Briggs, T. M. Koshut, W. S. Paciesas, and G. N. Pendleton, 1993, ApJL, 413, L101
Kumar, P., & Zhang, B., 2015, PhR, 561, 1
Lee, W. H., Wijers, R. A. M. J., & Brown, G. E. 2000, Phys. Rep., 325, 83
Levan, A. J., Tanvir, N. R., & Hjorth, J., 2015, GCN Circ. 18263 (http://gcn.gsfc.nasa.gov/gcn3/18263.gcn3)
Larson, S. L., & Hiscock, W. A. 2000, Phys. Rev. D, 61, 104008
Li, L.-X., & Paczyński, B. 1998, ApJL, 507, L59
Li, X., Hu, Y. M., Fan, Y. Z., & Wei, D. M. 2016, arXiv:1601.00180
Liu, T., Lin, Y. Q., Hou, S. J., & Gu, W. M. 2015, ApJ, 806, 58
Metzger, B. D., Martínez-Pinedo, G., Darbha, S. et al. 2010, MNRAS, 406, 2650
Moore, G. D. and Nelson, A. E., 2001, JHEP, 0109, 023
Nishizawa, A., & Nakamura, T., Phys. Rev. D, 90, 044048
Piran, T., 2004, RvMP, 76, 1143
Ruffert, M., & Janka, H. T. 1998, A&A, 338, 535
Ruffini, R., et al. 2015, GCN Circ. 18296 (http://gcn.gsfc.nasa.gov/gcn3/18296.gcn3)
Tanvir, N. R., Levan, A. J., Fruchter, A. S. et al. 2013, Natur, 500, 547
Will, C. M., 1998, Phys. Rev. D., 57, 2061
Yang, B., Jin, Z. P., Li, X. et al. 2015, Nat. Commun., 6, 7323
Zalamea, I., & Beloborodov, A. M. 2011, MNRAS, 410, 2302
Zhang, B., Zhang, B. B., Liang, E. W. et al. 2007, ApJL, 655, L25
Zhang, F.-W., Shao, L., Yan, J.-Z., & Wei, D.-M. 2012, ApJ, 750, 88
Zhang, F.-W., Zhang, B., & Zhang, B. 2015, GRB Coordinates Network, 18298, 1 (http://gcn.gsfc.nasa.gov/gcn3/18298.gcn3)