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Very high energy afterglow of binary neutron star mergers

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The joint detection of GW170817 and a short gamma-ray burst (GRB) has provided the first direct evidence that binary neutron star (BNS) merger produces GRB. Recently and unprecedentedly, very-high-energy (0.1–10 TeV) afterglow emission were reported from a few GRBs (e.g. MAGIC, H.E.S.S. and LHAASO observations), suggesting the prospects of multi-messenger detection of gravitational-wave counterparts with the next-generation gamma-ray detectors. We study GW-TeV joint detectability of BNS merger using a population model prescribing the distribution of common parameters (e.g. energetics, viewing angle) in both gravitational-wave and very-high-energy afterglow emission. We report the expected distributions of observables (distances, orientations, energetics and ambient densities) for detectable events and the joint GW-TeV detection rate for the CTA project.

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1. Introduction

The joint detection of the BNS merger GW170817 and a short gamma-ray burst (GRB) 170817A demonstrated the promise to identify and interpret high energy counterparts of gravitational-wave (GW) sources. GRBs have been observed to emit radiation beyond GeV energies with no clear cutoff [1], including short GRBs such as GRB 090510 [2, 3]. Recently, gamma-ray emission up to very-high-energy (VHE, > 0.1 TeV) range has been discovered from several GRBs: 190114C and 160821B [4–6] by the MAGIC Telescope, 180720B and 190829A by H.E.S.S. [7, 8]. The VHE emission has been modeled with a synchrotron self-Compton (SSC) origin in forward shock afterglow [e.g., 9–11], while synchrotron or external IC origin are also suggested [e.g., 8, 12]. VHE search was performed for the GW170817 event starting 5 hours post-merger [13, 14] but no significant emission was found, which is likely due to the significant off-axis observation ($\gtrsim 20°$).

The prospects of GW follow-up observations with CTA has been explored in the literature, mainly by using the phenomenological extension of the high energy spectra of short GRBs [e.g., 15–18] Therefore, considerations such as SSC component, off-axis observation (as in GW170817) are not discussed in detail by previous studies. In this proceeding paper, we will present a quantitatively modeling of CTA's GW follow-up detectability of VHE afterglow from BNS merger, taking into account the SSC emission component and off-axis observation.

2. Model

2.1 GW sensitivity model

The reach of GW interferometer is characterized by its horizon distance $D_{\rm GW}$ with $D^2_{\rm GW} \equiv \mathcal{M}^{5/3} S_I$, where $\mathcal{M}$ is the chirp mass of the binary, S_I is a quantity solely depending on the sensitivity profile of the interferometer [19]. It is defined such that the signal from an optimally-located and oriented BNS at $D_{\rm GW}$ can produce a signal-to-noise ratio (SNR) of 8 by ideal matched filtering in the detector's data stream, corresponding to a 5σ detection. The general SNR of a GW signal can be written as

$$\rho^2(d_L, \theta, \phi, \psi, \iota) = \rho_0^2 \frac{D^2_{\rm GW}}{d_L^2} \Theta^2(\theta, \phi, \psi, \iota) , \tag{1}$$

where d_L is the luminosity distance to the binary, Θ^2 represents the angular response pattern to the sky location of the source (θ, ϕ, inclinations ι, polarization angles ψ relative to the detector) combining the antenna patterns with a global maximum of unity corresponding to an optimally positioned and oriented source. The explicit functional form of Θ are given in [20]. We could define the GW visibility distance $d_{\rm GW}$ as

$$d_{\rm GW} \equiv D_{\rm GW}\Theta \tag{2}$$

$$D_{\rm GW} = \max_{\theta,\phi,\psi,\iota} d_{\rm GW} . \tag{3}$$

The detection criteria is then written as

$$d_L < d_{\rm GW} . \tag{4}$$

2.2 VHE sensitivity model

The onset of VHE emission is expected to follow shortly (~ 1 s) after the gravitational waves from a BNS merger, but usually there is a delay time before the start of follow-up observations. Given the delay time $t_{\rm delay}$, we determine a detection by CTA by the following criteria resembling the instrument exposure:

$$\langle \mathcal{F}|_{\rm jet} \rangle \equiv \frac{1}{t_{\rm exp}} \int_{t_{\rm delay}}^{t_{\rm delay}+t_{\rm exp}} \mathcal{F}|_{\rm jet}\, dt > \mathcal{F}|_{\rm CTA}(t_{\rm exp}) \tag{5}$$

where $\mathcal{F}|_{\rm jet} = \mathcal{L}|_{\rm jet}/(4\pi d_L^2)$ is energy flux spectrum from a Gaussian jet afterglow, $F|_{\rm CTA}$ is the CTA 5σ differential sensitivity in the $0.1-10$ TeV energy band. The CTA sensitivities are computed by the public Python package `ctool`[1] for an exposure time of $t_{\rm exp}$. For compatibility with GW sensitivity model, we could similarly define the VHE visibility distance d as

$$d_{\rm EM} \equiv \sqrt{\frac{\mathcal{L}|_{\rm jet}}{4\pi \mathcal{F}|_{\rm CTA}}} \tag{6}$$

$$D_{\rm EM} \equiv \max_X d_{\rm EM} , \tag{7}$$

where $D_{\rm EM}$ is the marginally detectable distance with optimized parameter X of the burst. The detection criteria then becomes

$$d_L < d_{\rm EM} . \tag{8}$$

2.3 Joint detectability model

The GW-VHE joint detection rate of BNS events is estimated by the following equation:

$$\mathcal{R}_{\rm joint} = \int_0^\infty P_{\rm joint}(d_L) \frac{\mathcal{R}_{\rm BNS}(z)}{1+z} \frac{dV}{dz} dz . \tag{9}$$

Here $P_{\rm joint}$ is the *averaged* detection probability for a source located at luminosity distance $d_L(z)$, i.e., the detectable fraction of a BNS population sampled from the assumed parameter space X. We define the joint GW-EM visibility distance as:

$$d_{\rm joint} \equiv \min(d_{\rm GW}, d_{\rm EM}) \tag{10}$$

$$D_{\rm joint} \equiv \max_X d_{\rm joint} . \tag{11}$$

and we use a joint GW-EM detection criteria as:

$$d_L < d_{\rm joint} . \tag{12}$$

Then the detectable probability is given by

$$P_{\rm joint}(d_L) = \int_{d_L^2 < d_{\rm joint}^2} dX . \tag{13}$$

[1] http://cta.irap.omp.eu/ctools/

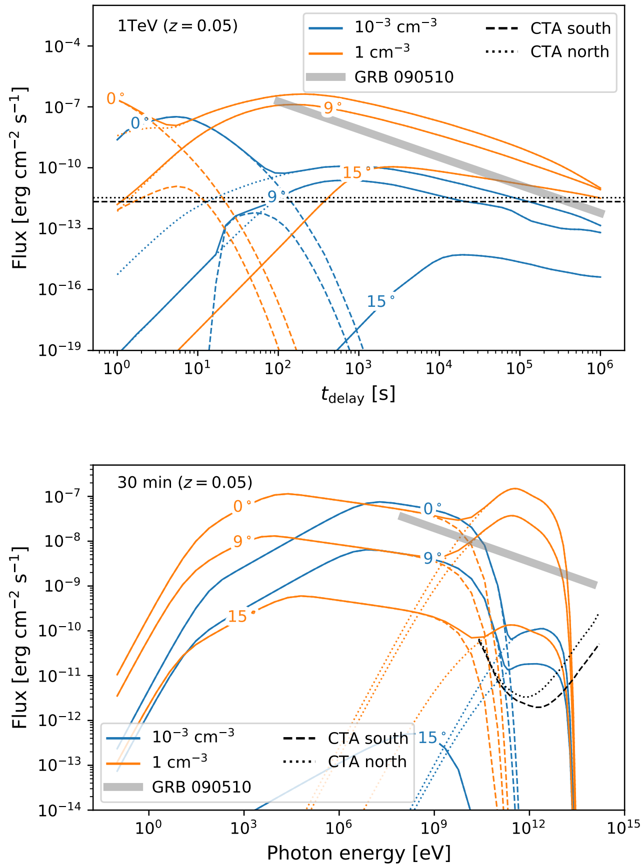

Figure 1: TeV light curves and multi-wavelength spectra from a simulated BNS merger event at $z = 0.05$, for various viewing angles and medium density. Contributions by synchrotron and SSC are indicated in dashed and dotted lines, respectively. 5σ sensitivities of CTA cites are compared assuming 30 min exposure and 20° zenith. The spectral extension of GRB 090510 is shown for comparison [2].

And the joint detection rate (ignoring cosmological evolution of BNS merger rate) is given by

$$\mathcal{R}_{\rm joint} \approx \frac{4\pi}{3}\mathcal{R}_{\rm BNS}\langle d^3_{\rm joint}\rangle_X \ . \tag{14}$$

The fraction of GW events also detectable by follow-up EM observation can be found by:

$$\frac{f_{\rm joint}}{f_{\rm GW}} = \frac{\left\langle d^3_{\rm joint}\right\rangle_X}{\langle d^3_{\rm GW}\rangle_X} \ . \tag{15}$$

One can derive the distributions of the observables x in the jointly-detected population with prior distribution $\mathcal{P}_x$:

$$\mathcal{P}_x|_{\rm joint} \equiv \frac{1}{\mathcal{R}_{\rm joint}}\frac{d\mathcal{R}_{\rm joint}}{dx} = \mathcal{P}_x\frac{\left\langle d^3_{\rm joint}\right\rangle_{X/x}}{\left\langle d^3_{\rm joint}\right\rangle_X} \ . \tag{16}$$

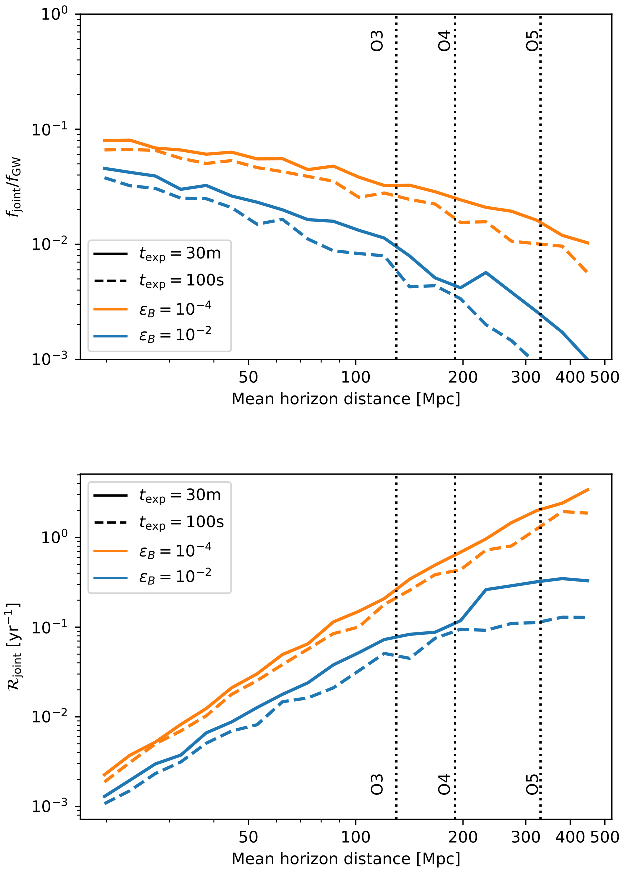

Figure 2: Upper: Jointly-detectable fraction within the GW detector reach. **Lower**: annual joint detection number versus GW detector reach. Local BNS merger rate of 320 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ is assumed [21].

Here $<>_{X/x}$ is the integral average over parameter set X but leaving out x as variable. We could use the function $\mathcal{M}_x$ defined as

$$\mathcal{M}_x \equiv \frac{\mathcal{P}_x|_{\rm joint}}{\mathcal{P}_x} = \frac{\left\langle d^3_{\rm joint}\right\rangle_{X/x}}{\left\langle d^3_{\rm joint}\right\rangle_X} \tag{17}$$

to indicate how the distribution $\mathcal{P}_x$ has changed under the GW-VHE joint observational bias.

3. Result and discussion

We use the Monte Carlo approach to evaluate GW-VHE joint detectability, by generating a large population ($> 10^5$) of BNS merger afterglow. Each event is defined by its random parameters, including short GRB parameters $X_{\rm sGRB} = E_0, \Gamma_0, \theta_j, n_0, \epsilon_e, \epsilon_B, p$ drawn from the distributions given by a decade of short GRB observations [22] and inclination parameters $X_{\rm incl} = \theta, \phi, \iota, \psi$ drawn from uniform distribution. Note that the shock electron and magnetic field parameters $\epsilon_e = 0.1$ and $\epsilon_B = 0.01$ are fixed in [22] due to their degeneracy with burst energy E_0 and density n_0 when

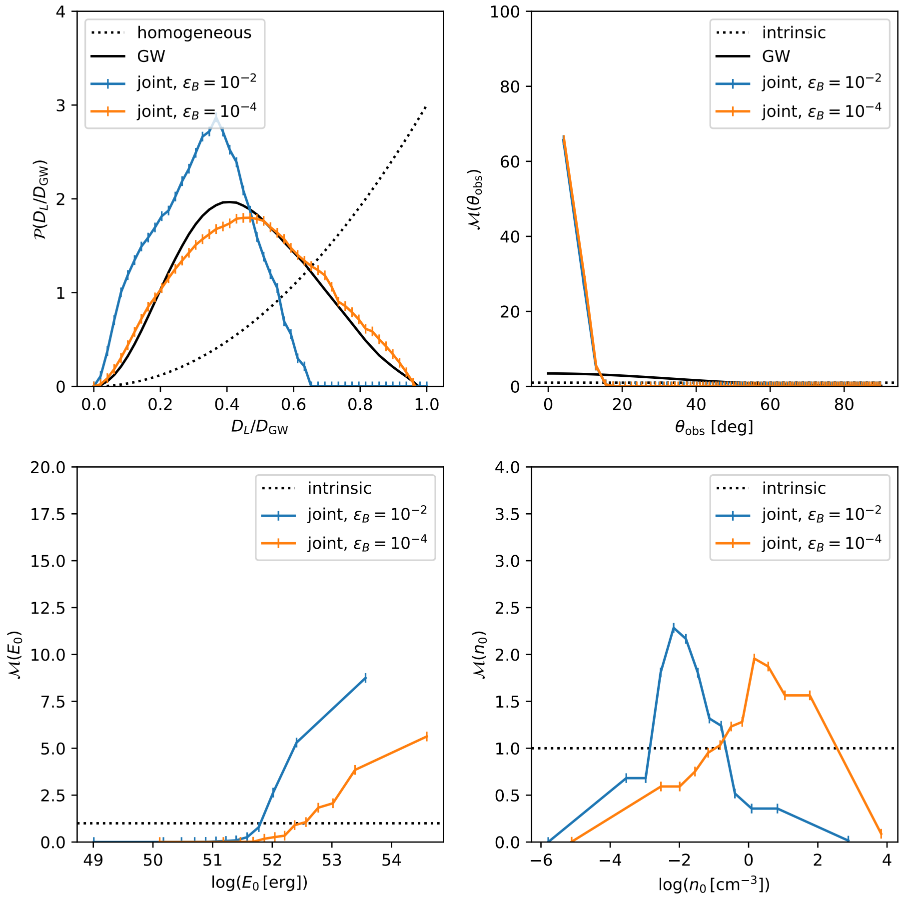

Figure 3: Upper left panel shows the luminosity distance distribution. **Other** panels show the observational bias indicator for viewing angle (upper right), isotropic energy (lower left) and CBM density (lower right) respectively, defined in (17) as the ratio of observed distribution $\mathcal{P}|_{\rm joint}$ to intrinsic distribution $\mathcal{P}$. Observational assumptions are 15-min delay and 30-min exposure.

reproducing the same synchrotron afterglow data, but they indicated that when choosing a value as low as $\epsilon_B = 10^{-4}$, the median of fitted E_0 and n_0 both increase by a factor of ≈ 10 compared to the $\epsilon_B = 0.01$ assumption. With such distribution, we tend to estimate a much brighter SSC component from the population, as the ratio of SSC to synchrotron luminosity scales with ϵ_e/ϵ_B [23]. Therefore, we additionally study an alternative BNS population with a choice of $\epsilon_B = 10^{-4}$ by manually scaling up E_0 and n_0 distribution by a factor of 10.

In Figure 1 we demonstrate TeV light curves and spectra powered by a Gaussian jet, taking into account attenuation by EBL absorption, compared with the extrapolated template of short GRB 090510 [2] that has been frequently used in previous CTA studies [e.g., 15–18]. We show two ambient densities are shown for typical values in old stellar populations ($n = 10^{-3}$ cm^{-3}) and in star forming regions ($n = 1$ cm^{-3}), respectively.

In Figure 2, we estimate the follow-up detectable fraction and the annual detection rate as a function of GW sensitivity (horizon distance). We find $f_{\rm joint}/f_{\rm GW} \lesssim 1\%$ for current and future sensitivities, and we estimate the joint detection rate by LIGO-CTA to be $\sim 0.1 - 2$ per year. This is an optimistic estimate since we do not take into account the duty cycle of the instruments. Assuming a fiducial duty cycle of 15% for CTA yields a smaller detection rate of $\sim 0.015 - 0.3$ per year.

In Figure 3, we show the probability density distribution of luminosity distance d_L to the sources, as well as the observational bias indicator $\mathcal{M}_x$ for viewing angle $\theta_{\rm obs}$, isotropic equivalent energy of the jet center E_0 and circumburst medium density n_0 defined in (17).

References

[1] M. Ackermann, M. Ajello, K. Asano, M. Axelsson, L. Baldini, J. Ballet et al., *The First Fermi-LAT Gamma-Ray Burst Catalog*, **209** (2013) 11 [1303.2908].

[2] M. De Pasquale, P. Schady, N.P.M. Kuin, M.J. Page, P.A. Curran, S. Zane et al., *Swift and Fermi Observations of the Early Afterglow of the Short Gamma-Ray Burst 090510*, **709** (2010) L146 [0910.1629].

[3] M. Ackermann, K. Asano, W.B. Atwood, M. Axelsson, L. Baldini, J. Ballet et al., *Fermi Observations of GRB 090510: A Short-Hard Gamma-ray Burst with an Additional, Hard Power-law Component from 10 keV TO GeV Energies*, **716** (2010) 1178 [1005.2141].

[4] MAGIC Collaboration, V.A. Acciari, S. Ansoldi, L.A. Antonelli, A. Arbet Engels, D. Baack et al., *Teraelectronvolt emission from the γ-ray burst GRB 190114C*, **575** (2019) 455 [2006.07249].

[5] MAGIC Collaboration, V.A. Acciari, S. Ansoldi, L.A. Antonelli, A.A. Engels, D. Baack et al., *Observation of inverse Compton emission from a long γ-ray burst*, **575** (2019) 459 [2006.07251].

[6] V.A. Acciari, S. Ansoldi, L.A. Antonelli, A. Arbet Engels, K. Asano, D. Baack et al., *MAGIC Observations of the Nearby Short Gamma-Ray Burst GRB 160821B*, **908** (2021) 90 [2012.07193].

[7] H. Abdalla, R. Adam, F. Aharonian, F. Ait Benkhali, E.O. Angüner, M. Arakawa et al., *A very-high-energy component deep in the γ-ray burst afterglow*, **575** (2019) 464 [1911.08961].

[8] H. E. S. S. Collaboration, H. Abdalla, F. Aharonian, F. Ait Benkhali, E.O. Angüner, C. Arcaro et al., *Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow*, *Science* **372** (2021) 1081 [2106.02510].

[9] E. Derishev and T. Piran, *The Physical Conditions of the Afterglow Implied by MAGIC's Sub-TeV Observations of GRB 190114C*, **880** (2019) L27 [1905.08285].

[10] N. Fraija, R. Barniol Duran, S. Dichiara and P. Beniamini, *Synchrotron Self-Compton as a Likely Mechanism of Photons beyond the Synchrotron Limit in GRB 190114C*, **883** (2019) 162 [1907.06675].

[11] X.-Y. Wang, R.-Y. Liu, H.-M. Zhang, S.-Q. Xi and B. Zhang, *Synchrotron Self-Compton Emission from External Shocks as the Origin of the Sub-TeV Emission in GRB 180720B and GRB 190114C*, **884** (2019) 117 [1905.11312].

[12] B.T. Zhang, K. Murase, P. Veres and P. Mészáros, *External Inverse-Compton Emission from Low-luminosity Gamma-Ray Bursts: Application to GRB 190829A*, **920** (2021) 55 [2012.07796].

[13] Fermi-LAT Collaboration, *Fermi-LAT observations of the LIGO/Virgo event GW170817*, *arXiv e-prints* (2017) arXiv:1710.05450 [1710.05450].

[14] H. Abdalla, A. Abramowski, F. Aharonian, F. Ait Benkhali, E.O. Angüner, M. Arakawa et al., *TeV Gamma-Ray Observations of the Binary Neutron Star Merger GW170817 with H.E.S.S.*, **850** (2017) L22 [1710.05862].

[15] I. Bartos, P. Veres, D. Nieto, V. Connaughton, B. Humensky, K. Hurley et al., *Cherenkov Telescope Array is well suited to follow up gravitational-wave transients*, **443** (2014) 738 [1403.6119].

[16] I. Bartos, T. Di Girolamo, J.R. Gair, M. Hendry, I.S. Heng, T.B. Humensky et al., *Strategies for the follow-up of gravitational wave transients with the Cherenkov Telescope Array*, **477** (2018) 639 [1802.00446].

[17] B. Patricelli, A. Stamerra, M. Razzano, E. Pian and G. Cella, *Searching for gamma-ray counterparts to gravitational waves from merging binary neutron stars with the Cherenkov Telescope Array*, **2018** (2018) 056 [1801.05167].

[18] I. Bartos, K.R. Corley, N. Gupte, N. Ash, Z. Márka and S. Márka, *Gravitational-wave follow-up with CTA after the detection of GRBs in the TeV energy domain*, **490** (2019) 3476 [1908.09832].

[19] L.S. Finn and D.F. Chernoff, *Observing binary inspiral in gravitational radiation: One interferometer*, **47** (1993) 2198 [gr-qc/9301003].

[20] B.F. Schutz, *Networks of gravitational wave detectors and three figures of merit*, *Classical and Quantum Gravity* **28** (2011) 125023 [1102.5421].

[21] R. Abbott, T.D. Abbott, S. Abraham, F. Acernese, K. Ackley, A. Adams et al., *Population Properties of Compact Objects from the Second LIGO-Virgo Gravitational-Wave Transient Catalog*, **913** (2021) L7 [2010.14533].

[22] W. Fong, E. Berger, R. Margutti and B.A. Zauderer, *A Decade of Short-duration Gamma-Ray Burst Broadband Afterglows: Energetics, Circumburst Densities, and Jet Opening Angles*, **815** (2015) 102 [1509.02922].

[23] R. Sari and A.A. Esin, *On the Synchrotron Self-Compton Emission from Relativistic Shocks and Its Implications for Gamma-Ray Burst Afterglows*, **548** (2001) 787 [astro-ph/0005253].