

Cherenkov Telescope Array is well suited to follow up gravitational-wave transients

I. Bartos,^{1,2★} P. Veres,^{3,4} D. Nieto,² V. Connaughton,⁵ B. Humensky,² K. Hurley,⁶ S. Márka,^{1,2} P. Mészáros,³ R. Mukherjee,⁷ P. O’Brien⁸ and J. P. Osborne⁸

¹*Department of Physics, Columbia University, New York, NY 10027, USA*

²*Columbia Astrophysics Laboratory, Columbia University, New York, NY 10027, USA*

³*Department of Astronomy and Astrophysics, Pennsylvania State University, University Park, PA 16802, USA*

⁴*George Washington University, Department of Physics, 725 21st St, NW, Washington, DC 20052, USA*

⁵*Center for Space Plasma and Aeronomic Research (CSPAR), University of Alabama in Huntsville, Huntsville, AL 35899, USA*

⁶*Space Sciences Laboratory, University of California-Berkeley, Berkeley, CA 94720, USA*

⁷*Department of Physics and Astronomy, Barnard College, Columbia University, New York, NY 10027, USA*

⁸*Space Research Centre, Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK*

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ABSTRACT

The first gravitational-wave (GW) observations will greatly benefit from the detection of coincident electromagnetic counterparts. Electromagnetic follow-ups will nevertheless be challenging for GWs with poorly reconstructed directions. GW source localization can be inefficient (i) if only two GW observatories are in operation; (ii) if the detectors’ sensitivities are highly non-uniform; (iii) for events near the detectors’ horizon distance. For these events, follow-up observations will need to cover 100–1000 deg^{−2} of the sky over a limited period of time, reducing the list of suitable telescopes. We demonstrate that the Cherenkov Telescope Array (CTA) will be capable of following up GW event candidates over the required large sky area with sufficient sensitivity to detect short gamma-ray bursts, which are thought to originate from compact binary mergers, out to the horizon distance of advanced LIGO/Virgo. CTA can therefore be invaluable starting with the first multimessenger detections, even with poorly reconstructed GW source directions. This scenario also provides a further scientific incentive for GW observatories to further decrease the delay of their event reconstruction.

Key words: gravitational waves – methods: observational – gamma-ray burst: general.

1 INTRODUCTION

Observing the electromagnetic counterparts of the first-detected gravitational-wave (GW) signals is one of the major goals of astronomy for the near future (Bloom et al. 2009; Kanner et al. 2012). Electromagnetic counterparts would greatly increase our confidence in the first detection, and could revolutionize our understanding of some cosmic phenomena (e.g. Abadie et al. 2012b; Evans et al. 2012; Bartos, Brady & Márka 2013; The LIGO Scientific Collaboration & The Virgo Collaboration 2014).

One of the most anticipated cosmic phenomena that is expected to result in the first GW detections is the merger of two compact stellar-mass objects, which are either neutron stars or black holes (Abadie et al. 2012a). Of special interest are binaries that consist of at least one neutron star, which can also produce electromagnetic radiation (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989; Lee &

Ramirez-Ruiz 2007; Bartos et al. 2013) as well as other messengers, such as cosmic rays or neutrinos (Waxman & Bahcall 1997; Bartos et al. 2011; He et al. 2012; Hümmel, Baerwald & Winter 2012; Ando et al. 2013; Murase, Kashiyama & Mészáros 2013).

Several promising emission processes have been suggested that would accompany compact binary mergers. First of all, short gamma-ray bursts (GRBs; Mészáros 2013) are thought to originate from these mergers. Gamma-rays can be produced in the outflows driven by an accreting black hole that forms in the merger (e.g. Nakar 2007). The afterglows of some of these short GRBs, produced by the interaction of the outflow with the ambient medium, represent an additional electromagnetic counterpart (Sari & Piran 1999; van Eerten & MacFadyen 2011). Further, energetic, sub or mildly relativistic outflows launched by a binary merger can also interact with the surrounding medium, producing quasi-isotropic emission in the radio band over a period of more than a year (Nakar & Piran 2011; Piran, Nakar & Rosswog 2013). The same outflow can also undergo *r*-process nucleosynthesis during its expansion, resulting in near-infrared–infrared radiation, called a kilonova (also

* E-mail: ibartos@phys.columbia.edu

called macronova; Li & Paczyński 1998; Kulkarni 2005; Metzger, Piro & Quataert 2008; Metzger et al. 2010; Berger 2013; Fernández & Metzger 2013; Kasen, Badnell & Barnes 2013; Tanvir et al. 2013).

With the available observational capabilities, a large fraction of the produced electromagnetic counterparts may only be detectable, if detectable at all, with follow-up observations guided by GW triggers (Kanner et al. 2008; van Eerten & MacFadyen 2011; Evans et al. 2012; LIGO Scientific Collaboration & Virgo Collaboration 2012; Metzger & Berger 2012; Bartos et al. 2013). The direction reconstruction of GW detectors, however, is limited to $\gg \text{deg}^2$ (LIGO Scientific Collaboration & Virgo Collaboration 2013). This substantially reduces the feasibility of many electromagnetic follow-up efforts, given the limited field of view of the most sensitive telescopes, and the limited sensitivity of larger-field-of-view telescopes. Nevertheless, a number of telescopes may be competitive at following up GW triggers with very low latency with strategies optimized to cover a significant fraction of the GW sky area. These include moderate-aperture telescopes with large field of view such as the BlackGEM Array¹ and the Ground Wide-Angle Cameras (GWAC; Götz et al. 2009) that will be dedicated to follow-up operations. Highly sensitive instruments with limited field of view, such as *Swift*, may also be promising follow-up facilities (Evans et al. 2012). Another interesting direction is the *Ultra Fast Flash Observatory (UFFO)* (Park et al. 2012), which will have a large field-of-view X-ray detector as well as sub-second optical follow-up capability.

Following up the first GW observations, probably around 2016–2018 (LIGO Scientific Collaboration & Virgo Collaboration 2013), will be particularly challenging. At this time, given the staged schedule of construction and commissioning of GW detectors, it is possible that direction reconstruction of the first detections will mainly rely on a two-detector network (or a three-detector network with highly non-uniform sensitivity; LIGO Scientific Collaboration & Virgo Collaboration 2013). This will substantially decrease the location accuracy of GW measurements, necessitating electromagnetic follow-ups with large, 100–1000 deg^2 , search areas at high sensitivity. Further, the direction of a GW event will typically be localized to multiple, disjoint sky regions at potentially distant parts of the sky, requiring follow-up observations to cover these separate sky regions. Radio follow-up observations, e.g. with the Square Kilometre Array (SKA; Ekers 2003) or LOFAR (de Vos, Gunst & Nijboer 2009), are another interesting alternative, given the expected long-lived radio emission following the binary merger (Piran et al. 2013).

In this paper, we propose and investigate the possibility for large-field-of-view electromagnetic follow-up observations of GW event candidates, using the Cherenkov Telescope Array (CTA; Actis et al. 2011). CTA is well suited for GW-follow-up observations for multiple reasons as follows.

(i) *Field-of-view*: CTA will be capable of monitoring a large sky area via survey-mode operation (either by pointing its telescopes in different directions, or by rapidly scanning a set of consecutive directions). It will be able to monitor the $\sim 1000 \text{ deg}^2$ area necessary for early GW triggers for which only an incomplete GW detector network is available. This survey mode will also be useful for later GW observations: since localization becomes less efficient with, e.g. decreasing signal-to-noise ratio (SNR), a significant fraction of GW event candidates will have large error regions even when more than two GW detectors are available.

(ii) *Coincident observational schedule*: CTA is expected to begin partial operation around 2017; therefore, it will probably be available to follow up the first GW detections. The anticipated completion of CTA is around 2020.

(iii) *Rapid response*: CTA has the capability to respond to target-of-opportunity requests and start monitoring the selected sky area within $\sim 30 \text{ s}$ (Dubus et al. 2013). This is important given the limited duration ($\lesssim 1000 \text{ s}$; Section 3) of high-energy photon emission connected with GRBs. The sensitivity of CTA to GRBs will be mainly determined by its so-called Large Size Telescopes (LST; Acharya et al. 2013), which are capable of the fastest response (180° slewing in less than 20 s; Inoue et al. 2013).

In the following, we discuss these points further in detail.

The use of CTA to follow up GW event candidates has been previously suggested by Doro et al. (2013). In this paper, we explore in detail the follow-up of GW event candidates by CTA, and the particular advantage of CTA in following-up poorly localized signals.

The paper is organized as follows. In Section 2, we discuss the expected sensitivity and localization capability of advanced GW detectors. In Section 3, we estimate the sensitivity of CTA for detecting short GRBs with known directions, exploring multiple emission models focusing on the distances relevant for GW detection. In Section 4, we describe the sensitivity of CTA in survey mode, focusing on directional uncertainties relevant for GW searches. Section 5 discusses the role of satellite-based GRB detectors in adding information to the follow-up process. Finally, Section 6 summarizes our results and presents our conclusions.

2 GW DETECTION FROM COMPACT BINARY COALESCENCES

2.1 Sensitivity

In order to understand the characteristic distances at which the first GW detections are anticipated, we briefly review the expected sensitivity of advanced GW detectors. This sensitivity is expected to be relatively low at the start of operation in 2015, and will gradually increase to design sensitivity towards 2019 (LIGO Scientific Collaboration & Virgo Collaboration 2013).

For estimating detection sensitivities, in the following, we focus on neutron star binary mergers. We will conservatively assume that all short GRBs originate from neutron star binary mergers, noting that the GW horizon distance for black hole–neutron-star mergers is greater. To characterize the sensitivity of a GW detector, we use the so-called horizon distance: the distance to which a source at optimal location and with optimal orientation is detectable with single-detector SNR 8 (e.g. Abadie et al. 2010). This SNR corresponds to a false alarm rate of $\ll 1 \text{ yr}^{-1}$ for a network of two detectors (LIGO Scientific Collaboration & Virgo Collaboration 2013), making it a useful limit for follow-up observations. We note here that direction-averaged sensitivity of a GW detector is ~ 1.5 times less than the horizon distance, which we take into account in detection rate estimates below. We assume that the rotation axes of the mergers approximately point towards the Earth, given that short GRBs are expected to be beamed. We consider a short-GRB rate of $\gtrsim 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$ for bursts that are beamed towards the Earth (Nakar, Gal-Yam & Fox 2006). Below we outline the GW observation schedule and detection prospects of neutron star binary mergers, based on the schedule presented by LIGO Scientific Collaboration & Virgo Collaboration (2013).

¹ <https://www.astro.ru.nl/wiki/research/blackgemarray>

2015: the horizon distance of Advanced LIGO (aLIGO) detectors during the first observation period in 2015 is expected to be limited: 90–180 Mpc. It is highly unlikely that a short GRB will occur within the corresponding detection volume of 10^{-4} – 10^{-3} Gpc³ during the expected 3 months of observation.

2016–2017: 6 months of joint aLIGO–Virgo observation run are envisioned, with aLIGO horizon distance of 180–270 Mpc, and a few times smaller horizon distance for Advanced Virgo. This corresponds to a detection volume of 0.01–0.02 Gpc³. Within this volume, there may be a binary neutron star merger during the observation time. A short GRB beamed towards the Earth within this volume is also possible (with probability $p \gtrsim 5$ –10 per cent).

2017–2018: an ~ 9 -months-long GW observation period will take place. The horizon distance of aLIGO will be 270–380 Mpc, twice as much as the sensitivity of Virgo. There will likely be multiple neutron star binary mergers within the corresponding detection volume of 0.03–0.1 Gpc³, with a good chance ($p \gtrsim 20$ –50 per cent) of a short GRB beamed towards the Earth within this volume and observation time.

2019+: extended observation at design sensitivity, with horizon distance ~ 450 Mpc. This corresponds to a detection volume of $\gtrsim 0.1$ Gpc³. On average, more than one short GRB beamed towards the Earth is expected within this volume for every year of operation. This sensitivity will likely further increase with the completion of additional GW detectors KAGRA (Kuroda 2011) and aLIGO India (LIGO Scientific Collaboration & Virgo Collaboration 2013).

2.2 Localization

The waveform of a GW signal detected by individual GW detectors is greatly degenerate with respect to source direction. To recover the direction of a GW event, multiple GW observatories are used, mainly taking advantage of the different time-of-arrival of the GW signal at different detectors (LIGO Scientific Collaboration & Virgo Collaboration 2013 and references therein).

In the literature, localization is mainly discussed for the case of three or more GW detectors with similar sensitivities (Cavalier et al. 2006; Röver, Meyer & Christensen 2007; Klimentko et al. 2011; Nissanke et al. 2011; Schutz 2011; Vitale & Zanolin 2011; Veitch et al. 2012; Nissanke, Kasliwal & Georgieva 2013). For the three-detector case, localization of a signal with single-detector SNR = 8 is typically ~ 100 deg² (90 per cent confidence; Fairhurst 2011). A fraction (~ 10 per cent) of the signals can be localized with higher precision (~ 10 deg²; LIGO Scientific Collaboration & Virgo Collaboration 2013; Nissanke et al. 2013). For black hole–neutron-star binaries, the black hole spin can further improve the precision of localization (van der Sluys et al. 2008; Raymond et al. 2009); spin, however, does not affect localization for neutron star binaries.

For cases in which the reconstructed sky region is too large for feasible follow-up, a possible strategy is to decrease the sky region by increasing the false dismissal rate of the observation.² In practice, the size of the reconstructed sky region can be significantly reduced if one focuses on encompassing a lower integrated confidence region. As an example, Klimentko et al. (2011), studying the localization of GW transients with three- and four-detector networks, found that the sky area corresponding to localization with

50 per cent confidence can be significantly smaller (up to $\times 10$) than the sky area encompassing 90 per cent confidence level (CL).

For the first observation runs with advanced GW detectors, as well as for some of the observation time later on, one can expect to have an essentially two-detector GW detector network. This will be the case early on due to the different construction schedules of aLIGO and Virgo, and partially later on due to the sub-100 per cent duty cycle of each individual observatory. It is therefore important to explore the localization capability of GW event candidates with using only two GW detectors.

Two-detector observations of GW sources, by only applying timing constraints, can constrain source direction to essentially a ring on the sky (van der Sluys et al. 2008; Fairhurst 2009; van der Sluys et al. 2009; Wen & Chen 2010; Fairhurst 2011). It is possible to further constrain the sky area by using amplitude and phase information (van der Sluys et al. 2009; Kasliwal & Nissanke 2014), but for practical purposes this will still leave a large localization uncertainty (Kasliwal & Nissanke 2014; LIGO Scientific Collaboration & Virgo Collaboration 2013) that is difficult to cover for many electromagnetic follow-up facilities. A recent numerical study by Kasliwal & Nissanke (2014), applying idealized Gaussian background noise and utilizing amplitude and phase information, shows that, using the two aLIGO detectors only, neutron star binary mergers with network-SNR > 12 can be localized to within 100–1000 deg² (with 95 per cent confidence), with a median localization of 250 deg².

A further complication is that the reconstructed sky area is typically discontinuous, due to the direction-dependent detector sensitivity. Parts of the sky area can be distributed over a large range of angles, raising an additional challenge to follow-up facilities.

Based on the results of Fairhurst (2011), we estimate the typical localization sky area for a two-detector network (LIGO Hanford and LIGO Livingston) to be ~ 2000 deg² for single-detector SNR = 8 at 90 per cent CL (Fairhurst 2011 considered two detectors at Hanford and one at Livingston; we converted this result to the two-detector-only case, which is $\sim \sqrt{3/2}$ greater). This sky area Ω scales with the SNR (see Wen & Chen 2010) and with CL (see Fairhurst 2011) as

$$\Omega \approx 2000 \text{ deg}^2 \left(\frac{8}{\text{SNR}} \right) \left(\frac{\text{erf}^{-1}(\text{CL})}{\text{erf}^{-1}(0.9)} \right), \quad (1)$$

where erf^{-1} is the inverse error function.

For sources within ~ 100 Mpc, another possible way of decreasing the localization uncertainty could be to focus on galaxy locations within the error region of the GW signal (e.g. Kanner et al. 2008). While this can decrease the set of directions that follow-up observatories need to survey, the benefit from focusing on galaxies decreases for larger distances and sky areas due to the following reasons: (i) for larger distances, the area–density of galaxies becomes comparable to the field of view of follow-up telescopes; therefore, there is no added benefit in looking at them individually; (ii) galaxy catalogues are incomplete beyond a few tens of megaparsecs (White, Daw & Dhillon 2011); therefore, the hosts of some GW events will be overlooked by a galaxy-based follow-up search; (iii) with a GW sky area of ~ 1000 deg², the number of galaxies within 200 Mpc is $\mathcal{O}(10^6)$ (Nissanke et al. 2013), making galaxy-based searches on this scale impractical for large sky areas.³

² That is, focusing on a smaller sky region, the probability that the real source direction is within this sky region becomes smaller.

³ Note that, for three or more available detectors and sufficiently high SNR, which is the likely case for some sources after ~ 2020 , galaxies will be useful even at the 200 Mpc scale (Nissanke et al. 2013).

3 DETECTING SHORT GRBS WITH CTA

So far multi-GeV electromagnetic emission has been detected only from a fraction of the short GRBs observed in the keV–MeV energy band (e.g. 081024B and 090510; Abdo et al. 2010b; Ackermann et al. 2010; Zhang et al. 2011). While this could be a consequence of their intrinsic emission mechanism, it could also be a result of the limited sensitivity of current high-energy gamma-ray observatories. Due to the limitations of available observations, in this section we calculate the multi-GeV photon emission from short GRBs based on their observed lower energy emission. Based on these calculations, we then estimate their detectability using the CTA (see Acharya et al. 2013 and references therein). We first consider the sensitivity of CTA when it is pointing at one particular direction. We then additionally take into account the effect of having a poorly reconstructed direction, and the change in sensitivity when the detector surveys an extended sky area.

3.1 The Cherenkov Telescope Array

The CTA is an international project leading to the realization of a new observatory for very high energy (VHE) gamma rays. CTA represents the next generation of imaging atmospheric Cherenkov telescopes (IACTs; for a historical review, see Hillas 2013), providing an order of magnitude improvement in sensitivity over the current-generation IACTs, along with improved angular and energy resolutions, and spanning about four decades in energy (from a few tens of GeV to above 100 TeV). CTA relies on the technique of imaging the Cherenkov light flashes emitted by the particle showers induced in the atmosphere by impinging gamma-rays, reconstructing the primary gamma-ray’s energy and arrival direction from several such images formed in the camera plane.

CTA plans to operate two sites, one in the Northern hemisphere and one in the Southern hemisphere, which together will provide full-sky coverage. Each installation will consist of an array of 50–100 telescopes in three different sizes, each one optimized for a particular energy range. CTA has begun its prototyping phase and the construction phase is expected to start in early 2015 with an estimated completion date of 2020, although the scientific studies may start as early as 2016.

It is worth noting that, for the first time in the field of ground-based VHE gamma-ray instruments, CTA will operate as an open observatory, allowing the entire scientific community to request observation time, as well as granting public access to the CTA data.

3.2 Observed multi-GeV photon emission from short GRBs

The Large Area Telescope on the *Fermi* satellite (hereafter *Fermi*-LAT; Atwood et al. 2009) has detected VHE emission from six short GRBs (out of ~ 70 GRBs detected at keV–MeV energies by the *Fermi* Gamma-ray Burst Monitor, hereafter *Fermi*-GBM; see public table⁴). Two of these were detected in the less stringent class of events, the LAT low-energy data, with the other four detected in a standard transient class analysis above 100 MeV. Two were seen above 1 GeV.

High-energy emission from short GRBs appears to be of two varieties: prompt emission that is coincident with the peaks seen in the *Fermi*-GBM data (though the first peak is often missing at high energies) and emission that persists for up to 100 s (Ackermann et al.

2010), decaying smoothly over time. Since *Fermi*-LAT is fluence limited, it is less likely to detect short GRBs, and thus the fraction of short-to-long GRBs seen in *Fermi*-LAT is much smaller (< 10 per cent) than that seen at lower, \sim MeV energies by *Fermi*-GBM (18 per cent). The fraction of high-energy emission ($\gtrsim 100$ MeV) to keV–MeV emission (in the band [10 keV, 1 MeV]), however, is higher for short GRBs than for long GRBs (well above 10 per cent, sometimes above 100 per cent compared to 10 per cent for long GRBs). This is mostly because the high-energy emission is extended in time whereas the prompt emission is contained within a 2 s period (see Abdo et al. 2010a). Thus, there appears to be a threshold effect for short GRBs based on the sensitivity of *Fermi*-LAT to the short-lived prompt emission, but those short GRBs that rise above the threshold exhibit interesting behaviour that makes them promising candidates for a more sensitive instrument, particularly in their long-lived emission.

Although of the short GRBs only GRB 090510 can be studied in detail, owing to poor the photon statistics for the other cases, the extended emission in LAT-detected GRBs in general appears to be spectrally harder than the prompt emission, with multi-GeV photons often detected hundreds of seconds after the prompt emission (e.g. Ackermann et al. 2014, 2013). LAT emission from the energetic GRB 090510 ($E_{\text{kin}} = 10^{53}$ erg) was observed for up to ~ 100 s (Ackermann et al. 2010; Zhang et al. 2011), indicating that longer duration, high-energy emission is possible even for short GRBs. This is in contrast with the prompt MeV-range emission of short GRBs, which typically lasts for less than one second.

The decay of the GeV light curves of GRBs (long and short) generally follows a power law in time, of index typically between -1.1 and -1.4 . This behaviour is the same as expected from the decay of an external shock afterglow (e.g. Ghisellini et al. 2010; Kumar & Barniol Duran 2010; Mészáros & Gehrels 2012). The typical photon spectral indices above the (\sim MeV) spectral peak are in the range of -2.1 to -2.6 , and in only one case has a high-energy spectral steepening been detected in the GeV range (in GRB 090926A; Ackermann et al. 2011). It is unclear whether this is due to source-intrinsic effects or to external absorption; there is no evidence for a spectral turnover or energy cutoff in any other *Fermi*-LAT GRB observed so far.

3.3 Possible origin and properties of multi-GeV photon emission

Only the first few seconds of the observed LAT emission could originate from a collisional photosphere (Beloborodov 2010), since the outflow duration is generally associated with the duration of the MeV prompt emission. Leptonic GeV emission by upscattering of photospheric soft photons by internal shocks (Toma, Wu & Mészáros 2011) or external shocks (Veres, Zhang & Mészáros 2013) could last longer than the photospheric emission, but at most by the angular time corresponding to the shock radius, $r_{\text{shock}}/c\Gamma^2$ (Γ is the Lorentz factor of the outflow), i.e. a few seconds to $\lesssim 10$ s – after that, the forward shock synchrotron and synchrotron-self-Compton emission would take over the GeV emission. In an external shock, the photon–photon self-absorption generally sets in at observer-frame photon energies \gtrsim TeV (Zhang & Mészáros 2001b); this is dependent on the bulk Lorentz factor (e.g. Ackermann et al. 2010; Hascoët et al. 2012), and it is additional to any external (induced by extragalactic background light, hereafter EBL) absorption, which also sets in at similar energies.

⁴ <http://fermi.gsfc.nasa.gov/>

Searches for TeV emission associated with GRBs so far have yielded only upper limits (e.g. Albert et al. 2006; Acciari et al. 2011; Abdo et al. 2012). The *Fermi*-LAT observation of 0.1 TeV photons from the nearby ($z = 0.3$) GRB 130427a shows that GRB spectra can extend up to \sim TeV energies, and GRBs are possible sources in this energy domain (e.g. Inoue et al. 2013).

Since CTA observations are expected to follow a GW trigger with a delay of ~ 100 s, we focus on the afterglow emission of GRBs, which also contains multi-GeV photons. The prompt emission observations can be facilitated by suitable precursor emissions, not uncommon in some cases of short GRBs (Troja, Rosswog & Gehrels 2010).

According to EBL models (Stecker, Malkan & Scully 2006; Domínguez et al. 2011), TeV photons at ~ 100 Mpc will not be significantly affected by pair annihilation with the EBL, while TeV sources from ~ 400 Mpc will have significant annihilation. Photons at sub-TeV energies (~ 0.1 TeV), coming from the largest sensitivity range of aLIGO/Virgo, will not be affected by EBL.

Since there has been no confirmed TeV-photon detection from GRBs so far, the spectral properties of GRBs in the TeV domain are largely uncertain. Nevertheless, for both short and long GRBs, there are cases in which a power-law component with a spectrum harder than $\gamma = -2$, $dN/dE \propto E^\gamma$ shows no cutoff up to multi-GeV energies (Abdo & The Fermi Collaboration 2009). This is encouraging for future CTA observations.

3.4 Observation latency

GeV emission is expected to start shortly after the merger of the compact binary, and it gradually fades away. CTA can therefore detect the most GeV photons if it commences the follow-up observation as soon as possible after the detection of the GW signal of the binary.

GW triggers for electromagnetic follow-up observations by initial LIGO/Virgo were distributed to observatories only $\gtrsim 10$ min after detection (Abadie et al. 2012b; Evans et al. 2012). The delay was mostly due to human monitoring.

An important ongoing effort for advanced GW analyses is the reduction of the latency of GW triggers distributed to follow-up observatories. Motivated by the electromagnetic emission following short GRBs shortly after the prompt emission, direction reconstruction methods aim to identify the sky area of GWs on less than a minute time-scales. For instance, BAYESTAR (Singer et al. 2014), a rapid direction reconstruction algorithm, was demonstrated to produce accurate sky areas in less than a minute after the detected merger of a binary neutron star. BAYESTAR will be used to reconstruct source directions from the beginning of advanced GW observations.

In future, the delay from GW detectors can decrease even further (Cannon et al. 2012). GW search algorithms will be capable of searching for the inspiral of a binary neutron star system even before its merger in practically real time. For sufficiently strong GW signals, this can allow for the detection and parameter estimation of the binary, even before the actual merger of the neutron stars, resulting in even shorter triggering of electromagnetic follow-ups.

Given the above delay of ~ 1 min for even early advanced GW observations, in the following we consider a conservative observational delay of $t_{\text{start}} = 100$ s following the binary merger, associated with a 1 min delay due to GW data analysis/detection and $\sim 1/2$ min delay due to the slewing of CTA. Nevertheless, we will also explore how changing t_{start} affects sensitivity.

3.5 Sensitivity of CTA

We estimate the sensitivity of CTA based on fig. 6 (upper; best performance curve) of Bernlöhr et al. (2013). This is the most recent public estimate of the sensitivity curve of CTA, produced by the CTA Monte Carlo working group using their baseline analysis method with the most up-to-date (public) Monte Carlo simulations of the array.

The GRB energy spectrum will likely cut off at some high-energy threshold (e.g. Zhang et al. 2011); therefore, we consider three scenarios, in which the cutoff energies are $E_{\text{cutoff}} = \{50, 100, 1000\}$ GeV. Up to these thresholds, we assume that the GRB photon energy spectrum follows a power law (see above). Since the expected differential sensitivity improves with photon energy faster than E^2 (Bernlöhr et al. 2013) in the energy range of interest, the greatest contribution to detection confidence will come from the highest energies just below the cutoff energy. We therefore conservatively approximate the sensitivity of the detector with its differential sensitivity in the highest energy bin below the threshold,⁵ noting that the integral sensitivity, using the complete energy range of the instrument, can be higher. For the $T_0 = 50$ h exposure shown by Bernlöhr et al. (2013), the expected differential sensitivity Φ_0 corresponding to the three energy thresholds is $E^2\Phi_0 = \{60, 17, 1.5\} \times 10^{-13}$ erg cm $^{-2}$ s $^{-1}$, respectively. Following the method described in Gou & Mészáros (2007), we calculate the sensitivity for an exposure time t_{exp} by determining the minimum fluence $\mathcal{F}(t_{\text{exp}})$ with which a source is detectable:

$$\mathcal{F} \approx \kappa \Phi_0 \left(\frac{T_0}{t_{\text{exp}}} \right)^{1/2} E_{\text{cutoff}}^2 t_{\text{exp}}, \quad (2)$$

where the constant $\kappa \leq 1$ depends on the width of the energy bin, as well as the spectral shape of the detector sensitivity and the photon flux from the source (it is ≤ 1 as long as the detector sensitivity decreases faster than the source spectrum). Below, we conservatively use $\kappa = 1$. In the following, we adopt a multi-GeV emission duration of $t_{\text{exp}} = 1000$ s. While this is longer than the duration of extended emission for observed for most GRBs, this may be due to the limited sensitivity of *Fermi*-LAT.

With $t_{\text{exp}} = 1000$ s, the limiting fluences for detection are

$$\mathcal{F}_{1000\text{s}} \approx \{80, 23, 2\} \times 10^{-9} \text{ erg cm}^2. \quad (3)$$

Above, the sensitivities are given for observations at 20° zenith angle (in the frame of CTA). The zenith angle will affect the lower energy threshold at which CTA becomes sensitive (e.g. Bouvier et al. 2011); therefore, at higher zenith angles, the source may be detectable only if its emission extends to higher energies.⁶ For simplicity, below we adopt the obtained sensitivities at 20° for our analysis.

3.5.1 CTA limits from synchrotron emission

Thus far, the prototypical short GRB with detected GeV-photon emission is GRB 090510 at $z = 0.9$ ($D_L = 5.8$ Gpc), for which the highest energy photon detected was 30 GeV (Abdo et al. 2009). With its duration of a few seconds, the prompt emission cannot be

⁵ Differential sensitivity is calculated by Bernlöhr et al. (2013) for energy intervals of equal log-scale width (0.2 in 10-based logscale). For cutoff energy E_{cutoff} , we take the energy interval ΔE to be $\Delta E = (1 - 10^{-0.2})E_{\text{cutoff}} \approx 0.37E_{\text{cutoff}}$.

⁶ Bouvier et al. (2011) approximated the lower cutoff energy to depend on the zenith angle as $\propto \cos(\theta_{\text{zenith}})^{-3}$.

Table 1. Fluence values for different emission and detection scenarios presented in the text, in units of 10^{-9} erg cm $^{-2}$, for different emission cutoff energies E_{cutoff} . CTA-detectable fluences for single pointing and survey mode (S_{det} , S_{survey}) are shown for 1000 s duration, and for 1000 deg 2 as well as 200 deg 2 observable sky area in the case of the survey mode (see Section 4.1). These detection fluences are calculated conservatively from the differential sensitivity of CTA (see text). For the fluence of synchrotron emission (S_{syn}), we take the parameters of GRB 090510, and an observation starting at $t_{\text{start}} = 100$ s after the binary merger and lasting for $t_{\text{duration}} = 1000$ s, except for the parameters stated explicitly in the table. For the fluence of SSC emission (S_{ssc}), we consider isotropic-equivalent GRB energy $E_{\text{kin}} = 10^{51}$ erg, an observation with $t_{\text{start}} = 100$ s and $t_{\text{duration}} = 1000$ s, and circumburst number density n stated in the table.

E_{cutoff} (energy cutoff)	50 GeV	100 GeV	1 TeV
S_{det} (CTA) (10^{-9} erg cm $^{-2}$)	80	23	2
S_{survey} (CTA - survey; 1000 deg 2)	800	230	20
S_{survey} (CTA - survey; 200 deg 2)	360	100	9
S_{syn} (GRB 090510-like; $D_L = 5.8$ Gpc)	50	40	20
S_{syn} (GRB 090510-like; $D_L = 300$ Mpc)	33 000	28 000	16 000
S_{syn} ($E_{\text{kin}} = 10^{51}$ erg; $D_L = 300$ Mpc)	190	160	90
S_{syn} ($E_{\text{kin}} = 10^{51}$ erg; $D_L = 300$ Mpc; $t_{\text{start}} = 30$ s)	360	310	170
S_{syn} ($E_{\text{kin}} = 10^{51}$ erg; $D_L = 300$ Mpc; $t_{\text{start}} = 10^3$ s)	30	25	14
S_{ssc} ($n = 10^{-1}$ cm $^{-3}$)	4400	5300	3700
S_{ssc} ($n = 10^{-3}$ cm $^{-3}$)	20	40	70

realistically observed by CTA in follow-up mode (a serendipitous pointing in the right direction at the right time could, nevertheless, lead to detection). The afterglow, however, is more promising. It follows a power-law decay (temporal index: $\alpha = -1.38$; De Pasquale et al. 2010), and it is detected with LAT up to ~ 100 s after the trigger.

We next estimate the total flux over a greater energy range and time interval, assuming that the observed emission around ~ 100 MeV and around ~ 100 s scale to higher energies (up to the threshold E_{CTA}) and longer duration (out to ~ 1000 s). For the energy spectrum, we extrapolate observations at 100 MeV of GRB 090510 to higher energies using the synchrotron emission by a shocked electron population with power-law index $p = 2.5$ (e.g. De Pasquale et al. 2010). For the time dependence, we extrapolate the flux of GRB 090510 at 100 s. We obtain the following initial flux:

$$\phi^{(090510)} \approx 5 \times 10^{-12} \text{ Jy} \left(\frac{t_{\text{start}}}{100 \text{ s}} \right)^{-1.38} \left(\frac{E_{\text{CTA}}}{50 \text{ GeV}} \right)^{-1.25}. \quad (4)$$

Starting the observations at $t_{\text{start}} = 100$ s (given the time delay due to the LIGO analysis and the slewing time of CTA), and observing for $t_{\text{duration}} = 1000$ s (characteristic duration of GeV-photon emission in GRB afterglows), yields a fluence of: $\mathcal{F} \approx 4.6 \times 10^{-8}$ erg cm $^{-2}$ for $E_{\text{cutoff}} = 50$ GeV and energy interval $[10^{-0.2} E_{\text{cutoff}}, E_{\text{cutoff}}]$.

For this burst, extrapolating the $\lesssim 1$ GeV afterglow spectrum to 50 GeV and beyond could be inaccurate, as for example in a simple synchrotron interpretation the maximum synchrotron energy is a decreasing function of time, and there may be a cutoff at these energies. If the synchrotron emission interpretation of the afterglow is correct, we expect a cutoff at $E_{\text{cutoff}} \approx 60(\Gamma/1000)$ GeV.⁷ Nevertheless, the presence and value of a cutoff at this point is uncertain, and the observed data do not necessitate a cutoff. We will therefore

⁷ This limit is obtained by equating the acceleration time-scale of the radiating electrons with their cooling time-scales (de Jager et al. 1996). The limit is dependent on acceleration efficiency.

also consider the speculative cases when the energy spectrum continues out to 0.1 and 1 TeV. We summarize the results for the cases discussed here in Table 1.

For the purposes of this study, we consider a GRB distance of 300 Mpc (characteristic distance at which aLIGO can detect a compact binary merger). GRB 090510 is a uniquely bright burst; thus, we also consider GRBs with lower kinetic energy. For fixed cutoff energy E_{cutoff} , the flux scales with distance and energy as (Granot & Sari 2002)

$$\phi^{\text{syn}} \propto E_{\text{kin}}^{(2+p)/4} D_L^{-2} (1+z)^{-(2+p)/4}. \quad (5)$$

We only list parameters important for our study and we do not consider varying microphysical parameters.

The fluence of a 090510-like GRB at $D_L = 300$ Mpc, observed with CTA from $t_{\text{start}} = 100$ s after trigger for a duration of $t_{\text{duration}} = 1000$ s is $\mathcal{F} \approx \{3.3, 2.8, 1.6\} \times 10^{-5}$ erg cm $^{-2}$ for the three cutoff energies. This is overwhelmingly bright, and can easily be detected by CTA. A more likely scenario for a GRB occurring at 300 Mpc is a burst with typical kinetic energy $E_{\text{kin}} \sim 10^{51}$ erg. The estimated fluence for this realistic case is shown in Table 1.

We also investigate the role of the time delay between the binary merger and the start of observations with CTA. To evaluate the possibility of a more delayed follow-up, we also consider an observation scenario for this typical burst for which the start of observation is $t_{\text{start}} = 1000$ s, with duration $t_{\text{duration}} = 1000$ s. We also consider the possible future scenario when GW observations are performed in quasi-real time, and GW event candidate triggers are distributed to astronomers with negligible delay. For this case, we consider a time delay of $t_{\text{start}} = 30$ s for the start of CTA observations. Results are shown in Table 1.

To consider a range of possible temporal delays, in Fig. 1 we show the detectability of GRBs ($E_{\text{kin}} = 10^{51}$ erg; $D_L = 300$ Mpc) with CTA as a function of t_{start} , with detectability defined as the ratio of GRB fluence over the detection threshold of CTA in survey mode. The results indicate that, for the lowest cutoff $E_{\text{cutoff}} = 50$ GeV, GRBs are only detectable with low delays ($t_{\text{start}} < 10$ s for ~ 1000 deg 2 and

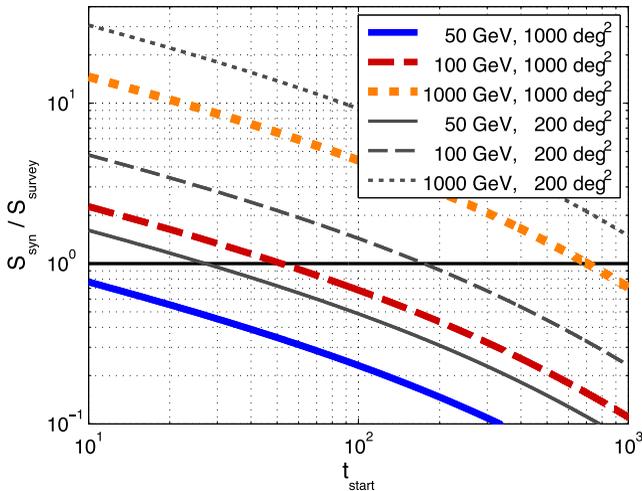


Figure 1. Detectability of short GRBs with CTA as a function of the delay t_{start} between the onset of the GRB and the start of observations, for different high-energy emission cutoff energies (E_{cutoff}). Results are shown for surveys over $\sim 1000 \text{ deg}^2$ as well as $\sim 200 \text{ deg}^2$ (see legend). The GRB ($E_{\text{kin}} = 10^{51} \text{ erg}$; $D_L = 300 \text{ Mpc}$) is considered detectable if its fluence S_{syn} (estimated assuming synchrotron emission and cutoff energy E_{cutoff}) is greater than the sensitivity S_{survey} of CTA in survey mode for an observation lasting for 1000 s. cf. rows 5–7 in Table 1, where fluences are shown for a few characteristic t_{start} values.

$t_{\text{start}} < 30 \text{ s}$ for $\sim 200 \text{ deg}^2$ sky area), but for higher energy thresholds, longer delays are acceptable without affecting detectability.

3.5.2 CTA limits from self-inverse-Compton scattering

For a synchrotron-emitting source, we also expect a self-inverse-Compton component between the synchrotron photons and their emitting electrons (resulting in synchrotron-self-Compton radiation, hereafter SSC). Here, we give a simplified treatment, by approximating the spectrum as joined power-law segments (for a detailed discussion of the SSC, see Sari & Esin 2001). SSC has approximately the same spectral shape as synchrotron emission. The peak SSC flux is scaled by the optical depth compared to the synchrotron flux: $\phi^{\text{SSC}} \approx \sigma_T n R \phi^{\text{syn}}$, where n is the circumburst density, R is the radius of the shock, and σ_T is the Thomson cross-section. In an adiabatically expanding shock, $R \propto t^{1/4}$ (Blandford & McKee 1976). We approximate the SSC spectral shape with a broken power law and neglect higher order terms (Sari & Esin 2001).

The Klein–Nishina effect will suppress emission at the highest energies and it may be important for $\sim \text{TeV}$ energies (Nakar, Ando & Sari 2009). There are no confirmed examples for SSC emission in short GRBs at GeV energies, although the long-lived afterglow of GRB 130427A may be interpreted as SSC emission (Liu, Wang & Wu 2013). Here, we will focus on numerical examples to evaluate possible TeV emission from an SSC component.

We utilize the parameters n , ϵ_B (fraction of energy in magnetic fields), ϵ_e (fraction of energy carried by electrons, E_{kin} (kinetic energy), and electron population power-law index p to describe the synchrotron component and to calculate the SSC flux.

For realistic parameters (e.g. $n = 10^{-1} \text{ cm}^{-3}$, $\epsilon_B = 10^{-1}$, $\epsilon_e = 10^{-0.5}$, $E_{\text{kin}} = 10^{51} \text{ erg}$, and $p = 2.5$) and for a GRB at 300 Mpc, we calculate the SSC fluence: $\mathcal{F} \approx \{4, 6, 3\} \times 10^{-7} \text{ erg cm}^{-2}$. For this set of parameters, the SSC emission will be detected at all three cutoff energies. For GWs originating from neutron star binary mergers, which might have experienced kicks from their places of birth,

the circumburst density might be lower. Changing $n = 10^{-3} \text{ cm}^{-3}$, which is roughly the halo density, in the previous case, we get a fluence of $\mathcal{F} \approx \{3, 4, 8\} \times 10^{-9} \text{ erg cm}^{-2}$. This lower fluence, which may be more realistic for binary mergers that left their host galaxies due to the kicks neutron stars can receive at their birth in supernovae (e.g. Fong & Berger 2013), can only be detected if it extends to $\sim \text{TeV}$ energies (and not in survey mode).

To characterize the dependence of the flux on the uncertain microphysical parameters, we fix the value of $p = 2.5$ and get $\phi_v \propto E_{\text{kin}}^{29/16} \epsilon_B^{7/8} \epsilon_e^3 n^{17/16}$. This means higher values of the equipartition parameter of the magnetic field and the electrons, as well as the density of the interstellar material, will facilitate a detection in the TeV band. These scalings are valid when the TeV range falls between the injection and characteristic frequencies of the SSC component, which is true for parameters not too different from those presented here.

3.5.3 Increased TeV flux from short-GRB late rebrightening

A non-negligible fraction of short GRBs are followed by softer, extended emission (Norris & Bonnell 2006). Considering their forward shock SSC emission in a refreshed shock (Rees & Mészáros 1998) or continuous injection (Zhang & Mészáros 2001a), these bursts can possibly produce a late rebrightening in the TeV range (Veres & Mészáros 2014). This increases the probability of detection compared to simple afterglow models. The time-scale of the rebrightening is 100–1000 s, the same order of magnitude as the response time of Cherenkov telescopes.

3.6 Joint detection rates

To estimate the rate of events that can be jointly detected by CTA and GW observatories, we consider the rate of short GRBs to be $\sim 10 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Guetta & Piran 2006; Coward et al. 2012; Siellez, Boër & Gendre 2014, see also Abadie et al. 2010), and assume uniform source density. For a fiducial direction-averaged distance of 300 Mpc within which a network of GW detectors can detect a neutron star binary merger (with rotation axis pointing towards the Earth; see Abadie et al. 2010), this corresponds to ~ 0.3 events per year. Taking into account an ~ 11 per cent duty cycle of CTA (Actis et al. 2011), and assuming that all short GRBs within the detection horizon of GW detectors can be detected by CTA, the rate of coincident detections is $\sim 0.03 \text{ yr}^{-1}$. A further decrease of ~ 50 per cent is expected from CTA being able to observe only for source elevations $\gtrsim 30^\circ$ above the horizon. This number, nevertheless, can further increase if sub-threshold GW events with lower SNRs are followed up, or if a sub-population of short GRBs originate from black hole–neutron-star mergers, which can be detected by GW observatories from larger distances. The estimate nevertheless indicates that a joint detection may require an extended period of operation.

4 CTA FOLLOW-UP SURVEY

In the previous section, we estimated the detectability of short GRBs with CTA, using a search with known source direction. In this section, we estimate the same detectability, but for the case of uncertain source direction, in which CTA needs to *survey* a sky area of up to $\sim 1000 \text{ deg}^2$. For comparison, we also estimate detectability for a more accurate, $\sim 200 \text{ deg}^2$ sky area.

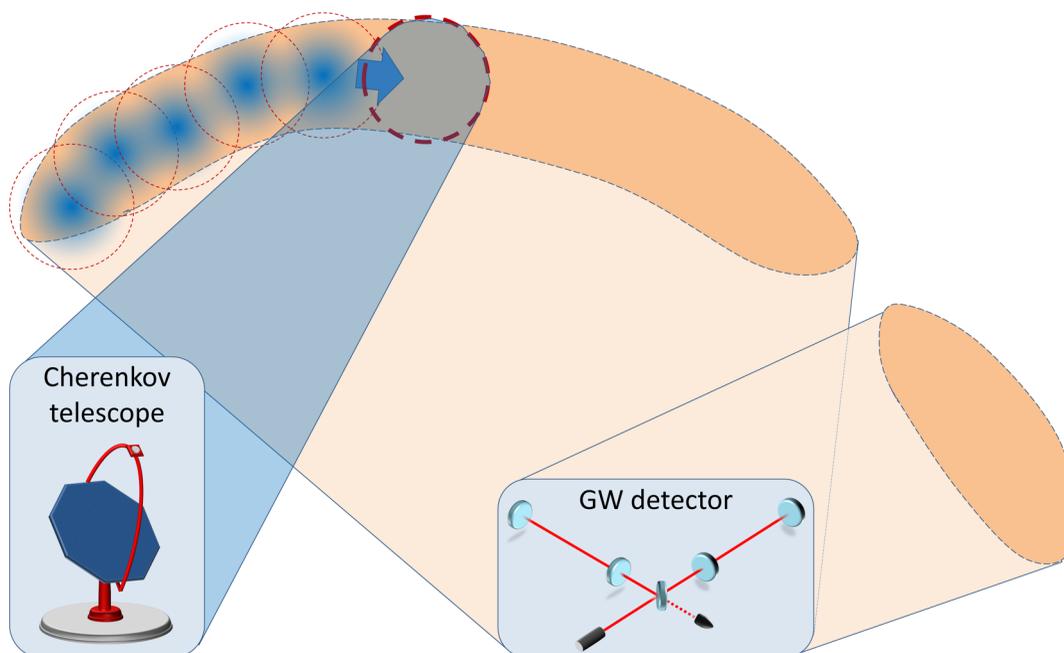


Figure 2. Schematic representation of the sky areas of a GW event candidate and the consecutive set of sky areas covered by a CTA follow-up observation in survey mode (convergent pointing). The illustration shows a discontinuous GW sky region. Note that searches will involve multiple Cherenkov telescopes and GW detectors.

CTA could carry out a fraction of its observations as ‘*sky surveys*’ (Acharya et al. 2013). Following the success of the High Energy Stereoscopic System (H.E.S.S.) Galactic plane survey constituting 230 h of observations (Aharonian et al. 2006), one of the science objectives of CTA will be to carry out a survey of the inner Galactic plane. CTA will be able to do this with 10-fold improvement in sensitivity compared to H.E.S.S. This corresponds to a uniform sensitivity down to 3 mCrab in about the same time as the H.E.S.S. survey.

In addition, there is the possibility of a dedicated ‘*all-sky survey*’ which will observe a quarter of the sky at a sensitivity of 20 mCrab in 370 h of observations (Dubus et al. 2013). This all-sky survey would open the possibility of a serendipitous detection of prompt emission from short GRBs. It is difficult to extrapolate the high-energy spectrum of a short GRB based on its low-energy emission as the high-energy spectrum has been characterized by extra spectral components above the declining low-energy flux. If we assume that 45 short GRBs detected by *Fermi*-GBM (~ 50 per cent sky coverage) per year could all potentially have high-energy emission within the CTA sensitivity, then in survey mode there would be 9 per year all-sky assuming a 11 per cent duty cycle for CTA, or 3 during the hours devoted to this all-sky survey. The probability of the survey patch coinciding with the GRB position is small but a serendipitous discovery is possible.

A recent review of the scientific motivation and impact of surveys with CTA (Dubus et al. 2013) points out that surveys have the advantage of not only generating legacy data sets, but having the potential for serendipitous discovery of TeV sources. Complementary to CTA, the High-Altitude Water Cherenkov (HAWC) detector will be operating in continuous survey mode, and offers the advantage of a high duty cycle compared to IACTs, which are constrained to observe only at night time, and likely only at low Lunar illumination. HAWC has higher threshold of operation (>1 TeV) and a sensitivity goal of 1 Crab above 1 TeV in a day or ~ 50 mCrab in a year of operations (DeYoung & HAWC Collaboration 2012). While

water Cherenkov detectors are excellent for transient sources and serendipitous searches, they cannot be reoriented (i.e. they cover only a fraction of the sky, ~ 16 per cent in the case of HAWC), and, compared to IACTs, have limited angular resolution and point source sensitivity, and operate at higher energy thresholds. CTA promises to offer a more competitive survey depth and angular resolution, with lower energy threshold for a moderate investment in observing time.

Inoue et al. (2013) describe planned wide-field survey CTA observations, and their potential to discover GRBs. These are not for follow-up of LIGO searches, but rather for a stand-alone GRB search by divergent pointing of the telescopes of CTA to achieve a wide field of view. Such extragalactic surveys have not been carried out by IACTs before.

The development of the tools that allow CTA to carry out a wide-field-of-view survey will also allow for the wide-field-of-view follow-up observations presented here. A schematic drawing of the sky coverage of such a follow-up observation with CTA is shown in Fig. 2.

4.1 Sensitivity of CTA in survey mode

Here, we estimate the sensitivity of CTA in a follow-up survey mode by comparing it to single-pointing observation, which is discussed above in Section 3 (hereafter single-pointing sensitivity).

A possible follow-up survey strategy with CTA is to cover the required sky area by pointing the whole telescope array (convergent pointing⁸) in a consecutive set of directions (see e.g. Dubus et al. 2013). This strategy can minimize the required software development for CTA as it relies on single-pointing observations. The sensitivity of this strategy can be directly compared to the results in

⁸ Note that one may not need to use all telescopes in this mode. For example, it may be sufficient to use the LSTs for this search.

Section 3. At any given time, CTA is pointing at a given direction; therefore, its sensitivity over a short time interval is the same as the single-pointing sensitivity.

The difference in the two sensitivities comes from a set of factors as follows.

(i) In survey mode, CTA will point at a specific direction only for a shorter time period in order to cover the full sky area during the expected duration of multi-GeV emission. To first order, this decreases search sensitivity by a factor dependent on the fraction of the total observation time spent on each direction. The sensitivity of searching the full error region therefore changes by a factor $f_{\Omega} \simeq [(\theta_{\text{CTA}}/2)^2 \pi / \Omega_{\text{GW}}]^{1/2}$ compared to a single-pointing survey, that is, the sky area visible to CTA at a given time (θ_{CTA} is the diameter of the field of view of CTA) over the area Ω_{GW} of the location error region of a GW trigger. Here, we assumed that the sensitivity is background dominated, i.e. sensitivity scales with the square root of the observation duration. Further, this estimate also assumes that each direction is observed for the same duration. This will not be the case, since the expected flux from a GRB will decay with time ($\propto t^{-1.4}$, where the time t since the onset of the GRB is known from the time of the GW signal). The survey will therefore need to spend time observing a given direction on the GW sky area that is proportional to t^3 . Here, for simplicity, we conservatively omit the effect of temporally non-uniform GRB emission.

(ii) Covering the GW error region with CTA tiles pointing in different directions will likely be sub-optimal. A set of CTA tiles is unlikely to exactly cover the GW error region without any overlap or overflow. A fraction of the surveyed sky area will be in directions which are not part of the GW sky area. Sub-optimal tiling will therefore introduce a factor $f_{\text{tiling}} < 1$ of decrease in the sensitivity of survey mode.

(iii) CTA has a finite slewing speed. Surveying an area larger than the field of view of CTA leads the detector to not observe in a fraction of the observation time that it spends slewing between different surveyed directions. For a total observation time T_{obs} and a slewing time t_{slew} , the decrease in detection sensitivity will be $f_{\text{slew}} = (1 - t_{\text{slew}}/T_{\text{obs}})^{1/2}$, where we again assume that the sensitivity is background dominated. Taking these modifications into account, the detectable fluence threshold S_{survey} for the survey mode of CTA will be

$$S_{\text{survey}} = S_{\text{det}} f_{\Omega} f_{\text{tiling}} f_{\text{slew}}, \quad (6)$$

where S_{det} is the single-pointing detection threshold of CTA.

To characterize the sensitivity of the survey mode of CTA, we estimate $S_{\text{survey}}/S_{\text{det}}$ using typical values for the parameters described above. Taking the field of view of CTA to be $\theta_{\text{CTA}} \approx 4.6$ (the field of view of the LSTs of CTA, which are the most important at the relevant energies; Dubus et al. 2013), and a GW error region with a total area of 1000 deg^2 , we get $f_{\Omega}(1000 \text{ deg}^2) \approx 0.13$. Similarly, a 200 deg^2 sky area gives $f_{\Omega}(200 \text{ deg}^2) \approx 0.29$. The efficiency of tiling will depend on the shape of the GW sky area. Nevertheless, the GW sky area is unlikely to be fragmented to parts much smaller than the field of view of CTA. Excess surveyed area will therefore come mostly from the ‘edge’ of the GW sky area, making this effect less significant than the decrease due to f_{Ω} . Further, the sensitivity of CTA within the field of view is non-uniform, which may require partially overlapping tiling. Below we adopt $f_{\text{tiling}} \approx 0.75$ to account for some sensitivity decrease due to tiling. To estimate f_{slew} , we consider a total observation time $T_{\text{obs}} = 1000 \text{ s}$. For equilateral tiling (see Dubus et al. 2013), if the GW sky area is much larger than the field of view of CTA, the characteristic total slewing angle

is $\Omega_{\text{GW}}/(2\cos(60^\circ)\theta_{\text{CTA}}) \approx 220^\circ$, which corresponds to a slewing time of $t_{\text{slew}} \lesssim 25 \text{ s}$, given that the most important LSTs have a slewing speed of $\sim 20 \text{ s}/180^\circ$ (Dubus et al. 2013). The slewing time is therefore negligible compared to the total observation time, even for somewhat fragmented GW sky areas. Below we consider $f_{\text{slew}} \approx (T_{\text{obs}} - t_{\text{slew}})/T_{\text{obs}} = 0.975$. Combining these results, we arrive at

$$S_{\text{survey}} \approx 0.1 S_{\text{det}}. \quad (7)$$

We use this conversion, together with S_{det} obtained in Section 3, to calculate S_{survey} . Results are shown in Table 1.

The above estimate for the sensitivity of CTA in survey mode considers the case of background-dominated detection, i.e. in which sensitivity is determined by the SNR. This will be the case for signal strengths for which the expected number of detected photons for a given pointing is $\gg 1$. Since survey-mode observations divide the full measurement time into many shorter measurements, each of these shorter measurements also have to satisfy the same criterion in order to be considered background dominated. To confirm that this will be the case, we estimated the number of detected photons for our different signal models (see Table 1), using the effective area of CTA from Bernlöhner et al. (2013). We find that, for $n_{\text{survey}} = \mathcal{O}(10)$ pointings during a survey, the number N_{γ}^{CTA} of photons detected from any of our GRB models with any of the considered cutoff energy thresholds will have $N_{\gamma}^{\text{CTA}} \gg n_{\text{survey}}$ for all cases in which the GRB fluence is above the detectability threshold. We therefore conclude that all cases can be considered to be background dominated.

In short, we find that the sensitivity of survey-mode searches, considering a sky area of $\sim 1000 \text{ deg}^2$, is ~ 10 per cent of the sensitivity of single-pointing searches, while a more focused survey over $\sim 200 \text{ deg}^2$ gives ~ 21 per cent. Table 1 shows that this sensitivity can still be sufficient to detect GRBs with parameters ($E_{\text{kin}} = 10^{51} \text{ erg}$; $D_{\text{L}} = 300 \text{ Mpc}$) for emission reaching $E_{\text{cutoff}} \gtrsim 100 \text{ GeV}$.

We note here that, alternatively to the convergent pointing discussed in this paper, surveys in so-called divergent mode are also possible, in which different telescopes point in different directions, therefore covering a larger part of the sky ($\sim 20^\circ \times 20^\circ$) at any given time (e.g. Dubus et al. 2013). The possible advantages of following up GW event candidates with such divergent-mode searches using MST will be examined in a future work.

5 GRB OBSERVATIONS AT KeV–MeV PHOTON ENERGIES

GRBs are typically the easiest to detect in the MeV energy range where they are expected to emit the bulk of their energy output. Current instruments focusing on GRB detection in the MeV range typically have large fields of view and can efficiently detect GRBs well beyond the reach of GW detectors (Barthelmy et al. 2005; Meegan et al. 2009; Hurley et al. 2011). Below we examine the observations of GRBs in the MeV energy range in the context of CTA follow-up observations presented above.

Observations of the prompt MeV emission can be interesting for the purposes of GeV follow-up observations for two reasons, which we discuss below.

5.1 Source localization with gamma-ray detection

The localization uncertainty of GRB observations is typically much smaller than the uncertainty of GW observations. If the MeV counterpart of a GW candidate is quickly identified by GRB detectors,

the reconstructed location can help focus CTA observations to a smaller sky area, therefore increasing search sensitivity and allow for longer and more informative observation.

The *Fermi*-GBM (Meegan et al. 2009) and the *Swift* Burst Alert Telescope on *Swift* (BAT; Barthelmy et al. 2005) are capable of identifying GRBs within a wide field of view, and alerting other observatories with little delay.

The short-burst population detected by *Swift*-BAT (9 per year) may be contaminated by weak collapsar events (Bromberg et al. 2013) so that the number of merger events may be smaller than 9 per year. The overlap with CTA is thus small, but any candidate can be efficiently observed without tiling.

Fermi-GBM has a duty cycle of 50 per cent for any point on the sky (the Earth's occultation and passage through the South Atlantic Anomaly account for the losses). *Swift*-BAT has a field of view of 1.4 sr, and can localize events to within ~ 2 arcmin and alert external observatories with a delay < 20 s.

For *Fermi*-GBM, GRBs are localized in real-time on board and automatically on the ground with only a few seconds latency. The automated ground locations are within about 7:5 of the true position 68 per cent of the time (17° for 95 per cent). A refined position available within 20 min–1 h after the GRB trigger is more accurate, with 68 per cent within 5° and 95 per cent within 10° . Efforts are underway to improve the real-time automated position to be of the quality of the refined position. With 45 short GRB detections per year, *Fermi*-GBM could provide 2 or 3 per year above the horizon for CTA to observe with a survey tiling strategy that would be more efficient than that described in Section 4.1 (Connaughton 2014).

Additionally, the *Fermi*-GBM team has recently implemented an offline search for short GRBs using a new event data type that will double or triple the number of short GRBs per year. The expected localization uncertainty will be at least 10° and probably larger as these are weaker events. Because of the unknown redshift distribution of these short bursts, and of short bursts generally, it is difficult to estimate how many of these will fall within the aLIGO horizon distance.

Event candidates detected by either *Swift*-BAT or *Fermi*-GBM can be used to aid CTA follow-up observations of GW candidates either by initiating CTA follow-up observations when a short GRB triggers the instrument (if the GW candidate is not identified quickly) or by reducing the amount of sky that needs to be covered using the GW localization information alone. Nevertheless, a significant fraction (~ 40 per cent) of nearby GRBs is not observed by either of these detectors. For these GRBs, CTA will need to rely solely on GW direction reconstruction.

The synergy with MeV GRB instruments could be valuable for GW follow-ups with CTA. It is unclear, however, whether *Swift* and *Fermi* will be operational in the CTA era or whether any other instrument with GRB detection and real-time localization capabilities will be operational. Possible missions include *UFFO* (CHEN 2011), *SVOM* (Götz et al. 2009), *MIRAX* (Braga et al. 2004), as well as other future ESA/NASA small missions.

5.2 Additional information on source

In some cases, the MeV counterpart of a GW event candidate is identified only after the time window in which CTA follow-up observations are feasible. While, in these cases, prompt MeV observations will not help with source localization, the joint detection of GWs, prompt MeV emission, and GeV emission can help us further understand the connection between the progenitor and gamma-ray emission in a wide energy band.

The interplanetary network (IPN: Hurley et al. 2011), an all-sky, full-time monitor of gamma-ray transients, is well suited for this purpose. In its current, nine-spacecraft configuration, it detects about 325 GRBs per year, of which 18 per year are short bursts. Of the 19 short bursts with spectroscopic redshifts, the IPN has observed all events up to $z = 0.45$, and 40 per cent of those with redshifts between 0.45 and 2.6. Thus, all known short GRBs at distances up to 2 Gpc have been detected by the IPN; as the luminosity function of short bursts is not known, however, it is conceivable that some weak events could go undetected. Their number cannot be estimated. The sensitivities and energy ranges of the individual detectors aboard the spacecraft vary considerably from one experiment to the next, but the overall IPN sensitivity can be characterized by a fluence of $\sim 10^{-6}$ erg cm $^{-2}$, and/or a peak flux of ~ 1 photon cm $^{-2}$ s $^{-1}$, in the 25–150 keV energy range. GRBs above these levels have a 50 per cent chance or greater of being detected by at least two spacecraft in the network.

The network presently consists of five spacecraft in near-Earth orbit, two at distances up to about 5 light-second from the Earth, and two in orbit around Mercury and Mars. Thus, when the duty cycles and planet-blocking constraints of the network as a whole are considered, the entire sky is viewed without interruption. The IPN localizes bursts by triangulation (i.e. arrival time analysis), and the error box dimensions have a broad distribution from arcminutes to tens of degrees, depending upon the GRB intensity and the number of spacecraft which observed it. The delays to obtain localizations range from hours in the best cases to a few days in the worst cases. Given the detection rates and localization areas, a temporal and spatial coincidence between an IPN GRB and a GW observation would be highly significant in almost all cases, and would considerably strengthen both the case for the reality of a GW detection, and its identification as a cosmic GRB. Indeed, the IPN and LIGO teams have worked together since LIGO's earliest engineering runs.

The configuration of the IPN changes continually as old missions are retired and new ones replace them. While it is virtually certain that some near-Earth missions will be retired in the near future, the exact configuration in the advanced LIGO era is unpredictable. Some near-Earth missions will be replaced by new missions; others will not. The reduction of the number of near-Earth spacecraft to two or three, however, would have relatively little impact, given their redundancy. The fates of the missions farther from the Earth depend on funding, as well as on their utility for the scientific objectives for which they were designed (only one is an astrophysics mission). It is conceivable that both planetary missions will be taken out of service, but that at least one new mission will come online. This would have the effect of truncating the distribution of error box areas below a few degrees. Nevertheless, the probability of a random spatial/temporal coincidence between a GW event and a GRB would still be sufficiently small to be very significant.

6 CONCLUSION

We explored the feasibility of following up GW events with CTA. We focused on the scenario in which the GW event is poorly localized, necessitating follow-up observations to cover up to ~ 1000 deg 2 of sky area. Limited localization can emerge from various detection scenarios. In the early advanced GW detector era, one can expect only the two LIGO observatories to operate at high sensitivity, and direction reconstruction with two detectors is limited. But even with further GW detectors in operation, GW event candidates with relatively low SNRs will also have poorly

constrained directions of origin, therefore requiring follow-up over a larger sky area.

We based our study on short GRBs, assuming that they originate from compact binary mergers, which are considered the most promising sources for the first GW detections.

While various follow-up observations (e.g. optical/infrared) will be difficult to carry out over larger ($\gg 100$ deg²) sky areas with the desired sensitivity, we find that CTA may be capable of efficiently detecting late-time high-energy gamma-ray emission from short GRBs. To estimate their detectability, we extrapolated the energy spectrum observed by *Fermi*-LAT to $\gtrsim 50$ GeV where CTA becomes sensitive. Currently it is unclear, due to the lack of observations, whether short-GRB spectra extend into this range, and to how high an energy. We considered different cutoff energies (from 50 GeV to 1 TeV), as well as multiple GRB emission scenarios, to investigate the sensitivity of CTA for these different cases.

Our results show that short GRBs with high-energy emission extending up to ~ 100 GeV can be detectable via CTA, even if CTA needs to survey a sky area of ~ 1000 deg² and if CTA observations are delayed by ~ 100 s following the onset of gamma-ray emission. Detection with lower energy cutoffs is also promising, although may require a dense circumburst medium, faster GW event reconstruction, smaller sky area, or closer source. For comparison, we considered an ~ 200 deg² sky area that can be achieved for some events with stronger GW emission, or if we restrict our search to a fraction of the sky area with the highest probability directions. For an ~ 200 deg² sky area, we find that GRBs even with cutoffs somewhat below 100 GeV can be detectable, although for a ~ 50 GeV cutoff one requires faster response than ~ 100 s.

Many of the events detected by both GW facilities and CTA will also likely be observed by GRB satellites. For observations with low latency, as in the case of *Fermi*-GBM and *Swift*-BAT, the localization of the GRB can significantly reduce the sky area CTA needs to cover in order to find the source. The detection of MeV emission can also be important in mapping the connection between GW and electromagnetic emission within a broad energy range.

We estimated the rate of events that can be jointly detected by CTA and GW observatories, consider a characteristic short-GRB rate of 10 Gpc⁻³ yr⁻¹, and a fiducial GW horizon distance of 300 Mpc. With ~ 11 per cent duty cycle for CTA, we find a limited detection rate of ~ 0.03 yr⁻¹. A further decrease of ~ 50 per cent is expected from CTA being able to observe only for source elevations $\gtrsim 30^\circ$ above the horizon. This number, nevertheless, can increase if sub-threshold GW events with lower SNRs are followed up, or if a sub-population of short GRBs originate from black hole–neutron-star mergers, which can be detected by GW observatories from larger distances. The estimate nevertheless indicates that a joint detection may require an extended period of operation.

Overall, we find that CTA is well suited to perform follow-up observations of GW events, even those with limited source localization. It can, therefore, be important to carry out a more detailed investigation of the possible follow-up observation strategies with CTA, and the expected joint sensitivity, beginning as early as in the installation phase. It will also be important to further our understanding of the phenomenology of GRB emission at \gg GeV energies.

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