Prospects for VHE monitoring of gamma-ray bursts with SWGO

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It has been established that Gamma-Ray Bursts (GRB) can produce Very High Energy radiation (VHE, $E > 100\,\mathrm{GeV}$), opening a new window for investigating particle acceleration and radiation properties in the most energetic domain. We expect that next-generation instruments in this energy regime, such as the Cherenkov Telescope Array (CTA), will mark a huge improvement in their observation. However, constraints on the target visibility and the limited duty cycle of Imaging Atmospheric Cherenkov Telescopes (IACT), affect their ability to react promptly to transient events. Here we use a grid of instrument performance estimates, based on the Extensive Air Shower (EAS) array concept proposed by the Southern Wide Field-of-view Gamma-ray Observatory (SWGO) collaboration, to evaluate SWGO's potential to detect and track VHE emission from GRBs. Observations by the *Fermi* Large Area Telescope (*Fermi*–LAT) at high energy ($E > 10\,\mathrm{GeV}$), identified some events with a distinct spectral component, which can represent a substantial fraction of the emitted energy and possibly occur very early in the process. Using models based on these properties, we estimate the possibilities that a wide field of view and large effective area ground-based monitoring facility has to probe VHE emission from GRBs. We show that the ability to monitor VHE transients with a nearly continuous scanning of the sky grants us the opportunity to simultaneously observe electromagnetic counterparts to gravitational waves and relativistic particles sources up to cosmological scales, in a way that is not accessible to IACTs.

Keywords: Instrumentation: detectors; gamma rays: general; gamma ray burst: general.

1. Introduction

The study of Gamma-Ray Bursts (GRB) represents one of the most challenging and fascinating frontiers of High Energy Astrophysics. Although they were discovered in the first years of space explorations with high energy detectors,[1] several aspects of their origin, their power, and their radiation mechanisms are still unclear. We know that GRBs are originated by ultra-relativistic jets of plasma, which are produced during the extremely fast accretion process that follows the collapse of a very massive star ($M \geq 20\,\mathrm{M}_\odot$) or the merger of a binary neutron star (NS), to form a *magnetar* or a black hole.[2] The process produces a flash of energetic photons, named *prompt emission*, followed by a smoothly decaying signal, called *afterglow*. Looking at the duration of the prompt phase, GRBs appear to show a bimodal distribution, where we distinguish a class of short events, with a prompt stage lasting less than 2 s, and another of long ones, whose prompt emission takes place for much longer times.[3,4] The two classes of events are consistent with two distinguished possible source types. Long GRBs have been associated with supernova explosions,[5,6] while the short ones fit better in the compact binary merger scenario,[7] as eventually demonstrated by the GRB 170817A–GW 170817 multi-messenger association that was also detected as a *kilonova*.[8–10]

In the past few years, observations performed with ground based Imaging Atmospheric Cherenkov Telescopes (IACT), such as MAGIC[11] and H.E.S.S.,[12] found evidence for Very High Energy γ-ray emission (VHE, $E \geq 100\,\mathrm{GeV}$) in the afterglow of some GRBs.[13,14] In addition, analysis of the data collected by the *Fermi* Large Area Telescope (*Fermi*-LAT)[15] demonstrated the existence of a high energy component in the spectra of some bright GRBs that extends above the 10 GeV energy range and can be detected also in association with the prompt emission.[16–18] Understanding the origin and the distribution of VHE radiation from GRBs is a key issue for their correct interpretation. It is expected that next generation γ-ray instruments, such as, for instance, the Cherenkov Telescope Array (CTA),[19] will provide exceptional new data in this field. Unfortunately, the unpredictable nature of GRBs and their fast spectral evolution makes it extremely difficult, for instruments with narrow field of view (FoV), of the order of few square degrees, to re-point and track GRB emission within very short times (below 10 s). A possible solution to this problem is using Extensive Air Shower detector arrays (EAS) to monitor large areas of the sky, with an instantaneous FoV of more than 1 sr and a nearly continuous duty cycle. Here we discuss the observational opportunities that a new instrument, based on a next-generation EAS array concept investigated by the Southern Wide-field-of-view Gamma-ray Observatory (SWGO),[20] will open in the study of GRBs.

This contribution is structured as follows: in §2 we describe the known and the expected VHE properties of GRBs; in §3 we present the potential monitoring capabilities of SWGO; finally, in §4 we discuss our results and we draw our conclusions.

2. VHE emission from GRBs

Several arguments suggest that GRBs should be able to produce prompt VHE radiation. The most likely interpretation of GRBs invokes relativistic shocks occurring either within the magnetized jet plasma (*internal shocks*, generally associated with the prompt stage), or between the jet and the surrounding environment (*external shocks*, more often considered as the source of the afterglow emission). In both cases, the energies associated with particles and magnetic fields are high enough to produce efficient leptonic radiation mechanisms and possibly to activate hadronic processes.[21–23] The combination of temporal and spectral properties of the emitted radiation provides fundamental indications on the characteristics of the source.

In general, a large fraction of the energy that a GRB releases in the prompt phase is found in the spectral range falling between few hundreds keV to some MeV.[24] The spectrum comes in the form of a combination of power-law components, known as the *Band function*.[25] The presence of relativistic charged particles in an intense magnetic field leads to the natural expectation that powerful synchrotron and inverse Compton radiation should be emitted.[26] While the prompt emission is characterized by fast pulse-like variability, with time-scales down to few milliseconds,[27] implying extremely compact emission regions, the observation of photons up to the MeV and even the GeV energy range requires very large bulk Lorentz factors ($\Gamma >> 100$), in order to suppress pair production opacity. In these conditions, the inverse Compton scattering of synchrotron radiation may lead to the production of photons up to the TeV domain.[28] The occurrence of ultra-relativistic shocks in high density environments, on the other hand, is theoretically able to activate photo-pion interactions that can extend the spectra beyond 300 GeV[23] and lead to potential associations with neutrino events.[29]

So far, the direct detection of VHE radiation has only been possible in the afterglow of a limited number of GRBs, thanks to ground-based follow up observations.[13,30–32] However, the monitoring campaign carried out by the *Fermi*-LAT space observatory led to the identification of a high energy spectral component, coming in the form of power-law emission, that appears to be a common feature of bright GRBs and may even arise very early in the event.[33] Due to the limited collecting area and the typical short duration of GRBs, the LAT observations are not able to place strong constraints on the VHE component of GRBs, as it is suggested by the fact that *Fermi* did not detect photons above ~ 30 GeV from GRB 190114C, while the same event was firmly detected up to almost 1 TeV. As a consequence, the results of *Fermi*-LAT observations can be used as a starting point to estimate the possible extension of the GRB properties to the VHE domain and thereby evaluate their detection opportunities for other instruments.

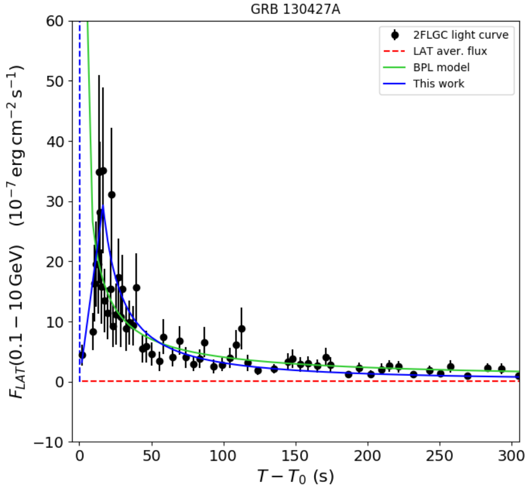

Fig. 1. Comparison between the *Fermi*-LAT light curve of GRB 130427A and the model based on Eq. (1) and Eq. (2). The vertical blue dashed line marks the start of the LAT signal temporal window, the red horizontal line is the average energy flux collected during the entire time of emission, the green continuous line is the 2FLGC power-law fit to the data, while the blue continuous line is a model using the light curve of Eq. (2).

Usually, we can express the high energy spectrum of a GRB as a function of energy in the form of:[a]

$$\frac{\mathrm{d}N(t)}{\mathrm{d}E} = N_0(t)\left(\frac{E}{E_0}\right)^{-\alpha}\exp[-\tau(E,z)] \quad [\mathrm{ph\,cm^{-2}\,s^{-1}\,GeV^{-1}}], \tag{1}$$

where $N_0(t)$ is the flux of photons per unit energy observed at time t, E_0 is the pivot energy, α is the spectral index, which is often within the range $1.5 \leq \alpha \leq 3$, with an average value close to 2, and $\tau(E,z)$ is the opacity due to pair production on Extragalactic Background Light photons (EBL), given as a function of energy and redshift. The temporal evolution of the flux is typically well represented by a power-law, or a broken power-law, that can be written as:

$$N_0(t) = \begin{cases} N_{peak}\left(\dfrac{t-T_0}{T_{peak}-T_0}\right) & \text{for} \quad T_0 \leq t \leq T_{peak} \\ N_{peak}\left(\dfrac{t}{T_{peak}-T_0}\right)^{-\gamma} & \text{for} \quad t > T_{peak}, \end{cases} \tag{2}$$

where we denoted with T_0 the trigger time, with T_{peak} the time taken to achieve peak emission, with N_{peak} the maximum flux, and with γ the temporal evolution index, which is often found to be $1 \leq \gamma \leq 2$.

[a]We assume for simplicity that the temporal evolution of the spectrum is only limited to a scaling factor, without relevant spectral changes.

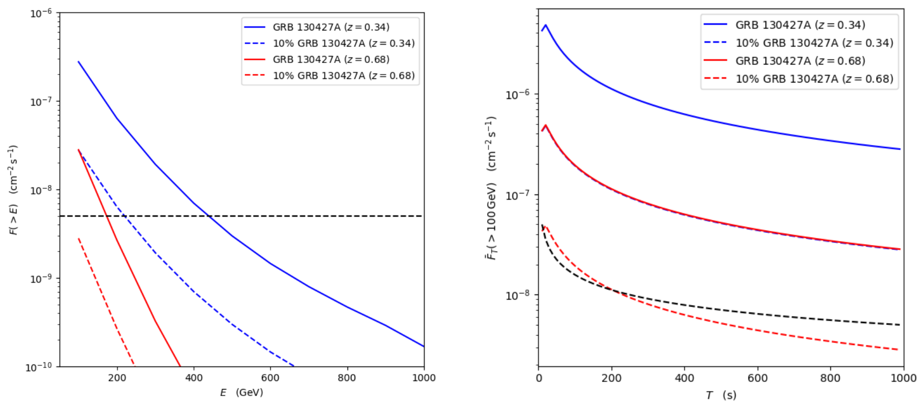

Fig. 2. **Left panel:** average photon flux expected above any given energy in 1000 s for a burst with the spectral and temporal characteristics of GRB 130427A (blue continuous line), an identical burst with 10% its strength (blue dashed line) and the same previous cases computed for twice the measured redshift (red continuous and dashed lines). The horizontal black dashed line represents a reference flux limit of $5 \cdot 10^{-9}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$. **Right panel:** instantaneous integral photon fluxes, expected above 100 GeV as afunction of time, compared with the detection threshold, in the assumption that the limiting flux scales as the square root of the observation time.

Using the second catalog of *Fermi*-LAT detected GRBs (2FLGC),[33] which provides measurements of the observed photon fluxes, in the energy range between 0.1 GeV and 10 GeV, together with information on the spectral index and on the light curve shape, for a sample of GRBs observed during 10 years of regular monitoring operations, we are able to apply Eq. (1), with the inclusion of Eq. (2), to estimate the expected high energy fluxes as a function of time, as it is illustrated for instance in Fig. 1. In principle, we can extend this type of spectra to the VHE domain and, thus, obtain an estimate of the expected fluxes. In practice, this operation is not directly possible, due to the lack of a redshift measurement for the majority of the LAT detected GRBs, which implies an unknown EBL opacity in Eq. (1). Although the effects EBL are generally negligible for the observed LAT band, they become quickly very important at higher energies, with a typical γ-ray horizon set by $\tau = 1$, which, for $z \approx 1$, already occurs at $E = 100\,\mathrm{GeV}$.[34] For this reason, we combined the spectral and temporal fits, which we obtained from the LAT data, with a set of simulations, aiming at estimating the effects of EBL opacity on the VHE extension of the GRBs that resulted in the brightest LAT observed fluxes.[35]

3. GRB monitoring with SWGO

A direct consequence of Eq. (1) is that the observation of VHE radiation, particularly from fast transient sources, requires the use of large instrumented areas. This characteristic can only be offered by ground-based facilities, such as IACTs or EAS

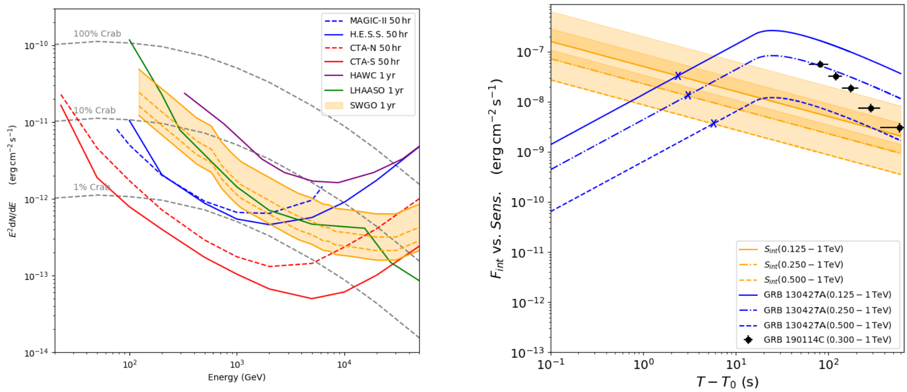

Fig. 3. **Left panel:** Spectral coverage and differential sensitivity of some currently operating and next-generation VHE observatories. The sensitivities are computed for a point-like source at a zenith distance of 20°. Different fractions of the Crab Nebula flux are shown for comparison. The shaded area is the sensitivity range expected for various configurations of SWGO.[36] **Right panel:** The expected integrated flux for a GRB 130427A-like event above 125 GeV, 250 GeV and 500 GeV, compared with the corresponding SWGO expected sensitivities. Crosses mark the estimated detection times. The VHE light curve of GRB 190114C above 300 GeV is also shown.[13]

detector arrays. The main advantage of IACT observatories is that they have excellent angular resolution and background rejection power, achieving the best possible sensitivity. On the other hand, these instruments can only operate during dark time and in clear sky conditions, implying a duty cycle of only $\sim 20\%$. In addition, the small FoV and the consequent need to respond to an external alert with target position information and subsequent re-pointing delay does not allow IACT instruments to cover the early GRB emission regime, where many critical observational constraints are expected by different theoretical models.

Thanks to their larger FoV and to the possibility to operate almost continuously, EAS detector arrays have better chances to cover a GRB and to act as an alert system themselves. The main problems of this solution are that EAS arrays need to be located at high altitudes ($> 4500\,\mathrm{m}$ a.s.l.), in order to be reached by the particle showers initiated by γ-ray primaries with $E \leq 1\,\mathrm{TeV}$, and that they need to deal with a strong background of cosmic-ray induced air showers. The sensitivity needed to detect the expected VHE signal of GRBs can be estimated by integrating Eq. (1) in time and in energy, with the observed properties of bright LAT bursts, using known or simulated redshifts. Figure 2 shows an example of such calculation. As it is clearly illustrated by the left panel of Fig. 2, the expected signal is a function of the characteristic burst properties, such has flux, duration, spectral index and redshift, and of the energy band that is covered by the observation. In particular, the amount of flux above 100 GeV is critically affected by redshift, meaning that only bright and relatively nearby events can be detected at larger energies. Taking as reference a limiting flux of $5 \cdot 10^{-9}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$, integrated above 100 GeV for an observing time of 1000 s, which is a reasonable estimate for an instrument concept based on the SWGO reference design,[36] it is possible to reach the VHE signal expected from GRBs down to 10% the power of the brightest LAT detected event up to $z \approx 0.7$.

The SWGO Collaboration is currently investigating the configuration of a next-generation EAS array, based on Water Cherenkov Detectors (WCD), to be installed at a high altitude site in the Southern Hemisphere. By adopting a detector concept able to trigger on low energy shower particles ($\sim$ 20 MeV), with high temporal resolution ($\sim$ 2 ns), it can be shown that an array of 80 000 m^2 can improve background suppression and achieve very good monitoring sensitivities, below the TeV energy domain.[36] Figure 3 presents an illustration of this concept, compared with other currently operating and planned facilities, together with an example of its expected performance, with respect to the temporal evolution of two GRBs with a detected high energy component. If we define the integrated flux expected in the VHE domain within an observation time T as:

$$F_{int}(T) = \frac{1}{T - T_0} \int_{T_0}^{T} \mathrm{d}t \int_{E_{low}}^{1\,\mathrm{TeV}} E \frac{\mathrm{d}N(t)}{\mathrm{d}E} \mathrm{d}E, \tag{3}$$

where the spectrum is defined through Eq. (1) and Eq. (2), we can easily verify that the times required to detect the incoming fluxes are significantly below 10 s, meaning that such configurations would be particularly effective to react to the early phases of the transient. Given the promising detection chances in case of GRBs with well measured energetic components, SWGO represents an attractive solution to investigate the properties of VHE emission in the early stages of GRBs and, thus, help solving the question of whether an energetic component associated with the burst onset is a common feature of GRBs or a distinguishing property of a specific event class.

4. Conclusions

The systematic investigation of GRBs in the VHE range will cover a fundamental role in the quickly evolving field of Multi-Wavelength and Multi-Messenger Astrophysics. After the first detection of Gravitational Waves (GW), which marked a corner stone in scientific research,[37] the execution of regular monitoring campaigns increased the chances of obtaining multiple detections of fast transients. The associated observation of GW 170817 and of the short GRB 170817A, in particular, represented the first direct evidence of the compact binary merger as a viable explanation to short GRBs and it opened the way to a wealth of cosmological and high energy physics tests.[8,9] A fundamental question related to the nature of GRBs and to their distinction in classes is whether the formation of the jet and its subsequent evolution involve substantial hadronic processes, a matter that could be unambiguously solved by the association of GRBs with neutrino events or with early VHE emission.[38]

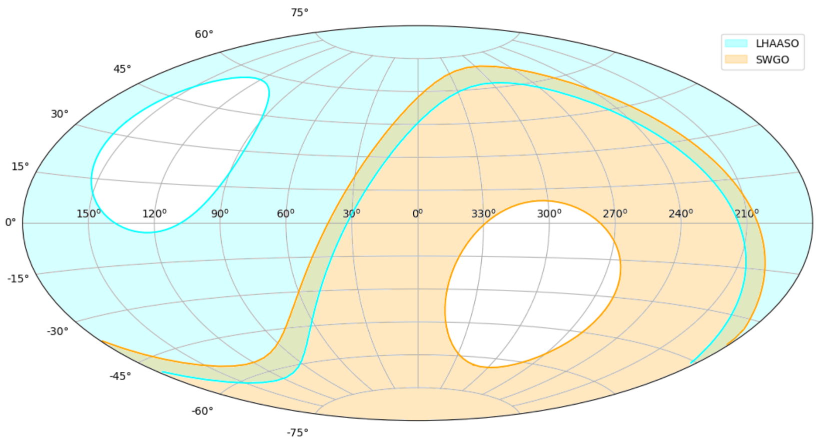

Fig. 4. Representation of the visible sky, within 30° from zenith, showing the sky regions covered by LHAASO (cyan shaded area) and by SWGO, assuming an observatory latitude close to 23° S (orange shaded area). The map is plotted in Galactic coordinates.

Evidence based on existing observations has firmly demonstrated that GRBs can produce energetic radiation and also that this spectral component may be associated with the elusive prompt emission.[17] The observation of early high energy photons, together with hints of the VHE detection of short GRBs, like in the case of GRB 160821B, challenges the external shock model predictions and suggests that additional mechanisms may be at work. Covering the VHE window, particularly in the early emission phase, will be a crucial requirement for the development of more advanced models. The ability to characterise the earliest properties of VHE emission will be fundamental both to improve the time-domain investigation of Multi-Messenger triggers, as well as to offer high quality alerts for follow-up observations that, as demonstrated by H.E.S.S. and further boosted by the upcoming investigations with CTA, can track the VHE evolution up to several hours in the afterglow.[30]

The large FoV and the nearly continuous operating time of EAS arrays make this type of instruments an ideal facility to survey the sky looking for fast transient sources. Their ability to cover large sky areas will help constraining the VHE properties of early GRB emission, with new implications on the involved radiation mechanisms. However, in order to observe events located at cosmological distances, they need to work effectively in the sub-TeV energy domain and, therefore, to be located in high altitude sites. The Large High Altitutde Air Shower Observatory (LHAASO),[39] in the Northern hemisphere, and SWGO, from the Southern hemisphere, have the potential to carry out a VHE monitoring program that will cover a large fraction of the visible sky, as illustrated in Fig. 4. If extended in the sub-TeV domain, this nearly constant scanning of the sky will help clarifying the VHE properties of GRBs by assessing the existence of spectral components that, though predicted in well justified models, are hard to detect with instruments that need to be triggered and subsequently pointed to the target. In addition, fostering a VHE monitoring ability will offer a new window to identify sources of energetic transients, like gravitational waves and high energy neutrinos. Clearly, the identification of possible counterparts to alerts issued by continuously operating experiments, such as *IceCube* and *LIGO/VIRGO*, will undoubtedly benefit from the existence of a network of VHE monitoring programs, able to detect energetic transients and, thus, to further refine the identification of their sources and their energy production mechanisms.

Acknowledgments

The SWGO Collaboration acknowledges the support from the agencies and organizations listed here: `https://www.swgo.org/SWGOWiki/doku.php?id=acknowledgements`. This research was funded by Fundação para a Ciência e Tecnologia, under project PTDC/FIS-PAR/4300/2020 and grant DL57/2016/cP1330/cT0002. Additional funding by CNPq Productivity Research, Grant no. 311997/2019-8, by Serrapilheira Institute Grant number Serra - 1812-26906, and by FAPERJ Young Scientist Fellowship no. E-26/202.818/2019 is also acknowledged.

References

1. R. W. Klebesadel, I. B. Strong and R. A. Olson, Observations of Gamma-Ray Bursts of Cosmic Origin, *The Astrophysical Journal Letters* **182**, p. L85 (June 1973).
2. S. E. Woosley, Gamma-Ray Bursts from Stellar Mass Accretion Disks around Black Holes, *The Astrophysical Journal* **405**, p. 273 (March 1993).
3. E. P. Mazets, S. V. Golenetskii, V. N. Ilinskii, V. N. Panov, R. L. Aptekar, I. A. Gurian, M. P. Proskura, I. A. Sokolov, Z. I. Sokolova and T. V. Kharitonova, Catalog of cosmic gamma-ray bursts from the KONUS experiment data, *Astrophysics and Space Science* **80**, 3 (November 1981).
4. J. P. Norris, T. L. Cline, U. D. Desai and B. J. Teegarden, Frequency of fast, narrow γ-ray bursts, *Nature* **308**, 434 (March 1984).
5. T. J. Galama *et al.*, An unusual supernova in the error box of the γ-ray burst of 25 April 1998, *Nature* **395**, 670 (October 1998).
6. J. S. Bloom *et al.*, The unusual afterglow of the γ-ray burst of 26 March 1998 as evidence for a supernova connection, *Nature* **401**, 453 (September 1999).
7. D. Eichler, M. Livio, T. Piran and D. N. Schramm, Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars, *Nature* **340**, 126 (July 1989).
8. B. P. Abbott *et al.*, Multi-messenger Observations of a Binary Neutron Star Merger, *The Astrophysical Journal Letters* **848**, p. L12 (October 2017).
9. B. P. Abbott *et al.*, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A, *The Astrophysical Journal Letters* **848**, p. L13 (October 2017).
10. P. K. Blanchard *et al.*, The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. VII. Properties of the Host Galaxy and Constraints on the Merger Timescale, *The Astrophysical Journal Letters* **848**, p. L22 (October 2017).

11. J. Aleksić *et al.*, The major upgrade of the MAGIC telescopes, Part I: The hardware improvements and the commissioning of the system, *Astroparticle Physics* **72**, 61 (January 2016).
12. F. Aharonian *et al.*, Observations of the Crab nebula with HESS, *Astronomy & Astrophysics* **457**, 899 (October 2006).
13. MAGIC Collaboration, Teraelectronvolt emission from the γ-ray burst GRB 190114C, *Nature* **575**, 455 (November 2019).
14. H. Abdalla *et al.*, A very-high-energy component deep in the γ-ray burst afterglow, *Nature* **575**, 464 (November 2019).
15. W. B. Atwood *et al.*, The Large Area Telescope on the Fermi Gamma-Ray Space Telescope Mission, *The Astrophysical Journal* **697**, 1071 (June 2009).
16. A. A. Abdo *et al.*, Fermi Observations of High-Energy Gamma-Ray Emission from GRB 080916C, *Science* **323**, p. 1688 (March 2009).
17. K. Asano, S. Guiriec and P. Mészáros, Hadronic Models for the Extra Spectral Component in the Short GRB 090510, *The Astrophysical Journal Letters* **705**, L191 (November 2009).
18. M. Ackermann *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, *The Astrophysical Journal* **716**, 1178 (June 2010).
19. CTA Consortium, *Science with the Cherenkov Telescope Array* (World Scientific Publishing Company, 2019).
20. U. Barres de Almeida, G. Giacinti and F. Longo, Benchmarking the Science for the Southern Wide-Field Gamma-ray Observatory (SWGO), *Proceedings of Science* **395**, p. 10 (July 2021).
21. J. I. Katz, Delayed Hard Photons from Gamma-Ray Bursts, *The Astrophysical Journal Letters* **432**, p. L27 (September 1994).
22. M. J. Rees and P. Meszaros, Unsteady Outflow Models for Cosmological Gamma-Ray Bursts, *The Astrophysical Journal Letters* **430**, p. L93 (August 1994).
23. M. Vietri, GeV Photons from Ultrahigh Energy Cosmic Rays Accelerated in Gamma Ray Bursts, *Physical Review Letters* **78**, 4328 (June 1997).
24. D. Gruber *et al.*, The Fermi GBM Gamma-Ray Burst Spectral Catalog: Four Years of Data, *The Astrophysical Journal Supplement Series* **211**, p. 12 (March 2014).
25. D. Band *et al.*, BATSE Observations of Gamma-Ray Burst Spectra. I. Spectral Diversity, *The Astrophysical Journal* **413**, p. 281 (August 1993).
26. H. Papathanassiou and P. Meszaros, Spectra of Unsteady Wind Models of Gamma-Ray Bursts, *The Astrophysical Journal Letters* **471**, p. L91 (November 1996).
27. E. Nakar and T. Piran, Temporal properties of short gamma-ray bursts, *Monthly Notices of the Royal Astronomical Society* **330**, 920 (March 2002).
28. T. Piran, The physics of gamma-ray bursts, *Reviews of Modern Physics* **76**, 1143 (October 2004).
29. M. G. Aartsen *et al.*, An All-sky Search for Three Flavors of Neutrinos from Gamma-ray Bursts with the IceCube Neutrino Observatory, *The Astrophysical Journal* **824**, p. 115 (June 2016).
30. H. Abdalla *et al.*, A very-high-energy component deep in the γ-ray burst afterglow, *Nature* **575**, 464 (November 2019).
31. O. Blanch, GRB 201216C: MAGIC detection in very high energy gamma rays, *The Astronomer's Telegram* **14275**, p. 1 (December 2020).
32. H. E. S. S. Collaboration, Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow, *Science* **372**, 1081 (June 2021).

33. M. Ajello *et al.*, A Decade of Gamma-Ray Bursts Observed by Fermi-LAT: The Second GRB Catalog, *The Astrophysical Journal* **878**, p. 52 (June 2019).
34. A. Saldana-Lopez, A. Domínguez, P. G. Pérez-González, J. Finke, M. Ajello, J. R. Primack, V. S. Paliya and A. Desai, An observational determination of the evolving extragalactic background light from the multiwavelength HST/CANDELS survey in the Fermi and CTA era, *Monthly Notices of the Royal Astronomical Society* **507**, 5144 (November 2021).
35. G. La Mura, U. Barres de Almeida, R. Conceição, A. De Angelis, F. Longo, M. Pimenta, E. Prandini, E. Ruiz-Velasco and B. Tomé, Gamma-ray burst detection prospects for next generation ground-based VHE facilities, *Monthly Notices of the Royal Astronomical Society* **508**, 671 (November 2021).
36. H. Schoorlemmer, R. Conceição and A. J. Smith, Simulating the performance of the Southern Wide-view Gamma-ray Observatory, *Proceedings of Science* **395**, p. 9 (July 2021).
37. B. P. Abbott *et al.*, Properties of the Binary Black Hole Merger GW150914, *Physical Review Letters* **116**, p. 241102 (June 2016).
38. M. Bustamante, J. Heinze, K. Murase and W. Winter, Multi-messenger Light Curves from Gamma-Ray Bursts in the Internal Shock Model, *The Astrophysical Journal* **837**, p. 33 (March 2017).
39. Z. Cao *et al.*, Introduction to Large High Altitude Air Shower Observatory (LHAASO), *Chinese Astronomy and Astrophysics* **43**, 457 (October 2019).