Astro2020 Science White Paper
All-Sky time domain astrophysics with Very High Energy Gamma rays

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☑Formation and Evolution of Compact Objects ☑Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☑Multi-Messenger Astronomy and Astrophysics

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Abstract: Transient astronomy has witnessed a remarkable evolution with the recent discoveries of gravitational waves (GWs), neutrino production in an active galactic nucleus (AGN), fast radio bursts (FRBs), and the long-awaited detection of a gamma-ray burst (GRB) at energies > 300 GeV. During the next decade, current and planned very-high-energy (VHE) telescopes with high duty

cycles, wide fields-of-view, and sensitivity above 100 GeV will provide unbiased sky coverage and high uptime of astrophysical transients, extend the energy range of VHE observations, and substantially increase the number of accessible targets. The next generation of ground-based observatories will achieve order of magnitude improvements in their sensitivity to VHE gamma rays. Extending their sensitivity to 100 – 300 GeV will greatly enhance our capability of monitoring extragalactic transients and provide multiwavelength and multimessenger follow-up. Below, we present key examples of transient sources which would be prime targets for wide field-of-view ground-based observatory, drawn from *Science Case for a Wide Field-of-View Very-High-Energy Gamma-Ray Observatory in the Southern Hemisphere* [1] If you'd like to cite results presented in this white paper, please cite the original paper.

1 Gamma-Ray Bursts

Gamma-ray bursts (GRBs) are transient events of gamma-ray emission lasting from milliseconds up to hundreds of seconds. In this brief time interval, GRBs release as much as $10^{51} - 10^{54}$ ergs of isotropic equivalent energy mainly in the sub-MeV energy range, becoming the most luminous gamma-ray sources in the sky. Since their discovery in 1969, GRBs have been the target of many observational efforts at all the wavelengths. However, the origin of these enigmatic objects is still poorly understood. The so-called long GRBs (with durations longer than $\sim$2 s) are likely associated with the violent death of very massive stars. In the case of short GRBs (with durations shorter than $\sim$2 s), the time scales and energies of the bursts are compatible with a merger of two compact objects such as a neutron star-neutron star or black hole-neutron star merger. This latter scenario has been recently confirmed by the first observation of a short GRB as the electromagnetic counterpart of gravitational waves (GW) emitted during the coalescence of two compact object [2].

Although GRB emission is widely observed from gamma rays down to radio wavelengths at different times from the event's onset, the first detection above 100 GeV was not made until January 2019. Observations by *Fermi*-LAT, including the detection of a $>$90 GeV photon from GRB 130427A [3] have proven that emission from GRBs can extend up to the VHE regime (Fig. 1). This was confirmed by the discovery of very high energy gamma rays ($>$300 GeV) from the GRB190114C by the MAGIC telescopes, with a significance $>20\sigma$ accumulated within the first few minutes of the observations (see ATel #12390). This detection shows that the transient sky at few hundred GeV still hides many surprises and enforces that GRBs are a clear physics case for a wide field-of-view gamma-ray observatory.

Follow-up observations in this energy range would represent an important step forward for GRB comprehension, potentially allowing for discrimination between different proposed emission scenarios. Indeed, many questions about the physical properties of GRBs still remain unanswered, such as the nature of the central engine and the mechanisms of particle acceleration and radiation; e.g., the magnetic field [4], the Bulk Lorentz Factor of the jet [5, 6], and polarization [7]. GRBs can also be used as a probe of their environment [e.g., 8]. High-redshift GRBs could be a cosmological tool to test Lorentz Invariance Violation[9], as well as provide important information on the intergalactic magnetic field [10, 11].

The detection of GRB-190114C shows that, with favorable conditions of low redshift and rapid follow-up, a firm detection is within the reach of the current IACT generation. However, one of the most limiting factors in GRB observation with ground-based, narrow-field instruments is their low duty cycle. Taking into account observational constraints, the typical duty cycle for an IACT is $\sim$10%. It is important to remark that, although achieving better sensitivity and a lower threshold energy than current generation IACTs, the forthcoming Cherenkov Telescope Array (CTA) will be characterized by a fairly similar duty cycle. In addition, the transient and unpredictable nature of GRBs makes it difficult for IACTs to observe them rapidly enough to catch the prompt to early-afterglow phases where certain scenarios favor the emission of VHE radiation. For a wide field-of-view observatory, a duty cycle $\sim$100% is achievable. It would allow for continuous monitoring of all GRBs inside its large field-of-view and thus increase the number of observations by a factor of $\sim$10 ($\gtrsim$10 GRB/month) with respect to IACTs.

Furthermore, the possibility to perform an archival data analysis will guarantee coverage of the important time window from the pre-burst phase up to the very early afterglow phase where IACT observations are strongly affected by delays in the alert chain. This is particularly important

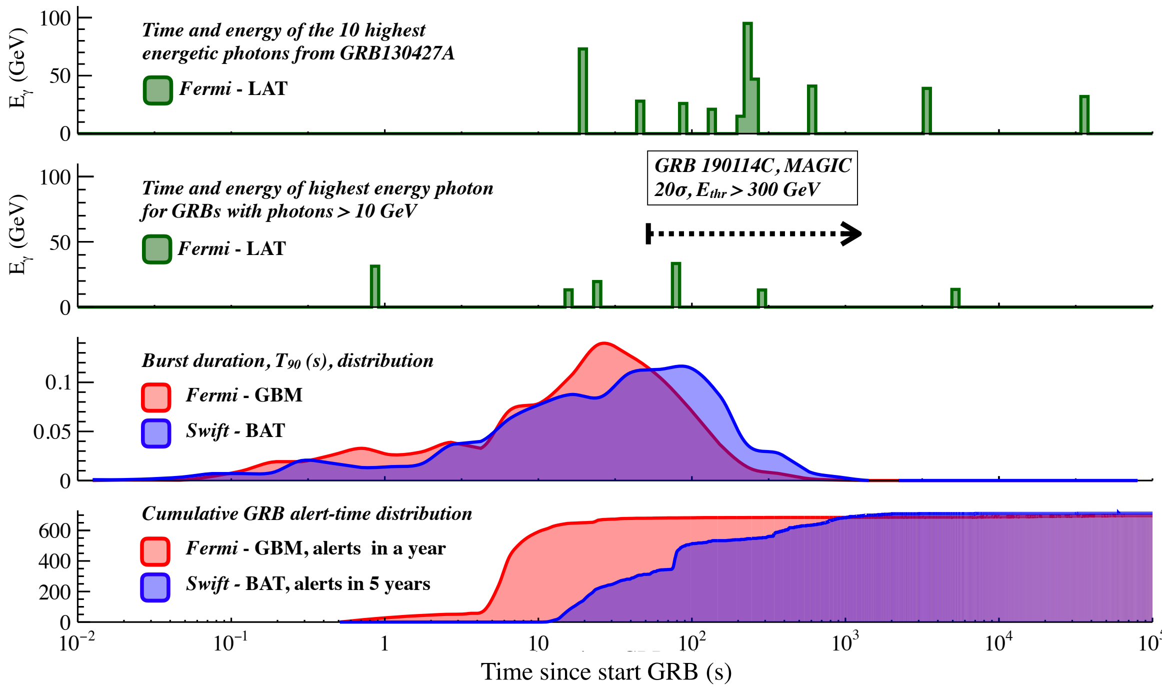

Figure 1: Timescales involved in GRB follow-up observations. From top to bottom: arrival time of high energy photons detected by Fermi-LAT from GRB130427A; arrival time of photons with $E > 10$ GeV from Fermi-LAT detected GRBs; burst durations in X-rays and delays induced due to the finite alert emission times.

for short GRBs, for which the necessary reaction time is usually much shorter than the response capability of any pointing (narrow-field) instrument.

Another exciting possibility is a blind search for new transient TeV phenomena, such as low-luminosity GRBs [12, 13, 14, 15]. This kind of search has not been performed by any gamma-ray instrument so far. It can be performed both offline, allowing for better sensitivity, as well as online, with a goal of alerting the multi-messenger community in real time. Such a dedicated real-time analysis can also help in pinpointing the location of GW or neutrino emitters which can have large localization uncertainties.

The recently established link between short GRBs and mergers of binary neutron star systems promises that the number and variety of GRB detection will improve significantly following the enhancements of the current and future GW interferometers. A wide field-of-view observatory can play a key role by observing GW/GRB locations over extended periods of time, uninterrupted by daylight or moonlight. Probing GeV-TeV emission with sufficiently large photon statistics during this otherwise inaccessible time interval would provide important information on the physics at work in GRBs. In particular, detailed long-term observations be useful to discriminate between the different proposed radiation mechanisms such as inverse Compton and/or hadronic emitting scenarios.

2 Gravitational Waves

Gravitational wave (GW) astronomy was launched with the start of operation of the LIGO and Virgo interferometers in their advanced configuration at the end of 2015. Very rapidly, the detection of GW signals from the mergers of binary black holes became an established window to the universe. Another crucial breakthrough was the first real joint GW multi-messenger observation: the first detection of GWs from the merger of a binary neutron star (BNS) system (GW170817 [2]). This was also the most extensive astronomical observational campaign up to date [16]. The observations of the associated GRB170817A and the subsequent Kilonovae emission across the electromagnetic spectrum clearly established GW multi-messenger astronomy as a new and very promising field of astrophysics.

Since GW data analysis is inherently complex, the time needed to analyze the data recorded by the interferometers to produce first sky localization of GW events will exceed the minute scale throughout the foreseeable future. BNS mergers are expected to be promising VHE emitters [e.g., 17, 18]. Although IACTs can react very quickly after the alert is published (e.g., H.E.S.S. observations started only 5 minutes after the publication of the GW170817A uncertainty region by Virgo/LIGO [19]), the timescale of the prompt VHE emission of GRBs is expected to be of the same order of magnitude. In the case of a delayed alert emission, a pointing instrument can miss it completely. The capability of a wide field-of-view gamma-ray instrument to provide archival data from this phase is therefore of the utmost importance.

During the planned operation of a wide field-of-view gamma-ray observatory, Advanced Virgo and Advanced LIGO will have reached their design sensitivity and new interferometers (e.g., KAGRA and LIGO-India) may have commenced their first data-taking operations. The individual duty cycle of GW detectors will likely remain around 80%, and thus one can expect a significant number of detected events: 4 – 80 BNS/yr assuming design sensitivity of Advanced LIGO/Virgo (years 2020+) up to 11 – 180 BNS/yr for the Advanced+ configuration of LIGO/Virgo (years 2024+) [20]. Even though follow-up observations of GWs are currently considered high-priority “targets of opportunity” for IACT-based observatories like CTA, the limited amount of available observation time (e.g., 5 hr/yr/site for CTA [21]) will force them to impose strict selection criteria for the most promising candidates. A wide field-of-view gamma-ray observatory would be able to record real-time high-energy gamma-ray data for all GW events falling into its field-of-view without having to select particular events to observe. Combined with the roughly ten-fold improvement in duty cycle of a wide field-of-view instrument compared to IACTs, these advantages translate directly into an enormous range of discovery opportunities including new classes of events, such as the large domain of currently unmodeled burst-like GW signals. The potential discovery of high-energy gamma-ray emission associated with GWs by a wide field-of-view gamma-ray observatory also creates increased opportunities for CTA. Being located in close proximity, real-time notifications of detection will allow CTA to react faster and perform detailed follow-up observations covering a large energy range with high sensitivity.

While at the time of operation of a next-generation wide field-of-view gamma-ray observatory most of the GW events will be recorded by at least three interferometers, their median sky localization will still be between $110 - 180\ \mathrm{deg}^2$ and $90 - 120\ \mathrm{deg}^2$ for observations in the years 2020+ and 2024+, respectively [20]. A large field-of-view is essential to cover these sizable regions instantaneously.

3 High-Energy Neutrinos

Another puzzling mystery is the origin of high-energy neutrino events, such as that discovered by the IceCube neutrino observatory in 2013 [22]. In $\sim$10 years of operation, IceCube has detected more than 100 astrophysical neutrino events[23]. They are believed to be produced in hadronic interactions inside cosmic sources, with VHE gamma rays as an expected additional byproduct.

The collaborations operating large scale neutrinos telescopes (e.g.IceCube, ANTARES, Baikal) performed several types of searches for neutrino sources in their data, including correlation studies with catalogues of gamma-ray bursts (GRBs) and gamma-ray emitting blazars. A very stringent upper limit of $<$1% was set on contributions from the prompt emission phase of GRBs to the diffuse astrophysical neutrino flux [24]. A less constraining limit of $<$27% was obtained for blazars from the 2nd $Fermi$-LAT blazar catalogue (2LAC) [25]. A correlation with the Galactic plane, together with ANTARES, was also investigated [26]. Blind searches for neutrino event excesses (in space and/or time) compatible with point sources also did not yield positive results [27],[28].

Neutrino telescopes, constantly monitoring large parts of the sky, are also used as triggering devices for electromagnetic observations when an interesting neutrino event (or increase in event rate) is observed [29, 30]. Due to the higher sensitivity and better angular resolution of electromagnetic observatories, they should be able to localize a potential joint gamma and neutrino source with higher precision than a neutrino detector alone, as well as obtain measurements of the redshift and the overall energetic output of the sources.

The most striking example so far of this kind of multi-messenger cooperation happened in September 2017 when the IceCube observatory detected the high energy neutrino IC-170922A, which could be associated to a known gamma-ray emitting blazar TXS 0506+056 [31]. A rapid dissemination of the event direction lead to extensive follow-up observations. A high level of activity of TXS 0506+056 was revealed in all wavelengths, most notably in GeV gamma rays monitored by the *Fermi*-LAT satellite. In the VHE gamma-ray regime ($E > 100$ GeV) the source was detected first by the MAGIC telescopes, with subsequent observations by VERITAS [32].

Thanks to the precise determination of the direction of IceCube-170922A, the chance probability for a high-energy neutrino to be detected in coincidence with a flaring blazar from *Fermi*-LAT catalogues was estimated to be at the 3σ level. A dedicated study of past IceCube observations of this object reveled another period of significant neutrino activity in the past (years 2014-2015), establishing it as a first potential source of cosmic neutrinos [33]. These exciting results propelled a plethora of theoretical explanations; see e.g., [34] and [35] for a discussion of TXS 0506+056 as a potential source of neutrinos and ultra high energy cosmic rays.

Unfortunately, no dedicated VHE gamma-ray observations were performed strictly simultaneous with the 2014-15 neutrino flare, and those available during the emission of the IC-170922A were not sensitive enough to register any signal. A large field-of-view VHE gamma-ray observatory would be able to provide this relevant information. Additionally, it could also deliver long-term monitoring data for objects (or sky regions) of interest and therefore vastly facilitate calculations of statistical significance of VHE gamma-ray flux correlations with neutrino signals. The planned KM3Net and Baikal-GVD neutrino detectors in the Mediterranean Sea and Lake Baikal will cover the Southern Hemisphere with sensitivity similar to IceCube's sensitivity coverage of the Northern Hemisphere with potentially better angular resolution. Therefore, a collaboration of a large field-of-view VHE gamma-ray observatory in the Southern Hemisphere and neutrino telescopes is essential for understanding the origins of the neutrino events and possibly also ultrahigh-energy cosmic rays.

4 Fast Radio Bursts

The transient sky continues to provide new surprises. One of the most prominent examples of a major astronomical mystery that has emerged in the last decade and now form a new class of transient objects are Fast Radio Bursts (FRBs). These millisecond-duration bursts were first noticed in 2007 in archival data taken with the Parkes radio telescope [36], with over 60 detections to-date (online catalog FRBCAT [37]). Due to their frequency-dependent dispersion properties, FRBs are considered to be of extragalactic origin with their distances estimated as $z \sim 0.1 - 1$ [37]. This is supported by the localization of a repeating source of FRBs within a small galaxy at $z = 0.19$ [38]. Several scenarios link the typical radio energy output of a few $10^{39} D^2_{\mathrm{1Gpc}}$ erg, assuming isotropic emission at distance $D_{1Gpc} = D/1\mathrm{Gpc}$, and the millisecond duration of FRBs to cataclysmic events involving compact objects (white dwarfs, neutron stars and/or black holes). A review of potential sources is available in [39]. Many of these scenarios show similarities with other transients also seen in the X-ray and multi-GeV gamma-ray bands, such as short and long GRBs [40, 41, 42]. Several models have also specifically suggested the existence of flares in the TeV band (e.g., [43, 44]). Nevertheless, no VHE γ-ray emission from those object has been discovered so far [45, 46, 47].

One of the drawbacks of IACT follow-up is the fact that the radio data analysis and the subsequent alert creation, emission, reception, and reaction of pointing instruments will not be able to reach the sub-second time scales of FRBs emission. Monitoring is also not ideal, as the duty cycle of the bursters is poorly constrained and could therefore lead to long coordinated observations during which no FRBs are detected in radio. Consequently, only monitoring instruments with a large field-of-view will be able to provide constraints on the gamma-ray emission in coincidence with the bursts detected in the radio domain.

5 Conclusions

The understanding of known, as well as searches for novel, transient phenomena are progressing at a fast pace at all wavelengths and for all astrophysical messengers. The combination of these observations will provide unprecedented insights into the most violent and intriguing phenomena: the acceleration mechanisms of GRBs, the origin of hadronic cosmic rays, high-energy neutrinos, and novel phenomena like FRBs.

A wide field-of-view very-high-energy gamma-ray observatory in the Southern Hemisphere would perfectly complement the existing and planned instruments to conduct these crucial observations. Thanks to its design, such a large monitoring instrument would be an excellent observatory to participate both in archival analyses and in real-time searches for transients at different timescales and would thus have a firm and well-defined place within the worldwide multi-messenger and multi-wavelength community.

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