Snowmass2021 - Letter of Interest

All-Sky Time-Domain Astrophysics with Very-High-Energy Gamma Rays[*]

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
□ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

Contact Information: (authors listed after the text)
Submitter Name/Institution: Kristi L. Engel / University of Maryland, College Park
Collaboration (optional): HAWC, SWGO
Contact Email: klengel@umd.edu

Abstract: Transient astronomy has witnessed a remarkable evolution with the recent discoveries of gravitational waves, fast radio bursts, high-energy neutrinos, and the long-awaited detection of a gamma-ray burst 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 for 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 multi-wavelength and multi-messenger follow-up. Below, we present key examples of transient sources which would be prime targets for a wide-field-of-view ground-based observatory such as the Southern Wide-field Gamma-ray Observatory (SWGO).

[*]This Letter contains excerpts and material from White Papers submitted for the Astro2020 Decadal Survey [1;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 detection of GWs from the merger of a binary neutron star (BNS) system (GW170817[3]). 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 produce first sky localization of GW events will exceed the minute scale throughout the foreseeable future. Although IACTs can react very quickly after the alert is published , the timescale of the prompt VHE emission of gamma-ray bursts (GRBs) is expected to be of the same order of magnitude. In the case of a delayed alert emission, a pointing instrument could 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 the Southern Wide-field Gamma-ray Observatory (SWGO), 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— one can expect a significant number of detected events[4]. Even though follow-up observations of GWs are currently considered high-priority "targets of opportunity" for IACTs like CTA, the limited amount of available observation time (e.g., five hr/yr/site for CTA[5]) will force the imposition of strict selection criteria for the most promising candidates. A wide-field-of-view ground-based observatory such as SWGO 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. SWGO will not only be able to cover these high-uncertainty regions, but also potentially locate VHE counterparts with smaller uncertainty (also of great interest to CTA and other IACTs). Combined with the roughly ten-fold improvement in duty cycle of SWGO 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 with SWGO also increases opportunities for CTA.

Fast Radio Bursts: 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[6], with over 120 detections to-date[7]. FRBs have possible links to cataclysmic events of compact objects such as white dwarfs, neutron stars, and black holes[8]. They also show similarities with other transientsseen in the X-ray and multi-GeV gamma-ray bands, such as short and long GRBs[9–11]. Several models have also specifically suggested the existence of FRB flares in the TeV band[12;13]. Nevertheless, no VHE gamma-ray emission from those objects has been discovered so far[14–16]. Similar to GWs, FRB follow-up observations require fast detector slewing on timescales of seconds or less, making wide-field-of-view observatories like SWGO ideal for these searches. Additionally, the temporal properties of repeating FRBs are so poorly constrained that even repeating FRBs cannot be easily monitored by pointed instruments.

High-Energy Neutrinos: High-energy neutrinos provide a crucial piece of information in the quest for the sources of high-energy cosmic-ray accelerators[17]. While the IceCube Collaboration has since detected an astrophysical flux of high-energy neutrinos[18], their source has yet to be identified. Towards this goal, it is advantageous to take the multi-messenger approach in order to take full advantage of the advantages of high-energy gamma-ray observations. The searches for transient high-energy gamma-ray emission correlated with high-energy neutrinos already revealed a first promising result: the detection of the flaring blazar TXS 0506+056 in coincidence with the high-energy neutrino IceCube-170922A[19]. Ideally furthering this effort, SWGO will be the only instrument that could provide the crucially needed unbiased, quasi-continuous light curves for such blazars in the Southern sky, as well as monitor for sources that are spatially consistent with the neutrino direction over a wide range of time scales[17], with no limit on the number of candidates that can be observed due to its wide field-of-view.

Gamma-ray Bursts: Gamma-ray bursts 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 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 GWs emitted during the coalescence of two compact objects[3].

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 July 2018. There have now been multiple detections of VHE gamma rays from GRBs, e.g., GRB 180720B[20] and GRB 190829A[21] by H.E.S.S., and GRB 190114C[22] (up to 1 TeV; SWGO's sensitivity to such a GRB shown in Figure 1) by the MAGIC Telescopes, with detections being carried out from the first few minutes up to several hours after the bursts' onsets. Of note, all of these VHE GRBs are long GRBs, with no VHE detection yet made of a short GRB, such as one that might be expected as a GW counterpart. The discovery of VHE gamma rays $>$300 GeV shows, in particular, that the transient sky at a 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 like SWGO.

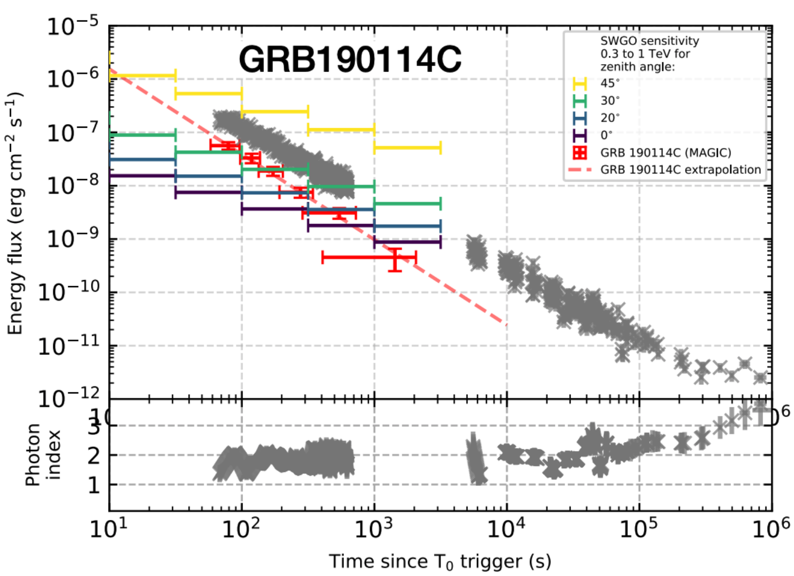

Figure 1: SWGO's sensitivity to a GRB like GRB 190114C from 0.3–1 TeV for different zenith angles. Results from MAGIC[22] included for comparison.

Follow-up and self-triggered 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[23], the Bulk Lorentz Factor of the jet[24–27], and polarization[28]. GRBs can also be used as a probe of their environment[29;30]. High-redshift GRBs could be a cosmological tool to test Lorentz Invariance Violation[31], as well as provide important information on the intergalactic magnetic field[32;33].

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Authors: A.M. Albert (Los Alamos National Laboratory), L.H. Arnaldi (CNEA/IB, Argentina), J.C. Arteaga-Velázquez (Universidad Michoacana, Mexico), H.A. Ayala Solares (Pennsylvania State University, University Park), U. Barres de Almeida (CBPF, Brazil), T. Bretz (RWTH Aachen University), C.A. Brisbois (University of Maryland, College Park), K.S. Caballero-Mora (UNACH, México), A. Carramiñana (INAOE, México), A. Chiavassa (Torino University, IT), R. Conceição (LIP/IST, Lisbon, Portugal), S. Dasso (IAFE, Argentina), J.C. Díaz-Vélez (University of Wisconsin–Madison), B.L. Dingus (University of Maryland), M. Durocher (Los Alamos National Laboratory), M.A. DuVernois (University of Wisconsin–Madison), R.W. Ellsworth (University of Maryland, College Park), K.L. Engel (University of Maryland, College Park), C. Espinoza (UNAM, México), K.L. Fan (University of Maryland, College Park), K. Fang (Stanford University, University of Wisconsin-Madison), N. Fraija (IA-UNAM, México), J.A. García-González (ITESM-EIC), G. Giacinti (MPIK, Germany), J.A. Goodman (University of Maryland, College Park), F. Guo (Los Alamos National Laboratory), J.P. Harding (Los Alamos National Laboratory), R.N. Hix (University of Maryland, College Park), D.Z. Huang (Michigan Technological University, Houghton), P. Huentemeyer (Michigan Technological University, Houghton), F. Hueyotl-Zahuantitla (UNACH, México), G. La Mura (LIP, Lisbon, Portugal), H. Li (Los Alamos National Laboratory), F. Longo (University and INFN Trieste), I. Martinez-Castellanos (NASA-GSFC/CRESST/UMD), J.A. Morales-Soto (Universidad Michoacana, Mexico), E. Moreno (BUAP, México), E. Mottola (Los Alamos National Laboratory), L. Nellen (ICN-UNAM, México), M. Newbold (University of Utah, Salt Lake City), E. Orlando (University of Trieste and Stanford University), A. Pichel(Instituto de Astronomía y Física del Espacio, CONICET-UBA, Argentina), E. Prandini (University of Padova, IT), C.D. Rho (University of Seoul, Seoul), A.C. Rovero (Instituto de Astronomía y Física del Espacio, CONICET-UBA, Argentina), E. Ruiz-Velasco (Max Planck Institute for Nuclear Physics), A. Sandoval (UNAM, México), M. Santander (University of Alabama, USA), M. Schneider (University of Maryland, College Park), A.J. Smith (University of Maryland, College Park), K. Tollefson (Michigan State University, East Lansing), B. Tomé (LIP/IST, Lisbon, Portugal), I. Torres (INAOE, México), R. Torres Escobedo (Universidad de Guadalajara, Mexico/Texas Tech University, Lubbock TX), J. Vícha (FZU, Prague, Czech Republic), E.J. Willox (University of Maryland, College Park)