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Very high energy sky monitoring with the Southern Wide-field Gamma-ray Observatory

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Abstract. The Southern Wide-field Gamma-ray Observatory (SWGO) is the proposal for a new ground-based γ-ray instrument in the Southern Hemisphere, which will use an array of water-Cherenkov particle detectors to provide continuous monitoring of a large portion of the sky at the very- and ultra-high-energies (VHE and UHE, respectively). At the low energy side, SWGO aims to push the observational range of wide-field ground-based γ-ray facilities down to a few hundred GeV, thus bridging the gap between space and ground-based facilities in the monitoring of the VHE sky. In the high energy domain, on the contrary, it will benefit from the optimal coverage of the Galactic Plane to map the distribution of UHE sources in the inner parts of the Galactic disk and close to the Galactic Center, leading to an extraordinary improvement in our ability to identify their most likely counterparts. In this contribution, we describe the concept of SWGO and its potential to constrain the physics of VHE emission and particle acceleration in γ-ray sources powered by relativistic jets and energetic shocks. We finally discuss its role within the global network of multi-messenger facilities.

1 Introduction

High Energy Astrophysics has recently witnessed several ground breaking discoveries. After the first detection of gravitational waves (GW) by the LIGO/VIRGO Collaboration [1], the binary neutron star (NS) merger that originated GW 170817 was the first event observed in conjunction with a short Gamma-Ray Burst (GRB) and subsequently associated with a kilo-nova [2, 3], thus providing further insight in the physics of NS and GRB. In the meantime, monitoring observation programmes, carried out by the IceCube observatory [4] and the *Fermi*-Large Area Telescope mission (*Fermi*-LAT, [5]) led to the identification of the γ-ray flaring blazar TXS 0506+056 as the likely source of an ultra-relativistic neutrino [6]. These highly anticipated and, yet, eagerly awaited discoveries demonstrated that the observation of the Universe in γ rays and other energetic particles could probe the fundamental laws of Physics at scales that are far beyond the reach of any laboratory experiment.

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In the Very High Energy domain (VHE, $E \geq 100\,\mathrm{GeV}$), the expected fluxes of incoming signals are very low and they require instrumented areas that cannot be supported by artificial satellites. However, primary particles with these energies can interact with the Earth's atmosphere and start extensive air showers (EAS) of photons and relativistic charged particles that propagate toward the ground and can eventually be detected. Their observation is based on two complementary techniques. The first one uses Imaging Atmospheric Cherenkov Telescopes (IACT) to observe the radiation flashes produced by the relativistic charged particles of the shower. The second one, instead, adopts arrays of particle detectors located in high-altitude sites to interact directly with the shower particles. IACT observatories, such as the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC, [7]), the Very Energetic Radiation Imaging Telescope Array System (VERITAS, [8]), the High Energy Stereoscopic System (H.E.S.S., [9]) and the next-generation Cherenkov Telescope Array (CTA, [10]) offer the best performance in terms of sensitivity to point-like sources, spatial resolution and energy resolution. On the other hand, they have a narrow field of view (FoV), up to a few square degrees, and they can only operate in dark conditions, making them unsuitable for continuous monitoring and extensive survey programmes. The particle detector arrays, such as the Astrophysical Radiation with Ground-based Observatory (ARGO, [11]), the Tibet Air Shower experiment (Tibet ASγ, [12]) the High Altitude Water Cherenkov (HAWC, [13]), and the recently completed Large High Altitude Air Shower Observatory (LHAASO, [14]), conversely, provide simultaneous coverage of large sky areas, up to approximately 2 sr, and they can operate almost continuously. Although we have a well-established strategy to grant nearly all-sky access to IACT facilities, at present, VHE γ-ray monitoring observatories are only being operated in the Northern hemisphere.

The Southern Wide-field Gamma-ray Observatory project (SWGO, [15]) aims at designing the latest generation, highly efficient and cost effective solution to install an extensive air-shower (EAS) detector array in the Southern hemisphere. Here we describe the fundamental concepts of the project, we discuss its scientific potential and we compare the performance estimates with the known or expected properties of possible targets. Finally, we conclude the contribution by discussing the role of SWGO in the framework of the global Multi-Messenger Astronomy network.

2 Project overview

The SWGO Collaboration[1] is currently formed by more than 50 institutions from 14 member countries. Additional support by associated scientists allows the involvement of the international community from even more countries. The primary goal of the collaboration is to produce a fully detailed solution to install a next-generation EAS array in the Southern hemisphere. Taking advantage of the continuous scanning of a wide FoV, such an observatory would complement the Northern facilities, attaining a nearly all-sky monitoring footprint, as illustrated in Figure 1.

The detector units used to build the array will be based on Water Cherenkov Detectors (WCD), which will be designed to optimize the signal collection and the particle recognition capabilities, thanks to very fine time resolution ($\Delta t \approx 2\,\mathrm{ns}$) and signal reconstruction techniques. The detector units may be deployed in an array consisting of a compact core, with a high filling factor ($ff \sim 80\%$) and an area of $S \approx 80000\,\mathrm{m}^2$, to track the low-energy showers initiated by sub-TeV primary particles, surrounded by a sparse array, with a filling factor degrading down to 1%, but extending to the order of $1\,\mathrm{km}^2$, which will instead observe the showers produced by the highest energy primaries.

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[1] https://www.swgo.org

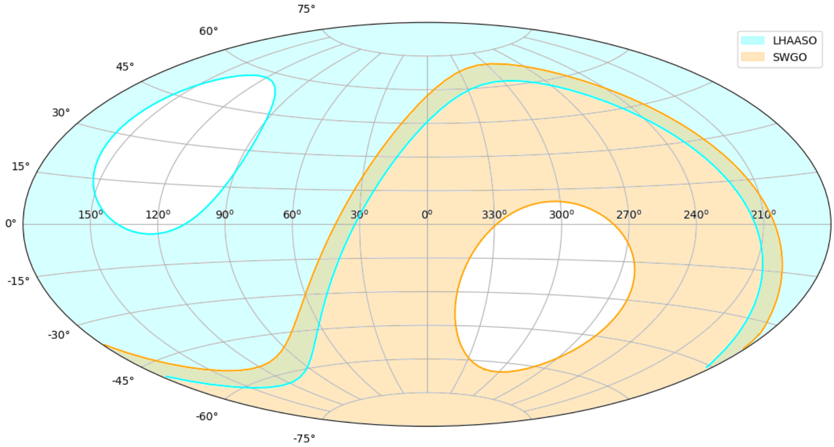

Figure 1. Representation of the visible sky, within 30° from zenith, showing the sky regions covered by LHAASO (cyan shaded area) and by SWGO, assuming an observatory latitude close to 23° S (orange shaded area). The map is plotted in Galactic coordinates.

The scientific potential of this experiment is huge. On one side, its location in the Southern hemisphere grants an optimal visibility of sky regions that cannot be currently monitored and that are very likely hosting a wealth of energetic sources, yet to be discovered. On the other, the experience gained with currently available monitoring facilities gives us an invaluable opportunity to design an instrument that can operate as a driver for follow-up campaigns, both by mapping the distribution of targets and by extending the simultaneous sky coverage of VHE monitoring facilities, in case of occurrence of transient and multi-messenger triggers. Its location close to the Southern Tropic, moreover, will result in an optimal coverage of the declination band of VHE transients that may be associated with IceCube and KM3NeT neutrino alerts. The project is presently in its Research and Development state (R&D), with the estimate of providing a fully detailed design proposal by the end of the year 2023. Construction and commissioning phases aim at completing the observatory in the 2030s, with a planned experiment duration of ten years.

3 SWGO Science goals

SWGO will open a new window to approach some of the most compelling problems in today's high energy particle physics and astrophysics, ranging from the nature of high-energy emission in extra-galactic transients to the origin of PeV cosmic rays (CR) and the search for dark matter particles. In many cases, it will represent an unrivalled facility for the exploration of time-variability aspects, as well as for mapping extended sources, such as the *Fermi Bubbles* and the star-forming regions where recent super-nova activity is expected to power *super-bubbles*. In addition, its extended energy coverage is intended to make it able to issue alerts for follow-up campaigns, thus complementing the global multi-messenger network of gravitational, electromagnetic, cosmic-ray and neutrino observatories. General descriptions of the scientific questions that SWGO can address have been provided in the form of a white paper [16]. Here we discuss a set of driving Science cases, also summarized in Table 1, for which recent studies and new findings, based on the *Fermi*, HAWC, and LHAASO

Table 1. SWGO Science driving benchmarks.

Target	Design driver	Expected requirement
Transient sources Gamma-Ray Bursts	Low-Energy sensitivity and site altitude	Minimum integration for 5σ detection: $F(E > 100\,\mathrm{GeV}) \approx 10^{-8}\mathrm{erg\,cm^{-2}\,s^{-1}}$ $N(E,t) \propto E^{-2} \cdot t^{-1.2}$
Galactic Accelerators: PeVatron Sources	High-energy sensitivity and energy resolution	Maximum exp-cutoff energy detectable at 95% CL in 5 years for: $F(1\,\mathrm{TeV}) = 5\,\mathrm{mCrab}$, $N(E) \propto E^{-2.3}$
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity and angular resolution	Maximum source angular extension detectable at 5σ in 5-yr integration for $F(> 1\,\mathrm{TeV}) = 5 \times 10^{-13}\,\mathrm{TeV\,cm^{-2}\,s^{-1}}$
Diffuse Emission: Fermi Bubbles	Background rejection	Cosmic-Ray residual background level $< 10^{-5}$ at 1 TeV
Fundamental Physics: Dark Matter from Galactic Halo	Mid-range energy sensitivity and site latitude	Maximum energy for $b\bar{b}$ thermal-relic cross-section limit at 95% CL for Einasto profile
Cosmic-rays: Mass-resolved dipole/ multipole anisotropy	Muon counting capability	Maximum dipole energy at 10^{-3} level log-mass dipole resolution at 1 PeV - goal is to achive $A = \{1, 4, 14, 56\}$; Maximum multipole scale > 0.1 PeV

experience, revealed the properties of different possible targets, suggesting what design characteristics will be needed to set the instrument's discovery potential.

3.1 Extra-galactic and transient sources

At the lowest energies, the core science of SWGO is focused on transient sources, exploiting the wide-field of view and near-continuous duty cycle of the observatory, along with its southern location, to work as a monitoring and trigger instrument complementary to CTA. At the few-hundred GeV energy scale, the two principal target sources are Active Galactic Nuclei (AGN) and GRB, which are, respectively, the candidate multi-messenger astrophysical counterparts of ultra high energy (UHE) neutrinos and GW events [2, 3, 6], and allow to probe the spectrum and intensity of the Extragalactic Background Light (EBL), through its redshift dependent opacity effects [17–19]. In terms of performance goals, the aim is to guarantee that SWGO will be an effective detector of serendipitous transients, able to issue fast triggers for other instruments, particularly in the case of GRBs, where it should have good performance in the first few kiloseconds from t_0, when source flux is higher [20].

As an example, Figure 2 presents an analysis of the detectability of the bright GRB 130427A at VHE energies, based on a light-curve extrapolation into the VHE domain [21], using different instrument performances and energy threshold prescriptions. The calculations show that an integral target sensitivity $\sim 10^{-9}\mathrm{ph\,cm^{-2}\,s^{-1}}$ between $0.1 - 1$ TeV (in 1 ks) is able to detect a source only a fraction of the brightness of GRB 130427A. This level roughly corresponds to the 1/6 brightest GRBs in the *Fermi*-LAT catalogue, and is statistically equivalent to securing one safe serendipitous GRB detection by SWGO per year, being additionally sufficient to guarantee regular (monthly) AGN flare triggers [22]. For bright and relatively nearby GRBs, such as GRB 190114C [23], this sensitivity would allow not only for the generation of an early (< 1 ks) trigger alert by SWGO, but also, in case of favourable observing conditions, of a short-time resolution of the early emission below the 100 s time-scale [21], with the possibility of probing the prompt phase in the VHE spectral range.

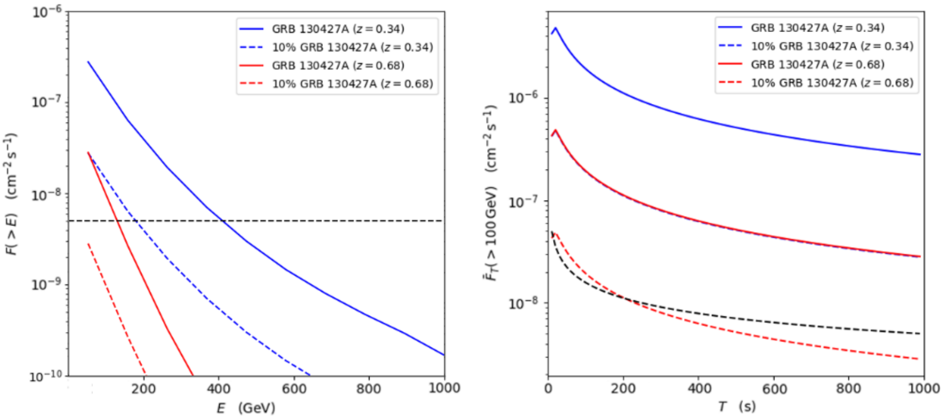

Figure 2. Left panel: average photon flux expected above any given energy in 1000 s for a burst with the spectral and temporal characteristics of GRB 130427A (blue continuous line), an identical burst with 10% its strength (blue dashed line) and the same previous cases computed for twice the measured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

3.2 Ultra-high energy domain

At the high extreme of SWGO's energy range, science is dominated by the search for PeVatrons. These are the putative sources responsible for the acceleration of knee cosmic-ray particles, whose signature in γ rays is expected to come in the form of a hard spectrum, with unabated emission beyond 100 TeV [24]. This science case has recently been reinforced by the Tibet ASγ detection of diffuse γ-ray emission in the Galaxy well above this energy range [25] and by LHAASO's detection of a number of PeV-emitting γ-ray sources in the Galactic Plane [26]. However, differences in the observing pattern of Tibet AS+MD and LHAASO result in a problematic reconstruction of the diffuse component, implying the need to cover a larger portion of the Galactic Plane. The identification of PeVatrons by means of the detection of a high-energy spectral cutoff signature, on the other hand, poses a requirement on the energy resolution of the observatory, of $\sim 30\%$ in the energy range above 100 TeV. A firm estimate on the required point-source sensitivity at these energies depends on knowledge of the Galactic hard-spectrum sources, which is largely missing. Still recent estimates suggest that an integral sensitivity above 100 TeV at the 10^{-13} ph cm^{-2} s^{-1} level (for 1-year integration) is required for an in-depth probe of the Galactic PeVatron population [24], where the lack of sources with spectral index close to -2 in LHAASO data is a matter of concern that may be solved by covering the central regions of the Galaxy [26].

The study of extended sources and of diffuse emission, whose highest-energy flux is generally linked to the fraction of PeVatrons among the Galactic accelerators, will critically depend on the background rejection power of the array, which aims to achieve a residual charged cosmic-ray background better than 10^{-3} at 10 TeV, and beyond $\sim 10^{-4}$ above 100 TeV. Above $\sim$ 10 TeV, the γ/hadron separation is strongly associated with the capability to detect single muons at the individual detector units. The science case for extended sources will be centered on the study of Pulsar Wind Nebulae (PWNe) and TeV Halos, which pose the principal

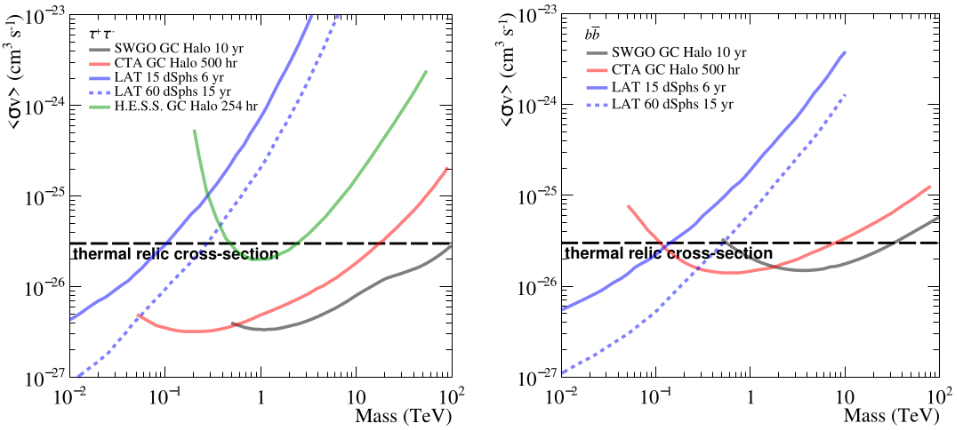

Figure 3. Expected sensitivity of SWGO to the detection of thermal relic Dark Matter signals from the Galactic Center Halo for the channels $\tau^+\tau^-$ (left) and $b\bar{b}$ (right). The plots show that the expected sensitivity of SWGO should allow to probe deep into the entire range of the thermal relic cross-section limits, extending CTA capabilities above a few TeV, up to 100 TeV. Figure adapted from [28].

benchmark constraints for the angular resolution of the observatory. Here, the goal will be to extend the detectability of these objects towards higher energies, above 10 TeV, and for angular extensions up to $\sim 3^\circ$, for which a relatively good angular resolution capability of approximately 0.15° is estimated to be necessary to resolve the vast majority ($> 97\%$) of the population [27].

3.3 Dark matter searches

The sensitivity and energy resolution of SWGO should also be sufficient to constrain the science goals for Dark Matter (DM) observations, for which the Galactic Center Halo is the most promising observational target, followed by some potentially interesting ultra-faint Dwarf Spheroidal galaxies (DSphs) that could be detected, for instance, by the Large Synoptic Survey Telescope (LSST, [29]). As shown in Figure 3, the best contribution of SWGO in the study of DM is its possibility to constrain the entire energy range of weakly interacting particle models (WIMP), especially above 30 TeV, where SWGO sensitivity could outperform that of CTA for reasonable integration times. In order to obtain this result, a point-source flux sensitivity of $\approx 3 \times 10^{-14}$erg cm^{-2} s^{-1} in the range between a few to several tens of TeV (for 5-year integration), as used in the figure, is the necessary requirement.

3.4 Cosmic-ray studies

At high energies, generally above $\sim$ 10 TeV, the capability to detect single muons is crucial for a good γ/hadron separation. This capability would have a large impact on the background rejection necessary for improving detectability of faint diffuse γ-ray emission [30], but it would also allow for unique mass-resolved charged cosmic-ray studies up to PeV energies. The science goal here is ultimately to understand the nature and the evolution of the cosmic-ray dipole and multipoles between 0.1 and several PeVs. The CR anisotropy investigation requires extended sky coverage, which is crucial for multipoles with low l-scale, but may be useful to search for variations in different directions for large l-scale studies, as well. The capabilities of SWGO aim at extending the anisotropy detection beyond the PeV-scale, investigating the CR spectrum in four mass groups ($A = \{1, 4, 14, 56\}$) and mesuring the multipole l-scale beyond 0.1 PeV.

4 Conclusions and outlook

Since the first VHE γ-ray detection [31], hundreds of sources have been discovered, including variable objects. Their study requires instruments able to continuously monitor large portions of the sky, sensitive to energies above those of satellite-based experiments. The detection of photons of extreme energies from the Galaxy [25, 26] strengthens the necessity for a large survey instrument with optimal access to the Galactic Plane and sensitivity beyond 100 TeV. In addition, the VHE properties observed in the extremely bright GRB 221009A [32–35], which has been observed to emit photons up to 18 TeV by LHAASO [36] from a redshift of $z = 0.151$ [37], further outlined the importance of obtaining all-sky coverage from VHE monitoring instruments. This will increase the number of GRB triggers that can be promptly covered and, consequently, probe their VHE properties and their interaction with the EBL with enhanced statistical significance.

The vision pursued for SWGO is of an observatory that aims to cover a wide energy range, bridging between satellite observations down to 100 GeV, and reaching towards the PeV energy domain [15]. Its location at a high altitude in the Southern hemisphere will provide a new window to an unexplored sector of the sky and, particularly, to the center of the Galaxy. Currently, in the R&D Phase, the project plans to deliver an Observatory proposal by 2023.

Acknowledgements

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