

## Benchmarking the Science for the Southern Wide-Field Gamma-ray Observatory (SWG0)

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The Southern Wide-field Gamma-ray Observatory (SWG0) is the project to build a new extensive air shower particle detector for the observation of very-high-energy gamma-rays in South America. SWGO is currently planned for installation in the Southern Hemisphere, which grants it a unique science potential among ground-based gamma-ray detectors. It will complement the capabilities of CTA, working as a wide-field instrument for the monitoring of transient and variable phenomena, and will expand the sky coverage of Northern Hemisphere facilities like HAWC and LHAASO, thus granting access to the entire Galactic Plane and the Galactic Center. SWGO aims to achieve excellent sensitivity over a very large target energy range from about 100 GeV to the PeV, and improve on the performance of current sampling array instruments in all observational parameters, including energy and angular resolution, background rejection, and single-muon detection capabilities. The directives for the final observatory design will be given by a number of key science goals which are being defined over the course of the Project's R&D phase. In this contribution we will present the core science topics and target performance goals that serve as benchmarks to guide SWGO's design configuration.

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## 1. Introduction

The direct detection of primary gamma-rays is only possible with space-based detectors, such as Fermi-LAT. However, the size and sensitivity limitations of satellite-borne detectors are prohibitive factors as fluxes become small towards higher energies. An alternative solution is to use the shower of particles produced as gamma-rays interact with the atmosphere for an indirect detection. These showers can be studied with observatories of two complementary types: imaging atmospheric Cherenkov telescopes, which are narrow field-of-view, highly sensitive pointing instruments, such as CTA [16], and high altitude air shower arrays, such as SWGO. Wide-field air shower arrays have the highest energy reach, and are ideal to search for transient sources (monitoring), and for the study of emission from very extended regions of the sky (surveying).

The potential of such a wide-field, and high duty-cycle, ground-based gamma-ray detector to address this observational programme has been demonstrated by the current-generation instruments HAWC [24] and ARGO [21], and has been recently extended in the Northern Hemisphere by LHAASO [8]. Nevertheless, no such instrument exists in the south, where there is great potential for the mapping of large scale Galactic emission as well as providing access to the full sky for transient and variable phenomena, including multi-messenger events [5]. Access to the Galactic Centre and complementarity with the major facility CTA-South are key motivations for the installation of such an observatory. There is also significant potential for cosmic-ray studies, including anisotropy, where the tropical latitude range between  $10^\circ$  and  $30^\circ$  represents a visibility gap for joint analysis between northern facilities and IceCube, at the South Pole [13].

### 1.1 The SWGO concept

The SWGO aims to cover an extended energy range, from the low energies, around 100 GeV, thus closing the gap between wide-field satellite and ground-based measurements, to the very-high energies, at the PeV scale. At low energies, the critical design factors are the amount of signal collected and the ability to cope with explosive trigger rates, whereas gamma/hadron discrimination will be based on the comparison of shower patterns at ground, exploiting the PMTs signal time resolution, e.g. [12]. At higher energies, the density of stations needed to ensure a good gamma/hadron discrimination based on individual muon tagging, and improved energy resolution, are crucial requirements [10], constraining the capacity to cover large areas at a limited cost.

Given those considerations, the general design concept of SWGO [14], which will serve as a baseline for further studies in the current R&D phase of the project, consists in a large (circa 80,000  $\text{m}^2$ ) and high fill-factor ( $\sim 80\%$ , corresponding to 4-5 $\times$  the HAWC effective area) core array of water Cherenkov detector (WCD) units, surrounded by an outrigger array of WCDs, arranged in a low fill-factor grid and covering an area of minimum 200,000  $\text{m}^2$  to provide high-energy sensitivity (but possibly extending up to the  $\text{km}^2$  scale to match LHAASO's UHE capabilities). The array is to be deployed at a high-altitude site in the Andes, at least 4.4 km above sea level [11].

The WCD detector units are optically isolated water volumes instrumented with photo-detectors and able to sample the shower front to provide time and particle energy density information, as well as muon tagging for background rejection. The final detector choices – if the WCD units will consist of tanks, bags deployed in a lake, or assembled in a pond-like structure – are still under investigation, as well as details of the individual detector unit design, photosensors and electronics.

## 2. The SWGO Science Case

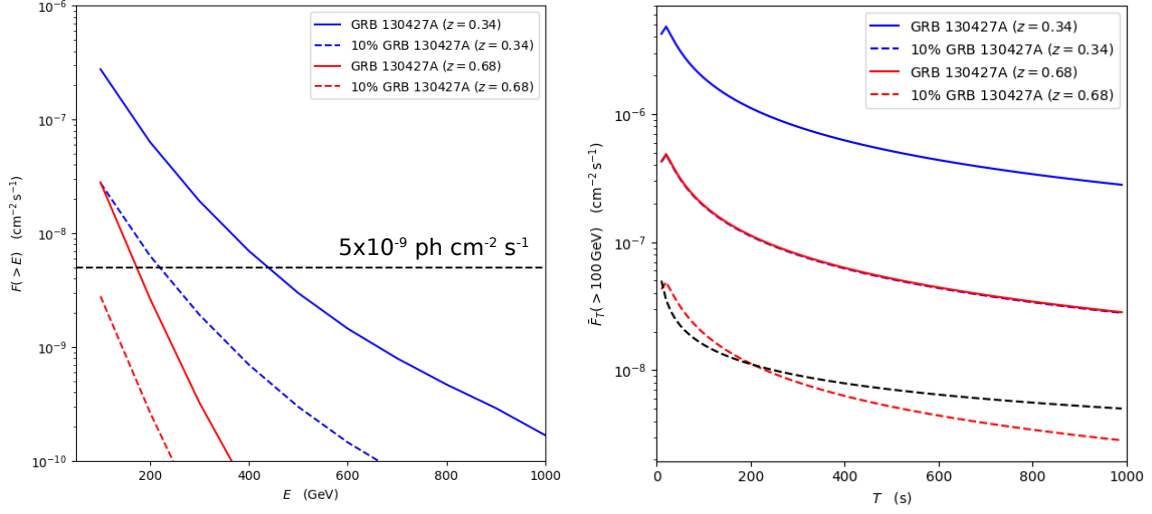
SWGO will probe extreme phenomena and astrophysical environments to address some of the most compelling questions of astro-particle and high-energy astrophysics of today, such as the origin of PeV cosmic rays and the nature of dark matter particles, as well as the study of highly energetic transient phenomena [5]. For many of its scientific objectives, the SWGO concept occupies a niche, which in some cases is unrivalled by current or planned facilities, given, among other reasons, the observatory's southern location, which will allow for direct observation of the Galactic Centre and the 'Fermi Bubbles', with ample view of the Galactic Plane. The new observatory will be a powerful time-variability monitor, mainly due to its planned lower-energy threshold, filling an empty place in the global multi-messenger network of gravitational, electromagnetic and neutrino observatories. In this regard, it should be able to issue alerts and be fully complementary to the next-generation Cherenkov Telescope Array, the CTA.

In the following, we will briefly describe the core science goals of SWGO, and their principal associated design characteristics, which together form a basis of justification for the design work of the current R&D phase of the project. Here, the current results from HAWC, and more recently LHAASO, provide a baseline for the new observatory science objectives, for which a detailed description was presented in an earlier white-paper by the Collaboration [5].

### 2.1 PeVatrons and galactic accelerators

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 gamma rays is expected to come in the form of a hard spectrum, with emission unabated beyond 100 TeV [7]. This science case has recently been reinforced by a detection, by the Tibet AS+MD array, of diffuse gamma-ray emission in the Galaxy well above this energy range [6], and by LHAASO's detection of a number of PeV-emitting gamma-ray sources in the Galactic Plane [27]. The identification of PeVatrons by means of the detection of a high-energy spectral cutoff signature (or lack thereof) 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 lacking, but recent estimates from [7] suggest that an integral sensitivity above 100 TeV at the  $10^{-13} \text{ ph.cm}^{-2}.\text{s}^{-1}$  level (for 1-year integration) is required for an in-depth probe of the Galactic PeVatron population, an estimate needing further consideration in face of the most recent LHAASO results [27].

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,  $\gamma$ /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 centred on the study of PWNe and TeV Halos, which pose the principal 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 circa  $0.15^\circ$  is estimated to be necessary to resolve the vast majority (over 97%) of the population [19].



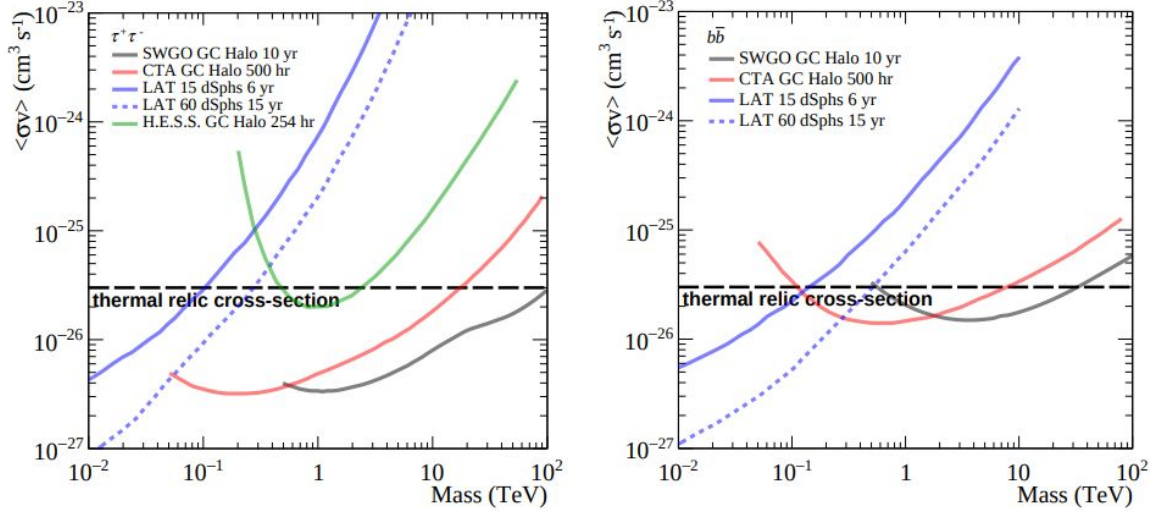
**Figure 1:** Expected photon flux at VHE energies from a light-curve parameterization [18] of the bright GRB 130427A as seen by Fermi-LAT [3]. The black dashed line indicates a target integral sensitivity for SWGO between 0.1 and 1 TeV for 1 ks integration time. The left plot shows the detectability, for various scalings of the integral source flux, as a function of energy, indicating the importance of a low-energy detection threshold for the experiment. The right plot presents the integral source flux above 100 GeV as a function of time since  $t_0$ , showing that an instrument like SWGO could perform well in detecting early-time triggers from GRBs.

## 2.2 Gamma-ray Bursts and transients

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-100 GeV energy scale, the two principal target sources are Active Galactic Nuclei (AGN) and Gamma-Ray Bursts (GRB), both of which are the candidate multi-messenger astrophysical counterparts of very high energy (VHE) neutrinos and gravitational wave (GW) events, respectively [1, 2, 15]. In terms of performance goals, the idea in the transients science case is to guarantee that SWGO will be an effective detector of serendipitous variable phenomena, able to efficiently trigger other instruments within short timescales, 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 [4].

Figure 1 presents an analysis of the detectability of the bright GRB 130427A<sup>1</sup> at VHE energies, based on a light-curve extrapolation into the VHE energies [18]. The calculations show that a target integral sensitivity  $\sim 10^{-9}$  ph.cm<sup>-2</sup>.s<sup>-1</sup> 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, and should also be sufficient to guarantee regular (monthly) AGN flare triggers [17]. For bright, and relatively nearby GRBs, such as GRB 190114C [20], this sensitivity would allow not only for the generation of an early (< 1ks) trigger alert by SWGO, but also, in case of favourable-condition observations, of a short-time resolution of the early emission at or below the 100 s timescale [18], with the possibility of probing the prompt phase at VHEs.

<sup>1</sup>From which Fermi-LAT detected its highest-energy photon of 94 GeV [3]



**Figure 2:** Expected sensitivity of SWGO to the detection of thermal relic Dark Matter signals from the Galactic Center Halo for the channels  $\tau^+\tau^-$  and  $b\bar{b}$  [25]. The plots show that the expected sensitivity of SWGO should allow probing deep into the entire range of the thermal relic cross-section limits, extending CTA capabilities above a few TeV, up to 100 TeV.

### 2.3 Dark Matter searches

The sensitivity and energy resolutions of SWGO should also be sufficient to constrain the science goals for Dark Matter observations, for which the Galactic Centre Halo is the most promising observational target, along with some potentially interesting ultra-faint Dwarf Spheroidal galaxies (dSphs) that could be detected e.g., by LSST [23]. As shown in Figure 2, the niche of SWGO in the study of Dark Matter is the possibility to constrain the entire energy range of WIMP models, especially above 30 TeV, where SWGO sensitivity could outperform that of CTA for reasonable integration times. For that, a point-source flux sensitivity of  $\approx 3 \times 10^{-14}$  erg.cm $^{-2}$ .s $^{-1}$  in the range between a few to several 10s TeV (for 5-year integration), as used in the figure, is the target goal.

### 2.4 Cosmic-ray studies

As already mentioned, at high energies, generally above  $\sim 10$  TeV, the capability to detect single muons is crucial for a good gamma-hadron separation, and this capability would impact not only the background rejection necessary for improving detectability of faint diffuse gamma-ray emission (as discussed in [22]), but 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 of the evolution of the cosmic-ray dipole and multipoles between 0.1-multi PeV, and is subdivided into:

- extending the dipole anisotropy detection to beyond the 1 PeV energy (at  $10^{-3}$  level);
- achieving the decomposition of the cosmic ray spectrum into four mass groups  $A=\{1, 4, 14, 56\}$ , in the 0.1-1 PeV energy range;
- measuring the multipole  $l$  – scale of the cosmic-ray anisotropy, for events with energies above 0.1 PeV, and in particular extending it beyond  $l = 5$  ( $\sim 35^\circ$ ) above 0.1 PeV, and beyond  $l = 20$  ( $\sim 10^\circ$ ) around 10 TeV (at  $10^{-3}$  level).

Science Case	Design Drivers	Benchmark Description
Transient Sources: Gamma-ray Bursts	Low-energy sensitivity & Site altitude <sup>a</sup>	Min. time for $5\sigma$ detection: $F(100 \text{ GeV}) = 10^{-8} \text{ erg/cm}^2.\text{s}$ , PWL index = -2., $F(t) \propto t^{-1.2}$
Galactic Accelerators: PeVatron Sources	High-energy sensitivity & Energy resolution <sup>b</sup>	Maximum exp-cutoff energy de- tectable 95% CL in 5 years for: $F(1 \text{ TeV}) = 5 \text{ mCrab}$ , index = -2.3
Galactic Accelerators: PWNe and TeV Halos	Extended source sensitivity & Angular resolution <sup>c</sup>	Max. angular extension detected at $5\sigma$ in 5-yr integration for: $F(>1 \text{ TeV}) = 5 \times 10^{-13} \text{ TeV/cm}^{-2}.\text{s}$
Diffuse Emission: Fermi Bubbles	Background rejection	Minimum diffuse cosmic-ray residual background level. Threshold: $< 10^{-4}$ level at 1 TeV.
Fundamental Physics: Dark Matter from GC Halo	Mid-range energy sensitivity Site latitude <sup>d</sup>	Max. energy for $b\bar{b}$ thermal relic cross-section limit at 95% CL in 5-years, for Einasto profile.
Cosmic-rays: Mass-resolved dipole / multipole anisotropy	Muon counting capability <sup>e</sup>	Max. dipole energy at $10^{-3}$ level; Log-mass resolution at 1 PeV – goal is $A=\{1, 4, 14, 56\}$ ; Maxi- mum multipole scale $> 0.1 \text{ PeV}$

**Table 1:** SWGO Science Benchmarks. <sup>a</sup>Site altitude to be greater than 4.4 km above sea level. <sup>b</sup>Energy resolution  $< O(30\%)$  throughout core energy range 1-100 TeV. <sup>c</sup>Angular resolution  $\sim 0.15^\circ$  throughout core energy range 1-100 TeV. <sup>d</sup>Site latitude not constraining among candidate sites under consideration. <sup>e</sup>WCD units with muon identification capability for  $\gamma$ /hadron discrimination.

### 3. Science Benchmarks for SWGO

The ultimate goal of a new observatory is to discover novel astrophysical phenomena that expand the frontiers of knowledge. Since these cannot be constrained beforehand, experimental design must proceed on the basis of reasonable extrapolations from current understanding (the *known unknowns*). To this purpose, a set of core science cases has been defined, as detailed in [9], which aim to guide the definition of options for the R&D studies, and later to benchmark the final observatory design. They reflect the minimum set of science goals aimed for by the Observatory, and directly translate into detector performance requirements.

Table 1 briefly lists the core science goals discussed in Section 2, and their associated design characteristics, which imply a number of basic performance requirements: (i) a dense array core and excellent  $\gamma$ /hadron separation for low-energy detection threshold,  $< 300 \text{ GeV}$ ; (ii) an extended sparse array with peak point source sensitivity at  $\sim 100 \text{ TeV}$ ; (iii) muon tagging capability at WCD units for cosmic-ray studies and improved background suppression; and (iv) improved angular ( $\sim 0.15^\circ$ ) and energy ( $< 30\%$ ) resolutions throughout the core energy range 1-100 TeV. A set of quantitative benchmarks were derived which will be used to assess and compare the performance of the different SWGO candidate array configurations under investigation during the R&D Phase.



## 4. Conclusions and Outlook

Since the first VHE gamma-ray detection [26], 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 recent detection of photons of extreme energies from the Galaxy [6, 27] strengthens the necessity for a large survey instrument with ample access to the Galactic Plane and sensitivity beyond 100 TeV. The vision pursued for SWGO [14] is of an observatory that aims to cover a wide energy range, bridging between satellite observations down to 100 GeV, and reaching towards the PeVs. Its location at high altitude in the Southern Hemisphere will provide a window to an unexplored sector of the sky and, particularly, to the centre of the Galaxy. Currently in R&D Phase, the project plans to deliver an Observatory proposal by 2023.

## Acknowledgements

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