Frascati Physics Series Vol. 74 (2022) ISBN: 978-88-86409-76-6
Frontier Objects in Astrophysics and Particle Physics
September 25- October 1, 2022

STATUS OF THE SOUTHERN WIDE-FIELD GAMMA-RAY OBSERVATORY (SWGO)

Ulisses Barres de Almeida
Brazilian Center for Physics Research (CBPF)
Rua Dr. Xavier Sigaud 150, 22290-180 Rio de Janeiro, Brazil
on behalf of the SWGO Collaboration

Abstract

The Southern Wide-field Gamma-ray Observatory (SWGO) is the Collaboration to build a new extensive air shower array in South America for the observation of very- to ultra-high-energy gamma-rays, and is currently engaged in the design and prototyping work towards the realisation of this future facility. SWGO will use an array of water-Cherenkov-based particle detectors to provide a wide field and high duty cycle view of the southern sky, complementing CTA and the existing particle arrays of the Northern Hemisphere, such as HAWC and LHAASO. Towards the lower energies, SWGO aims to push the observational range of wide-field ground-based gamma-ray facilities down to a few hundred GeV, thus bridging the gap with space-based instruments in the monitoring of the VHE sky. In this contribution, I will provide an overview of the status of the project and plans for the future, including performance expectations and science goals, as well as ongoing activities towards the site search and technological developments.

1 A wide-field gamma-ray observatory in the south

Astrophysics' most extreme accelerators can be effectively probed with ground-based gamma-ray facilities, which provide a diagnosis of the high-energy processes ongoing in the sources. Both cosmic rays and gamma-rays initiate extensive air showers (EASs) in the atmosphere, consisting of a large number of secondary relativistic particles that can be measured by terrestrial detectors using a variety of experimental techniques. These particles create Cherenkov light that can be imaged from the ground using telescopes with large reflective surfaces – the imaging atmospheric Cherenkov technique, IACT. The secondary particles distribution can also be directly measured at ground-level using particle detectors. Together, these observational approaches cover a wide range of energies, from about 30 GeV to a few PeV.

The advantage of the air-Cherenkov method is that light can be detected over the entire shower development, thus exploiting the whole atmosphere as calorimeter. Due to the large number of Cherenkov photons emitted, energy resolutions of the order of 15% are typically achieved. The air-Cherenkov pulses are short close to the shower core (order of 10 ns), allowing to achieve a good angular resolution of 0.1° over a wide energy range. Furthermore, most of the emitted light in the optical range (mainly blue) reaches the ground with only little absorption, so that the energy threshold is lower compared to the particle detection technique, which requires the charged secondary particles to have sufficient energy to reach observation level.

The conventional extensive air shower (EAS) array is a particle sampler that measures the secondary particles of the shower front reaching the ground. Many technologies can be applied to such purpose, the most common ones employing water-Cherenkov detectors (WCD) or scintillator units. From the basic working principle of these technologies, it results that particle samplers operate as transit observatories with continuous duty cycle and a wide field-of-view (FoV) of $\gtrsim$ sr. Such detectors also have typically high energy thresholds, since only the most energetic showers penetrate deep enough in the atmosphere to produce measurable signals from charged particles or secondary high-energy photons at ground level. One of the principal advantages of the particle detection technique is the possibility of directly measuring the muon component of the EAS, which allows for effective background rejection and operation into the ultra-high energy range, above several tens of TeV.

The differences between air-Cherenkov detectors and ground particle arrays highlight the importance that both types of instruments be operated in synergy. To ensure an adequate global latitude-longitude coverage with both experimental approaches is therefore one of the main objectives of the field for the near future. From the side of ground particle arrays, this means the installation of the first instrument of its kind in the southern hemisphere.

High-altitude EAS arrays have recently opened-up a new observational window in Astronomy, significantly increasing the number of detected gamma-ray sources in the very- to ultra-high energy domain (VHE to UHE) [1]. In particular, these instruments have been successful in detecting very extended emission around bright sources [2], and achieved unprecedented sensitivity above 100 TeV, detecting the first Galactic sources up to the PeV [3]. These remarkable results have all been obtained in the Northern sky, increasing the expectations towards the development of a new instrument in the South, from where most of the Galaxy is visible, and many prominent targets such as the Galactic Center and the Fermi Bubbles can be accessed. Other primary targets, which would benefit from an all-sky coverage for the monitoring and triggering of transient sources, and which motivate an improved sensitivity below 1 TeV, are Active Galactic Nuclei (AGN) and Gamma-ray Bursts (GRBs), as recently demonstrated by LHAASO [4].

2 Status of the SWGO Collaboration

SWGO is an international collaboration for the planning and design of a major ground-based gamma-ray observatory in the Andes. It resulted from the joint effort between members of two initiatives targeting the construction of a wide-field air shower array in the Southern Hemisphere, namely the SGSO Alliance [5] and the LATTES Project [6]. Today, SWGO is a strong international collaboration with over 60 institutes distributed in 14 countries, numbering almost 200 scientists, which bring together the experience of previous experiments such as the Pierre Auger Observatory, HAWC, and LHAASO. A large contingent of the participating scientists are from Latin America.

The observatory proposal consists on a baseline design [7] that would significantly increase the effective area of the observatory with respect that of HAWC, and lower its detection energy threshold, through a combination of a high fill factor core array (well above 50%, within an area of sim 10^{4-5} m2) and installation at higher elevation site, near 5 km above sea level. Another main objective of the Collaboration's research programme is to improve the background rejection power by, e.g. cost-effective solutions to the identification of muons at individual detector units. In order to achieve greater energy sensitivity for PeVatron searches, the proposal also involves complementing the core detector with a large sparse array, of up to 1 km^2.

3 Research and Development for SWGO

The SWGO Collaboration is currently in the research and development stage of the project, which seeks to provide a complete plan for the building and operation of the future gamma-ray facility. Following the considerations presented above, the baseline design that will guide the R&D of the observatory consists of:

- a ground-level particle detector array with duty cycle close to 100% and order steradian field of view, to be installed in South America above 4.4 km altitude, between latitudes -30° and -15°.
- to cover a broad energy range, from about 100 GeV to over 100 TeV, and possibly extending up to the PeV scale.
- to be based mostly on water Cherenkov detector units, consisting on a high fill-factor core with an area far greater than that of HAWC and significantly superior sensitivity, surrounded by a low-density outer array.

3.1 General Progress Status

The reference configuration presented in [7] guides the SWGO R&D programme, and serves as baseline for the array design optimisation and detector technology options. Table 1 describes the key characteristics of this reference array configuration, which is composed of an outer array with at least 800 detectors placed 16 meters apart from each other, surrounding a core array with circa 5,700 water tanks arranged in a compact regular grid.

There are two primary choices being investigated for the water-Cherenkov detector (WCD) units, with the core and outer arrays sharing the same fundamental unit design. The first is a double-layer cylindrical tank with 3.8 m diameter and top and lower heights of 2.5 m and 0.5 m, respectively [8, 9]. The

Table 1: SWGO reference configuration. Two WCD unit options are listed.

Component	Parameter	Reference design
Core Array	Geometry	160 m radius circle = 80,400 m^2
	Fill Factor	≈ 80%, ~ 5,700 units
Outer Array	Geometry	at least 300 m outer radius = 202,200 m^2
	Fill Factor	≈ 5%, ~ 880 units
WCD units	Double-layer	∅ 3.8 m; 0.5 m (bottom) + 2.5 m (top) height
	Multi-PMT	∅ 3.8 m; 2.75 m height
Photodetectors	Option	Large-area 8" PMT
	Geometry	Central up/downward facing or 3-pt star (Y)
Electronics	Requirement	Nano-second inter-cell timing
Reference Site	Altitude	4,700 m a.sl.

upper layer of the WCD is used for calorimetry of the electromagnetic shower component, whereas the bottom layer is mostly used for muon tagging. A single, large-area PMT is placed centrally in each layer. Deployment in an artificial pond or a natural lake is being investigated to increase shielding against laterally penetrating particles. The second alternative is a multi-PMT, shallow WCD tank, with diameter of 3.8 m and a height of 1.75 m, which aims to identify the passage of muons by means of the asymmetrical illumination of three upward-facing PMTs placed at its base [10].

Project R&D is anticipated to be concluded in 2024, along with the choice of the installation site. It should be followed by a Preparatory Phase for finalisation of the engineering array and identification of resources, aiming at a start of observatory construction in as early as 2026.

Site shortlisting and candidate configurations for optimisation simulations have just been concluded. The final array and detector unit configuration will be optmised based on scientific performance, following a series of science benchmarks that have been defined according to the core science cases chosen for the observatory [11]. The detailed plans for construction and operations of the SWGO observatory will be consolidated into a Conceptual Design Report, to be delivered at the end of R&D.

3.2 Candidate site investigations

The site selection process for SWGO was separated in a three-step process consisting on candidate sites identification, site shortlisting and final selection of primary and backup site for the observatory installation. Site shortlisting has just been completed at Q3 2022.

Two fundamental site requirements can be derived from the basic concept of sampling the shower front: that of a large flat available area (i.e., for an extended array with a good fraction of instrumented surface) and the requirement of high altitude installation sites, both of which are necessary to achieve satisfactory shower reconstruction and overall performance.

As a result of its Southern Hemisphere location, SWGO will be able to fully exploit the synergies with CTA, while extending the range of Northern wide-field installations like LHAASO, for an all-sky coverage. SWGO is therefore anticipated to be deployed at a latitude range between -15° and -30°, in order to maximize the exposure to galactic sources, and in particular the Galactic Center ($\delta = -28.9°$), and to concurrently optimize overlap with LHAASO. This criteria, together with the altitude restrictions, for which a location above 4.4 km a.s.l. is desirable, leaves the Andes, in South America, as the only possible choice for sites.

Preliminary site identification studies have found suitable options in Argentina, Bolivia, Chile, and Peru, each of which has unique qualities and more closely matches some of the alternatives for the array design or detector technology under consideration. Table 2 indicates the preferred and back-up sites, as defined after the shortlisting process. Preferred sites will now undergo in-depth studies towards final site selection. Generally speaking, the biggest elements under consideration to a final choice are water access, of which ~ $10^5\,\mathrm{m}^3$ will be required, flatness over a large available area of at least $1\,\mathrm{km}^2$, and general availability of local infrastructure and quality of site accessibility [12].

4 Detector Development Options

As seen in the Figure 1, various technological options are being investigated for the individual WCD units [13]. In particular, two mechanical concepts are being considered: bladders installed in surface tanks, which can be made of metal as in HAWC or rotomolded plastic as in the Pierre Auger Observatory;

Table 2: SWGO candidate sites.

Country	Site Name	Latitude	Altitude [m a.s.l.]	Notes
Argentina	Alto Tocomar	24.19 S	4,430	
	Cerro Vecar	24.19 S	4,800	Primary
Bolivia	Chacaltaya	16.23 S	4,740	
Chile	Pajonales	22.57 S	4,600	
	Pampa La Bola	22.56 S	4,770	Primary
Peru	Imata	15.50 S	4,450	
	Sibinacocha	13.51 S	4,900	Lake site
	Yanque	15.44S	4,800	Primary

and floating bladders deployed directly into a natural lake [14] or an artificial pool.

The capability to discriminate between gamma and CR-induced air showers is the fundamental element of the technique, essential to achieve good sensitivity. Above several TeV, gamma/hadron discrimination can be greatly improved by exploring the low muon content of gamma-ray induced air-showers, using muon detection as a veto to suppress the CR background. At lower energies, cosmic-ray showers are muon-poor, so that gamma/hadron discrimination must be based on the distribution of particles at ground. Here, one relies on the observable differences in the structure of secondary particles at ground, which depends on the nature of the EAS-initiating particle and, in the case of hadronic cascades, present pronounced sub-structures from the decay of neutral pions. In both cases, a good sampling of the shower front, by means of sufficient array fill-factors, is essential.

Two methods are under evaluation to identify muons within the individual detector units: the dual-layer WCD, with a gamma-hadron separation technique based on the use of vertical segmentation to identify energetic muons (of typically a few GeV) that reach the bottom layer detector [8, 9]; and the use of shallow, multi-channel WCDs [10], which would distinguish muons from electromagnetic particles based on the rise times of the signals and the charge asymmetry between the PMTs. Additionally, new analysis techniques are being researched [15, 16]. Figure 2 shows an schematic depiction of the different

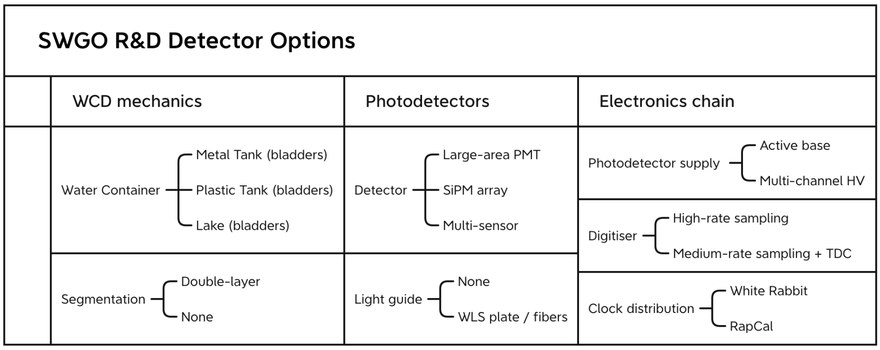

Figure 1: SWGO detector components and main options under study [13].

WCD unit configurations under consideration in the array simulations.

5 Analysis and simulations for array configuration

The definition of a baseline configuration for the array layout and detector unit design, as presented earlier, serves as the basis for performance evaluation and project development during the R&D phase. Further investigation into array configuration options is then guided by a set of predetermined quantitative scientific benchmarks designed to evaluate observatory performance [11]. The phase space under study is bracketed by the set of configurations shown in Figure 3.

The fundamental design elements to consider are the overall array area, fill factor, and site elevation. The effective area, gamma/hadron discrimination efficiency, and the angular resolution, over a target energy range, will be the main quantities considered in evaluating the performance of the array.

The key array configuration trade-offs (at a fixed cost) are anticipated to play out between the performance at low energies (>1 TeV), dependent largely on site elevation, fill factor, and detector unit threshold, and at high energies (>100 TeV), driven by the total area of the array and the background rejection efficiency. As already mentioned, a crucial component of the study will be the capability to distinguish between air showers started by cosmic rays and gammas over the entire energy range of operations.

Simulation work is currently ongoing [17] to assess the performance of

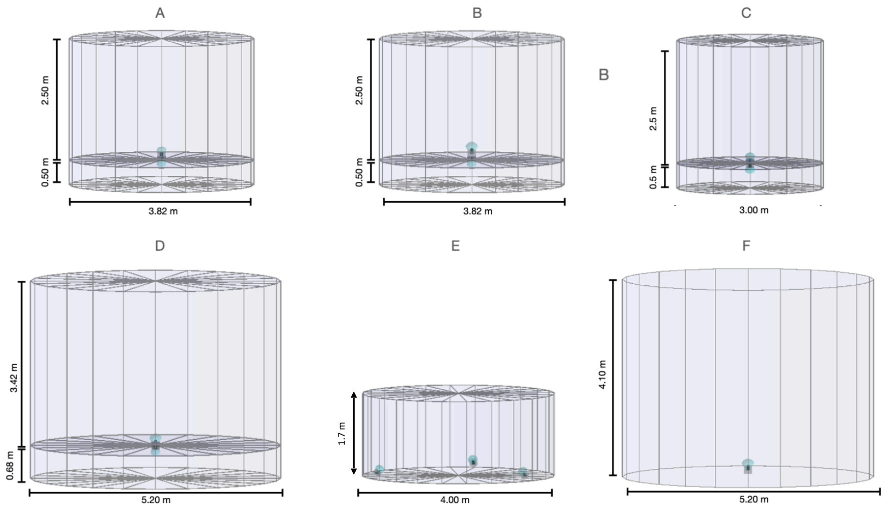

Figure 2: SWGO water-Cherenkov detector unit configurations under study.

the different array designs and detector choices. In terms of array sensitivity to point sources, the phase space bracketed by the options under investigation are shown in Figure 4. The Array A1 configuration in Figure 3 serves as the minimal configuration stated in Table 1, which establishes the performance baseline. In general, decreasing the threshold for individual units and deployment at higher altitude locations can reduce the gamma-ray energy detection threshold. Gains in overall sensitivity will result from improvements in angular resolution and background rejection. The size of the external array and the background rejection efficiency at UHE, which scales with the total available muon detection area, will determine the amount of energy increase reported over 100 TeV.

The optimisation work is being carried out at predetermined altitudes, between 4.1 and 5.2 km, for a same observatory site and magnetic field, and for a fixed estimated total array cost.

6 Science perspectives

The key scientific topics that the SWGO Collaboration plans to focus on, some of which are unique to facilities in the Southern Hemisphere, include:

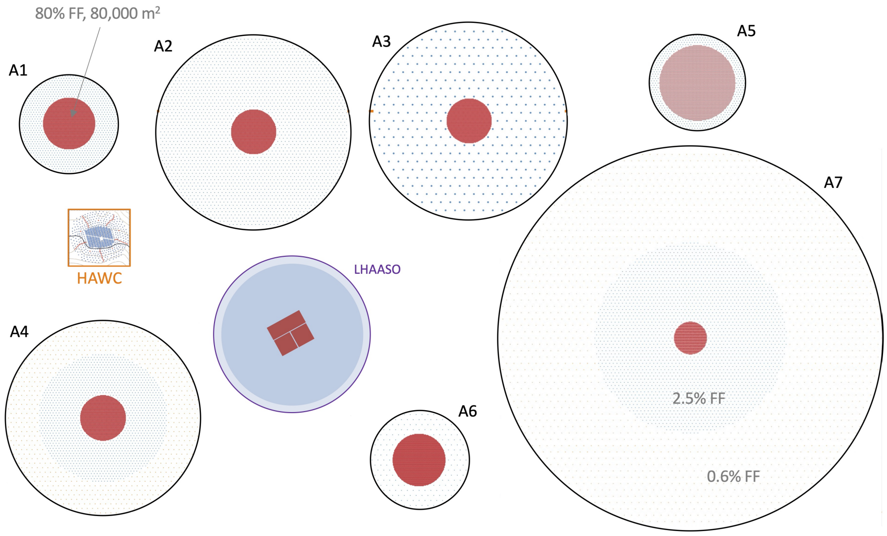

Figure 3: Illustration of the range of array configuration options currently under investigation by the SWGO Collaboration. The baseline array configuration described in Table 1 refers to option A1 of Figure 2. Image Credits: The SWGO Collaboration.

- At lower energies, <1 TeV, transient sources are the main goal, making use of the observatory's wide field of view and nearly constant duty cycle to serve as a complementary monitoring and triggering tool for CTA. The primary scientific objectives are gamma-ray bursts (GRBs) and active galactic nuclei (AGN), which are also the potential multi-messenger counterparts of gravitational waves and VHE neutrinos, respectively.
- At the high-energy end of the spectrum, >100 TeV, the search for PeVatrons, the purported sources responsible for the acceleration of the most energetic cosmic ray particles of the Galaxy, dominates the scientific objectives.
- Deep searches for Dark Matter signals up to 100 TeV are possible thanks to access to the Galactic Center and Halo, covering the entire energy range of WIMP models.
- The improvement in angular resolution at energies higher than a few

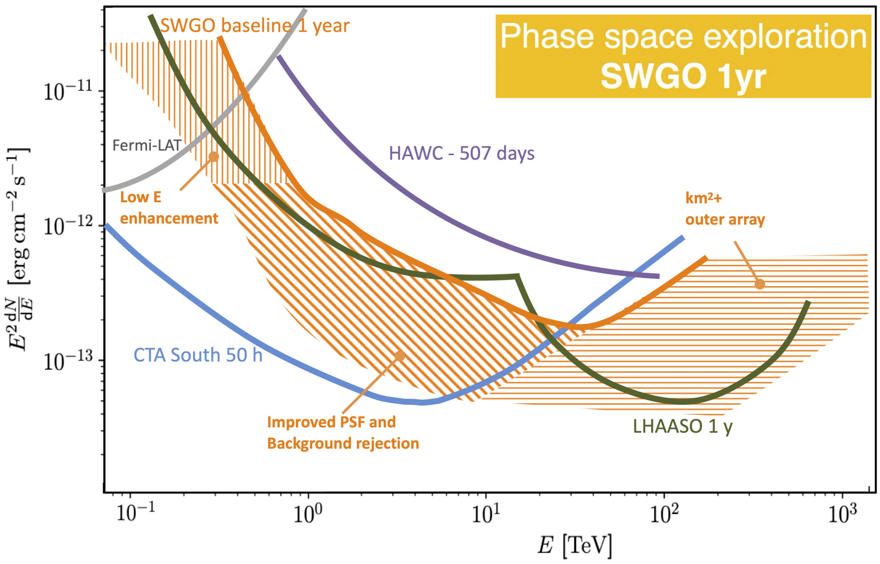

Figure 4: Phase-space explored for SWGO. The orange bracketed phase-space is compared to the differential point-source sensitivity of various experiments [17]. The *"baseline"* curve refers to the reference configuration, equivalent to array A1. The lower limit of the orange band corresponds to a factor of 30% improvement in the PSF and a factor of 10× improvement in background rejection efficiency. The size of the outer array is the main parameter driving the high-energy enhancement.

tens of TeV will be useful for the study of galactic diffuse emission and extended sources, like PWNe and TeV Halos.

- The accurate measurement of the muon content in hadronic showers will be made possible by the effective single-muon detection capability of detector units, allowing for studies of mass-resolved cosmic rays from tens of TeV to the PeV scale.

7 Conclusions and Outlook

Significant work has already been made toward the final SWGO design, and the prospects from the current stage of the R&D phase point to an instrument of exceptional performance to be realized in the Andes within this decade. Over the next year we will apply the science benchmarks describing the key science goals of SWGO, to evaluate the trade-offs associated with the various detector unit and array design options under investigation, in order to deliver SWGO as the most valuable tool across a wide range of key scientific areas.

Once ready, SWGO will be a powerful complement to CTA, and the combined SWGO and LHAASO data will provide crucial full-sky coverage for population studies, mapping of the diffuse emission of the Galaxy, measurement of cosmic ray anisotropy, and monitoring of the VHE to UHE transient sky. Alongside the array and detector options evaluations, prototype detector units are being developed at member institutions around the globe, and prepared for deployment and testing at candidate sites over the course of the next several months. At the end of 2023, or early in 2024, all these work fronts are expected to converge towards the final site-detector option definition for SWGO. This will mark the conclusion of the project R&D, and give way to the building of an engineering array for final design optimisation.

8 Acknowledgements

U. Barres de Almeida acknowledges partial funding from a FAPERJ Thematic Grant E-26/211.342/2021 and a FAPERJ Young Scientists Excellence Fellowship E-26/202.818/2019.

References

1. A. Albert *et al*, Astrophys. J. **905**, 76 (2020).
2. A.U. Abeysekara *et al*, Science **358**, 6365 (2017).
3. Z. Cao *et al*, Nature **594**, 33 (2021).
4. Y. Huang *et al*, GCN Circular **32677**, 22/10/11 (2022).
5. A. Albert *et al*, eprint arXiv:1902.08429 (2019).
6. P. Assis *et al*, Astrop. Phys. **99**, 34 (2018).
7. H. Schoorlemmer *et al*, PoS(ICRC2021) **395**, 903 (2022)
8. F. Bisconti & A. Chiavassa eprint arXiv:2205.02148 (2022)

9. S. Kunwar *et al*, eprint arXiv:2209.09305 (2022)
10. P. Assis *et al*, Eur. Phys. J. C **82**, 899 (2022).
11. U. Barres de Almeida *et al*, PoS(ICRC2021) **395**, 893 (2022).
12. M. Doro *et al*, PoS(ICRC2021) **395**, 689 (2022).
13. F. Werner *et al*, PoS(ICRC2021) **395**, 714 (2022).
14. H. Goksul *et al*, PoS(ICRC2021) **395**, 708 (2022).
15. R. Conceição *et al*, Eur. Phys. J. C **81**, 542 (2021).
16. R. Conceição *et al*, J. Cosm. Astrop. Phys. **10**, 86 (2022).
17. H. Schoorlemmer *et al*, PoS(ICRC2021) **395**, 903 (2022).