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SWGO: a wide-field of view gamma-ray observatory in the southern hemisphere

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ABSTRACT: The recent LHAASO and HAWC results opened the way to the search of gamma ray sources emitting at energies above 100 TeV. Both detectors are in the northern hemisphere; the need for such an observatory in the southern hemisphere is therefore clear. The goal of the SWGO collaboration is the construction of a wide field of view, high duty cycle observatory to explore the Southern hemisphere sky searching for gamma ray sources at energies above 100 GeV. Such an array will detect extensive air showers particles and must be able to select the photon originated showers from the background of the hadronic ones. The experiment must be located in a site at latitude between 10° and 30° degrees south and at an altitude above 4400 m a.s.l. The baseline detection technique chosen by the collaboration is Water Cherenkov Detectors. The array will have a central region with high fill factor (>60%) and a large (about 1 km^2) outer region with a much lower fill factor (around 4–5%).

KEYWORDS: Gamma telescopes; Large detector systems for particle and astroparticle physics; Cherenkov detectors

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[1]The complete collaboration author list is the same as: https://doi.org/10.22323/1.444.0963.

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1 Introduction

Ground-based observatories searching for very high energy emission from cosmic photon sources, both transients and steady sources, have brought in the last years very important discoveries: for instance, the detection of transient events with multi-messengers [1, 2] and the detection of galactic sources at E $>$ 100 TeV [3].

Two distinct approaches have been developed to detect the cascades of particles initiated by $\geq$ 10 GeV photons: direct detection of shower particles at mountain altitudes, and the imaging of Cherenkov light emitted by shower particles. Powerful arrays of imaging atmospheric Cherenkov telescopes (IACTs) are present in both hemispheres: MAGIC [4] and VERITAS [5] in the North and HESS [6] in the South. In the case of ground-level particle detectors however, only the Northern hemisphere is well-equipped, with the HAWC [7] and LHAASO [8] installations.

The two techniques are complementary: IACT provide a better energy (15%) and angular (0.1°) resolution and a more powerful background rejection (typically around 10^{-3} already at 100 GeV, with a 70% photon detection efficiency). But such instruments have a modest field of view (4° diameter) and have a limited operation time, as they can operate only during the night, excluding full moon periods (strongly limiting their duty cycle). On the contrary Extensive Air Showers (EAS) particle detectors can observe the whole overhead sky (1 steradian field of view) and operate with nearly 100% duty cycle, but this technique is less effective in background rejection (very challenging and limited, i.e. $\sim 10^{-1}$, at 100 GeV, about 10^{-2} at 1 TeV, and then extremely powerful, 10^{-4}–10^{-5}, above 100 TeV) and offers a limited angular (0.2°) and energy (>30%) resolution. Because of these features, IACT are better suited for detailed studies of known sources, while EAS particle detectors are more effective for the search of transient events and of extreme galactic accelerators.

As already mentioned, the two currently operating EAS particles detectors are both located in the Northern hemisphere, while there is a clear lack of such an observatory in the Southern one. Many key regions and objects are uniquely accessible from a Southern site, including the Galactic Centre, (most of) the Fermi Bubbles and the inner Galactic plane, but also several key (relatively) local extra-galactic objects. Besides such observatory will have a great opportunity to detect a high mass WIMP annihilating in the central part of our galaxy.

The realization of a wide-field of view, high duty cycle observatory in the Southern hemisphere would therefore bring a relevant contribution to the study of high energy astrophysics and astroparticle physics.

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2 Status of the project

The SWGO [9] (Southern Wide-field Gamma-ray Observatory) Collaboration was founded in 2019 with the goal of realizing a wide field of view, high duty cycle observatory, located at a latitude between $-10°$ and $-30°$ (to observe the galactic center) and at an altitude of at least 4400 m a.s.l. (having the goal of reaching an energy threshold as low as 100–200 GeV); having such constraints the only possible sites are in South America in the Andes. The SWGO Collaboration is currently formed by 66 institutions from 14 member countries; supporting scientists allow the involvement of a dozen additional countries.

The collaboration has identified as base detection technique Water Cherenkov Detectors (WCD). All supposed layouts include a high fill factor (80%) central area, covering a surface ($\sim$ 80 000 m^2) larger than HAWC mainly dedicated to the study of the low energy range, and an outer region with a smaller fill factor ($< 5\%$) distributed over a $\sim$ km^2 area, mainly used to study the high energy range. The SWGO collaboration will complete the research and development phase at the end of 2024 with the publication of a Conceptual Design Report (CDR). The path to prepare the CDR has been marked by successive internal milestones that the collaboration has internally defined and are reported in table 1. Currently we are completing the milestone M6, and the forthcoming two milestones require two main decisions to be taken by the collaboration: the definition of the preferred site and the finalization of the experiment design.

Table 1. Internally defined milestones to finalize the SWGO research and development phase.

M1	R&D Phase Plan Established
M2	Science Benchmarks Defined
M3	Reference Configuration & Options Defined
M4	Site Shortlist Complete
M5	Candidate Configurations Defined
M6	Performance of Candidate Configurations Evaluated
M7	Preferred Site Identified
M8	Design Finalised
M9	Conceptual Design Report Complete

2.1 Detector options

To ensure the optimal design for the water Cherenkov detector units, the SWGO collaboration is exploring different detector technologies.

- Tanks: individual detector units mechanically separated and individually deployed, with light tight liners within roto-moulded plastic (as in Auger) or steel (as in HAWC) tanks. Prototypes of a roto-moulded and of a steel tank are shown in figure 1.
- Ponds: multiple large artificial water volumes retaining walls and optical separation between units (as in the WCD detector of LHAASO).
- Lake: deployment of detector unit bladders filled with pure water directly into a natural lake [10].

Any EAS array dedicated to the search of photon sources must at first select the overwhelming background due to charged cosmic rays showers. A long-established discriminant between gamma and background showers is muon content, and the power of this approach has recently been demonstrated by LHAASO [11]. Two different approaches are being pursued in SWGO to tag (or better count)

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Figure 1. Tanks prototypes: roto-moulded tank installed at CBPF Rio De Janeiro (left panel) and steel tank mounted at Arequipa University (right panel).

muons passing through individual detector units: a double layer approach [12] and multiple-PMTs in a single shallow layer [13].

The tanks option is the more flexible one, allowing a variety of deployments and the possibility of future expansions of the initial array. The maintenance of the array elementary cells will be possible and relatively easy being them separated one from the other. In the tank option the muon detection can be realized with two optically separated layers: the upper one measuring all EAS particles and their transit time, and a lower one measuring the EAS penetrating component (muons). But for the isolated tanks of the outer array we must face the problem of the contamination due to low energy electromagnetic particles entering the tanks from side walls. Different solutions are currently evaluated, but at the moment of writing (November 2023) no final decision has been taken.

Both pond and lake options do not necessitate shielding from low energy particles entering from the sides, but they are less flexible, and the detector maintenance will be more complicated. In the lake option one must also consider the variability of the water level (both seasonal and due the waves) and the positioning of the detectors.

The Cherenkov light emitted by EAS particles will be measured by light sensors, almost certainly photomultipliers (PMT), that are highly reliable instruments that can operate in remote sites, with very low failure rates, for very long times (as for instance demonstrated by the Pierre Auger Observatory [14] and HAWC experiments). Various options have been studied: for the single shallow layer tanks, three PMTs will be placed at the bottom of the tank at 120° one from the other. While in the double layer tanks we are currently evaluating different options always consisting of a central light sensor upward looking, placed at the bottom of the upper layer, and a second one downward looking, placed at the top of the upper layer. Two different realizations are currently under study for these sensors: a single large (8″ or 10″) PMT (see figure 2, left panel) or a system of at least seven 3″ PMTs (see figure 2, right panel).

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Figure 2. Prototypes of single large PMT (left panel) and of a system of multi PMT composed by seven 3′′ PMTs (right panel).

To define the layout of the detector units the collaboration has currently completed a significant number of simulations for the detector and array configurations (Milestone 5 of table 1). Figure 3 shows several examples of the 14 detector and array layout configurations being assessed. These configurations have been chosen to investigate key design elements and array configurations while maintaining a consistent cost framework. Parameters such as station dimensions, number and size of the photo-sensors, and the balance between compact (for lower energies) and sparse array (for higher energies) are being thoroughly examined. This ongoing exercise, set to be completed by end 2023, will provide valuable insights into how to identify the most favourable options to be considered.

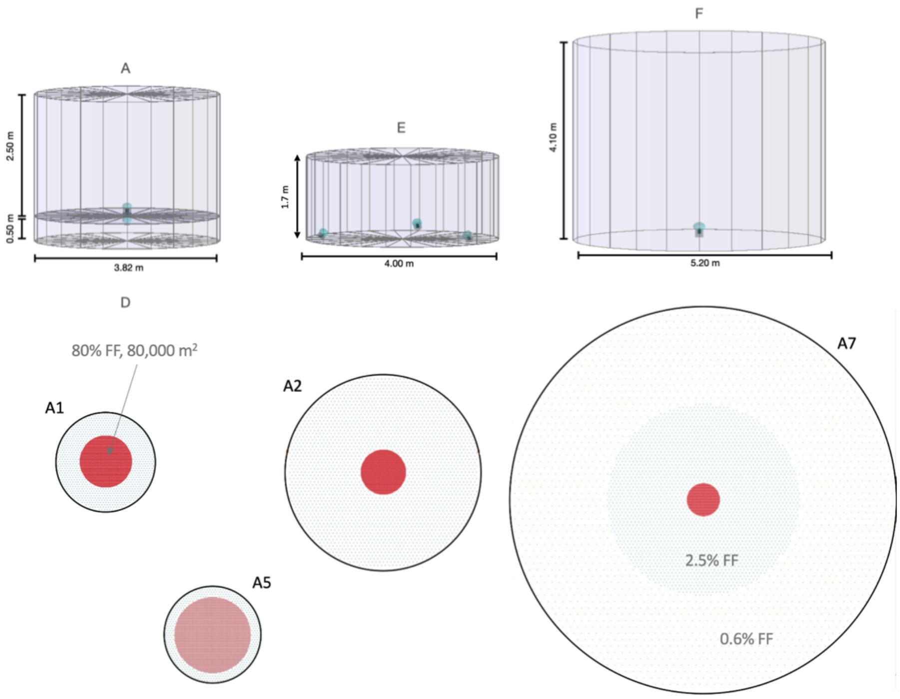

Figure 3. Top: examples of the six water-Cherenkov detector unit configurations currently being studied for SWGO. Bottom: illustrative examples showcasing the seven array configuration options currently under investigation.

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2.2 Site selection

The SWGO collaboration is investing a lot of effort to choose the site to build the observatory [15]. Starting from the requirements defined setting-up the project a lot of informations have been collected through collaborative efforts of the members from the hosting countries as well as through dedicated site visits conducted by SWGO collaboration members. Various factors have been taken into consideration, including altitude, local topology, environmental conditions, site access, transport costs, as well as the availability and cost of essential resources such as water, power, and network connectivity. In order to gather detailed information about the site conditions, an autonomous station specifically designed for environmental characterisation has been developed and deployed at each candidate site [16].

The shortlist of the proposed sites among which the preferred one will be selected is given in table 2. A choice of photos from some of the visited sites is shown in figure 4.

Table 2. SWGO candidate sites.

Country	Site Name	Altitude [m] a.s.l.	Latitude	Notes
Argentina	Alto Tocomar	4430	24.19	
	Cerro Vecar	4800	24.19	
Chile	Pajonales	4600	22.57	
	Pampa La Bola	4770	22.25	
Peru	Imata	4450	15.50	
	Sabinacocha	4900	13.51	Lake site
	Yanque	4800	15.44	

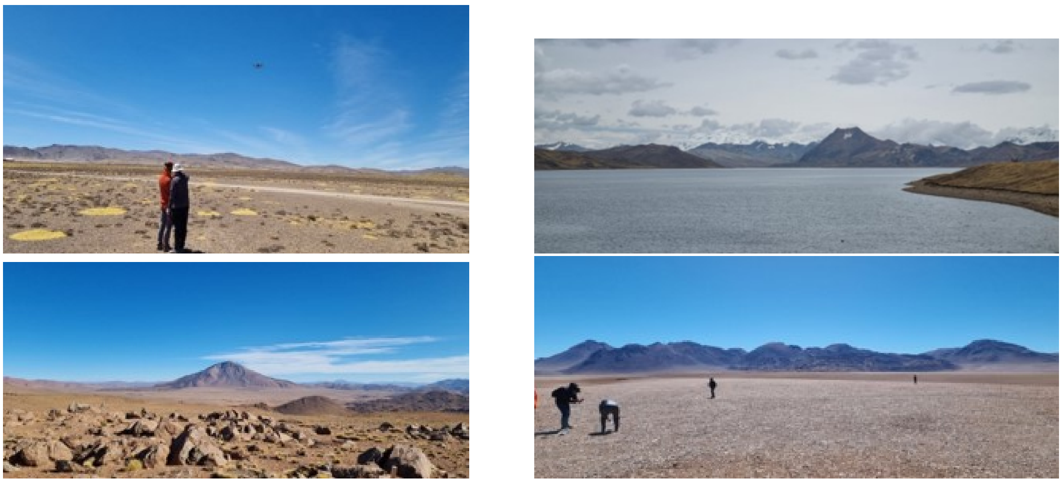

Figure 4. Pictures of some of the candidate sites for the construction of the SWGO experiment: Imata top left, Sabinacocha top rigth, Cerro Vecar bottom left, Pampa La Bola bottom right.

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3 Science goals

The scientific outputs of an experiment like SWGO cover various areas, ranging from high energy astrophysics to fundamental physics. The main SWGO science cases are used as a guidance during the R&D studies and serve as benchmarks for evaluating various options and trade-offs in the final observatory design. In table 3 are summarized the main cases that SWGO is actively pursuing, along with their main design drivers for the observatory design and the corresponding benchmarks under consideration. These benchmarks represent a minimum set of science goals that encompass the complete range of performance requirements for the observatory.

Table 3. SWGO Science Benchmarks and associated design drivers. Flux sensitivities are all calculated for 5 years, and the quoted energy threshold is defined at near-peak detection effective area, to provide a source-independent reference.

Core Science Case	Design Drivers	Benchmark Description
Transient Sources: **Gamma-ray Bursts**	Low-energy Site altitude	Minimum time for 5σ detection $F(100\,\text{GeV}) = 10^{-8}\,\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}$.
Galactic Accelerators: **PeVatron Sources**	High-energy sensitivity Energy resolution	Maximum exp-cutoff energy detectable 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	Max. angular extension detected at 5σ in 5 years integration for: $F(>1\,\text{TeV}) = 5\times10^{13}\,\text{TeV}\,\text{cm}^{-2}\,\text{s}^{-1}$.
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	Maximum energy for $b\bar{b}$ thermal relic cross-section at 95% CL in 5 years, for Einasto profile.
Cosmic-rays: **Mass-resolved dipole** **Multipole anisotropy**	Muon counting capability	Max. dipole energy at 10^{-3} level. Log-mass resolution at 1 PeV, goal is A = 1, 4, 14, 56. Maximum multipole scale 0.1 PeV.

The science goals described in table 3 will provide relevant insights allowing to establish certain performance constraints that the future observatory must reach. For instance:

- To detect transient events is necessary to have an energy threshold as low as possible, which can be lowered by raising the altitude at which the observatory will be built.
- The accurate study of galactic accelerators and their identification requires good energetic ($< 30\%$) and angular ($\sim 0.15^\circ$) resolution.
- The search for mass resolved primary cosmic ray anisotropy will only be possible separating the events by the charge of the primary particle. The possibility of obtaining this separation is related to the resolution that the array will have in measuring the number of muons in the showers.

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4 Conclusion and perspectives

The SWGO collaboration plan is to complete the milestones listed in table 1 by the end of 2024. This requires to take some critical decisions before (site selection and array finalization). The collaboration is trying to accurately evaluate the pro and cons of different solutions comparing them in terms of the foreseen scientific outputs. Then we will proceed implementing, in the chosen site, an engineering array, around 10% of the full experiment. It is worth noting that already this engineering array will have a number of tanks comparable to the HAWC one, therefore we can already expect first scientific results from it. Afterward the construction will continue and the current hypothesis is to complete the observatory construction by 2030. The plan is to operate the observatory for at least 20 years.

Acknowledgments

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