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CTAO status and perspective

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Abstract. The Cherenkov Telescope Array Observatory (CTAO) is the upcoming next-generation ground-based gamma-ray observatory. CTAO will have two sites, one located in the northern hemisphere in the Roque de los Muchachos Observatory, La Palma (Spain) and a sourthern site in Paranal (Chile). CTAO will count on improved sensitivity, angular and spectral resolution with respect to the current generation of imaging atmospheric Cherenkov telescopes (IACTs) and will cover a broader energy range. In this contribution, we review the current status of CTAO and address the scientific questions that CTAO aims to answer. We outline the science perspectives of CTAO and the timeline of the observatory.

1 Introducing the Cherenkov Telescope Array Observatory

Current generation of Imaging Air Cherenkov Telescopes (IACTs) established very-high-energy gamma-ray (VHE, E>100 GeV) astronomy as a fully-developed discipline. The maturity of the field is underscored by the discovery of over 300 VHE sources by these ground-based experiments[1]. The next step is the creation of an open observatory with improved capabilities. For this purpose, the Cherenkov Telescope Array Observatory (CTAO) Consortium[2], a worldwide team of ∼1600 members from more than 150 institutes, devised the concept of the CTAO, the first open ground-based gamma-ray observatory [1]. CTAO will count with two arrays of telescopes in both hemispheres and will have telescopes of three different sizes. This will allow for a full-sky coverage, increased energy range and sensitivity, among other improvements (see following sections).

1.1 The telescopes

Three types of telescopes are required to fully cover the expected CTAO energy range from 20 GeV up to 300 TeV (see Fig. 1). These telescopes are being built by different In-Kind Contributors (IKC)[3], each dedicated to a telescope class.

- Large-Sized Telescopes (LSTs): IACTs with large collection areas (diameter of 23 meters) of parabolic shape. They dominate the low-energy energy range of CTAO, with maximum

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[1]see http://tevcat.uchicago.edu/
[2]https://www.ctao.org/partners/ctao-consortium/
[3]https://www.ctao.org/partners/in-kind-contributors/

sensitivity between 20 and 150 GeV. They are being developed and installed by the LST collaboration, composed of by almost 500 scientists and engineers from 82 institutions across 11 countries.

- Medium-Sized Telescopes (MSTs): designed to cover the core energy range of CTAO, with energies from 150 GeV to 5 TeV. Their reflector is a modified version of the Davies-Cotton design, with a diameter of 11.5 m. Two different cameras designs will be used, once for each array site. The MSTs will be deployed by the MST collaboration, an international group of institutes from 8 different countries.
- Small-Sized Telescopes (SSTs): their design is a modified Schwarzschild-Couder dual-mirror. The primary mirror has a diameter of 4.3m, while the secondary has a 1.8m-diameter. The SSTs will cover the higher end of the energy energy range, between 5 TeV to 300 TeV. The SSTs will be built by an international collaboration from nine different countries.

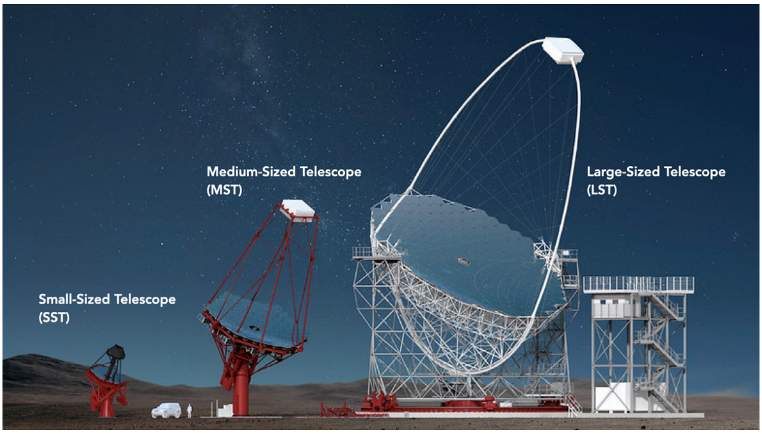

Figure 1. Three classes of telescopes are required to cover the full CTAO energy range (20 GeV to 300 TeV). Credit: Gabriel Pérez Díaz, IAC (adapted).

1.2 Array sites and configurations

CTAO will be distributed in two sites to have a complete view of the night sky. The CTAO-North array will be located in the Observatorio Roque de los Muchachos (ORM), in the Canary Island of La Palma, Spain, while the CTAO-South array will be installed in the Atacama desert, Chile (Fig. 2). The *Alpha configuration* (see Fig. 3) describes the two array compositions during the first construction phase.

CTAO-North will cover an area of ~0.5 km^2 and it will be composed of 4 LSTs and 9 MSTs. It will also count with an operations building and calibration and atmospheric characterization equipments. This northern array will be specialized in extragalactic physics and will be optimized in the low and intermediate energy range (~20 GeV - 5 TeV). The construction of the core part of the array, the LSTs, is on-going. The first Large-Sized Telescope (LST-1) was inaugurated onsite in 2018. LST-1 is currently under commissioning and it is already producing technical and scientific results (see e.g. [2–6]). The remaining three LSTs (LST-2, LST-3 and LST-4) are being installed at ORM, with an expected date of inauguration by early 2026.

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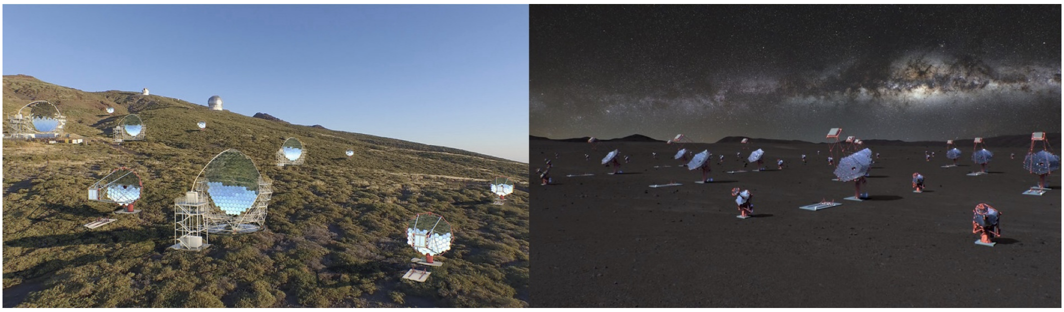

Figure 2. Rendering of the CTAO-North (left) and CTAO-South (right) Alpha configurations. Credit: CTAO (adapted).

CTAO-South will cover an area of ~3 km^2. It will be optimized for energies between 150 GeV to 300 TeV, the medium and high-energy end, specialized in Galactic sources. The approved Alpha Configuration will include 37 SSTs and 14 MSTs and does not include LSTs. However, the PNRR CTA+ program approved in 2022, aimed at strengthening transient science in CTAO-South, will add 2 LSTs and 5 additional 5 SSTs to the originally planned Alpha Configuration.

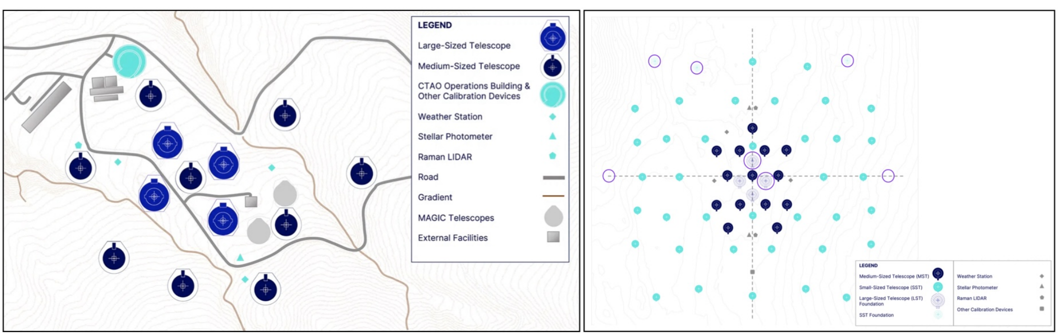

Figure 3. Alpha configurations for CTAO-North (left) and CTAO-South (right). The empty purple circles denote the intended positions of the telescopes of the CTA+ program. Credit: CTAO (adapted).

1.3 Performance

CTAO will provide enhanced capabilities relative to current-generation IACTs, as reflected in the performance of the Alpha configuration[4]. CTAO will count with an increased energy range from 20 GeV up to 300 TeV, which will allow the study of a broad range of scientific cases (see Section 2).

[4]https://www.ctao.org/for-scientists/performance/

Sensitivity

Fig. 4 shows the differential sensitivity[5] for 50-h observation time for both CTAO-North and CTAO-South. The sensitivity of both arrays improve with respect to current experiments such as H.E.S.S.[6], MAGIC [7] and VERITAS[7]. The extended energy range and improved sensitivity allows for an overlap in the low-end with space-borne instrumentation such as *Fermi*-LAT[8] and on the high-end with ASTRI Mini Array [8] and shower detectors such as HAWC [9], LHAASO [10] or future SWGO [11].

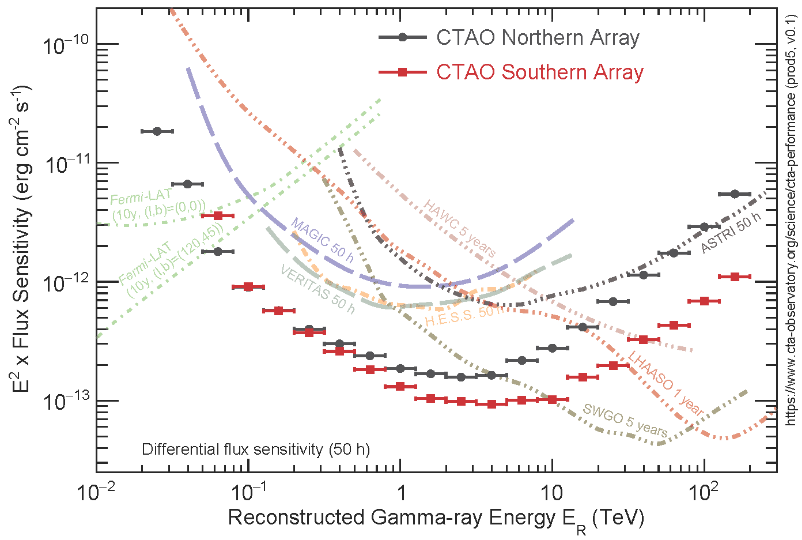

Figure 4. Differential sensitivity for the Alpha configuration, compared to current and future instrumentation. Credit: CTAO.

Short-time sensitivity

CTAO will also count with unprecedented sensitivity at short timescales (Fig. 5), up to a 10^4-10^5 improvement with respect to the space-born LAT instrument onboard Fermi[9]. This high sensitivity is specially important for the follow-up and discovery of transient events. The low energy threshold of the LSTs (~20 GeV) together with their fast repositioning (~25 sec) is crucial for the discovery and detection of transients at the low-end of the CTAO energy range.

2 Scientific cases

CTAO will address three main topics: understanding the origin and interaction processes of cosmic particles, probing extreme environments and exploring new frontiers in physics. The

[5]The differential sensitivity is calculated as the minimum flux needed to obtain a 5-standard-deviation detection of a point-like source.

[6]Preliminary sensitivity curves for H.E.S.S.-I (stereo reconstruction), based on and adapted from Holler et. al 2015

[7]https://veritas.sao.arizona.edu/about−veritas/veritas−specifications

[8]https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

[9]Pass 8 analysis, extragalactic background, standard survey observing mode

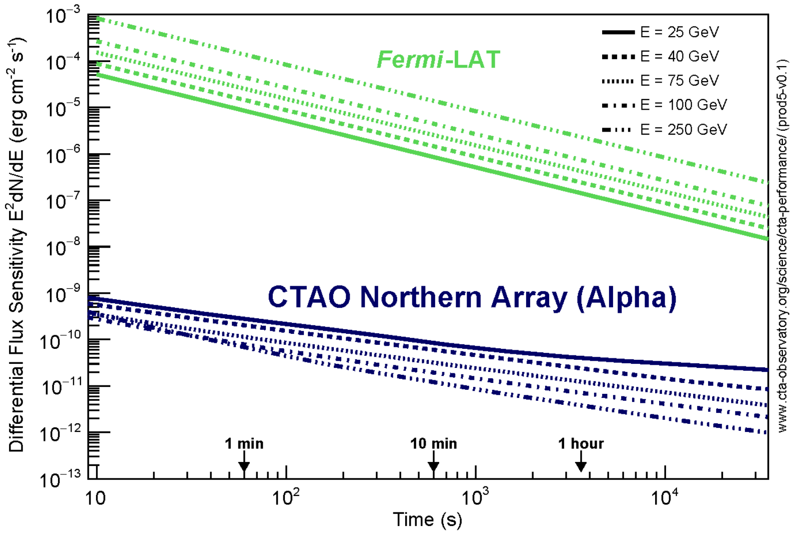

Figure 5. Differential flux sensitivity for the CTAO-North Alpha configuration (blue) in terms of the observation time, compared to *Fermi*-LAT, at different energies. Credit: CTAO.

CTAO Consortium has designed a series of multipurpose observations optimized to address the scientific objectives of CTAO, the *Key Science Projects* [12]. These KSPs have transversal synergies (see Fig. 6) and contribute to answer different science questions [13]. CTAO will perform surveys of different sky regions: Galactic Centre, Galactic Plane, Large Magellanic Cloud and a portion of the Extragalactic sky. It will study cosmic particles through the dedicated KSPs cosmic ray PeVatrons and Star-forming systems. CTAO will also probe extreme environments via Transients and Active Galactic Nuclei KSPs and will explore new Physics with the Dark Matter (DM) program and Galaxy Clusters KSPs.

Theme		Question	Dark Matter Programme	Galactic Centre Survey	Galactic Plane Survey	LMC Survey	Extra-galactic Survey	Transients	Cosmic Ray PeVatrons	Star-forming Systems	Active Galactic Nuclei	Galaxy Clusters
Understanding the Origin and Role of Relativistic Cosmic Particles	1.1	What are the sites of high-energy particle acceleration in the universe?		✔	✔✔	✔✔	✔✔	✔✔	✔	✔	✔	✔✔
	1.2	What are the mechanisms for cosmic particle acceleration?		✔	✔	✔		✔✔	✔✔	✔	✔✔	✔
	1.3	What role do accelerated particles play in feedback on star formation and galaxy evolution?		✔		✔				✔✔	✔	✔
Probing Extreme Environments	2.1	What physical processes are at work close to neutron stars and black holes?		✔	✔	✔			✔✔		✔✔	
	2.2	What are the characteristics of relativistic jets, winds and explosions?		✔	✔	✔	✔	✔✔	✔✔		✔✔	
	2.3	How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?					✔	✔			✔✔	
Exploring Frontiers in Physics	3.1	What is the nature of Dark Matter? How is it distributed?	✔✔	✔✔		✔						✔
	3.2	Are there quantum gravitational effects on photon propagation?						✔✔	✔		✔✔	
	3.3	Do Axion-like particles exist?					✔	✔			✔✔	

Figure 6. KSPs and questions to be addressed. From [12].

Dedicated CTAO Consortium publications are being prepared, focused on various topics of these KSPs. In this section, we present the recently updated cases (for others, see [12, 13]).

- **Galactic Plane Survey (GPS)**. A Survey of the Galactic Plane is foreseen with CTAO. [14] simulated a total observation time of 1620 h spread over 10 years, optimizing the observational strategy in terms of pointing and scheduling. CTAO GPS can potentially increase the number of known Galactic TeV emitters by a factor five.
- **Cosmic ray PeVatrons**. CTAO will aim at identifying hadronic PeV emitters (PeVatrons). [15] showed that the GPS will have limited spectral sensitivity to identify PeVatrons in scanning mode, detectable only if they are point-like sources with hard proton spectra. This could lead to the detection of about 9 hadronic PeV supernova remnants. Otherwise, deep observations $O(100)$h shall be performed for sources with $\Gamma \leq 2.3$ (typical exposure of 250 h). An alternative strategy would be to observe with the SSTs during moonlight conditions in expense of twice the observational time.
- **Galactic Transients**. [16] explored the detection of new Galactic TeV emitters displaying transient signal. CTAO will potential detect transient emission from microquasars during flaring states, such as Cygnus X-1 and Cygnus X-3 and low-mass X-ray binaries with low-viewing angle. It will potentially detect flaring emission from the Crab pulsar-wind nebula in few hours, even making use of the LST subarray only, as well as new novae explosions.
- **DM from the Galactic Centre**. CTAO will map the inner Galaxy to map the diffuse emission. CTAO may be able to probe thermally produced weakly interacting particles (WIMPs), one of the most discussed DM candidates, since it will reach the 'thermal' cross-section for TeV-scale DM [17]. The improved capabilities of CTAO translate into an extended range of DM masses to test theoretical benchmark of the thermal annihilation rate.
- **DM line searches**. CTAO will search for DM signals from annihilating or decaying DM from both the Galactic Centre (observation time 500 h) and dwarf spheroidal galaxies (600 h) [18]. Both monochromatic line signals and more general spectral shapes that would evidence DM are considered. CTAO sensitivity to spectral lines will improve by a factor $\sim$2 at 1 TeV with respect to ground-based experiments.
- **Cosmology and fundamental physics**. Observations of Active Galactic Nuclei (AGNs) with CTAO will help better constrain gamma-ray propagation and absorption on the extragalactic background light (EBL) [19]. CTAO will measure the EBL up to z=2 with less than a 15% statistical uncertainties. These observations of the extragalactic sky will allow to test the intergalactic magnetic field (IGMF) and probe physics beyond the Standard Model, such as axion-like particles or Lorentz invariance violation.
- **Perseus galaxy cluster**. Galaxy clusters show strong evidence to be DM-dominated. The Perseus cluster is one of the most massive and nearby clusters and the brightest in the X-ray sky. [20] discussed the capability of CTAO to detect diffuse emission from this region and the potential contribution from cosmic rays and DM, as well as the observing strategy to be followed. CTAO will set new constraints to the cosmic ray contribution and to DM annihilation and decay scenarios, specially exploring new regions of the parameter space for DM decay for WIMPS at TeV.
- **Large Magellanic Cloud (LMC) Survey**. A deep survey of about 340 h is foreseen with CTAO on the LMC, including regions of interest such as the remnant of supernova SN 1987A or 30 Doradus, the most luminous HII region of the Local Group [21]. It will allow detailed spectral studies of the four known point-like TeV emitters in the region and the detection of extra dozen sources, mainly supernova remnants and pulsar-wind nebulae. Prospects for signal from DM annihilation are also explored.

3 Summary

CTAO will be the first VHE observatory with improved sensitivity, energy range and angular and spectral resolution compared to current experiments. LST-1 is already operational and producing technical and scientific results, while the installation of the remaining three LSTs of CTAO-North is ongoing. These milestones mark the beginning of CTAO's journey to reality. CTAO will mark a new era in VHE astrophysics, opening new research lines through a rich science program reflected in the KSPs. CTAO will lead to a plethora of discoveries and push the frontiers of Physics.

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