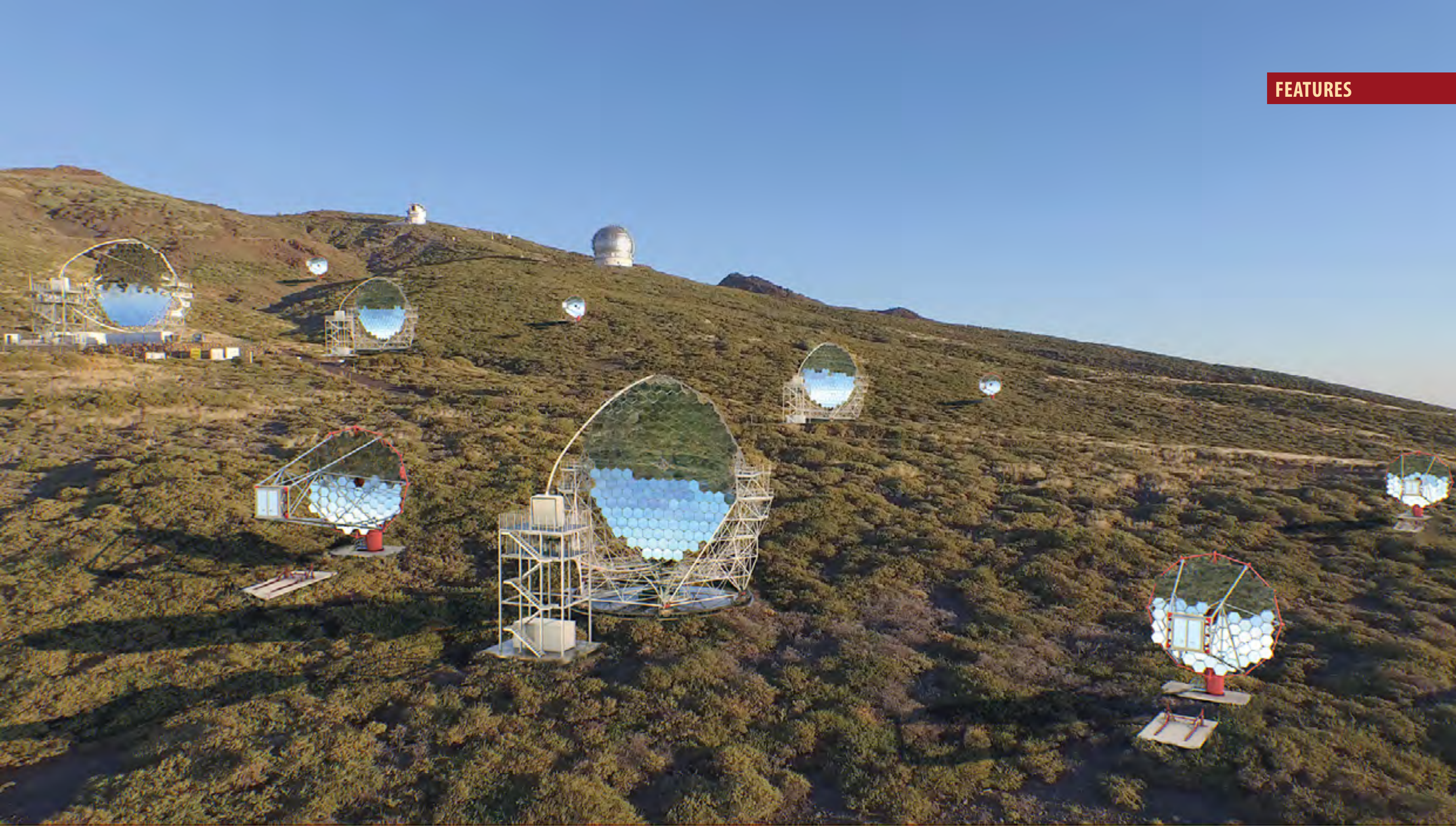

THE EXPLORATION OF THE GAMMA-RAY SKY WITH THE CTAO

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The Cherenkov Telescope Array Observatory (CTAO) represent the next generation of gamma-ray astronomy research infrastructures. Among the messengers from the highest energy universe, gamma rays have the highest event rates, hence they play a key role in the multi-messenger approach involving neutrino and gravitational wave probes, which on the other hand propagate without attenuation.

In partnership with astronomy facilities covering radio to X-rays, gamma rays from space, and neutrinos and gravitational waves, the CTAO[1] will explore the nature of dark matter, respond to and provide alerts of flares and gamma-ray bursts, and shape the multi-messenger future enabling also theoretical modelling of how the most powerful accelerator in the universe work. The prototype of CTAO's Large-Sized Telescopes is LST-1, and its achievements during its commisioning phase, herald the expected outstanding performance of the Observatory.

The gamma-ray window of the Universe is the widest band of the electromagnetic spectrum, but still the least explored. It ranges from a few MeV to tens of PeV (= 10^{15}eV). CTAO (see a rendering of CTAO-North in Fig. 1) will cover the energy range from ~20 GeV to more than 300 TeV. Over the past few decades, many sources of gamma-ray emission have been detected from the ground by H.E.S.S., MAGIC and VERITAS in the 25 GeV to 100 TeV region and these collaborations have joined their efforts to achieve better observational capability by about a factor of 10 and extend the energy range. With an array of •••

▲ **FIG. 1:** Rendering of the CTAO-North (Credit: CTAO).

[1] www.ctao.org/

▸ FIG. 2: The prototype of the Large-Sized Telescope, the LST-1, at the CTAO-North site in La Palma, Spain (Credit: Otger Ballester, IFAE).

• • • more than 60 telescopes, CTAO angular resolution in the multi-TeV region will be ~ 0.02°, enabling precise morphological studies of extended galactic sources. At the time of writing this article, more than 6,600 gamma-ray sources (point-like and extended) have been detected by the Fermi satellite [1], of which 308 show TeV photon emission[2]. These sources range over a wide variety of classes facilitating a huge potential of extensive scientific studies.

The Cherenkov Telescope Array

The CTAO will be a distributed research infrastructure (RI) with two array sites: CTAO-South in the southern hemisphere at the ESO premises in the Atacama Desert in Paranal, Chile, and CTAO-North, in the northern hemisphere at the IAC's Roque de los Muchachos observatory in La Palma, Spain, together achieving full sky coverage. A Science Data Management Centre at the DESY campus in Zeuthen, Germany, inaugurated on 14 Oct. 2024, will coordinate the processing activities of data centres including CSCS in Lugano, Switzerland, PIC in Barcelona, Spain, and INAF/INFN in Italy. The final legal entity, the CTAO ERIC, which should enter into operation in 2025, will have its headquarters at the INAF premises in Bologna.

Gamma-ray emissions from extragalactic sources travel far and their intrinsic fluxes are attenuated on the way to the Earth since the bulk of gamma-ray photons interact with the low-energy photons of the extragalactic background light (EBL). Those EBL photons are composed primarily of ultra-violet, optical, and infrared photons generated by star formation over the history of the universe, which provides crucial information on galaxy evolution and cosmology. Among the most extreme extra-galactic sources Active Galactic Nuclei (AGNs) have a supermassive black hole in their centre which accretes surrounding matter, forming a very luminous accretion disk. Some AGNs show two relativistic jets coming out from the vicinity of the black hole, which seems to be related to such an accretion process. AGNs emit extremely bright electromagnetic radiation in a wide range of wavelengths from accelerated electrons and eventually hadrons in their jets and winds. When the AGN's relativistic jet is pointing almost directly towards Earth, it is called a blazar. Blazars are the largest class of AGNs in the gamma-ray sky, mainly is classed as BL Lacertae (BL Lac) objects or Flat-Spectrum Radio Quasar (FSRQ) active galaxies. Other important extragalactic sources are Gamma-Ray Bursts (GRBs), extremely powerful, short-lived outbursts of radiation triggered by either collision of neutron stars or the death of a massive star, as well as starburst galaxies and galaxy clusters. Only in the recent years GRBs have been observed from ground at extremely high energy surpassing 10 TeV. The Galactic gamma-ray emitter population includes pulsars, globular clusters, Supernova Remnants (SNRs), TeV halos, and Pulsar Wind Nebulae (PWNe). Also the Galactic Centre (GC) region is a gamma-ray emitter up to PeV energies, although the most powerful accelerator in the region has still to be identified [2]. The GC region is densely packed with candidate accelerators, including the young SNR Sgr A East, massive stellar clusters, and the non-thermal radio compact radio source Sgr A*, the central super-massive black hole. Sgr A* is now in a low activity phase of its life, while millions of years ago, it could have been responsible for the so called 'Fermi Bubbles', a reservoir of electrons

[2] TeVCat2 is an online catalogue for TeV Astronomy: https://tevcat2.uchicago.edu/

and possibly cosmic rays extending tens of kpc away from the GC and forming two blobs seen in gamma rays, X-rays and microwaves [3].

Some of the most pressing questions in astrophysics, such as the origin of (galactic and extragalactic) cosmic rays and the nature of dark matter can be addressed using gamma rays. Other important aspects of fundamental physics are also covered by gamma-ray astronomy including tests of Lorentz invariance violation, as well as galaxy formation and cosmology. Thus, with the detection of new and also known gamma-ray sources with finer angular and energy resolution due to improvements in the instrumental sensitivity and technology, CTAO could be the key player to solve the challenging riddles on various frontiers in sciences. A detailed summary of the scientific potential and capabilities of CTAO can be found in the "CTAO Science book" [4].

Ground-based gamma-ray astronomy

CTAO utilises the Imaging Atmospheric Cherenkov Telescope (IACT) technique. Gamma rays do not directly reach the ground as they are absorbed in the Earth's atmosphere. Their interactions with atmospheric nuclei results in the creation of extensive atmospheric showers (EAS) composed of photons and secondary particles. As many of the charged particles in these cascades travel faster than the speed of light in the atmosphere, they emit Cherenkov photons along their paths towards the Earth's surface. These brief flashes of Cherenkov light, lasting a few nanoseconds (ns), travel through the atmosphere and can be detected by IACT segmented mirrors and projected on their ns-sensitive cameras which detect between one and thousands of photons and recording the events. Such photons include not only the signal but also diffuse night sky background photons, hence the event images need to be isolated to measure the EAS longitudinal development, including its spatial, temporal, and calorimetric characteristics. After a detailed cleaning routine identifying the signal region(s) in the camera, the state-of-the-art IACT data analyses parameterise the event images by extracting geometric and stereoscopic features. Based on the extracted features, machine learning algorithms can be trained to reconstruct the properties of the primary particle of the shower such as the particle type, its energy and direction of arrival. As an example, convolutional neural networks can reconstruct the primary particle properties directly from the event images (see *e.g.* [5]).

LST-1: An Outstanding Prototype for the CTAO

The northern site of the Observatory, CTAO-North, will be composed of four Large-Sized Telescopes (LSTs) with optical reflecting surfaces of 23 m diameter and nine Middle-Sized Telescopes (MSTs) of 12 m diameter reflectors. CTAO-South will host 4 MSTs and 37 Small-Sized Telescopes (SSTs) that will cover a collection area of a few km^2. An enhancement plan of such layout includes also two LSTs, which are funded.

The LSTs are relevant for the energy range down to 20 GeV and for the study of transient phenomena such as flares of AGNs and GRBs, precision measurements of pulsars and other Galactic sources, measurement of the EBL and dark matter searches. The LST prototype of CTAO-North (see Fig. 2), called "LST-1" is under commissioning and already collecting a significant amount of observational data since a couple of years. The performance of the LST-1 has been validated on observations of the Crab Nebula, the standard candle of very-high energy gamma-ray astronomy, and its pulsar [6].

Recently, a study of the CTAO LST Collaboration has set limits on the flux from the galactic PeVatron LHAASO J2108+5157, an ultra-high energy gamma-ray source capable of emitting gamma rays above PeV, using 49 hr of LST-1 data. This led to an extensive multi-wavelength study, combining the LST-1 observations with XMM-Newton (X-ray telescope) and Fermi-LAT (soft gamma-ray satellite) data, suggesting as possible interpretation that the source could be a PWN with a TeV halo [7].

Another highlight of the LST-1 is the detection of the 2021 outburst of RS Ophiuchi (RS Oph), a recurrent symbiotic nova with a recurrence time scale of 15 years. This historic event, also detected by H.E.S.S. and MAGIC (current generation of IACT facilities), is the first discovery of very-high energy gamma rays from a nova. Novae are luminous explosions in binary systems with a white dwarf and a companion star, which are triggered by a thermonuclear runaway when the white dwarf accretes a critical amount of matter from the secondary. The origin of the high energetic gamma-ray emission of those objects, whether it is hadronic or leptonic, were subject of active and intense debate prior to the outburst. The low energy threshold of LST-1 allowes for a detailed spectrum analysis down to ~30 GeV, bridging the very-high energy data to the soft gamma-ray regime of Fermi-LAT and supporting a hadronic origin for the gamma-ray emission [8] as also suggested by the observations of H.E.S.S. and MAGIC.

The detection of FSRQ OP 313 at very-high energies by LST-1 is an additional milestone and a demonstration of the outstanding performance of the prototype. Although OP 313 was previously detected at lower energies by Fermi-LAT, it had never been detected above 100 GeV, marking this as LST-1's first scientific discovery. With these results, OP 313, which is located about 8 billion light years away at a redshift of $z = 0.997$, now stands as the most distant AGN ever observed by a IACT. This exceptional dataset is a valuable asset for studying the EBL and intergalactic physics.

Outlook

The described findings highlight LST-1's capabilities and the potential of the upcoming CTAO arrays. The construction of CTAO-North is currently on going and the four LSTs are expected to be completed in 2026, followed by the completion of the full array of the northern site MSTs. Construction of roads and infrastructure at the CTAO-South site has started and the installation of the first MST is expected next year. The future is bright and shines in gamma rays and the CTAO will be looking! ■

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