CRIS-MAC2024 IOP Publishing
Journal of Physics: Conference Series **3053** (2025) 012015 doi:10.1088/1742-6596/3053/1/012015

Discovery of the Very High Energy emission from the distant FSRQ OP 313 with the Large-Sized Telescope prototype.

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Abstract. In December 2023 the Large-Sized Telescope prototype (LST-1) of the Cherenkov Telescope Array Observatory (CTAO) observed the distant (z=0.997) Flat Spectrum Radio Quasar (FSRQ) OP 313 following an alert of increased activity by the Fermi-LAT Space Telescope. Thanks to its very low energy threshold and large effective area LST-1 detected very-high-energy (VHE, E>100 GeV) emission from OP 313. OP 313 is the tenth FSRQ ever detected in the VHE regime and the furthest blazar ever detected so far at these energies. This result represents the first scientific discovery of the LST-1, showing the exceptional capabilities of CTAO, whose LST northern array is currently under construction in La Palma (Canary Islands, Spain).

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1 Introduction

Particle acceleration mechanisms in extreme astrophysical environments can be studied through their Very High Energy (VHE, $E_\gamma > 100$ GeV) emission. VHE photons carry also information about processes occurring during their propagation and of their Cosmic Rays progenitors.

The Cherenkov Telescope Array Observatory (CTAO) is the next generation ground-based gamma-ray facility and will consist of 2 arrays, one in each hemisphere for full sky coverage. In the northern site, at the Observatorio Roque del Los Muchachos in the Spanish island of La Palma, 2 types of telescopes are foreseen: 4 Large-Sized Telescopes (LSTs) and 9 Medium-Sized Telescopes (MSTs). The array layout is shown in Figure 1. In the southern site, close to Cerro Paranal (Chile), 14 MSTs and the 37 Small-Sized Telescopes (SSTs) will cover an area of 3 km^2, composing the so-called alpha configuration, that will be complemented by at least 2 LSTs.

	LST	MST	SST
North	4	9	0
South	2	14	37

Table 1: Telescope types foreseen in the two CTAO sites.

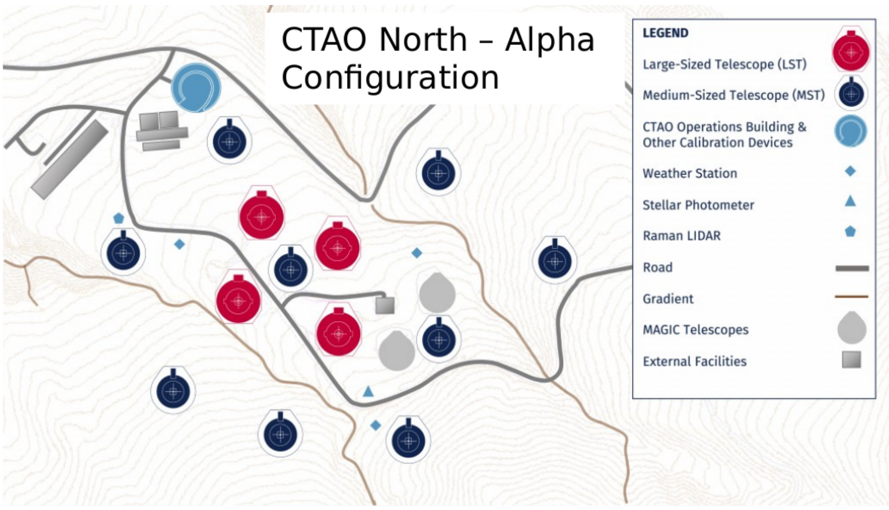

Figure 1: The CTAO North layout (*Alpha Configuration*). From *www.ctao.org*.

2 The Large-Sized Telescopes

The CTAO northern array sensitivity [1], shown in Figure 2, below 200 GeV will be dominated by the LSTs, aiming at an energy threshold of a few tens of GeV. Thanks to the low energy threshold, overlapping with direct measurements, its high sensitivity and its fast repositioning capabilities, the LST array will be an ideal instrument to study transients and faint, soft sources. The low energy threshold is also the key parameter to allow to observe very distant sources, since the extragalactic background light (EBL) absorption increases with energy, the observable horizon reduces accordingly. An energy threshold of around 30 GeV would allow to detect powerful sources up to redshift $z < 2$.

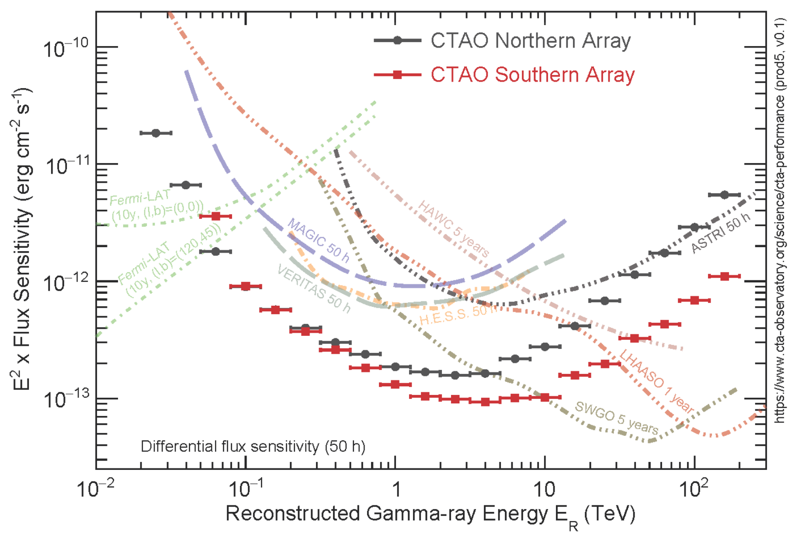

Figure 2: The CTAO sensitivity (Northern array in black and Southern array in red) compared with other instruments. In the energy range below 200 GeV the sensitivity is dominated by the LSTs. From *www.ctao.org*.

2.1 The LST prototype

The Large-Sized Telescope prototype (LST-1) [2], depicted in Fig. 3, has a 23 m diameter dish on an alt-az mount with circular rail. The structure, in carbon fiber and steel, provides at the same time enough stiffness and relatively light-weight (total moving mass of 120 tons) to allow fast repositioning. LST-1 can point any sky direction in less than 20 s to promptly react to fast transient alerts. The ∼400 m^2 faceted mirror has a parabolic shape to preserve the timing information of the collected photons. The 3 m x 3 m camera hosts 1855 PMTs, covering a total field of view of 4.5^o. LST-1 is designed to reach an energy threshold of 20 GeV, hence overlapping with satellites but with several orders of magnitude larger collection area.

Figure 3: The Large-Sized Telescope prototype at sunset. Credits: Sarah A. Brands, 2018.

2.2 Performance of LST-1

The performance of the telescope has been evaluated by means of detailed Monte Carlo (MC) simulations and observations of the Crab Nebula. The MC model has been tuned on observed data and then the full simulation has been validated by means of the comparison of several reconstructed parameters with those obtained by real observations, showing a very good agreement. The telescope performance has been estimated for observations at different zenith angles and with energy-dependent quality cuts for different gamma-ray efficiencies. The results have been extensively reported in [3], in Fig. 4 the sensitivity for two different analyses compared with the MAGIC one is shown. The angular resolution of LST-1 is shown in Fig. 5 at different zenith angles compared with the MAGIC one.

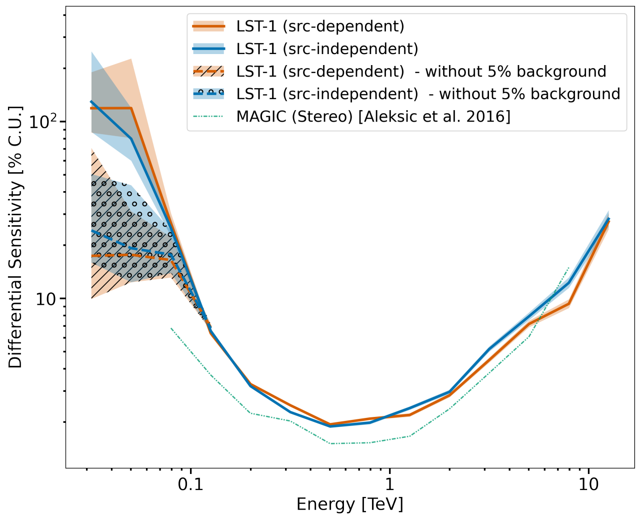

Figure 4: From [3]. Sensitivity of LST-1 compared with MAGIC. The errors bands include systematic and statistical uncertainties. It is also shown with the textured bands the effect of the request of signal larger than 5% of the background, which dominates and limits the sensitivity at low energy.

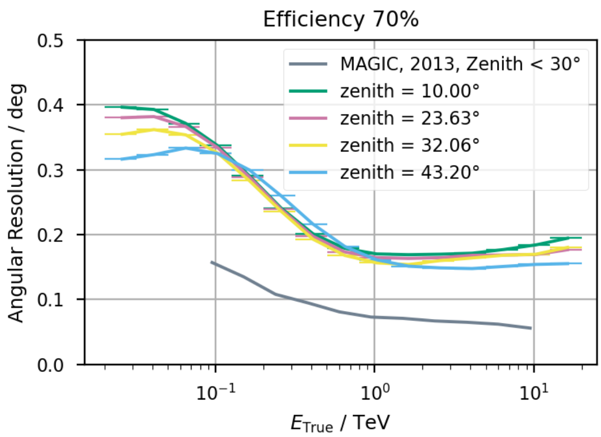

Figure 5: From [3]. The angular resolution, for events passing an energy dependent gammaness cut defined accordingly to 70% gamma-ray efficiency. In black MAGIC angular resolution.

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As expected for a single telescope the performance is worse than a stereoscopic system like MAGIC, for instance the sensitivity of LST-1 at 1 TeV is 1.5 times worse than MAGIC. However thanks to LST's larger mirror a lower energy threshold is achieved and thanks to the larger field-of-view the difference at the highest energies decreases. It is worth noting that the full LST array, with 4 telescopes, will have a sensitivity at least 5 times better than MAGIC at 100 GeV (see Fig. 2). As a final check we studied the Crab Nebula Spectral Energy Distribution (SED) as measured by LST-1, shown in Fig. 6. The result is in perfect agreement with the spectrum measured by MAGIC and shows a significant overlap in the energy range covered by Fermi-LAT.

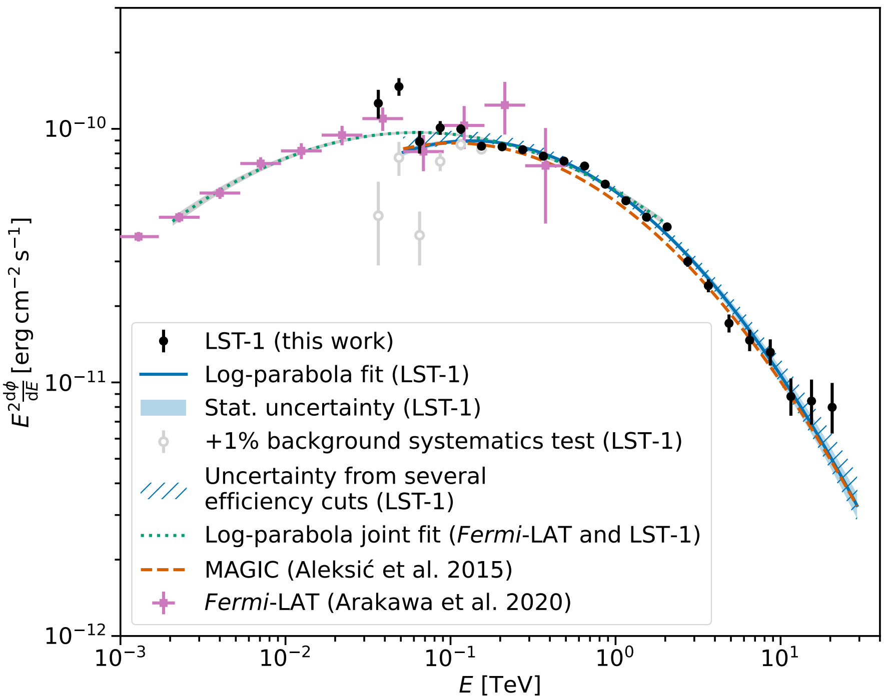

Figure 6: From [3]. The Crab Nebula SED measured by LST-1, compared with MAGIC and Fermi-LAT.

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2.3 Status of the LST project

The CTAO Northern site will host 4 LSTs and 9 MSTs. The next 3 LSTs, namely LST-2 to LST-4 are currently under construction (photo of the site as in May 2024 in Fig. 7). At the moment of writing this document, LST-4 and LST-3 have their 23-m diameter dishes mounted on the mounts. The installation of the arch and the camera support structure of LST-4 is foreseen within summer 2024. The construction of the 3 telescopes will occur in parallel and the installation of the cameras is foreseen within the end of 2025. Right after, the commissioning of the LST array will start.

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Figure 7: Picture of the CTAO northern site, taken in May 2024.

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3 Flat Spectrum Radio Quasars

Flat Spectrum Radio Quasars (FSRQs) are a class of Blazars, Active Galactic Nuclei (AGNs) with their jets aligned to the line-of-sight from Earth. Blazars are extremely powerful sources and their emission extends over the whole electromagnetic spectrum. Blazars are typically highly variable and the origin of their variability, from hours to days timescale, is still unknown. FSRQs are radio-loud quasars with an optical spectrum showing strong emission lines. Despite more than ∼800 have been detected in gamma-rays by Fermi-LAT, only 9 have been detected at very high energies until December 2023, suggesting a possible internal absorption mechanism, in addition to the EBL absorption affecting more the higher energies.

4 Detection of VHE emission of OP 313

OP 313 (R.A. = 197.619432 deg, Decl. = +32.345495 deg [4]) is a FSRQ at redshift z=0.997 (∼8 billion light-years) [5]. It is a known source detected in the HE domain by Fermi-LAT (4FGL J1310.5+3221 [6]).

In the last months of 2023 and in the first months of 2024 OP 313 has been active as shown in Fig. 8 with the light curve measured by Fermi-LAT. The November 2023 flare occurred during full moon, so it was not possible to perform observations by Imaging Atmospheric Cherenkov Telesopes.

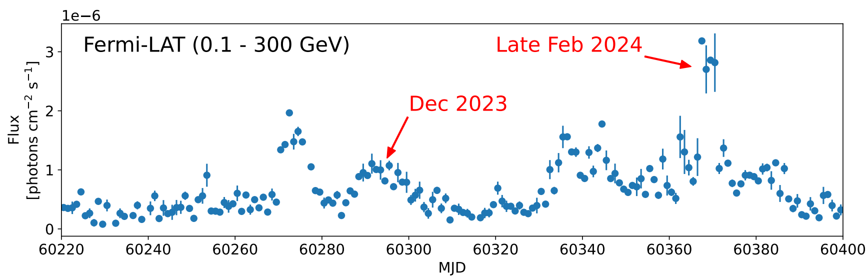

Figure 8: The OP 313 light curve (LC) in the period Nov 2023 - March 2024 observed by Fermi-LAT (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/).

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In December 2023 the source was again active and on the Dec 1st 2023 the Fermi-LAT collaboration issued an Atel [7]. Follow-up target-of-opportunity observations were carried out by LST-1, which observed OP 313 from Dec 9th to 14th, for a total of 6 hours of good data, obtaining a detection with significance of $> 5\sigma$ [8]. The flare was observed until Dec. 18th. In total the OP 313 December 2023 flare has been observed by LST-1 for a total effective time of 14.6 h, reaching an excess significance of about

13 σ. In Figure 9 the preliminary θ^2 distribution of the excess counts is shown. The average flux above 100 GeV during the December 2023 flare has been estimated in ∼0.28 C.U. The excess is clearly visible in the analysis energy bin for E $<$ 250 GeV, no excess is seen at higher energies. OP 313 is the tenth FSRQ detected at VHE, the furthest blazar ever detected in VHE gamma-rays, and the 2^{nd} furthest source ever observed at VHE. The multiwavelength observations, including the VHE domain with LST-1, of the flares of OP 313 will allow to set constraints on the EBL models.

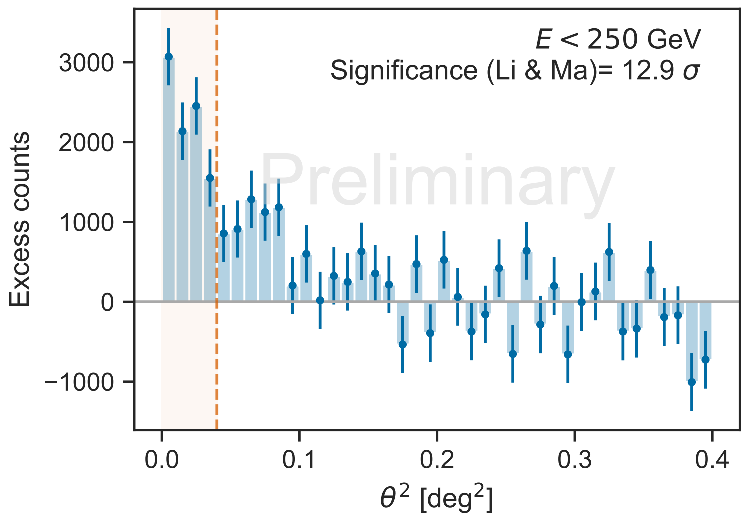

Figure 9: The OP 313 θ^2 plot of the December 2023 flare.

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5 Conclusions

The detection of OP 313, the furthest blazar ever detected at the VHE at z=0.997, is the first LST-1 discovery. It is the 10^{th} FSRQ detected at VHE and its detection and the ongoing modeling of the emission will shed light on the particle acceleration mechanism occurring at this powerful sources. The extremely good performance of LST-1 is very encouraging in view of the upcoming CTAO.

Aknowledgments

This work was conducted in the context of the CTAO-LST Project. We gratefully acknowledge financial support from the agencies and organizations listed here:
https://www.ctao.org/for-scientists/library/acknowledgments/
https://www.lst1.iac.es/acknowledgements.html
This work is also part of the project “SKYNET: Deep Learning for Astroparticle Physics”, PRIN 2022 (CUP: D53D23002610006).

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