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Prospects and latest optical intensity interferometry results with the MAGIC and CTAO-North LST telescopes

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PoS(ICRC2025)935

Along with their gamma-ray observations at very high energies (VHE;20 GeV - 100 TeV), the two 17-m MAGIC telescopes (at Roque de los Muchachos Observatory, La Palma) have also been utilized as an optical stellar intensity interferometer (SII) for the last six years. The calibration and validation of the setup, alongside the first measurement of the stellar angular diameter of 13 massive stars, were published in a performance paper in early 2024 [1]. Around the same time, the technical advancements developed for MAGIC were applied to the first Large-Sized Telescope of the northern hemisphere array of the Cherenkov Telescope Array Observatory (CTAO-North LST-1), a 23-m diameter telescope located near MAGIC. Three more LSTs should be completed beginning of 2026 and they may be equipped in the same manner as LST-1. We will focus on our first measurements with the MAGIC+LST-1 SII and our prospects for this and the MAGIC+LST1-4 SII for the study of several objects that are also known to emit in gamma rays: novae, such as the upcoming T CrB; winds from massive stars, particularly colliding-wind binaries; and Be stars which are typical companions in VHE gamma-ray binaries.

39th International Cosmic Ray Conference (ICRC2025)
15–24 July 2025
Geneva, Switzerland

1. The MAGIC Stellar Intensity Interferometer (SII)

The main objective for Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the MAGIC telescopes, is to observe the very-high-energy (VHE;20 GeV - 100 TeV) gamma-ray night-sky. In order to perform this kind of observations, IACTs make use of several technical features that make them incidentally well suited for intensity interferometry observations: they come in groups (each combination of telescopes is a different baseline and orientation), they have time resolution of nanoseconds (needed to resolve the correlation signal), they are sensitive to single photo-electrons (and therefore coherence of individual photons) and they have large reflective mirrors (more photons means more statistics and better S/N).

In recent years, the MAGIC telescopes have undergone several technical modifications to additionally act as an intensity interferometer [2–4]. A new digitizer and GPU-based real-time correlator were implemented. Also, a dedicated configuration of its Active Mirror Control to focus the light to the infinite instead of the typical altitude of Extense Atmospheric Showers of 10 km and to concentrate it into just one or two photo-multipliers (PMTs). And finally, the automatic deployment of optical filters using the white target holder, that allows the system to transform into an intensity interferometer in less than a minute and then back to VHE observations just as quickly (useful for transients). This makes the MAGIC Stellar Intensity Interferometer (MAGIC SII) an extremely high duty cycle instrument. The observations have mainly been performed during Moon breaks, which are periods with bright Moon-light conditions in which IACTs cannot perform sensitive VHE observations, but the intensity interferometer can, thanks to the optical filters that greatly reduce the amount of blue Moon-light that gets into the PMT.

The MAGIC SII setup has been thoroughly calibrated and its systematics studied. This work has crystallized in the form of a performance paper that was published in early 2024 [1]. In this paper, the sources of systematics and their contribution to the uncertainties in the correlation measurements are shown, as well as the angular diameter measurements for 9 stars consistent with measurements by other experiments in the same wavelength range (Blue, 400-440 nm). Given the agreement with other experiments and the proven understanding of the systematics, the team was able to report 13 stellar angular diameters never before measured in Blue band, for a total of 22 measured angular diameters reported. Furthermore, prospects for the MAGIC+LST-1 SII and MAGIC+4LSTs SII were presented.

2. Addition of LST-1 to the MAGIC SII and prospects for MAGIC+4 LSTs

In 2024, another IACT next to the MAGIC telescopes, the first Large-Sized Telescope (LST-1) of Cherenkov Telescope Array Observatory (CTAO) was added to the setup. In fact, other 3 LSTs are currently being installed in La Palma [5]. The addition was possible by implementing a few technical modifications: two filters were mounted on the white target holder, similar to the setup in each MAGIC camera, allowing to remotely place the filters in front of any pixel; one of the front-end boards was redesigned to extract a replica of the central PMT analog signal as well as an optical transmitter; and an optical fiber was routed towards MAGIC counting house and connected to the existing correlator. The addition was successful and the correlation from all three channel combinations (MAGIC 1 & MAGIC 2, MAGIC 1 & LST-1, and MAGIC 2 & LST-1) is detected as can be seen on the left side of Fig. 1, proving that the implementation is not only possible but also easily scalable.

There are some hardware differences between MAGIC and LST-1 that make the addition of LST-1 very beneficial to the interferometer: the LST-1 mirror dish is 23 m in diameter instead of 17 m, so the mirror area is much larger (370 m^2 vs 236 m^2), also the photo-detectors quantum efficiency of ~ 40% and optical efficiency of ~ 60% are better than those of the MAGIC telescopes. This allows to observe fainter objects and detect correlation signal within less observing time. Not only that, but the distance and relative position of the telescopes allow to access longer baselines (from 86 m to 150 m for MAGIC+LST-1 SII and 250 m for MAGIC+4LSTs) and different simultaneous orientations (3 for MAGIC+LST-1 SII and 15 for MAGIC+4LSTs), which are needed to measure smaller objects and objects without circular symmetry. These characteristics translate into an increase in sensitivity of factor 4 and a factor 10 if 4 LSTs are added instead, being able to achieve a relative uncertainty in the angular diameter of 10% in just 2.5 h for stars up to B magnitude ~3.2, ~5 and ~6 respectively, as shown in Fig. 13 of [1]. The current setup consists of one correlator with 4 channels, which is enough for the MAGIC+LST-1 SII since it only needs 3 channels, but adding three telescopes for the MAGIC+4LSTs SII implies adding at least two more channels (6 in total). One or two pixels per telescope are needed to perform systematic studies and calibration, but the pixels used for calibration and monitoring of the night-sky background do not need to be connected to the correlator.

The setup is being tested and calibrated. A few measurements of calibrator stars from MAGIC SII performance paper in the Blue band and other stars measured by CHARA in the near-infrared have been compared with new measurements with the MAGIC+LST-1 SII, as shown in Fig. 1. The great accordance between all of them shows that the setup is indeed meeting the expectations.

2.1 Science cases with current Stellar Intensity Interferometers

The prime targets for the use of the intensity interferometry technique at baselines of ~100 m are main sequence stars of angular diameters between 0.5 and 2 milliarcseconds (for reference, the Moon has an average angular diameter of ~ 30 arcmin while Sagittarius A* is ~ 50 microarcseconds). These are generally main sequence massive stars. The most simple scenario is the determination of their stellar radii by fitting the spatial coherence measurements to an uniform disk model. By measuring the angular diameter of a star of known distance one can obtain an independent measurement of the physical star radius that can be used to test different stellar models and determine other physical parameters like mass, age or temperature.

With the addition of LST-1 to the MAGIC SII and the possibility to add 3 more LSTs in the future, new science cases can be explored.

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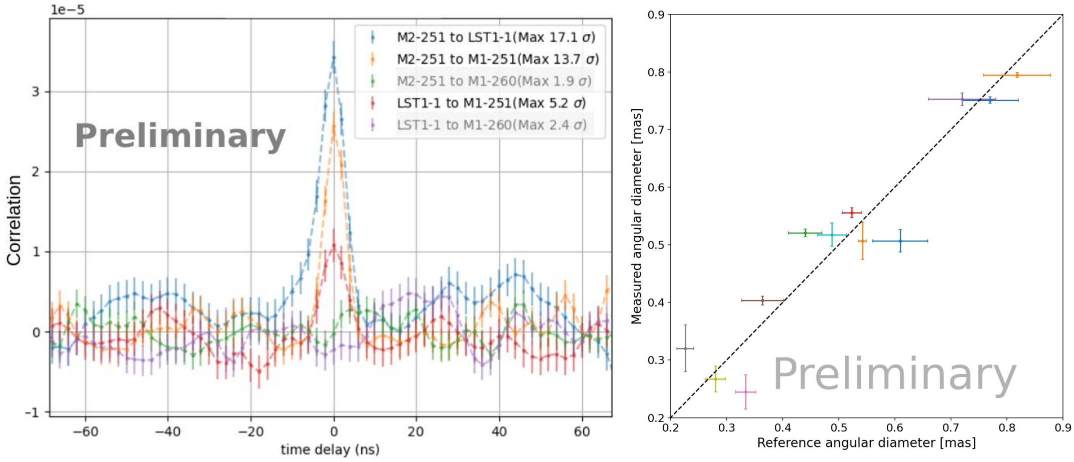

Figure 1: Left: significant measurement of correlation in three channels simultaneously: blue MAGIC 2 with LST-1, orange MAGIC 2 with MAGIC 1 and red LST-1 with MAGIC 1. Right: angular diameter measurements of 12 stars, comparing the measurements from MAGIC+LST-1 SII with MAGIC SII [1] (Blue band) and CHARA [6] (Near-Infrared) as reference values.

2.2 Novae

By studying novae one can study proton acceleration and their contribution to cosmic rays. One of the biggest unknowns when observing these events in VHE is the dominance of hadronic or leptonic mechanisms in the first moments of the explosion, hence the necessity of observing them during the optical rise. If VHE measurements are interleaved with SII observations during the first few minutes and hours, it would be possible to measure the size of the expanding shell, hence constraining leptonic emission models.

Since MAGIC+LST-1 SII has the unique characteristic of being able to switch in a matter of seconds or minutes between VHE and SII observations, this is a science case worth exploring with the setup. As it is shown in Fig. 2, depending on different combinations of evolving angular diameter (different for different shock velocity) and brightness, our simulations show that both setups, MAGIC+LST-1 SII and MAGIC+4LSTs SII, would be able to measure the shape and size of the shell for several hours after the explosion.

2.3 Be stars

In most VHE gamma-ray binaries, particles are accelerated in the shock between a pulsar wind and the wind of the companion star. Said companion is usually a massive star, and in most cases, a Be star. Be stars are a kind of fast rotating star, with a few spectral particularities, mostly due to the presence of a disk. Fast rotating stars are stars that spin so rapidly that the photosphere becomes oblate. The effective gravity decreases towards equatorial regions (gravity darkening), even producing mass loss that form circumstellar disks. These kind of stars when observed in the Fourier space would not present a radially symmetric pattern but an elliptical one, allowing to measure a changing angular diameter and therefore oblateness. By measuring the oblateness of Be

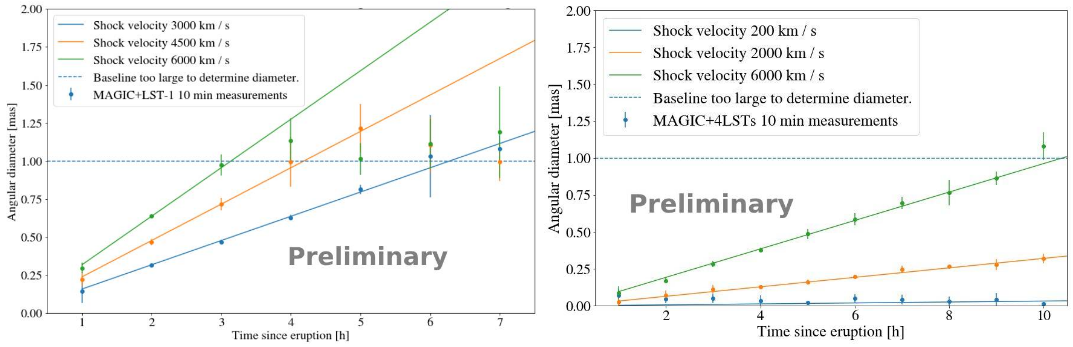

Figure 2: Left: Simulated measurements in snapshots of 10 min performed with MAGIC+LST-1 SII of a nova explosion of 3.3 Bmag at a distance of 3 kpc for shock velocities of 3000, 4500 and 6000 km/s. Right: Simulated measurements in snapshots of 10 min performed with MAGIC+4LSTs SII of a nova explosion of 5.5 Bmag at a distance of 3 kpc for shock velocities of 200, 2000 and 6000 km/s. For both cases, the best results are obtained up to ∼1 milliarcsecond of angular size.

stars one can gain insight into the mass-loss rate and the evolution of the disk, which directly relates to VHE emission when interacting with the wind of the companion (when present).

Thanks to the implementation of the new MAGIC+LST-1 SII setup that allows to probe longer baselines and different orientations, the measurement of the shape of one such star has been possible: gamma Cassiopeiae (γ Cas). This kind of systems are believed to host a Be star together with a white dwarf, and could emit X-rays. MAGIC SII has been collecting data between 2022 and MAGIC+LST-1 SII since 2024. The preliminary results from the analysis of MAGIC SII data (∼55h) and MAGIC+LST-1 SII data (∼2h) 2024 data are shown in figure 3. The preliminary values are in accordance with expected values from literature and also with equivalent measurements performed between 2023 and 2024 by VERITAS SII [7]: angular diameter of the major axis of 0.59 ± 0.01 mas, ratio between minor and major axes of 0.76 ± 0.02 and position angle of the equator of 34 ± 3 deg (only statistical uncertainties taken into account for the three quantities). Moreover, as shown by the right side of Figure 3, the oblate uniform ellipse model is preferred over the non-oblate uniform disk model: χ^2_ν = 1.13 for the oblate model and χ^2_ν = 2.73 for the non-oblate model. More complex models including gravity darkening are being studied for future publication.

With the addition of the other 3 LSTs to the setup, we would be able to obtain similar results and uncertainties for a larger sample of fast rotating stars up to B magnitude ∼ 6, as shown for 5h simulations of a 5.45 Bmag fast rotator already shown in [8].

2.4 Colliding-wind binaries

Wind-wind collision in massive star binary systems can lead to high temperature shocks. These shocks can produce radio and optical emission as well as X-rays or even VHE gamma rays. Therefore, studying the size and placement of the shocks can help to better constrain current hydrodynamic models. This is in principle possible since colliding winds produce emission lines that can be singled out. Not only that but clumps from within the winds and they are expected to evolve

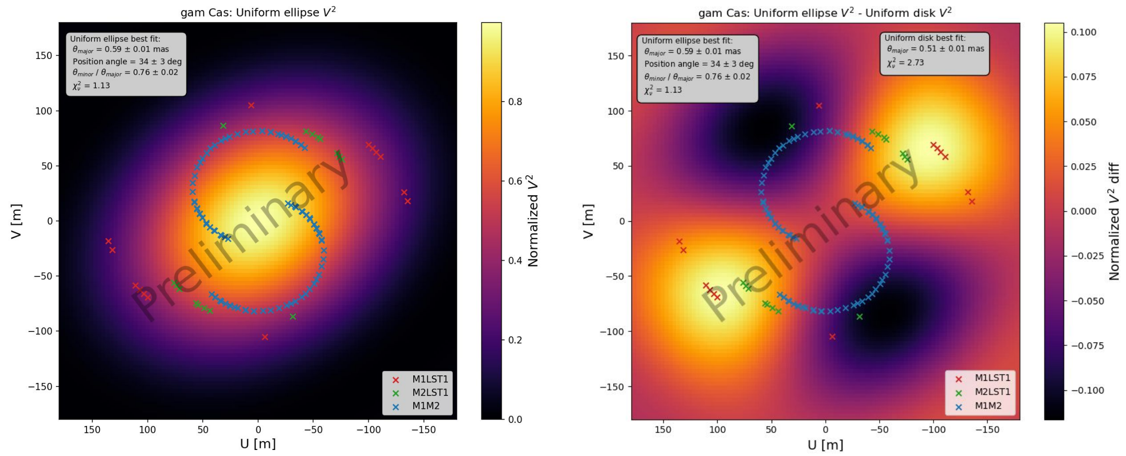

Figure 3: Left: UV plane (Fourier space) showing the reconstructed spatial coherence or normalized squared visibility for the star γ Cas, along with the position of the measurements for every combination of MAGIC+LST-1 SII from 2024. The results for the major axis, axis ratio and position angle are also shown in the legend, along with a goodness of fit that shows that the oblate uniform ellipse model is preferred over the non-oblate uniform disk model. Right: difference in normalized squared visibility between the uniform ellipse model and the uniform disk model.

with time. One of these systems is γ^2 Vel, and was already studied with the Narrabri SII, measuring the size and roughly the shape of the emission region [9]. The benefits of combining intensity interferometry with spectroscopy and photometry are clear, expanding the parameters that can be constrained and studied, such as the physical radii (depending on the distance), absolute magnitude, surface gravity or effective temperature.

3. Conclusions

MAGIC and CTAO-LST collaborations are working together, devoting time and effort to achieve the most sensitive setup possible with no negative impact to VHE observations. The compared measurements of calibrator stars proves that we understand the setup and it is working as expected. The successful measurement of the shape of the fast rotator γ Cas is just one of the promising science cases that we have begun or continued to explore. Synergies between VHE gamma-ray astronomy and optical intensity interferometry are very clear and further strengthen the case for this technique to be implemented in future VHE gamma-ray observatories like CTAO.

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Acknowledgments

We would like to thank the Instituto de Astrofísica de Canarias for the excellent working conditions at the Observatorio del Roque de los Muchachos in La Palma. The financial support of the German BMBF, MPG and HGF; the Italian INFN and INAF; the Swiss National Fund SNF; the grants PID2019-104114RB-C31, PID2019-104114RB-C32, PID2019-104114RB-C33, PID2019-105510GB-C31, PID2019-107847RB-C41, PID2019-107847RB-C42, PID2019-107847RB-C44, PID2019-107988GB-C22, PID2022-136828NB-C41, PID2022-137810NB-C22, PID2022-138172NB-C41, PID2022-138172NB-C42, PID2022-138172NB-C43, PID2022-139117NB-C41, PID2022-139117NB-C42, PID2022-139117NB-C43, PID2022-139117NB-C44 funded by the Spanish MCIN/AEI/ 10.13039/501100011033 and "ERDF A way of making Europe"; the Indian Department of Atomic Energy; the Japanese ICRR, the University of Tokyo, JSPS, and MEXT; the Bulgarian Ministry of Education and Science, National RI Roadmap Project DO1-400/18.12.2020 and the Academy of Finland grant nr. 320045 is gratefully acknowledged. This work was also been supported by Centros de Excelencia "Severo Ochoa" y Unidades "María de Maeztu" program of the Spanish MCIN/AEI/ 10.13039/501100011033 (CEX2019-000920-S, CEX2019-000918-M, CEX2021-001131-S) and by the CERCA institution and grants 2021SGR00426 and 2021SGR00773 of the Generalitat de Catalunya; by the Croatian Science Foundation (HrZZ) Project IP-2022-10-4595 and the University of Rijeka Project uniri-prirod-18-48; by the Deutsche Forschungsgemeinschaft (SFB1491) and by the Lamarr-Institute for Machine Learning and Artificial Intelligence; by the Polish Ministry Of Education and Science grant No. 2021/WK/08; and by the Brazilian MCTIC, CNPq and FAPERJ.

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Acknowledgments

We gratefully acknowledge financial support from the following agencies and organisations: Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Fundação de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP), Fundação de Apoio à Ciência, Tecnologia e Inovação do Paraná - Fundação Araucária, Ministry of Science, Technology, Innovations and Communications (MCTIC), Brasil; Ministry of Education and Science, National RI Roadmap Project DO1-153/28.08.2018, Bulgaria; Croatian Science Foundation (HrZZ) Project IP-2022-10-4595, Rudjer Boskovic Institute, University of Osijek, University of Rijeka, University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Zagreb, Faculty of Electrical Engineering and Computing, Croatia; Ministry of Education, Youth and Sports, MEYS LM2023047, EU/MEYS CZ.02.1.01/0.0/0.0/16_013/0001403, CZ.02.1.01/0.0/0.0/18_046/0016007, CZ.02.1.01/0.0/0.0/16_019/0000754, CZ.02.01.01/00/22_008/0004632 and CZ.02.01.01/00/23_015/0008197 Czech Republic; CNRS-IN2P3, the French Programme d'investissements d'avenir and the Enigmass Labex, This work has been done thanks to the facilities offered by the Univ. Savoie Mont Blanc - CNRS/IN2P3 MUST computing center, France; Max Planck Society, German Bundesministerium für Bildung und Forschung (Verbundforschung / ErUM), Deutsche Forschungsgemeinschaft (SFBs 876 and 1491), Germany; Istituto Nazionale di Astrofisica (INAF), Istituto Nazionale di Fisica Nucleare (INFN), Italian Ministry for University and Research (MUR), and the financial support from the European Union – Next Generation EU under the project IR0000012 - CTA+ (CUP C53C22000430006), announcement N.3264 on 28/12/2021: "Rafforzamento e creazione di IR nell'ambito del Piano Nazionale di Ripresa e Resilienza (PNRR)"; ICRR, University of Tokyo, JSPS, MEXT, Japan; JST SPRING - JPMJSP2108; Narodowe Centrum Nauki, grant number 2023/50/A/ST9/00254, Poland; The Spanish groups acknowledge the Spanish Ministry of Science and Innovation and the Spanish Research State Agency (AEI) through the government budget lines PGE2022/28.06.000X.711.04, 28.06.000X.411.01 and 28.06.000X.711.04 of PGE 2023, 2024 and 2025, and grants PID2019-104114RB-C31, PID2019-107847RB-C44, PID2019-104114RB-C32, PID2019-105510GB-C31, PID2019-104114RB-C33, PID2019-107847RB-C43, PID2019-107847RB-C42, PID2019-107988GB-C22, PID2021-124581OB-I00, PID2021-125331NB-I00, PID2022-136828NB-C41, PID2022-137810NB-C22, PID2022-138172NB-C41, PID2022-138172NB-C42, PID2022-138172NB-C43, PID2022-139117NB-C41, PID2022-139117NB-C42, PID2022-139117NB-C43, PID2022-139117NB-C44, PID2022-136828NB-C42, PDC2023-145839-I00 funded by the Spanish MCIN/AEI/10.13039/501100011033 and "and by ERDF/EU and NextGenerationEU PRTR; the "Centro de Excelencia Severo Ochoa" program through grants no. CEX2019-000920-S, CEX2020-001007-S, CEX2021-001131-S; the "Unidad de Excelencia María de Maeztu" program through grants no. CEX2019-000918-M, CEX2020-001058-M; the "Ramón y Cajal" program through grants RYC2021-032991-I funded by MICIN/AEI/10.13039/501100011033 and the European Union "NextGenerationEU"/PRTR and RYC2020-028639-I; the "Juan de la Cierva-Incorporación" program through grant no. IJC2019-040315-I and "Juan de la Cierva-formación"' through grant JDC2022-049705-I. They also acknowledge the "Atracción de Talento" program of Comunidad de Madrid through grant no. 2019-T2/TIC-12900; the project "Tecnologías avanzadas para la exploración del universo y sus componentes" (PR47/21 TAU), funded by Comunidad de Madrid, by the Recovery, Transformation and Resilience Plan from the Spanish State, and by NextGenerationEU from the European Union through the Recovery and Resilience Facility; "MAD4SPACE: Desarrollo de tecnologías habilitadoras para estudios del espacio en la Comunidad de Madrid" (TEC-2024/TEC-182) project funded by Comunidad de Madrid; the La Caixa Banking Foundation, grant no. LCF/BQ/PI21/11830030; Junta de Andalucía under Plan Complementario de I+D+I (Ref. AST22_0001) and Plan Andaluz de Investigación, Desarrollo e Innovación as research group FQM-322; Project ref. AST22_00001_9 with funding from NextGenerationEU funds; the "Ministerio de Ciencia, Innovación y Universidades" and its "Plan de Recuperación, Transformación y Resiliencia"; "Consejería de Universidad, Investigación e Innovación" of the regional government of Andalucía and "Consejo Superior de Investigaciones Científicas", Grant CNS2023-144504 funded by MICIU/AEI/10.13039/501100011033 and by the European Union NextGenerationEU/PRTR, the European Union's Recovery and Resilience Facility-Next Generation, in the framework of the General Invitation of the Spanish Government's public business entity Red.es to participate in talent attraction and retention programmes within Investment 4 of Component 19 of the Recovery, Transformation and Resilience Plan; Junta de Andalucía under Plan Complementario de I+D+I (Ref. AST22_00001), Plan Andaluz de Investigación, Desarrollo e Innovación (Ref. FQM-322). "Programa Operativo de Crecimiento Inteligente" FEDER 2014-2020 (Ref. ESFRI-2017-IAC-12), Ministerio de Ciencia e Innovación, 15% co-financed by Consejería de Economía, Industria, Comercio y Conocimiento del Gobierno de Canarias; the "CERCA" program and the grants 2021SGR00426 and 2021SGR00679, all funded by the Generalitat de Catalunya; and the European Union's NextGenerationEU (PRTR-C17.I1). This research used the computing and storage resources provided by the Port d'Informació Científica (PIC) data center. State Secretariat for Education, Research and Innovation (SERI) and Swiss National Science Foundation (SNSF), Switzerland; The research leading to these results has received funding from the European Union's Seventh Framework Programme (FP7/2007-2013) under grant agreements No 262053 and No 317446; This project is receiving funding from the European Union's Horizon 2020 research and innovation programs under agreement No 676134; ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.