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Cherenkov Telescope Array: 120 telescopes and 6500 mirror segments to explore the very high-energy Universe

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Abstract. Throughout history, we humans have always looked up to the sky trying to understand the mysteries that the Universe reserved for us and to evolve in a knowledge that was unreachable here on Earth. Over time, we have developed, not only further understanding of the Cosmos itself, but also better tools that allow us to delve into physics questions that help science and society to grow. In this new era of technology, the Cherenkov Telescope Array (CTA), the next generation of ground-based gamma-ray telescopes, was born with the aim of unveiling unanswered enigma of the most violent and exotic sources in the Cosmos and to revolutionize our conception of the highest-energy Universe.

1. Introduction

In 1912, the Austrian physicist Victor Hess discovered, through diverse balloon flights, that the ionized particles density increased with the altitude V. F. Hess (1912). As a result of this investigation, Hess aptly concluded that there were charged particles arriving from outside the Earth's atmosphere, responsible for this ionization. By that time, their nature was still unknown and hence, the physicist Robert Millikan decided to name them *cosmic rays* R.A. MillikaN & G.H. Cameron (1926). However, we now know that they are not rays: cosmic rays are extremely energetic charged particles coming from the Universe -with energies usually much higher than those reachable in the man-made accelerators- that are composed of protons and Helium nuclei in 99%, whilst the remaining 1% are electrons, positrons, heavier nuclei, etc. Although undeniable important physics can be done observing cosmic rays, they cannot give us information about the sources that originated them. As consequence of their charge, they are deflected randomly by the interstellar magnetic fields in their way to Earth, erasing any opportunity to track back their origin. In order to reveal the sources capable of accelerating particles to such energies, we need to study the neutral products of those cosmic rays, the light they emit when they are accelerated or interact with matter within the sources: we observe gamma rays. Gamma rays are the most energetic electromagnetic radiation, covering a broad photon energy range -from approximately one mega-electronvolt (MeV)- so vast that it does not have a well-defined upper limit. Such energies cannot be explained through thermal emission, and so, we need to evoke non-thermal processes to explain the origin of gamma rays: this energetic light is produced by cosmic rays interacting with matter, magnetic or other photon fields in turbulent, violent and explosive environments. To be able to observe gamma rays, we need to search for extreme sources, such as the remnants of supernova explosions produced when the ejected material hit the environment, wind nebulae created by very fast rotating ultra-dense stars, known as pulsars, born as a consequence of the death of a massive star or supermassive black holes at the center of other galaxies that gobble up the surrounding matter and eject relativistic beams of particles moving almost at the speed of light.

2. Cherenkov Telescope Array

CTA will observe gamma rays with about 10 trillion times more energy than the light we can see with our naked eyes, from around 20 gigaelectronvolts (GeV) to 300 teraelectronvolts (TeV). Some radiation, like the visible light, can travel across the atmosphere down to the ground, but gamma rays interact with the nuclei in the Earth's atmosphere, preventing the most energetic electromagnetic radiation from reaching us. To detect high-energy gamma rays, scientists can make use of satellites, but they have small collection areas and therefore, they can only be used to detect energies up to GeV. At higher energies, the Imaging Atmospheric Cherenkov Telescopes (IACTs) dominate the exploration of gamma rays. This technique is the one applied by CTA and consists on the indirect detection of gamma rays: When a gamma ray arrives to the Earth's atmosphere and interacts with the nuclei there, it produces charged particles, specifically an electron-positron pair, if its energy is higher than 20 MeV. If these particles have also enough energy (higher than a "critical energy" of 86 MeV), they will give rise to photons again and these, in turn, can produce more charged particles, which can emit more light, and so on, triggering this way a particle cascade. It is known that there is nothing in the Universe that can move faster than the speed of light in a vacuum. However, in other mediums like water or even the air in the atmosphere, light moves slower and hence, there are particles that can overtake the speed of light in such mediums. And thus, a magic effect happens: when the charged particles of those cascades move faster than the speed of light in the air, they produce a very fast bluish light, called Cherenkov light. This light, whose existence was discovered by the physicist Pavel A. Cherenkov P. Cherenkov (1934), presents wavelengths between 300 and 500 nm, with a peak at around 320 nm, and lasts only a few nanoseconds, which prevents us from seeing it with our eyes. Our brain is not capable of processing such fast signal, for which we need to use extremely rapid and accurate cameras. The shape of the Cherenkov light around the track of the particle is a cone, similar to the sonic boom. The combination of all particles' contributions produces a full circle of Cherenkov light that reaches the ground and is captured by the telescopes. This light is rapidly processed by the electronics in the telescopes' camera which decide whether to record it or not following pre-programmed algorithms. The shape that the light leaves on the detectors of the camera provides valuable information regarding the primary gamma ray that initiated the particle cascade, such as its energy and direction Fig.1.

Therefore, by *detec1414ting* Cherenkov light, scientists can obtain information about the gamma rays and hence, about the sources that emitted them. CTA will apply this technique by means of 118 telescopes split into two arrays, one in the northern hemisphere in the Instituto de Astrofsica de Canarias' (IAC's) El Roque de los Muchachos Observatory (La Palma, Spain), also known as CTA-North, and another in the southern hemisphere in the European Southern Observatory's (ESO's) Paranal Observatory (Atacama Desert, Chile), called CTA-South (Fig.2) Thus, with two sites in both hemispheres, CTA will have access to the entire high-energy sky.

The study of gamma rays from Earth, the so-called ground-based gamma-ray astronomy, is actually a very young field that has still much science to explore. It was only 30 years ago, when the Whipple 10-m telescope, placed at the formerly known as "The Mount Hopkins Observatory", detected, for the first time, gamma rays at TeV energies coming from the Crab Nebula. Since 1989, the

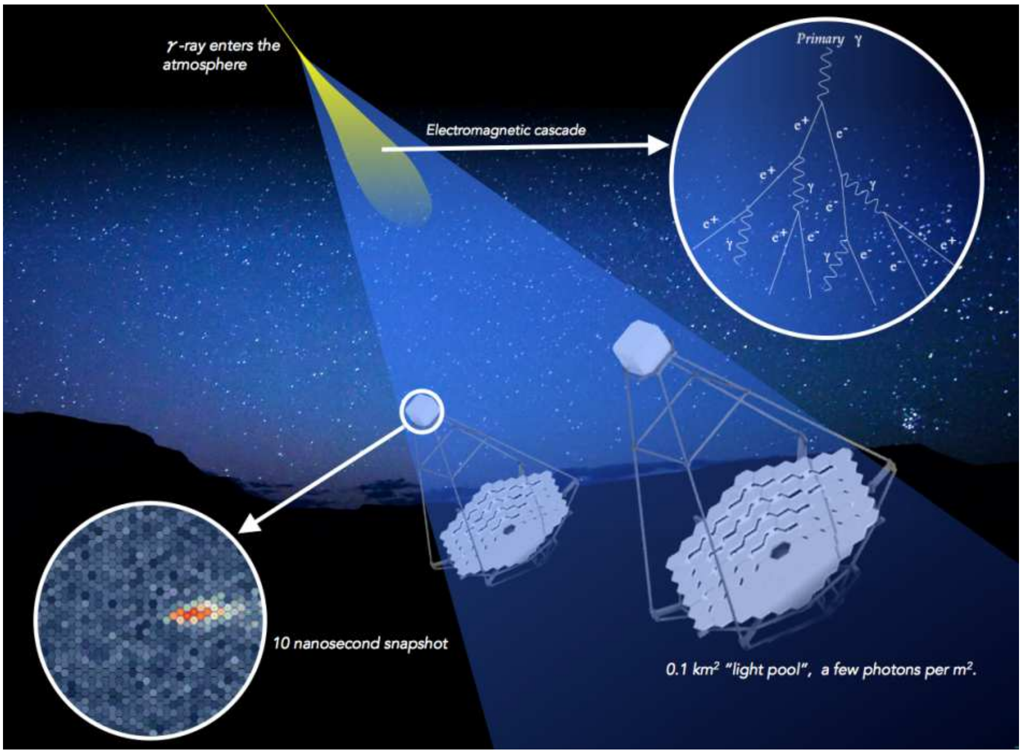

Fig. 1. Particle cascade and Cherenkov light captured by CTA telescopes. The image left by the Cherenkov light in the cameras is also shown. Credit: CTA Collaboration.

technique has thrived enormously, establishing definitely a new discipline with the detection of more than 150 new astrophysical sources and providing major impact results in the gamma-ray astronomy field and physics in general by the current major operative ground-based gamma-ray instruments: H.E.S.S. (with five telescopes near the Gamsberg mountain, Namibia), MAGIC (with two telescopes in La Palma, Spain) and VERITAS (with four telescopes in Arizona, US). CTA will take this discipline a step beyond both in technology and science, developing state-of-the-art telescopes and instrumentation: CTA will provide a wider energy range, from 20 GeV to 300 TeV, allowing it to reach high-redshifts and extreme accelerators; with at least 24 times more telescopes, the CTA observatory will significantly boost the detection area, increasing photon rate and providing access to the shortest timescales phenomena; placed in two sites, the observatory will have access to the entire sky and will enhance surveying capability, monitoring capability, and flexibility of operations; it will present better angular resolution and larger field of view (FoV) improving the ability of studying extended sources; it will have an improved energy resolution from former gamma-ray instruments, allowing it to look for so far unknown gamma-ray spectral features; CTA will improve the overall performance of current instruments, but especially important is its approximately 10 times better sensitivity (Fig.3).

With such unprecedented accuracy and sensitivity, CTA will be able to increase the list of known celestial objects with 1,000 new sources and to address some of the most intriguing questions in astrophysics. Moreover, CTA will not only give a completely new view of the high-energy sky, but it will also be the first world-wide observatory open to the

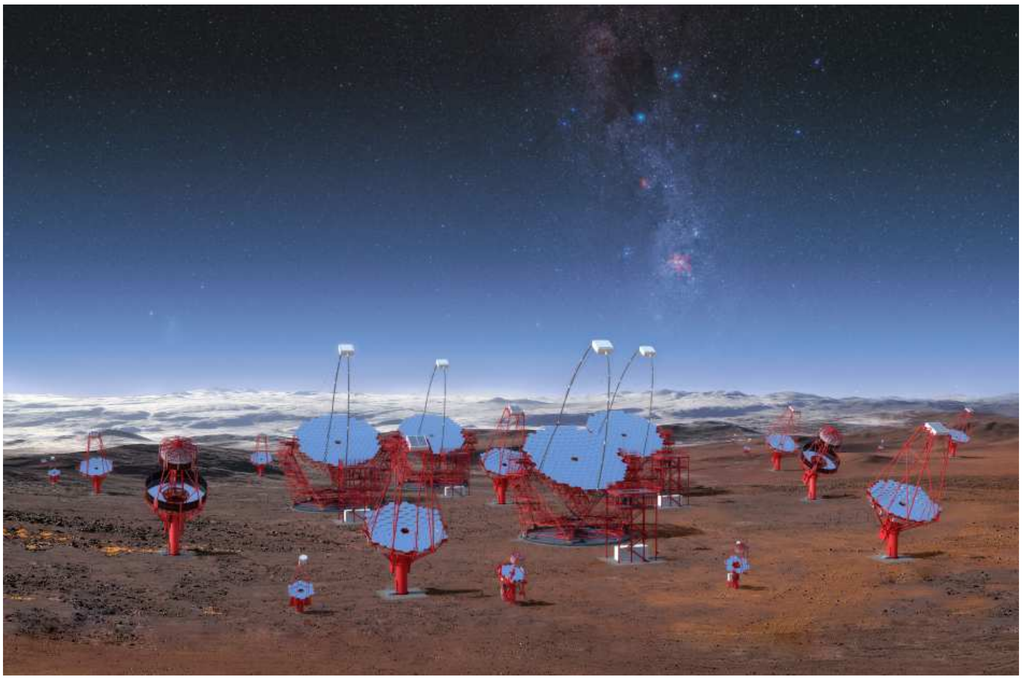

Fig. 2. Rendering of the center of CTA-South array at ESO's Paranal Observatory. The illustration is not an accurate representation of the final array layout but illustrates the enormous scale of the CTA telescopes and array itself. Credit: CTAO/M-A. Besel/IAC (G.P. Daz)/ESO.

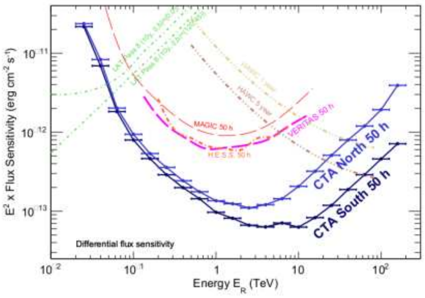

Fig. 3. CTA's differential sensitivity flux compared to current gamma-ray instruments. Credit: CTA Collaboration.

astronomical and particle physics communities, providing a unique resource of very high-energy data products and tools suitable for non-expert users. CTA will be therefore an unprecedented powerful and accessible observatory for the study of very high-energy gamma rays. It is already the evolution of gamma-ray astronomy.

In terms of science, with its superior performance, CTA is expected to expand the gamma-ray emitter catalogue tenfold, as mentioned before, and to even discover new physics, seeking to address a wide range of questions in astrophysics and fundamental physics, which can be gathered into three major study themes The CTA consortium (2019)

Understanding the origin and role of relativistic cosmic particles. Hess realized that we were being bombarded constantly by charged particles, but we still lack a full understanding on how and where they are produced. CTA aims to shed light on the sites of, and mechanisms for, cosmic particle acceleration in the Universe, as well as to understand the role that accelerated particles play in feedback on star formation and galaxy evolution. One of the main observational targets to disentangle these questions is the Galactic plane.

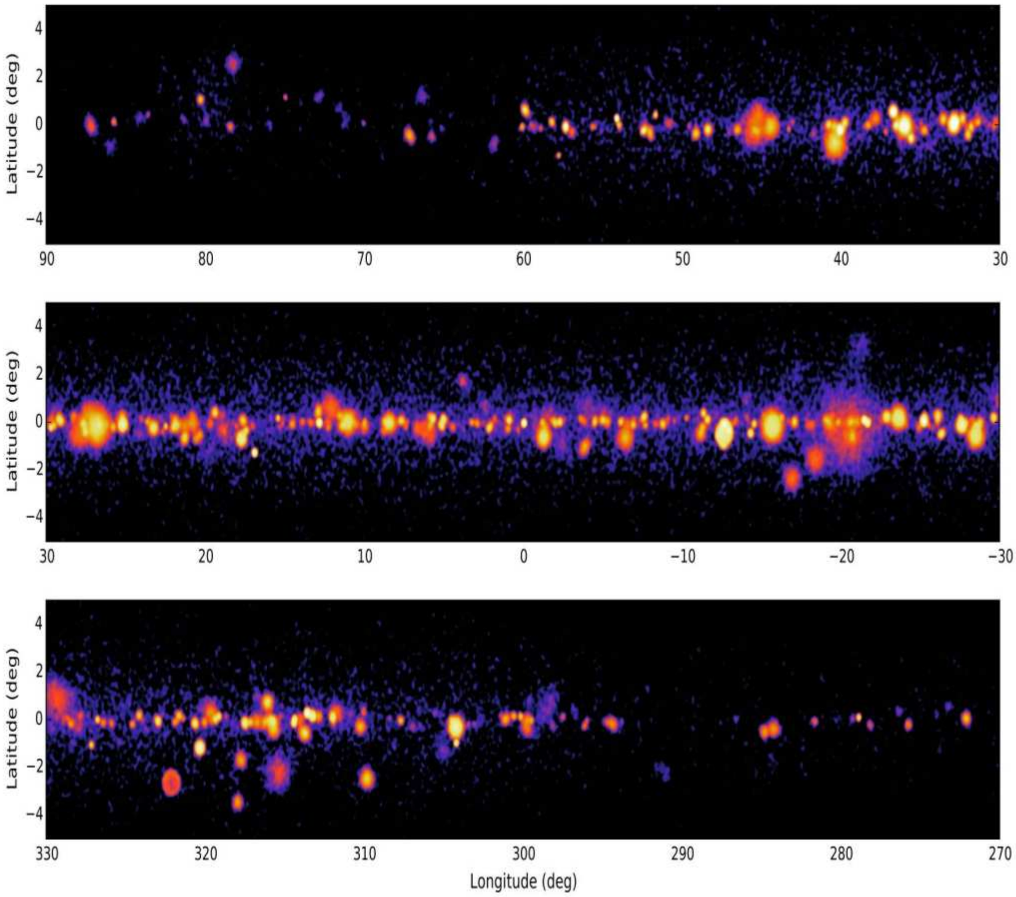

Fig. 4. Simulated sky map of the inner region of the galactic plan that CTA will obtain during the Galactic plane survey. Credit: CTA Collaboration.

Fig.4 shows a simulation of what CTA may observe during a survey of the Galactic plane region The CTA consortium (2019). Scientists estimate that CTA will obtain more than 400 individual gamma-ray sources, most of them never seen before by previous ground-based instruments or satellites. More sources, new detections, can provide priceless information regarding the physics that allow particles being accelerated to the highest energies and, with such large celestial objects catalogue, to finally understand the origin of cosmic rays. Are, for example, the supernova remnants responsible for the cosmic rays at petaelectronvolts (PeV) energies in our Galaxy? Especially important for this commitment will be the broad CTA energy coverage and angular resolution that will allow to map with an unprecedented accuracy.

Probing extreme environments. The most energetic electromagnetic radiation and cosmic rays can only originate in the most violent and extreme sources of our Cosmos, such as black holes or neutron stars. These compact objects are known to be born after the death of massive stars in supernova explosions and gamma rays are known to be emitted from their vicinity, for example within relativistic jets. However, the mechanisms that rule the gamma-ray emission are not completely understood. CTA will delve into these objects trying to understand the physical processes that work close to them, and the characteristics of the relativistic jets, winds and explosions that arise from these sources. Some types of these objects are known to be persistent gamma-ray emitters, whilst others, particularly interesting, produce gamma rays in an unpredictable way. The latter are the so-called "transients", for which an optimal multi-wavelength and multi-messenger alert network is needed to observe them in time. Galactic transients emitting jets have been detected in the GeV band but not at very high energies so far and hence, CTA is expected to give a new insight into the physical processes of these objects owing, among other features, to its low energy threshold of 20 GeV W. Bednarek (2013), E. de Oña Wilhelmi, et al. (2013), J. M. Paredes, et al. (1977).

Exploring frontiers in physics. Thanks to a major improvement in sensitivity and energy range, CTA will be able to study the most fundamental physics, including one of the biggest mysteries in science, the dark matter. Despite constituting great part of the total mass of the Universe, dark matter manifests only by its gravitational effects, since it has very little or no interaction with electromagnetic light or baryonic matter. CTA will seek to discover its nature and distribution in our Universe by looking to the gamma rays produced when dark matter particles (believed to be Weakly Interacting Massive Particles, or WIMPs) annihilate each other when they interact, leaving a singular shape in the gamma-ray spectrum. Well-supported theories predict the probability of these interactions as well as the best regions in the Universe to carry out observations, but we need to observe with telescopes as sensitive as CTA to increase the chances of major breakthroughs. Moreover, scientists will try to probe any deviation from the Einstein's theory of Special Relativity as well as the existence of axion-like particles, whose existence was postulated in 1977 R. D. Peccei & H. R. Quinn (1977) but not demonstrated yet. Insights in any of these topics would mean a revolution not only in gamma-ray astronomy, but also in particle physics, cosmology and in physics in general.

In order to achieve these science goals, three classes of telescopes are required to fulfill the aforementioned performance, including CTA energy range (20 GeV - 300 TeV): The Large-Sized Telescopes (LSTs), the Medium-Sized Telescopes (MSTs) and the Small-Sized Telescopes (Fig.5).

To cover the lowest sensitivity, below ˜150 GeV, CTA will have 4 LSTs located at the center of each CTA array. Each LST stands 45 meters tall and weighs around 100 tons, turning it into one of the biggest Cherenkov telescopes ever built. Despite its size, the LST will be extremely fast, capable of repointing anywhere in the observable sky in 20 seconds, especially crucial to avoid missing external transient alerts. Its mirror dish is 23-m diameter, with parabolic shape, and its camera has a FoV of 4.5^o. The latter is formed by 1855 photomultiplier tubes (PMTs), devices that transform the incoming light into electrical signal to be analyzed and stored afterwards. The prototype of the LST, the LST-1, was officially inaugurated in the CTA-North site in La Palma on October 2018, in a ceremony that joined more than 200 guests from around the world, with distinguished speakers like the Nobel Prize for Physics in 2015 Prof. Takaaki Kajita and the Spain's first astronaut and Minister of Science, Innovation and Universities, Pedro Duque. The LST-1 is the only prototype placed in a CTA site and after a critical revision of the design, which is currently ongoing, it is expected to become the first CTA telescope. On the other hand, to capture the CTA's core energy range (between 150 GeV and around 5 TeV), CTA-North will be composed of 15 MSTs, while CTA-South will host 25. With a bit less than 30 meters tall and a weight of 82 tons, the MST will support a 12-m modified Davies Cotton dish that focus the light in a PMT camera. So far, there are two cameras designed for this telescope in charge of the middle energies: the FlashCam with around 1750 PMTs and ˜7.5^o of FoV, and the NectarCam with ˜1850 PMTs covering a FoV of 8^o. One MST prototype was installed near Berlin in 2012 and is currently under testing. A dual-mirrored version of the MST, the so-called prototype Schwarzschild-Couder Telescope (pSCT), was proposed as

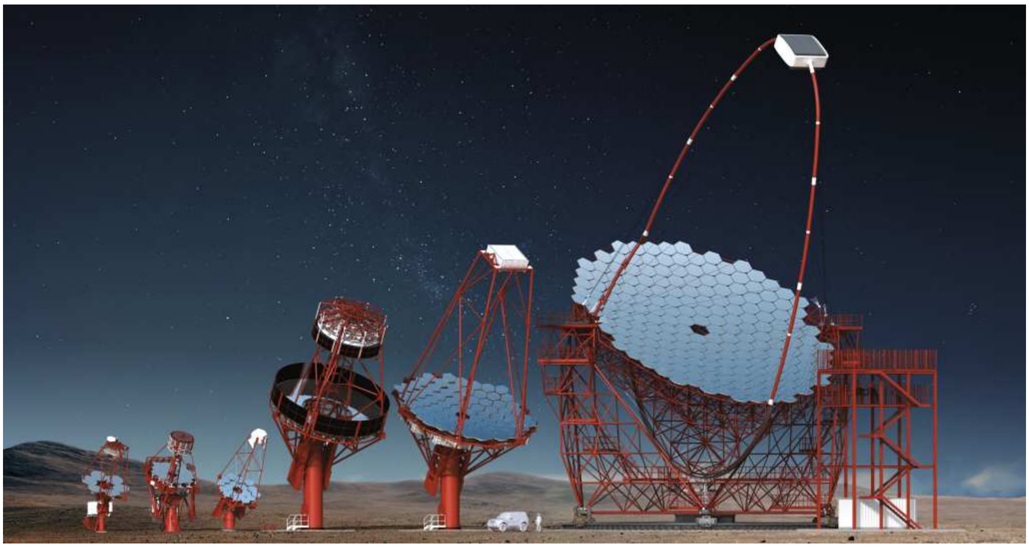

Fig. 5. Rendering showing all CTA telescopes' design proposals. From left to right: the SST-2M GCT, SST-2M ASTRI, SST-1M, MST-pSCT, MST and LST. Credit: Gabriel Prez Daz/IAC.

an alternative for this energy band. The dual-mirror system is theoretically expected to provide better focus of the light and hence, greater imaging detail, improving the detection especially of faint sources. The prototype of the SCT telescope has recently been inaugurated in the Whipple Observatory in Arizona on January this year. And finally, the highest energies above 5 TeV will be covered by the SSTs, which will outnumber all the other telescopes with 70 of them in the southern hemisphere array, spread out over several square kilometers. There are three proposals for the SST's design, one single-mirror and two dual-mirror designs. The SST-1M is the single-mirror design with 4 meters diameter Davies Cotton reflector, which weighs ~9 tons and covers a ~9^{o} FoV with a silicon photomultiplier (SiPM) camera composed of 1296 pixels. The SiPM, like PMTs, are detectors in charge of transforming the light into electrical signal. The SST-2M GCT, a dual-mirror low-mass design with only ~8 tons, has a 4 meters diameter primary and a 2 meters secondary mirrors. Its camera is also composed of SiPM, with a total of 2048 pixels, covering a FoV of ~9.2^{o}. Finally, the ASTRI telescope makes used of a dual-mirror Schwarzschild-Couder configuration, weighs 19 tons and has a camera of 2368 SiPMs, which allows it to cover a FoV of ~10^{o}. It has a 4.3 meters diameter primary mirror and a 1.8 meters secondary mirror. It was in 1905, when the German physicist Karl Schwarzschild proposed a design for a two-mirror telescope to eliminate much of the optical aberration. Although this idea was latter enhanced by Andre Couder in 1926, was not used as it was considered too complicated. Almost 80 years later, in 2007, a study at the University of California Los Angeles (UCLA) showed that this design could be applied for IACTs. Thus, the idea was used in the ASTRI telescope, which was inaugurated in September 2014 at the Serra La Nave on Mount Etna (Sicily, Italy), becoming the first Schwarzschild-Couder telescope to be built and tested. In October 2016, the ASTRI prototype demonstrated the viability of this kind of design by showing a constant point spread function of a few arcminutes.

Fig.6 shows the North Star observed by ASTRI with different offsets (from 0^{o} to 4.5^{o}) with respect to the central optical axis of the telescope. The recorded images have the same angular size, confirming that the point spread function keeps invariable E. Giro, et. al. (2017).

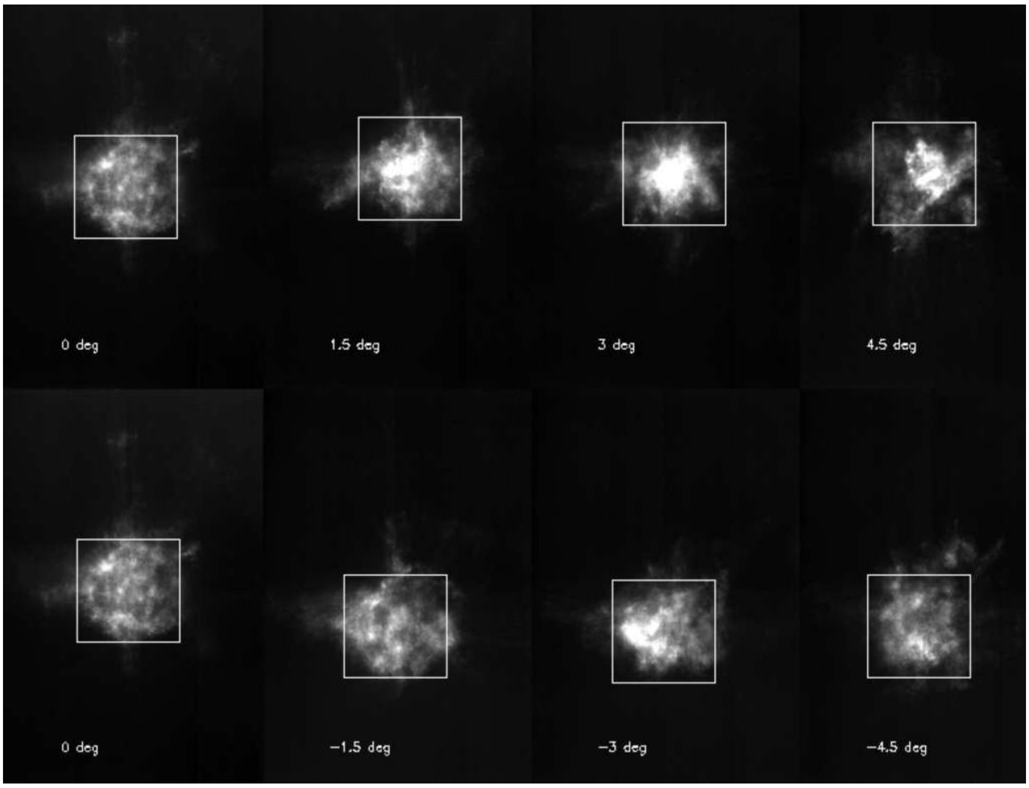

Fig. 6. Images of Polaris (North Star) observed by ASTRI with different offsets from the optical axis of the telescope. E. Giro, et. al. (2017)

All these differences (the height, the weight, the type of detectors, the FoV, even the design) will make the CTA telescopes capable of combining to observe the very high-energy sky in an unprecedented way. However, there is something that remains unchanging for all prototypes: all of them have tessellated mirrors. The LST's 23-m diameter reflector is formed by more than 200 hexagonal facets; MST covers its 12-m diameter dish with ˜90 hexagonal segments, whilst the alternative pSCT uses 48 mirror panel modules for its primary dish and 24 for the secondary one; the SST-1M's mirror is divided into hexagonal facets, the SST-2M GCT's primary and secondary mirrors are divided into 6 petal-shaped segments each of them, and finally, ASTRI presents its primary 4.3 m mirror segmented into 18 hexagonal facets, while its 1.8 m secondary mirror is the only monolithic. The observatory will manage more than 6500 mirror segments essential to focus the light and capture it. The evident questions now would be why CTA telescopes do not make use of single mirrors and who had the idea of "breaking" the mirrors to make science.

In gamma-ray astronomy we need big telescopes because low-energy gamma rays produce small particles cascades with low amount of Cherenkov light and therefore, we have to build large mirrors capable of capturing every single Cherenkov photon, so that we have enough information. Moreover, along with the advances in detector technology, the instrument becomes more sensitive to faint sources. This condition does not apply only to the gamma-ray regime: in the visible band, if we double the size of the telescope's mirror, we would be able to see objects with certain brightness twice as far away. Therefore, larger mirrors do definitely play a key role in astronomy. However, there is an intrinsic problem in this size evolution: fabricating large pieces of glass is not an easy task. It is not just creating a plate of glass, but this must have certain curvature, adapted to the optics of the telescope, would need to be manufactured, tested, shipped and installed, while preventing any damage on it. The LST's 23-m diameter dish has a reflector surface of 400 m^2, which corresponds to almost two times the area of a single tennis court. Fabricating and moving a monolithic mirror of such dimensions is just inconceivable. Luckily, in 1932, an Italian astronomer came up with the solution of segmented mirrors: his name was Guido Horn d'Arturo. Guido Horn was born in 1879 in the coastal city of Trieste and graduated in 1902 in the University of Vienna with a thesis on cometary orbits. He started his research career at the Observatories of Trieste and later Catania, but moved to Bologna after the end of the First World War. There, he assumed the position of Director of the Observatory as well as Professor in Astronomy in the University in 1921. He spent more than 30 years in these positions, working on different investigations, including the construction of a large reflective surface made of a mosaic of hexagonal mirror elements. This instrument, whose project initiated in 1932, is still located in the Torre della Specola in Bologna. This fruitful scientific activity was only interrupted for seven years, between 1938 and 1945, due to the shameful Jewish persecution lived during the Second World War (Fig.7)

In one of his works, published in 1950 G. Horn D'Arturo (1950), Guido Horn explained that the main problem to build large mirror surfaces was that the thickness of the mirror had to be proportional to the diameter: in large mirrors, if the thickness is too thin, it will lose the given shape conferred by the smoothing, while if it is too thick, it could cause deformation of the reflecting surface even if the material is very viscous. Problems that a new era in astronomy ahead of him could not abide. His "Telescopio a tasselli", as he originally called the first segmented telescope in human history composed of 61 hexagonal facets of about 1.8 meters, was an undoubted revolution in his time and for the coming multi-wavelength astronomy: not only CTA will make use of this technique, but other big projects such as the Keck telescopes, the future ELT or even space telescopes such as the James Webb already do or will. Moreover, all preceding ground-based Cherenkov telescopes made use or still operate thanks to segmented dishes, which allowed scientists to improve the technique. Actually, the technology used to manufacture each ASTRI's mirror segment is a modified version of the so-called glass cold slumping process G. Pareschi, et al. (2008) already developed years ago for the second MAGIC telescope and also adopted for the MST's mirror. In this delicate process, the thin glass foils are bent through thermo-forming processes, then assembled in a stiff and lightweight "sandwich" structure with the aid of a honeycomb core, and finally coated a high reflective layer (R. Canestrari, et al. (2013) (Fig.8).

Fig. 7. Guido Horn d'Arturo with one of his segmented mirrors.

At the beginning, Guido Horn had also to face problems with his "Telescopio a tasselli". He had to deal with the spherical aberration, an optical problem by which the external parts of a spherical mirror tend to focus the light rays closer than they should, by a factor of half of the mirrors radius. He was able to overcome this problem by moving some mirrors ahead according to the distance from the center to make the focal plane of all of them coincident, correcting the optical aberration and obtaining images of stars with good spatial reso-

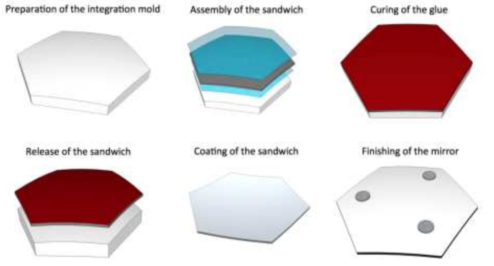

Fig. 8. Manufacturing process of the ASTRI's segmented mirrors. R. Canestrari, et al. (2013)

lution. The reduction of this optical aberration was in fact only possible because he was working with a tessellated mirror. Nowadays, we still need to address this and other challenges, even related to the use of segments, such as the misalignment, that could blur the images. The facets of Cherenkov telescopes can suffer from misalignment due to different causes, like extreme weather conditions (for example, high-speed wind gusts or ice between the facets as a result of extreme temperature changes) or even the self-weight of the structure at certain zenith positions. Fortunately, technology has evolved from Guido Horn's epoch, and many tasks are now automatized: to solve misalignment, several actuators are placed in the back of each facets, moving them with a precision of less than tens of micrometers. This technology development provides CTA with an incredible pointing accuracy. The contribution of Guido Horn d'Arturo was recognized by the ASTRI team, led by the Istituto Nazionale di Astrofisica (INAF), in a ceremony on November 10th 2018 in which the prototype telescope was dedicated to the Italian astronomer, following a proposal of the Italian Astronomical Society (SAIt). The moving ceremony gathered Horn's family members, along with local authorities and special guests that dedicated some words to Guido Horn's work and its relevance for the ground-based gamma-ray astronomy field.

Guido Horn's legacy is unquestionable, he certainly inspired the following generations of astronomers, and we owned him part of the astronomy evolution. Science grows up with the creativity and great effort of many people around the world investigating in different fields that combine their results to overcome new challenges. CTA, a global collaboration proud of its diversity with more than 200 institutes from 31 countries, also works to play an important role in the development of the future of gamma-ray astronomy and physics in general, supported by major breakthroughs achieved in the past and motivated by the exceptional achievements still to come. It is our turn to inspire new generations of scientists.

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