

Cherenkov Telescope Array: the World's largest VHE gamma-ray observatory

Roberta Zanin on behalf of the CTA Observatory, CTA Consortium and LST Collaboration^{a,*}

^aCherenkov Telescope Array Observatory gGmbH,
Via Gobetti, Bologna, Italy
E-mail: Roberta.Zanin@cta-observatory.org

Very-High Energy (VHE) gamma-ray astroparticle physics is a relatively young field, and observations over the past decade have surprisingly revealed almost two hundred VHE emitters which appear to act as cosmic particle accelerators. These sources are an important component of the Universe, influencing the evolution of stars and galaxies. At the same time, they also act as a probe of physics in the most extreme environments known - such as in supernova explosions, and around or after the merging of black holes and neutron stars. However, the existing experiments have provided exciting glimpses, but often falling short of supplying the full answer. A deeper understanding of the TeV sky requires a significant improvement in sensitivity at TeV energies, a wider energy coverage from tens of GeV to hundreds of TeV and a much better angular and energy resolution with respect to the currently running facilities. The next generation gamma-ray observatory, the Cherenkov Telescope Array Observatory (CTAO), is the answer to this need. In this talk I will present this upcoming observatory from its design to the construction, and its potential science exploitation. CTAO will allow the entire astronomical community to explore a new discovery space that will likely lead to paradigm-changing breakthroughs. In particular, CTA has an unprecedented sensitivity to short (sub-minute) timescale phenomena, placing it as a key instrument in the future of multi-messenger and multi-wavelength time domain astronomy. I will conclude the talk presenting the first scientific results obtained by the LST-1, the prototype of one CTA telescope type - the Large Sized Telescope, that is currently under commission.

37th International Cosmic Ray Conference (ICRC 2021)
July 12th – 23rd, 2021
Online – Berlin, Germany

*Presenter

1. Introduction

Very-High Energy (VHE) gamma-ray astroparticle physics is a relatively young, and rapidly evolving field of research exploring our Universe at the most extreme energies: **Very-High Energies (VHEs)** mean above few tens of GeV up to hundreds of TeV.

Established with the discovery of the first **VHE** emitter, the Crab Nebula, in 1989 by the Whipple Observatory [1], the field has witnessed a remarkable range of exciting results over the past decades. On one hand, **VHE** observations have surprisingly revealed more than two hundreds **VHE** emitters which appear to act as cosmic particle accelerators. These sources are an important component of the Universe, influencing the evolution of stars and galaxies. At the same time, they also act as a probe of physics in the most extreme environments known - such as in supernova explosions, and around or after the merging of black holes and neutron stars. On the other hand, **VHE** observations have provided a new tool to study specific aspects of very different disciplines, such as dark matter or cosmology, thanks to the observable imprints left by the self-annihilation of dark matter particles or the interaction of gamma rays with either exotic particles or lower-frequency background photons. This led to the establishment of new fields of research at the intersection of these disciplines, such as, for instance, the gamma-ray cosmology.

The advent of the multi-messenger astronomy has strengthen even further the importance of this fairly new window of exploration. It is only the exchange and the combination of data from different messengers and across the whole electromagnetic spectrum, up to the most extreme energies, that can provide deep insights into the most violent phenomena ever observed.

Since the Earth's atmosphere is not transparent to gamma rays, they can be directly detected only by space-born instruments. However, beyond few hundreds of GeV the currently existing satellites, over their integrated life cycles, do not provide adequate statistics for detailed precision studies. The **VHE** astronomy, therefore, mainly relies on indirect detection techniques by ground-based telescopes that detect the products of the secondary charged particle cascades (dubbed as **Extensive Air Shower (EAS)**) produced when a gamma ray strikes the Earth's atmosphere. There are two techniques that have been proven successful: the particle sampling arrays and the **Imaging Atmospheric Cherenkov Telescopes (IACTs)**. The latter image the a-few-nanosecond timescale flashes of Cherenkov radiation generated by the cascade of secondary relativistic charged particles while travelling in the atmosphere with a velocity higher than the speed of light in the air. **IACTs** are a special kind of optical telescopes that collect the **EAS**-generated Cherenkov light (peaking at around 350 nm) into large segmented reflector surfaces that, in turn, focalize it into a pixelized, high-speed camera. At the focal plane, an image of particle showers (i.e., an event) is formed allowing for the estimation of the direction and the energy of the primary gamma rays. With the third generation of **IACTs**, consisting of three major facilities: **MAGIC**, **H.E.S.S.** and **VERITAS**, the imaging Cherenkov technique is well-established and has now reached a level of maturity that makes possible the transition from an experiment-like to an observatory-like way of operating.

So far, the existing **VHE** experiments have provided exciting glimpses, but often falling short of supplying the full answer. A deeper understanding of the TeV sky requires a significant improvement in sensitivity at TeV energies, at least a factor 2 larger **Field of View (FoV)** with respect to the currently running facilities, as well as an arc-minute angular resolution and energy resolution of the order of 10%. Broadening the energy coverage with respect to the existing ground-based facilities

significantly increases the exploration phase space. At the lowest edge, reaching 20 GeV energy threshold allows to access the Universe down to its origins (i.e. close to the Big Bang). This is, in fact, about the energy at which the Universe turns back transparent to gamma rays since the absorption due to pair production of gamma rays (of higher energies) with infrared-to-optical photons from the [Extragalactic Background Light \(EBL\)](#) becomes negligible. This absorption is energy dependent: if the horizon for 1 TeV gamma rays is about 100 Mpc, it increases by a factor 10 for 100 GeV gamma rays. On the other hand, at the highest edge of the energy range, an extension up to several hundreds of TeV would push the exploration in a still poorly studied region of the electromagnetic spectrum. A more in depth study of the early Universe requires also a remarkable advance in the detection capabilities of violent, transient phenomena. This translates into improved sensitivity for minute-to-day timescale events, a largest possible sky coverage, as well as a couple of tens of seconds response to external alerts: being pointing instruments, [IACTs](#) rely on triggering alerts of flaring sources coming from lower frequencies observations.

The next generation [VHE](#) gamma-ray facility, the [Cherenkov Telescope Array Observatory \(CTAO\)](#), is the answer to this need. Conceived as a large array of [IACTs](#), it is not simply the brutal-force implementation of many telescopes of the same kind. Instead, it foresees three different telescope types, each of which optimized in its specific energy range, in two arrays that are operated as a single astronomical observatory. The three types of telescopes provide, cost-efficiently, the desired wide energy coverage (20 GeV-300 TeV), whereas the two arrays the largest sky coverage. At the lowest energies, gamma rays are abundant but their Cherenkov flashes very faint, hence, a small number of telescopes with large reflective surfaces (light-collection areas) is sufficient. This led to the design of the [Large-Sized Telescope \(LST\)](#) with a parabolic optical design and a reflective surface of 23 m diameter. Conversely, at the highest energies, gamma-ray photons are rare but their Cherenkov light flashes very bright, hence many telescopes are needed to cover a large detection area, but their light collection area can be small. This led to the design of the [Small-Sized Telescope \(SST\)](#), a rather small [IACT](#) compared with the existing ones with a reflective surface of 4.3 m diameter, but cost-effective. [Medium-Sized Telescopes \(MSTs\)](#) are [CTAO](#) workhorses optimized for the core [VHE](#) range, i.e. the TeV range, with a reflective surface of 12 m diameter and the same optical design as [H.E.S.S.](#) and [VERITAS](#). Table 1 shows the main parameters of the three type of [CTAO](#) telescopes.

The design of the array layout (i.e., the arrangement of the telescopes on the ground), in its full-scope configuration, foresees three concentric sub-array layouts, one per telescope type, with an increasing averaged distance between neighboring telescopes when moving outwards: at the centre, a small (few units), and compact (averaged telescope distance of about 80 m) sub-array of [LSTs](#), surrounded by few tens of [MSTs](#) distributed on an area smaller than 1 km², and with an average distance between neighboring telescopes of about 160 m and the outer ring of [SSTs](#) covering the largest possible detection area with a 210-250 averaged distance between neighboring telescopes.

The design phase of the [CTA](#) project, after more than a decade, is now coming to its end. The construction scope of the [CTA](#) Observatory has been approved by the [Board of Government Representatives \(BGR\)](#) on June 24, 2021. This is an important milestone that will lead, within the next year, to the establishment of the final legal entity, the [CTAO European Research Infrastructure Consortium \(ERIC\)](#), hence to the official start of the Construction phase. The latter is expected to last at least 5 years. The [CTA](#) Observatory is geographically distributed with the Headquarters

	LST	MST	SST
energy range of optimization	20-150 GeV	0.15-5 TeV	5-300 TeV
optical design	parabolic	Davies-Cotton	Schwarzschild-Couder
primary dish diameter	23 m	12 m	4.3 m
focal length	28 m	16 m	2.15 m
total weight	100 tonne	82 tonne	17.5 tonne
type of camera sensors	PMTs	PMTs	SiPMs
number of pixels	1855	1855 (NectarCam) 1764 (FlashCam)	2048
camera FoV	4.3°	~7°	8.8°

Table 1: Main parameters of the three types of CTAO telescopes. The table is split into three sections: the first one refers to the driving energy range considered for the optimization of the design, the second section refers to mechanical and optical parameters, whereas the last one to the camera parameters.

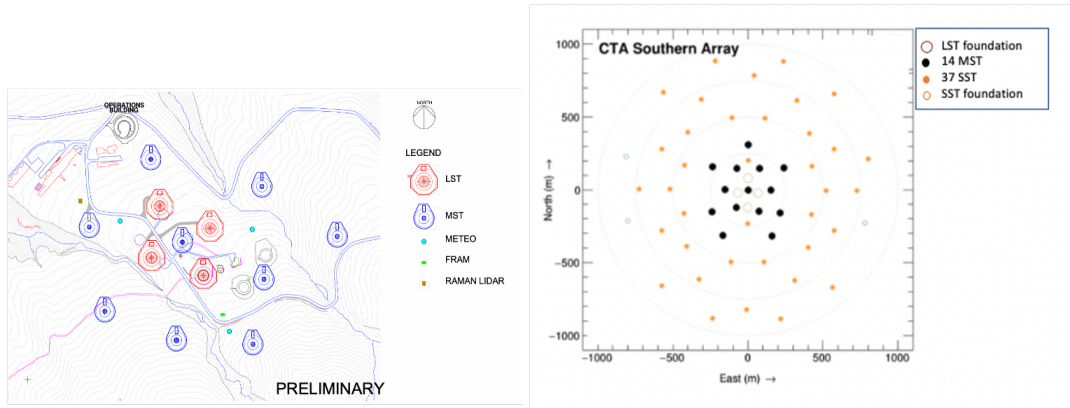


Figure 1: Preliminary layouts of the two CTAO arrays of the Alpha Configuration. On the left: Northern Array in the Canary island of La Palma (Spain). On the right: Southern Array at Paranal (Chile).

located in Bologna (Italy), a Science Data Management Centre in Zeuthen (Germany) and two Observation Stations, one located in the Canary island of La Palma (Spain) and the other one in Chile. The corresponding two arrays are dubbed as CTAO Northern Array and CTAO Southern Array.

In the initial configuration, called *Alpha Configuration*, the CTAO Northern Array includes 4 LSTs and 9 MSTs, covering an area of about 0,25 km², in the Observatorio Roque de los Muchachos (ORM) at about 2200 m asl. Whilst the CTAO Southern Array consists of 14 MSTs and 37 SSTs located in the Atacama desert, 11 km southeast of the ESO Paranal Observatory. The footprint of the Southern Array is much larger than the Northern one with an overall area of about 3 km². The difference in size between the two arrays is justified by a temporary specialization of the two observation stations in terms of core science cases: the Southern one focuses on the Galactic targets being better visible from the Southern hemisphere, leaving to the Northern one the extra-Galactic sky as a priority. The latter is dominated by transient phenomena from sources at cosmological distances, thus requiring the lowest possible energy threshold to compensate the EBL absorption.

This is guaranteed by the presence of the 4 **LSTs**. On the other hand, the Southern Array is required to reach the highest energies, at hundreds of TeV, to be able to establish the existence of PeVatrons, i.e., astrophysical sources able to accelerate cosmic rays up to the most extreme energies in our Galaxy (PeV energies), thus producing a factor ~ 10 less energetic gamma rays.

The layouts of the two **CTAO** arrays for the *Alpha Configuration* are illustrated, in their preliminary fashion, in Figure 1. A detailed description of the layout optimization process can be found in [4].

CTA will be the next generation gamma-ray detector showing a paradigm change also in terms of operation of this kind of facilities. It will determine the transition between experiments built and operated by international collaborations using proprietary software and data formats, to an astronomical observatory that will deliver data to the whole scientific community. As such, **CTAO** will be a proposal-driven observatory where the observing time can be requested by submitting either Standard Proposals or **Key Science Projectss** (**KSPs**) in response to an **Announcement of Opportunity** (**AO**) call. The latter will be issued at least once per year. The evaluation of the proposals, performed by a committee of external members, i.e., the **Time Allocation Committee** (**TAC**), will be based only on scientific merit. The great most of the **CTAO** observing time is reserved to scientists belonging to **CTAO ERIC** member states, although a small fraction will be open to worldwide researchers. The latter is dubbed as **International Community Observing Time** (**ICOT**).

The observatory will then calibrate and reduce the data [2]: only the event lists with their associated **Instrument Response Functionss** (**IRFs**) (dubbed, in **CTA** jargon, as Data Level 3 - **DL3**), will be released together with a set of science tools that will allow to analyze them. All data will become publicly available with no restrictions after one year of proprietary period.

2. CTAO performance

The **CTAO** arrays of the *Alpha Configuration* are expected to show a significant leap in sensitivity with respect to the currently existing facilities of the same kind and over the entire energy range. In particular, the on-axis differential sensitivity for 50 hr of observations will be a factor 5 to 10, depending on the specific array and the energy range, better than the **MAGIC/H.E.S.S./VERITAS** one, as shown in Figure 2. Even more significant it will be the boost in terms of off-axis differential sensitivity: the gamma-ray **FoV**¹ of **CTAO**, when using sub-arrays that do not include **LSTs**², is about 3.5° . The **CTAO** arrays will also display a factor 2 improvement in angular resolution³ with respect to **MAGIC/H.E.S.S./VERITAS**. This will translate into a sub-arcminute resolution: the best resolution in the high- and very-high energy gamma-ray band in the world.

When considering the **CTAO** arrays in the context of existing or future external facilities, we would need to consider the gamma-ray instruments characterized by an overlapping energy range. In particular,

- **in the sub-TeV energy range**, between 20 GeV and ~ 1 TeV, **CTAO** overlaps with satellites, in particular with *Fermi-LAT* that is still in operation. **CTAO** outperforms this space-born

¹The gamma-ray **FoV** is defined as

²**LSTs** are characterized by a smaller optical **FoV** (see Table1) since their driving science cases are transient and cosmological sources, both expected to mainly show a point-like emission.

³The angular resolution is defined as 68% containment radius.

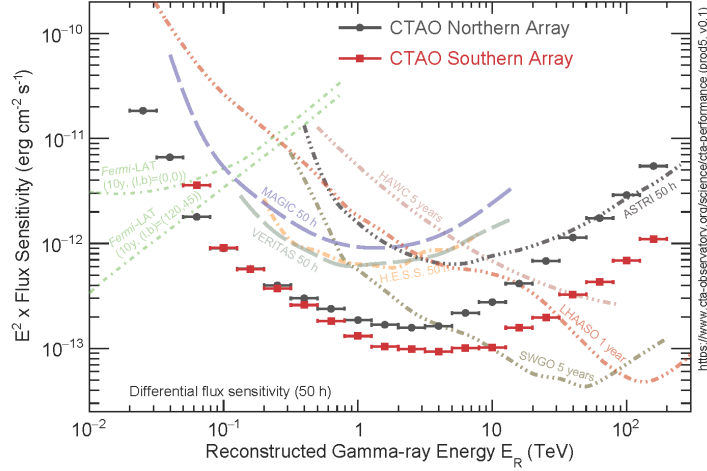


Figure 2: On-axis differential flux sensitivity for point-like sources of the two CTAO arrays compared to that of external facilities with an overlapping energy range.

telescope for long-term exposures (i.e. more than 10 hr), at energies larger than about 50 GeV. On short time scales, from minutes to days, instead, CTAO is more than 10^3 (10^6) at 25 GeV (at 250 GeV) times more sensitive than *Fermi*-LAT, as shown in Figure 3.

- **in the TeV and multi-TeV energy range** CTAO overlaps with particle array detectors, which IACTs, and, in particular, CTAO, are fully complementary with. Whilst, CTAO is a precision instrument with unprecedented angular and energy resolutions that allow to perform detailed precision studies, the particle shower arrays, with their larger detection area, and bigger FoV, can survey more efficiently the sky at the highest energies, above several tens of TeV.

The performance plots shown in this work are derived from detailed Monte Carlo (MC) simulations. The MC simulations are similar to the ones presented in [3], but obtained using *Corsika* program version 7.7100, an updated detector model of the CTAO telescopes, and optimized array layouts (the so-called ‘Production 5’ or ‘Prod 5’). These are state-of-art results obtained with the standard reconstruction algorithms including Hillas parameters, and Boost Decision Tree (BDT) algorithms for the estimation of the event direction, as well as its probability of being a gamma ray [3]. However, there is still quite some margin for improvement by using more advance analysis techniques, like for instance the event-type based analysis, that is currently under evaluation [5]. The latter consists in dividing the events into sub-samples based on their reconstruction quality. These sub-samples are treated as independent observations, each of which with its own IRF. Several purely deep-learning driven algorithms for the full-event reconstruction are also under investigation [6–9].

In reality, CTAO performance will suffer from the constant changes of the Earth atmosphere being it integral part of IACTs. Different atmospheric conditions, such as clouds, can reduce the fraction of Cherenkov photons produced in EASs that reach the telescopes, affecting in turn their performance. CTA scientific community is already getting prepared by studying in detail the impact of the various atmospheric conditions on CTAO performance. The results are presented in [10].

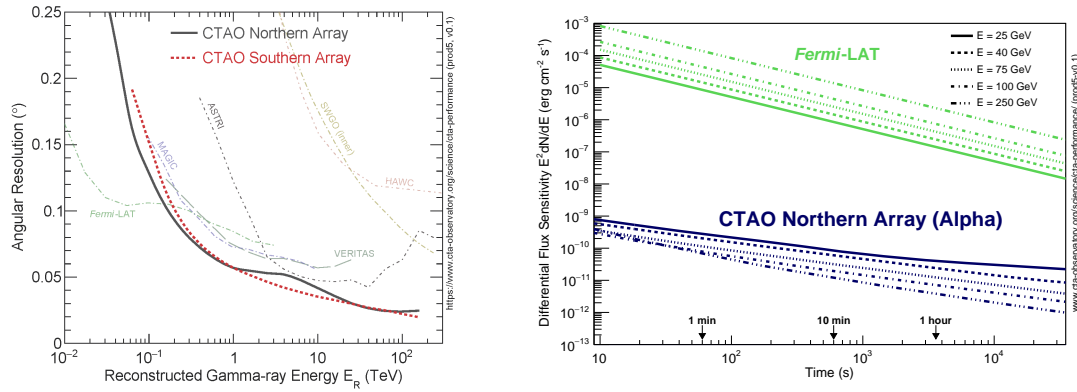


Figure 3: *On the right:* Angular resolution of CTAO compared to other existing and future facilities. On-axis differential flux sensitivity for point-like sources of the two CTAO arrays compared to that of external facilities with an overlapping energy range. The bump in the angular resolution curve of the Northern Array at around 5 TeV is connected to the smaller FoV of the LSTs with respect to that of the MSTs: it indicates the transition from events with a large multiplicity including also LST images to events with MST images only. *On the left:* Differential flux sensitivity at different energies as a function of the observing time for the CTAO Northern Array, compared to the Fermi-LAT one.

3. Science Goals

Transient phenomena have been always included in the CTA core science program because related to the most extreme, violent events in our Universe. In addition, time-domain astronomy at TeV energies is a field that encloses a huge discovery potential given the unprecedented sensitivity on short time scales that CTA will display. However, in this historical moment, where the multi-wavelength astrophysics has reached its apex - with the spread of observatories that release data openly, and the proliferation of data format standards, and common software libraries that allow to analyze and combine data of any frequency -, and the multi-messenger has given birth thanks to detection of the electromagnetic counterparts of Gravitational Waves (GWs) and UHE neutrino events, the transient science case of CTA has strengthen, if possible, even further. The three main source classes in this context are: Gamma Ray Bursts (GRBs), GW and UHE neutrino follow-up observations. The prospects for these three science cases have been computed following the same approach: first a synthetic source population has been created based on open-source theoretical codes (*POSITIVE* [11] for GRBs, *FIRESONG* [12] for neutrino events and *GW COSMOS* [13] for GW events), then the gamma-ray emission from these simulated sources has been estimated based on phenomenological assumptions, and finally this emission has been convoluted with the CTAO IRFs to simulate the CTAO response. The obtained simulations allow to estimate the detection rate for CTA that, however, depends on several different parameters of either observational (latency from the alert receipt, zenith angles, geomagnetic field strength, ...) or intrinsic physical nature (viewing angles, luminosity, source density). The exploration of the parameter phase space for the three distinct cases is presented in detail in [11, 14, 15], but as a summary, the CTA detection rate for GRBs is expected to be about 2 per year [16]. In order to increase the chances of detection of this kind of rare events a lot of attention is being paid to the optimization of the observational strategy,

in particular, to the pointing pattern & cadence in order to cover the largest total alert uncertainty region guaranteeing the minimum exposure time to achieve a potential 5σ detection [13, 17].

The legacy science program for CTAO includes few surveys [18], in particular:

- **the Galactic Plane Survey (GPS)**, an entire scan of the Galactic plane up to $\sim 5^\circ$ in latitude with a sensitivity spanning around 5 mCrab.
- the Galactic Centre Survey that partially overlaps the GPS but provides deeper observations (with a sensitivity down to 2 mCrab) of a 20deg^2 degree region around the Galactic Centre.
- the **Large Magellanic Cloud (LMC)** Survey that can be carried out with 10 distinct pointings from the Southern Array.
- the extra-galactic survey that will perform the first unbiased scan of the **VHE** sky. As such it hides a huge discovery space. The aim of this survey would be to cover 25% of the sky with a sensitivity of about 5 mCrab.

These surveys will allow CTA to perform, for the first time at TeV energies, unbiased source population studies. CTA capabilities on this topic were addressed by producing full-sky simulations of the GPS and of an ad-hoc synthetic population of AGNs.

A full-sky simulation of the CTA GPS is shown in Figure 4. The considered sky models include a synthetic population of **Pulsar Wind Nebulae (PWN)**, one of **SuperNova Remnants (SNRs)** that comprises all their evolutionary stages and also their possible interaction with nearby molecular clouds, and a sample of gamma-ray binaries, and one of pulsars. Since the synthetic source populations include also bright sources that could have been already detected with existing observations, the objects at the bright end of the flux distributions were retained and substituted by real measurements to get a more realistic sky model. The latter were extracted from *gammacat*⁴, a catalogue of TeV sources detected by **MAGIC**, **H.E.S.S.** and **VERITAS**, the 3FHL [20] and the 2nd **HAWC** catalogue [21]. A more detailed description of the sky models can be found in [19]. This set of simulated data was used to estimate the CTA capabilities in terms of population studies of the two dominant source classes: **PWN** and **SNRs**. If, on one hand, a transformation jump in population size is expected to the **PWN** field, on the other hand, a much larger exploration volume is envisaged for the study of **SNRs** [19]. In particular, CTA will be able to detect **SNRs** up to the other side of our Galaxy with a 5 to 10 times better flux sensitivity.

The synthetic population of **AGNs** was obtained by extrapolating the energy spectra of all the gamma-ray bright **AGNs**, with known redshift, detected by *Fermi*-LAT and included in the 4LAC catalogue [22]. More details can be found in [23]. The obtained results show that CTA will enlarge the gamma-ray horizon up to a redshift of at least 2 and will increase the number of non-flaring **AGNs** by at least a factor of 2 [23].

One of the key strengths of CTAO is undoubtedly its superb capability in performing precision studies thanks to its excellent angular and energy resolution at **VHE** energies. This is what makes CTAO a unique instrument at **VHEs**, and fully complementary to other existing, or future, particle shower arrays whose energy band coverage overlaps substantially. The synergy with these

⁴<https://github.com/gammapy/gamma-cat>

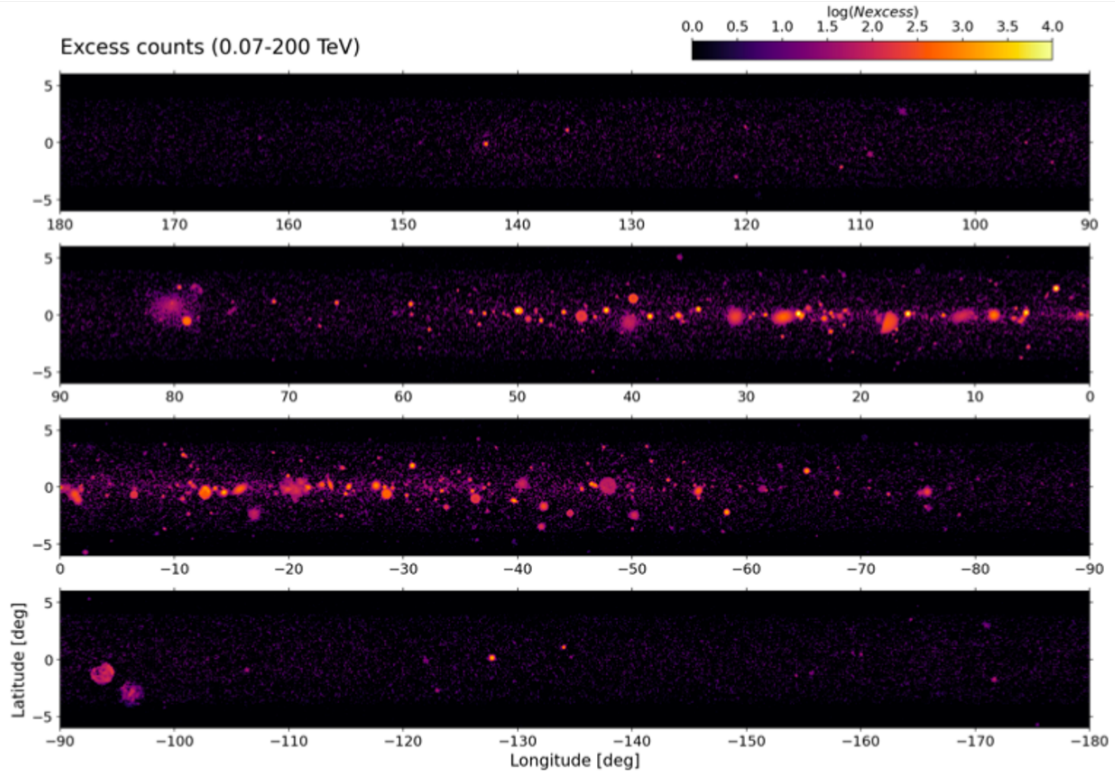


Figure 4: The simulated CTA Galactic Plane Survey. Excess counts above the instrumental background model in the 70 GeV - 200 TeV energy range. Taken from [19].

instruments, and also the neutrino telescopes, is particularly important in the context of the Galactic Cosmic Rays (CRs) physics that is deeply engaged in the search for PeVatrons: gamma-rays sources capable of accelerating cosmic rays to the highest possible energies, i.e. PeV energies. CTA imaging and spectral measurements of the recently discovered 100 TeV emitting sources [21, 24, 25] will, in fact, significantly contribute to solve the thorny issue of the origin of the Galactic CRs at the highest energies. In particular, as shown by simulations in the test case of G106.3+2.7, morphological studies may be more powerful than spectral ones in disentangling between the hadronic and leptonic origin of the gamma-ray emission [26].

Precision performance capabilities, i.e., angular and energy resolution, will be crucial also in the fields of gamma-ray cosmology and fundamental physics. Only an excellent energy resolution and good control of systematic uncertainties will allow a significant detection of smoking gun features of new physics [27], such as the coupling of Axion-Like Particles (ALPs) to photons that can produce a reduced effective optical depth and oscillatory patterns in AGN spectra, or the presence of Lorentz Invariance Violation (LIV) that leads to a significant gamma-ray opacity reduction at energies above a ten of TeV. At the same time, these CTA capabilities will also provide the possibility to measure the IGMF strength either by detecting broad spectral features due to the IGMF-induced low-energy cascade contribution, or by measuring the extension to the halos surrounding the point-like emission of AGNs. In particular CTA measurements will almost close the gap between the existing IGMF constraints and the maximal field strength consistent with galaxy

formation models [28]. Another fundamental contribution of CTA to the gamma-ray cosmology is related to EBL measurements: whilst small redshift blazars with cut-off at 10 TeV will probe the still under-constrained cosmic IR background up to $100\mu\text{m}$, high redshift (beyond $z = 1$) will instead make possible to study the EBL evolution over cosmic time [28].

Last, but not least, CTA will act as a powerful dark matter discovery instrument. Thanks to its unprecedented sensitivity, CTA will be able to explore the “Holy Grail” region of the WIMP scenario, down to the relic thermal cross section, for the still-unexplored heavier end of the WIMP masses. The most promising dark matter searches for CTA are those performed on survey data from the Galactic Centre, where the density of dark matter is expected to be the highest [29, 30]. However, there are also prospect studies based on observations of Galaxy clusters [31] and dark sub-halos [32].

4. First results from the LST-1

The LST-1 [34] was built by the LST Collaboration as the prototype CTA LST at the Observatorio Roque de los Muchachos (ORM), the site where the CTAO Northern Array will be deployed, and where the two MAGIC telescopes are situated (in Figure 1 the LST-1 is the most Southern one, whereas the MAGIC telescopes are the two telescopes in grey). The LST-1, shown in Figure ??, was inaugurated in October 2018 and since then it is under commission. Soon, once the commissioning will be over, and the acceptance review successfully passed, the LST-1 will become the first telescope of the CTA Observatory, as the first one of the four LSTs which the CTAO Northern Array consist of.

As part of its commissioning program, the LST Collaboration has already taken more than 250 hours of gamma-ray data while the telescope was pointing at bright, known VHE emitting sources. The results of these observations will be summarized in this work, but a detailed presentation can be found in several different contributions to this conference that will be cited along the way.

The Queen source of any IACT commissioning is the Crab Nebula: being it considered as the standard candle of the discipline, it is used to measure the performance of the new instrument and to cross-calibrate it with other existing telescopes. Commissioning Crab Nebula data have been used to tune the parameters of the Monte Carlo simulations to the characteristics of the telescope and also to estimate the key performance parameters such as angular resolution, energy resolution and sensitivity. The corresponding results are shown in [35].

The energy spectrum of the Crab Nebula obtained with two independent analyses (using different selection cuts) on a reference dataset of 3.5 hr is compatible within the systematic uncertainties with the measurements by the MAGIC collaboration [35].

Taking advantage from the fact that the Crab Nebula is powered at its centre by the Crab pulsar - one of the few gamma-ray pulsars detected at VHEs [51] up to about 1 TeV [52] - CTAO pulsar-detection capabilities could be tested by using the same dataset. The LST-1 detected the Crab pulsar at 9.2σ level on 43.7 hr of observation considering averaged phase, as shown on the right panel of Figure 5. The ratio between the emission by the two characteristic peaks of the Crab Pulsar light-curve, i.e., P1 and P2, allows to estimate the energy threshold of the analysis to be about 50 GeV. This is a remarkable result from the technical point of view: it verifies the time-stamping system and represents a first important step towards the validation of the low-energy performance of the LSTs.

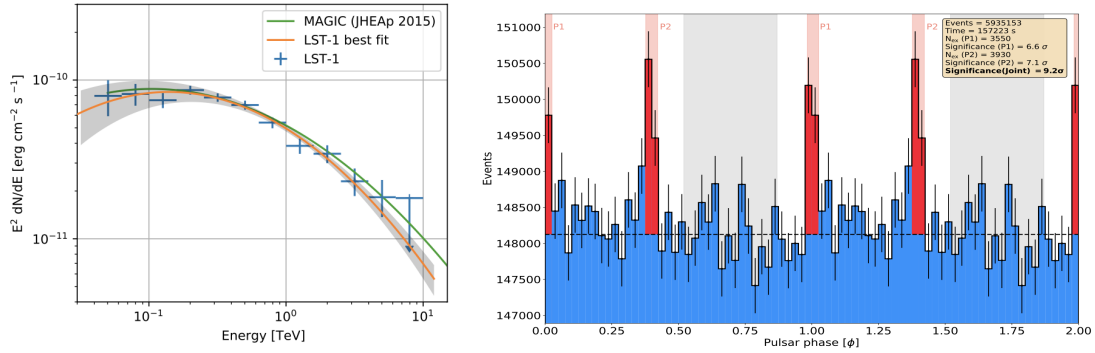


Figure 5: LST-1 results on commissioning Crab data. *Right panel:* Crab Nebula SED obtained with the source-dependent analysis (refer to [35] for more details) and compared with the MAGIC measurement [50]. The grey band identified the systematic uncertainty. *Left panel:* Crab Pulsar light-curve obtained by using ~ 44 hr. [35]

The LST-1 has been cross-calibrated with the two MAGIC telescopes, that situated at the same site, just about 100 m away, can look at the same EAS-generated events. An offline trigger software routine can select events generated by the same shower when the two systems simultaneously point at the Crab Nebula. These events were used to check the correlation between the MAGIC- and the LST-1 reconstructed energy. Preliminary results show a 5% discrepancy by fitting a Gaussian around the peak of the relative difference distribution. Considering the systematic uncertainty of the MAGIC energy scale, it indicates that the accuracy of the LST-1 energy estimation is almost comparable to that of the MAGIC estimation [37]. The LST collaboration also performed a combined analysis of the simultaneously recorded, LST-1 and MAGIC data on the Crab Nebula. The preliminary results show the detection of the Crab Nebula at 18.1σ level in ~ 37 min, by considering only events triggered by the three telescopes [37].

Several other known bright gamma-ray sources, mainly AGNs, were observed and detected by the LST-1. The latest detection of the BL Lac source was announced with the ATel #14783⁵, showing the community that the LST collaboration is already capable of releasing results within one day from the data taking. Since transient phenomena constitute the core program of the LST sub-system, a prototype transient handler system that receives, in real-time, science alerts from the Gamma-ray Coordination Network (GCN) network, was installed on the LST-1. Thank to this system, it was able to already observe one GRB within 15 minutes from the receipt of the alert [38]. Among the GRB observations so far carried out by the LST-1, it is worth to mention those on GRB201216C that occurred the day after its detection at VHEs by the MAGIC Collaboration. Unfortunately no signal from this GRB was detected by the LST-1 due to the too large latency between the alert trigger and the observations [38]. Such a long latency is explained by the fact that this event happened before the installation of the transient handler system.

⁵<https://astronomerstelegram.org/?read=14783>

5. R&D for future upgrades

Despite the CTAO Construction Phase has not started yet, there are already several R&D activities aimed to prototype the next generation instrumentation and/or to investigate new scientific opportunities for the CTA Observatory. Among the various, we would like to mention three of them whose impact could be significant on the Observatory itself.

- a new **SiPMs-based camera design for telescopes with large light collection areas**, such as the LSTs. The transition from PMTs to SiPMs provides higher duty cycle and robustness, as well as a higher granularity (higher number of pixels) that translates into an improved angular resolution and background rejection power. However this transition has been successfully adapted for the small cameras of the SSTs [49], it imposes a certain number of new technical challenges to reach the required performance gain down to 20 GeV, thus to be used for LST-type of telescopes. Since the SiPMs have larger light collection area, and higher sensitivity in the near-IR, the background rate increases dramatically hampering the detection capabilities of low-energy gamma rays (close to the 20 GeV energy threshold). At the same time, the increased number of pixels affects the power consumption and the data throughput driving the design choices for the front-end and the digital readout towards integrated circuits. A detailed description of the status of this new camera prototype can be found in [42].
- a new MST-type of telescope: **the Schwarzschild-Couder Telescope (SCT)**. Its design foresees novel 9.7 m aperture, aplanatic, dual-mirror Schwarzschild-Couder optical design [44] that offers a wide FoV and a superior off-axis optical PSF, and a compact SiPM camera [43] that allows for a large number of camera pixels. These two features allow for an improvement of the imaging capabilities by up to one order of magnitude over the one-mirror Davies-Cotton design. The prototype SCT, dubbed as pSCT, has been constructed at the Fred Lawrence Whipple Observatory in Arizona, USA. The first observations of the Crab Nebula obtained in January 2020 proved to be successful. The reader is referred to [45] for further information on this observational campaign.
- a new scientific objective for CTAO: **stellar intensity interferometry**. It can provide a sub-milliarcsecond imaging of nearby main sequence stars and binary systems, that in turn, will shed light on stellar phenomena, such as rotational deformation, accretion effects, and the universality of star-spot (sun-spot) cycles.
This builds on the idea that IACTs can be used as interferometric telescopes with kilometer scale baseline separations. Intensity interferometry, in fact, exploits the time-correlation of the instantaneous intensity of light observed at two or more separated locations. Contrary with the more common amplitude interferometry, it is practically insensitive to optical imperfections of the telescope and atmospheric turbulence, making IACTs optimal optical telescopes for this purpose. Current ground based VHE gamma-ray facilities, such as MAGIC and VERITAS are proving the technical feasibility of this idea. The obtained results are already very promising [46–48].

These studies could result in excellent development proposals to be submitted to the CTA Observatory in the context of the CTAO development program calls.

References

- [1] T. Weeks et al. *Observation of TeV Gamma Rays from the Crab Nebula Using the Atmospheric Cherenkov Imaging Technique*. ApJ 342, 379
- [2] M. Noethe et al. . Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 962, 2021
- [3] K. Bernlohr et al. *Monte Carlo design studies for the Cherenkov Telescope Array*, Astroparticle Physics, 43, 141, 2013
- [4] O. Gueta et al. *The Cherenkov Telescope Array: layout, design and performance*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 88, 2021
- [5] T. Hassan et al. *Performance of a proposed event-type based analysis for CTA*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 1143, 2021
- [6] T. Miener et al. *Reconstruction of stereoscopic CTA events using deep learning with CTLearn*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 710, 2021
- [7] P. Grespan et al. *Deep-learning-driven event reconstruction applied to simulated data from a single Large-Sized Telescope of CTA*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 1440, 2021
- [8] M. de Bony de Lavergne et al. . Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 272, 2021
- [9] J. Aschersleben et al. *Application of pattern spectra and CNNs on CTA data*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 168, 2021
- [10] M. Pecimotika et al. *Performance of the Cherenkov Telescope Array in the presence of clouds*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 77, 2021
- [11] M.G. Bernardini et al. *POSyTIVE – a GRB population study for the Cherenkov Telescope Array*. Proceedings of the 36th International Cosmic Ray Conference - PoS(ICRC2019), Busan (South Korea) ID 598, 2019
- [12] Tung C.F. et al. *FIRESONG: A python package to simulate populations of extragalactic neutrino sources*. Journal of Open Source Software, 6(61), 3194
- [13] B. Patricelli et al. *Searching for Gamma-Ray counterparts to Gravitational Waves from merging binary neutron stars with the Cherenkov Telescope Array* JCAP

- [14] B. Patricelli et al. *Searching for very-high-energy electromagnetic counterparts to gravitational wave events with the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 326, 2021
- [15] O. Sergijenko et al. *Sensitivity of the Cherenkov Telescope Array to emission from the gamma-ray counterparts of neutrino events*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 329, 2021
- [16] L. Nava et al. *Gamma-Ray Bursts detected at Very High Energies*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 1471, 2021
- [17] Bartos et al. *Gravitational-wave follow-up with CTA after the detection of GRBs in the TeV energy domain*, MNRAS 490, 3
- [18] CTA Consortium *Science with CTA*, World Scientific 2019
- [19] Q. Remy et al. *Survey of the Galactic Plane with the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 186, 2021
- [20] M. Ajello et al. *3FHL: The Third Catalog of Hard Fermi-LAT Sources*. ApJS 232, 2 217
- [21] A.U. Abeysekara et al. *The 2HWC HAWC Observatory Gamma Ray Catalog*. ApJ, 843, 1 2017
- [22] *The Fourth Catalog of Active Galactic Nuclei Detected by the Fermi Large Area Telescope*, ApJS 892, 2 2019
- [23] A. Brown et al. *Active Galactic Nuclei population studies with the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 245, 2021
- [24] Z. Cao et al. *Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ -ray Galactic sources*. Nature, 594, 33 2021
- [25] M.Amenomori et al. *Potential PeVatron supernova remnant G106.3+2.7 seen in the highest-energy gamma rays*. Nature Astronomy 5, 460 2021
- [26] G.Verna et al. *HAWC J2227+610: a potential PeVatron candidate for the CTA in the northern hemisphere*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 1140, 2021
- [27] J. Vovk et al. *CTA prospects for probing cosmology and fundamental physics with gamma rays*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 497, 2021
- [28] A. Abdalla et al. *Sensitivity of the Cherenkov Telescope Array for probing cosmology and fundamental physics with gamma-ray propagation*. JCAP, , 2021

- [29] A. Abdalla et al. *Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre*. JCAP 2021
- [30] C. Eckner et al. *Sensitivity of the Cherenkov Telescope Array to a dark matter signal from the Galactic centre*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 316, 2021
- [31] J. Perez-Romero et al. *Sensitivity of CTA to gamma-ray emission from the Perseus galaxy cluster*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 288, 2021
- [32] J. Coronado-Blazquez et al. *Sensitivity of the Cherenkov Telescope Array to Dark Sub-halos*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 544, 2021
- [33] A. Carosi et al. *The Cherenkov Telescope Array transient and multi-messenger program*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 833, 2021
- [34] D. Mazin et al. *Status and results of the prototype Large Size Telescope of CTA*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), 2021
- [35] R. Lopez-Coto et al. *Physics Performance of the Large Size Telescope prototype of the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 395 2021
- [36] A. Di Piano et al. *Physics Performance of the Large Size Telescope prototype of the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID , 2021
- [37] Y. Ohtani et al. *Cross-calibration and combined analysis of the CTA-LST prototype and the MAGIC telescopes*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 560, 2021
- [38] A. Carosi et al. *First follow-up of transient events with the CTA Large Size Telescope prototype*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 835, 2021
- [39] T. Saito et al. *Commissioning of the camera of the first Large Size Telescope of the Cherenkov Telescope Array*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 509, 2021
- [40] Y. Kobayashi et al. *Camera Calibration of the CTA-LST prototype*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 532, 2021
- [41] L. Foffano et al. *Monitoring the pointing of the Large Size Telescope prototype using star reconstruction in the Cherenkov camera*. Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 392, 2021.

- [42] M. Heller et al. *Development of an advanced SiPM camera for the Large Size Telescope of the Cherenkov Telescope Array Observatory*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 347, 2021
- [43] L. Taylor et al. *Design and performance of the prototype Schwarzschild-Couder Telescope camera*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 1027, 2021
- [44] D. Ribeiro et al. *Prototype Schwarzschild-Couder Telescope for the Cherenkov Telescope Array: Commissioning the Optical System*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 474, 2021
- [45] B. Mode et al. *Detection of the Crab Nebula by the prototype Schwarzschild-Couder Telescope*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 830, 2021
- [46] C. Delgado et al. *Intensity interferometry with the MAGIC telescopes*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 693, 2021
- [47] D. Kieda et al. *The VERITAS-Stellar Intensity Interferometry (VSII) survey of Stellar Diameters*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 803, 2021
- [48] D. Kieda et al. *Status of the VERITAS Stellar Intensity Interferometry (VSII) System*, Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID 710, 2021
- [49] R. White et al. , Proceedings of the 37th International Cosmic Ray Conference - PoS(ICRC2021), Berlin (Germany), ID , 2021
- [50] MAGIC Coll. *Measurement of the Crab Nebula spectrum over three decades in energy with the MAGIC telescopes*, JheAp 5, 6 2015
- [51] VERITAS Coll. *Detection of Pulsed Gamma Rays Above 100 GeV from the Crab Pulsar*, Science 334, 69 2011
- [52] MAGIC Coll. *Teraelectronvolt pulsed emission from the Crab pulsar detected by MAGIC*, A&A 585, A133 2016