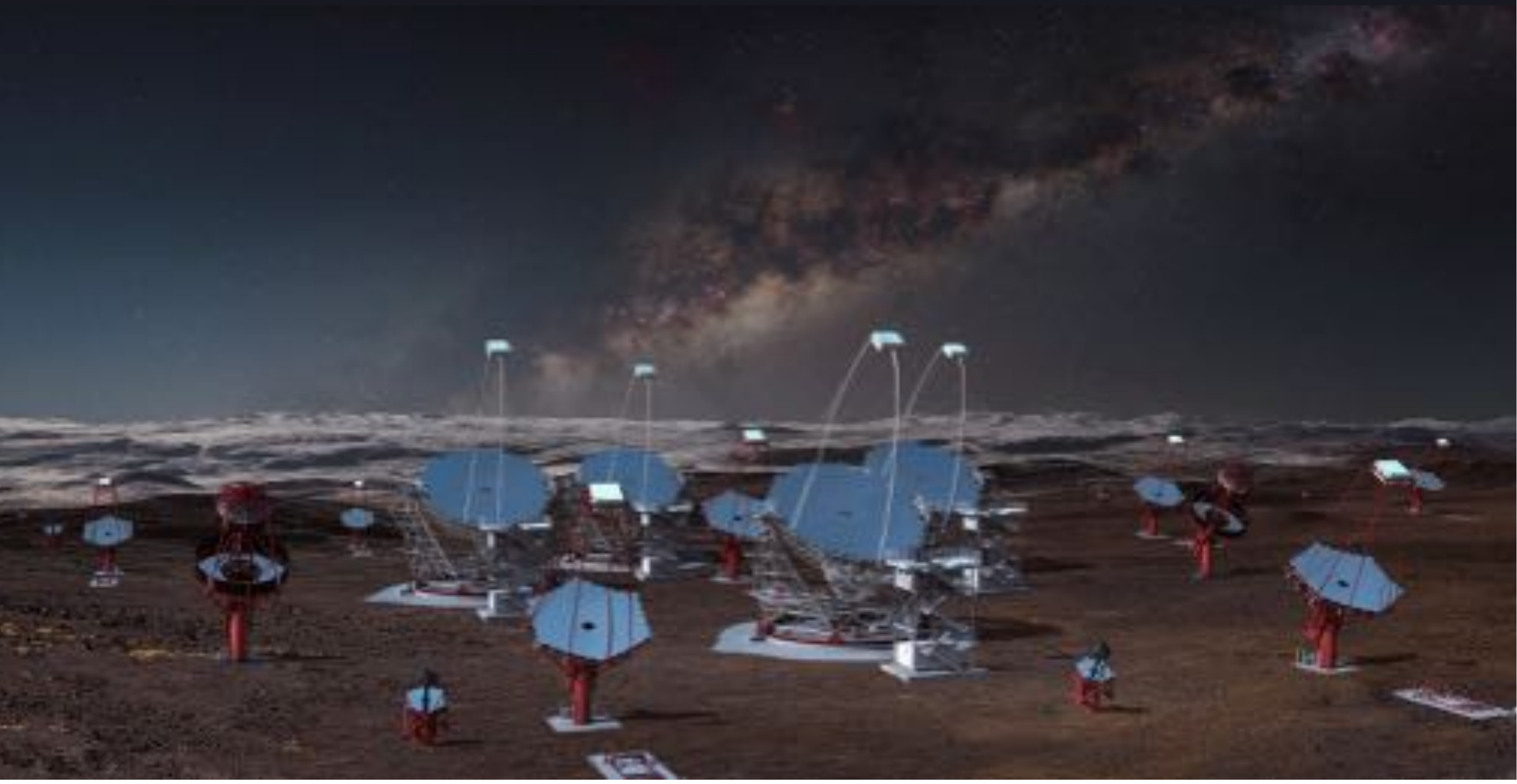
The Cherenkov Telescope Array Observatory

White paper on the Swiss participation to CTAO and perspectives



cta
cherenkov telescope array

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CSCS
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Introduction

The Cherenkov Telescope Array Observatory (CTAO) is the next generation of gamma-ray astronomy research infrastructure with a leading role worldwide in multi-wavelength and multi-messenger studies of the Universe. It will unravel the mysteries of extreme astrophysical environments in partnership with new astronomy facilities chasing neutrinos and gravitational waves together with the large ground and space-based observatories, exploring radiation from the radio band to gamma rays. At energies beyond the mass of the proton, gamma-ray astronomy has the potential to unravel the sources of cosmic rays, the charged particles that continuously bombard our atmosphere up to energies well beyond those achievable by any possible accelerator on Earth. CTAO will explore these extreme accelerators and the accelerating mechanisms that they host, and how cosmic rays forge their hosting galaxies.
CTAO is the successor of the H.E.S.S., MAGIC and VERITAS instruments, bringing together the communities of particle physic and high-energy astrophysic, of the order of 1’400 scientists and engineers. It includes high-technology instrumentation to which the Swiss Community heavily contributed. It will be an observatory accessible by scientists worldwide through a science-driven observing time allocation process.

CTAO is a landmark of the European Strategy Forum on Research Infrastructure (ESFRI) and has the highest priority in the roadmap of the Astroparticle Physics European Consortium (APPEC). It will be built and operated by the CTAO European Research Infrastructure Consortium (ERIC) for the next three decades, starting from August 2023. In order to benefit from all the investment set in the project, it will be a milestone for Switzerland to join as a member the CTAO ERIC, as currently it is a Founding Observer.

This White Paper presents the status of the Swiss participation in CTAO and a view of the areas of scientific interest of Swiss researchers. It describes the current contributions towards the completion of the observatory construction and aims at illustrating the project to a wide community and at gathering scientific interest. The CTAO-CH collaboration unifies more than 35 researchers in prestigious institutions: the University of Geneva, Zürich and Bern, and in the federal institutes of technology ETHZ and EPFL. The Swiss contribution to the construction of CTAO is financed by the State Secretariat for Education, Research and Innovation (SERI). The Swiss National Supercomputing Centre (CSCS) in Lugano will host one of the four CTAO off-site data centres and will offer an infrastructure for large data processing platforms in astronomy, developed in synergy with the needs of the Square Kilometer Array Observatory.

Einführung

Das Cherenkov Telescope Array Observatory (CTAO), die Gammastrahlen-Astronomie-Forschungsinfrastruktur der nächsten Generation, wird weltweit eine führende Rolle bei Multiwellenlängen- und Multi-Messenger-Untersuchungen des Universums spielen. Es wird in Zusammenarbeit mit neuen astronomischen Instrumenten, die Neutrinos und Gravitationswellen messen, die Geheimnisse extremer Zustände aufdecken und gemeinsam mit den grossen boden- und weltraumgestützten Observatorien Strahlung vom Radioband bis hin zu Gammastrahlen erforschen. Bei Energien jenseits der Protonenmasse hat die Gammastrahlenastronomie das Potenzial, die Quellen der kosmischen Strahlung zu entschlüsseln: geladene Teilchen die die Erde bombardieren und Energien erreichen, die weit oberhalb davon sind, was mit denkbaren irdischen Beschleunigern erreicht werden kann. CTAO wird diese kosmischen Beschleuniger und die Beschleunigungsmechanismen, erforschen und untersuchen, welche Auswirkungen diese Strahlung auf Galaxien hat.

CTAO ist ein Meilenstein des Europäischen Strategieforums für Forschungsinfrastruktur (ESFRI) und hat höchste Priorität in der Roadmap des Astroparticle Physics European Consortium (APPEC). Es wird vom CTAO European Research Infrastructure Consortium ab Herbst 2023 gebaut und für mindestens 30 Jahre betrieben. CTAO wird ein Observatorium sein, das Wissenschaftlern weltweit durch eine wissenschaftsbasierte Beobachtungszeitzuteilung zugänglich sein wird. CTAO ist der Nachfolger der Instrumente H.E.S.S., MAGIC und VERITAS und bringt etwa 1400 europäische Teilchenphysiker, Hochenergie-Astrophysiker und Ingenieure zusammen. Zu der Entwicklung der nötigen Hochtechnologie-Instrumenten hat die Schweizer Gemeinschaft massgeblich beigetragen.

Dieses White Paper stellt den Stand der Schweizer Beteiligung an CTAO dar und gibt einen Überblick über die wissenschaftlichen Interessengebiete der Schweizer Forscher. Es beschreibt die aktuellen Beiträge zur Fertigstellung des Observatoriumsbaus und zielt darauf ab, das Interesse einer breiten wissenschaftlichen Gemeinschaft zu wecken. Die CTAO-CH-Zusammenarbeit vereint mehr als 35 Forscher in renommierten Institutionen (Universitäten Genf, Zürich und Bern sowie in den Eidgenössischen Technischen Hochschulen ETHZ und EPFL). Der Schweizer Beitrag zum Bau des CTAO wird vom Staatssekretariat für Bildung, Forschung und Innovation (SBFI) finanziert. Das Swiss National Supercomputing Centre (CSCS) in Lugano wird eines der vier CTAO-Rechenzentren beherbergen und eine Infrastruktur für grosse Datenverarbeitungsplattformen in der Astronomie bieten, die in Synergie mit den Bedürfnissen des Square Kilometer Array Observatory entwickelt wird.

Introduction

L’observatoire Cherenkov Telescope Array (CTAO), dédié à la recherche astronomique dans le domaine des rayons gamma, jouera un rôle de premier plan au niveau mondial dans les études multi-longueurs d'onde et multi-messagers de l'Univers. Il percera les mystères d’environnements extrêmes en concert avec les nouvelles installations détectant neutrinos et ondes gravitationnelles et avec les grands observatoires terrestres et spatiaux qui explorent les rayonnements du radio aux rayons gamma. À des énergies supérieures à la masse du proton, les rayons gamma permettent de découvrir les sources des rayons cosmiques, qui bombardent continuellement notre atmosphère à des énergies bien supérieures à celles que pourrait atteindre n'importe quel accélérateur concevable sur Terre. CTAO explorera ces accélérateurs extrêmes, comment ils fonctionnent, ainsi que leurs impacts sur les galaxies et l’Univers.

CTAO est un observatoire emblématique du forum stratégique européen sur les infrastructures de recherche et a la plus haute priorité dans la feuille de route du consortium européen pour la physique des astroparticules. Il sera construit et exploité par le CTAO European Research Infrastructure Consortium pour les trois prochaines décennies, à partir de l'automne 2023. CTAO sera un observatoire accessible aux scientifiques du monde entier avec une répartition du temps d'observation axée sur la science. CTAO est le successeur des instruments H.E.S.S., MAGIC et VERITAS et rassemble les physiciens des particules et astrophysiciens des hautes énergies, environ 1400 scientifiques et ingénieurs. CTAO comprend une instrumentation de haute technologie à laquelle la Suisse a fortement contribué.

Ce livre blanc présente l'état de la participation suisse à CTAO et des domaines d'intérêt scientifique des chercheurs suisses. Il décrit les contributions actuelles en vue à l'achèvement de la construction et vise à rassembler la communauté scientifique. La collaboration CTAO-CH réunit plus de 35 chercheurs dans des institutions prestigieuses (Universités de Genève, Zürich et Berne, ainsi que les écoles polytechniques fédérales ETHZ et EPFL). La contribution suisse à la construction de CTAO est financée par le Secrétariat d'Etat à la Formation, à la Recherche et à l'Innovation (SEFRI). Le Centre national suisse de calcul scientifique (CSCS) à Lugano accueillera l'un des quatre centres de données de CTAO et offrira une infrastructure pour les grandes plateformes de traitement de données astronomique, développée en synergie avec les besoins du Square Kilometer Array.

Introduzione

L'Osservatorio Cherenkov Telescope Array (CTAO), l'infrastruttura di ricerca di nuova generazione per l'astronomia a raggi gamma, avrà un ruolo di primo piano a livello mondiale nello studio dell'Universo a più lunghezze d'onda e più messaggeri. Svelerà i misteri delle sorgenti estreme in collaborazione con le nuove strutture astronomiche che ricercano i neutrini e le onde gravitazionali ed insieme ai grandi osservatori terrestri e spaziali che esplorano le radiazioni dalle onde radio ai raggi gamma. Ad energie superiori alla massa del protone, l'astronomia dei raggi gamma ha il potenziale per svelare le fonti dei raggi cosmici, che bombardano continuamente la nostra atmosfera fino ad energie ben superiori a quelle raggiungibili da qualsiasi acceleratore concepibile sulla Terra. Il progetto esplorerà questi acceleratori estremi, il modo in cui funzionano queste particelle e il loro impatto sulle galassie e sull'Universo.

Il CTAO è un punto di riferimento del Forum strategico europeo sulle infrastrutture di ricerca (ESFRI) e ha la massima priorità nella tabella di marcia del Consorzio europeo di fisica astroparticellare (APPEC). Sarà costruito e gestito dal consorzio europeo per le infrastrutture di ricerca (CTAO ERIC) per i prossimi 3 decenni, a partire dall'autunno 2023. Sarà un osservatorio accessibile a scienziati di tutto il mondo grazie a processi di allocazione del tempo di osservazione meritocratici. CTAO è il successore degli strumenti H.E.S.S., MAGIC e VERITAS, e riunisce le comunità europee di fisici delle particelle ed astrofisici delle alte energie, dell'ordine di 1.400 scienziati e ingegneri. Il progetto comprende una strumentazione di alta tecnologia alla quale la Comunità svizzera ha contribuito in modo significativo.

Questo White Paper presenta lo stato della partecipazione svizzera al CTAO e una visione delle aree di interesse scientifico dei ricercatori svizzeri. Descrive gli attuali contributi per il completamento della costruzione dell'osservatorio e mira a raccogliere l'interesse di un'ampia comunità scientifica. La collaborazione CTAO-CH riunisce più di 35 ricercatori in prestigiose istituzioni (Università di Ginevra, Zurigo e Berna, e politecnici federali ETHZ e EPFL). Il contributo svizzero alla costruzione del CTAO è finanziato dalla Segreteria di Stato per la Formazione, la Ricerca e l'Innovazione (SEFRI). Il Centro nazionale svizzero di supercalcolo (CSCS) di Lugano ospiterà uno dei quattro centri dati del CTAO e offrirà una infrastruttura per la piattaforma di elaborazione di grandi dati in astronomia, sviluppata in sinergia con le esigenze dello Square Kilometer Array Observatory.

Introducziun

L'observatori Cherenkov Telescope Array (CTAO), deditgà a la retschertga astronomica en il champ dals radis gamma, vegn a giugar ina rolla decisiva a nivel mundial en la perscrutaziun da multi-lunghezzas da l'unda e multi-substanzas currieras da l'univers. Ensemen cun las installaziuns novas che detecteschan neutrins ed undas da gravitaziun e cun ils gronds observatoris sin terra ed en l'univers che exploreschan la radiaziun en il sectur da radio fin als radis gamma vegn el a scuvrir ils misteris dals ambients extrems. Cun energias superiuras a la massa dal proton lubeschan ils radis gamma da scuvrir ils origins dals radis cosmics che bumbardeschan d'in cuntin noss'atmosfera cun energias lunschor superiuras a quellas che mintga acceleratur pensabel sin il mund pudess cuntanscher. L'observatori vegn a perscrutar quests acceleraturs extrems, co els accelereschan las particlas sco er lur effects sin las galaxias e l'univers.

Il CTAO è in observatori da model dal forum da strategia europeic per las infrastructuras da perscrutaziun e ha la prioritad absoluta en la roadmap dal consorzi europeic per la fisica da particlas astronomicas. A partir da l'atun 2023 vegn el a vegnir bajegià e manà per ils proxims trais decennis dal CTAO European Research Infrastructure Consortium. Il CTAO vegn ad esser in observatori accessibel a scienziadas e scienziads da l'entir mund. La repartiziun dal temp d'observaziun è orientada tenor la scienza. Il CTAO è il successur dals instruments H.E.S.S., MAGIC e VERITAS e reunescha fisicher.a.s da particlas ed astrofisicher.a.s che s'occupan da l'energia auta, quai èn circa 1400 scienzad.a.s ed inschigner.a.s. El cumprenda in instrumentari d'auta tecnologia, al qual la Svizra ha contribuì a moda considerabla.

Quest cudesch alv preschenta il stadi da la participaziun svizra al CTAO e dals champs d'interess scientifics dals perscrutaders svizzers. Sco cudesch programmatic descriva el las contribuziuns actualas en vista a la realisaziun da l'observatori e duai radunar la cuminanza scientifica. La cooperaziun CTAO-CH reunescha dapli che 30 scienziad.a.s dad instituziuns enconuschentas (las universitads da Genevra, Turitg e Berna sco er las scolas politecnicas federalas Turitg e Losanna). La contribuziun svizra a la construcziun dal CTAO vegn finanziada dal Secretariat da stadi per furmaziun, retschertga ed innovaziun (SEFRI). Il Swiss National Scientific Computing Centre (CSCS) a Lugano vegn a dar albiert ad in dals quatter centers da datas dal CTAO e porscher ina plattafurma per l'elavuraziun astronomica da datas, sviluppada en sinergia cun ils basegns dal Square Kilometer Array.

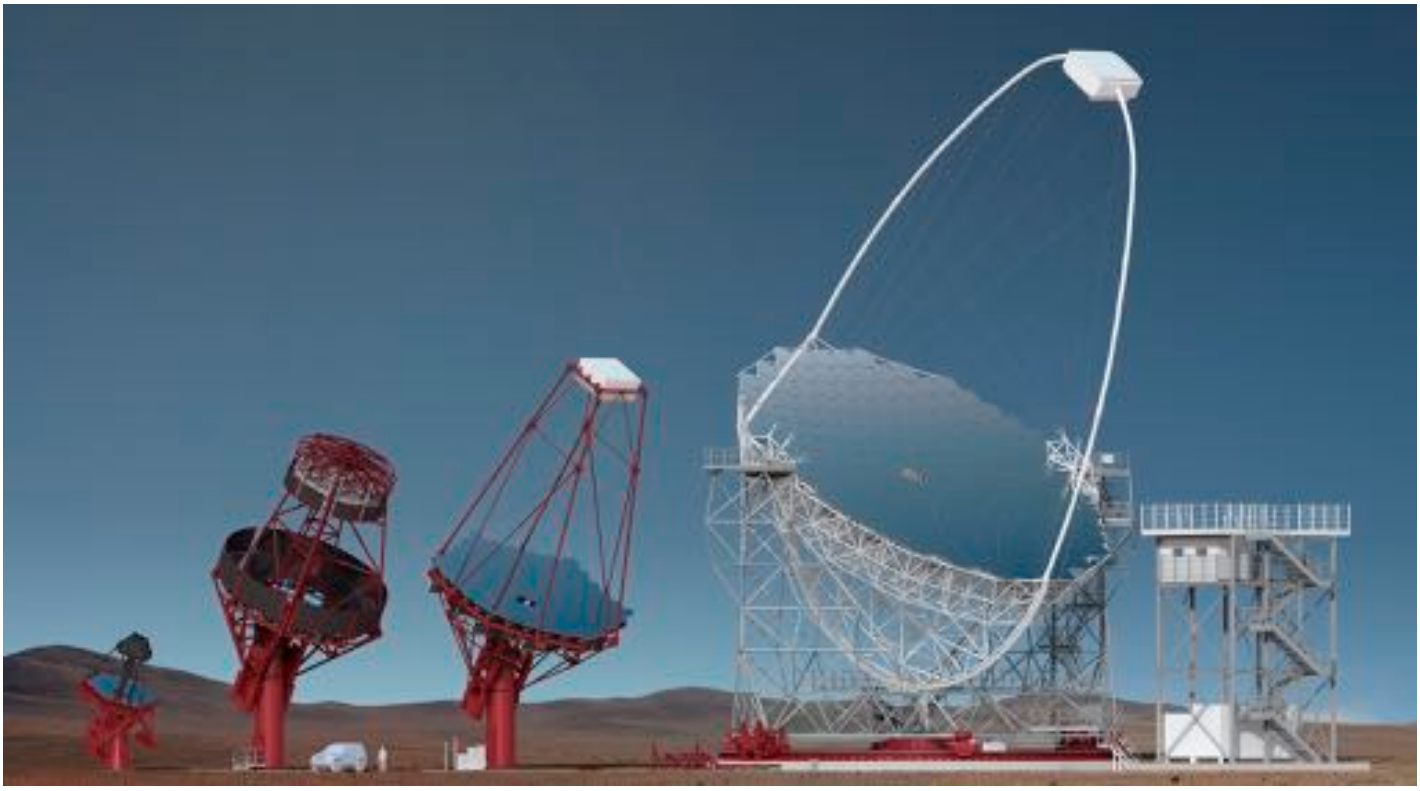


Fig. 1: The four telescope designs of CTAO, from left to right: the two innovative Schwarzchild-Couder telescopes, the Small Sized Telescope (SST) with 4 m diameter equivalent mirror surface and the about 12 m Telescope (SCT); the Davies-Cotton Middle Sized Telescope (MST) of about 12 m diameter optical system and the Large Sized Telescope (LST) with 23 m diameter parabolic reflecting surface. The SSTs, MSTs and LSTs will be deployed for the Alpha-configuration of CTAO, currently in construction (Credit: Gabriel Pérez Diaz, IAC)

CONTENTS

Breakthroughs in Gamma-ray Astrophysics in a Multi-Messenger context

High-energy astrophysics is the study of the Universe through radiation and messengers emitted by high-energy or decaying particles. These particles are heated or accelerated close to deep gravitational potentials (such as black holes and neutron stars), large electromagnetic fields, shocks in diffuse media, or forged in stars. High-energy astrophysics uses the information from about 19 decades of energy of photon radiation and additional 10 decades covered by charged particles, protons and ionised nuclei named the cosmic rays, reaching 10^{22} eV, neutrinos (see Fig. 14) and as well gravitational waves. It uses celestial objects with extreme conditions of matter and magnetic fields as laboratories to explore the laws of physics and their possible violations leading to new discoveries. Such studies involve many fields of modern physics and astrophysics and cosmology, particle and plasma physics, electrodynamics and optics, data science and instrumentation.

After the first attempts in the 50'ies and the discovery of the first TeV source by Whipple in 1989, the Crab Nebula supernova remnant (SNR), the instruments H.E.S.S., MAGIC and VERITAS opened a new wavelength domain for astronomy with very-high-energy (VHE) gamma-rays (0.05–100 TeV). Radiation at these energies differs fundamentally from that detected by astronomical instruments at lower energies: TeV gamma rays cannot be generated thermally by the emission of hot celestial objects. The energy of thermal radiation reflects the temperature of the emitting body, and apart from the Big Bang, there is nothing hot enough to emit such gamma rays. Instead, high-energy gamma rays probe a "non-thermal" Universe, where mechanisms other than thermal emission allow the concentration of large amounts of energy into a single quantum of radiation. High-energy gamma rays can be produced in a top-down fashion by decays of hypothetical heavy dark matter particles or cosmic strings, both relics which might be leftovers from the Big Bang. In a bottom-up fashion, gamma-rays can be generated when high-energy particles – accelerated for example in gigantic shock waves created in stellar explosions – collide with ambient gas particles or interact with electromagnetic fields or in the coalescence of massive objects. The flux and energy spectrum of the gamma rays reflect the flux and spectrum of the high-energy particles. They can therefore be used to trace these cosmic rays (CRs) in distant regions of our own or other galaxies.

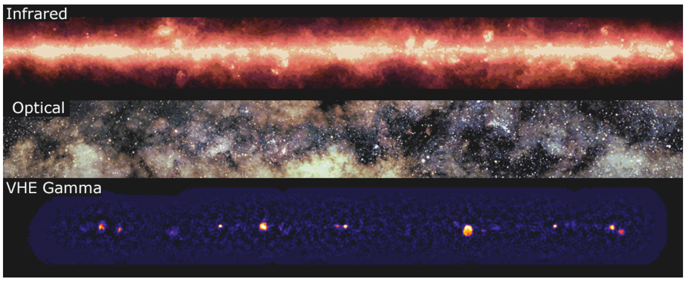


Fig. 2: The Milky Way viewed (from bottom to top) in gamma rays, visible and infrared light (H.E.S.S.).

Energies are in units of electron-Volts or eV, the typical energy of a visible photon. 1 GeV is a billion eV, 1 TeV, a thousand GeV or the kinetic energy of a flying mosquito, a lot of energy for a particle with infinitesimally small mass. 1 PeV is a thousand TeV and 1 EeV is a thousand PeV. 1 ZeV, a thousand EeV, is the highest particle energy measured in the Universe, in the cosmic-ray spectrum.

Imaging the Universe with gamma-rays

The first images of the Milky Way in VHE gamma rays were obtained in recent years and reveal a chain of gamma-ray emitters lining the Galactic plane, demonstrating that sources of high-energy radiation are ubiquitous in our Galaxy (Fig. 2). Sources of this radiation include supernova shock waves (Fig. 3), where electrons and atomic nuclei are accelerated and generate the observed gamma rays. Another important class of objects in this context are nebulae surrounding pulsars, where strong rotating magnetic fields give rise to a steady flow of high-energy particles.

Some of the objects discovered are binary systems, where a black hole or neutron star orbits a massive star. Along the elliptical orbit, the conditions for particle acceleration vary and hence the radiation intensity is modulated with the orbital period. These systems are particularly interesting because they allow the study of how particle acceleration processes respond to varying ambient conditions. One of several surprises was the discovery of "dark sources", objects emitting high-energy radiation not yet identified in other bands.

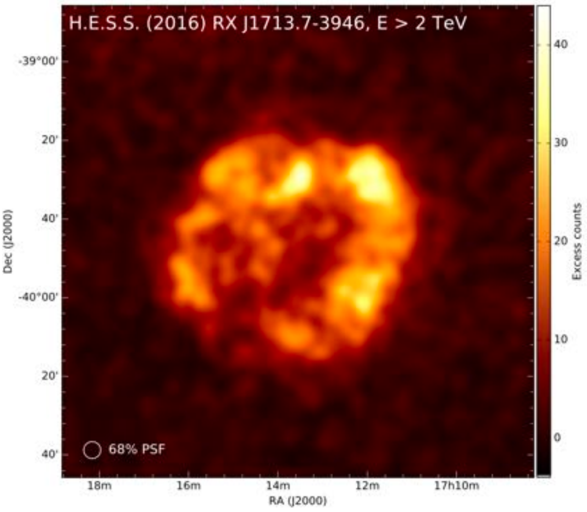


Fig. 3: TeV image of SNR RXJ 1713.7-3946, where the morphology of the shock front is probed with precision of 0.6 pc equivalent to an angular resolution of 0.036° [arXiv:1609.08671]

Serendipitously, from the core of our Galaxy, two Bubbles, identified by the Fermi-LAT experiment constitute a reservoir of electrons and eventually CRs to a distance of a few tens of kpc (Fig. 4). They may constitute a relic of a past big meal of Sgr A*, the black hole in the Galactic Centre.

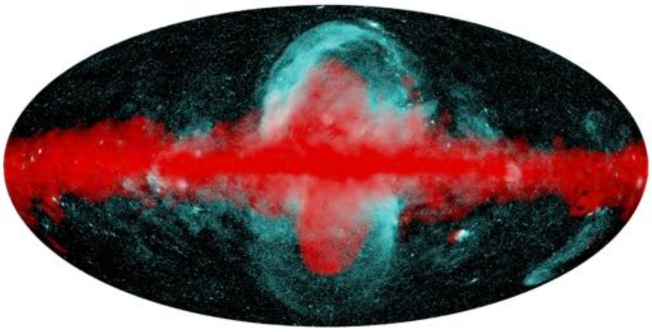


Fig. 4: Fermi Bubbles composite image: Fermi (red)–eROSITA (cyan) respectively at 100 MeV - 300 GeV and 0.6-1 keV [arXiv:2012.05840].

Beyond our Galaxy, about 100 extragalactic sources of high-energy radiation have been discovered, located in active galaxies, where a supermassive black hole at its core is fed by a steady stream of gas and is releasing enormous amounts of energy. Gamma rays are believed to be emitted from the vicinity of these black holes and from the jets along their axis of rotation, allowing the study of the processes occurring in these violent and poorly known environments.

These recent breakthroughs in VHE gamma-ray astronomy were achieved with Imaging Atmospheric Cherenkov telescopes (IACTs). When a gamma ray interacts with the atmosphere, it generates a cascade of secondary electrons travelling faster than the speed of light in air emitting a bluish light in the direction of a cone of about 1° opening, named Cherenkov light. This is seen as a pulse of a few nanoseconds illuminating an area on the ground of about 250 m in diameter with only about 20 photons/m^2 for a 500 GeV gamma-ray at an altitude of 2000 m. Telescopes are equipped with large optical reflectors with areas in the 100 m^2 range projecting the image of showers in cameras with fast photosensors in their focal planes (Fig. 5). The direction and energy of the primary gamma-ray can be reconstructed from the axis of the elliptical image of the particle cascade and the charge developed by the light captured by the sensors, respectively. While the image of a gamma-ray event is elliptical, CR images are blurred. Such imaging technique allows to single out gamma-rays among the 5 orders of magnitude larger CR background. A gamma-ray source image pointed by a telescope appears from the superposition of many signal-like events. If multiple telescopes image the same shower in a stereoscopic mode, as in CTAO, the rejection of the CR background and the precision in pointing the source and reconstructing the source energy flux strongly improves.

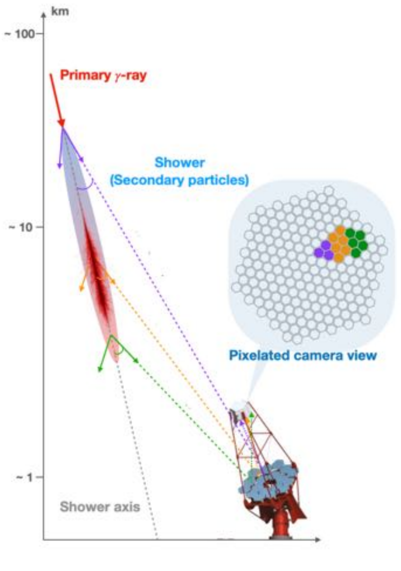


Fig. 5: Gamma-ray shower elements detected by the pixels of a IACT camera where the shower image is projected.

Science with the Cherenkov Telescope Array

Supernova remnants & pulsar wind nebula

The Galaxy is crossed by ionised nuclei of incredible energies (hadronic cosmic rays), corresponding to the temperature that the Universe had during the big bang, before hadrons formed in the Universe. CTAO will discover the accelerators of these particles.

Which are the sources of cosmic rays in the galaxy and can they explain the CR spectrum at PeV energies?

What are the accelerating mechanisms explaining the observed CR and gamma-ray source spectra? How do CRs emerge from sources in interstellar space?

Where is the transition between galactic and extragalactic CRs?

Why do CRs carry as much energy per unit volume in galaxies as that in starlight, interstellar magnetic fields, or motions of interstellar gas?

The CR spectrum is largely dominated by protons up to the so-called knee (found at Z x 1 PeV, where Z is the CR charge). Above the proton knee at 1 PeV, their chemical composition becomes heavier and the spectrum steepens. To maintain their intensity, galactic sources must inject in the form of accelerated particles a power or luminosity about 8 orders of magnitude larger than that of the Sun, namely about 10^{41} erg s^{-1}. For years, the scientific community largely accepted that the galactic supernova remnants (SNRs) can be responsible for the acceleration of the bulk of galactic CRs, as about 10% of their ejecta can provide this power, as pointed out by the famous Swiss astronomer F. Zwicky in 1934. Nonetheless, many new potential accelerators such as pulsar wind nebulae (PWNs), stellar clusters, binary stars, and transient sources such as novae have been discovered by the new generation of experiments. SNRs remain strong accelerator candidates but it remains to be understood why the maximum energy of the particles accelerated in SNRs achieve an energy 10 times smaller than the observed knee, limited by the lifetime of the shock. Additionally, the spectra of these sources do not match those predicted by the Diffusive Shock Acceleration (DSA) theory, a subclass of the Fermi acceleration mechanisms formulated in 1949. The so-called first-order mechanism in the velocity of the shock is considered the most efficient process to transfer a small percentage of the star explosion energy into particle acceleration. This problem challenges plasma physicists, who, to explain the observed spectra, introduced magnetic field amplification effects. These can be provided by the growth of instabilities at different scales, like acoustic instabilities in an inhomogeneous medium, involving charged particle current and magnetic field resonant streaming instabilities. Other studies are performed on turbulent phenomena such as magnetic reconnection or density fluctuations in turbulent magnetised plasma. Modified DSA theories are benchmarked by detailed studies of shock morphologies, as in the SNR image in Fig. 3. CTAO will observe SNRs with a sensitivity increased by a factor of 5-10 with respect to current experiments and up to the other side of the Galaxy. The increased energy coverage towards lower and higher energies will allow sensitive tests of acceleration models and

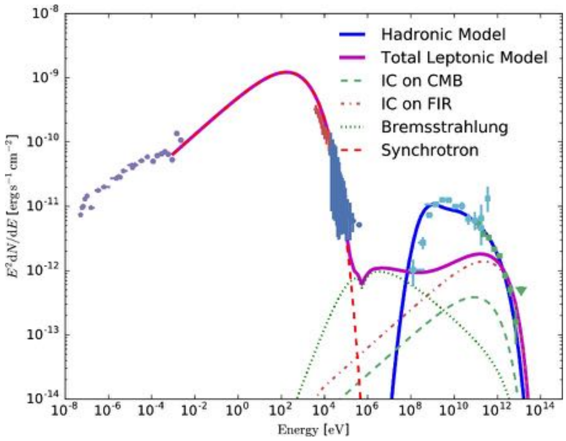


Fig. 6 Spectral energy distribution of Cassiopeia A, a 320 yr-old SNR. The pion decay model tracing protons (blue line) best fits the MAGIC data [arXiv:1707.01583].

determination of their parameters and might allow identifying the signature of neutral pion decay in the high-energy end of their spectral emission distributions (SEDs), hence allowing to identify, in synergy with neutrino telescopes, CR sources. Examples of candidate hadronic SNRs are emerging, typically most efficient in the first few 100 yr of their shock life, as for the Cas A in Fig. 6. PWNs surrounding pulsars are another abundant source of high-energy particles, including potentially high-energy nuclei. Energy conversion within pulsar winds and the interaction of the wind with the ambient medium and the surrounding supernova shell challenge current ideas in plasma physics. The recent discovery by LHAASO of a dozen regions in our Galaxy emitting PeV gamma rays has stimulated even more interest to unveil the origin of galactic CRs. These regions have been associated with known counterparts potentially capable of accelerating particles to relativistic energies. In some cases, such regions are particularly extended and led to the discovery of pulsar halos. One of these sources was recently observed by the first LST of CTAO and by other facilities, allowing scientists from the UniGe to develop a leptonic model of the source (Fig. 7) calling for a population of diffuse sources to explain the highest energy galactic CRs.

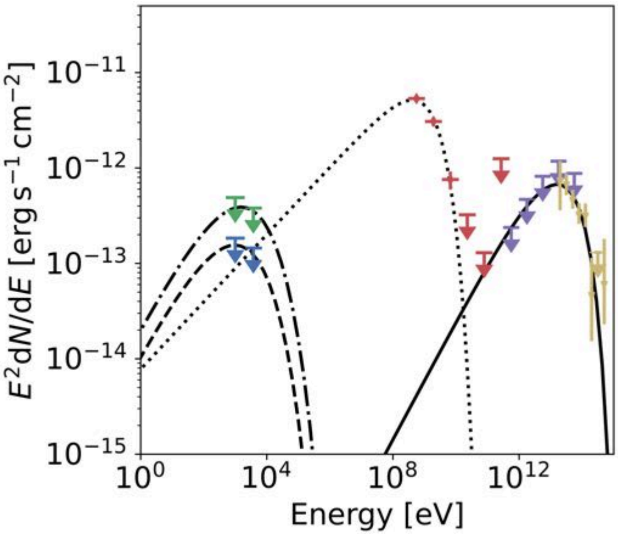


Fig. 7: Spectral energy distribution of LHAASO J2108+5157: yellow points are LHAASO data; violet points are upper limits (UL) at 2σ from LST; red points from Fermi-LAT on top of a pulsar emission model (dotted line) and a leptonic model of synchrotron (dashed) and inverse Compton (solid line) constrained by the XMM-Newton UL at low-energy to a magnetic field < 2 μG [arXiv:2210.00775].

Pulsars

A pulsar magnetosphere is a plasma-rich region outside a rapidly rotating, highly magnetised neutron star. The magnetosphere acts as a mediator through which the rotational energy of the pulsar is converted into the acceleration of charged particles and produces VHE gamma-ray emission.

What are the underlying mechanisms responsible for the particle accelerations in the magnetosphere of pulsars?

How exactly do pulsars produce pulsed VHE radiation?

How the future CTAO observations can constrain the competing models to explain the gamma-ray pulse radiation?

Pulsar magnetospheres are efficient accelerators, involving general relativistic electrodynamics with a strong magnetic field. Particles that can escape the magnetosphere, streaming away, creating the so-called pulsar wind. Emissions from the pulsars themselves have also been detected at TeV energies indicating two components: (i) pulsed radiation with pulsar period - produced by particle acceleration in the pulsar magnetosphere and (ii) non-pulsed (steady profile with possible flares and slow variations as seen in observations at GeV energies of the Crab pulsar) produced by the Pulsar wind nebula. Focusing on the pulsed gamma-ray emission allows to separate the processes occurring in the magnetosphere from the emission of the surrounding nebula. Competing models predict characteristic cut-off features in the spectra of pulsed gamma rays in the low-energy range of CTAO. By exploring these spectral characteristics, CTAO can help constrain and refine existing models, ultimately advancing our understanding of particle acceleration mechanisms in the magnetosphere of pulsars.

Stellar systems

Massive stars generate powerful winds during their short life and explode in a supernova. When their wind collides, they heat the gas to millions of degrees and accelerate particles. They inject a large amount of energy into the Galaxy. CTAO is required to study the geometry of these regions, how far acceleration can go and how individual systems vary with time.

How does particle acceleration work in diffuse shocks?

Could stellar winds collectively accelerate the bulk of the TeV to EeV cosmic rays?

Could the pressure exerted by accelerated particles quench stellar formation and shape galaxy evolution?

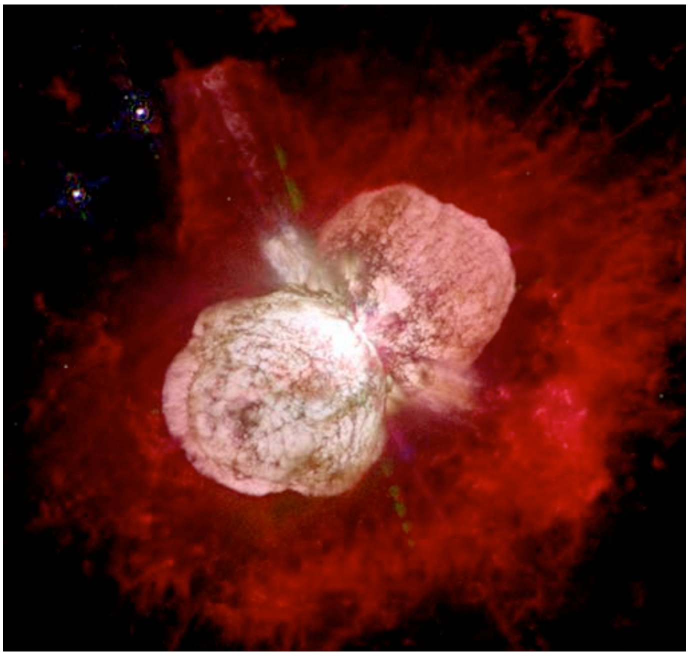


Fig. 8: Eta Carinae is made of 2 among the most massive stars of the galaxy, both emitting powerful winds colliding together [Credit: NASA].

While the classical paradigm emphasises supernova explosions as the dominant source of cosmic rays, it has been speculated that CRs are also accelerated in stellar winds around massive young stars before they explode as supernovae, or in star clusters. Indeed, there is growing evidence in existing gamma-ray data for a population of sources related to young stellar clusters and environments with strong stellar winds. However, the current instruments' sensitivity prevents the detailed study of these sources of gamma radiation. The Carina Nebula is one of the most active HII regions. It harbours 8 open stellar clusters with more than 60 O-type stars, 3 Wolf Rayet (WR) stars, and η Carinae (see Fig. 8), the only colliding-wind binary firmly established to emit gamma rays. Scientists of the Astronomy Department of UniGe have measured the periodic modulation of its gamma-ray emission during two entire orbits of the system. Confrontation of these data with MHD simulations suggests that the X-ray to GeV emission is of leptonic origin while the GeV-TeV photons are likely associated with hadronic emission generated by proton-proton collisions. These γ rays are produced via diffuse shock acceleration along the shocks formed in the wind-collision system. The huge luminosity of the primary star (5 million times larger than the luminosity of the Sun), provides a very large pool of soft photons as a target for γ-γ absorption. The variability of that absorption will be very well observable by the southern CTAO array on a daily/weekly timescale and will allow to confirm the physical mechanisms at play and constrain system parameters.

Micro-quasars & γ-ray binaries

A large part of the stars in the Galaxy form binary systems where two companion stars orbit around each other. When one of the stars reaches the end of its life and gravitationally collapses, it is replaced by a compact object: a neutron star or a black hole. The compact object may become a bright X-ray or gamma-ray source and the exact mechanisms involved are quite enigmatic. In some cases, it is not even clear if the powering energy is from matter falling on the compact object. It is evident that these galactic binary systems offer unique laboratories to study stellar mass black holes and neutron stars. The physical conditions (gas density, radiation, and magnetic field) change periodically along the eccentric orbit of the compact object around the companion star, changing the source

Some VHE gamma-ray emitters in the Milky Way are in known binary systems, consisting of a compact object – a neutron star or black hole – orbiting a conventional star. Only several such systems have been observed with the current generation of gamma-ray telescopes. CTAO will uncover an entire population of such systems.

Why some binary systems are active at high energy while others are not?

What powers particle accelerators in gamma-ray binaries?

What is the mechanism of gamma-ray emission from these systems?

activity and its high-energy emission. Some galactic stellar-mass black holes in binaries can be surrounded by accretion disks and accelerate jets, they are called "micro-quasars". Understanding the mechanisms leading to high-energy activity in these sources can thus help clarifying the mechanisms powering quasars and their jets in active galactic nuclei. Most of the compact objects in stellar binary systems do not appear as gamma-ray sources. It is not clear what triggers the VHE emission and how the acceleration efficiency evolves with the age of the system. CTAO sensitivity will enable the detection of weaker sources and statistical studies of the gamma-ray binary source population. It will also provide insights into the origin of high-energy activity through high quality measurements of the spectral and timing properties of brighter sources.

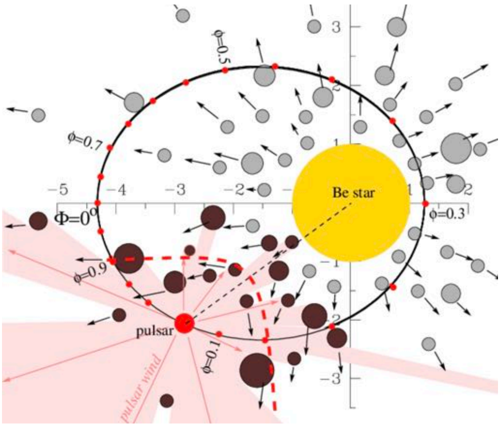


Fig. 9 The gamma-ray binary LS I +61 303 with a relativistic outflow from a young neutron star collides and a clumpy wind from a Be-type massive star [arXiv:0802.1174].

The Galactic Centre and Plane

The centre of the Milky Way hosts a zoo of high-energy sources, including a supermassive black hole 4 million times heavier than the Sun, the most recent galactic supernova, multiple SNRs, PWNs, and active star-forming regions. It also features a complex interstellar environment with strong magnetic fields and giant molecular cloud complexes that serve as cosmic-scale high-energy particle detectors. The high-energy activity of the Galactic Centre region injects huge amounts of energy into the interstellar medium and inflates bubbles filled with high-energy particles spanning tens of degrees in the sky. CTAO will make a deep exposure of the Galactic Centre region (Fig. 10), to find out if it is the black hole that emits gamma-rays, or if the emission comes from a SNR or PWN. It will also make a detailed survey of the region around the Galactic Centre, to trace the locations of injection of energetic particles in the region, understand the mechanism of their diffusion and escape into the outflow powering the Fermi Bubbles (Fig. 4) and to search for dark matter. In the energy region beyond 500 GeV, synergic work is ongoing between extensive air shower gamma-ray experiments such as LHAASO, HAWC, Tibet ASγ and neutrino telescopes such as IceCube and KM3NeT to observe the secondary gamma-rays and neutrinos from the diffuse flux of cosmic rays wandering millions of years in our galaxy interacting on the interstellar matter and producing them from pion decays. These measurements have the power to drive cosmic-ray composition models and reach a better understanding of their acceleration and propagation to the knee. This work will be supported by CTAO deep surveys to disentangle the contribution of single accelerators along the plane.

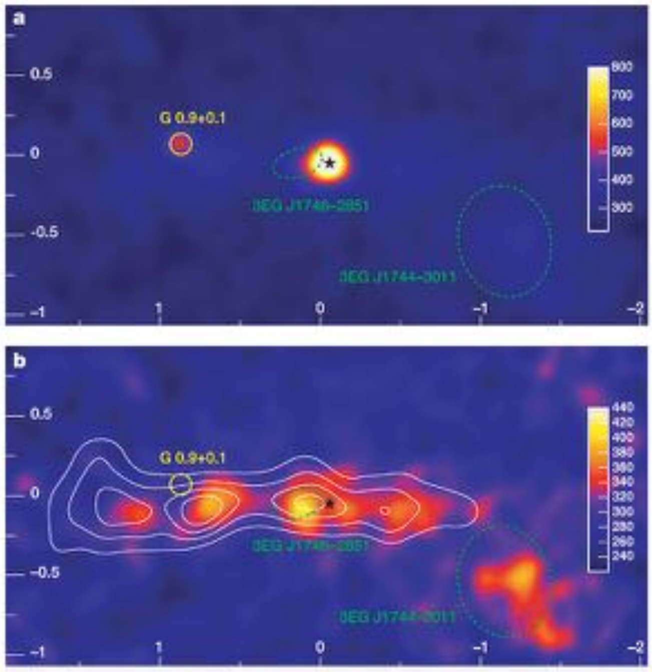


Fig. 10: H.E.S.S. image of the Galactic Centre (b) after the subtraction of 2 dominant objects (a) with the black hole Sgr A indicated with a black star. White contours indicate molecular emission tracing gas and cosmic rays illuminating giant molecular clouds and SNRs. [arXiv:0603021].*

Active galactic nuclei

Most massive galaxies of the Universe probably host an SMBH in their core but only about 1% of them are active i.e. are efficiently converting gravitational energy of in-falling matter into radiation. Active Galactic Nuclei (AGNs) probably share a common grand-design with different environments and viewing angle explaining their different observational properties (Fig. 11). AGNs with a high accretion rate are probably surrounded by an accretion disk, capable of efficiently converting gravitational energy to ultraviolet and X-ray radiation close to the black hole. Some of these disks launch high-velocity (relativistic) winds. Stars and clouds of gas are orbiting around, the latter producing broad emission optical lines. Molecules are evaporated close to the central regions and are found at a distance, forming a torus-shaped distribution of dust clouds. These clouds hide the active nucleus for a large fraction of the viewing directions and thermalise the radiated gravitational energy in the infrared. In most galaxies, the accretion rate, and the gas density, are so low that a disk cannot form. Gas is then advected in the black hole converting a small fraction of the gravitational energy to light.

Ultra-relativistic jets powered by Super Massive Black Holes (SMBHs) in the core of AGNs are the most impressive particle accelerators in the Universe. We do not know what triggers the formation of jets and do not yet understand the details of particle acceleration. As most of the jet power can be emitted in the gamma-ray band, CTAO will provide key information to answer the questions:

How do black holes transfer rotational energy to jets?

What is the structure of jets?

Can they accelerate cosmic-rays to ZeV energies?

How to explain the dynamics of jets and their variability?

What is the role of mildly jetted AGNs and hidden accelerators?

SMBHs with high and low-accretion rates can launch jets accelerating particles. Jets are predominantly detected in the radio via the synchrotron emission of the accelerated electrons, up to very large distances from the black hole. Jets are probably formed when the spin energy of the black hole can be extracted to accelerate particles to relativistic energies via magnetic field lines stretched close to the black-hole horizon (Fig. 12). Because of relativistic effects, most of the jet power is focused in a narrow cone in the jet direction. SMBHs with jets pointing towards the direction of the Earth appear very bright and rapidly variable. They are

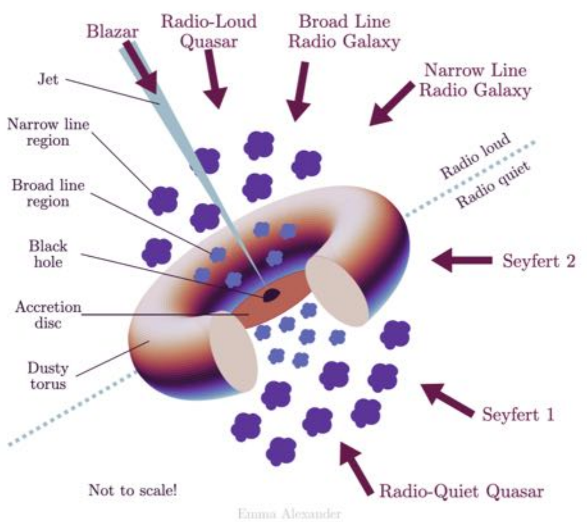


Fig. 11: AGN simplified scheme where the appearance of different features of an active galaxy powered by a black hole depends on the viewing angle indicated by arrows [arXiv:astro-ph/9506063].

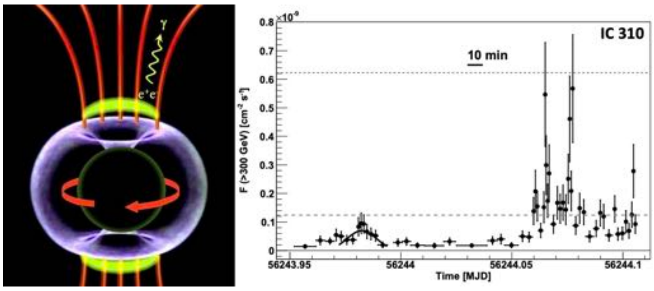


Fig. 12: Gamma-ray emission fast variability for the AGN IC310 (right) possibly due to particle acceleration in the "vacuum gaps" in the black hole magnetospheres (yellow on

named blazars and are bright from the radio to the VHE gamma-rays. Their spectral energy distribution (SED) shows a low-energy radio-optical synchrotron component and a gamma-ray component interpreted as inverse Compton emission of the same electrons in purely **leptonic scenarios.** High-energy gamma rays can also be emitted from the interactions of ultra-relativistic cosmic rays, potentially accelerated in the jets, with the ambient radiation or matter. These interactions would also produce particle showers and in particular high-energy neutrinos travelling along the jet (**hadronic models**).

On 22 Sep. 2017, a high-energy neutrino was identified by the IceCube neutrino telescope at the South Pole from the direction of a blazar, TXS 0506+056, flaring in the gamma-ray band as observed also by Fermi-LAT and MAGIC. A coincident observation of gamma-rays and neutrinos represents a smoking gun for the identification of CR sources, as in their interactions with ambient gas or matter they produce both. Later on, a more significant excess of neutrinos was identified from that direction by scientists at the DPNC/UniGe using historical data when the blazar was flaring in the radio and optical but not in gamma-rays. This triggered alternate structured jet models with multiple zones of particle and radiation production. Future more sensitive detections of multi-messenger transient activities in blazars by CTAO will shed light on the nature of phenomena powering high-energy activity in AGN jets.

The observed variability of the SED of AGNs and blazars is confronted with models involving leptonic and hadronic scenarios, with complex patterns entangling acceleration mechanisms and jet geometry, with the latter impacting the long-term trends and the former responsible for short timescales. Acceleration processes, such as shock-in-jet models, are considered where inhomogeneities, evolving due to hydrodynamic instabilities, produce relativistic shocks traversing the jet flow. These accelerate particles through diffusive shock acceleration and produce mid/short timescale variability at all wavelengths. This could not explain very fast variability episodes, such as those in Fig. 12, observed at TeV energies, with timescales of minutes. Hence, they triggered the attention on processes, such as magnetic reconnection, and modern particle-in-cell simulations, which have been able to reproduce spectra typical of Fermi acceleration and close to the observed spectral curvature and cutoffs. Long-term timescales require taking into account geometrical factors impacting on the beaming, such as changes in the jet orientation and bending and the transparency of the emitting region.

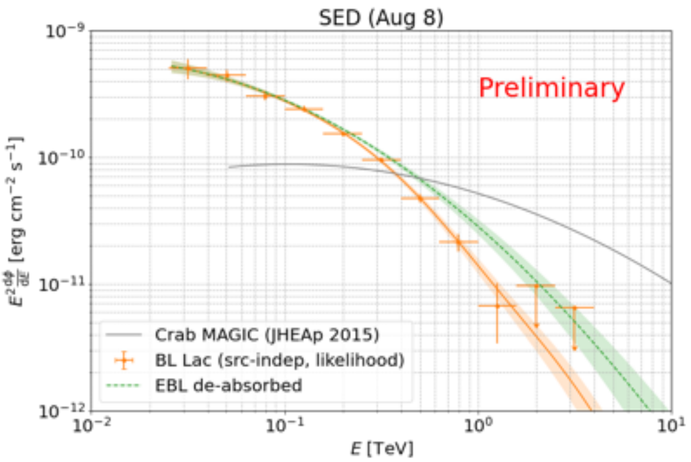


Fig. 13 The BL Lac measured and injected spectrum during a prominent flare in Aug. 2021 by LST-1.

The order-of-magnitude improvement of sensitivity that will be available with CTAO will allow to see details of the puzzling fast variability of the gamma-ray emission and to determine its minimal time scale. The integration of CTAO into the network of communicating observatories will allow triggering multi-messenger observations of fast-variable gamma-ray flares. During the science commissioning operation, in Aug. 2021, the CTAO LST-1 telescope detected a highly significant flare from the blazar *BL Lac*. With an analysis reconstructing gamma-rays using the full detector waveform of every camera pixel, scientists at the DPNC/UniGe could detect the flare down to an energy of 20 GeV (Fig. 13). Several telescopes in stereoscopic mode will detect such flares to even lower energies, where the number of photons is larger. On the time span of CTAO operations, it will be possible to combine and cross-correlate its data with those of the next generation of observatories: SKAO in the radio, Vera Rubin Observatory, E-ELT and Euclid in the visible, the proposed Athena or AMEGO in the X-rays, the neutrino telescopes IceCube-Gen2 and KM3NET, and the upgrades of Pierre Auger and Telescope Array and its successors from space and ground for UHECRs.

It is conjectured that jetted AGNs are responsible for the acceleration of the UHECRs, the highest-energy particles reaching ZeV energies. UHECRs could induce the high-energy neutrinos that contribute to the puzzling astrophysical diffuse neutrino signal discovered by IceCube a decade ago at energies above 100 TeV. Fig. 14 provides an overview of the radiation, the discovered cosmic neutrino flux by IceCube and the CR energy densities in the Universe. The diffuse gamma-ray energy density connects with the neutrino flux and, at even higher energies, with the UHECR flux. Actually, only a part of the cosmic neutrino flux can be due to jetted AGNs as searches for neutrinos from stacked Fermi blazars set upper limits at 20-50% contribution level, depending on the injection CR spectral index assumed for all of them. It is also noted that the cosmic neutrino flux overcomes the Waxman and Bahcall (WB) upper limit calculated as if UHECRs are injected from extragalactic sources transparent to UHECRs and neutrinos. Additionally, gamma-ray bursts are also disfavoured as UHECR sources due to the null results of coincident searches with neutrinos. The magnetic fields in their jets might be too high for protons to be able to generate

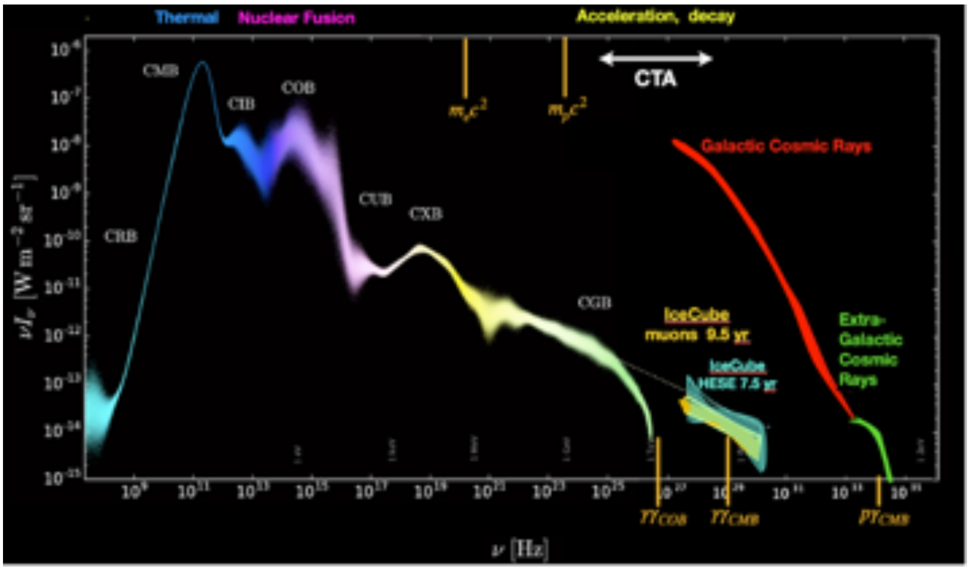


Fig. 14: Radiation spectrum in the Universe from radio to gamma rays [from arXiv:1805642]. In addition to higher energies the galactic CRs span 19 orders of magnitude (red) and the extragalactic CRs (green) other 4 four up to 10^{22} eV. Two derivations of the diffuse neutrino spectrum are shown [arXiv:2301.06320].

UHECRs or their baryon loading too low. All this evidence hints at an important role of calorimetric systems that can overcome the WB limit, as all the hadrons lose their energy inside the accelerating region, TeV radiation is absorbed and only neutrinos escape, but not UHECRs.

One of such system, NGC 1068, first emerged as a candidate calorimetric neutrino source in a search performed at DPNC/UniGe. This close-by Seyfert II AGN, hosting a starburst region and a very mildly relativistic jet, is identified by IceCube with more than 70 neutrinos with a significance of more than 4σ to be of astrophysical origin. NGC 1068 shows a clear excess of gamma-ray emission up a few tens of GeV in Fermi-LAT data initially pointed out by scientists at the Astronomy Department/UniGe, and interpreted as inverse Compton emission from the AGN on the starburst low-energy photons [arXiv:1008.5164]. On the other hand, gamma rays are not detected by MAGIC in TeV gamma rays. The emerging spectrum is therefore of leptonic origin, contrasting with the IceCube detection. The absence of a gamma-ray counterpart to neutrinos triggered AGN corona models, where neutrinos are accelerated in the region surrounding the horizon of the SMBH. NGC 1068 is a composite system and there might be also contributions of other acceleration processes such as AGN-driven winds from the accretion disk and/or shock acceleration from the starburst region from wind bubbles with consequent proton-proton interactions. Such a composite object will be an interesting target for the CTAO LSTs to explore the interplay between the AGN and starburst winds.

Future frontier of AGN studies

The current generation of IACTs detected the blazars closer to us and a few not-jetted AGNs. CTAO will massively expand the sizes of the VHE detected blazar and AGN source samples, and it will uncover aspects of the cosmological evolution of the blazar population, by detecting high-redshift sources. This will open the possibility of a systematic study leading to a possible relation between the observed characteristics of the VHE signals and AGN populations. There might be an evolutionary relation between blazar sub-classes, the understanding of which is limited by the still small sample of VHE-detected blazars. The increased statistics will allow to determine the model parameters that derfine the efficiency of particle acceleration in one or another type of AGN and what triggers, quenches, or enhances the acceleration process.

Even though the CTAO angular resolution (Fig. 24) is not enough to image the vicinity of SMBHs, it is still possible to "zoom" into the region close to it if the gamma-ray signal is magnified by the effect of gravitational lensing of a massive galaxy (Fig. 15). In this case, the micro-lensing of the AGN emission by stars in the lensing galaxy passing close to the line-of-sight, temporarily magnifies the flux from the very compact region in the AGN central engine. This provides a possibility to measure the size of the gamma-ray emitting source. CTAO will have enough sensitivity to detect such micro-lensing and locate the gamma-ray source within the AGN in the lensed sources.

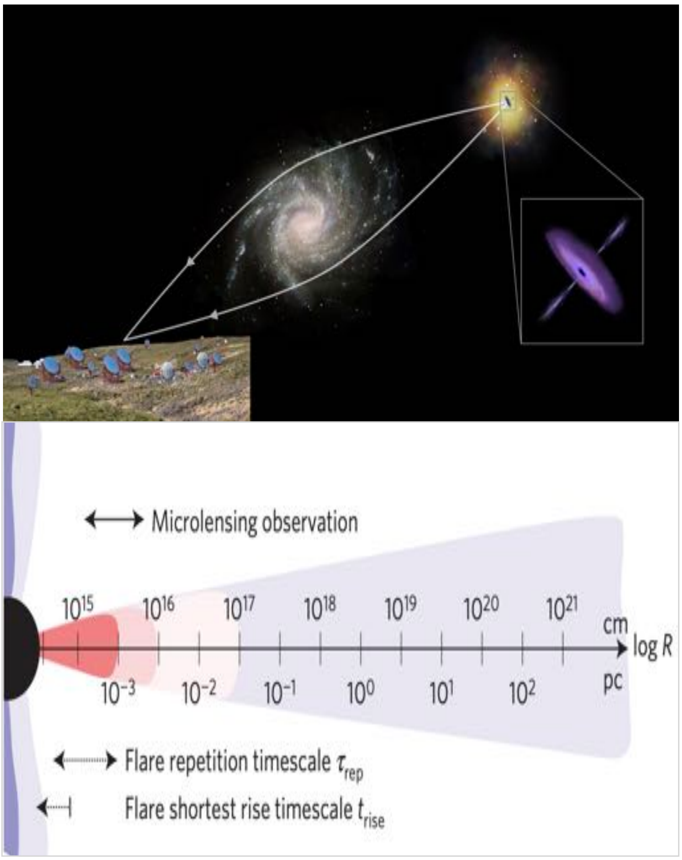


Fig. 15: AGN gravitational lensing and the derived size constrain of the gamma-ray blazar PKS 1830-211 [Neronov et al., Nat. Phys. 11 (2005) 664].

Gamma-ray bursts and multi-messenger transients

High-energy transient sources, like Gamma-Ray Bursts (GRBs), appear in the sky only for short periods of about a few to thousands of seconds. Their study requires coordinated campaigns synchronised and communicating telescopes in which CTAO will be integrated. Recently, it was proved that transient sources can emit electro-magnetic radiation and gravitational waves. CTAO will address the questions:

Which is the origin of GRBs?

Do these explosions leave a long-lived CR accelerator or are they purely leptonic?

What is the nature and variety of other repeating or not transients? What powers particle acceleration into them?

Powerful particle accelerators in astronomical objects require a huge power to maintain electric and magnetic fields. The necessary power may be available only for short moments, as, for example, when a tidal disruption event (TDE) occurs with an SMBH engulfing matter, or during the gravitational collapse of a massive star or a merger of binary neutron stars (BNS). It is commonly believed that gravitational collapses of massive stars are mostly at the origin of long GRBs with their "prompt" gamma-ray emission lasting about 10^3 s and that short GRBs of the order of 1 s originate from BNS mergers, as observed for the gravitational wave event GW 170817 (see Fig. 18). The BNS merger event occurring on Aug. 17, 2017, triangulated by the LIGO and Virgo interferometers was followed by the prompt gamma-ray emission detected 1.7 s after by Fermi-GBM and INTEGRAL ACS, followed by an optical/IR/UV afterglow emission that allowed the identification of the host galaxy NGC 4993 at about 40 Mpc distance. This event is a milestone of Multi-Messenger astrophysics, which informed us on items concerning gravitation and cosmology, particle and nuclear physics and astrophysics.

GRBs were the first transients discovered back in the 60th. Only now we are beginning to understand their origin, thanks to the new Multi-Messenger approach but the details of their origin and their relation to cosmic rays remain largely not understood.

The most credited model for GRBs, the fireball model (see Fig. 16), concerns the hot relativistic fireball generated by an SN collapse or a BNS merger. The fireball forms after the catastrophic event and expands isotropically in the jet frame. After its adiabatic expansion, the fireball becomes optically thin to prompt gamma-ray emission of keV to MeV photons lasting from ms to 1000 s, followed by internal shock collisions between faster and slower blobs in the jet. When the fireball is decelerated by the surrounding medium, the afterglow emission happens in all bands.

The current generation of IACTs has revealed the afterglow at TeV energies and possibly of a short GRB. These last are particularly hard to detect as current IACTs need about minutes to point to alerts from the network of astronomical observatories for gamma-ray transients. Only several GRBs have been detected in the VHE band so far. The small size of the GRB sample seen in gamma-rays from the ground is also due to the small FoV of IACTs. CTAO telescopes are specially designed for a large FoV (5°-9°) and to be able to re-point in a few tens of seconds. The 100-ton heavy body of the LST can turn in the direction of a GRB within about 30 s. This capability, combined with the high sensitivity of the cameras, will reveal a large population

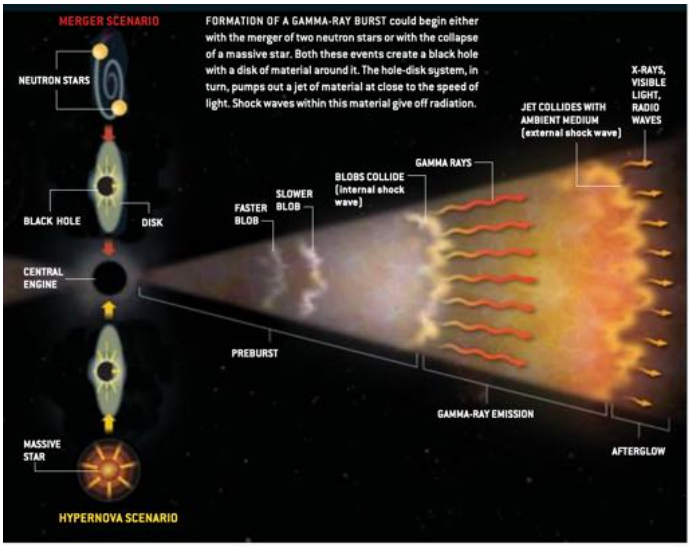


Fig. 16: Fireball model [Gehrels et al. (2002)].

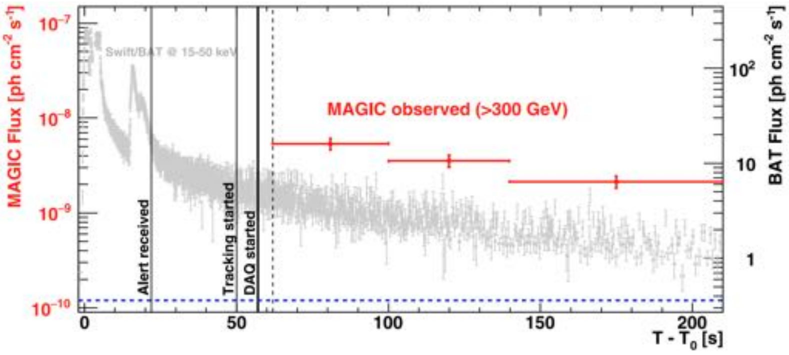


Fig. 17: Measurements of VHE gamma-ray emission from GRB190114C by MAGIC (red) and SWIFT/BAT (grey points with error bars) at lower energies [arXiv:2006.07249].

of VHE GRBs by automatically repointing in their direction right at the moment of their appearance in the sky and following up the sources deep into the afterglow phase. It is currently not clear what is the mechanism of the highest energy gamma-ray emission from GRBs. Recent detections with MAGIC and H.E.S.S. telescopes (see Fig. 17) reveal hard spectra that are at odds with the possibility that gamma-rays are produced as the result of the scattering of low-energy photons by the accelerated electrons. An alternative hypothesis of synchrotron origin would require peculiar source parameters, such as unreasonably fast relativistic motions.

Particularly puzzling is the recent detection of gamma-rays with energies higher than 10 TeV from GRB 221009A by the LHAASO gamma-ray telescope. It indicates that the intrinsic spectrum of GRBs may be hard also in the 10 TeV band, making the problem of their theoretical understanding even more severe.

The better quality of CTAO data and the larger source sample of observed GRBs will help solving the puzzle of their VHE emission mechanism. New types of transients will also be the object of Multi-Messenger campaigns, such as GW mergers and fast radio bursts, which at least in part may originate from earthquakes in highly magnetised stars (magnetars). The imminent start of operations of the massive sky surveys of the Vera Rubin Observatory in the visible band and SKAO in the radio, will result in an "avalanche" of transient detections. The variable and transient activity of astronomical sources will be discovered automatically in the survey data every day and reports on the discoveries will be broadcasted to CTAO and other telescopes for rapid follow-up observations. This will certainly lead to discoveries of new types or unexpected transient activities. A proper understanding of the physics of these diverse transients will require the availability of data at all energies, including the gamma-ray range. CTAO will provide such data and help to uncover the nature of the new rich variety of transient phenomena in the sky. It is not clear a priori which of the Multi-Messenger transient sources are active at high-energy. For example, the BNS merger events that are sources of short GRBs and also of GWs (see Fig. 18) certainly accelerate particles, but the highest energy gamma-rays produced by these particles may not be able to escape from the dense radiation environment of the source. CTAO detection or non-detection of different types of transients will help clarifying the nature of the physical processes taking place during the brief period of source appearance. Another example is given by “dormant” SMBHs in the centres of galaxies, that may suddenly become active during short TDEs.

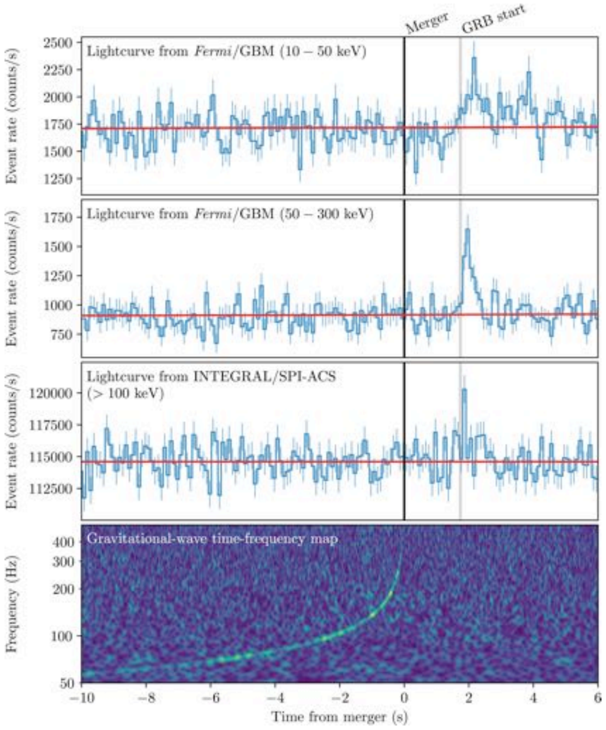


Fig. 18 Gamma-ray and GW 170817 [arXiv:1710.05834].

It cannot be predicted a priori if the transient AGN emerging from the TDE would function as a particle accelerator. We need first to look at TDEs and detect (or not) the gamma-ray sources associated with them. Transient phenomena may occur not only in "one-time" violent transformations of astronomical sources but also due to cataclysmic events in persistent sources, such as AGNs, flaring simultaneously in multiple energy bands, with subtle relations between their variability patterns.
Blazar monitoring programs of CTAO will shed light on inter-band connection, evidence for quasi-periodicity, jet emission morphology and geometry.

Galaxy clusters

Galaxy clusters are very large structures in the Universe grouping thousands of galaxies and CR storehouses since CRs produced in its member galaxies remain confined into them for a long time. Probing the density of CRs in clusters via their gamma-ray emission provides a calorimetric measure of the total integrated non-thermal energy output of galaxies. Accretion or merger shocks in clusters of galaxies provide an additional source of high-energy particles (Fig. 19). The emission from galaxy clusters is predicted at levels just below the sensitivity of current instruments. Scientists at the Astronomy Department/UniGe detected the Perseus cluster up to 0.1 MeV using INTEGRAL and measured upper limits on the GeV gamma-ray emission of the cluster of galaxies. Observations by the ETHZ group with MAGIC provided upper limits in the energy range 100 GeV to TeVs that indicate an energy density of CRs of less than 5% of that of the thermal gas. CTAO will provide more information about the energy of higher-energy galactic CRs.
Jets and radio lobes generated by AGNs have a dramatic impact on their surrounding environment and on galaxy clusters. X-ray emission from regions affected by jet lobes can be the result of inverse Compton scattering of accelerated electrons, indicating that particle acceleration can have an important role. CTAO will detect many more of these regions to better understand such injection processes from lobes and jets.

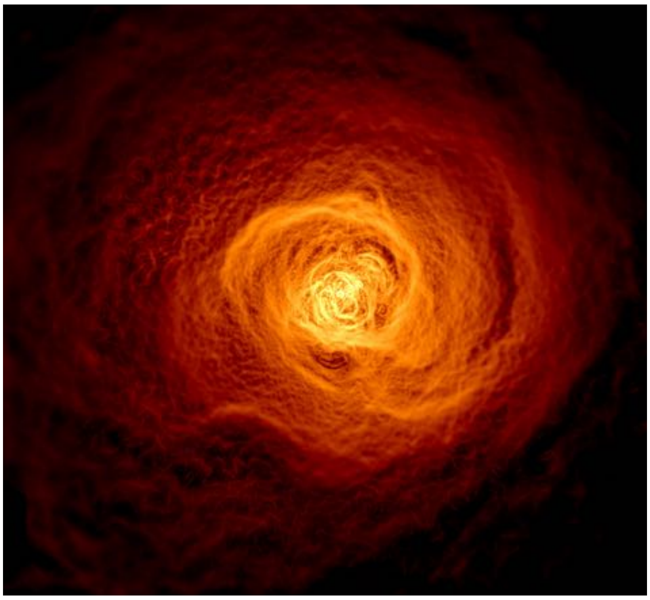


Fig. 19: Shock waves in the Perseus cluster from radio and X-ray observations. They might have been created by the collision of a small cluster (including only 10'000 billions stars) with the main cluster [arXiv:1705.00011].

Particles are trapped in the magnetic fields of galaxy clusters and accumulate for the entire age of the Universe. Hence, clusters keep the memory of the entire non-thermal activity of their components. CTAO will be sensitive enough to detect clusters of galaxies at high energies and to measure their CR content.

What is the CR yield from galaxies and AGNs over the age of the Universe?

Hierarchical structure formation generates shocks, do they accelerate particles?

Are particles accelerated in cluster collisions/mergers?

What about injection by large-scale radio lobes and jets?

Cosmology: cosmic radiation fields

In the range of the visible, the Extragalactic Background Light (EBL) is the cumulative light emitted by stars forming galaxies and AGNs, then reprocessed by surrounding gas and emitted in the infrared during their existence. It informs us on the evolution of star formation and AGN activity, and possibly on other unaccounted sources of light during the history of the cosmos. The EBL can be measured accurately by CTAO, from the absorption of injected gamma rays by sources on the way to us due to interactions with the EBL. This measurement addresses the questions :

Is the expansion rate deducible from it in agreement with the early or local universe measurements of the Hubble constant?

How did star formation and AGN population evolve?

The Universe is not transparent above 100 GeV, as gamma-rays interact with visible or infrared photons, and convert into a pair of electron and positron. This reaction suppresses the gamma-ray flux from distant sources. The suppression gets stronger with increasing distance, so that far-away sources are undetectable, defining a ``gamma-ray horizon''. While in the Fermi-LAT experiment working from 100 MeV to 300 GeV measures the most distant blazar B3 1428+422 at a redshift of z = 4.72, CTAO will be more limited in its horizon to values of z ~ 2, where the role for accessing this region will strongly depend on the ability to push the energy threshold of the LSTs down to 10 GeV with modern analysis methods based on machine learning. The modification of the flux from distant sources due to the energy-dependent absorption of gamma-rays allows measuring the EBL properties and its evolution with time. CTAO will be able to observe many more AGNs and GRBs than its precursors. Gamma-ray observations provide information on the star formation history, evolution of the AGN population and on possible unconventional sources of visible, infrared and ultraviolet light, such as decays of dark matter particles. This indirect measurement is interesting since the EBL is difficult to measure directly because the sky is illuminated by the much stronger Zodiacal light from dust in the solar system. The EBL from gamma-ray observations has some tension (Fig. 20) with direct measurements, possibly indicating that the correction for the Zodiacal light o direct measurements needs improvements or that our understanding of gamma-ray propagation is incomplete. This might hint at an unaccounted new physical process (such as the conversion between gamma-rays and axion-like particles) which could increase the transparency of the Universe to gamma-rays. It is also possible that the EBL spectrum has additional unforeseen components, like the emission from decaying dark matter particles, not yet been considered. The measurement of the EBL by CTAO is sensitive to the expansion rate of the Universe. An independent measurement of this rate is important because it can help to resolve the "Hubble constant tension", the debated inconsistency between various H_0 measurements that may point to the incompleteness of the currently accepted cosmological model. Current results are shown in Fig. 21 with two new players between the standard ones, the Type Ia SN and the Cosmic Microwave Background (CMB).

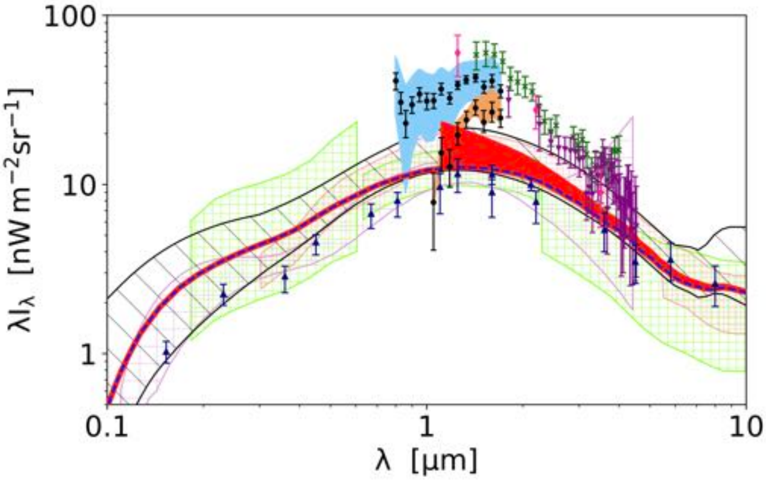


Fig. 20: Comparison of EBL direct measurements (upper data points) with estimates from gamma-ray observations (shaded regions) and lower bounds from galaxy counts (lower data points). The red shaded range shows possible additional EBL component from axion-like particles [arXiv:1911.13291].

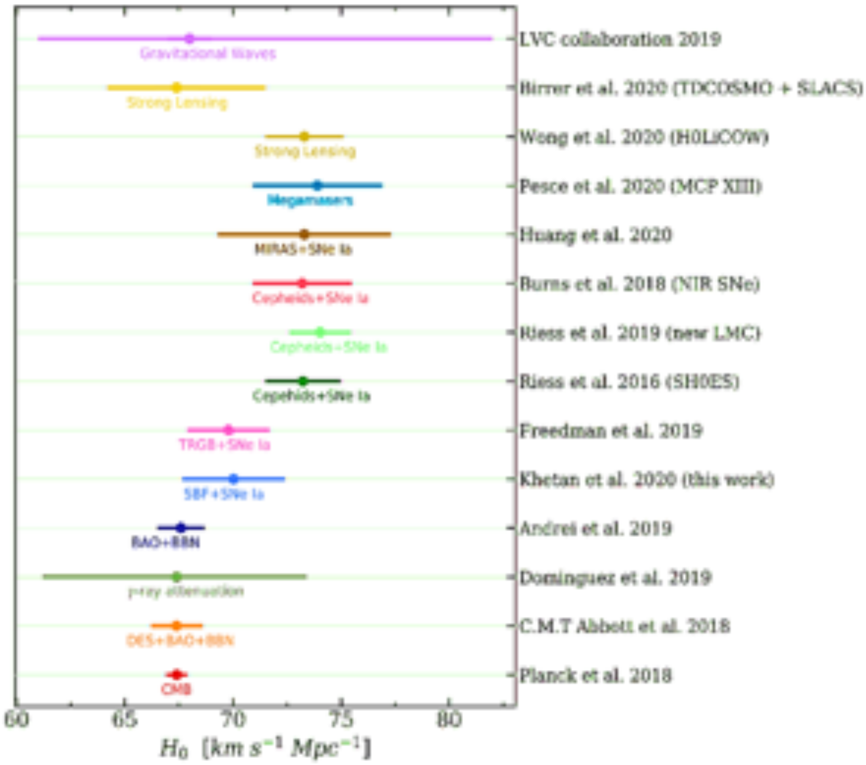


Fig. 21 Current overview of H_0 measurements [arXiv:2008.07754]

The expected precision of the H_0 constant measurement by CTAO has been recently discussed in a CTAO paper, with other cosmology topics of interest [arXiv:2008.07754]. Fig. 22 shows the improvement of CTAI (yellow stars) with respect to H.E.S.S. and Fermi-LAT arrays: notice that the statistical and systematic error is characterised by two regions as for the transition between LSTs and MSTs. CTAO will enable a measurement of γ-ray absorption on the EBL with a statistical uncertainty below 15% up to a redshift z = 2.

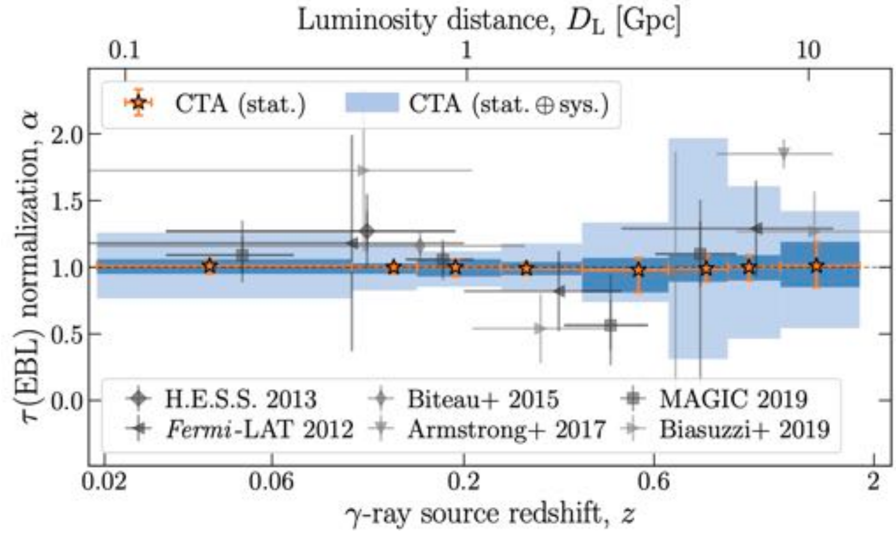


Fig. 22 The CTAO precision on the optical depth versus redshift of EBL photons for 839 hr of observation of CTAO [arXiv:2008.07754]

Cosmology: dark matter

Most of the matter in the Milky Way is dark, likely composed of yet unknown particles predicted in extensions of the Standard Model of particle physics. Interactions of the dark matter particles in the Milky Way and in other galaxies result in signals observable by telescopes. On the way to us in the intergalactic space axions might interact with gamma-rays distorting the observed AGN spectra. CTAO will shed light on the quest on the dark matter nature.

Is dark matter composed of Weakly Interacting Massive Particles (WIMPs) or in the form of Axion-Like Particles (ALPs)?

What is the lifetime of dark matter particles?

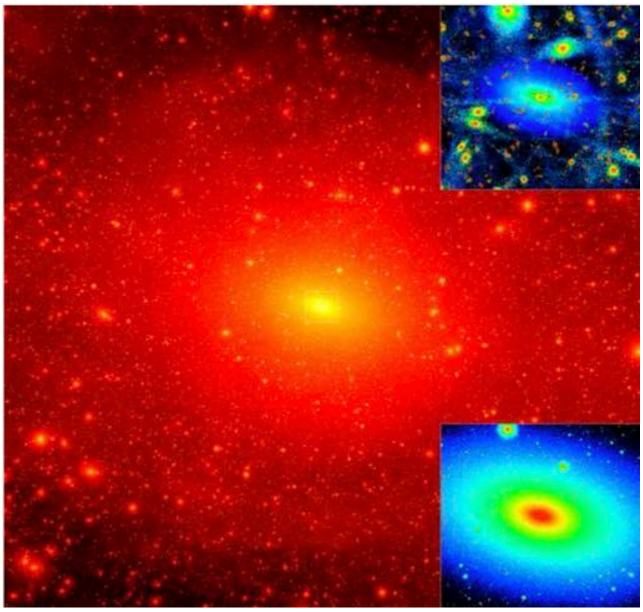


Fig. 23: Simulated dark matter halo of the Milky Way within 800 kpc and zoom on the central 40 kpc in the insert images [arXiv:0805.1244].

All the known matter in the Milky Way resides in a small region at the bottom of a gravitational potential well produced by dark matter. Most of the galaxy's mass and volume is filled with the elusive dark matter that manifests itself only through its gravitational pull. Many theoretical models assume that the dark matter particles still interact among themselves and with the conventional matter but with very tiny cross-sections. Large direct detection experiments, like XENON and its future successor DARWIN, are being deployed in attempts to catch some of the dark matter particles and make them produce signals in detectors placed on the Earth. This is possible if the dark matter is made of WIMPs with masses between several GeV to TeV energies. Alternatively, the sparks of radiation or particles and neutrinos from pair-wise collisions of dark matter particles leading to their destruction (annihilation) everywhere in the Galaxy can be seen by telescopes based on Earth or on space-based detectors. The AMS experiment on the International Space Station, with Swiss scientists at the forefront, hints to an excess of anti-electrons and seeks for a background-free signature of heavy anti-matter from dark-matter annihilation. In the case of WIMPs, the cross-section of the annihilation is known, so that the strength of the "annihilation glow" of the Milky Way can be predicted with high confidence. CTAO will have sufficient sensitivity to detect the WIMP annihilation in the central part of the Milky Way, if WIMPs indeed constitute the bulk of the dark matter. Otherwise, it will strongly constrain the possible existence of WIMPs. Gamma-ray observations also can reveal another type of signal produced by decaying dark matter particles that are very light, with masses that are comparable or smaller than the masses of the lightest known particles, neutrinos. In this case, the decaying dark matter particles may emit visible-infrared photons that would contribute to the EBL. Such contribution is detectable with CTAO. Heavy unstable dark matter particles would decay with the production of gamma-rays, also detectable with CTAO.

Another candidate for dark matter is the hypothetical Axion-Like Particle (ALP). In a strong magnetic field, a TeV photon could convert into an ALP, and convert back into a photon in another strong field. These ALP-gamma-ray oscillations would introduce features in the spectra of distant AGNs which could lead to indications for the existence of ALPs.

Cosmology: magnetic fields

Vast voids between galaxies host tiny magnetic fields that may be relics of the Big Bang, generated during the first microseconds of the existence of the Universe. If this is so, these fields carry information about the Universe just moments after its birth. The intergalactic magnetic fields influence gamma-ray signals from distant sources. CTAO measurement of this influence will help to answer the questions

What are the properties of the intergalactic magnetic fields and are they of cosmological origin?

What led to their generation right after the Big Bang?

Gamma-ray interactions with the EBL photons result in deposition of electron and positron pairs all over the Universe, including vast voids between galaxies. These pairs are electrically charged and their trajectories are deflected by such magnetic fields present in the voids. This effect is observable, because electrons and positrons emit detectable secondary gamma rays in interactions with the CMB photons. The intergalactic magnetic field parameters, such as its strength and correlation length, are not yet measured. CTAO will be able to pinpoint the field parameters and verify their cosmological origin. This measurement, combined with complementary measurements in the radio-band by SKAO and CMB data will establish a new cosmological probe, sensing the state of the Universe just instants after the Big Bang. Magnetic field generation in the Early Universe has most probably been driven by processes that are not described by our current knowledge. Several phenomena beyond the Standard Model of Particle Physics are observed in the present-day Universe such as dark matter and dark energy or asymmetry. Information on the physical processes in the Early Universe that may be obtained through new cosmological magnetic field probe will help us to understand the nature of these phenomena.

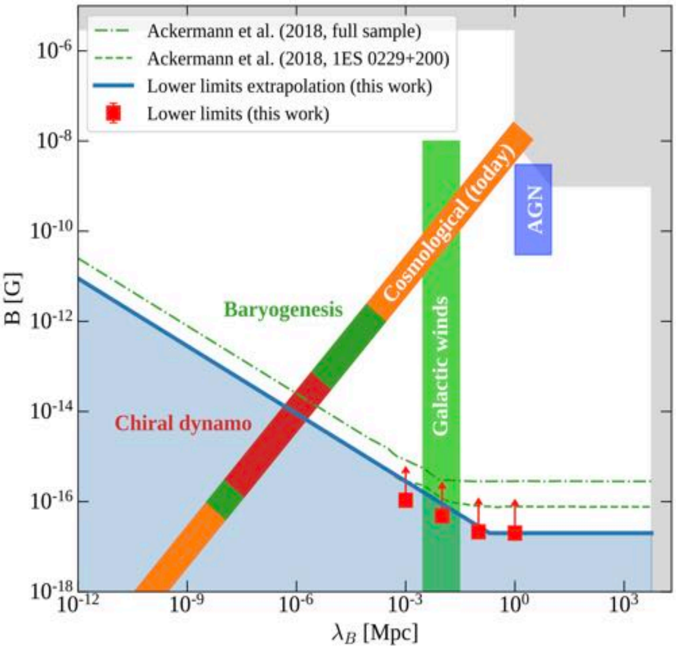


Fig. 24: Known upper bounds on the strength and correlation length of intergalactic magnetic fields (grey shading) and lower bound from gamma-ray observations (blue shading). Coloured threads show theoretical predictions to be explored by CTAO [arXiv:2210.03321].

Measurement of the cosmological magnetic field may also help in resolving the long-standing problem of the origin of magnetic fields in galaxies and galaxy clusters. Such fields are known to be the result of dynamo amplification of pre-existing seed fields, but the nature and properties of these fields are not known. The cosmological magnetic field can in fact be the seed field for the galactic dynamos. Magnetic fields in the Early Universe excite primordial gravitational waves and later on they may affect the cosmological recombination of protons and electrons into atoms and leave an observable imprint on the CMB properties. Magnetic fields are amplified today during the formation of galaxies and galaxy clusters. The amplified fields are detectable with radio telescopes like SKAO, through the Faraday rotation effect. All the known matter in the Milky Way resides in a small region at the bottom of a gravitational potential well produced by dark matter filling the galaxy which manifests itself only through its gravitational pull. The only way to tackle this problem is a Multi-Messenger approach between CTAO-SKAO and ET and LISA, which will search for the Stochastic GW Background.

The Cherenkov Telescope Array Observatory

Fig. 25: Rendering of the CTAO Northern Array with the existing MAGIC telescopes on the right [Gabriel Pérez Díaz, IAC]. The Southern site is in Fig. 1.

The Cherenkov Telescope Array Observatory (see http://cta-observatory.org) is the new generation gamma-ray observatory inheriting from the current generation of telescope arrays H.E.S.S., MAGIC, and VERITAS. For the first time, CTAO will unify the worldwide research groups working in this field in a common strategy for realising an observatory, resulting in a unique convergence of human resources and know-how.

CTAO will be composed of 2 arrays of IACTs at about 2000 m a.s.l. at the ESO premises in Paranal, Chile, and at the site of Roque de Los Muchachos La Palma, Canary Islands. CTAO will be a distributed infrastructure composed of 2 arrays of telescopes, a Science Data Management Centre in DESY-Zeuthen coordinating 4 off-site data centres, one of which will be in Switzerland, and a headquarter in Bologna. In the baseline configuration (named Alpha) there will be 4 Large Sized Telescopes (LSTs) with optical reflecting surfaces with 23 m diameter and 9 Middle Sized Telescopes (MSTs) with 12 m diameter reflectors in the Northern Site at the Observatory of Roque de Los Muchachos in the La Palma Canarian Island (see Fig. 23). At the Southern Array, located at the ESO premises of Paranal in Chile, 14 MSTs and 37 Small-Sized Telescopes (SSTs) will cover an area of a few km^2 (Fig. 25). The SSTs for the first time will pioneer two technologies in the field: dual mirrors in a Schwarzchild-Couder configuration (see Fig.1) and silicon photomultipliers as photosensors instead of photomultipliers (SiPM) as adopted by the LSTs and MSTs. SiPMs were first pioneered in Switzerland by the FACT project (see Fig. 27) and by the SST-1M.

Recently, Italy approved the INAF-INFN project to deploy additional 2 LSTs in the Southern site which ideally will be complemented by other 2 LSTs in the next future for best performance in the 20 GeV - 500 GeV region. The Swiss Institutes are strongly committed to the LST construction and long-term operation.

CTAO array performance

The spectacular astrophysics results obtained by the current IACTs demand a more sensitive observatory. The IACT technique is by now well established and, at least in the core energy range above 100 GeV, the performance and the limitations of current instruments are well understood. This allows a reliable extrapolation towards a next generation of instruments, providing vastly improved performance and increased flexibility to accommodate a large community of users. CTAO aims at a better sensitivity in the core energy range by roughly one order of magnitude. Three different sizes of telescopes will achieve a sensitivity covering a very wide energy range from 20 GeV (overlapping with space-based gamma-ray instruments such as Fermi-LAT) up to 300 TeV. The angular resolution below 0.05° above 1 TeV (see Fig. 26) and 2 milli-Crab flux sensitivity (meaning that a flux in the TeV region 1000 smaller than the Crab Nebula measured one would be detectable at 2σ confidence level) in a few years for the Galactic Plane gamma-ray survey. CTAO will reveal finer details in the sources and unprecedented detection rates, enabling researchers to track transient phenomena on very short time scales.

The Key Science Projects of CTAO

The number of scientists attracted to the still-young field of gamma-ray astronomy is growing at a steady rate, drawing from other fields such as nuclear and particle physics, in addition to the increased interest by other parts of the astrophysical community, such as radio and X-ray astronomers. About 1’400 scientists from about 30 research institutes formed the CTA Consortium (CTAC), which has promoted the Science of CTAO. This made CTAO the most prominent priority of international Roadmaps, e.g. the APPEC Roadmap 2017-2026 and the ESFRI Roadmap where it is a landscape project together with SKAO and E-ELT. The **Key Science Projects (KSP)** of CTAO were studied and are now collected in the Science Book (arXiv:1709.07997) and reserved observation time is planned to bring the foreseen results. The KSP are built around 3 major pillars of CTAO Science: 1) Cosmic rays (how and where they are accelerate? their propagation and their impact on the environment); 2) Probing extreme environments and the processes close to neutron stars, black holes and relativistic jets, winds and explosions; exploring cosmic voids and magnetic fields; 3) Physics frontiers beyond the standard model of particle physics (the nature of the dark matter and how is it distributed, the existence of axion-like particles, violations of Lorentz invariance for high-energy photons.

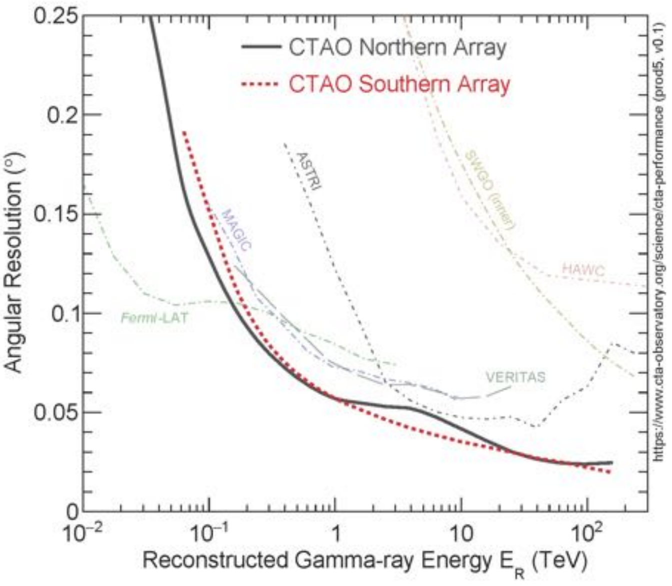


Fig. 26: Angular resolution of Northern and Southern CTA sites and existing and future gamma-ray observatories.

The CTAO observatory organisation and Swiss participation

In the 1980’s, after almost 20 years of developments, X-ray astronomy moved from PI led experiments to observatories open to the scientific community at large. This evolution led to the enormous success of X-ray astronomy which is presently one of the major branches of astronomy. Ten years ago, the hard X-ray-MeV community followed the same route and now, it is the turn of the GeV–TeV community, where the ambition of CTAO entered the ESFRI Roadmap thanks to the strong convergence of the European and Intercontinental communities of high-energy astronomers and particle physicists. They share a clear vision to move from experiments such as H.E.S.S., MAGIC and VERITAS, which release only a small amount of high-level data, to an observatory structure serving a broad community.

For the first time, the intention to participate to the establishment of CTAO of the scientists in Switzerland appeared in the CHIPP document on the achievements of the CHIPP Roadmap 2005-2010, and clarified in the following 2018-2020 CHIPP Roadmap containing the Recommendation 6: “CHIPP recommends a further *strengthening of ties with the CHAPS community, both scientifically and technically. As an instrument of common interest for both communities, Switzerland should secure access to CTAO at a level that is appropriate for the size of the Swiss researcher community interested in CTAO…*”. This recommendation for a joint effort of the CHIPP and CHAPS for the establishment of Multi-Messenger Astrophysics in Switzerland with CTAO and gravitational wave infrastructures is repurposed in the Roadmap document 2025-2028. The size of the CTAO future users has ramped up to approach now 3% of the project and they are spread in the major institutes in Switzerland (UniGe, ETHZ, EPFL, UZH and Bern).

Despite this apparently small fraction, the Swiss scientists cover many responsibility roles. In 2007 the UZH, UniGe and ETHZ joined the CTA Consortium to start the concept and design studies. The Swiss scientists had a leading role in the design years and in the definition of the science goals and participated to the proposal of the cameras of the MSTs, the actuators to move the mirrors of LSTs and MSTs, and a very performing concept of small size telescopes, the SST-1M after the FACT experience with silicon photomultipliers, that were adopted for the SSTs and SCTs (see Fig. 1 and next sections). This work was mostly sustained by the competitive programs of SNSF Sinergia, FLARE and R'Equip and by the support of involved Institutes and Research Foundations, as Boninchi and Schmidheiny in Geneva.

In 2014 UZH, DESY and INAF funded the legal interim entity of the observatory, the CTAO GmbH which will be in operation to 2024. Prominently, Prof. Straumann of UZH covered the role of Managing Director of the CTAO GmbH from 2016 to 2018. Since then, CTAO is governed by a Council including the representatives of associated nations, advised by a STAC.

In Switzerland, CTAO joined the SERI Roadmap for large Research Infrastructures in 2016 and in fall of 2019, UZH transferred the share of votes to the UniGe. For the period 2021-2024, two Performance Agreements were signed with SERI, one coordinated by the UniGe on the LST, Data Pipeline and Preservation System (DPPS) and on the Array Control and Data Acquisition (ACADA) software of CTAO. Currently, the plans for the 2025-2028 period have been evaluated as Category A in the Swiss Roadmap process by the SNF and the project can guarantee the participation to the development of relevant software and hardware as in-kind contributions described in the next sections.

CTAO will transit to an ERIC legal entity in Aug. 2023 (see schedule below) with 13 member and observer nations (Australia, Austria, Czech Republic, France, Germany, Italy, Japan, Poland, Slovenia, Spain, Switzerland, United Kingdom, the Netherlands) and the Intergovernmental Organisation ESO. The transition to the ERIC is an extremely important phase: Switzerland will initially join as a Founding Observer, and then it is extremely relevant that it joins as a full member to fully profit from the accession to the observation time of CTAO for long term. The schedule of the project is highlighted below with major milestones.

During the operation of CTAO, including the operation of one of the 4 CTAO off-site Data Centres in Switzerland, the allocation of the observation time, beyond the legacy time of CTAO for the Key Science Projects and the reserved time for various agreements with the hosting country (Spain) and the ESO, will be prioritised based on scientific excellence. For the first time in this field, CTAO will generate large amounts of data in part publicly accessible, allowing data mining in addition to targeted observation proposals. Other data will be accessible through policies and tools in use in the astronomical observatories based on the excellency of proposed science from the member states of the observatory. CTAO aims to emerge as a cornerstone in a networked multi-wavelength, multi-messenger exploration of the Universe. Proposals can be submitted to request normal observations, observations coordinated with other observatories, target of opportunity and will be selected based on scientific merit through a peer-review process.

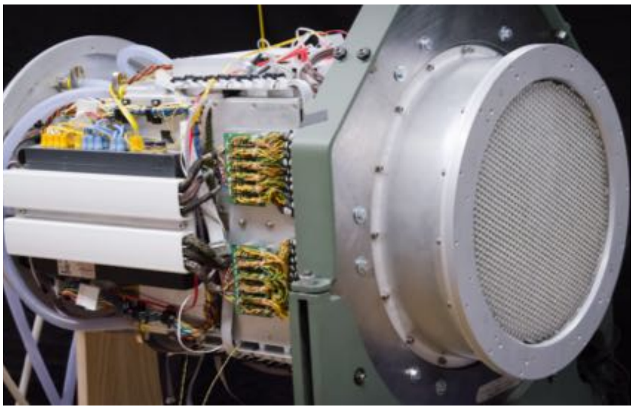
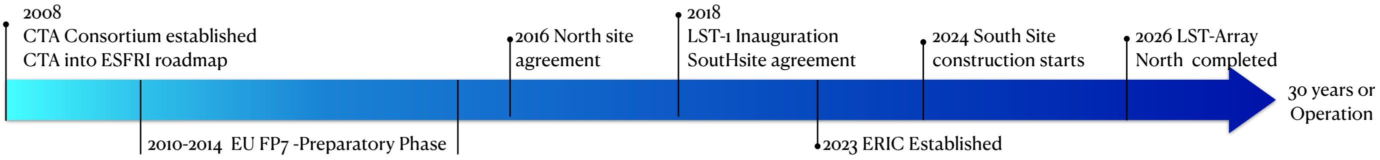


Fig. 27 The FACT SiPM camera



The Swiss actors

The DPNC – University of Geneva

The Département de Physique Nucléaire et Corpusculaire (DPNC) has Astroparticle as one of its 3 pillars, with high-energy particle physics and neutrinos. It has a long-standing tradition in building detectors, with outstanding workshops on electronics and mechanics specialised in silicon detectors that supported CTAO over time. The DPNC has designed and built the SST-1M telescopes, now taking data in stereo mode at the Ondřejov observatory. Its cameras were designed, developed and tested in the DPNC clean chamber. They implement advanced analog electronics for silicon photomultipliers (SiPM) that led to new ideas in the photo-sensing domain and medical applications. The DPNC has a longstanding program on cosmic ray physics from space with implementation and operation of well-known detectors in the field of direct CR measurements and dark matter, and astrophysical sources such as gamma-ray bursts. These are AMS, DAMPE, HERD, POLAR2 and now the prototype for Cherenkov detection from space TERZINA. The CTAO group at the DPNC, also involved in IceCube, SST-1M, LHAASO and MAGIC, has experience in hardware engineering and scientific data analysis. It is run by: Prof. Teresa Montaruli who joined the DPNC as Full. Professor in 2011 from UW-Madison, coordinating the CTAO-CH collaboration; Prof. Domenico della Volpe, project manager of the SST-1M and LST lead system engineer; MER Matthieu Heller leading the LST working group on the LST advanced camera. The DPNC is responsible for the calibration of the CTAO arrays and of the quality of their data.


The SST-1M camera.

The Astronomy Department – University of Geneva

The extreme Universe group of the astronomy department of the University of Geneva started its activities in 1988. The group was selected by the European Space Agency in 1995 to build and operate the data centre of Europe's gamma-ray space observatory INTEGRAL, in operation for more than 20 years. This included all activities from the decoding of spacecraft telemetry to the provision of high-level scientific products to the scientific community worldwide. The activities developed to support or lead other high-energy space missions such as POLAR, XRISM, POLAR-2, Athena and ground experiments such as FACT, MAGIC and CTAO. In parallel to their various operational duties, scientists are active in different research fields ranging from the study of various types of X-ray binaries, pulsars and their winds, massive stars and their winds, supernova remnant, active galactic nuclei, galaxy clusters, gamma-ray bursts and dark matter/cosmology using all types of astronomical facilities. On average, the group contributed to 50 referred papers per year. They led the first scientific paper based on data from the first CTAO telescope LST-1. The department is providing several in-kind contributions to CTAO: the software handling in real time the data of all CTAO telescopes (about one million CD-ROMs per observing night), the control software for several CTAO telescope types, the distributed data management system, archiving of the order of 10 PB of data per year. These efforts are led by Profs Roland Walter, Stephane Paltani and Dr Nicolas Produit.


The INTEGRAL spacecraft

Institute for Particle Physics and Astrophysics – ETH Zurich

The Institute for Particle Physics (recently merged with Astrophysics) has a long tradition of building and operating detectors at accelerators (e.g. CMS) as well as in space (e.g. AMS). In 2003, a group led by Prof. Felicitas Pauss and Adrian Biland joined the MAGIC collaboration to explore the highest energetic photons. The MAGIC telescope has a diameter of 17m and is able to point to any location in the sky within less than 30s. To achieve this, it is not built as a solid steel structure, but has a lightweight CFK frame. Nonetheless, the CFK frame deforms when pointing to different orientations, drastically reducing the optical quality of the instrument. Therefore, each of the 234 individual mirrors is equipped with an Active Mirror Control (AMC) to correct for this deformation. MAGIC was the first instrument equipped with AMCs, and in 2003 the performance was far from satisfactory. The ETH group took over responsibility and made the system work well within specifications. The group built an improved AMC for the second MAGIC telescope. Later, the UZH group took over the AMC for CTAO. When SiPMs became available, the group built within 4 years the first SiPM camera for the FACT telescope. In 2012, this success convinced CTAO to use similar sensors for the SSTs. Prof. Adrian Biland is active in MAGIC, FACT and CTAO in several positions since 2003, e.g. in MAGIC: convenor for fundamental physics (-2010), AMC coordinator (2004-), (Co-)chair of the collaboration board (2017-); in FACT: spokesperson (2007-); in CTA: board of working group convenors (2006-2012), board of governmental representatives (2020-).

The FACT telescope

Department of Physics – University of Zurich

The Physik-Institut at UZH has a long history of detector development in particle and astroparticle physics. Specific to CTAO the main early involvement under Prof. U. Straumann was the development of FlashCam, a prototype camera for the MSTs, which was successfully tested in 2018 and it is now operating on the largest H.E.S.S. telescope leading to various breakthroughs. In particular, the group developed active control elements for automatic control of the mirror segments, as well as FPGA-based digital readouts of photon detection. Currently, the CTAO-related research activities are in Intensity Interferometry (led by Prof. Prasenjit Saha) and machine learning (led by Prof. Nicola Serra) for the Advanced Camera program. The research in Intensity Interferometry consists both of theory and simulations, and the development of new detectors. For the latter, the expertise developed earlier with FPGAs at UZH in the context of FlashCam is relevant. Prof. Saha was the coordinator of the stellar intensity interferometry working group of the CTA Consortium in 2022. In machine learning the primary focus lies in exploring the potential applications of deep learning, including their applicability to FPGAs. Nicole Serra’s group also holds a prominent position in LHCb, and is also actively involved in several notable projects, including SHiP, with Prof. Serra at the helm as the physics coordinator, along with SND@LHC and the Mu3e experiments. Prof. Serra's team showcases considerable experience in the realm of neural networks and is accountable for the Data Acquisition (DAQ) firmware of the UT.

The FlashCam for MSTs

Physics Department – University of Bern

The Physics Institute of the University of Bern has been active in space research since the 1960s and has led and helped develop >30 space experiments from Apollo 11 to the ROSETTA and CHEOPS missions. The institute has built structural elements for numerous ground and space experiments. In August 2021, Prof. M. Falanga was appointed Professor of High Energy Astrophysics at the University of Bern. With Prof. Falanga's commitment to UniBe, the CTAO is considered cross-disciplinary for the Physics Institute at the University, combining the Space Science Division and the High-Energy Physics Laboratory, which also deals with some aspects of particle astrophysics. Prof. Falanga has extensive experience in data reduction, analysis, and theoretical interpretation of compact objects in high-energy astrophysics. As a first step, Prof. M. Falanga, who recently became interested in CTAO, will be involved in the Data Quality Pipeline of DPPS. In the era of CTAO, when the detectors are extremely sophisticated devices and new physics is discovered, measurements of the quality of the recorded data guarantee not only solid and reproducible scientific results, but also open the way to new discoveries. The scientific interest of the Bern group he is forming is related to the magnetosphere of a pulsar, the most extreme places in the universe due to their magnetic fields, plasma composition, emission of electromagnetic radiation and particle acceleration. The Bern group is interested in the mechanisms that allow pulsars to produce and accelerate gamma-rays, aside from software building.

Artistic view of CHEOPS.

Advanced Quantum Architecture Laboratory – EPF Lausanne

The Advanced Quantum Architecture Laboratory (AQUA Lab) was founded in 2003 by Prof. Edoardo Charbon upon the premise of creating sensors capable of detecting single photons. As of mid-2023, the lab has graduated 33 PhD students and over 100 M.S. students in various disciplines, including electronics, CMOS and cryo-CMOS design, and photodetector and radio-frequency design. The lab holds several records: the highest timing accuracy in a SPAD (single-photon avalanche diode) at 7.5ps FWHM, the highest PDP (photon detection probability) in a CMOS SPAD at 78%, the smallest DCR (dark count rate) at 10mcps at cryogenic temperatures, and the smallest SPAD pitch at 2.2μm.

The lab is responsible for many innovations, including the first deep-submicron SPAD in 2007, the first 3D-stacked SPAD camera in 2015, and the first megapixel SPAD camera. Many single-photon sensors came out of the lab, including the SwissSPAD family, capable of high dynamic range at high frame rates, the LinoSPAD family, for reconfigurable single-photon sensing, the Piccolo and Ocelot sensors, for TCSPC (time-correlated single-photon counting), and nanoSPAD, a high-performance array of raw SPADs.

Many applications have taken advantage of SPAD image sensors created by the AQUA Lab, often achieving unprecedented performance. This includes FLIM (fluorescence lifetime imaging microscopy), FRET (Förster resonance energy transfer), PET (positron emission tomography), time-resolved Raman spectroscopy, LiDAR (light detection and ranging), quantum distillation, and quanta burst photography.

The lab's spin-offs are active in automotive LiDAR, microscopy, and high-performance SPAD processing.

The role of the AQUA Lab in CTAO is the creation of imaging sensors with unprecedented speed and dynamic range, as well as fast analog-to-digital converters for SiPMs.

Astronomy Laboratory – EPF Lausanne

SKA precursor telescope MeerKAT in South Africa.

The Laboratory of Astrophysics (LASTRO) of EPFL is involved in a wide range of projects in the domains of visible light and infrared astronomy (SDSS, DESI, 4MOST, MOONS ground-based facilities, Euclid space mission). Prof. Jean-Paul Kneib at LASTRO leads the Swiss participation in the Square Kilometer Array Observatory (SKAO), a next-generation radio array that will survey the radio sky with unprecedented sensitivity. LASTRO, in collaboration with CSCS and FNHW, is engaged in the management of the SKA Big Data, which is a major information and communication technology challenge for the upcoming decade. This emerging expertise in astronomical Big Data has allowed LASTRO to take responsibility for setting up and running one of the four Off-site Data Centres (Off-site DC), in collaboration with CSCS, and to join the collaboration around the LST sub-array of CTAO (Prof. Andrii Neronov, Dr Volodymyr Savchenko). Understanding of astronomical sources visible in gamma rays with CTAO and in the radio band with SKAO requires analysis and interpretation of diverse multi-wavelength and multi-messenger (radio-to-gamma-ray, neutrino and possibly gravitational wave) data. The CTAO data management team at LASTRO is leading the Multi-Messenger Online Data Analysis (MMODA) platform based on a novel approach of cloud computing technology connected to the European Open Science Cloud and promoting Open Research Data practices.

Swiss National Supercomputing Centre – CSCS Lugano

CSCS develops and operates a high-performance computing and data research infrastructure that supports world-class science in Switzerland. CSCS resources are used by scientists for a diverse range of purposes – from high-resolution simulations to the analysis of complex data, to the development of software codes exploiting the potential of the next generation of computing architectures. CSCS has a strong track record in supporting the processing, analysis and storage of scientific data, and is investing heavily in new tools and computing systems to support data science applications. For more than 15 years, CSCS has been involved in the analysis of the many petabytes of data produced by scientific instruments such as the Large Hadron Collider (LHC) at CERN and is also hosting other scientific platforms such as the Materials Cloud from NCCR Marvel, eBrains from the Human Brain Project or the Numerical Weather Forecast from MeteoSwiss.

Starting in early 2022, a joint effort of the CTAO and SKAO groups is establishing CSCS as an infrastructure for astrophysics. CSCS is one of the four off-site data centres for CTAO.

The group is led by Mr Pablo Fernandez, who coordinates the international effort as data centre manager. They pursue synergies with SKAO which aims at optimising the usage of software (such as RUCIO), infrastructure services (such as Kubernetes) and the usage of GPUs in CTAO and SKAO on Alps, the new infrastructure at CSCS that will support these science platforms at scale.

The Swiss participation in CTAO

Foundations: FACT and SST-1M

The Swiss involvement in gamma-ray astronomy instrumentation has been foundational. Nowadays, SiPMs are replacing photo-multiplier tubes in almost every single-photon sensitivity application. Their potential for gamma-ray astronomy was identified very early by the Swiss *gamma-ray* community that refurbished a HEGRA telescope installed at the observatory of La Palma with a Cherenkov camera based on SiPM sensors. Led by ETHZ, the First G-APD Cherenkov Telescope (FACT) was a pathfinder of this technology and it is in operation since 2011.

Given the successful achievement of FACT, the UniGe group, in collaboration with a consortium of Polish and Czech institutes, decided to further develop this approach and proposed a Davies-Cotton telescope with a SiPM camera for the SST array, the SST-1M. The camera features custom hexagonal SiPMs developed by DPNC/UniGe in collaboration with Hamamatsu Photonics, and hollow light concentrators. The latter resulted from a joint development between the UniGe and the Swiss company Thin Film Physics AG to achieve high optical efficiency and adopt a cost-effective injection moulding plastic technique for production. Always in collaboration with Thin Film Physics AG, the DPNC introduced for the first time an optical filter coated onto the protection window to enhance the response for Cherenkov light and suppress the night sky background. This solution is now used in other Cherenkov telescopes of CTA.

Two SST-1Ms were built and are currently installed in the Czech observatory of Ondřejov (Fig. 29) where they are performing observations of the brightest and closest known gamma-ray sources The project was scrutinised by a panel of international experts set-up by CTAO for a final selection of the SST array technology. Despite a spotless technical evaluation of the SST-1M solution, being compliant with the observatory requirements and using mature technologies ready for mass production, the dual mirror telescope solution was eventually selected. However, the proven performance and cost-effective design brought the LHAASO collaboration to adopt a similar photosensing plane for the camera of their Wide Field-of-View telescopes. The cost saving of the SST-1M approach allowed to build 16 instead of 12 telescopes for the same budget. It is also worth mentioning that the technologies developed for the light guides and the window with Thin Film Physics AG were adopted by LHAASO which also produced their element in Switzerland.

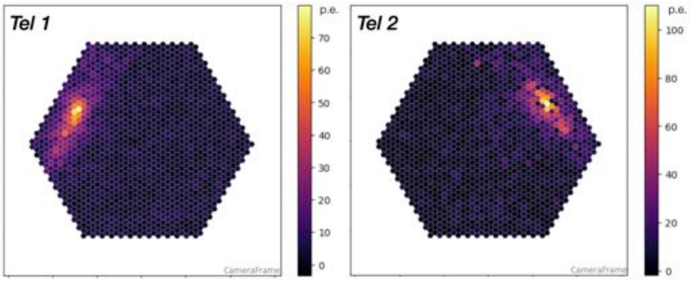


Fig. 28: Cherenkov air shower recorded in the stereoscopic mode by the SST-1Ms at the Ondřejov site.

Recently, the stereoscopic observations with the SST-1Ms were made possible (Fig. 28) which ensures that the Crab Nebula SNR can be detected in less than an hour. An example of an event captured in stereoscopic mode is shown in Fig. 28. The estimation of the primary particle energy, arrival direction and its type are largely improved by combining information from both telescopes.

The UNIZH group was since the beginning also involved in the MST project of CTAO and gave fundamental contributions to the FlashCam camera project which will equip the MSTs in the Southern site. Additionally, the actuator technology developed by the University of Zürich was identified by CTAO as a possible common element of all telescopes and is now produced by the Swiss company Diener AG, for LSTs and eventually for the MSTs.

Fig. 29: An SST-1M installed in Ondřejov.

The participation in the LST+ project

Fig. 30: The first CTAO Large Size Telescope in La Palma [Mireia Nievas Rosillo]

The LST array of CTAO is composed of four telescopes in the Northern site in the approved baseline configuration (Alpha-configuration). While this did not envisage having a LST array in the Southern site, in 2022 the INAF collaborators obtained a grant from the European Community recovery funds for building two LSTs in the South. The LST project has been extended into the LST+ project which includes the provisions to CTAO of 2 LSTs in the Southern site. The LST array targets the low-energy end of the gamma-ray spectrum visible from the ground to about 20 GeV. LSTs are relevant for the study of transient phenomena such as flares of AGNs, GRBs, precision measurements of pulsars and other galactic sources. The role of the LSTs is extremely relevant as it can cross-correlate the ground-based indirect measurements of gamma rays with atmospheric showers with the space-based direct measurements. The Swiss groups joined the LST collaboration in 2019 working in different areas, establishing themselves among the key players in its organigram in the following construction work packages and for data processing and analysis.

The LST system engineering

In 2019, the LST project underwent a Critical Design Review (CDR) to assess if the design implemented in the first prototype LST-1 had no major pitfalls and could be eligible for acceptance by CTAO. LST management approached the DPNC group to help in the process and provide some know-how in system engineering (SE). Prof D. Della Volpe serves as the lead system engineer for the LSTs and took over the CDR process to bring it to completion. Dr M. Heller and later M.sc. Eng. M. Stodulska, from the same group, acted as a deputy system engineer. The UNIGE SE team brought the CDR to success, communicates all LST technical aspects with CTAO and follows up on the operation and commissioning activities. The SE team has an active role in the definition of the system requirements for the European tender happening in 2023 for LST2-4 and will coordinate the activities for the construction of the southern LST array in 2025-28.

The advanced SiPM camera

The Swiss experience acquired during the development of the FACT and SST-1M telescopes is utilised at its maximum for the development of the future camera for the LST. The University of Geneva, represented by M. Heller, is coordinating this activity within the LST collaboration. This activity is very relevant for future opportunities for Switzerland to participate in the hardware implementation of the telescopes, as indicated by the declaration of interest signed in June 2021 by the UNIGE Rector, Prof. Y. Flückiger and the Director of ICCR of Tokyo University, Nobel Laureate T. Kajita and the LST spokesperson Prof. M. Teshima. The main driver of this initiative is to use SiPMs for the LSTs, as they offer twice more sensitivity to Cherenkov light when compared to classical photomultiplier tubes. Their sensitive dimension (limited to 1 cm^2 as they are noisy devices and also integrate more background light) is smaller than that of photomultipliers. This implies a potentially improved camera resolution and capability to capture smaller details in the showers (see Fig. 31). These can be fully exploited by modern analysis techniques. This imposes strict requirements on the camera design as four times more pixels are needed to cover the same field of view. Such an increased number of pixels has a dramatic impact on the camera power consumption, a challenge being tackled with innovative low-power application-specific integrated circuits (ASICs) developed in by the DPNC, the AQUA Lab/EPFL and ETHZ in a FLARE project. The ASICs will be general purpose for SiPM signal amplification and digitisation at GHz-speed developed in cooperation with Swiss microelectronics companies. Additionally, the DPNC is collaborating with UZH on the development of new triggering techniques

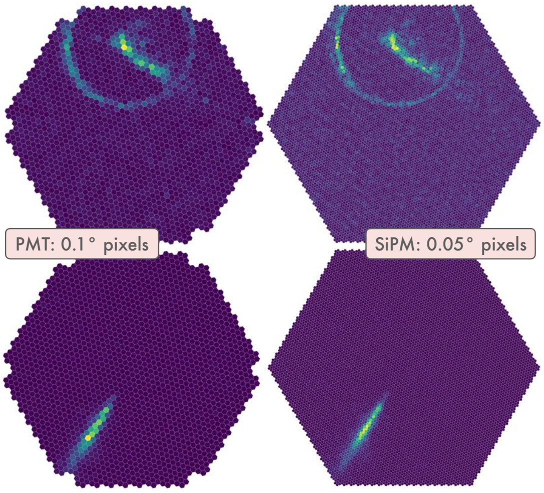


Fig. 31: Simulation of a proton shower (top) and a gamma shower (bottom) in the existing (left) and advanced (right) LST camera.

based on real-time artificial intelligence inference running on hardware accelerators. Prof. Serra at UZH has acquired strong know-how in developing deep-learning algorithms that can run on field-programmable gate arrays (FPGAs) in the frame of the LHCb detector of the Large Hadron Collider at CERN. The principle is that thanks to artificial intelligence algorithms, the decision whether an image acquired by a camera is registered or not is not only based on whether the intensity in any region of the camera is higher than a given threshold but it can be also based on more complex information, such as how much the image resembles an extensive air shower. The challenge will be to develop algorithms which are robust enough to deliver a stable outcome at different levels of background light and to do so with the minimum possible processing power. The overall aim will be to lower the detection threshold of the LSTs and target energy thresholds as low as 10 GeV. All these state-of-the-art developments involve Swiss industries as described below.

Synergies with industrial partners

The Swiss industry, namely Diener AG, has been already involved in the construction of the LSTs of the Northern array. The actuators were designed firstly at ETHZ and then at UZH and Diener AG proved to have the skill in precision mechanics and to be very competitive in terms of cost. Thanks to an encouragement SERI financing, the DPNC group is in charge of the provision of the actuators for two LSTs to be deployed at the Southern site. This is important as this work will imply technology transfer between the company and the Swiss-involved institutes, resulting in leadership in the production of these precision-motor elements. Currently, also the MST project is considering Diener for the actuator provision and the company is being encouraged to participate in the international tender which should happen in 2024 for the MST construction.

In order to follow up fast transient phenomena, such as gamma-ray bursts, the LSTs need to slew in a few tens of seconds. Though lightweight with respect to its dimensions, the 100 tons of LST weight need quite some power. This fast slew can happen only 1-2 times per night at maximum, so it is not sustainable to dimension the power system to provide this peak power. The system has a maximum power absorbed by the grid of 60 kW, and is equipped with an energy storage system, which is charged slowly over time but can provide 600 kW for fast slewing. The system currently installed in LST-1 has been already built by ABB AG, which was selected among many international companies. A future involvement of ABB Suisse will be explored for the energy storage of the LSTs in the southern array. This activity can establish synergy with a big company, deeply involved in power systems and sustainable energy, which can evolve with new approaches towards a more sustainable scientific observatory for instance by adding solar panels for powering the control system, or using more efficient and eco-sustainable systems.

In addition to these components, R&D work is ongoing on sensors and associated electronics. The addition of the LSTs in the south and the future refurbishment of LST-1 and MAGIC telescopes, also open a new window of opportunities to contribute to advanced technology elements and exploit the expertise developed in Switzerland as pioneers of the SiPM technology in the field of gamma-ray astronomy. A new digital photon counter (DiPC) is being designed and prototypes with CMOS technology by ETHZ and EPFL. Additionally, two state-of-the-art ASICs are being developed by the DPNC and EPFL which will be also further developed in a to-be-proposed EC project for 2024 INFRA-TECH called M2Tech supported by CTAO, MAGIC, ET, Virgo and KM3NeT. In order to exploit best their performance, Swiss companies will take care of the packaging of the circuits individually. At a later stage to reach very low noise levels, the two ASICs will be combined in a single package which will offer a one of kind ASIC which will open a new era for the low-power analog to digital conversion for SiPMs.

Being able to run complex AI inference on hardware accelerators such as GPU, FPGA or ASICs is an extremely active field of research with a wide range of applications. The algorithms used for the trigger decisions of the future LST cameras will have to deal with very high-input data rates. Not only algorithms will have to be extremely optimised, but also the hardware to run them. Swiss companies will have a critical role to develop this hardware.

The expertise of Swiss partners has also a return in medical diagnostics, with the project led by Prof. Della Volpe to develop a gamma probe for radio-guided surgery financed by the H2020 ATTRACT Framework.

Participation in Data Processing

CTAO would not work without software, computers and vast amounts of storage. CTAO has designed a system (Fig. 32) to support the operations from telescope control and data processing at the telescope sites (ACADA), to the Data Pipeline and Preservation System (DPPD) processing CTAO data in four data centres in Europe, and the interface to the scientific community from proposal handling to the distribution of data (SUSS). Switzerland participates at different levels in the development of the CTAO data processing system and is providing one of the four data centres, as presented below.

The telescope control software

The control software for the LST and SST telescopes is based on the ALMA observatory common software (ACS) framework. The control logic of each telescope is separated into three main components: Camera Manager, Structure Manager and Telescope Manager. The Telescope Manager is orchestrating the other two and is the main entry point for the CTAO Array Control and Acquisition (ACADA) system to control the telescopes. All control software is designed to implement the full list of CTAO use-cases for regular data-taking and long-term maintenance of the instruments. Initially developed for the SST-1M, from 2019 the team at the Astronomy Department/UniGe has been involved in the development of the central control software system for the LSTs, namely the Telescope Control Unit (TCU). The software has been successfully deployed in 2020 on-site and made it possible the remote control and monitoring of the telescope during the lockdown and the Cumbre Vieja volcano eruption on La Palma island when the physical presence of operators was not possible. By now the TCU system has reached the level of fully automatic schedule-based operations, which only requires general supervision of the telescope and weather conditions by remote operators. For the commissioning phase, the TCU also implements the MAGIC follow-up operations mode to perform common observations with LSTs for cross-calibration and reach higher sensitivity. In 2022 CTAO started a formal process of LST-1 integration into ACADA. Integration includes a few major milestones: integrate ACADA with LST-1 using interfaces, test the interfaces, test ACADA deployment on the LST-1 IT centre and test the execution of end-to-end operations with the integrated ACADA-LST-1 system. The LST-1 integration activity will be useful for the future acceptance of telescopes by CTAO and paves the path to serve other telescope types. Dr V. Sliusar of the Astronomy Department is the lead developer of TCU and LST deputy software coordinator. Changes in the

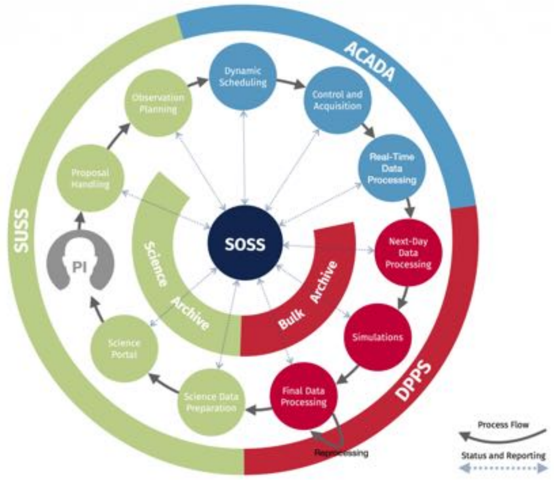


Fig. 32: The CTAO data processing [Credit CTAO].

LST hardware at the Southern site have to be included to account for the higher seismic risk and will require TCU software adaptation but the same components, frameworks, general principles and control logic can be re-used.

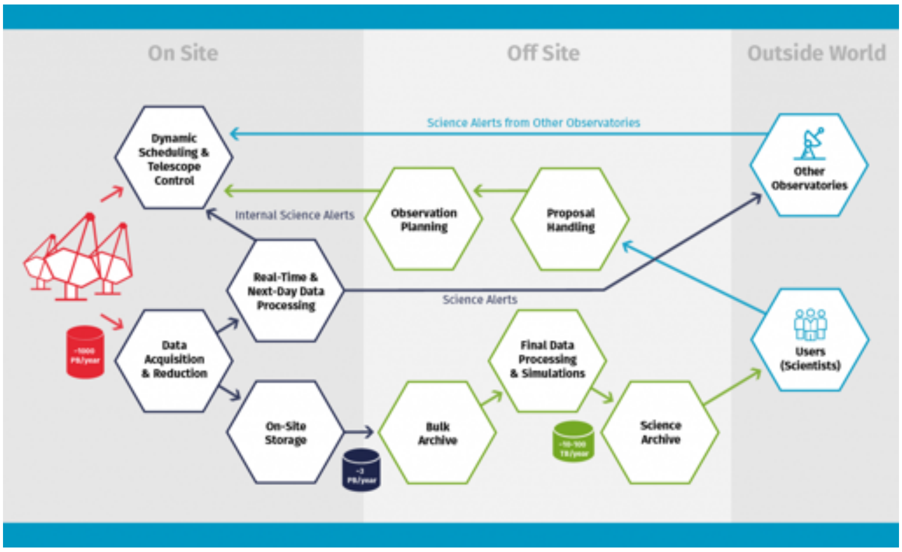


Fig. 33: The CTAO dataflow diagram [Credit CTAO].

The on-site array data handler

The Array Data Handler (ADH) is the ACADA subsystem responsible for handling the event triggers and the raw data from the data producers on-site (see Fig. 33). The main source of raw data are the Cherenkov cameras of telescopes, with a total throughput of 200 and 300 Gbps for the Northern and Southern sites, respectively. Such a volume would be difficult to transfer off-site and very costly to store and process. ADH thus implements the Software Array Trigger component and Data Volume Reduction step to only record events detected simultaneously by several telescopes and reduce the amount of data by a factor of 50, while retaining most of the information relevant to Science. Another factor of 2 or more will be achieved via formatting and lossless compression. The remaining data produced on-site can be categorised into three types: monitoring, engineering and auxiliary. The former two will be acquired from the monitoring subsystem once per day. Auxiliary data will be directly written to the on-site repository by the relevant subsystems. ADH is a cornerstone real-time subsystem of ACADA, featuring many interfaces and a distributed architecture. The coordination of this work is done at the Department of Astronomy / UniGe with Dr Eng. Etienne Lyard in first line and involves also ETHZ and partners in Germany and Poland. The interfaces to the Cherenkov cameras are designed and implemented with contributions from camera teams throughout Europe, Japan and the USA.

The bulk data management system

The bulk data management system (BDMS) is a sub-system of CTAO computing providing the distributed archive for the (Petabyte) bulk data, stored and processed by four data centres. The BDMS is responsible for the archival storage of large-scale data products following the Open Archival Information System (OAIS), an ISO standard. This standard was first developed for space scientific missions and the INTEGRAL archive (developed at UniGe in 1995) was the first designed according to this model. The BDMS ingests the raw data produced by the ADH at the telescope sites, preserves the data in the CTAO data centres and makes the data available to the workload management system, processing the data to higher levels. The main functional units of the BDMS are ingest; distributed data management; archival storage; query and file access; and administration. The ingest component includes validation checks that verify the conformance of every file before ingesting them for preservation. It also extracts scientific metadata. The data management uses the RUCIO framework developed at CERN for LHC (ATLAS and CMS) data management and guarantees that data products are preserved at least in two distinct CTAO data centres.

The array calibration and data quality

CTAO aims to provide scientists with the highest quality data to meet its ambitious science program. High accuracy in measuring the energies and directions of primary cosmic particles requires an excellent understanding of the detector and the environment. The CTAO data processing system foresees two key subsystems to achieve the desired performance: a calibration subsystem of the DPPS called CalibPipe and a Data Quality pipeline for the assessment and monitoring of the data flow. As the CTAO data processing system is data-centric, we refer to the subsystems of the data processing chain as pipelines through which data flows while being transformed (reduced or augmented).

The CTAO operates with three categories of data. Category-A data are the result of the online data analysis and are used to provide science alerts to the astrophysics community and for optimal time-observation schedules. No offline-calculated or refined calibrations are applied to the Category-A data. The Category-B data are generated the day after the observation. They include preliminary offline calibrations, augmenting their quality and precision. This data is released to the PI of the corresponding observation proposal for early analysis. Finally, the Category-C data are produced within one month of the data taking and include state-of-the-art knowledge of the array telescopes' performance and observation conditions. They include, when needed, a set of tailored simulations to improve the qualitative description of the instrument response to the gamma-ray signals. The Calibration and Data Quality pipelines deal with the Category-B and Category-C data.

The Calibration pipeline functionality is divided into three major blocks. The first one concerns atmospheric calibrations. A proper understanding of the atmosphere composition is vital for ground-based gamma-ray astrophysics because the atmosphere plays the role of the radiative medium where the atmospheric showers produce the Cherenkov light. It thus becomes de-facto a part of the detector. The Calibration pipeline provides a comprehensive assessment of the state of the atmosphere, including long-term modelling, as well as the corrections for the short-term transient effects caused by the aerosols and dust particles. The second calibration functionality block addresses the individual telescope calibrations of pointing, timing and gain calibration of the telescope's main camera; and optics calibration, including the optical point spread function and absolute optical throughput.
The third functional block performs the inter- and cross-calibration of the whole array aiming at improving the absolute energy scale determination and time calibration of the array.

The Data Quality pipeline delivers the quality metrics and ranks recorded data according to its quality and suitability for certain physics analyses. It consists of frontend and backend packages. The frontend package manages the interfaces with other components of the CTAO Data Processing software and provides a user interface for the operators and scientists of the CTAO. The backend package contains the core algorithms for data quality monitoring and data certification and classification.

The contribution to the development of the Calibration and Data Quality pipelines is led by the DPNC/UniGe group. It covers completely the design and implementation of the Calibration software and foresees a significant contribution to the Data Quality package. On top of this, Mykhailo Dalchenko, coordinator of the Calib Pipeline, is seconded to CTAO at the 50% level as the Data Processing and Preservation System (DPPS) Software Architect and Georgios Voutsinas will be seconded as Calibration Scientist, to determine the scientific impact of the Calibration Pipeline.

Off-site data Centre

Switzerland is in a unique position to host one of the 4 off-site Data Centres (DC) due to its existing infrastructure for high-performance computing and data analysis at CSCS and experience in the Worldwide LHC Computing Grid (WLCG), from which CTAO inherits its data centre technologies. The Swiss off-site DC in Lugano will archive about half of the raw and simulated data. The data volume is expected to reach 50 Peta bytes by 2030. These big volumes will be processed at CSCS by the DPPS to produce high-level data products for use by astronomers, with the data production rate increasing as more telescopes join operations in the next few years.
The Swiss DC is already serving as the Off-site DC for the first operational Large Size Telescope of CTAO, for which a full archive of the raw data (close to 2 PetaBytes) has been transferred. CSCS is also providing the major part of the computing and storage for the production of the CTAO Monte-Carlo simulation and is

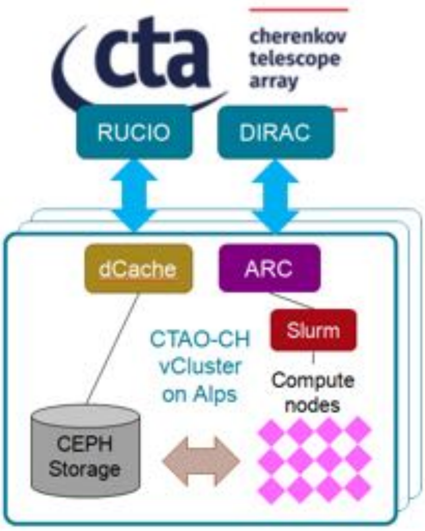


Fig. 34: The Main components of the Swiss off-site DC: ARC and dCache middleware from WLCG receiving workload and data from RUCIO and DIRAC respectively, which in turn runs batch jobs and stores data at CSCS.

setting up the computing environment for the first CTAO Science Data Challenge. In order to store and analyse this increasing data flow, both storage and compute backends were provided at CSCS exclusively for CTAO in a virtual Cluster code-named Vanil Noir, on top of the new Alps Infrastructure. These backends are deployed using modern software-defined infrastructure mechanisms and are built using Linux containers and Kubernetes.

At the beginning of 2024, the Alps Infrastructure will be expanded with a very significant amount of multi-GPUs nodes with NVIDIA Grace Hopper Superchips that will enable large, energy-efficient machine learning workflows such as neural network training and inference. Some of the software elements of the virtual cluster of CTAO are shown schematically in Fig. 34.

Convolutional neural network (CNN) analysis

Swiss scientists are investigating the use of CNNs to perform the low-level data analysis of Cherenkov telescopes data [arXiv:1907.02428]. The standard γ-hadron separation based on binary decision trees (BDTs) was outperformed under specific conditions (see Fig. 35). This network was used to process Crab Nebula data of LST-1 and again the CNNs outperformed the standard analysis. Other networks were trained to reconstruct the energy and origin direction of γ-ray events. CNNs outperformed the standard analysis also for energy reconstruction. Further developments are ongoing.

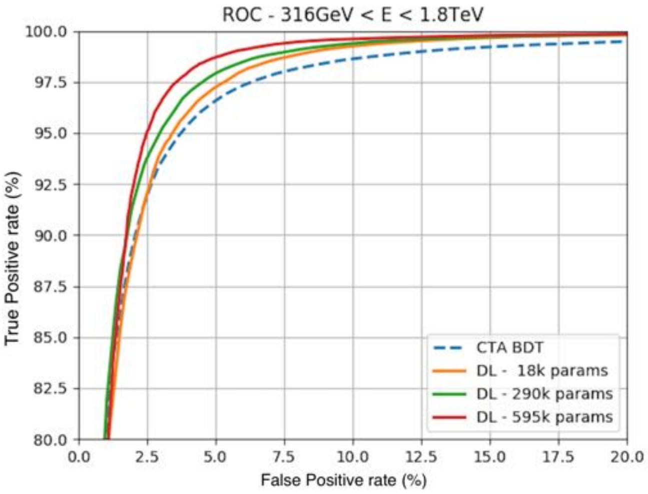


Fig. 35: Efficiency curves comparing several CNNs to the standard BDT algorithm for the separation of hadrons and γ-rays. Higher curves are better.

Stellar Intensity Interferometry

Last, but not least, is the possibility of operating the CTAO telescope arrays in a different observing mode, that of optical intensity interferometry. This technique effectively turns the telescope array or any subset of it into a giant optical telescope, with albeit low signal-to-noise, but angular resolution far beyond any current facility. The pioneering work on using the same array as both an atmospheric Cherenkov telescope and an intensity interferometer goes back to Hanbury Brown and others in the 1960s, but was not competitive with other techniques till recently. Since 2020, VERITAS, MAGIC, and H.E.S.S. have all successfully implemented intensity interferometry to measure stellar diameters. With its much larger collecting area and km-scale distribution, CTAO would be ideal for indirect imaging at optical wavelengths of stars and stellar outflows. Especially exciting are processes that also produce gamma-rays, such as colliding winds in massive stellar binaries. The groups at UZH and UniGe are contributing to the stellar intensity interferometry science case being discussed for inclusion in CTAO.

Perspectives

In Switzerland, high-energy astrophysics developed since the 90'ies at a sustainable rate by participating in international projects like XMM, RHESSI, INTEGRAL, MAGIC, AMS, DAMPE, POLAR2 and IceCube. A community of scientists and engineers active in the domain has built up, internationally recognised. Part of it is eager to participate in an expanding research field which has matured in Europe in the Cherenkov Telescope Array Observatory project.

Multi-Messenger programs are at the border of two communities, astronomers and particle physicists. They merge the interest in the search for New Physics that is seeded for by particle physicists and astrophysicists. The Standard models of particle physics and cosmology are clearly intimately connected and require a joint effort to fully understand the nature of dark matter, the magnetic fields that accelerate the universe and the extreme conditions of matter that allow us to probe as close as we can the initial conditions in the universe.

CTAO will lead the Multi-Messenger field to a precision era, driving the new-born astronomies with neutrinos and gravitational waves.

Together with common science goals, the particle physics and astronomy communities share a very strong need to work with Big Data and Artificial Intelligence, and with advanced technology instrumentation in photonics, electronics, and optical systems. This represents a vibrant asset allowing for cross-fertilisation over the next decades.

Switzerland will benefit from the operation of a data centre, based at the CSCS, where communities in three large infrastructures, LHC, CTAO and SKAO, will store and process their data. This represents a great convergence of interest for the most efficient and long-term sustainable digital infrastructure devoted to research. In the future frame of 2025-2028 of the Swiss Roadmap for Research Infrastructures, we will operate one of the 4 offsite data centres of CTAO, participate in the construction operation of the LSTs in the Northern and Southern sites, validating their delivery process to CTAO, as well as we will fulfil the Swiss commitments on the software of the array.

Impressum

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CTAO

[Credit Maximilian Linhoff]