Exploring the Universe at the Highest Energies
High above the clouds, atop the rocky peaks of the island of La Palma and nestled in a valley of the great, desolate expanse of Chile’s Atacama Desert, the foundations are being laid for the world’s largest and most advanced ground-based observatory for gamma-ray detection.

Stargazers have long used these vantage points and others to marvel at the wonders of our Galaxy and beyond, working to unlock their mysteries and expand our understanding of the Universe. The Cherenkov Telescope Array (CTA) will push that perspective to reveal an entirely new and exciting view of the turbulent sky, revolutionizing what we know about the violent, high-energy Universe.

The current generation of ground-based gamma-ray detectors – the five H.E.S.S. telescopes located in Namibia, the two MAGIC telescopes in La Palma and the four VERITAS telescopes in Arizona – have been exploring the high-energy Universe since 2003, increasing the number of known gamma-ray-emitting celestial objects from 10 to more than 150. With more than 100 telescopes located in the northern and southern hemispheres, CTA will use its unprecedented accuracy and sensitivity to expand this registry of known objects tenfold and to address some of the most perplexing questions in astrophysics. Not only will CTA break new ground in our understanding of the Universe, it will be the first of its kind to be open to the world-wide astronomical and particle physics communities as a resource for data from unique, very-high energy astronomical observations.

Unprecedented, powerful, accessible.

Let the next evolution begin...
The light you see from distant stars, planets and other celestial objects comes from just a small portion of the electromagnetic spectrum. Much more of the radiation is invisible to the human eye.

The full spectrum ranges from the low frequencies and long wavelengths of radio waves and microwaves to the mid-range frequencies found in infrared, optical (visible) and ultraviolet light to the very high frequencies of X-rays and gamma rays. The frequency range of gamma rays is so vast that it does not even have a well-defined upper limit. In fact, the gamma rays CTA will detect are about 10 trillion times more energetic than visible light!

Optical telescopes have been capturing the visible light of the night sky since the early 17th century, putting the beauty of the Universe on display. To get a more complete picture of the phenomena and the physical mechanisms at work, scientists hunt with telescopes specially tuned to capture different frequencies of light. With its ability to view the highest-energy processes in the Universe, CTA will be a vital asset in improving our understanding of some of the most volatile and mysterious phenomena we know of or have yet to discover.

Imagine what these cosmic messengers will tell us…
At the heart of a galaxy billions of light years away, a supermassive black hole, having a mass a billion times that of the Sun, accumulates a very hot disk of material and gas. As the hot disk churns violently, it shines brighter than all the surrounding stars and discharges jets of highly energetic particles that travel beyond the bounds of its galaxy. It is in extreme environments like this where gamma rays are born.

However, no object, not even a supermassive black hole, produces gamma rays directly. Gamma rays are the product of subatomic particles (usually protons or electrons) that get accelerated in extreme environments typically associated with these violent events. Explosions, outbursts or powerful jets accelerate particles to nearly the speed of light. Gamma rays are produced when the particles collide with matter and radiation fields in or around the sources or in interstellar space. The gamma rays travel across the universe to galaxies beyond, transporting with them the secrets of their birthplace.

In our own Galaxy, CTA will look for the remnants of supernova explosions, wind nebulae produced by rapidly spinning ultra-dense stars known as pulsars and for more normal stars in binary systems or in large clusters. Beyond our Galaxy, CTA will detect star-forming galaxies and galaxies with supermassive black holes at their centres (active galactic nuclei) and, possibly, whole clusters of galaxies. The gamma rays detected with CTA may also provide a direct signature of dark matter, evidence for deviations from Einstein’s theory of special relativity and more definitive answers to the contents of cosmic voids.
The Earth is constantly bombarded by cosmic rays, primarily in the form of high-energy protons and atomic nuclei; however, a full understanding of the source and production mechanisms for these cosmic rays has not been realized. The natural accelerators of cosmic rays within our own Galaxy are capable of accelerating subatomic particles to much higher energies than the Large Hadron Collider, the most powerful particle accelerator on Earth. However, as cosmic rays are electrically charged, their paths are scrambled in the magnetic fields between their sources and the Earth, making it nearly impossible to trace them back to their origin.

1. Understanding the Origin and Role of Relativistic Cosmic Particles

On the other hand, gamma rays – some of which are by-products of high-energy cosmic-ray acceleration – do not have an electric charge to deviate their path as they pass through magnetic fields. A direct path allows the gamma rays to transport images of their sources and the energetic particles that created them.

CTA’s broad energy coverage and unprecedented angular resolution will enable us to look for the possible sources of cosmic rays within our own Galaxy and beyond and map the role they play in the feedback processes at work as stars form and galaxies evolve.
The gamma rays CTA will detect are at energies well beyond those of X-rays or even gamma rays detected by space instruments. As such, they encode information about the physical processes at work in some of the most energetic environments in the Universe. The black holes and neutron stars born when massive stars reach the end of their lives and explode are of particular interest. Gamma rays have been observed coming from jets of many black holes, although the exact mechanisms by which this emission process occurs are not fully understood. The capabilities of CTA will enable us to address these questions with an unprecedented level of accuracy.

Accessing energies as low as 20 GeV will allow CTA to probe transient and time-variable gamma-ray phenomena in the very distant Universe with unprecedented precision.

The Universe hosts a diverse population of astrophysical objects that explode, flare up or intensify activity in dramatic and unpredictable fashion across the entire electromagnetic spectrum and over a broad range of timescales, spanning milliseconds to years. Collectively designated as “transients,” many are known to be prominent emitters of high-energy gamma rays and are also likely sources of non-photonic, multi-messenger signals such as cosmic rays, neutrinos or gravitational waves. They are of great scientific interest, being associated with catastrophic events involving relativistic compact objects such as compact stars, neutron stars or black holes. CTA will observe the LMC for several of its science objectives, including to gain insight into the transport of cosmic rays on large scales — from their release into the interstellar medium to their escape from the galaxy.

**II. Probing Extreme Environments**

### Target: Transients – Random Blasts Full of Information

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A major step forward in sensitivity and energy coverage brings discoveries in fundamental physics, or how the Universe behaves at its most basic level, well within CTA’s reach. Specifically, CTA will seek to discover the nature and properties of dark matter, probe the existence of axion-like particles and test possible deviations from Einstein’s theory of special relativity. Any of these discoveries would mean a revolution for particle physics and cosmology.

Target 1: Dark Matter – One of Science’s Greatest Mysteries

Dark matter is thought to account for a large part of the mass of the Universe, but its nature remains one of the greatest mysteries in science. Dark matter manifests itself by its gravitational effects and seems to occur in far larger quantities than normal matter, but do not emit or absorb electromagnetic radiation, making it very difficult to detect. CTA will attempt to find dark matter by looking for the gamma rays produced when dark matter particles interact and annihilate with one another. The project will be sensitive enough to probe the weakly interacting massive particle (WIMP) parameter space and could test whether dark matter is a specific type of ‘cold dark matter’ or a ‘warm dark matter’ (WDM). Dark matter could be made up of WIMPs, a type of subatomic particle predicted by the Standard Model of particle physics that has not yet been observed. The gamma rays produced by dark matter will be detectable by CTA, and provide a direct way to test the theory of general relativity in the most extreme environments of the Universe. CTA will attempt to find dark matter by looking for the gamma rays produced when dark matter particles interact and annihilate with one another. The project will be sensitive enough to probe the weakly interacting massive particle (WIMP) parameter space and could test whether dark matter is a specific type of ‘cold dark matter’ or a ‘warm dark matter’ (WDM). Dark matter could be made up of WIMPs, a type of subatomic particle predicted by the Standard Model of particle physics that has not yet been observed. The gamma rays produced by dark matter will be detectable by CTA, and provide a direct way to test the theory of general relativity in the most extreme environments of the Universe.

An energy resolution of 10 percent will improve CTA’s ability to look for spectral features and clean up the backgrounds that can contaminate the search for dark matter particles.

Target 2: The Voids Between Galaxies – Unexplored Regions of the Universe

Most of the Universe is very close to empty, with matter grouped into galaxy clusters, super-clusters and filaments, separated by huge voids. These voids are a matter of great interest to CTA, as they span the largest observable structures in the Universe. CTA will probe these voids to understand the role of dark energy in shaping the structure of the Universe. CTA will look for the extragalactic background light (EBL) to probe these voids. EBL represents the light emitted by all galaxies since the birth of the Universe and includes clues to the early history of the Universe. To probe these voids, CTA will be looking for gamma rays that are produced when gamma rays from distant galaxies collide with the EBL. These gamma rays will be detected by CTA, and provide a direct way to test the theory of general relativity in the most extreme environments of the Universe.
Gamma Ray Detection with Cherenkov Light

We know how gamma rays are born, but how will CTA detect them and decode the details of their origin? Interestingly, CTA will not detect gamma rays directly because they never actually make it to the Earth’s surface.

After their long journey from their sources, the gamma rays interact with the atmosphere, producing cascades of subatomic particles also known as air showers. Nothing can travel faster than the speed of light in a vacuum. However, in air, a very energetic charged particle can travel faster than light, whose speed is reduced by the index of refraction of the air. Thus, very-high energy particles in the atmosphere can create a cone of blue “Cherenkov light” (discovered by Russian physicist Pavel Cherenkov in 1934) similar to the sonic boom created by an aircraft exceeding the speed of sound. Although the light is spread over a large area (250 m in diameter), the cascade only lasts a few billions of a second. It is too faint to be detected by the human eye but not too faint for CTA’s telescopes with their large light-collecting mirrors and sensitive light sensors. When the Cherenkov light reaches CTA’s telescopes, the mirrors will reflect the light so the cameras can capture the event. The cameras will be sensitive to these faint flashes and use extremely fast detectors to capture the light and then convert it into an electrical signal that is digitised and transmitted to record the image of the light.
Capturing the particle showers from a gamma ray that hits the Earth’s atmosphere is like the classic scenario of “looking for a needle in the haystack.”

In fact, the expectation for the rate of gamma rays is only one per metre squared per year from a bright source, or one per metre squared per century from a faint source. To improve its ability to detect gamma rays, CTA will split more than 100 telescopes between two array locations – one in the northern hemisphere and one in the southern hemisphere to explore the entire sky.

The Array Locations

CTA South
Chile, Paranal
~ 5 km²

area covered by the array of telescopes

CTA North
Spain, La Palma
~ 0.5 km²

area covered by the array of telescopes

Northern Hemisphere Site

CTA’s northern hemisphere site is located on the existing site of the Instituto de Astrofísica de Canarias’ (IAC’s) Roque de los Muchachos on the island of La Palma, a Spanish island in the Canary Islands. It is one of the world’s leading sites for astronomical observatories from the Northern Hemisphere and will host the MAGIC telescopes. The northern hemisphere array will focus on CTA’s low- and mid-energy ranges from 20 GeV to 20 TeV.

Southern Hemisphere Site

The southern hemisphere site is less than 10 km southeast of the European Southern Observatory’s (ESO’s) existing Paranal Observatory in the Atacama Desert in Chile, which is considered one of the driest and most isolated regions in the world – a dark paradise for stargazers. The southern hemisphere site is 4 km² in size and will host 99 telescopes. The southern hemisphere array will span the entire energy range of CTA, covering gamma-ray energies from 20 GeV to more than 300 TeV.

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The current generation of ground-based detectors have cracked the door open to the high-energy universe, giving us a glimpse of what there is to see. But with CTA, the hope is that the door will be pushed wide open to reveal an entirely new view of the cosmos. This will be no small feat; scientists and engineers around the world have been working for more than a decade to plan CTA and build the next-generation discovery machine. How will they do it? Simply put, by pooling their knowledge and resources to build the most advanced Cherenkov telescopes ever constructed and by building more of them than ever before.

The project to build CTA is well on its way to construction; as of early 2017, working prototypes exist for all but the largest telescope design and site infrastructure work is underway to prepare for the first pre-production telescopes on site. Three classes of telescope are required to cover the full CTA energy range (20 GeV to 300 TeV). For its core energy range (100 GeV to 10 TeV), CTA is planning 40 Medium-Sized Telescopes distributed over both array sites. Eight Large-Sized Telescopes and 70 Small-Sized Telescopes are planned to extend the energy range below 100 GeV and above 10 TeV, respectively. The telescopes are arranged within the arrays based on their different energy domains. Low-energy gamma-ray events (best detected by larger telescopes) happen more frequently, requiring a small number of LSTs in close proximity, while the high-energy events (most economically detected by smaller mirrors) are extremely rare, requiring a large number of SSTs spread over several kilometres. The MSTs' broad energy range cover the middle of CTA's energy range.
The Small-Sized Telescopes (SSTs) will outnumber all the other telescopes and will be spread out over several square kilometres in the southern hemisphere array. This is because VHE gamma-ray showers produce a large amount of Cherenkov light, and the SSTs are sensitive to the highest energy gamma rays. SST mirrors will be about 4 m in diameter and will have a wide field of view of 9 degrees. Three different SST implementations are being prototyped and tested – one single-mirror design and two dual-mirror designs.

The SST-1M is a single-mirror design with a 4 m diameter (focal length of 5.6 m) reflector that uses hexagonal mirror facets. The SST-1M project teams are in Czech Republic, Ireland, Poland and Switzerland. A prototype of the telescope is being tested in Krakow, Poland.

The SST-2M ASTRI design is a dual-mirror Schwarzschild-Couder configuration. The 4.3 m diameter primary mirror is segmented into hexagonal facets and the 1.8 m secondary mirror is monolithic. Teams in Italy, Brazil and South Africa are contributing to ASTRI. In 2016, the ASTRI prototype in Serra La Nave, Italy, demonstrated the viability of the Schwarzschild-Couder design for the first time since its initial conception in 1905 and detected its first Cherenkov light in 2017.

SST-2M GCT is also a dual-mirror design. The optics are very similar to those of the SST-2M ASTRI, but the GCT emphasizes a low-mass design. The 4 m diameter primary and the 2 m secondary mirrors are each divided into six petal-shaped segments, and a fold-up shelter will protect the telescope when it is not observing. The GCT is being built by teams in Australia, France, Germany, Japan, the Netherlands and the United Kingdom. While undergoing testing in Meudon, France in 2015, the GCT prototype was the first CTA prototype to detect Cherenkov light.

CTA will use more than 7,000 highly-reflective mirror facets (90 cm to 2 m diameter) to focus light into the telescopes’ cameras.
At the centre of both arrays (25 in the southern hemisphere and 15 in the northern hemisphere) and scattered just beyond the LSTs, CTA’s “workhorses”, the Medium-Sized Telescopes (MSTs), will be tasked to cover the middle of CTA’s energy range.

MST mirrors will be 12 m in diameter and will have two different camera designs. Their wide field of view of 8 degrees will enable the MSTs to take rapid surveys of the gamma-ray sky.

The MSTs are being designed and built by an international collaboration of institutes and universities from Austria, Germany, France, Brazil, Poland, Spain, Switzerland and Italy. An MST prototype was deployed in Berlin in 2012 and is currently undergoing performance testing.

A dual-mirrored version of the MST, the Schwarzschild-Couder Telescope (SCT), is proposed as an alternative type of medium telescope. The SCT’s two-mirror optical system is designed to better focus the light for greater imaging detail and improved detection of faint sources. In collaboration with the SST-2M and MST groups and institutes in Germany, Italy, Japan and Mexico, institutes in the United States have been the pioneers of the SCT design since 2006. A prototype of the SCT is under construction at the Whipple Observatory in Arizona.

**Medium-Sized Telescope**

**MST Main Parameters**

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**Proportions**

- Northern Hemisphere Array 15 MSTs
- Southern Hemisphere Array 25 MSTs

- Small-Sized Telescope (SST)
- Medium-Sized Telescope (MST)
- Large-Sized Telescope (LST)
At the centre of both the northern and southern hemisphere arrays, a cluster of four Large-Sized Telescopes (LSTs) looms. Standing tall at 45 m and weighing in at about 100 tonnes, the LSTs are CTA’s biggest telescopes. Why so big? Because gamma rays with low energies produce small showers with a low amount of Cherenkov light, telescopes with large mirrors are required to capture them. LST mirrors will be 23 m in diameter and parabolic in shape, and the cameras will have a field of view of 4.5 degrees. But looks can be deceiving – these massive telescopes also must be very nimble to capture brief, low-energy gamma-ray signals. The plan is for the LSTs to be able to re-position to a new target in the sky within 20 seconds. More than 100 scientists and engineers from Brazil, Croatia, France, Germany, India, Italy, Japan, Spain and Sweden are working together to design and build the LSTs. An LST prototype is being constructed on CTA’s site on the island of La Palma and is scheduled to be completed in 2018.
If any of the real-time analysis reveals an unexpected gamma-ray signal, alerts will be generated to adapt the CTA observing schedule and to notify other observatories. This instant alert system will help to ensure CTA and its partners do not miss significant cosmic events. Processed images will then be transmitted to central computing facilities for further processing and to be archived. The calibrated image data will be used to reconstruct the properties of individual gamma rays. The energy and arrival direction of the gamma rays will be provided to science users of the Observatory and used to make spectra, lightcurves and images of astrophysical objects. The CTA Science Data Management Centre (SDMC), to be located on the DESY campus in Zeuthen, Germany, will coordinate the processing and long-term preservation of the data, in addition to providing the data, tools and support to the scientific users of the facility.

### Measuring the Light with CTA Cameras

When a gamma-ray initiates an air shower, the resulting faint blue-ultraviolet Cherenkov light will last only a few billiowths of a second. The mirrors of CTA’s telescopes will be tasked with capturing the flash, but measuring the light will be the role of the cameras. While the camera designs are slightly different for each telescope type, they all are driven by the faint light yield and short duration of the Cherenkov light flash.

To detect the short flashes of light produced by cosmic rays and gamma rays as they hit the earth’s atmosphere, the telescopes’ cameras must be about a million times faster than a digital camera. To do this, they will use high-speed digitisation and triggering technology capable of recording shower images at a rate of one billion frames per second and sensitive enough to resolve single photons.

Depending on the camera, photomultiplier tubes (PMTs) or silicon photomultipliers (SiPMs) will convert the light into an electrical signal that is then digitised and transmitted to record the image of the cascade. SiPMs can operate during high levels of moonlight, improving CTA’s efficiency in collecting Cherenkov light during moonlight conditions. Both sensors will be more efficient and advanced than what is used in current generation instruments.

CTA’s cameras will use both photomultiplier tubes (PMTs) and silicon photo multipliers (SiPMs) for a rate of more than 200 Mio photodetector light-sensitive pixels.

### From Data to Discovery

Once the telescopes record the Cherenkov images of a cascade, any undesirable “noise” in the image will be suppressed to reduce its size before it is analysed in real time. If any of the real-time analysis reveals an unexpected gamma-ray signal, alerts will be generated to adapt the CTA observing schedule and to notify other observatories. This instant alert system will help to ensure CTA and its partners do not miss significant cosmic events. Processed images will then be transmitted to central computing facilities for further processing and to be archived.

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To calculate CTA’s baseline performance, computer models are used to simulate the sequence of events from the development of the particle cascade in the atmosphere and the propagation of Cherenkov light to the capture and focus of the light by the telescopes’ mirrors and the electronic processing of the data. The result is performance expectations that include a tenfold improvement in sensitivity over current instruments, making CTA the most sensitive instrument at energies beyond the X-ray regime.

The Guest Observer Programme is a proposal-based system that will provide users access to observing time for observations requiring anywhere between a few to hundreds of hours of usage. Archive Access to CTA data will be made available on the INAF campus in Bologna, Italy, will be the central office responsible for the overall administration of Observatory operations. Observations will be carried out by operators, and then the data will be calibrated, reduced and, together with analysis tools, made available to the principal investigator in common astrophysics data formats. After a proprietary period of time, data will be made openly available through the CTA data archive. CTA observation time and data products will be provided to users through several different modes:

With a sensitivity as low as 20 GeV and as high as 300 TeV, pushing CTA beyond the edge of the known electromagnetic spectrum, CTA is expected to provide a completely new view of the sky.

CTA will be the first ground-based gamma-ray observatory open to the world-wide astronomical and particle physics communities as a facility devoted to high-energy astronomy.

Learn more about CTA’s performance expectations.

The Key Science Projects will ensure key science issues identified by the CTA Consortium are addressed and could require anywhere between 100 and 1,000 hours of observation time.

For science, CTA...

- Will have a sensitivity beginning at 10 GeV to tens of Teraelectronvolts.
- Will detect sources in a broad range of the electromagnetic spectrum.
- Will provide a completely new view of the sky.
CTA will venture beyond the high-energy frontier, seeking to expand our knowledge of the Universe for the benefit of all. But CTA is more than just a tool for science – its value goes far beyond its potential for discovery.

CTA will inspire future scientists and stargazers to challenge the known and to probe the unknown.

CTA will push the limitations of technology to look at the high-energy Universe with more precision than ever before.

CTA will connect people and institutions from around the world and promote stronger cooperation for the common good.

A Global Collaboration

From its base in Europe to the Americas, Asia, Africa and Australia, the CTA collaboration spans the globe.

The CTA Consortium, established in 2008, includes 1,350 members from 210 institutes in 32 countries and continues to grow as the excitement for CTA’s prospective discoveries builds. The group of scientists and engineers are engaged in the scientific and technical development of CTA.

The CTAO gGmbH, and its Project Office, manages the construction project and implementation of CTA and is governed by a council of shareholders and associate members from 11 countries (as of May 2017).

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CTA’s ongoing success would not be possible without worldwide financial support from a mounting number of agencies and organizations. CTA receives array components as in-kind contributions from the CTA Consortium members funded by the shareholders and associate members of the CTAO gGmbH. In addition, the project and this work have been financed by:


The European Union’s Horizon 2020 research and innovation programs under agreement No 676134.

Learn more about the CTA Funding Agencies and Organisations
www.cta-observatory.org/about/funding-sources