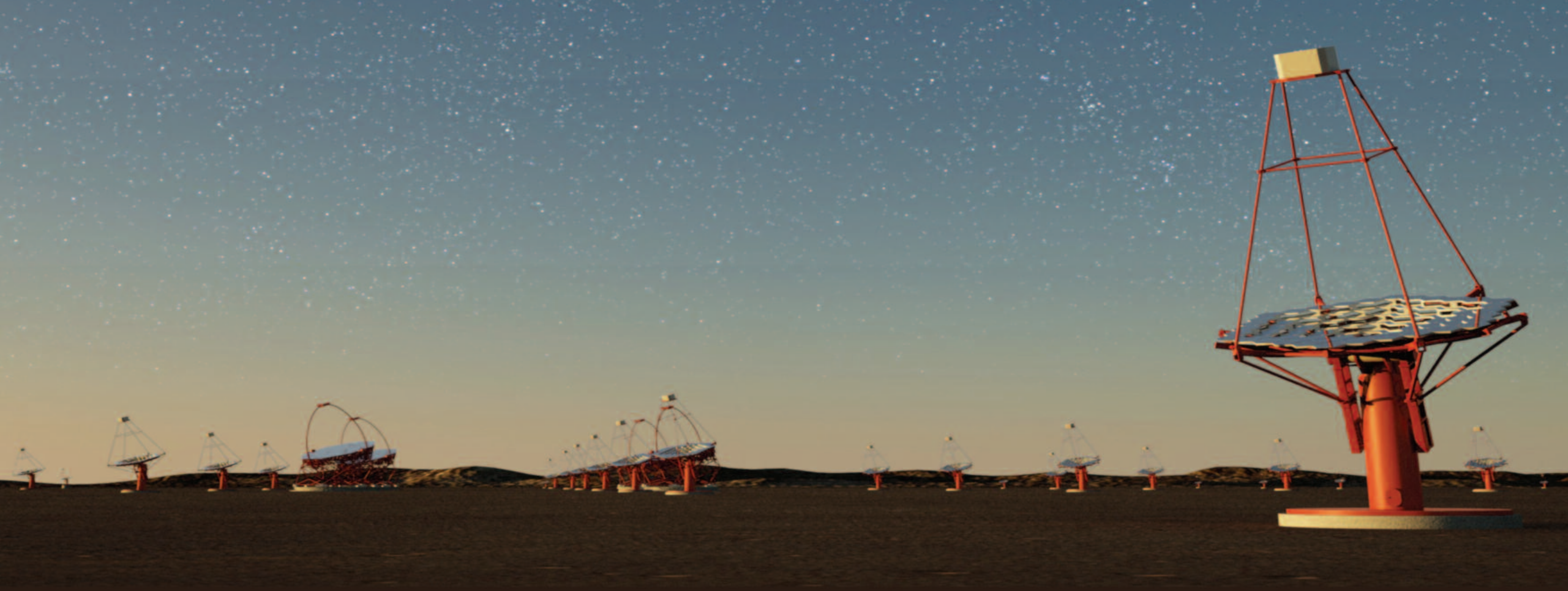
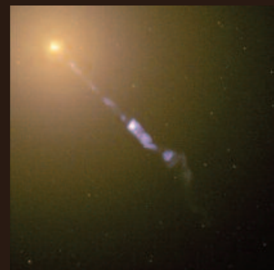
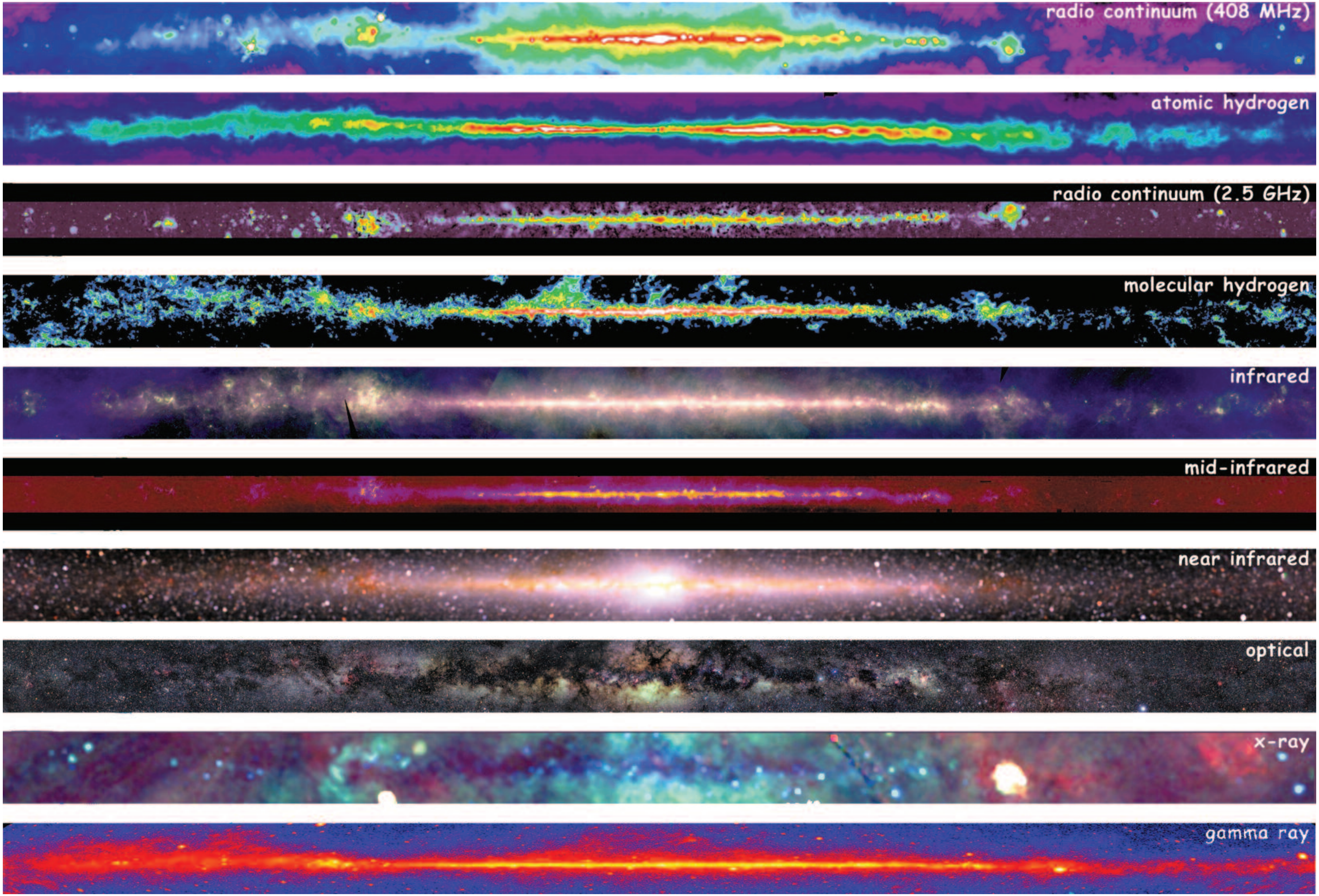


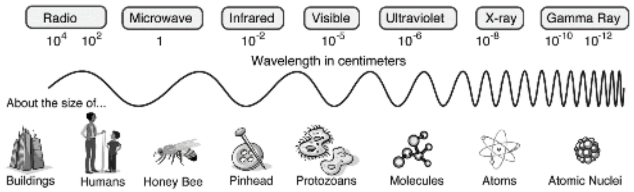
The Cherenkov Telescope Array

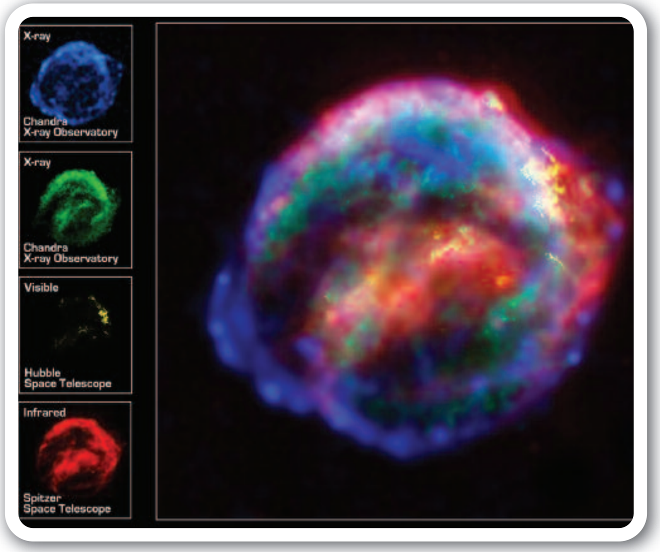


An observatory for ground-based gamma-ray astronomy



• Our Milky Way Galaxy imaged at ten different regions of the electromagnetic spectrum, from radio waves to gamma rays. A poster showing these images along with detailed information about each of them is available at http://tinyurl.com/l7yuj2q. (Credit: NASA)





• TOP - Comparison of the sizes of waves of light in regions spanning the electromagnetic spectrum. The physical wavelength (in centimetres) is listed, along with depictions of objects of comparable size. (Credit: NASA/GSFC)

• BOTTOM - Kepler's Supernova Remnant is the result of a supernova explosion discovered by Johannes Kepler in 1604. Each colour in the combined image (top) represents a different region of the electromagnetic spectrum, shown in the small panels at the left: X-rays at two frequencies from the Chandra X-ray Observatory (blue and green), visible light from the Hubble Space Telescope (yellow), and infrared light from the Spitzer Space Telescope (red). The X-ray and infrared light cannot be seen with the human eye. By colour-coding those images and combining them with Hubble's visible-light view, astronomers can assemble a more complete picture of the supernova remnant. (Credits: NASA/ESA/JPL-Caltech/R. Sankrit & W. Blair, Johns Hopkins University)

What Are Gamma Rays?

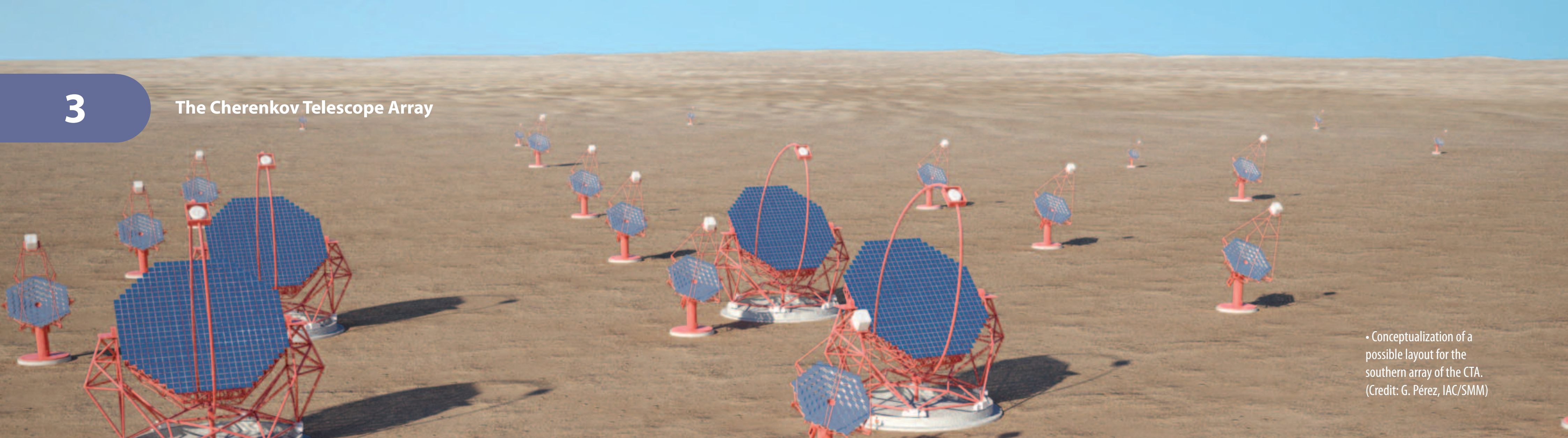
> Providers of the highest energy view of the Universe

Astronomy is the oldest scientific discipline, due perhaps to the spectacular vista that a clear night gave the first humans and still gives us today. Our eyes, however, are sensitive to only a tiny fraction of the light reaching us from space.

The light we see actually consists of electromagnetic waves with a range of frequencies, akin to the notes on a piano. A typical piano contains 7 octaves of keys, varying from low-frequency sounds on the far left of the keyboard, to high-frequency sounds on the far right. Likewise, light can be split into different frequencies, and the full range – the entire piano in our analogy – is known as the electromagnetic spectrum. Radio waves (used for communication) and microwaves (used in the home for cooking) are found at low frequencies. As the frequency increases, the next form of light encountered is infrared; remote controls use infrared light to transmit the signal when you change the channel on your TV set. The visible light to which our eyes are sensitive has a slightly higher frequency than infrared, and makes up only a narrow band of the electromagnetic spectrum. In our piano analogy, visible light can be thought of as middle-C on the keyboard. Beyond this we have ultraviolet light, which causes sunburn on exposed skin, followed by X-rays, which are used by your dentist. At the far right of the piano keyboard, we have gamma rays, the highest-frequency light known. As frequency is directly related to energy, this is also the most energetic form of light known. At this point, our piano analogy begins to break down, as the frequency range covered by gamma rays is vast, and without a well-defined upper limit - we would need another piano just for gamma rays!

To astronomers, the electromagnetic spectrum provides many opportunities to find out about the Universe. As shown in the figures on the left, taking images of the night sky with telescopes which have been built to access every frequency range in which light is produced gives us a unique perspective on the Universe and allows us to distinguish the physical mechanisms at work. Gamma-ray observatories (such as the Cherenkov Telescope Array) form a vital part of this arsenal of astronomical instrumentation, as they allow us to access the highest energy view of the Universe.

"To astronomers, the electromagnetic spectrum provides many opportunities to find out about the Universe."



• Conceptualization of a possible layout for the southern array of the CTA. (Credit: G. Pérez, IAC/SMM)

The Cherenkov Telescope Array

> CTA – A bold revolution in ground-based gamma-ray astronomy

The gamma rays that CTA will detect are extremely rare; only a few low energy gamma rays per square metre per year strike the top of the Earth's atmosphere. There are even fewer gamma rays in the highest energy range CTA can detect, with only a few per square metre per century hitting the top of the Earth's atmosphere. Through particle physics processes which occur in the atmosphere a single gamma ray can produce a large shower of secondary particles (including visible light), spreading the signal from the gamma ray over a huge area -- equivalent to 1,000,000 square metres in the sky. This, coupled with the fact that each CTA telescope will make an independent measurement of incoming gamma rays, means that both the sensitivity and accuracy of the observatory will be unprecedented.

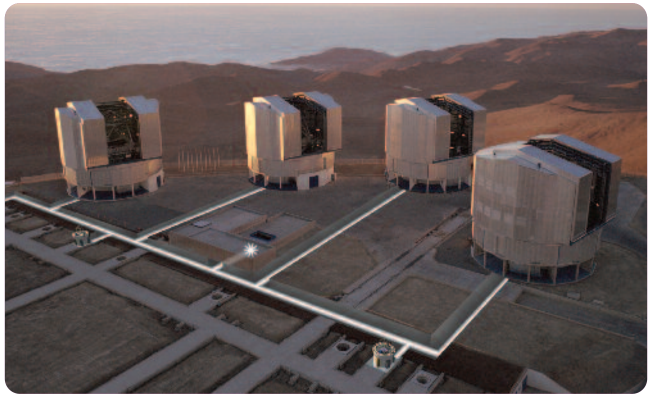
In the CTA era, arrays are planned in both the Southern and Northern Hemisphere. The Southern Hemisphere CTA array will be composed of the three telescope classes detailed below.

At its centre the array will have several large (24-metre diameter) telescopes sensitive to the lowest-energy gamma radiation. The amount of secondary visible light produced by a gamma ray is comparable to its energy. Large telescopes are therefore used to detect the small secondary light signal from low-energy gamma radiation; possessing large mirrors large telescopes collect as much of this light as possible. Surrounding these will be an array of many medium-sized (12- metre diameter) telescopes; these will be the workhorses of the array, sensitive to intermediate energy gamma radiation. Finally, the medium-sized telescopes will be surrounded by a large array of smaller (around 4-metre diameter) telescopes sensitive to the highest-energy gamma rays. Such high-energy events are rare, but each one is relatively bright; hence, smaller, but more numerous telescopes are required to study them.

At the highest energies, the most interesting sources of gamma rays lie within our own Galaxy, and are best observed from the Southern Hemisphere. The northern array will spend a greater fraction of its time looking beyond our Galaxy, where sources of lower energy gamma rays are more dominant; hence, it will be constructed from large and medium-sized telescopes.

•INSET TOP: The Very Large Telescope (VLT) on Cerro Paranal, Chile, is an observatory for visible and infrared light comprised of four telescopes with 8.2-metre primary mirrors. Like CTA, the VLT is part of the International Virtual Observatory Alliance (IVOA), whose members are shown in the bottom inset diagram. (Credits: ESO; AVO)

• Artists impression of the CTA observatory at night. (Credit: CTA)



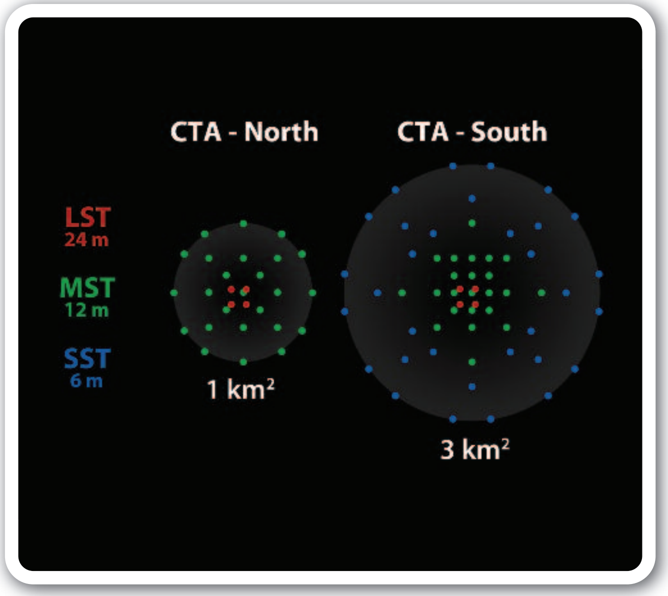
The CTA Observatory

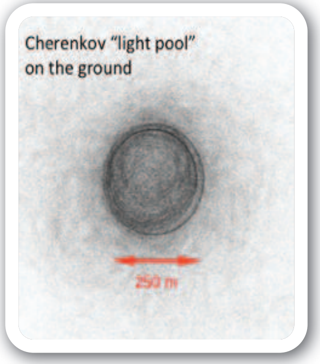
The Northern and Southern CTA arrays will together constitute the CTA Observatory, which will be the first ground-based gamma-ray observatory open to the worldwide astronomical community as a resource offering data from unique high-energy astronomical observations. CTA will also feed its data into the Virtual Observatory, which allows astronomers to interrogate multiple data centres in a seamless and transparent way, provides new powerful analysis and visualization tools within that system, and gives data centres a standard framework for publishing and delivering services using their data. This is particularly important because combining measurements taken at different frequencies, such as in the gamma-ray and X-ray bands, can provide a greater understanding of the underlying astrophysical mechanisms.

"The Northern and Southern CTA arrays will together constitute the CTA Observatory, which will be open to the worldwide astronomical community as a resource offering data from unique high-energy astronomical observations."

How CTA Works

The gamma rays that CTA will detect don't make it all the way to the ground. The Earth's atmosphere extends so far, its total density is equivalent to that of iron. Instead, when the gamma rays interact with the top of the Earth's atmosphere they produce cascades of charged subatomic particles (electrons and positrons), known as air showers. Many of the particles in these showers are moving faster than the speed of light in air (but still slower than the universal limit of the speed of light in a vacuum). In 1934, the Russian physicist Pavel Cherenkov noted that the result of charged particles travelling faster than the local speed of light through a transparent medium (such as air or water) is a bluish glow subsequently dubbed Cherenkov radiation (as used here and commonly in astronomy, the term radiation means the release of energy in the form of light). It is the light-speed equivalent of the sonic boom created by an aircraft traveling faster than the speed of sound. It is the Cherenkov radiation produced by air showers initiated by gamma rays that CTA will image. The amount of Cherenkov light produced by a gamma ray is proportional to its energy, with higher energy gamma rays producing more Cherenkov light. However, astronomy with Cherenkov light is challenging. Although the light is spread over a large area about 250 m in diameter on the ground, the flash of Cherenkov light from a gamma-ray air shower lasts only a few billionths of a second, and is far too faint to be detected by the human eye. However, a telescope with a large mirror to collect light and a camera with a fast enough response can detect the Cherenkov light and image the air shower generated by a gamma ray.



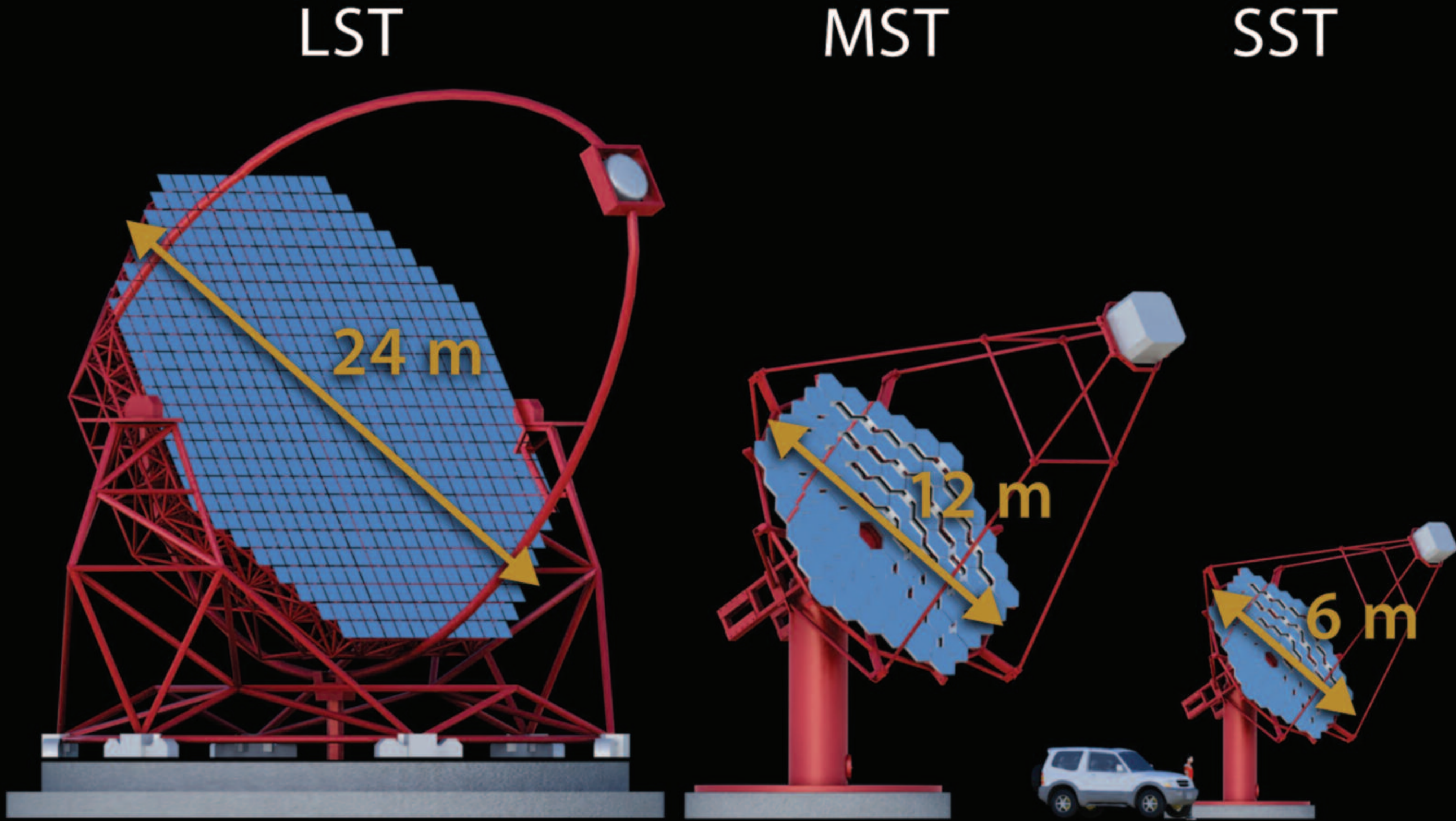


• LEFT - Example potential layouts of large, medium, and small CTA telescopes in Northern and Southern Arrays. (Credit: G. Pérez, IAC/SMM)

• TOP LEFT - Illustration of a gamma-ray air shower and its Cherenkov radiation illuminating a telescope. Inset panel shows the corresponding image seen by the camera on the telescope.

• TOP RIGHT - Simulated distribution of Cherenkov light on the ground produced by a single 100 giga-electronvolt (GeV) gamma ray. The Cherenkov light signal is constituted of many individual photons (shown here as points) separated by a large distance on the ground.

Combining the signals from these different telescopes will allow CTA to determine precisely the location in the sky from which the gamma ray originated and simultaneously measure the energy of the gamma ray with unprecedented accuracy.



• Diagram illustrating the different sizes of telescope which constitute CTA. A car and driver are shown for relative scale. Telescopes with secondary mirrors are not shown. (Credit: G. Pérez, IAC/SMM)

The Scientific Potential of CTA

> The fascinating discoveries to be made at the high-energy frontier

Most of the light we're used to seeing is emitted by hot objects and is known as thermal radiation. The hotter the source of this radiation, the higher the frequency of light produced. However, it's not possible for objects to get hot enough to produce gamma rays; these must be produced by a different mechanism. Non-thermal mechanisms often rely on the presence of sub-atomic particles, usually protons or electrons, that have been accelerated to extremely high velocities. For this reason, gamma rays trace the energy skeleton of the Universe, and through them one sees not a static Universe but a violent, dynamic sky, filled with events such as the aftermath of supernova explosions, or jets produced close to supermassive black holes at the cores of so-called active galaxies.

With CTA we will be able to access the gamma-ray window onto the Universe with a factor of 10 or more improvement in sensitivity compared to previous instruments. This, coupled with the broad energy coverage and superb resolution of the observatory, will give us the clearest look yet at some of the most extreme environments in the Universe. In addition, by probing the highest-energy gamma rays, CTA will address fundamental questions about the nature of space, time, matter, and energy.

CTA will allow us to tackle scientific questions in 3 distinct areas.

1. Cosmic Particle Acceleration, Propagation, and Impact

The Earth is known to be constantly bombarded by cosmic rays, primarily in the form of high-energy protons and atomic nuclei; however, the actual source and production mechanisms of these cosmic rays are still unknown. The natural accelerators of cosmic rays within our own Galaxy are capable of accelerating sub-atomic particles to much higher energies -- that is, to much faster speeds -- than the Large Hadron Collider, the most powerful particle accelerator constructed so far on Earth. However, as cosmic rays are electrically charged, their paths towards us are scrambled in the magnetic fields between the Earth and their source, making it difficult to be certain of their origins. On the other hand, gamma rays -- some of which are by-products of high-energy cosmic-ray production -- are waves of light, not particles, and do not have an electric charge. 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 cosmic rays play in the feedback processes at work as stars form and galaxies evolve.

• TOP - The Starry Night by Vincent Van Gogh, a reminder that CTA will reveal a dynamic and vibrant gamma-ray sky full of extended objects. (Credit: Van Gogh, Vincent, The Starry Night, 1889, Oil on Canvas, Museum of Modern Art, New York)

• BOTTOM - The Crab Nebula is a supernova remnant, all that remains of a tremendous stellar explosion. Observers in China and Japan recorded this supernova nearly 1,000 years ago, in 1054. It emits detectable light in every region of the electromagnetic spectrum, including gamma rays. An image from the Hubble Space Telescope, which observes in the visible light part of the electromagnetic spectrum, is shown here. (Credit: NASA/ESA/J. Hester and A. Loll , Arizona State University)

2. Extreme Environments

The gamma rays to which CTA is sensitive are the highest-energy electromagnetic radiation available to any observatory. As such, they encode information about the physical processes at work in some of the most violent environments within the Universe. The black holes and neutron stars left when extremely massive stars reach the end of their lives are of particular interest. Although even light cannot escape from beyond the event horizon around a black hole, material that is spiraling into the black hole can radiate X-rays and lower-energy radiation. Gamma rays have also been observed coming from jets near the event horizon of many black holes, although the exact mechanisms by which this process occurs are as yet not fully understood. The excellent angular and energy resolution of CTA will enable us to address these questions with a hitherto impossible level of accuracy.

3. The Frontiers of Physics: Exploring the Void

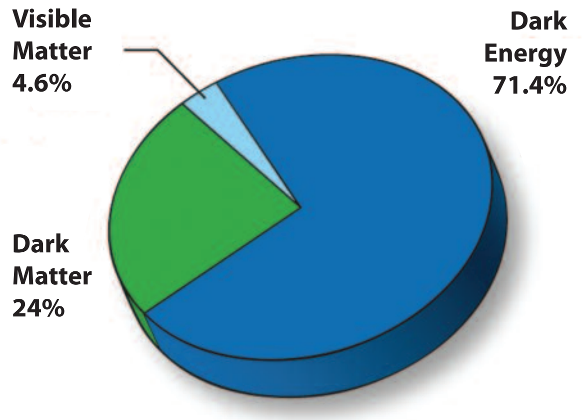
Our Universe is thought to contain hundreds of billions of galaxies, each containing hundreds of billions of stars. These galaxies are attracted to each other by the force of gravity and so are often seen in large structures known as clusters.

Between galaxy clusters are vast regions of apparently-empty space, known as cosmic voids. CTA will be able to probe the subtle effects of the radiation fields, magnetic fields, and space-time foam within these voids -- the last unexplored region of the Universe.

The Search for Dark Matter: In astronomy and cosmology, dark matter is thought to account for a large part of the total mass in the Universe. CTA will be a dark matter discovery instrument of unprecedented sensitivity, and will potentially provide a tool to study the particle physics and astrophysics properties of the as-yet-unidentified dark matter particles.

The Varying Speed of Light? A central concept of Albert Einstein's famous Theory of Relativity is that the speed of light in a vacuum is constant, with the same value everywhere in the Universe. However, recent theories of quantum gravity suggest that the speed of light itself may depend on the energy of the radiation, with the possibility that this effect may be detectable at the highest energies. Through observing the most distant objects at the highest energies possible, CTA will able to test these theories. This will greatly aid physicists seeking to marry the two great theories of 20th century physics -- general relativity and quantum mechanics.

A deeper discussion of each of these science areas can be found on pages 19-24.



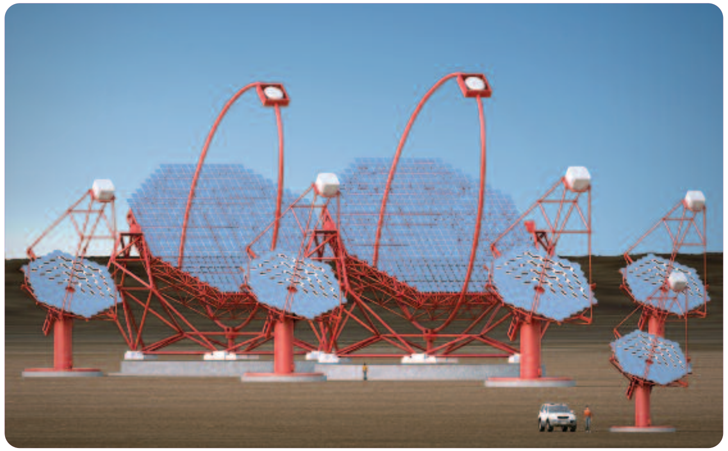
• TOP - Components of the Universe by mass. (Credit: WMAP/NASA)

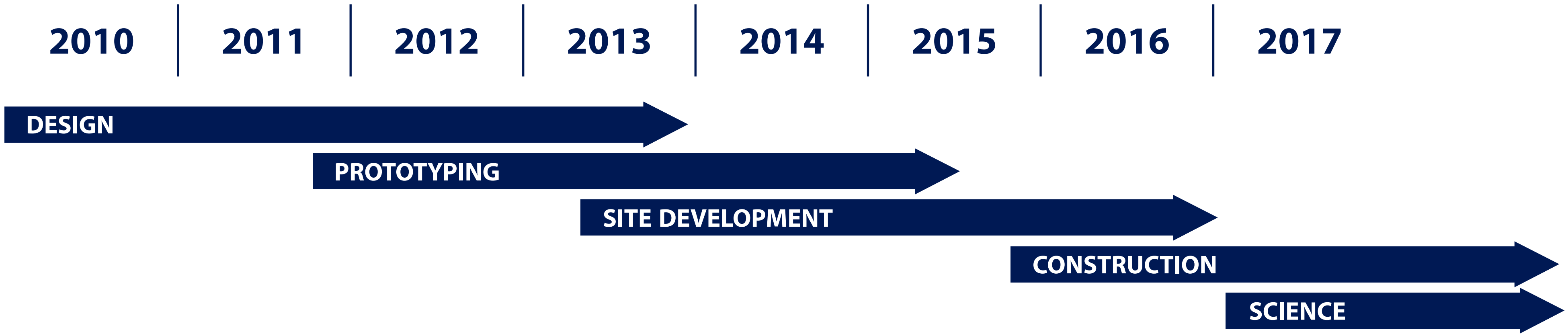
• BOTTOM - Hubble Space Telescope visible light image of Abell 2218, a rich galaxy cluster composed of thousands of individual galaxies. (Credits: NASA/ESA/J. Richard, Caltech)

CTA Project

> Timeline & Key Facts

- CTA will detect the highest-energy photons ever seen
- CTA will have a broad coverage of 5 orders of magnitude -- a factor of 100,000 -- on the energy scale
- CTA will have a large collection area (of over 1,000,000 m^2) and a gamma-ray detection rate of 10x current instruments
- CTA will have a large field of view and will be able to access almost all parts of the night sky
- CTA will operate as an observatory open to all astronomers, with telescope arrays in the Northern and Southern Hemispheres





The Challenges of Building CTA

A large breadth of technical expertise and experience exists among the body of scientists and engineers who work within the CTA consortium. Nonetheless, challenges remain. Most important is driving down the costs of telescope components while also making sure that they are reliable. It is relatively easy to repair and maintain a few telescopes, as found in current ground-based gamma-ray observatories, but maintaining 60, 70, or even 100 telescopes presents a whole new set of problems. Technology is also ever changing, particularly in the area of light detection. New detectors are expected to be available in the near future which innovative two-mirror telescope designs might be able to exploit. Mirror technologies are another area of active research – CTA will require many large, robust, highly reflective, and easily reproducible mirrors, and this is not an easy task.

> "Most important is driving down the costs of telescope components while also making sure that they are reliable."

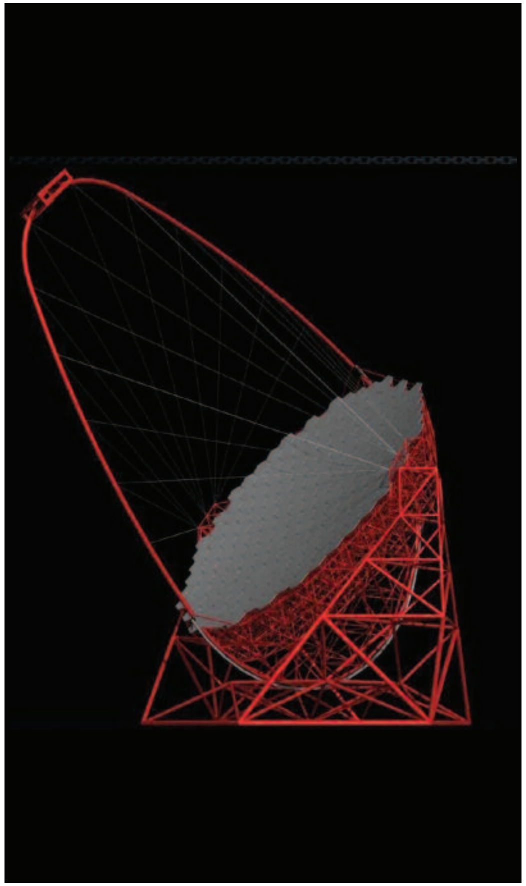
• CTA Medium-Sized Telescope (MST) prototype, constructed by the Deutsches Elektronen-Synchrotron (DESY) Research Centre at the Berlin Science Park Adlershof. (Credit: DESY/Zeuthen)

CTA Technology: The Telescopes

> CTA will be constructed of several different classes of telescope to detect gamma rays of different energies

Large-Sized Telescopes (LSTs)

Gamma rays with low energies produce a relatively small amount of Cherenkov light for the CTA telescopes to detect. To capture these images, telescopes with large mirrors are required. The LST has a parabolic-shaped mirror with a diameter of 24 metres. The entire telescope structure will have a weight of approximately 50 tonnes; nonetheless, in order to capture short-lived, low-energy gamma-ray signals an LST will be able to slew to any position on the sky within 20 seconds.



• Concept art for the Large Sized Telescope (LST).

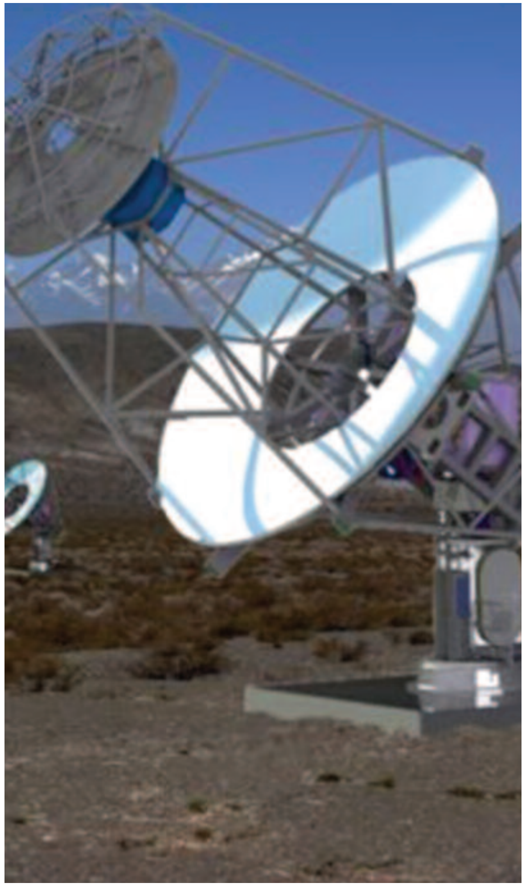
Medium-Sized Telescopes (MSTs)

The MSTs will be the workhorses of CTA and, like all CTA telescopes, are designed with simplicity, robustness, and reliability in mind. The telescopes have a mirror with a 10-12 metre diameter. The MSTs will have a large field of view of around 8 degrees, enabling them to easily observe Galactic gamma-ray sources that can be numerous in a given area of the sky or extremely extended. For example, the gamma-ray-emitting region of the supernova remnant RX J1713.7-3946 has a diameter of approximately 1 degree -- twice as large as the full moon!

• Medium-Sized Telescope (MST) prototype (Credit: DESY/Zeuthen).

Schwarzschild-Couder Telescopes (SCTs)

The CTA consortium has developed an innovative 2-mirror design known as Schwarzschild-Couder telescopes (SCTs), with a 9.6-metre primary mirror and a 5.4-metre secondary mirror. These SCTs are complementary to the MSTs, and operate in a similar gamma-ray energy detection range and with a comparably large field of view. However, the secondary mirror can focus light into a smaller area, which provides greater imaging detail, better detection of faint light, and the possibility to use smaller -- and potentially less expensive -- detectors.



• Concept art for the Schwarzschild-Couder Telescopes (SCTs).

Small-Sized Telescopes (SSTs)

The SSTs will have a diameter of 4 metres, and are sensitive to the highest energy gamma rays. They will be numerous and widely separated in the CTA southern observatory, as a large amount of Cherenkov light over a large area of the sky is produced by very high-energy gamma-ray air showers. Two main design classes are proposed for the SSTs, which are essentially smaller variants of the MSTs and SCTs. As CTA moves into the construction phase, the SST design will be finalized.

• Small-Sized Telescope (SST) prototype (single-mirror design), constructed at the H. Niewodniczański Institute of Nuclear Physics Polish Academy of Sciences in Kraków. (Credit: J. Niemiec).

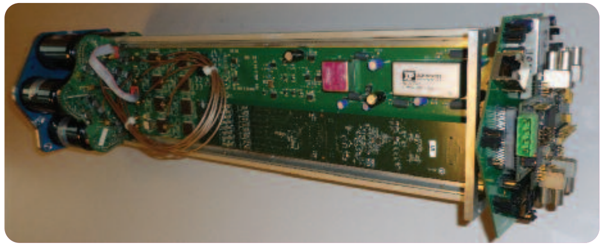
CTA Technology: Measuring the Light

While capturing light is the role of the mirrors in the CTA telescopes, measuring this light is the role of the cameras, which are each slightly different for each telescope type. They all have similarities, however, largely driven by the brightness and short duration of the Cherenkov light flash.

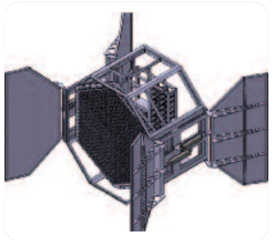
A typical Cherenkov light flash from a gamma-ray-initiated extensive air shower lasts for only a few billionths of a second. It's also much dimmer than normal star light, and typically has a colour towards the blue end of the visible light range, even extending somewhat into the ultraviolet part of the electromagnetic spectrum. The CTA cameras must therefore be fast and sensitive to faint blue-UV light flashes.

The pixels of the cameras are typically formed from individual photomultiplier tubes (PMTs), which convert light into an electrical signal. Where your mobile phone may have a several megapixel camera (making millions of individual measurements of the light within an image), gamma-ray telescopes typically have cameras with mere thousands of pixels spread over a much larger area. However, the pixels in the CTA cameras are sensitive to very faint flashes of light on much faster timescales, and are able to take exposures lasting only a few billionths of a second. In total, for all of the CTA cameras approximately 100,000 PMTs will be required. Consequently, CTA is working closely with industry to allow the needs of CTA to be incorporated into bespoke PMT designs. These PMTs will have a 50% greater efficiency for detecting blue and UV light compared to conventional PMTs, offering CTA greater sensitivity than previous generation cameras for ground-based gamma-ray astronomy.

For the physically smaller cameras of the SCT and SST (dual mirror option), two different light detection technologies are being considered. Multi-anode PMTs provide multiple pixels in a compact package, suitable for the size of these cameras. Another option is to use silicon-based photomultipliers that could provide even greater efficiency for recording blue and UV light. Both of these technologies are currently under investigation for inclusion within CTA.



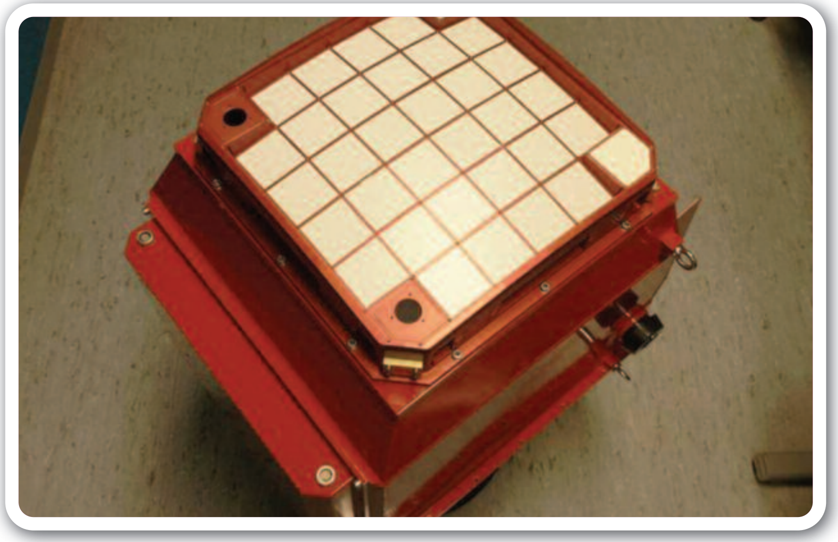
•TOP: Early version (V0) of the NECTAr readout module used in the NectarCAM camera. (Credit: Glicenstein, J.F. et al., Proceedings of ICRC 2013)

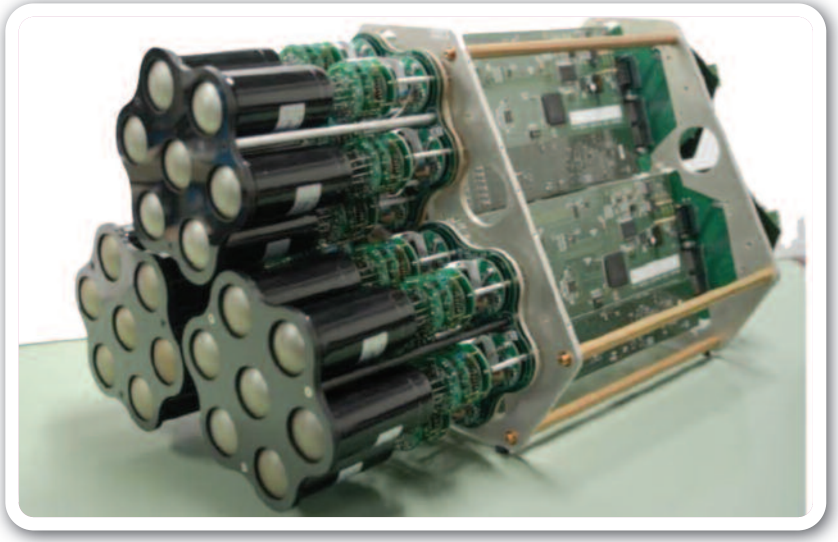


•BOTTOM LEFT - Drawing of a possible implementation of a FlashCam-based MST camera. Front and rear doors are open, isolation panels as well as light guides are not shown. (Credit: Puhlhofer, G. et al., arXiv: 211.3684v1)

•BOTTOM RIGHT - Front view of the FlashCam 12-pixel PDP module. PMTs are from Hamamatsu (R11920, the current baseline option for CTA). (Credit: Puhlhofer, G. et al., arXiv:1211.3684v1)

“A typical Cherenkov light flash from a gamma-ray-initiated extensive air shower lasts for only a few billionths of a second.”



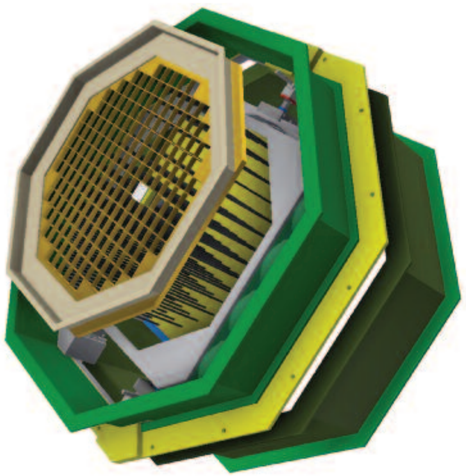


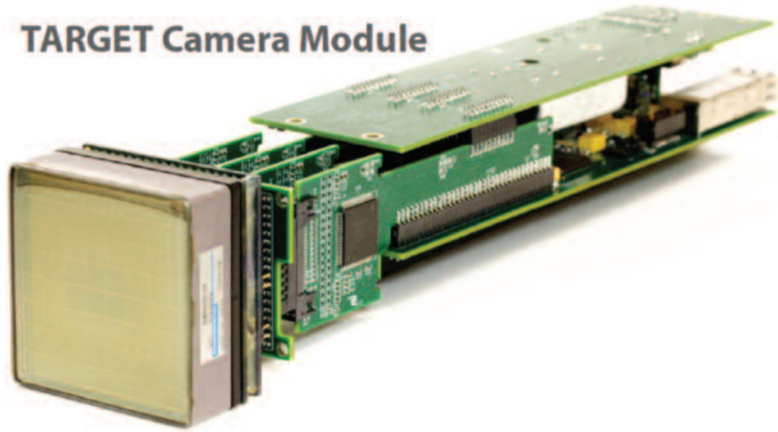
•LEFT TOP - CHEC prototype during construction showing the light-detecting end of the camera. (Credit: R. White)

•RIGHT TOP - Electronics modules for the Large-Sized Telescope camera, consisting of three clusters of light detectors (seven photomultiplier tubes in each cluster, on the left in the image) and the backend electronics and readout system. More than 250 of these clusters will be arranged in a hexagonal structure in each LST camera. (Credit: Kubo et al. 2013, Proc. 33rd ICRC)

•LEFT BOTTOM - Mechanical structure of the SCT camera. Camera modules are inserted in the lattice. (Credit Vandenbroucke, J. et al., arXiv:1407.4151)

•RIGHT BOTTOM - A photo of the TARGET 1 camera module. (Credit Vandenbroucke, J. et al., Proceedings of ICRC 2011)





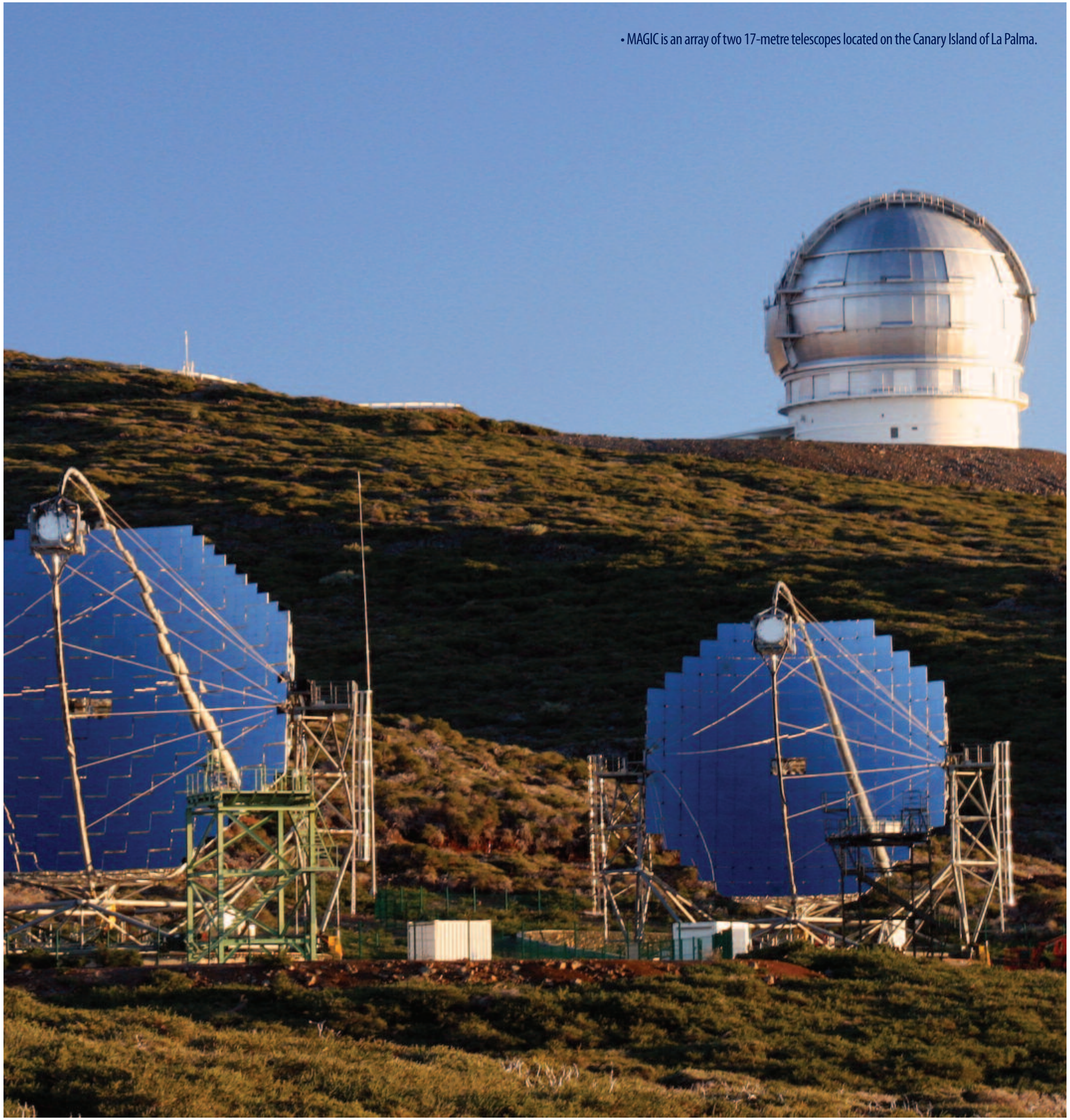
Current Generation Instruments

The current generation of ground-based gamma-ray observatories (shown to the right) started yielding results in 2003, and increased the number of known gamma-ray-emitting objects in the sky from around 10 to over 100. CTA will swell the gamma-ray catalogue by another factor of 10, detecting over 1000 new objects.

CTA will build on these successes through combining:

- The stereo principle using telescopes of different sizes pioneered by H.E.S.S.
- The imaging technique developed by VERITAS (and its predecessor Whipple).
- The use of fast pulse sampling, initially trialled at MAGIC.

CTA will enhance each of these techniques through the use of advanced hardware and sophisticated analysis methods.



• MAGIC is an array of two 17-metre telescopes located on the Canary Island of La Palma.

• VERITAS is an array of 4 12-metre telescopes located in Arizona, USA.

• H.E.S.S. is an array of 1 28-metre and 4 12-metre telescopes located in Namibia.

1. ARGENTINA
2. ARMENIA
3. AUSTRALIA
4. AUSTRIA
5. BRAZIL
6. BULGARIA
7. CROATIA
8. CZECH REPUBLIC
9. FINLAND
10. FRANCE
11. GERMANY
12. JAPAN
13. MEXICO
14. NAMIBIA
15. NETHERLANDS
16. NORWAY
17. POLAND
18. SLOVINIA
19. SOUTH AFRICA
20. SWEDEN
21. SPAIN
22. SWITZERLAND
23. GREECE
24. INDIA
25. IRELAND
26. ISRAEL
27. ITALY
28. UNITED KINGDOM
29. UNITED STATES OF AMERICA

The CTA Consortium

The CTA Consortium consists of over 1000 scientists working in 193 institutes in 29 countries:

Argentina, Armenia, Australia, Austria, Brazil, Bulgaria, Croatia, Czech Republic, Finland, France, Germany, Greece, India, Ireland, Israel, Italy, Japan, Mexico, Namibia, Netherlands, Norway, Poland, Slovenia, South Africa, Spain, Sweden, Switzerland, the UK, and the USA.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Cosmic Particle Acceleration, Propagation, and Impact

> Where do cosmic rays come from?

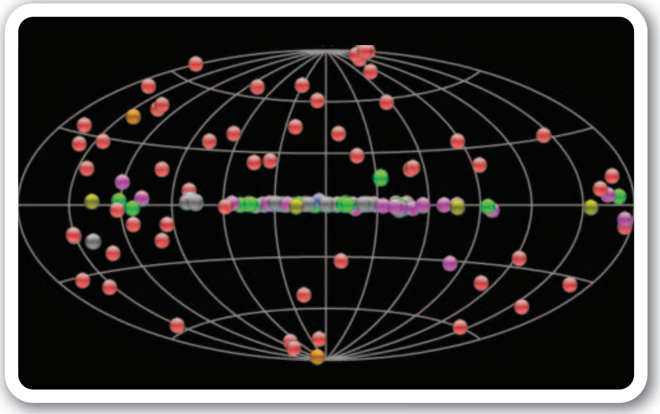
CTA offers us a factor of 10 greater sensitivity and a higher resolving power to provide more detailed images than current ground-based gamma-ray observatories. CTA will show us the gamma-ray sky in greater detail than was possible before, but what will we see?

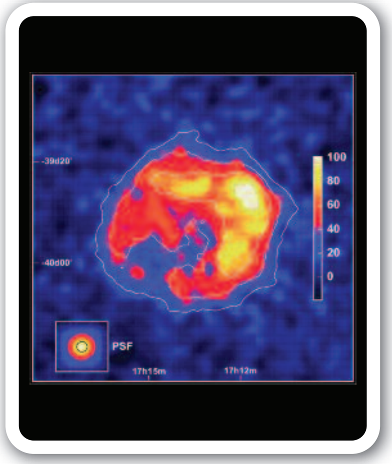
Looking along the plane of our Galaxy with a very-high-energy gamma-ray telescope reveals numerous gamma-ray sources, arranged like a string of pearls. CTA can probe these objects and offer us a unique insight into the various phases of the life cycle of stars. Of particular scientific interest are the extreme explosions known as supernovae, which occur at the end of the life of a massive star.

Stars are powered by the fusion of light elements into heavier elements. Over its lifetime, a star becomes layered like an onion, with heavier elements toward its center. Once the core is converted to iron (which cannot fuse into heavier elements without adding energy to the star), gravity collapses the star into itself. A quantum mechanical effect called degeneracy halts the core collapse, leaving behind a hot, dense neutron star. The outer layers rebound and are blown away from the star. For very massive stars, enough material falls back onto the neutron star to collapse it further into a black hole.

A supernova emits enough energy to briefly outshine the entire galaxy in which it resides. The huge energies involved in supernovae make them ideal places to produce the cosmic rays discussed earlier. Many scientists believe that supernovae produce the majority of cosmic rays within our own Galaxy. This theory derives from the typical amount of energy released by a supernova and the observed rate at which supernovae occur. However, since cosmic rays have been seen at energies higher than those achievable within a supernova, supernovae alone can't solve the mystery of the source of cosmic rays. By mapping the highest-energy gamma rays seen from supernovae with unprecedented angular and energy resolution, CTA will shine new light on the mechanisms by which cosmic rays are accelerated and help to quantify the contribution that supernovae make to the total amount of cosmic radiation seen.

"A supernova emits enough energy to briefly outshine the entire galaxy in which it resides. The huge energies involved in supernovae make them ideal places to produce cosmic rays."





• TOP - Map of currently known very-high-energy gamma-ray sources. The map is plotted in galactic coordinates, so the "equator" is the plane of the Milky Way and the "poles" are the directions above and below our Galaxy. The colours indicate different types of objects. For more information and an interactive version of this diagram, see http://tevcat.uchicago.edu/.

• BOTTOM - Gamma-ray image of the supernova remnant RX J1713.7-3946 obtained with H.E.S.S. The diameter of the outermost white contour is more than twice the size of the full moon in the sky. (Credit: Aharonian et al. 2006, A&A, 449, 223)

> Investigating the role of cosmic rays in galactic evolution

In our Galaxy, the total energy of all cosmic rays is comparable to the energy density of starlight, of interstellar magnetic fields, and of the kinetic energy density of interstellar gas. This suggests that cosmic rays themselves play a significant role in the evolution and formation of galaxies.

Cosmic rays are thought to ionize and heat the dense clouds of molecular gas occurring in star-forming regions within galaxies. This suggests that the cosmic rays produced by dying stars (supernovae) feed back into the production mechanisms for new stars, and hints at the processes behind galactic evolution. CTA is expected to detect gamma rays produced by this cosmic radiation, allowing us to study this effect first hand.

On larger scales, huge voids or bubbles are seen in clusters of galaxies such as Hydra A (shown opposite). The main source of the pressure supporting these bubbles is not known, but cosmic rays could play a significant role. If this is the case, then we would expect a large flux of gamma rays that will likely be visible with CTA.

• Composite image of the Hydra A galaxy cluster showing a region of X-ray emission observed by the Chandra X-ray Observatory (blue) and jets of radio emission observed by the Very Large Array (red), superimposed on a visible light image from the Canada-France-Hawaii telescope and the Digitized Sky Survey that shows the galaxies in the cluster (yellow-white). (Credits: X-ray -NASA/CXC/U.Waterloo/ C.Kirkpatrick et al.; Radio - NSF/NRAO/VLA; Visible - Canada-France-Hawaii-Telescope/DSS)

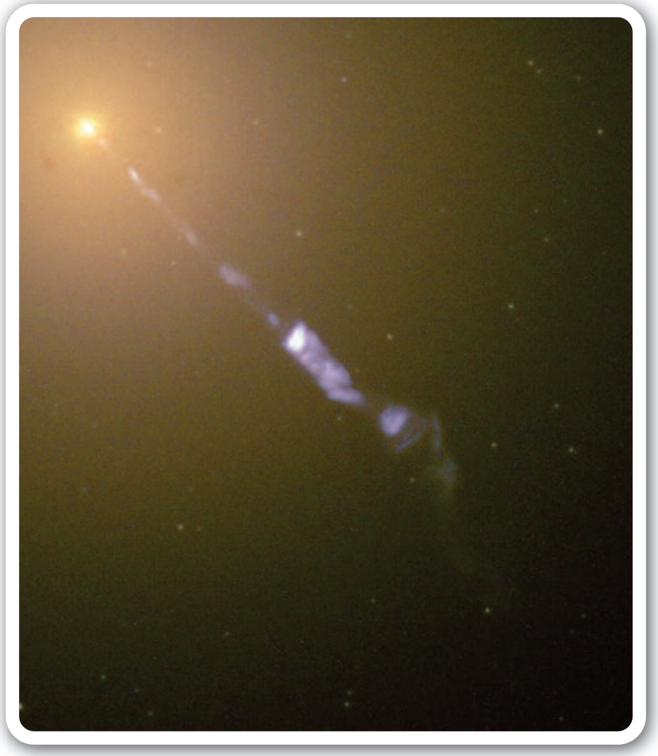
• Hubble Space Telescope visible light image of pillars of gas and dust in the Eagle Nebula (M16), a star-forming region in our Galaxy. (Credit: NASA/J. Hester and P. Scowen, Arizona State University)

Imaging Extreme Environments

> Supermassive black holes

Astronomers believe that most galaxies have a supermassive black hole at their centre (or nucleus). In normal galaxies such as our own, there is little material near the black hole and it remains "quiet." However, in so-called active galaxies, gas, dust, and even nearby stars are falling into the black hole under the influence of its tremendous gravity. This material forms a rotating disk around the black hole. Friction in the disk heats the material as it spirals inward, and it emits light, often in the form of X-rays. Two jets of matter can be produced, moving away from the black hole in opposite directions at speeds close to the speed of light. Such relativistic jets are sources of a great deal of radiation, including very-high-energy gamma rays. Active Galactic Nuclei (AGN) are the most numerous objects on the extragalactic gamma-ray sky. When they occasionally undergo giant outbursts of gamma rays, AGN can also outshine nearby objects in our own Galaxy. The gamma rays they produce tell us about physical processes at extreme energies close to a black hole.

• Cosmic powerhouse -- an artist's view of the nuclear region of an active galaxy, where a disk of accreting gas and dust (orange/yellow) spirals onto the central supermassive black hole. A powerful, collimated jet of particles emitting radio waves (blue) is launched perpendicular to the disk. (Credit: NASA/JPL/Caltech)



• Hubble Space Telescope visible light image of the active galaxy M87. A defining feature of AGNs is the presence of huge jets of particles and radiation that shoot out in opposite directions. Only one of the jets is visible in this image; the other one is behind the galaxy pointing away from us. (Credit: NASA/The Hubble Heritage Team, STScI/AURA)

> Measuring light from the first stars using CTA

Even travelling at the speed of light, gamma rays produced in distant AGN can take billions of years to reach Earth. As they travel the enormous void of intergalactic space, they interact with the matter and radiation that they encounter. Because gamma rays of different energies interact to a greater or lesser extent, the reduction in the number of gamma rays of particular energies that we see at Earth can tell us something about the material in the intervening space. For example, gamma rays can interact with infrared light from the earliest stars, and be converted into sub-atomic particles (electrons and positrons). This means that the gamma-ray signal we see is reduced. The size of this reduction and its dependence on the energy of the gamma rays gives us a direct measure of the amount of starlight from the earliest stars, providing a window onto the early Universe. With its wide energy range and high sensitivity, CTA will be able to precisely measure this effect.

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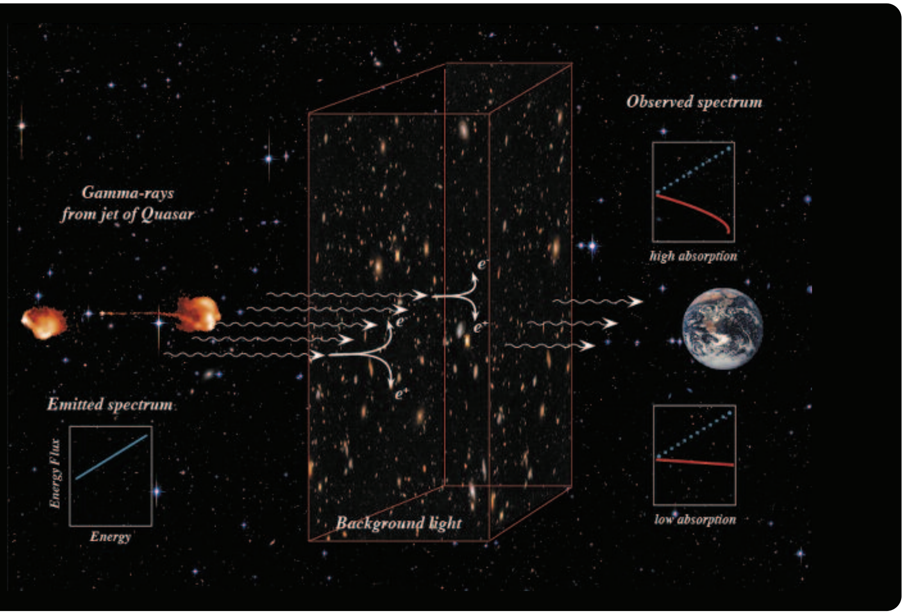
• Effects of the diffuse extragalactic background light (EBL) on the gamma-ray emission from a distant quasar. Before reaching the Earth, the gamma rays are partly absorbed by colliding with the EBL photons produced by all the stars and galaxies in the Universe. If the density of EBL photons is high, then a significant number of the highest-energy gamma rays are absorbed and leave a substantial deficit in the observed distribution of measured energies (observed spectrum, upper panel). If, instead, the EBL photon density is low, then the absorption of high-energy gamma rays is less extreme (observed spectrum, lower panel). (Credit: H.E.S.S.).



The Frontiers of Physics

> The nature of dark matter

Roughly 80 per cent of the mass of the Universe is made up of material that astronomers cannot observe directly. Known as dark matter, this mysterious ingredient does not normally emit or absorb any detectable amount of light. So why do astronomers think it dominates the material content of the Universe?

In the 1930s, studies of the orbital velocities of stars in our own Galaxy, as well as the motions of individual galaxies in galaxy clusters, suggested that there was "missing mass" that was not emitting light but was exerting a gravitational influence on the "luminous matter" around it. In the 1960s and 1970s, this result was extended by observing the speeds at which visible stars are rotating around the centers of other galaxies. It became clear that the Universe contained more matter than could be accounted for by the visible material. Evidence for the existence of dark matter has grown, although we still lack direct evidence of its existence or identity.

The familiar material of the Universe, known as baryonic matter, is composed of primarily protons, neutrons, and electrons. We can easily detect this kind of matter, so dark matter must consist of some other species of particle, called non-baryonic matter.

Different candidates for the identity of dark matter have been suggested by theorists, with perhaps the most popular being Weakly Interacting Massive Particles (WIMPs). These bizarre particles emerge as part of supersymmetry theories that aim to develop a single unified theory that explains the four fundamental physical forces -- gravity, the electromagnetic force, and the strong and weak nuclear forces. The idea is that all of the particles that we know about -- electrons, neutrinos, protons, and so on -- have a more massive "supersymmetric partner" particle that interacts only weakly, via gravity and the weak nuclear force, with normal baryonic matter.

However, if two supersymmetric dark matter particles collide, they should destroy one another. In this process of annihilation, gamma rays can be emitted, which can then be detected and studied with CTA. This gives astronomers a unique opportunity to find clues that can lead to the identity and sources of dark matter.

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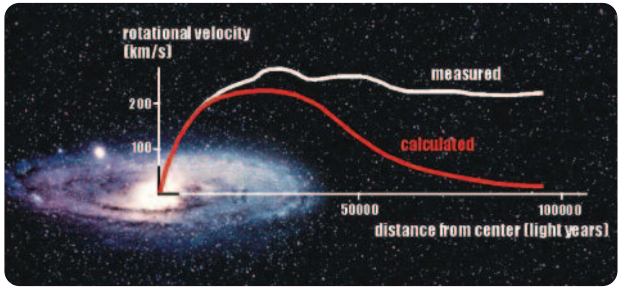
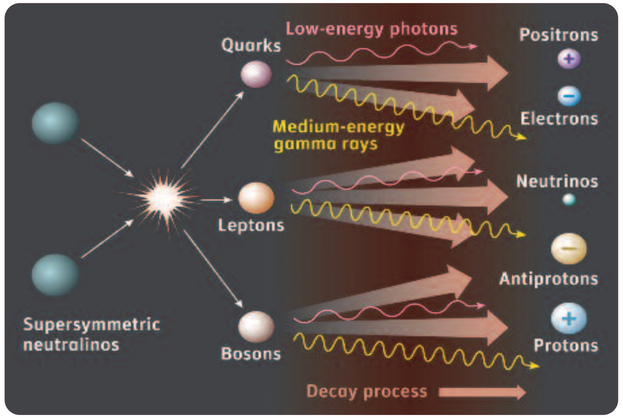




• TOP - Rotation curves of the Andromeda Galaxy. The measured rotational velocities of the outer stars around the centre of the galaxy (white line) are significantly higher than the velocities that would be expected from the estimated mass of the visible matter in the galaxy (red line). This discrepancy can be explained if over 80% of the galaxy's mass is dark matter. (Credit: Queens University)

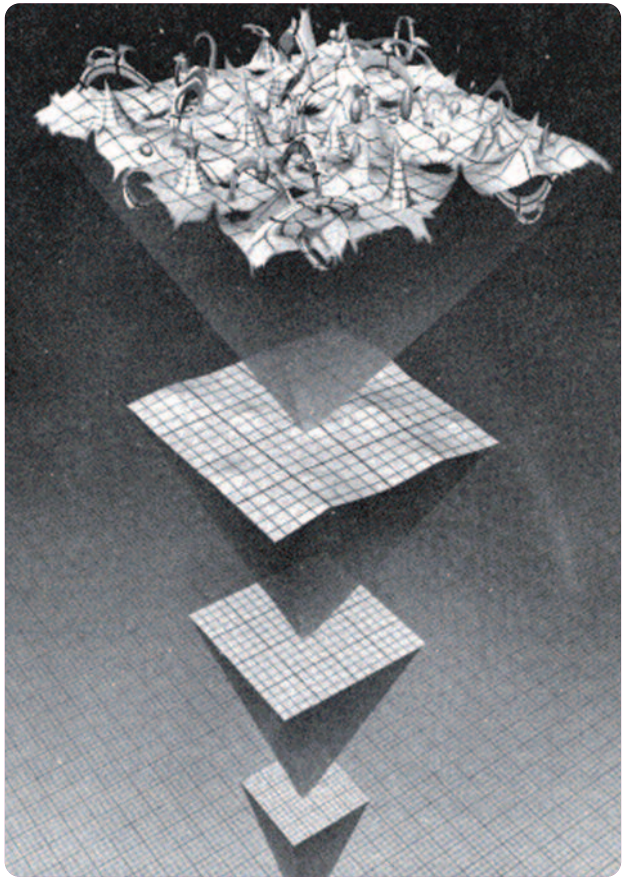
• BOTTOM - Schematic showing the production of gamma rays, along with lower energy photons and subatomic particles, through the annihilation of supersymmetric particles with their anti-matter equivalents. (Credit: Sky & Telescope / Gregg Dinderman.)

> Is the speed of light always constant?

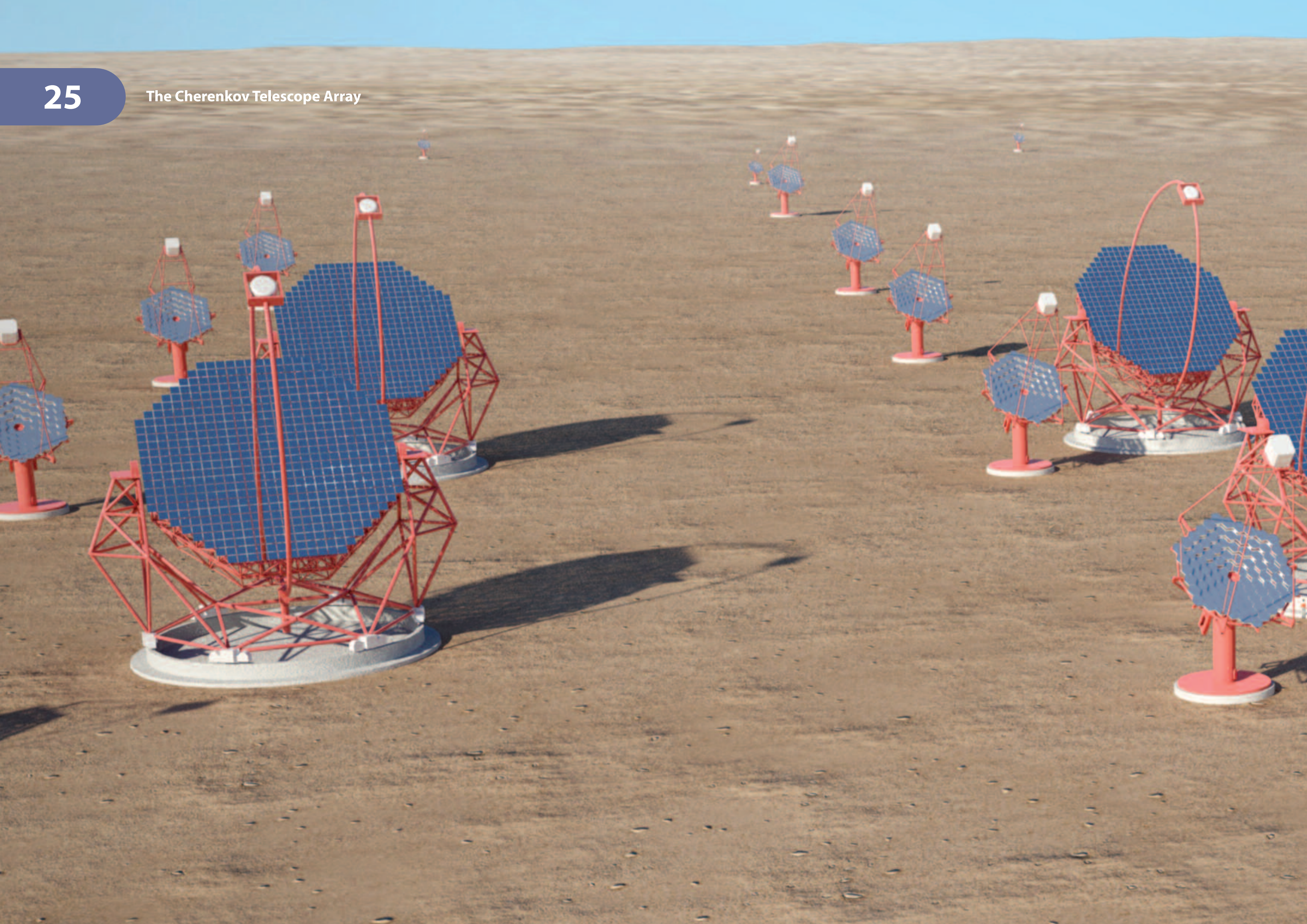
There are four known forces of nature: gravity and electromagnetism, which we experience every day, and the weak and strong nuclear forces, which are important only inside atomic nuclei. Physicists suspect that these are all expressions of a single fundamental force. Indeed, we already know that electromagnetism and the weak nuclear force are two different aspects of the electroweak force that was only present as a single, merged force shortly after the Big Bang, when the young Universe was extremely hot. The problem is that gravity does not appear to behave like the other forces. For example, all of the other forces have an associated particle that "passes" the force from one place to another; in the case of electromagnetism, it's the photon. So far, we have seen no evidence for such a "gravity particle", but numerous theories have been proposed to explain how it might exist; broadly, these are called "quantum gravity," theories. Evidence to suggest that quantum gravity is real is difficult to find, because (although it sometimes doesn't feel like it!) gravity is by far the weakest force. One way to find the required evidence might be through an effect called Lorentz invariance violation.

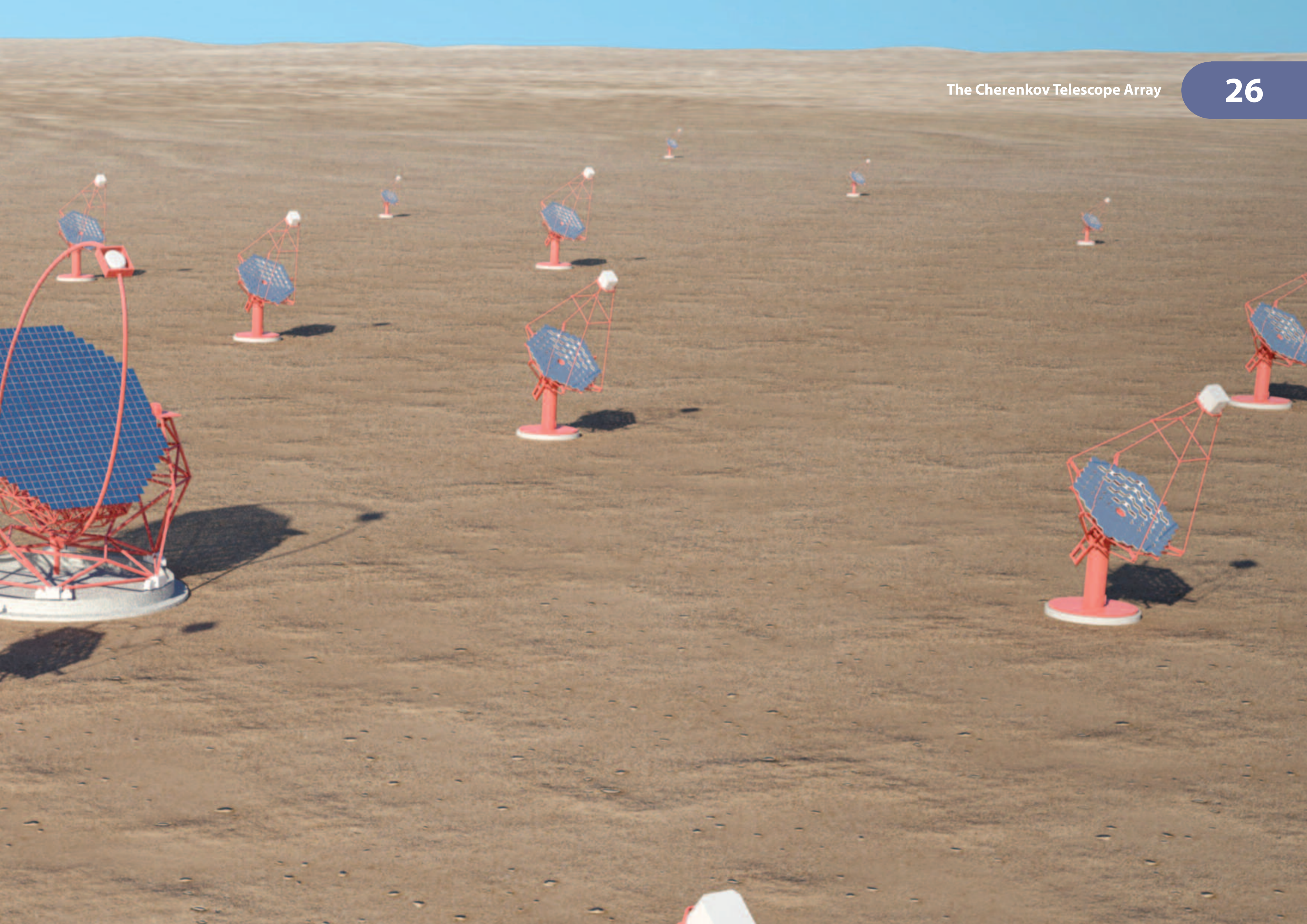
As discussed earlier, one of Einstein's fundamental ideas is that the speed of light in a vacuum is a constant – this is called Lorentz invariance. Some theories of quantum gravity suggest that the speed of light is actually not a constant, but varies with the energy of the photons of light. If present, this would be a tiny effect, so to observe it one must compare photons of very different energies that have travelled a long distance from a single origin. Fortunately, nature has provided us with very distant, high-energy beacons that offer a chance to observe this effect – the active galactic nuclei. With its enhanced sensitivity and wide energy coverage, CTA will be able to observe gamma rays coming from the rapid outbursts of AGN and test whether the low- and high-energy photons arrive at different times (which would indicate that they travelled from the AGN to Earth at different speeds).

"One of Einstein's fundamental ideas is that the speed of light is constant; some theories of quantum gravity suggest it isn't and CTA might be able to determine if this is the case."



• Illustration of an empty region in the Universe under intense magnification. At the tiny quantum scale, empty space is believed to be full of tiny energy fluctuations known as space time foam. Our current understanding of gravity does not extend to these very small sizes. A theory of quantum gravity would be required to understand the structure of the Universe at the smallest distance scale. (Credit: Cocktail Party Physics)





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