The Cherenkov Telescope Array

Swiss participation and perspectives

CTA

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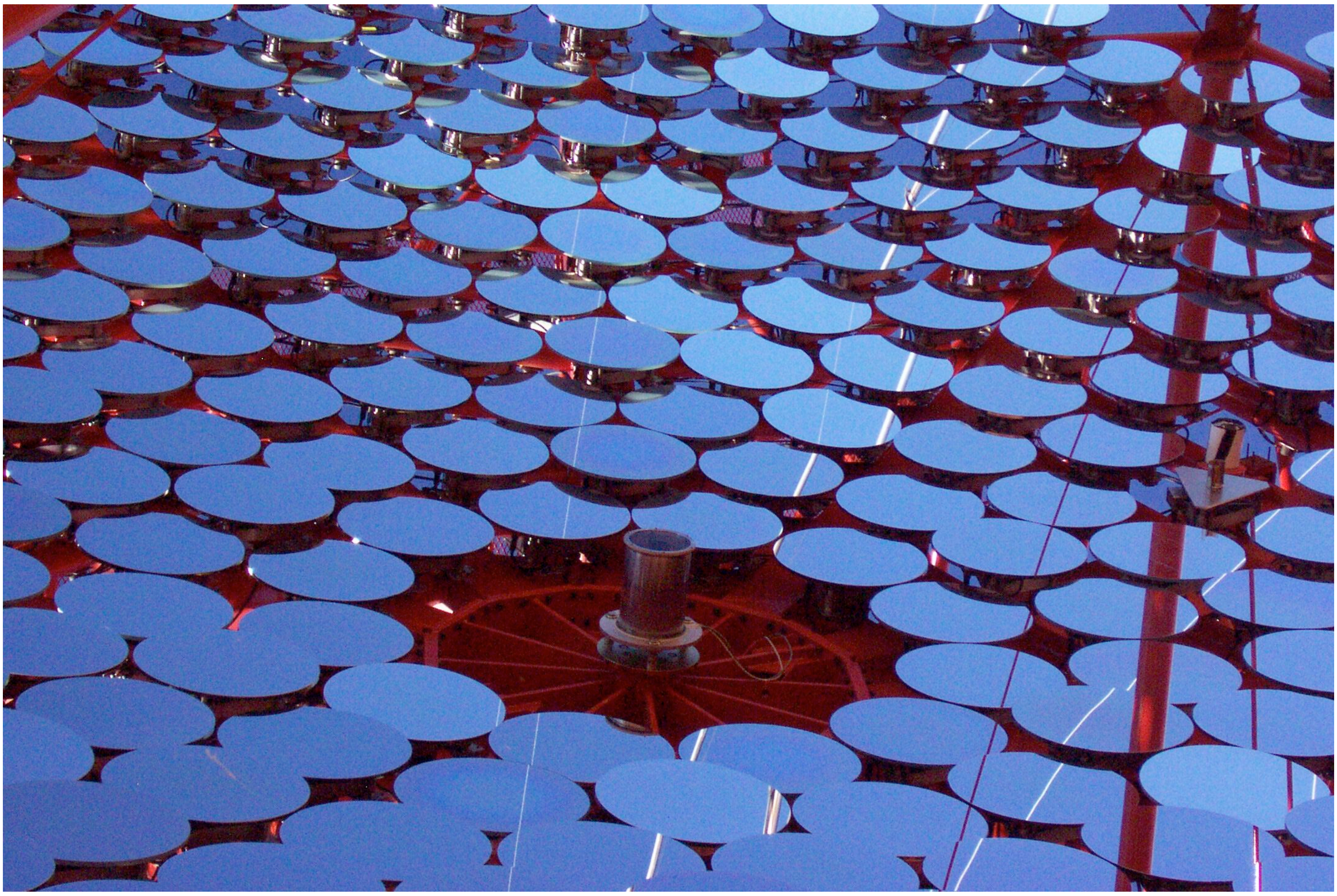
Executive Summary

CTA, the Cherenkov Telescope Array, is the most ambitious next generation experiment in ground based gamma-ray astrophysics. As the successor of the H.E.S.S. and MAGIC instruments, it brings together the European particle physicists and high energy astrophysicists communities. CTA is highly ranked in the ASPERA and ASTRONET roadmaps and is listed as an emerging project in the ESFRI roadmap of 2006.

The CTA collaboration – more than 30 research institutes – is now organizing itself. This document presents a plan for the Swiss contribution to CTA and perspectives for the future as defined by the four leading institutes in the field in Switzerland: the INTEGRAL Science Data Centre and Department of Nuclear and Particle Physics at the University of Geneva, the Institute for Particle Physics at ETH Zurich and the Paul Scherrer Institute.

Swiss scientists have the ambition to lead the effort behind the establishment of the Cherenkov Science Data Centre and the construction of a novel solid-state camera prototype for CTA.



The segmented mirror of the H.E.S.S. Cherenkov telescope

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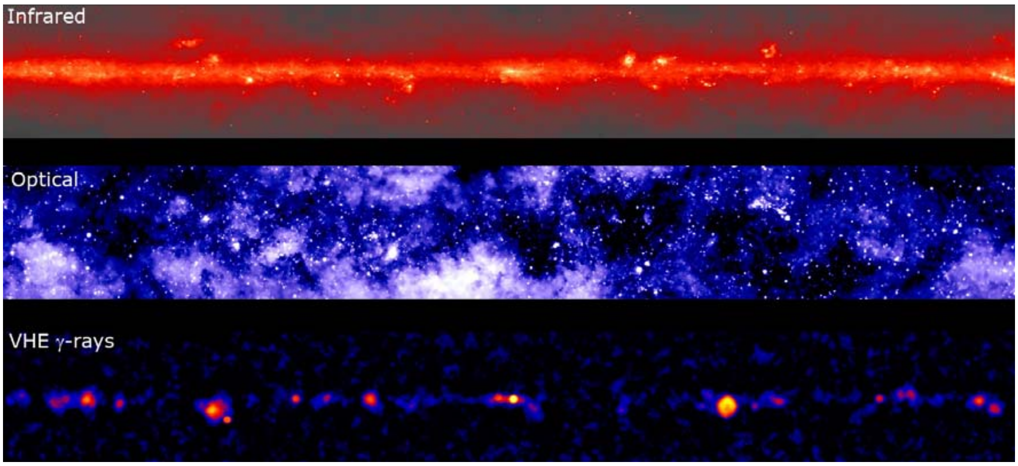
A breakthrough in TeV astrophysics

In March 2007, the High Energy Stereoscopic System (H.E.S.S.) project was awarded the Descartes Research Prize of the European Commission for offering "A new glimpse at the highest energy Universe". Together with the instruments MAGIC and VERITAS (in the northern hemisphere) and CANGAROO (in the southern hemisphere, like H.E.S.S.), a new wavelength domain has opened for astronomy, the domain of very high energy gamma-rays (0.1 – 100 Tera electron volts; 10^{11} – 10^{14} eV), energies which are a million million times higher than the energy of visible light.

Radiation at these energies differs fundamentally from that detected by astronomical instruments at lower energies: GeV to TeV gamma-rays cannot conceivably be generated thermally by emission from 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 in the known Universe. Instead, high energy gamma-rays probe a "non-thermal" Universe, where mechanisms other than thermal emission by hot bodies 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 heavy particles such as the hypothetical dark matter particles or cosmic strings, both relics which might be left over from the Big Bang. In a bottom-up fashion, gamma-rays can be generated when high energy nuclei – accelerated for example in gigantic shock waves created in stellar explosions – collide with ambient gas particles. The flux and energy spectrum of the gamma-rays reflect the flux and spectrum of the high energy nuclei. They can therefore be used to trace these cosmic rays in distant regions of our own Galaxy or even in other galaxies.



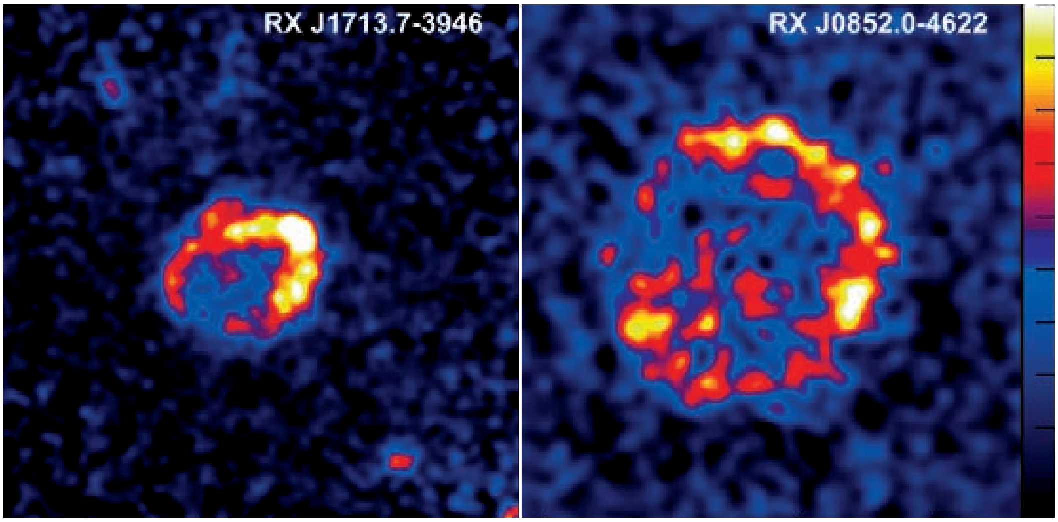
The Milky Way viewed in very high energy gamma-rays (bottom panel), compared to its appearance in visible and infrared light

Imaging the Universe

The first images of the Milky Way in very high energy 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. Sources of this radiation include supernova shock waves, where atomic nuclei are presumably 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 the varying ambient conditions. One of several surprises was the discovery of "dark sources", objects which emit high energy radiation, but have no obvious counterpart in other wavelength regimes. In other words, there are objects in the Galaxy which are so far only visible and detectable in high energy gamma-rays.

Beyond our Galaxy, well over a dozen extragalactic sources of high energy radiation have been discovered, located in active galaxies, where a super massive black hole at the centre 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



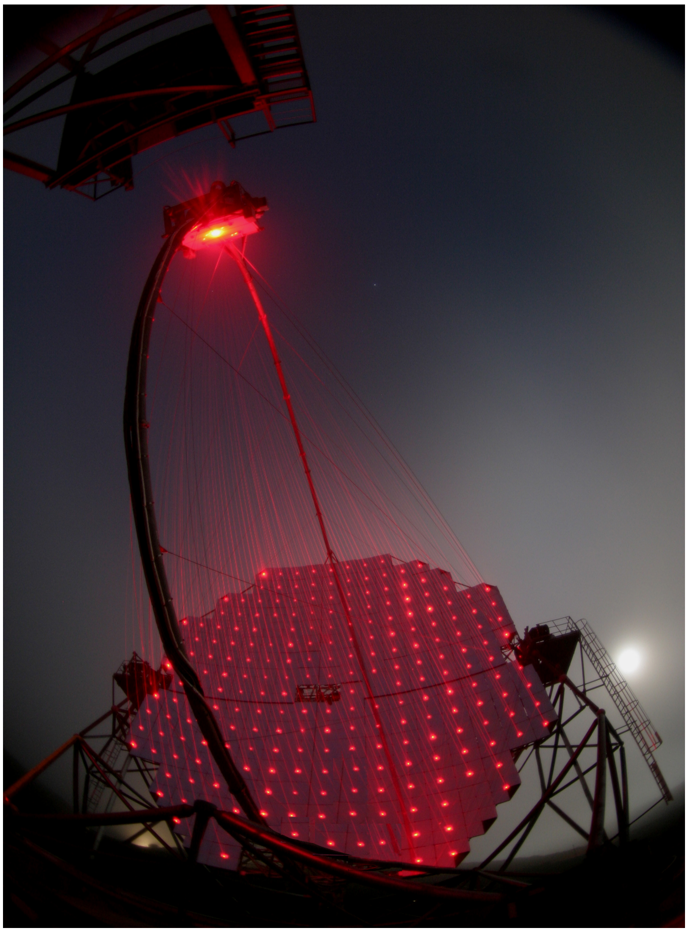
TeV images of shock fronts in supernova, revealing cosmic acceleration of energetic particles

black holes, allowing the study of the processes occurring in this violent and as yet poorly understood environment.

Cherenkov technique

The recent breakthroughs in very high energy gamma-ray astronomy were achieved with Cherenkov telescopes. When a gamma-ray enters the atmosphere, it interacts with atmospheric nuclei and generates a cascade of secondary particles through the atmosphere at speeds higher than the speed of light in the gas. These particles emit a beamed bluish light, the Cherenkov light. The Cherenkov photons are emitted in a pulse which lasts about 10 ns. They illuminate an area on the ground of about 250 m in diameter. Optical telescopes can be used to image the particle cascade by detecting the secondary Cherenkov emission and hence reconstruct the trajectory of the initial gamma-ray. Large optical reflectors with areas in the 100 m^2 range and beyond operated at dark sites are required to collect enough Cherenkov photons to image the particle cascades. An image of the gamma-ray sky can be created by accumulating trajectory data from many photon induced cascades.

The imaging atmospheric Cherenkov technique was pioneered by the Whipple Telescope in the United States. After more than 20 years of development, the first source of very high energy gamma-rays, the Crab Nebula, was detected in 1989. The Crab Nebula is among the strongest sources of very high energy gamma-rays, and is often used as a standard candle. Modern instruments, using multiple telescopes to track the cascade from different perspectives and employing fined-grained photon detectors for improved imaging, can detect sources down to 1% of the flux of the Crab Nebula. The use of "stereoscopic" telescopes to provide images of the cascade from different viewing points was pioneered by the European HEGRA instrument, precursor of the current H.E.S.S. and MAGIC telescopes.

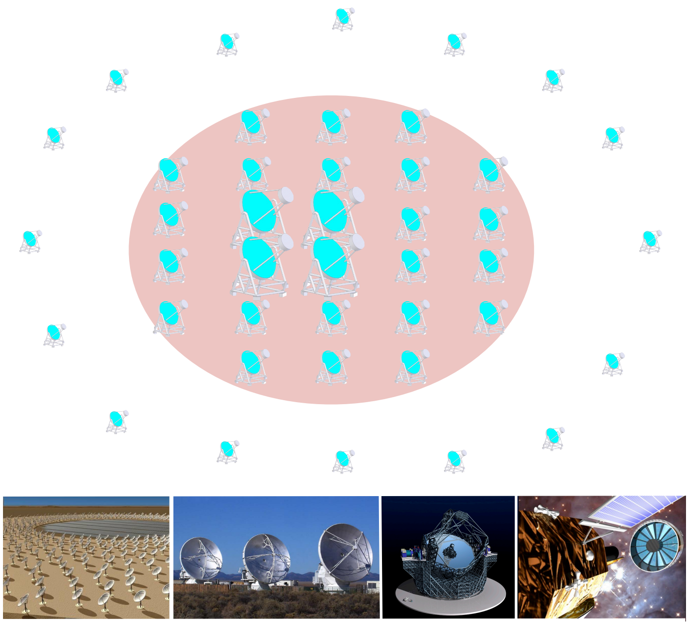


Alignment of the mirrors of the MAGIC telescope

The Cherenkov Telescope Array

A new research infrastructure

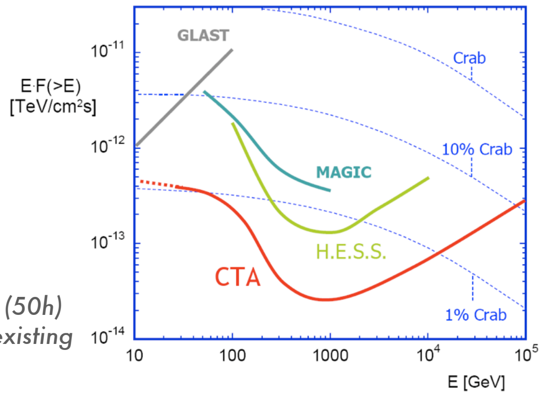
In the field of very high energy gamma-ray astronomy, Europe with H.E.S.S. and MAGIC holds a clear leading position. The spectacular astrophysics results from current Cherenkov instruments have generated considerable interest in both the astrophysics and particle physics communities and have spawned the urgent wish for a next-generation, more sensitive and more flexible facility, able to serve a large community of users. The proposed CTA facility – an array of Cherenkov telescopes building on proven technology deployed on an unprecedented scale – will allow the European scientific community to remain at the forefront of the advancement of research. CTA is a new facility, well beyond the conceivable upgrades of existing instruments such as H.E.S.S. or MAGIC. The CTA project for the first time unifies the research groups working in this field in Europe in a common strategy, resulting in a unique convergence of efforts, human resources, and know-how. Interest in and support of the project span scientists from more than 30 research institutes all over Europe, in the Czech Republic, Finland, France, Germany, Italy, Ireland, the Netherlands, Poland, Spain, Switzerland, and the United Kingdom, wishing to use such a facility for their research and willing to contribute to its design and construction. CTA will offer worldwide unique research services to users from different countries. The number of young 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 increased interest by other parts of the astrophysical community, such as radio and X-ray astronomers. For the first time in this field, CTA will generate large amounts of data open to public access, allowing data mining in addition to targeted observation proposals. Accessible through policies and tools in use in the astronomical observatories, CTA aims to emerge as a cornerstone in a networked multi-wavelength, multi-messenger exploration of the Universe.



Possible telescope configuration for CTA (top) together with other observatories of the 2020s: SKA, ALMA, ELT and XEUS

CTA Performance

Imaging atmospheric Cherenkov radiation is by now a well established technique 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 instrument, providing vastly improved performance and increased flexibility to accommodate a large community of users. The CTA observatory aims at increasing sensitivity in the core energy range from about 100 GeV to about 10 TeV by roughly one order of magnitude, and at the same time aims at expanding the energy range for very high energy gamma-ray astronomy towards both lower and higher energies, effectively increasing the usable energy coverage by a factor of ten. Furthermore CTA will provide both significant improvements in angular resolution, revealing finer details in the sources, and unprecedented detection rates, enabling researchers to track transient phenomena on very short time scales.



CTA sensitivity (50h) compared to existing instruments

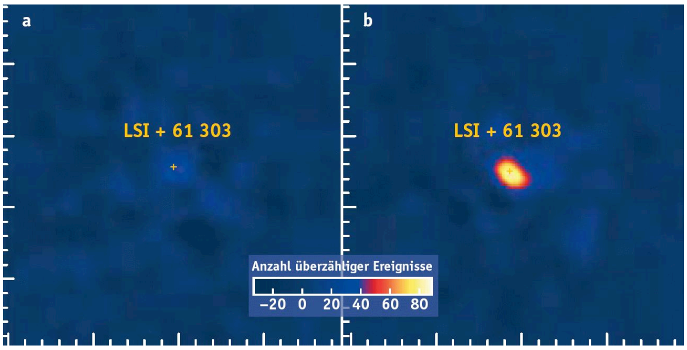
Astrophysics with CTA

The high energy phenomena, which can be studied with CTA, span a wide field of galactic and extragalactic astrophysics, of plasma physics, particle physics, astroparticle physics, and fundamental physics of space-time. They encode information on the birth and death of stars, on the matter circulation in the Galaxy, and on the history of the Universe.

Supernovae remnants, pulsar wind nebulae, and cosmic rays. A paradigm of high energy astrophysics is that cosmic-rays are accelerated in supernova explosion shocks. While particle acceleration up to energies well beyond 10^{13} eV has now clearly been demonstrated by H.E.S.S., it is by no means proven that supernovae accelerate the bulk of cosmic rays. The large sample of supernovae which will be observable with CTA, in some scenarios several hundred objects, and in particular the increased energy coverage towards lower and higher energies will allow sensitive tests of acceleration models and determination of their parameters. Pulsar wind nebulae surrounding the pulsars created in supernova explosions 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.

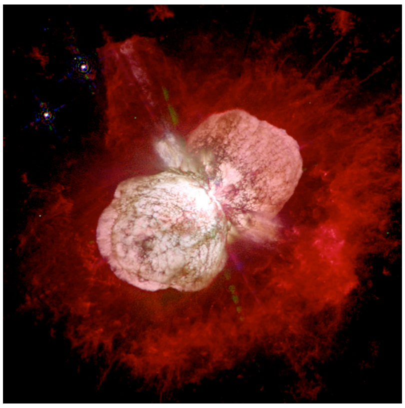
Pulsar physics. Pulsar magnetospheres are known to act as efficient cosmic accelerators, yet there is no accepted model for this particle acceleration, a process which involves electrodynamics with very high magnetic fields as well as the effects of general relativity. Pulsed gamma-ray emission allows the separation of 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 CTA. Compared to gamma-ray space instruments, CTA with its much larger detection rate is not affected by glitches in pulsar periods which may compromise periodicity measurements requiring very long integration times.

Micro-quasars and X-ray binaries. Three very high energy gamma-ray emitters are currently known which are binary systems, consisting of a compact object – a neutron star or black hole – orbiting a massive star. Whilst many questions are open concerning gamma-ray emission from such systems – in some cases it is not even clear if a pulsar-driven nebula around a neutron star or accretion onto a black hole is the energy source – it is evident that they offer a unique chance to "experiment" with cosmic accelerators. Along the eccentric orbits of the compact objects, the environment (including crucially the radiation field) changes periodically, resulting in a modulation of the gamma-ray flux, allowing the study of how particle acceleration reacts to these environmental conditions. Equally interesting, the physics of micro-quasars in our own Galaxy resembles the processes occurring around supermassive black holes in distant active galaxies, except for the much faster time scales, providing insights into these mechanisms.



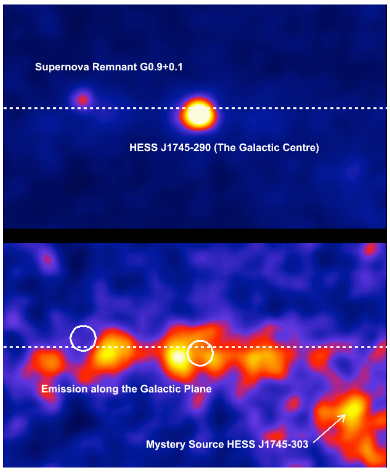
Variable TeV signal from the X-ray binary LSI +61 303

Stellar clusters and stellar systems. While the classical paradigm emphasizes supernova explosions as the dominant source of cosmic rays, it has been speculated that cosmic rays are also accelerated in stellar winds around massive young stars before they explode as supernovae, or around 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, lack of instrument sensitivity currently prevents the detailed study and clear identification of these sources of gamma radiation.



Eta Carinae generates shocks which accelerate particles

The Galactic Centre. The Galactic Centre hosts the nearest supermassive black hole, as well as a variety of other objects likely to generate high energy radiation, including hypothetical dark matter particles which may pair-annihilate and produce gamma-rays. Indeed, the Galactic Centre has been detected as a source of high energy gamma-rays, and indications for high energy particles diffusing away from the central source and illuminating the dense gas clouds in the central region have been detected. In observations with improved sensitivity and resolution, the Galactic Centre provides a rich reservoir of interesting physics from particle acceleration via the not well known diffusive propagation of cosmic-ray particles to exotic phenomena such as acceleration and curvature radiation of protons at the edge of rapidly spinning black holes.



TeV sources in the galactic centre (top) and diffuse emission (bottom)

Active galaxies. The supermassive black holes at the cores of active galaxies are known to produce outflows which are strong sources of high energy gamma-rays. The fast variability of the gamma-ray flux on minute time scales indicates that gamma-ray production must occur near the black hole, assisted by highly relativistic motion resulting in a contraction of time scales when viewed from an observer on Earth. Details of how these jets are launched by the black hole and even the kinds of particles of which they consist are poorly understood. Multi-wavelength observations with high temporal resolution can distinguish different scenarios, but are at the edge of the capability of current instruments.

Galaxy clusters. Galaxy clusters act as storehouses of cosmic rays, since all cosmic rays produced in cluster galaxies since the beginning of the Universe will be confined to the cluster. Probing the density of cosmic rays in clusters via their gamma-ray emission thus 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. Emission from galaxy clusters is predicted at levels just below the sensitivity of current instruments.

Cosmic radiation fields and cosmology. Via their interaction with extragalactic light, high energy gamma-rays from distant galaxies allow the extraction of cosmological information on the density of light in extragalactic space and therefore about the formation history of stars in the Universe. Gamma-rays experience an energy-dependent attenuation when propagating through intergalactic space, due to electron-positron pair production on the extragalactic background light. This phenomenon allows determination of extragalactic light levels, unimpeded by the overwhelming amount of foreground light from the solar system and the Galaxy, which makes direct measurements prone to very large systematic uncertainties. Pair-production halos surrounding active galaxies may even allow measurement of the evolution of light intensity with redshift.

Search for Dark Matter. The dominant form of matter in the Universe is a yet unknown type of dark matter, most likely in form of a new class of particles such as predicted in supersymmetric extensions to the standard model of particle physics. Dark matter particles accumulate in, and cause, wells in gravitational potential, and with high enough density they are predicted to have annihilation rates resulting in detectable fluxes of high energy gamma-rays. CTA would provide a sensitive probe of this annihilation radiation, and will help to verify if such particles – which by then might be discovered at the Large Hadron Collider LHC – form the dark matter in the Universe.

Probing space-time. Due to their extremely short wavelength and long propagation distances, very high energy gamma-rays are sensitive to the microscopic structure of space-time. Small-scale perturbations of the smooth space-time continuum, as predicted in theories of quantum gravity, should manifest themselves in a (tiny) energy dependence of gamma-ray propagation speeds. Burst-like events of gamma-ray production, e.g. in active galaxies, allow this energy dependent dispersion of gamma-rays to be probed and can be used to place limits on certain classes of quantum gravity scenario, and may possibly lead to the discovery of effects associated with quantum gravity.

γ-ray astrophysics in Switzerland

INTEGRAL Science Data Centre (ISDC) – University of Geneva

The high energy group of the astronomical observatory 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 INTEGRAL Science Data Centre. The group then moved from the Geneva observatory to a beautiful close-by setting in Ecogia.

INTEGRAL and its science data centre

While designing the gamma-ray observatory of the European Space Agency, INTEGRAL, it was decided that the science data centre should be provided by the scientific community in order to best match the science analysis functionalities with the needs of the scientists. This allowed the community to use the competence and the willingness of institutes and funding authorities to actively contribute to this important element of the mission. This decision lead to the creation of ISDC, a centre to which a consortium of 12 institutes in Europe and the United States have contributed. The main funding source is provided by the Swiss authorities and the State of Geneva and its University.

Since the launch of INTEGRAL (October 17, 2002), the data are transmitted continuously from the detectors on-board to ISDC. The data are analyzed three times at ISDC, within seconds to detect gamma-ray bursts, within hours to detect new sources in the sky or particular variations of sources and within weeks to extract the most information possible from the data and distribute it to the science community world-wide. Following the success of the INTEGRAL operations, ESA selected ISDC and Geneva observatory to perform part of the processing for the Planck and Gaia missions, to be launched in the next years. ISDC has already been chosen by the scientific community to provide the science data centre for the next major european X-ray observatory, XEUS.

Some 40 people from more than 10 countries work together at the ISDC. The team is made of some 15-20 engineers and technicians, 14 PhD scientists, 4-5 PhD students and 3 administrative staff. They developed and now operate a large range of complex software that exceeds in their capabilities all the original expectations. ISDC has also benefited from many contributions from outside engineers and scientists, in particular those associated with the teams that built the INTEGRAL instruments.

High energy astrophysics at the ISDC

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, stellar formation, massive stars, supernova remnant, active galactic nuclei, galaxy clusters, gamma-ray bursts and dark matter/cosmology using all types of astronomical facilities. Since 1998, 11 PhD thesis have been conducted with 4 additional ones on-going. During the last years, ISDC scientists contributed in 50 referred papers per year on average. ISDC scientists participate in the CTA, XEUS and POLAR projects.

The INTEGRAL spacecraft

Institute for Particle Physics (IPP) – ETH Zurich

For more than ten years, the experimental research activities at the Institute for Particle Physics concentrate on two main pillars: particle physics at accelerators and astro-particle physics.

Research groups at IPP have a long-term tradition of successful participation in experiments at the high energy frontier, from the design to prototyping, construction, operation and data analysis of large-scale experiments like the L3 and LHC experiments at CERN.

IPP is contributing in a major way to the CMS experiment at LHC.

Astro-particle physics at IPP

IPP members initiated the L3+Cosmics experiment at CERN. From the data collected until November 2000, a variety of important results have emerged, related to cosmic rays and astro-particle physics. IPP also played a leading role in the design and construction of the AMS detector. A prototype (AMS-01) was installed on the space shuttle Discovery during a 10 days mission in 1998 and demonstrated the feasibility to operate a large magnetic spectrometer in space. AMS-02 should be installed at the International Space Station in the near future. One of the main objectives is to investigate whether antimatter exists in the Universe today in a measurable quantity.

Since 2003 IPP participates in MAGIC, a Cherenkov telescope experiment observing very high energy gamma-rays from galactic objects such as supernova remnants, pulsars or binary systems, as well as extra-galactic objects, most notably Active Galactic Nuclei and Gamma-Ray Bursts. IPP has been involved in the commissioning of the MAGIC-I telescope, the improvement of the Active Mirror Control (AMC) and strongly contributes to data analysis. In addition, IPP is responsible for the design and construction of the AMC for MAGIC-II, presently under construction on the Canary Island of La Palma.

Research and development performed in collaboration with PSI on novel photo detectors (gAPDs) demonstrated the feasibility to use this new device for a substantially improved camera to detect the Cherenkov light from high energy gamma-rays. The next step is to build a prototype camera using gAPDs and new readout electronics in view of a possible future application for CTA.

IPP is also strongly involved in the CTA studies since the very beginning. We are represented in the adhoc CTA steering committee and participate in several CTA working groups.

The MAGIC telescope located at the Roque de los Muchachos Observatory on the Canary Island of La Palma

DPNC – University of Geneva

The Department of Nuclear and Particle Physics of the University of Geneva has a track record in excess of 15 years concerning the design, manufacture and exploitation of silicon tracking devices, calorimeters and scintillation detectors for particle physics. Recent projects include the central tracking chamber and the silicon vertex detector for the L3 experiment at CERN, the silicon detector for the NASA AMS and the CERN ATLAS experiments as well as the complete hardware for the FAST experiment at PSI.

Astro-particle physics at DPNC

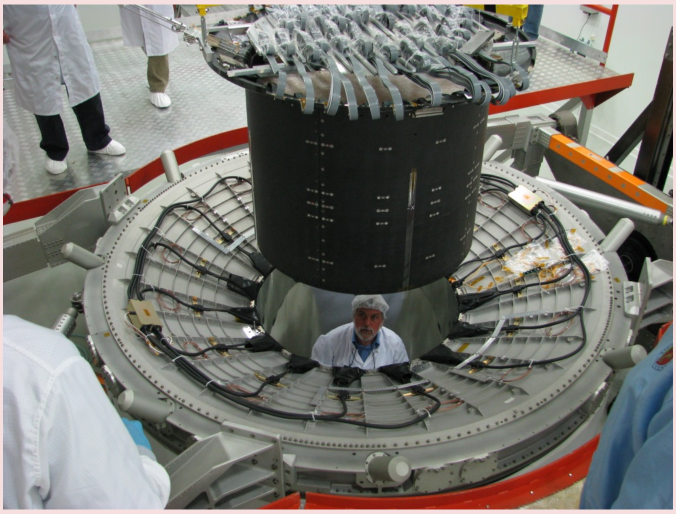
DPNC participated to the LEP experiment L3 which measured the Z^o resonance and the number of families of leptons existing in nature as well as limits on the mass of the Higgs boson. These results have profound implications on the big bang theory and on cosmology.

DPNC is a founding member of the collaboration building and operating the Alpha Magnetic Spectrometer (AMS), which will analyze cosmic radiation of galactic and extragalactic origin at an altitude of about 400 km above Earth. A precursor flight on NASA Space Shuttle mission STS-91 already took place in June 1998, using the prototype detector AMS-01.

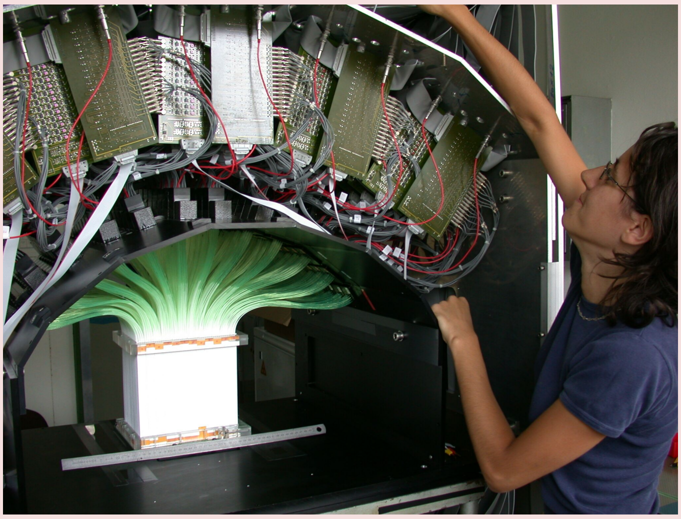
Based on this experience, a new detector was conceived which is being completed. The detector is scheduled to be 'launch ready' at the end of the year 2008. The University of Geneva group has responsibilities for the assembly and integration of the main detector, i.e. the Silicon tracking detector, and for its associated read-out electronics.

DPNC is also collaborating with the ISDC in the framework of the POLAR project, a Compton camera measuring the polarization of photons from gamma-ray bursts. The scintillating bar technology for this device is based on the hardware of the Fibre Active Scintillator Target (FAST) experiment at the Paul Scherrer Institute which aims at measuring the muon lifetime and the strength of the weak interaction with a precision of 10^{-6}.

The DPNC astro-particle physics group has also contributed significantly to the analysis of data from the AMS-01 mission and the preparation of AMS-02 data analysis. The group has specialized on the subjects of heavy ion detection and photon detection by conversion in the AMS spectrometer.



Insertion of the AMS tracking detector into the magnet structure



FAST experiment at the Paul Scherrer Institute

Paul Scherrer Institute (PSI) – Villigen

The Paul Scherrer Institute (PSI) is one of the leading European laboratories pushing forward the development of novel particle detectors and associated readout electronics for high energy physics, which are used in other fields of research as well. PSI has made important hardware contributions to the space astronomical missions XMM-Newton, RHESSI, the James Webb Space Telescope and POLAR.

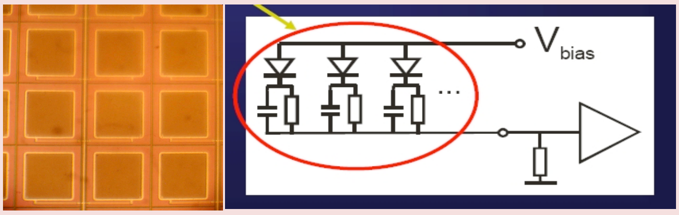
PSI has developed two technologies which are key elements for a novel CTA camera.

Solid state photo detectors

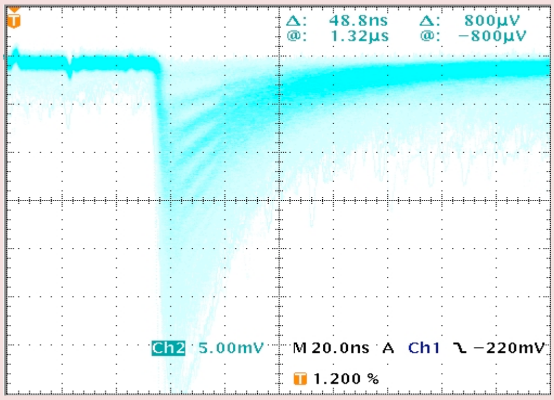
The photo sensors in the electromagnetic calorimeter of the CMS experiment at LHC have to operate in an extremely harsh environment. CMS with PSI as leading institution developed in close collaboration with Hamamatsu Photonics a radiation hard avalanche photodiode (APD). Some 100 prototypes have been characterized and during the mass production of the final device 140 thousand APDs have been subject to a screening procedure in order to ensure a reliability of 99.9%.

The recently developed Geiger-mode avalanche photodiodes (gAPDs) have a substantially improved sensitivity and can detect single photons with a high efficiency of more than 60%. They have properties similar or even superior to photomultiplier tubes and are therefore also named silicon photomultiplier.

Advantages of this novel device are a high internal gain (10^5 to 10^6), the small dimension, a relative low bias voltage (<100 V), insensitivity to magnetic fields and prolonged exposure to light. PSI works closely with the producers on the optimization of the gAPDs.



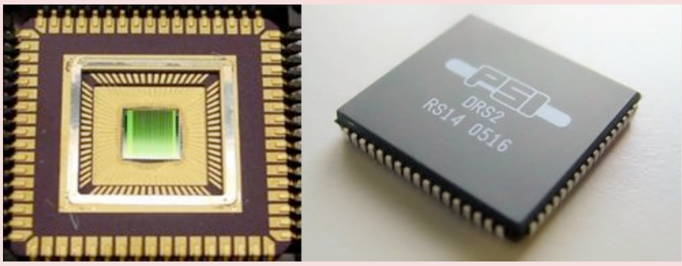
Design principle of a gAPD: a large number (100 to 10000 per mm²) of small photodiodes are connected in parallel



Signal from weak light flashes detected with a gAPD which is directly connected to an oscilloscope. The lines are caused by flashes containing one, two, three and more photons

Domino Ring Sampling Chip DRS

This PSI development acts as a "time stretcher" which allows the recording of very fast signals with a standard ADC. The DRS chip is a switched capacitor array (SCA) designed in a 0.25 µm CMOS process. It is capable of sampling analog waveforms from 10 MHz to 5 GHz. The stored waveforms can be read out and digitized with commercial ADCs at a speed of 33 MHz. The high channel density (12), deep sampling depth (1024 bins), low power consumption (100 mW) and low dead time (3 µs if reading out 100 samples) make this chip ideally suited for experiments involving photomultiplier, avalanche photo diodes and drift chamber readout, as well as for industrial applications such as hand held oscilloscopes.



The DRS chip without and with ceramic package

Swiss participation in CTA

The high energy astrophysicists at ISDC and the particle physicists at IPP, DPNC and PSI plan to have a strong Swiss participation in CTA. ISDC, together with IPP and DPNC, plan to lead the effort behind the establishment of the science data centre for CTA. In addition, with the expertise of PSI, these institutes plan to lead the construction and scientific exploitation of a novel solid-state camera prototype for CTA.

Cherenkov Science Data Centre

Switzerland is in a unique position to host the Cherenkov Science Data Centre as the ISDC and IPP teams together combine the knowledge of the Cherenkov telescope techniques, construction and calibration and of the organization, build-up and operation of a worldwide data centre active in high energy astrophysics. The team also represents the needs and interests of both the astronomical and astro-particle communities.

CTA will provide a high quality set of data complimentary to those obtained with other major astronomical facilities on the ground and in space. Many problems in modern astronomy require the use of several of these facilities together in order to understand the physics of the objects under study. Within the next 10–15 years, Switzerland will host a centre which will make data from major European high energy astronomical observatories (CTA, INTEGRAL, XEUS) available in inter-operable format and provide an integrated level of service to the scientific community. This centre will foster scientific research in high energy astrophysics in the world and in Switzerland and will enhance the world-wide visibility obtained by Switzerland through ISDC.

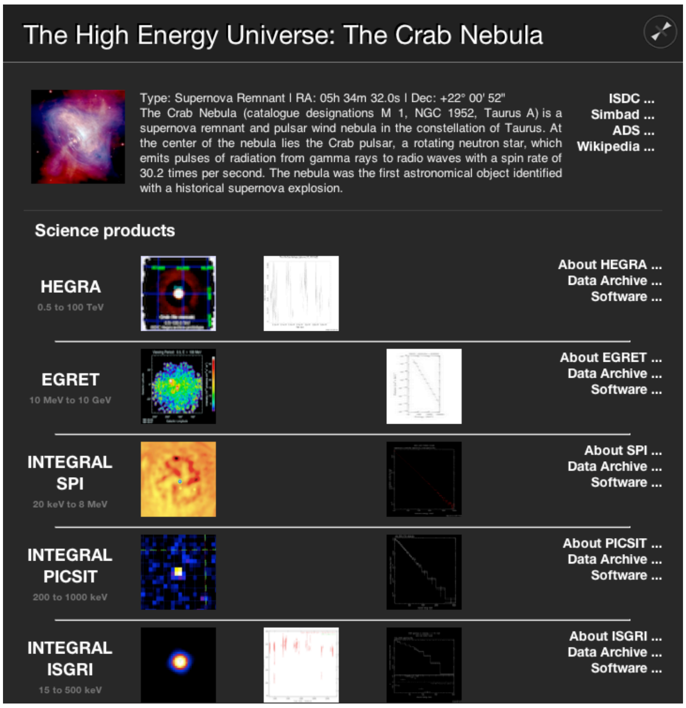
CTA, the first TeV observatory

In the 1980's, after 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 branch 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, as illustrated by the extraordinary interest triggered by the recent results of H.E.S.S. and MAGIC.

CTA will be the first Cherenkov telescope conceived from the start as an observatory. The CTA project merges various teams organized around PI led experiments with a larger community to build the most ambitious world-class observing facility in the field.

The CTA observatory will have most of its observing time available as a guest observer program open to the scientific community at large. Principal investigators from any country worldwide can submit observing proposals in response to announcements of opportunity. 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.

The data resulting from an observation will be made available to the guest observer during a proprietary period before becoming public. The data, calibration and software will be open and easily manageable to allow any PhD student to analyze CTA data and publish results. We estimate that CTA will detect a thousand



The High Energy Universe: The Crab Nebula

Type: Supernova Remnant I RA: 05h 34m 32.0s I Dec: +22° 00' 52"
The Crab Nebula (catalogue designations M 1, NGC 1952, Taurus A) is a supernova remnant and pulsar wind nebula in the constellation of Taurus. At the center of the nebula lies the Crab pulsar, a rotating neutron star, which emits pulses of radiation from gamma rays to radio waves with a spin rate of 30.2 times per second. The nebula was the first astronomical object identified with a historical supernova explosion.

Multi-mission source archive prototype at the ISDC sources and will conduct of the order of a hundred observations per year. The community of CTA users (observers and archive users) will be a few hundred scientists. These numbers are similar to what ISDC is used to manage for INTEGRAL, in fact the CTA and INTEGRAL user communities overlap to some extend.

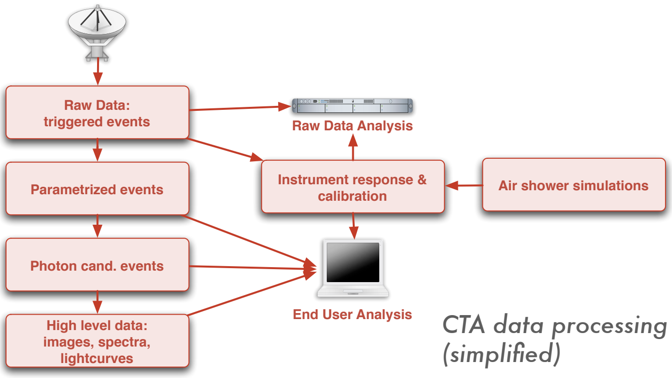
Policies, time allocation and science operations

One of the roles of the science data centre, together with the observatory governing bodies, is to establish policies, documentation and software tools which will allow potential observers to access the observatory, first by submitting proposals. Additional tools are needed to manage the proposals, organize and support a time allocation committee, manage and schedule observations and support the community for the organization of target of opportunity observations and multi-wavelength campaigns. Finally, monitoring of the observatory usage and performance and reporting is an essential aspect to support the observatory governing and financing bodies. ISDC scientists have a broad view of all these aspects by participating closely to the INTEGRAL operations and acting as proposers or time allocation committee members for a wide selection of observatories.

On-site data centre activities

The sky at GeV-TeV energies is much more variable than in visible wavelengths. Some sources shine during limited periods of time (minutes-hours) and must be studied during these periods to organize follow-up observations.

The CTA telescopes will generate about 10 TeraBytes of raw data per observing night and will be located on one or two remote sites. These sites will most probably lack broad-band network connections which would be necessary to transfer even reduced data (10 GB/night) in near real time to the data centre for analysis. As a consequence, a quick-look data analysis will have to be performed on-site in near real-time. This analysis will be used to check the quality of the data and detect whether major events have taken place in the patch of the sky observed by CTA. In case of detection of new sources or of unexpected events, an alert will be generated which will help, where appropriate, to modify the foreseen observation plan or trigger follow-up observations with other observing facilities. Some adjustments may also be needed according to the weather reports. Some level of interaction with the observer during the data taking should also be planned and in case of special scientific needs data products will need to be distributed to the observer very quickly. For an observatory of the sensitivity of CTA, with the possibility that various parts of the telescope array could point to various targets, one of the on-site scientists is expected to work full-time for the activities listed above. Each week a package of about 100 tapes will be shipped to the science data centre. A temporary archive corresponding to two months of data will be needed on-site.



CTA data processing (simplified)

Raw data archive

The raw data tapes received in Europe will be checked and a backup will be created. Finally the data will be uploaded to the raw data archive. The growth rate of this archive is estimated to be of the order of three PetaBytes per year. Hence, the raw data storage represents the most significant hardware cost in the CTA data processing chain. The most cost effective solution will probably be based on tape robots and a disk staging area. This will need to be revisited before implementation.

A standard data reduction chain for the raw data will be developed. The total size of the output data is a factor 1000 smaller than the raw data size. This renders the storage and handling of the input data for the higher level processing relatively simple even at today's standards. A mere volume of three TeraBytes per year will have to be stored and handled during the operational phase. Some physics goals however, will only be achievable by directly accessing the raw data and do require a lot of expert knowledge. This together with the standard raw data processing implies that the raw data will be read by a small and well identified number of users. Apart from the high volume of input data, the amount of CPU power required for the raw data processing is moderate. We estimate that a small cluster with some 10 nodes will be sufficient.

Calibration, standard processing and science archive

The community of CTA users will not be limited to those most familiar with the instrumentation, but will span astronomers of different fields. This imposes that the data be made accessible in a format which can easily be understood and with the support necessary to allow their full scientific exploitation. A further important aspect of CTA is that its data will be used in different research projects during many years. It is, therefore, necessary to build an archive of the CTA products. This archive will include event lists in a format that is easily transportable as well as the results of a standard data analysis.

A data model will be developed together with a standard analysis pipeline which will use the raw data to produce calibrated gamma-ray events together with a set of standard scientific results for each observation. The data model and the software can be built using the same concepts and basic tools developed by ISDC for INTEGRAL and other missions, reducing the overall implementation and maintenance costs. All the data products will be archived and made available first to guest observers and then to the public. Public data concerning specific sources in the sky will be made available with data from INTEGRAL, XEUS and other experiments. This source archive concept is already being prepared for INTEGRAL at ISDC.

Large observatories and scientific instruments develop and last for much longer than usual software life time. The analysis software needs therefore to be open and very simple and shall avoid any short lifetime products developed in the community or by the industry. The data products can of course be interfaced with the most popular fancy interfaces, tools or concepts (Virtual observatories, GRID, specific analysis packages) for a relatively small effort. The primary responsibility of the science data centre is to provide well calibrated and usable data and dedicated software tools and not to develop short-lived software technologies.

Off-line analysis and user support

The data centre has to provide to the CTA users a copy of its analysis software which will allow scientists to repeat, customize and refine the standard analysis and extract the relevant information from the data for publication. The open data format will also allow scientists to use their own or other tools to reduce the data as well as to use the standard tools developed over the years in the scientific community for imaging, spectral and time series analysis.

The analysis software will be completely independent from any infrastructure, to insure that any component can be used everywhere without the data centre system. The distributed software will of course be available free of any license fee and ported on the major user platforms. This is a standard practice, in particular enforced for INTEGRAL at ISDC. The input to the off-line analysis tools are the standard data products retrieved from the CTA archive. The user shall be able to handle standard data of different levels (from raw data to the high-level data products). Taking into account that different observers will have different level of expertise in CTA data analysis, the users should have the possibility to call most off-line analysis tools from a comprehensible graphical user interface, in which all or only essential parameters are requested, with other parameters set to best-guess default values.

The data centre will also need to support the CTA users and help new users to use the facility by providing a help-desk, yearly data analysis training courses and a newsletter.

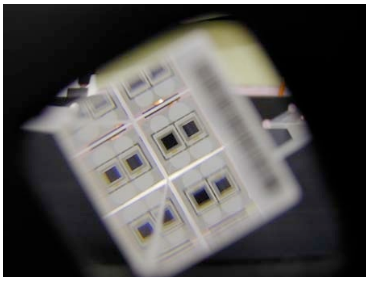
Data from other Cherenkov arrays

The data obtained by the past and current Cherenkov arrays (in particular MAGIC and H.E.S.S.) will need to be made accessible to the scientific community in the same format as and interoperable with the CTA data. These data will represent only a small fraction of the CTA data volume, however some specific work will need to be performed to make them freely accessible in an open data format. This work is essential to build an historic archive of relevant TeV data that could be used for future scientific research. The work on the data of HEGRA is already on-going at ISDC.

Solid-State Cherenkov Camera

The heart of a Cherenkov telescope is the light detection system, a camera for very low intensities, and the associated electronics. It typically consists of Winston cone light concentrators, photomultiplier tubes and analogue electronics to condition the signals. A crucial parameter of the light detection system is the quantum efficiency of the photo detectors. For photomultiplier tubes, the probability to detect an incident photon hitting the photocathode varies between 25 and 35% for the wavelength range of the Cherenkov light. DPNC of University of Geneva has extended usage and integration experience with the latest metal mesh photomultipliers from the FAST project.

An important step forward in photo-detection is represented by the recent development of Geiger mode Avalanche Photo-Diodes (gAPD) or silicon photomultiplier (SiPM). gAPDs promise photon detection efficiencies of more than 60%, a factor two higher than photomultiplier tubes. The Paul Scherrer Institute is one of the leading European laboratories pushing forward the development of APDs for usage in high energy physics. In the framework of the CMS electromagnetic calorimeter project, 140 thousand APDs have been characterized, integrated, calibrated and commissioned into an LHC detector. PSI continues to work in close contact with industry to help develop and improve gAPDs for optical applications in physics.


APD detectors developed for CMS at PSI, observed through a scintillator bar

In the context of CTA, we propose to develop a camera prototype based on gAPD technology. To be realistic, the prototype must contain of the order of 1000 pixels, consisting of several gAPDs each, with complete infrastructure, mechanics and adapted readout electronics. Qualification as a candidate technology for massive use in CTA also requires usage of the camera under realistic conditions. A simple possibility is to integrate the prototype into a refurbishment of the HEGRA CT3 telescope on the La Palma site. Another possibility is to install it on one of the telescopes which will be developed as prototype for CTA. Our camera will therefore serve not only for technology testing purposes, but will allow scientific observations.

At this point in time, gAPD chips are produced with low yield and thus at rather high end-user cost. Part of the project will thus be devoted to work with industry on the improvement of the manufacturing procedures towards lower unit cost. However, the prototype camera will use currently available chips, to study in parallel the optimum integration into the camera and to develop readout electronics based on the DOMINO chip design from PSI. Integration studies will include an assessment of temperature and high voltage stabilization, mechanical tolerances and protection against impacts from the environment.

A central issue will be to establish a modular approach that can be readily industrialized for mass production. For this purpose, we propose to work closely with the Swiss industry from the beginning. The aim is to be in a competitive situation when the decision on camera technology for the CTA telescopes will be taken.

The table below shows the estimated cost of the gAPD camera prototype development, totaling about 1.3 M€. The total development should extend over no longer than two years and end up with a long-term test under realistic conditions inside the refurbished CT3 telescope or an equivalent mount.

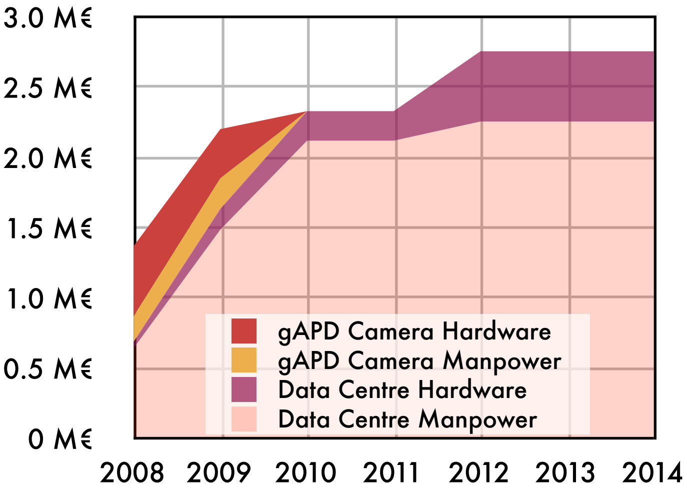
	Manpower [FTE]	Hardware [k€]
gAPD detectors	1.0	300
Winston cones		50
Front-end electronic	0.7	120
Trigger logic	0.7	150
Housing	1.0	80
Power supply	1.0	150
Total	4.4	850

Cost estimate for the prototype gAPD camera

Cost estimates

The cost of the various data centre activities have been evaluated using the experience of ISDC in building and running the data centre for INTEGRAL; the experience of the H.E.S.S. and MAGIC teams; the experience of ESA and ESO, running time allocation committees, observation scheduling and data transfers; and the experience of CERN in managing Peta-Bytes archives. The costs have been estimated taking into account that the data centre is developed in coordination with those of other missions, in particular INTEGRAL and XEUS, which offers cost savings, optimized long term maintenance and operations, solidity and stability. Note that scientific research by PHD students and young postdocs is not included.

The yearly costs are presented in the table below for various data centre activities in terms of manpower (FTE) and hardware costs and differentiated for the development and operational phases. They assume a development of 3 years before operations and a single site for CTA. These figures do not include the local office space and running costs (to be made available by the University of Geneva) nor the on-site housing. During the cost analysis each activity was split in various tasks. At that stage the cost of each of the tasks could have an uncertainty as large as 30%. The accuracy of the total cost, summing all activities, reaches 10%. The hardware costs are dominated by the raw data archive whose size (and cost) will depend on the detailed design of CTA. The spending profile for both the Cherenkov science data centre and the prototype gAPD camera are presented in the figure above and amount to about 2.5M€/y on average. This yearly cost will decrease after 3-4 years in operations.



Spending profile, assuming CTA operations will start in 2012

We plan to have this investment led by Switzerland and shared by an international consortium. This is essential to ensure that the data centre design and activities match the need and also benefit from the expertise of the broadest community. This also provides the solidity and stability required to support CTA over many years. For five years of operation, the Swiss participation will be of the order of 5% of the total estimated construction cost of CTA. Note that INTEGRAL operations may end close to when CTA becomes operational, providing a smooth transition at ISDC.

	Manpower [FTE]		Hardware [k€/y]	
	Development	Operations	Development	Operations
Management and infrastructure	4.0	4.0	25	25
Policies, time allocation and science operations	1.7	1.7	0	25
Calibration, standard processing and science archive	10.0	8.5	25	40
Archival of other Cherenkov array data	2.0	1.0	0	0
Offline analysis and user support	1.5	2.5	0	0
On-site data centre activities	1.5	3.0	70	40
Raw data archive	2.5	4.0	90	370
Total	23.2	24.7	210	500

Cost estimates for the Cherenkov Science Data Centre

Perspectives

High energy astrophysics developed in Switzerland (mostly in Geneva and Zurich) since the 90's at a sustainable rate by participating to international projects like XMM, RHESSI, INTEGRAL and MAGIC. During the same time a community of scientists and engineers active in the domain has built-up from a few to about 40 people. This community is recognised internationally and is eager to participate in an expanding research field which matures in Europe through the Cherenkov Telescope Array project.

By providing the science data centre for INTEGRAL, CTA and, later, for XEUS, Switzerland brings a very valuable and concrete participation in these projects and plays a central role in many aspects to foster the development of high energy astrophysics in Europe and in the world. Hosting the data centre for high energy astrophysics brings an important responsibility and visibility during the development, operations and post-operations of all these science missions. The worldwide scientific community relies on the services provided and this permits scientists working in Switzerland not only to participate in the science but also to take responsibilities that are central to the success of these experiments.

PSI has developed key technologies for high energy physics which could find an important application in the CTA cameras. Building a prototype camera will allow to qualify the technology and prepare industrialized mass production in view of building close to a million detectors for CTA.

Astrophysics at very high energies interest both the astronomical and the particle physics communities. This cross fertilization will grow further over the next decade and the location of both the Cherenkov Science Data Centre and CERN in Geneva will certainly help the process and provides many opportunities in terms of joint activities, fostering of ideas and public visibility. The very central place of Geneva in particle physics will be reinforced and extended towards astro-particle sciences.

Impressum

The Cherenkov Telescope Array
Swiss Participation and Perspectives
November 2007

Contributions:

CTA FP7 design study proposal
H.E.S.S. & MAGIC collaborations
ISDC, IPP, DPNC & PSI

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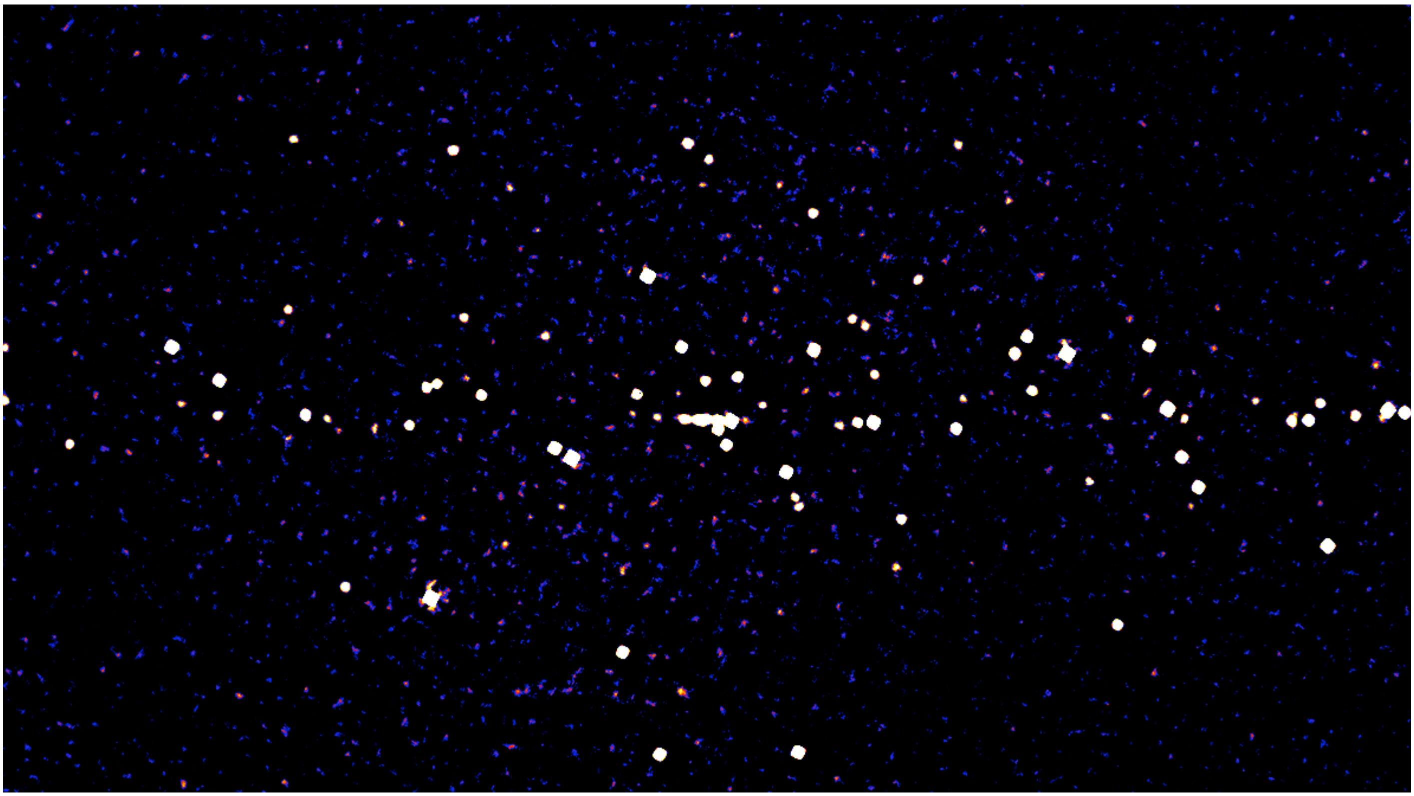
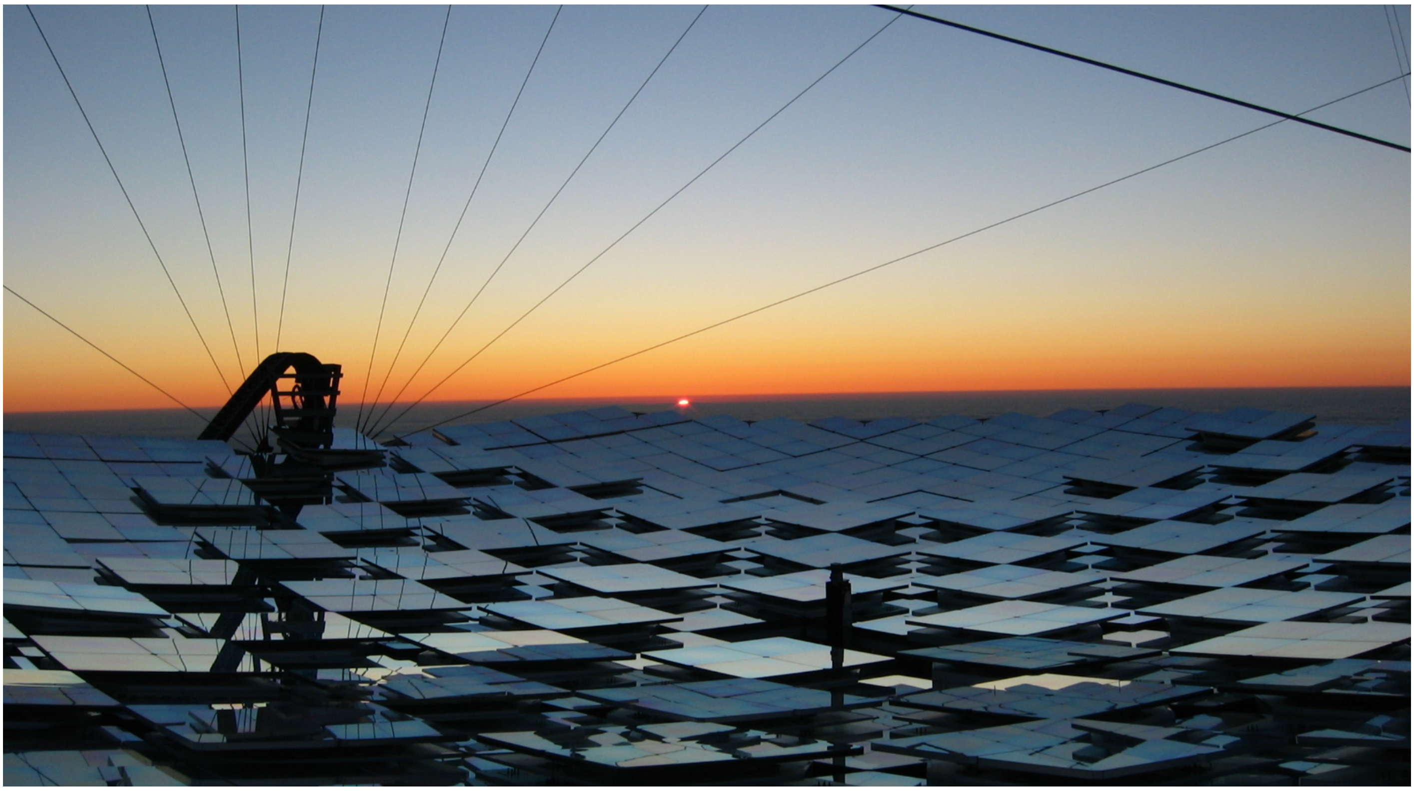


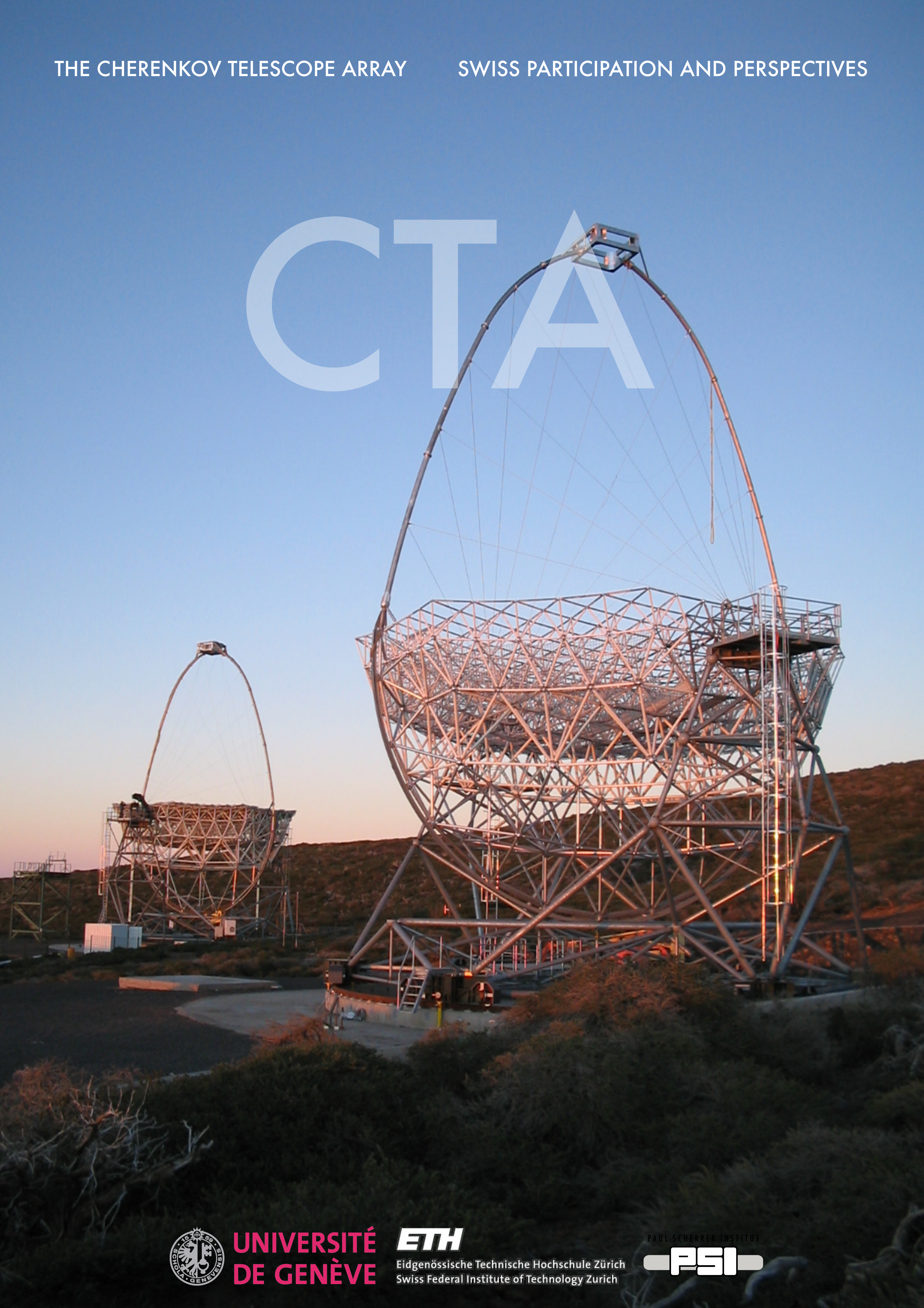
The central regions of the Milky Way, observed at soft gamma-rays by INTEGRAL : black holes and neutron stars



Sunset on the MAGIC segmented mirror; observations are about to start

THE CHERENKOV TELESCOPE ARRAY SWISS PARTICIPATION AND PERSPECTIVES

CTA



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