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THE CHERENKOV TELESCOPE ARRAY PROJECT: CURRENT STATUS AND SCIENCE GOALS

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Abstract

The Cherenkov Telescope Array (CTA) will be the next generation gamma-ray observatory, open to the scientific community, to investigate the very-high-energy emission from a large variety of celestial sources in the 20 GeV - 300 TeV energy range. The full array, distributed over two sites, one in the northern and one in the southern hemisphere, will provide whole-sky coverage and will improve the sensitivity with respect to the current major arrays such as H.E.S.S., MAGIC and VERITAS by a factor of five to twenty, depending on the energy. CTA will investigate a much higher number of already known classes of sources, going to much larger distances in the Universe. Along with accurate variability and spatially-resolved studies, these improvements will also enable population studies. Moreover, new light will be shed on new classes of TeV

* see https://www.cta-observatory.org/consortium_authors/authors_2018_05.html for full author list

sources, such as GRBs and clusters of galaxies. Furthermore, by pushing the high-energy limit to E $>$ 100 TeV, CTA will allow a thorough exploration of the cut-off regime of the cosmic accelerators. The search for an annihilation signature of dark matter in the Galactic halo and in prominent dwarf spheroidal galaxies is one of the most important goals of CTA. We review the current status of the CTA project, introducing the highlights from the telescope prototypes and discuss the main CTA Key Science Projects, which will focus on major scientific cases, allowing us to provide legacy data sets of high value to a wider community.

1 Introduction

Very high energy gamma-ray astronomy (VHE; E$>$ 100 GeV) is a relatively young field with great scientific potential. The current generation atmospheric Cherenkov telescopes (H.E.S.S., MAGIC, and VERITAS), along with air shower experiments (e.g. ARGO-YBJ, Milagro and HAWC) and with the *Fermi* and *AGILE* satellite instruments, have firmly established the field, discovering VHE radiation from more than 150 sources, comprising many source classes. A number of individual sources, both within and outside of our Galaxy, have been well-studied but there are many others that are not well-characterized or understood. It seems clear that our current knowledge represents just the tip of the iceberg in terms of the number of sources and source classes and in terms of our ability to confront the existing theoretical models. CTA will transform our understanding of the high-energy universe by discovering many hundreds of new sources, by measuring their properties with unprecedented accuracy, and also by exploring questions in physics of fundamental importance. The major scientific questions that can be addressed by CTA are the following, grouped into three broad themes:

Theme 1: Understanding the Origin and Role of Relativistic Cosmic Particles
• What are the sites of high-energy particle acceleration in the universe?
• What are the mechanisms for cosmic particle acceleration?
• What role do accelerated particles play in feedback on star formation and galaxy evolution?

Theme 2: Probing Extreme Environments
• What physical processes are at work close to neutron stars and black holes?
• What are the characteristics of relativistic jets, winds and explosions?
• How intense are radiation fields and magnetic fields in cosmic voids, and how do these evolve over cosmic time?

Theme 3: Exploring Frontiers in Physics
• What is the nature of dark matter? How is it distributed?
• Are there quantum gravitational effects on photon propagation?
• Do axion-like particles exist?

2 Core Programme

Over the lifetime of CTA, most of the available observation time will be divided into the Guest Observer (GO) Programme, where time will be awarded based on scientific merit, and a Core Programme of a number of major legacy projects. Director's Discretionary Time and host country reserved time will comprise the remaining time. The CTA Consortium has developed the Core Programme that consists of proposed Key Science Projects (KSPs) that are characterized by having an excellent science case and clear potential to advance beyond the state of the art, the production of legacy data sets of high value to the wider community, and clear added value for the project to be done as a KSP rather than part of the GO Programme (e.g. because of the scale of the project or the expertise required in carrying it out). This Core Programme has been described in the document "Science with the Cherenkov Telescope Array" [1)]

The proposed CTA Key Science Projects include: (i) Dark Matter Programme, (ii) Galactic Centre Survey, (iii) Galactic Plane Survey, (iv) Large Magellanic Cloud Survey, (v) Extragalactic Survey, (vi) Transients, (vii) Cosmic-ray PeVatrons, (viii) Star Forming Systems, (ix) Active Galactic Nuclei, and (x) Clusters of Galaxies. A few highlights from these projects are described here, focusing on the surveys and the search for dark matter:

• **The Galactic Centre Survey** consists primarily of a deep (525 h) exposure with pointings on a small grid centered on Sgr A*; this exposure covers the central source, the centre of the dark matter halo, the primary diffuse emission and multiple supernova remnant (SNR) and pulsar wind nebula (PWN) sources. An extended survey (300 h) of a 10° x 10° region around the

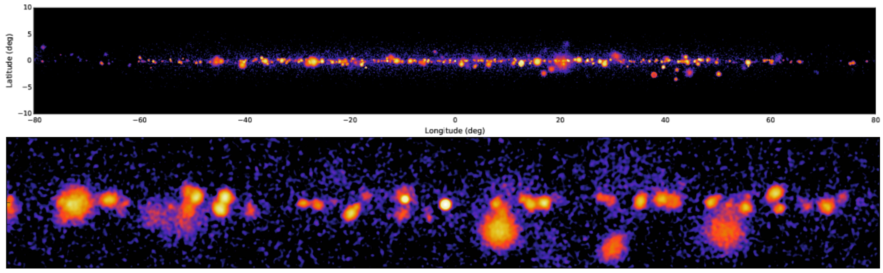

Figure 1: Top: simulated CTA image of the Galactic plane for the inner region, $-80^\circ < l < 80^\circ$, adopting the proposed Galactic Plane Survey observation strategy and a source model that contains supernova remnant and pulsar wind nebula populations as well as diffuse emission. Bottom: a close-in view of a 20° region in Galactic longitude.

Galactic centre would cover the edge of the Galactic bulge, the base of the Fermi Bubbles, the radio spurs and the Kepler SNR.

• **The Galactic Plane Survey** is a survey of the entire Galactic plane, with deeper exposure in the inner Galaxy and Cygnus region. The survey will be a factor of 5-20 more sensitive than previous surveys carried out at very high energies and is thus expected to sample a much larger fraction of the log N - log S distribution of Galactic sources, as shown in Figure 1. The discovery of many hundreds of sources in the Galactic Plane Survey will be an important pathfinder for later GO proposals.

• **The Large Magellanic Cloud (LMC) Survey** will cover this star-forming galaxy in its entirety, resolving regions down to 20 pc in size and with sensitivity down to a luminosity of $\sim 10^{34}$ erg/s. Long-term monitoring of SN 1987A will be carried out, provided the source is detected in the first phase of the survey.

• **The Extragalactic Survey** will be the first wide-field (one-quarter of the sky) survey of the VHE sky at high sensitivity. Aimed to provide an unbiased sample of galaxies (particularly active Galactic nuclei, AGN), the survey will also be sensitive to unexpected phenomena at high Galactic latitudes.

• **The Dark Matter Programme** is centered on the indirect search for dark matter via the weakly interacting massive particle (WIMP) annihilation signal [2]. As shown in Figure 2, the deep exposure of the Galactic centre region will allow CTA to reach a sensitivity to a thermal relic WIMP over a wide mass region, thus nicely complementing searches done with the *Fermi* satellite, at the Large Hadron Collider and by direct-detection experiments. Additional dark matter targets include dwarf spheroidal galaxies, the LMC and the Perseus cluster. The effect of systematics is drastically reduced for dwarf spheroidal galaxies compared to the extended Galactic Halo, explaining the significant interest in observations of dwarfs.

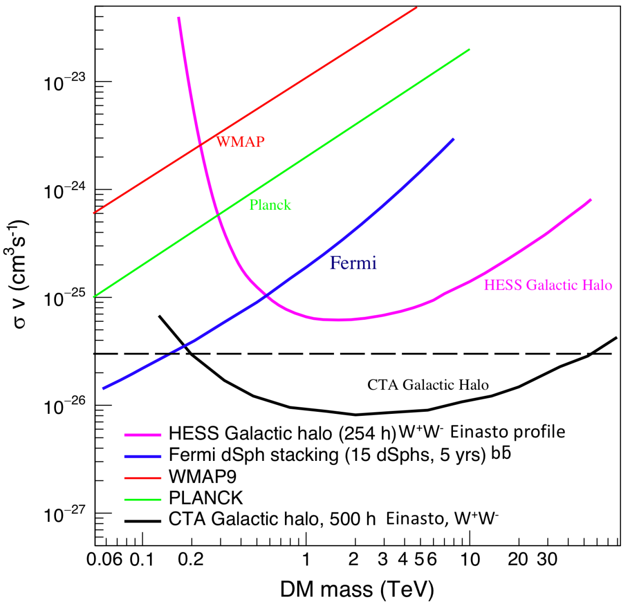

Figure 2: Current best limits on the annihilation cross-section from indirect detection (*Fermi*-LAT dwarf spheroidal galaxies stacking analysis, W^+W^- channel [3]), H.E.S.S. Galactic halo W^+W^- channel [5]) and cosmic microwave background (WMAP and Planck $b\bar{b}$ channel [4]) experiments compared with the projected sensitivity for CTA from observations of the Galactic halo for the Einasto profile, W^+W^- channel. The expectation for CTA is optimistic as it includes only statistical errors. The effect of the Galactic diffuse emission can affect the results by $\sim 50\%$. The dashed line shows the thermal relic cross section [2]).

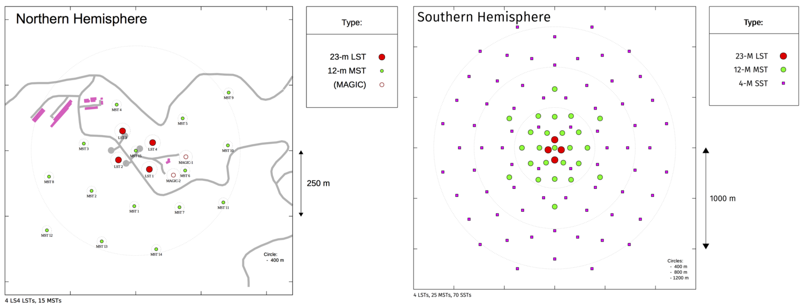

Figure 3: Possible layouts for the baseline arrays for CTA South (left) and CTA North (right). The LSTs are identified by the red circles, the MSTs by the green circles, and the SSTs by the purple squares.

3 CTA Design: Performance Goals, Concept, and Array Layouts

To achieve these broad science goals in a meaningful way, CTA must improve upon the performance of existing instruments in many areas simultaneously. The various performance goals, along with the science drivers that provide their impetus, are the following:

• **High sensitivity** (a factor of up to ten improvement over current experiments): impacts all science topics;

• **Wide Energy Coverage** (20 GeV to $\geq$ 300 TeV): low-energy sensitivity is needed to detect the most distant sources whose spectra are cut off from absorption on intergalactic radiation fields; very high-energy reach is needed to detect "PeVatron" sources that would help explain the origin of cosmic rays up to the knee in the spectrum;

• **Full-sky Coverage** (arrays in both hemispheres): enable the full characterization of the VHE universe and access to unique sources in both hemispheres;

• **Wide Field-of-View** ($\sim$ 8 deg): permits more rapid surveys and better study of extended sources;

• **Excellent Resolution** in angle (few arc-minutes) and energy ($\sim$10%): permits good reconstruction of source morphology and spectra,

• **Rapid Response** ($\sim$30 s slewing to/from anywhere in observable sky): enables rapid follow up of transient sources.

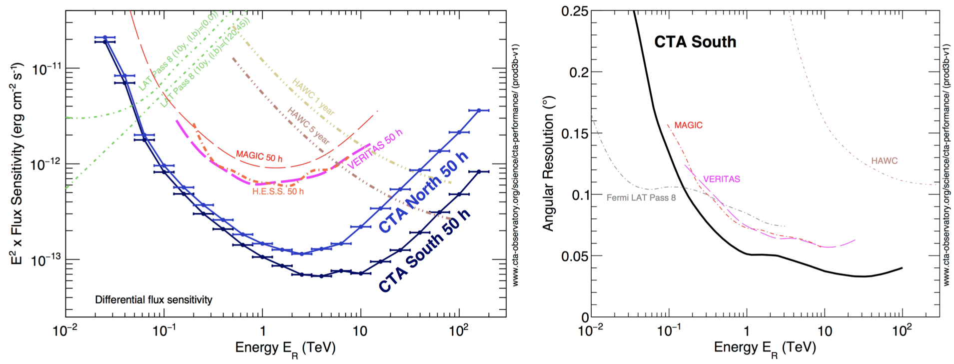

Figure 4: Left: Differential energy flux sensitivities for CTA (south and north) and selected existing gamma-ray instruments for five standard deviation detections in five independent logarithmic bins per decade in energy. For the CTA sensitivities, additional criteria are applied to require at least ten detected gamma rays per energy bin and a signal/background ratio of at least 1/20. The curves for *Fermi*-LAT and HAWC are scaled by a factor of 1.2 to account for the different energy binning. The curves shown give only an indicative comparison of the sensitivity of the different instruments, as the method of calculation and the criteria applied are different. Right: Angular resolution expressed as the 68% containment radius of reconstructed gamma rays (the resolution for CTA-North is similar).

To meet these performance goals, CTA will extend the atmospheric Cherenkov technique to its logical next level, by deploying large arrays of telescopes that cover an area on the ground that is significantly larger than the Cherenkov light pool. Compared to the existing instruments consisting of several telescopes separated by about 100m, the larger number of telescopes and the larger area covered by CTA will result in: i) a much higher rate of showers contained within the footprint of the array, ii) a better sampling of the showers from different viewing angles that will greatly improve the shower reconstruction and the cosmic-ray background rejection, and iii) a lower energy threshold since the central part of the shower (with the highest Cherenkov photon density) gener-

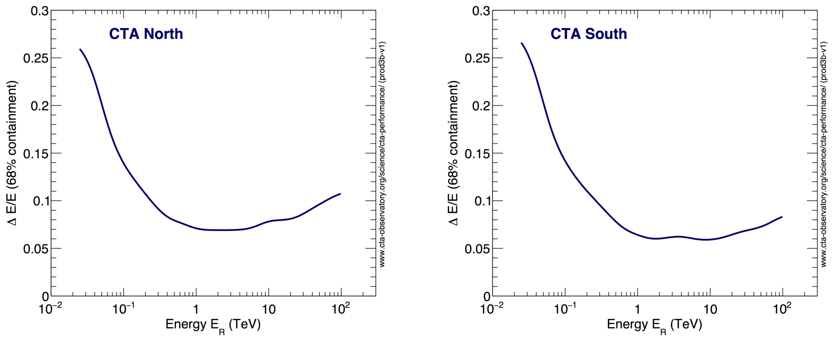

Figure 5: Energy resolution as a function of reconstructed energy (the result depends only weakly on the assumed gamma-ray spectrum). On the left for the North site and on the right for the South site.

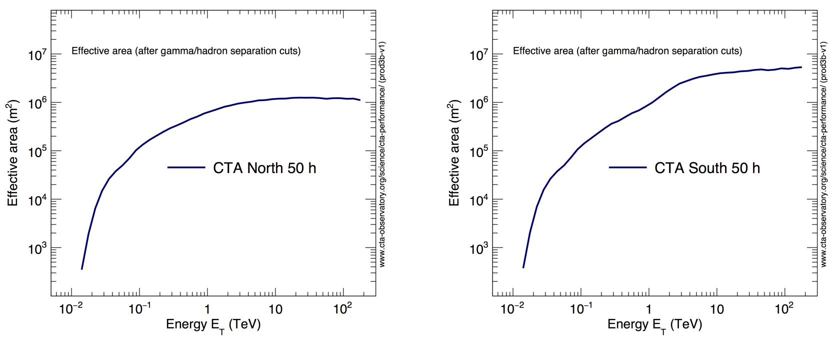

Figure 6: Effective collection area after gamma/hadron separation cuts but without any cut in the reconstructed event direction optimized for 50 h observation time for the North site (left) and the South site (right).

ally falls within the array. To achieve the goal of wide energy range within cost constraints leads to the logical choice of a graded array of telescopes of different sizes. In CTA, the lowest energies are covered by four large-sized telescopes (LSTs) that are capable of detecting gamma rays down to 20 GeV. The core

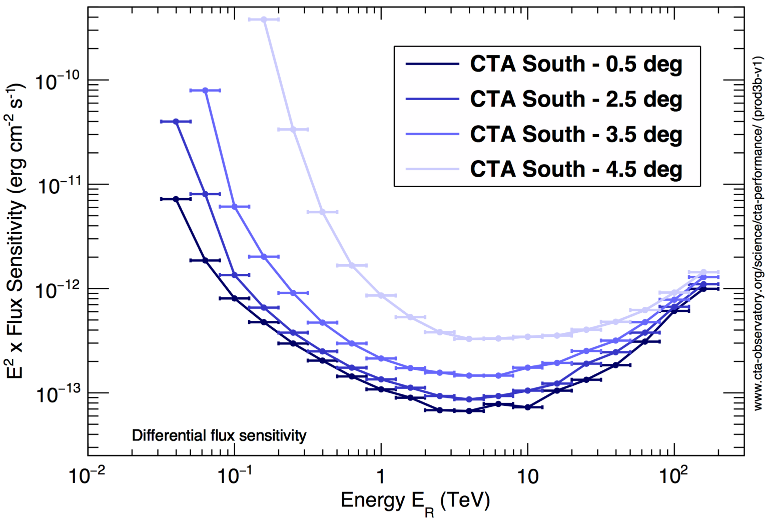

Figure 7: Differential sensitivity curves for a point-like source at increasing angular distances from the centre of the FoV.

energy range of 100 GeV to 10 TeV is covered by an array of 25 (South) or 15 (North) medium-sized telescopes (MSTs), and, for the Southern array, the highest energies are covered by a several km^2 array of 70 small-sized telescopes (SSTs). To achieve fast-response to low-energy transients such as gamma-ray bursts, the LSTs will incorporate very rapid slewing. Conversely, to achieve a wide field-of-view for surveys and extended Galactic sources, the MSTs and SSTs will employ wide-field cameras. To realize full-sky coverage, CTA arrays will be deployed in both hemispheres. The small-sized telescopes are only planned for the Southern array because the highest energies are most relevant for the study of Galactic sources. The layout of the telescopes in the CTA arrays has been determined over a number of years by a multi-step process starting with semi-analytic estimates and continuing with large-scale simulations that include full shower and detector modeling. The latest simulations incorporate site-dependent effects (including altitude, geomagnetic field, and telescope positioning constraints) to assess the performance attributes of CTA.

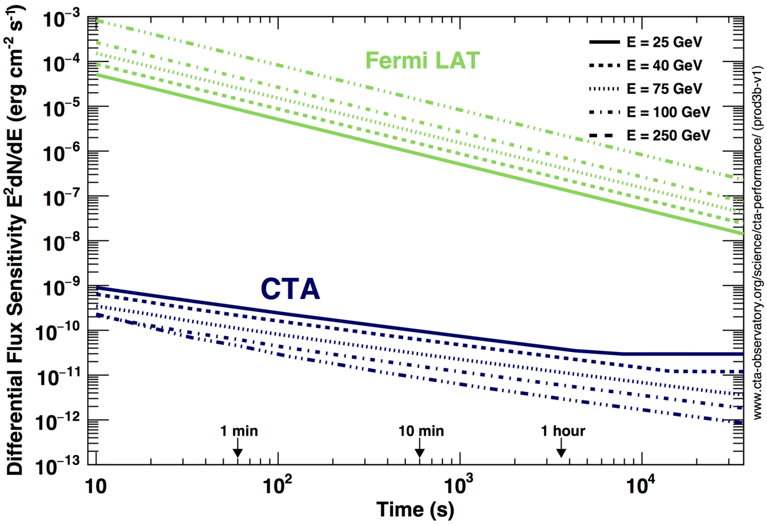

Figure 8: Differential flux sensitivity of CTA at selected energies as a function of observing time in comparison with the *Fermi*-LAT instrument (Pass 8 analysis, extragalactic background, standard survey observing mode).

Figure 3 shows the current baseline array layouts for the Southern and Northern CTA sites resulting from this optimization process. Figure 4 shows on the left the differential energy flux sensitivities for CTA (South and North) and on the right the angular resolution expressed as the 68% containment radius of reconstructed gamma rays. Figure 5 shows on the left the energy resolution as a function of reconstructed energy for the North site and on the right for the South sites. Figure 6 shows the effective collection area after gamma/hadron separation cuts but without any cut in the reconstructed event direction optimized for 50 h observation time for the North site (left) and the South site (right). Figure 7 shows the differential sensitivity curves for a point-like source at increasing angular distances from the centre of the FoV. The radius of the FoV region in which the sensitivity is within a factor 2 of the one at the centre is around 2 degrees near the CTA threshold, and >3 degrees above a few 100 GeV. Figure 8 shows the differential flux sensitivity of CTA at selected energies as a function of observing time in comparison with the *Fermi*-LAT instrument (Pass 8 analysis, extragalactic background, standard survey observing mode). The differential flux sensitivity is defined as the minimum flux needed to obtain a 5-standard-deviation detection from a point-like gamma-ray source, calculated for energy bins of a width of 0.2 decades. An additional constraint of a minimum of 10 excess counts is applied. Note that especially for exposures longer than several hours, the restrictions on observability of a transient object are much stricter for CTA than for the *Fermi*-LAT. CTA will be able to observe objects above 20 degrees elevation during dark sky conditions.

4 Current Status of CTA

CTA was conceived and is being designed by the CTA Consortium (CTAC), a collaboration of more than 1400 scientists and engineers from 32 countries around the world. The Consortium has developed the primary science themes of CTA and Consortium Institutes are expected to provide the bulk of the CTA components, including telescopes, cameras and software. The CTA Observatory (CTAO) was established in 2014 to provide the legal entity to oversee the CTA Project Office that manages the construction of CTA. Governed by a Council of country representatives, CTAO will be responsible for observatory operations and data management. During the last several years, the progress towards realization of CTA has been accelerating. The baseline design and core technologies are now established, several prototype telescopes have been completed and are undergoing testing, the two CTA sites have been selected, and a large portion of the required funding has now been identified. Thus, the project is well positioned for a construction start in 2018 and the turn-on of full operations by the middle of the next decade.

4.1 CTA Sites

CTAO activities will be carried out at the two CTA array sites and at the CTA Headquarters (HQ) and Science Data Management Centre (SDMC). Pending successful completion of hosting agreements, the CTA HQ will be hosted at the INAF site in Bologna, Italy and the CTA SDMC will be on the DESY campus in Zeuthen, Germany. Following a lengthy process that included detailed assessment and external review, the CTA Resource Board (a precursor to the CTA Council) selected the following two sites to host CTA arrays:

• South: European Southern Observatory (ESO) Paranal site in Chile
• North: Instituto de Astrofisica de Canarias (IAC) Roque de los Muchachos Observatory site in La Palma, Spain.

Activities to prepare the sites are well underway in both hemispheres. Technical and infrastructure studies are being carried out in the context of the Royal Institute of British Architects (RIBA) process. CTA is currently in the advanced design phase (RIBA-3) and is approaching the technical design phase (RIBA-4). Specific activities include power, lightning protection, geotechnical, ground investigation, and general infrastructure (roads, buildings, foundations, etc.) studies. On La Palma, the construction of the first prototype LST has started and presently (May 2018) 123 mirrors have been installed. This prototype is expected to become the first LST in the Northern CTA array.

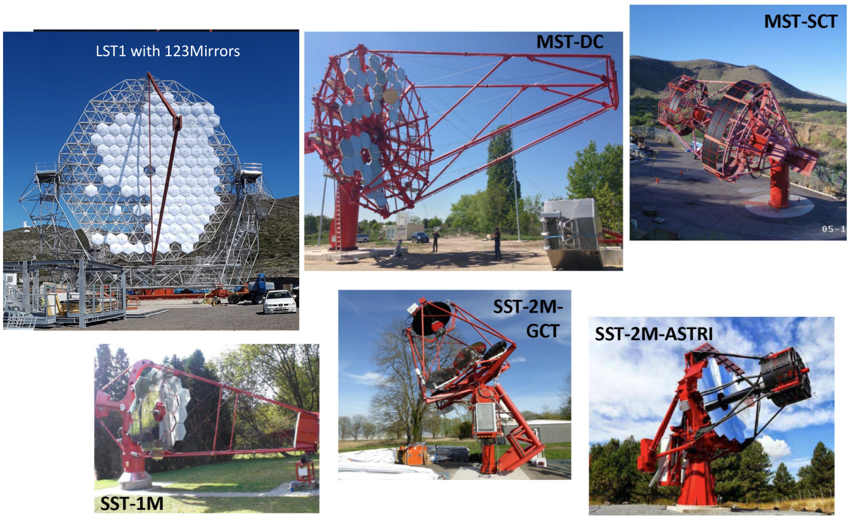

Figure 9: Prototype telescopes being developed for CTA. Top row (left to right): LST in construction (May 2018), MST-DC in Germany, MST-SCT in USA. Bottom row (left to right): SST-1M in Poland, SST-2M-GCT in France, and SST-2M-ASTRI in Italy.

4.2 Prototype Telescopes

Extensive work has been carried out within the CTA Consortium over a number of years to prototype the hardware and software for all three telescope types. This work builds on the successes and experiences of the current generation of imaging atmospheric Cherenkov telescopes, but it also makes use of new techniques. For example, in the telescope design, both single mirror (based on the traditional Davies-Cotton, or DC, design) and dual mirror (based on the Schwarzschild-Couder, or SC, design) approaches are being developed. For the photosensors in the cameras, both photomultiplier tubes (PMTs) and Silicon photomultipliers (Si-PMs) are being evaluated. In all camera designs, the read-out electronics (typically using 1 GS/s high-speed sampling ASICs) are contained in the focal-plane box. Figure 9 shows recent photos of the various prototype CTA telescopes. For the LST, the requirement of a large mirror area to reach the lowest gamma-ray energies has led to a single mirror design using a 23 m diameter parabolic reflector. This very large telescope will use PMTs. For the MST, two designs are being considered. A single mirror DC design has been developed at a site in Adlershof, Germany that makes use of a 12 m diameter dish with a focal length of 16 m and a PMT camera. Two read-out schemes are being prototyped that make use of 250 MS/s Flash-ADCs with digital storage and 1 GS/s ASICs. A dual mirror SC MST prototype is being built at the Whipple Observatory in Arizona, USA that will employ a 9.7 m primary mirror and a compact high-resolution camera using Si-PMs. For the SST, three approaches are being considered, with each having a primary mirror size of 4 m diameter and cameras using Si-PMs. Two of these use the SC design: the SST-2M-ASTRI prototyped at Serra La Nave, Sicily, Italy and SST-2M-GCT in Meudon, France. The third SST prototype, SST-1M, is being developed in Krakow, Poland and makes use of the DC design.

5 Synergies

CTA will have important synergies with many of the new generation of astronomical and astroparticle observatories. As the flagship VHE gamma-ray observatory for the coming decades, CTA plays a similar role in the VHE waveband as the SKA in radio, ALMA at millimetre, or E-ELT/TMT/GMT in the optical wavebands, providing excellent sensitivity and resolution compared to

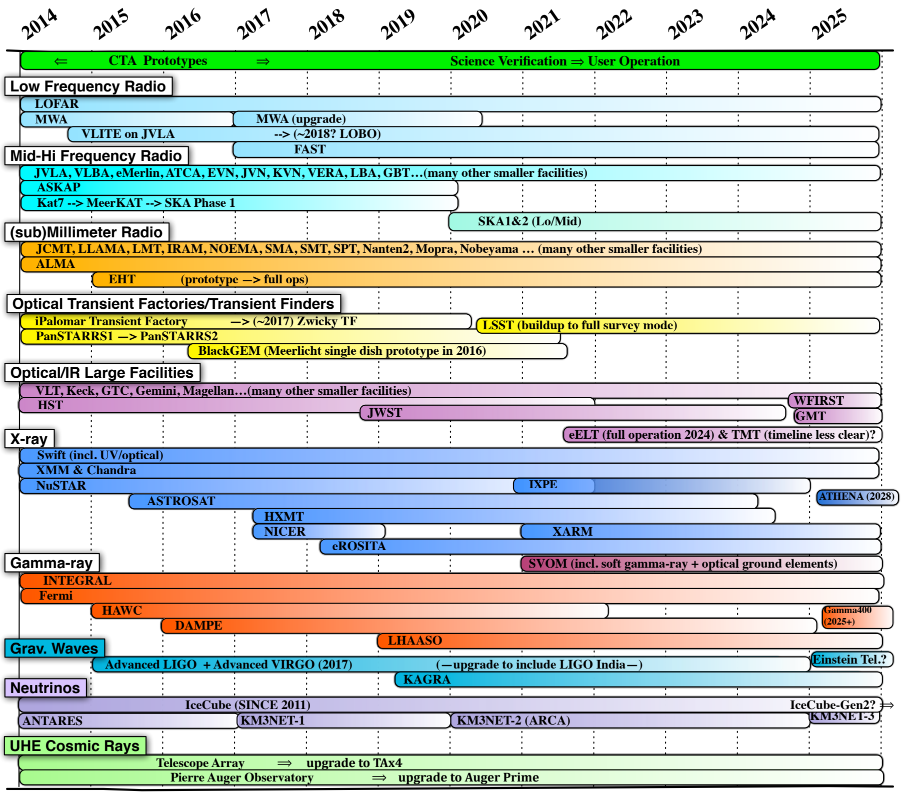

Figure 10: Timeline of major multi-wavelength/multi-messenger facilities over the next decade. Note that the lifetimes of many facilities are uncertain, contingent on performance and funding. We indicate this uncertainty via the gradient, but have chosen timelines based on the best information currently available.

prior facilities. At the same time, the scientific output of CTA will be enhanced by the additional capabilities provided by these instruments (and vice-versa). Multi-wavelength (MWL) and multi-messenger (MM) studies using CTA provide added value to the science cases in two main ways:

- Non-thermal emission: To understand the origin of cosmic rays and the ex-

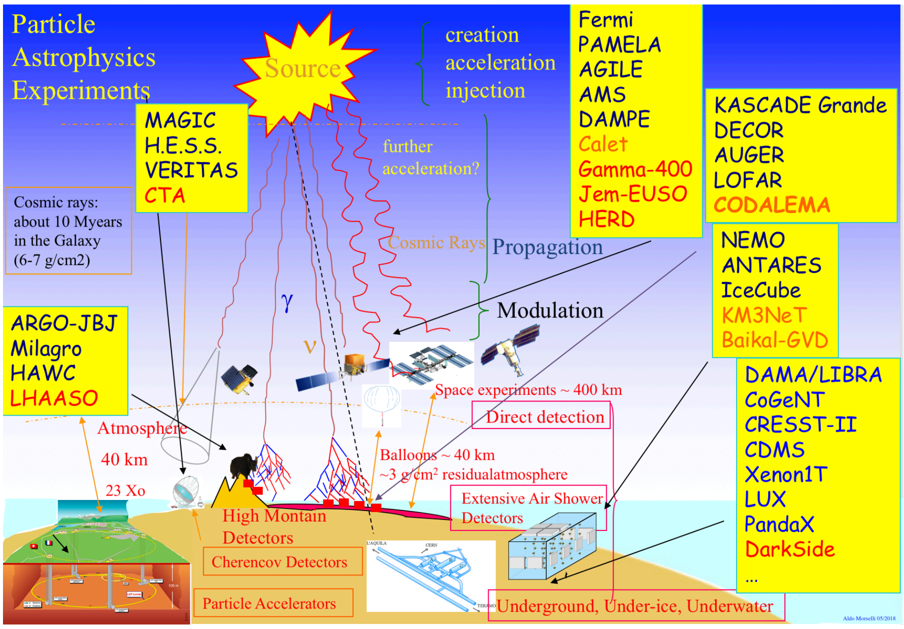

Figure 11: Indirect, direct and accelerator experiments for the study of the fundamental laws of nature and the search of dark matter (future experiments are in red).

treme physical environments that produce them, it is necessary to study non-thermal signatures that span many orders of magnitude in frequency in the broad-band spectral energy distribution (SED) of a given object. In the case of time-variable emission, such studies require simultaneous observations and/or alerts and triggers between observatories.

• Source properties: Information on the nature of gamma-ray emitting sources can be provided by MWL observations, enabling, for example, the object class, environmental conditions or the distance to be established. For this purpose, simultaneous observations are in general not required, except for the need to characterize transient sources, for example in the case of gamma-ray burst red-shift measurements.

The need for (simultaneous) MWL and MM observations has been considered as a factor in the site selection process for CTA and in the preparations for CTA science. A summary timeline of major facilities is shown in Figure 10.

All these facilities will contribute together with all the indirect, direct and accelerator experiments to the study of the fundamental laws of nature and the search for dark matter in the sky, on-ground, in the water, in ice, underground and at accelerator machines, as shown in Figure 11 (future experiments are in red).

6 Acknowledgments

We gratefully acknowledge financial support from the agencies and organizations listed here: http://www.cta-observatory.org/consortium_acknowledgments.

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