Astro2020 Project White Paper

The Cherenkov Telescope Array

Principal author: David A. Williams
University of California Santa Cruz
daw@ucsc.edu
(831) 459-3032

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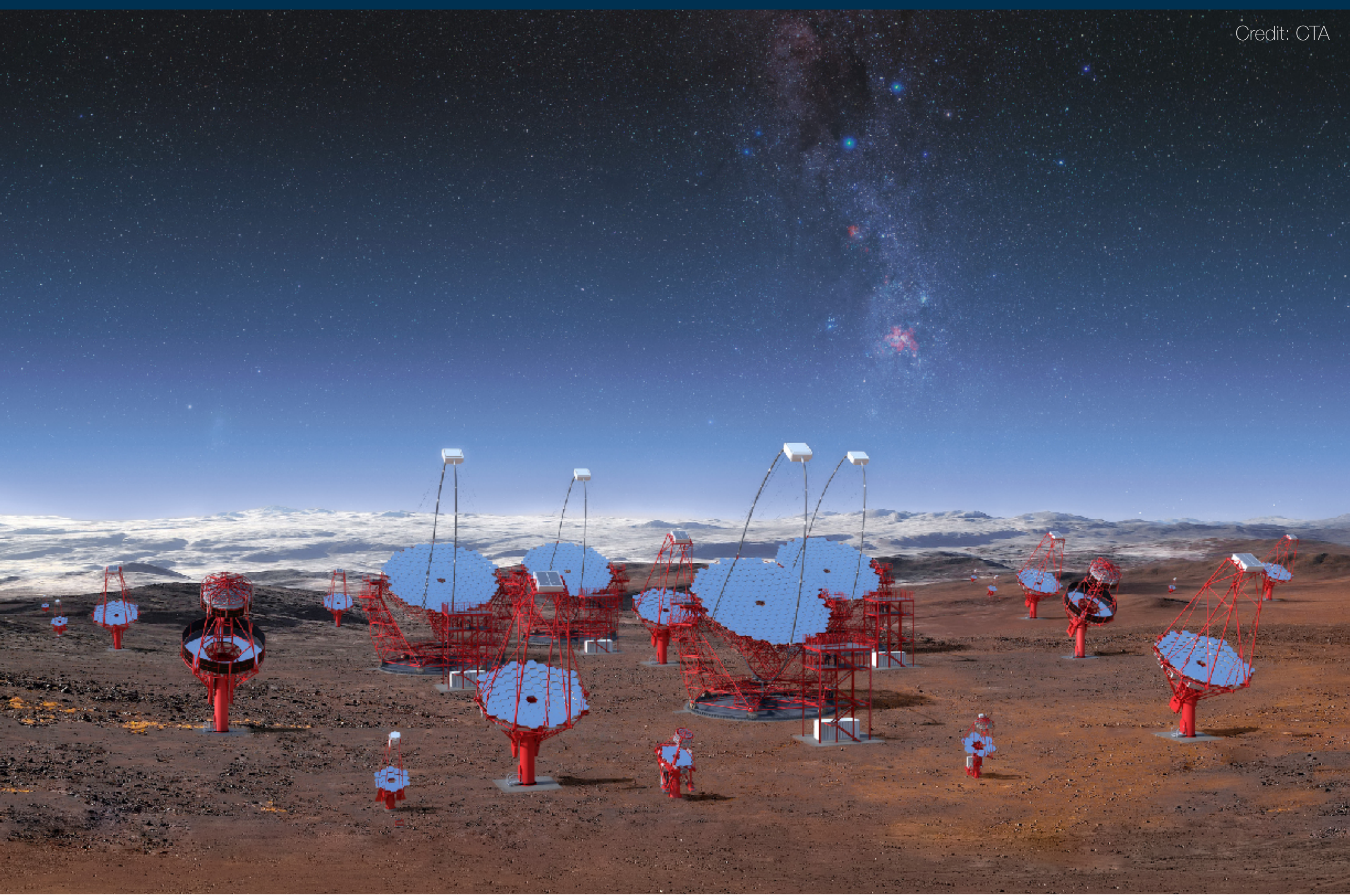

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Co-authors

— Barbara Balmaverde, *INAF, Osservatorio Astrofisico di Torino, Italy*
— Wystan Benbow, *Center for Astrophysics | Harvard & Smithsonian*
— Niccolò Bucciantini, *INAF, Osservatorio Astrofisico di Arcetri, Italy*
— James Buckley, *Washington University in St. Louis*
— Michael Burton, *Armagh Observatory and Planetarium, United Kingdom*
— Roberto Capuzzo-Dolcetta, *Sapienza, Università di Roma, Italy*
— Sylvain Chaty, *AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, France*
— Paolo Coppi, *Yale University*
— Alessandro Costa, *INAF, Osservatorio Astrofisico di Catania, Italy*
— Filippo D'Ammando, *INAF, Istituto di Radioastronomia, Bologna, Italy*
— Giovanni De Cesare, *INAF, Osservatorio di Astrofisica e Scienza dello Spazio, Bologna, Italy*
— Tristano Di Girolamo, *University of Naples "Federico II," Italy*
— Michele Doro, *University of Padova & INFN Padova, Italy*
— Nicola Giglietto, *INFN Bari and Politecnico di Bari, Italy*
— Bohdan Hnatyk, *Astronomical Observatory of Taras Shevchenko National University of Kyiv, Ukraine*
— Jamie Holder, *University of Delaware*
— Brian Humensky, *Columbia University*
— Phil Kaaret, *University of Iowa*
— David Kieda, *University of Utah*
— Kazunori Kohri, *KEK, Japan*
— Manel Martinez, *IFAE-BIST, Spain*
— Ignacio A. Minaya Flores, *University of Liverpool, United Kingdom*
— Razmik Mirzoyan, *Max-Planck-Institute for Physics, Germany*
— Aldo Morselli, *INFN Roma Tor Vergata, Italy*
— Reshmi Mukherjee, *Barnard College and Columbia University*
— Daniel Nieto Castaño, *Universidad Complutense de Madrid, Spain*
— Marek Nikolajuk, *University of Bialystok, Poland*
— Rene Ong, *UCLA*
— A. Nepomuk Otte, *Georgia Institute of Technology*
— Giovanni Pareschi, *INAF, Osservatorio Astronomico di Brera, Italy*
— Giovanni Peres, *University of Palermo, Italy*
— Andreas Reisenegger, *Pontificia Universidad Católica de Chile*
— Giuseppe Romeo, *INAF, Osservatorio Astrofisico di Catania, Italy*
— Marcos Santander, *University of Alabama*
— Eva Sciacca, *INAF, Astrophysical Observatory of Catania, Italy*
— Fabian Schüssler, *IRFU, CEA, Université Paris-Saclay, France*
— Olga Sergijenko, *Astronomical Observatory of Taras Shevchenko National University of Kyiv, Ukraine*
— Justin Vandenbroucke, *University of Wisconsin*
— Vladimir Vassiliev, *UCLA*
— Serguei Vorobiov, *University of Nova Gorica, Slovenia*

On behalf of the CTA Consortium,
https://www.cta-observatory.org/about/cta-consortium/

1 Introduction

To advance the state of the art in very-high-energy (VHE) γ-ray astrophysics, an international consortium of ~1500 scientists from 31 countries has converged on the concept of the Cherenkov Telescope Array (CTA) [1]. CTA will consist of two large arrays of imaging atmospheric-Cherenkov telescopes (IACTs), see Fig. 1, using techniques pioneered in the U.S. at the Fred Lawrence Whipple Observatory with the Whipple 10-meter IACT that detected the first sources of VHE γ-rays. These VHE γ-rays are observed via the Cherenkov light produced in particle cascades (showers) generated when they interact in the Earth's atmosphere. A key step in CTA, aside from technological improvements and an increase in telescope quantity, is the use of different-sized IACTs to cost-effectively specialize on different parts of the CTA energy regime (20 GeV – 300 TeV). CTA is envisioned as an open observatory (i.e. *full community access to investor countries*), and will provide full-sky coverage via locations in both the Northern and Southern Hemispheres. High-level CTA data will be available on a public archive after a proprietary period of typically one year.

CTA will be the world's largest and most-sensitive γ-ray observatory. Planning for CTA in the U.S. began in the context of the AGIS (Advanaced Gamma-ray Imaging System) concept, consisting of an array of high-angular-resolution, wide-field telescopes with novel Schwarzschild-Couder optics. This work led to positive endorsements by the HEPAP PASAG panel [2] and the Astro2010 Decadal survey [3], which included U.S. participation at the level of $100M (shared among NSF Astronomy, NSF Physics, and DOE High-Energy Physics) in a united, international effort as one of the recommended large-scale, ground-based projects. The AGIS group merged into the CTA Consortium in 2010, and the participants of all the existing major IACT instruments worldwide are now working together towards CTA's implementation. CTA is *the* major VHE particle astrophysics project in Europe, where it was included in the 2008 Roadmap of the European Strategy Forum on Research Infrastructures (ESFRI) and was designated as an ESFRI Landmark in 2018. It is listed as one of the Magnificent Seven projects comprising the European strategy for astroparticle physics published by ASPERA, and was highly ranked in the strategic plan for European astronomy of ASTRONET. In the U.S., the HEPAP P5 sub-panel review of projects in particle physics noted the unique capabilities of CTA for the detection of dark

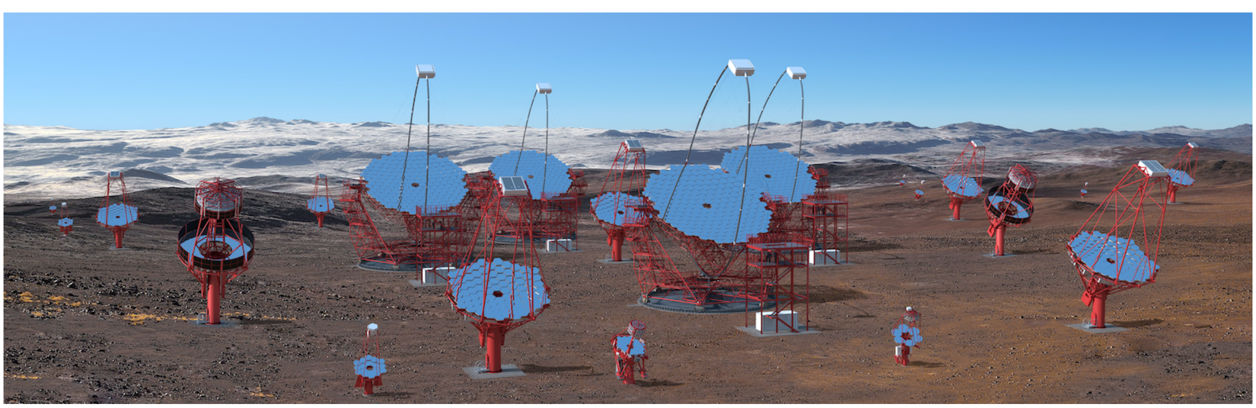

Figure 1: Artist's concept of the Cherenkov Telescope Array southern site, using engineering drawings of the individual telescopes. Four large-sized telescopes (LSTs) in the center are surrounded by arrays of medium-sized and small-sized telescopes, MSTs and SSTs, respectively.

matter and recommended participation in CTA as a multidisciplinary project [4]. In the face of budget realities this decade, U.S. participation in CTA was presented as a mid-scale project to the Astro2010 mid-decade review, to be competed in NSF mid-scale programs, which the panel found would "have a significant positive impact on the scientific productivity of the observatory and would give U.S. scientists leadership roles in the CTA program" [5].

The transformational capabilities of CTA require an observatory that is in the large ground-based project class, but as a multi-national project, no single nation needs to bear even the majority of the cost. Significant U.S. support for CTA construction and operations, at the level of a mid-scale project, would give *all* U.S. scientists access to the observatory.

The contents of this white paper draw extensively from the recently completed volume *Science with the Cherenkov Telescope Array* [6] written by the CTA Consortium.

2 Key Science Goals and Objectives

Ground-based γ-ray astronomy is a young field with enormous scientific potential. The possibility of astrophysical measurements at teraelectronvolt (TeV) energies was demonstrated in 1989 with the detection of a clear signal from the Crab Nebula above 1 TeV with the Whipple 10-m IACT [7]. Since then, the instrumentation for, and techniques of, astronomy with IACTs have evolved to the extent that a flourishing new scientific discipline has been established, with the detection of more than 200 sources and a major impact in astrophysics and more widely in physics. The current major arrays of IACTs: H.E.S.S., MAGIC, and VERITAS, have demonstrated the huge physics potential at these energies as well as the maturity of the detection technique. Many astrophysical source classes have been established, some with many well-studied individual objects, but there are indications that the known sources represent the tip of the iceberg in terms of both individual objects and source classes. CTA will transform our understanding of the high-energy universe and will explore questions in physics of fundamental importance. As a key member of the suite of new and upcoming major astroparticle physics experiments and observatories, CTA will exploit synergies with gravitational wave and neutrino observatories as well as with classical photon observatories (see Astro2020 science white paper [8]). CTA will address a wide range of major questions in and beyond astrophysics, which can be grouped into three broad themes, each corresponding to an Astro2020 science white paper as indicated:

Theme 1: **Understanding the Origin and Role of Relativistic Cosmic Particles** [9]. The existence of highly energetic cosmic particles has been known for more than a century. CTA observations will contribute by providing answers to basic questions such as:

- 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** [10]. VHE γ-rays can be used to explore environments of extreme energy density, as well as to probe another type of extreme environment, the cosmic voids that exist in the space between galaxies. Specific questions concern:

- 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** [11]. VHE γ-rays also allow us to explore questions related to fundamental physics, reaching far beyond astrophysics. Topics addressed include:

- What is the nature of dark matter? How is it distributed?
- Are there quantum gravitational effects on photon propagation?
- Do axion-like particles exist?

The CTA Consortium (see Sec. 5) has prepared a proposal for a Core Program of highly motivated observations to address these science themes. The program, encompassing approximately 40% of the available observing time over the first ten years of CTA operation, is made up of individual Key Science Projects (KSPs). The science cases have been prepared over several years by the CTA Consortium, with community input gathered via a series of workshops connecting CTA to neighboring communities. A major element of the program is the search for dark matter via the annihilation or decay signature of weakly interacting massive particles (WIMPs). The strategy for dark matter detection places the expected cross-section for a thermal relic within reach of CTA for a wide range of WIMP masses from ~200 GeV to 20 TeV. This makes CTA extremely complementary to other approaches, such as high-energy particle collider and direct-detection experiments. CTA will also conduct a census of particle acceleration over a wide range of astrophysical objects, with quarter-sky extragalactic, full-plane Galactic and Large Magellanic Cloud surveys planned (see Fig. 2). Additional KSPs are focused on transients, acceleration up to PeV energies in our own Galaxy, active galactic nuclei, star-forming systems on a wide range of scales, and the Perseus cluster of galaxies. All provide high-level data products which will benefit a wide community, and together they will provide a long-lasting legacy for CTA.

While CTA is designed as a γ-ray observatory it will, as part of its normal operation, collect an enormous quantity of valuable information on charged cosmic rays. Of particular interest are the highest energy cosmic-ray electrons, which must be associated with nearby particle accelerators (and can therefore be studied using CTA data in both the γ-ray and electron channels), and heavy nuclei, which can be separated using their direct Cherenkov emission

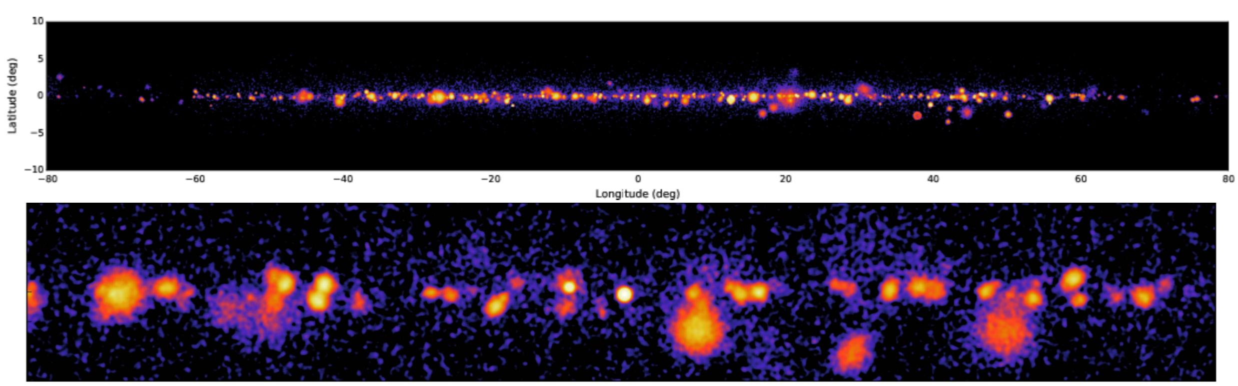

Figure 2: Top: simulated CTA image of the Galactic plane for the inner region, $-80° < l < 80°$, adopting the proposed Galactic Plane Survey Key Science Project observation strategy and a source model incorporating both supernova remnant and pulsar wind nebula populations, as well as diffuse emission. Bottom: a zoom of an example 20° region in Galactic longitude. [6]

(i.e. from the primary cosmic ray, rather than from the secondary products in an air shower). Both γ-ray and cosmic-ray observations with CTA rely on nanosecond-timescale cameras to detect Cherenkov light. Several other uses for the very large optical-photon collection area of the CTA telescopes exist. Observations of optical targets with CTA could include the use of intensity interferometry, to provide unprecedented angular resolution at blue wavelengths for bright sources (see Astro2020 white paper [12]).

The broader astronomical community has expressed interest in the capabilities of CTA, as reflected in multiple science white papers submitted to the Astro2020 call. In particular, its capabilities to characterize Galactic (e.g. [13, 14]), and extragalactic sources(e.g. [15, 16, 17]), and perform multimessenger searches (e.g. [18, 19, 20]) has been highlighted as it will enable the most sensitive observations of these objects in the VHE band.

3 Technical Overview

CTA will be an observatory with arrays of IACTs on two sites, aiming to:

- improve upon the sensitivity level of current instruments by an order of magnitude at 1 TeV,
- boost detection area by at least an order of magnitude, and hence photon rate, providing access to the shortest timescale phenomena,
- substantially improve angular resolution (by a factor ~2) and field of view (by a factor >2 in *diameter*) and hence ability to image extended sources,
- provide energy coverage for photons from 20 GeV to at least 300 TeV, to give CTA reach to high redshifts and extreme accelerators,
- dramatically enhance surveying capability (~400 times faster), monitoring capability, and flexibility of operation, allowing for simultaneous observations of objects in multiple fields,
- serve a wide user community, with provision of data products and tools suitable for non-expert users, and
- provide access to the entire sky, with sites in two hemispheres.

CTA will be operated as an open, proposal-driven observatory for the first time in VHE astronomy. The observatory-mode operation of CTA is expected to significantly boost scientific output by engaging a research community much wider than the historical ground-based γ-ray astronomy community.

The very wide energy range covered by the southern CTA array necessitates the use of three different telescope sizes: referred to as Large-, Medium- and Small-Sized Telescopes (LSTs, MSTs and SSTs). The LSTs provide sensitivity at the lowest energies and SSTs at the highest. There are multiple strong motivations for the wide CTA energy range: the lowest energies provide access to the whole universe (avoiding significant $\gamma-\gamma$ absorption on the extragalactic background light); the highest energies are needed to study the extreme accelerators which we know from direct cosmic-ray measurements are present in our Galaxy; a wide energy range maximises the chances of serendipitous detection of new source classes with unknown spectral characteristics, for example in the search for dark matter with an unknown WIMP mass; a wide energy range is key for discrimination between scenarios and to identify features. All objects which have been studied over a wide energy range with good signal to noise using current IACT arrays exhibit features in their γ-ray spectra. Conversely, the narrow energy range and lower signal to noise measurements more typical of current generation instruments invariably result in spectra which are consistent with power-law forms. In the north, where the inner regions of the Galaxy are not visible, there will be a greater emphasis on extragalactic targets. Therefore, in the interest of optimisation of the observatory, the northern CTA array will be implemented with only LSTs and MSTs.

Access to the full sky is necessary as some of the phenomena to be studied by CTA are rare and individual objects can be very important. For example, the most promising galaxy cluster, the brightest starburst galaxy and the only known gravitationally-lensed TeV source are located in the north. The inner Galaxy and the Galactic Centre are key CTA targets and are located in the south. Full sky coverage ensures that extremely rare but critically important events (for example a Galactic supernova explosion, bright gravitational wave transient, or nearby γ-ray burst) will be accessible to CTA.

Individual CTA telescopes will have Cherenkov cameras with wide field of view: >4.5° for the LSTs, >7° for the MSTs and >8° for the SSTs. The wide camera field serves a dual purpose: to provide contained shower images up to large impact distance (improving collection area and resolution) for on-axis γ-rays and to increase the γ-ray field of view of the system as a whole. This characteristic of CTA is critical for the observation of very extended objects and regions of diffuse emission, as well as for surveys. Furthermore, the wide field reduces systematic errors, with a uniform response over regions much larger than the point-spread-function size (not always the case for current generation instruments).

The CTA design (the "baseline") is for 99 telescopes in the south (4 LSTs, 25 MSTs, 70 SSTs) and 19 in the north (4 LSTs, 15 MSTs). The large telescope number and individual-telescope wide fields of view result in a CTA collection area which is one or more orders of magnitude larger than current generation instruments at essentially all energies, with substantial benefits for imaging, spectroscopy and light-curve generation. Multi-square-kilometer collection area is essential at the highest energies, where there is essentially zero background even in long exposures and sensitivity is limited by the collection of sufficient signal photons. For very-short-timescale phenomena, CTA is background free over much of its energy range and the large collection area is the key performance driver.

For events incident in the central parts of the CTA arrays, the number of recorded shower images will be >10 for all but the lowest energies. These high image multiplicities, combined with the contained nature of events and image information superior to existing instruments, provide excellent energy and angular resolution. A precision approaching 1 arc-minute on individual photons will be obtained for the upper end of the CTA energy range, see Fig. 3, the best resolution achieved anywhere above the X-ray domain.

The ability to rapidly respond to external alerts, and to rapidly issue its own alerts, is built into the CTA design. In particular, the LSTs, where the energy range covered provides access to essentially the whole universe, are optimised for rapid movement, with a goal slewing time of 20 s (requirement of 50 s) to anywhere in the observable sky. A real-time analysis pipeline will enable the identification of significant γ-ray activity in any part of the field of view and the issuing of alerts to other instruments within one minute.

The dramatic improvement in the point-source sensitivity of CTA with respect to current instruments is a consequence of the combination of improved background rejection power, increased collection area and improved angular resolution. The improved background rejection power is achieved primarily through high image multiplicity and is particularly important for

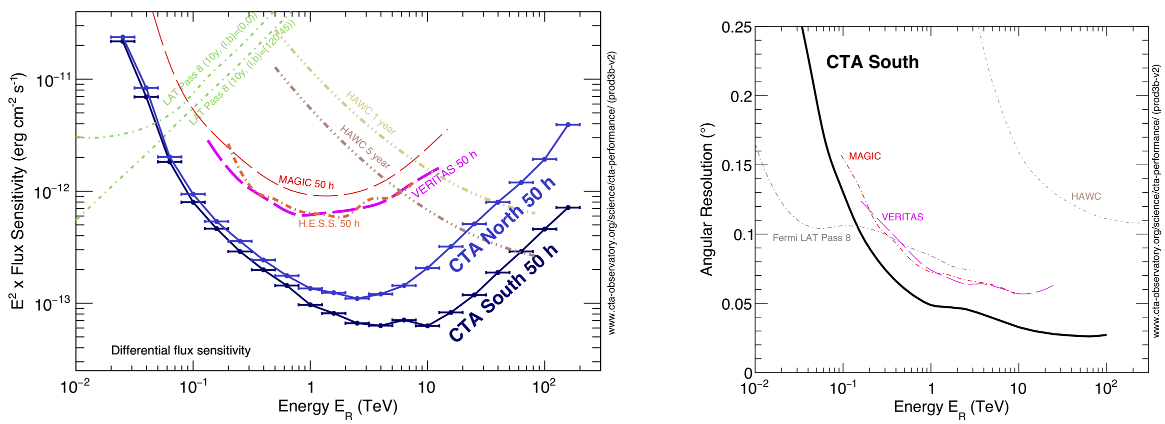

Figure 3: Comparisons of the CTA performance with selected existing γ-ray instruments. Left: differential energy flux sensitivities for CTA (south and north) for five standard deviation detections in five independent logarithmic bins per decade in energy. For the CTA sensitivities, additional criteria are applied to require at least ten detected γ-rays per energy bin and a signal/background ratio of at least 1/20. The *Fermi*-LAT and HAWC curves are scaled by a factor of 1.2 to account for different energy binning. The curves shown give only an indicative comparison between the different instruments, as the method of calculation and the criteria applied are different. In particular, the definition of the differential sensitivity for HAWC differs due to the lack of energy reconstruction for individual photons in the HAWC analysis from which this curve is taken [21]. Right: angular resolution expressed as the 68% containment radius of reconstructed γ-rays (the resolution for CTA-North is similar). These plots represent the understanding of the performance of CTA at the time of completion of this document; for the latest CTA performance plots, see https://www.cta-observatory.org/science/cta-performance.

the study of extended, low-surface brightness objects and for low-flux objects where deep exposures are required. Figure 3 compares the sensitivity and angular resolution of the CTA arrays to a selection of existing γ-ray detectors.

4 Technology Drivers

For 50 years, ground-based γ-ray telescopes have successfully used single, tessellated mirror-surface designs. Designs of this type have been prototyped for all three sizes of CTA telescope, including the first LST at the northern site on La Palma (formally a prototype until it is accepted by the CTA Observatory as an in-kind contribution).

Evolving scientific needs motivated a search for a new design that features both better angular resolution and a wider field of view (FoV). Better angular resolution translates directly into better sensitivity to point sources, which are generally studied in the regime limited by the background from charged cosmic rays. It also enables the mapping of spatially-extended sources in sharper detail, enabling improved morphological studies important to understanding the particle acceleration processes involved. A wider FoV also improves the efficiency of survey observations and the response to transient events that are not well localized. It increases the effective collection area of the telescope as well, by enabling the detection of showers at larger impact

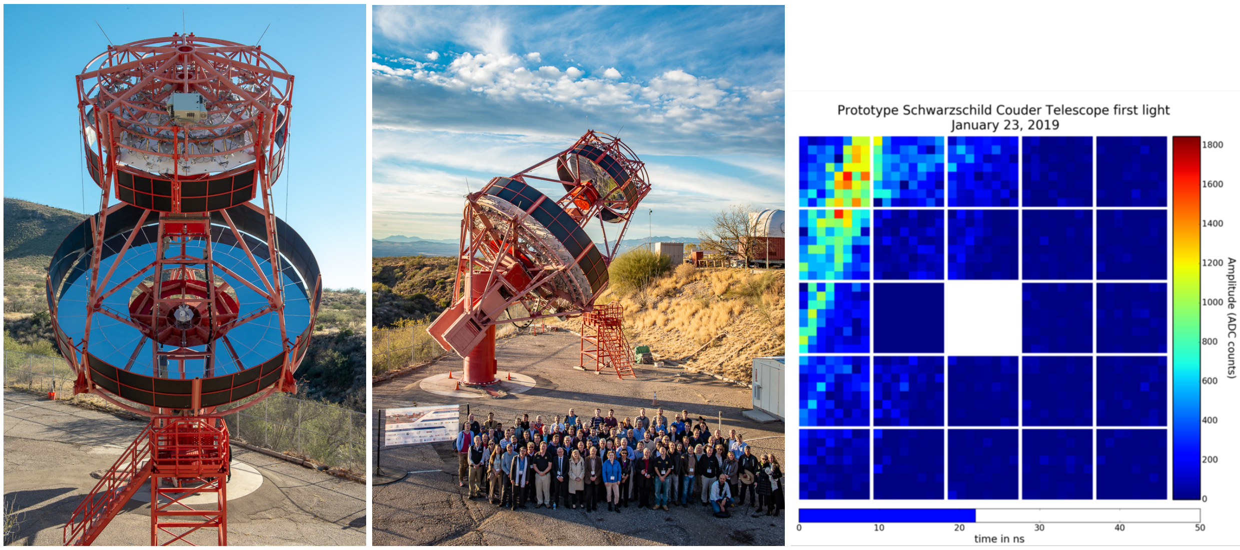

Figure 4: Left: The prototype dual-mirror Schwarzschild-Couder telescope (pSCT) at the Whipple Observatory. Center: The pSCT inauguration on January 17, 2019. Right: First-light image from the pSCT on January 24, 2019. The central camera module is not installed to make way for a camera alignment module.

parameter and reducing the cases of truncated large images in the camera.

The angular resolution of current IACT arrays is still far from the intrinsic limit of the technique that is determined by shower fluctuations. It can be substantially improved for large arrays of IACTs if the camera pixels can be reduced below the current size (~0.15°), and if the image quality of the telescope optical system can be correspondingly improved; the pixel size is matched to the optical point-spread function (PSF) for cost optimization. Ideally, the pixel resolution should match (or oversample) the transverse size of the central region of the cascade, typically spanning a few minutes of arc.

Improving the camera resolution while at the same time increasing its FoV is problematic for existing IACT designs. A telescope with prime-focus optics has comatic aberrations which can be reduced only by increasing the focal length. This, in turn, increases the plate scale and therefore the physical size of the individual pixels of a given angular size in the camera. The resulting telescope's cost is then dominated by expensive large-aperture photomultiplier tubes (PMTs). The conventional "single-mirror" MST for CTA has a 2.5-m diameter (8° FoV) camera with ~2000 1.5" PMTs with 50 mm spacing corresponding to 0.18° diameter pixels. A focus of the U.S. effort within CTA has been pioneering a new IACT design which overcomes these limitations by constructing a dual-mirror system [22, 23]. This optical design, a Schwarzschild-Couder Telescope (SCT), was first proposed in 1905 by Karl Schwarzschild [24], who provided analytic solutions for the figures of both mirrors. Its optics largely cancel aberrations and demagnify the images. However, only recently have mirror fabrication technologies reached the sophistication and cost needed to build an SCT.

A prototype (pSCT) has been built at the Whipple Observatory in Arizona, see Fig. 4, with primary support[1] from the U.S. NSF and with collaborators from Germany, Italy, Japan, Mexico

[1]Collaborative Research: MRI Consortium: Development of a Novel Telescope for VHE Gamma-Ray Astro-

and the United Kingdom. Currently configured with a partial camera, the implementation of a complete camera is under way.[2] The telescope was inaugurated and achieved first light in January 2019. Its operation is currently being optimized so that its performance can be evaluated.

Verification of the pSCT performance is the main outstanding technical question. Simulations show a ~30% sensitivity improvement on-axis for an array with the SCT's design, compared to an array with the conventional prime-focus design, which corresponds to *nearly a factor of two reduction in observation time for background-limited sources* (as most are) [25, 26]. The improvement off-axis is even larger, improving the speed of surveys, measurements of extended sources, and searches for poorly localized or serendipitous transients.

5 Organization, Partnerships, and Current Status

The development of CTA is currently organized by the Cherenkov Telescope Array Observatory (CTAO) gGmbH, a German non-profit corporation having shareholders from 11 nations, not including the U.S. so far, and the European Southern Observatory (ESO). The CTAO Council of shareholder representatives is the governing body of the organization; the U.S. has an observer invited to CTAO Council meetings.

The sites chosen for CTA are both within the grounds of existing observatories: ESO at Paranal in Chile in the south and the Observatorio del Roque de los Muchachos (ORM) of the Instituto de Astrofísica de Canarias (IAC) on La Palma in Spain in the north. Agreements between CTAO and each observatory have been completed and signed.

The CTA Consortium (CTAC) is a scientific collaboration established in 2010 consisting of ~1500 members from 31 nations. The U.S. members of the AGIS project merged into the CTA Consortium in 2010, consistent with Astro2010 recommendations, and currently number ~75, the sixth largest national delegation. The CTAC has been the main group driving the development of CTA, identifying the science goals and designing the instrumentation needed to meet them. CTAC technical work packages have built and tested prototype CTA telescopes (see Sec. 4). CTAC science working groups have enumerated [1, 6] and continue to develop the CTA science capabilities. U.S. scientists are active within CTAC, several having leadership roles, including the Co-Spokesperson of the Consortium as a whole, Rene Ong (UCLA).

The U.S. members of CTAC are organized as CTA-US with an elected Chair, Deputy Chair and Executive Committee. CTA-US members are at the following colleges, universities and laboratories: Alabama, Barnard, CSU East Bay, Case Western, Center for Astrophysics | Harvard & Smithsonian, Chicago, Columbia, Delaware, Georgia Tech, Hawaii, Iowa, Iowa State, Minnesota, Penn State, Purdue, Texas Tech, SLAC, Stanford, UCLA, UC Santa Cruz, Utah, Washington (St. Louis), Wisconsin, Yale.

For the construction and operation of the CTA Observatory, the formation of a European Research Infrastructure Consortium (ERIC), headquartered in Bologna, Italy, has been proposed. The CTAO ERIC would replace the existing CTAO gGmbH and receive its assets. The first stage application for the ERIC has been submitted to the European Union, and a board of governmental representatives (BGR) is preparing the documents needed for the subsequent stages of the application. The U.S. has an observer invited to the meetings of the BGR and is

physics, PHY-1229792 ($2,548,939), PHY-1229205 ($959,000), and PHY-1229654 ($370,277).

[2] MRI Consortium: Development of a Wide Field-of-View Camera for the Schwarzschild-Couder Gamma Ray Telescope, PHY-1828168 ($2,195,309).

not currently participating as a proposed member. Precedent suggests that the U.S. is unlikely to formally join the ERIC, but could participate as a partner either under the terms of the ERIC charter or through a bilateral agreement with the ERIC.

U.S. participation in CTAO construction will be in the context of membership in CTAC and coordination with CTAO (either the gGmbH or the ERIC). It is envisaged that CTAO will be constructed by the receipt of in-kind contributions built by teams of CTAC members, together with cash contributions to CTAO for project staff and infrastructure construction at the observatories. As discussed elsewhere in this document, the U.S. groups hope to make a substantial contribution to the completion of the medium-sized telescope arrays, in collaboration with international partners from CTAC.

6 Schedule

As discussed in the Introduction, CTA has been in development for some time and the concept was reviewed in the last decadal survey. One of the *New Worlds, New Horizons* conclusions was: "Complex and high-cost facilities are essential to major progress in astronomy and astrophysics and typically involve collaboration of multiple nations and/or collaboration of federal and non-federal institutions. These partnerships bring great opportunities for pooling resources and expertise to fulfill scientific goals that are beyond the reach of any single country. However, they also present management challenges and require a new level of strategic planning to bring them to fruition."[3] The CTA project has been confronting these challenges while at the same time designing, building and evaluating prototypes of the candidate telescope designs.

It is planned to build CTA in two phases. Phase I consists of construction of the infrastructure for the full array and installation of a subset of telescopes to form partial arrays. Phase 2 consists of the operation of the Phase I arrays for science and the installation of the remaining telescopes to complete the arrays. The goal for Phase 1 is a "threshold implementation," consisting of 15 MSTs and 50 SSTs in the south and 4 LSTs and 5 MSTs in the north. The ultimate scope of Phase 1 will depend upon the available funding.

Work on the infrastructure, including telescope foundations, is planned to begin at both sites in 2020. The southern site is within the ESO grounds but is a "green field" requiring more development than La Palma. The first telescopes are expected to be accepted on site in 2020 in the north and in 2022 in the south. The completion of Phase 1 and start of Phase 2 are planned for the beginning of 2025. The existing VERITAS VHE γ-ray telescopes in the U.S. are currently supported to operate until mid-2022 and are expected to sunset as CTA operations ramp up.

For some time, it has appeared that U.S. participation in CTA construction would more naturally fit in Phase 2. However, it could be possible in Phase 1 with the current schedules, especially in the south.

A ten-year science program has been developed for CTA. It includes Key Science Programs, as discussed in Sec. 2, requiring somewhat less than half of the observing time over the ten-year period. The KSPs will be undertaken by the CTA Consortium. The balance of the observing time will be allocated to observers *from nations supporting CTA construction and operations* through a time allocation process administered by CTAO. Although it is envisaged that CTAO may have a useful life well beyond the initial ten years, a decision about continued operation (and continued U.S. participation) would be subject to review at a suitable time in the future.

7 Cost

CTA as a whole is a large, ground-based project. A cost estimate prepared by the CTAC for review by the CTA Science and Technical Advisory Committee (STAC) in 2015 and using 2015 costs obtained a total project cost of €400M. This estimate is roughly consistent with the $400M estimate by the Astro2010 review [3].

A key to accomplishing the impressive science that is possible with CTA is the completion of the MST arrays, which cover the core energy region 100 GeV–10 TeV. To this end, we seek construction support in the U.S. sufficient to provide 10 MSTs to CTA. This support could be used to build 10 complete telescopes or to provide a larger number of telescope subsystems, in collaboration with international partners, such that the total number of resulting telescopes is 10 more than could be completed without U.S. participation.

The SCT prototyped in the U.S. (see Sec. 4) is designed to fulfill the MST role while delivering superior performance to a conventional single-mirror telescope. A cost estimate for these telescopes prepared by the CTAC SCT work package for the HEPAP P5 (Particle Physics Projects Prioritization Panel) review in 2013 obtained a cost of $89M for 24 SCTs in 2013$ (including 30% contingency). By this estimate, the current cost of ten such telescopes would be ~$40M.

The CTAO project office is currently updating the CTA costs in order to provide a cost book as part of the Stage 2 application for the CTAO ERIC. The revised cost book is not yet available, but is expected to be completed within the timeframe of the Astro2020 deliberations. A high-level cost review is scheduled for autumn 2019. The initial revised costs are higher than previous estimates. In part, this is the result of a policy decision to incorporate the on-site installation and commissioning costs for each telescope into the telescope cost, since groups providing telescopes to the observatory will be expected to complete installation and commissioning prior to hand-off to CTAO.

In summary, although *New Worlds, New Horizons* recommended U.S. participation in CTA at the level of a large ground-based project, we now seek **U.S. participation in CTA at the level of a medium, ground-based project.** The Mid-Decade Review supported this approach [5].

U.S. participation in supporting CTAO operations would be expected to be roughly in proportion to the fraction of CTAO construction funded by the U.S., at a level of $2–3M per year. *Supporting CTAO construction and operations is critical for preserving CTA access for U.S. scientists.* As with existing VHE γ-ray instruments, such as VERITAS and HAWC, science with CTA data would be supported in the U.S. by investigator-initiated proposals.

8 Summary

The current generation of IACT arrays, H.E.S.S., MAGIC, and VERITAS, have established the power of the atmospheric Cherenkov technique, increasing the number of known VHE γ-ray emitters more than twelvefold. The energy range covered by these observations, above ~100 GeV, is just above the prime energy coverage of *Fermi*-LAT and probes the most energetic particles produced in the most extreme environments in the Universe. CTA is designed to improve upon these current instruments in sensitivity by roughly an order of magnitude, as well as in angular resolution, field of view and energy coverage. Access for U.S. scientists to this unique large-scale (>$400M) ground-based capability can be secured by a highly leveraged U.S. investment at the mid-scale level.

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