Snowmass2021 - Letter of Interest

The Cherenkov Telescope Array (CTA): A Transformational Instrument for Fundamental Physics and Cosmology with Very High-Energy Gamma Rays and Cosmic Rays

Thematic Areas:
■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
■ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

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Abstract: CTA is an instrument for γ-ray and cosmic ray astrophysics in the very high-energy range (E$\gtrsim$100 GeV), designed to achieve a factor 5–20 improvement in sensitivity (depending on the energy) compared to current instruments. It will provide unprecedented opportunities to study extreme astrophysical environments, perform unique tests of fundamental physics, and sensitively search for dark matter (DM) signatures, reaching the thermal relic cross section for DM masses $\gtrsim$200 GeV. In particular, it can probe DM masses above $\sim$1 TeV, which are inaccessible to current or foreseen direct detection or accelerator production experiments. Observations of extragalactic γ-rays enable tests of Lorentz invariance and probe the intervening medium, yielding measurements of the extragalactic background light and cosmological parameters, as well as providing potential evidence for intergalactic magnetic fields and axion-like particles. CTA is an international project that has profited from strong U.S. participation in both science planning and technology development. A novel telescope design to substantially enhance CTA performance in the core 0.1–10 TeV energy range is a proposed U.S. hardware contribution. U.S. support for CTA construction, not yet committed, will enhance the science reach of the observatory and ensure U.S. access to this transformational facility and the discoveries it will enable.

CF6: CTA — A New Facility for Very High-Energy γ-Ray and Cosmic Ray Astrophysics

The Cherenkov Telescope Array (CTA) will be a next-generation instrument sensitive to γ-rays and cosmic rays (CRs) in the very high-energy range (VHE, E $\gtrsim$100 GeV). The CTA design consists of two large arrays of imaging atmospheric Cherenkov telescopes (IACTs) that detect VHE γ-rays and CRs through the observation of Cherenkov light produced in air showers initiated by these particles. The arrays, one in the Northern and the other in the Southern hemisphere, will provide full-sky coverage by combining IACTs optimized for different energies in the 20 GeV–300 TeV range. CTA builds on the pioneering U.S. legacy of the Whipple 10-m γ-ray telescope and the current-generation VERITAS telescope array, as well as the HEGRA, MAGIC, and H.E.S.S. projects abroad.

For fifty years, IACTs have used optical systems that are based on a single mirror, prime-focus Davies-Cotton or parabolic design. The U.S. participants in CTA have led an international collaboration to build and demonstrate an innovative 9.7-m dual-mirror prototype Schwarzschild-Couder telescope (SCT) for CTA, which has the potential to transform the field by offering major improvements in angular resolution and off-axis sensitivity over a wide 8° field of view.[1–5] The SCT design, which incorporates original ideas for the optics, mechanics, and electronics, has a cost comparable to existing IACTs of similar aperture. Simulations show a $\sim 30\%$ sensitivity improvement for an array that uses SCTs when compared to conventional prime-focus telescope designs, resulting in nearly a factor of two reduction in observation time for most sources.[6;7] The wide-field design also improves the sky survey speed, observations of extended sources, and searches for poorly localized or serendipitous transients (*e.g.* gravitional wave or neutrino events). The first detection of a VHE γ-ray source with the prototype SCT was recently achieved,[8;9] validating the technological approach.

A European Research Infrastructure Consortium (ERIC) is currently being formed to manage the CTA Observatory. When the ERIC is approved (currently anticipated in 2021), construction will officially begin on northern and southern CTA arrays that will be reduced in scope compared to the full design. This initial construction phase will be followed by operations and enhancement phases in which the arrays are operated for science and additional telescopes are added to enhance the scientific performance. We are working to add ten or more SCTs to CTA during the enhancement phase.

A detailed discussion of the CTA scientific capabilities can be found in the volume *Science with the Cherenkov Telescope Array*[13] and in recent white papers submitted to the Astro2020 Decadal Survey.[14–18] The remainder of this letter presents a brief introduction to the capabilities of CTA to address critical issues at the Cosmic Frontier, such as indirect searches for dark matter (DM) and tests of fundamental physical laws. How the addition of (SCT) telescopes to CTA can enhance the outcomes of these studies will be a topic of investigation during the Snowmass study.

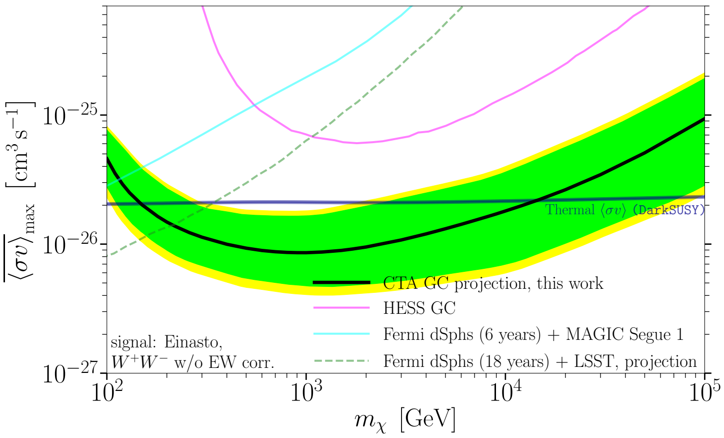

Figure 1: CTA sensitivity curve[10] (black) and H.E.S.S. limits[11] (magenta) for WIMP dark matter signatures based on Galactic Center observations. Upper limits from *Fermi*-LAT observations of dwarf galaxies[12] are also shown. CTA results will constrain the thermal relic abundance level for a wide range of WIMP masses.

CF1: Indirect Searches for WIMP Dark Matter with CTA

Among the prominent particle candidates for DM are weakly interacting massive particles (WIMPs), which are expected to self-annihilate to produce prompt or secondary γ-rays for a wide range of models. The unparalleled 20 GeV–300 TeV sensitivity of CTA enables indirect DM searches by observing cosmic targets where a WIMP annihilation signal may be discernible from other astrophysical processes. The Galactic Center (GC) region will be an essential target for this purpose,[10;13;15] given its relative proximity and expected large DM density. CTA will indeed reach the canonical velocity-averaged thermal annihilation cross-section of $\sim 3 \times 10^{-26}$ cm^3 s^{-1} (Fig. 1) for a WIMP mass in the range ∼0.2–20 TeV, something which is not possible at the higher masses with current instruments *of any type*. Together with *Fermi*-LAT constraints on DM lighter than ∼200 GeV, the WIMP paradigm will be severely constrained in the case of non-detection. Models with a large photon yield from DM annihilation will be constrained to even smaller cross sections. Other CTA studies, such as TeV halo observations around nearby pulsar wind nebulae[19] and CR electron+positron spectrum measurements up to hundreds of TeV,[13;20] will also be fundamental to understanding potential signatures of WIMP annihilation or decay in CR indirect searches (e.g. AMS-02[21]). In conclusion, the WIMP paradigm, either through detection or non-detection will be significantly impacted by CTA results.

CF2 and CF3: Constraints on Axion-Like Particles with CTA

VHE γ-rays can interact with astrophysical magnetic fields to convert to axion-like particles (ALPs). If they reconvert to γ-rays before reaching Earth, they can be detected by CTA. However, their transmission probably is changed as a result of spending part of their journey as ALPs, leaving a potential imprint on the "γ-ray " spectra of sources which can be measured with CTA.[13;15;22;23]

CF7: Cosmic Probes of Fundamental Physics with CTA

The cosmic particles that CTA will study are produced in extreme astrophysical accelerators, propagate over long distances, and are potentially accompanied by other cosmic messengers such as CRs, neutrinos and gravitational waves (GW). These unique characteristics enable powerful tests of fundamental physics, the study of the intergalactic medium, and multi-messenger probes of astrophysical processes.

As they propagate over cosmological distances, VHE γ-rays are absorbed via pair production on infrared photons from the extragalactic background light (EBL). The measurement of the redshift-dependent softening of VHE γ-ray source spectra can therefore be used to measure the EBL spectrum (for example[24]), which encodes the integrated history of structure formation and stellar evolution in the Universe. As the amount of attenuation depends on the expansion rate and matter content of the Universe, EBL studies provide a complementary measurement[25] of H_0 and Ω_m. The yet-undetected intergalactic magnetic field (IGMF) may also imprint a signature measurable by CTA on the arrival direction and timing distribution of secondary GeV-TeV γ-rays initiated by these EBL-induced pairs.[26] The search for other propagation effects such as an energy-dependent dispersion in the VHE γ-ray arrival time from a brief flare of a distant source, or the appearance of spectral features can set stringent constraints on physics beyond the Standard Model, such as Lorentz invariance violation, in addition to constraints on ALPs discussed in the previous section.[13;15;23;27]

CTA will exploit deep synergies with GW and neutrino observations. VHE neutrinos are expected to be accompanied by VHE γ-rays due to the decay of neutral and charged pions in hadronic cosmic ray interactions at their source or during propagation. The combined operation of CTA with next-generation neutrino telescopes such as IceCube-Gen2[28] or KM3NeT[29] will enable searches for cosmic ray acceleration sites and the study of the hadronic Universe. GW sources such as binary neutron star mergers have also been proposed as VHE γ-ray emitters,[30] and CTA will implement a follow-up program[13] of GW alerts from the aLIGO/Virgo/KAGRA interferometers[31] that will probe the high-energy emission from these events.

These fundamental physics studies with CTA will complement and exploit a rich observational program that will combine VHE γ-rays with multi-wavelength and multi-messenger observations to probe astrophysical environments with extreme electromagnetic and gravitational conditions, such as supernova remnants, active galactic nuclei, star-forming regions, galaxy clusters and astrophysical transient events.

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