Astro2020 Science White Paper

Exploring Frontiers in Physics with Very-High-Energy Gamma Rays

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract:

This white paper briefly summarizes what can be learned over the coming decade in studies of fundamental physics through ground-based gamma-ray observations over the 20 GeV to 300 TeV range. The majority of the material is drawn directly from Science with the Cherenkov Telescope Array [1], which describes the overall science case for CTA. The superior sensitivity and energy coverage of CTA will allow unprecedented exploration of the frontiers of physics. We request that authors wishing to cite results contained in this white paper cite the original work.

Introduction

VHE gamma-ray observations offer a window to some of the most energetic environments in the Universe, in which gamma-ray production occurs due to particle acceleration in extreme conditions of gravitational or magnetic fields. Astrophysical observations with imaging atmospheric Cherenkov telescopes (IACTs) offer powerful ways to search for physics beyond the current Standard Model, such as exploring the nature of Dark Matter. TeV observations can also be used to place constraints on physical laws at energies well beyond the reach of terrestrial accelerators, from TeV to Planck scales. Results from current generation IACTs, such as H.E.S.S., MAGIC and VERITAS, have demonstrated that TeV astrophysics has come of age, with the potential for carrying out detailed studies in particle physics, cosmology and astrophysics.

A larger telescope array with improved technology could be implemented in the first part of the coming decade and could achieve an order of magnitude improvement in sensitivity, combined with better angular resolution and sensitivity over a wider range of energies (20 GeV – 300 TeV), which we refer to here broadly as “very high energy,” VHE. The science capabilities of such an instrument (and the optimization of its design) have been studied extensively by the Cherenkov Telescope Array (CTA) Consortium [1]. It would transform our understanding of the high-energy universe and explore questions in physics of fundamental importance.

The superior sensitivity and energy coverage of CTA will allow unprecedented exploration of the frontiers of physics. CTA will reach the expected thermal relic cross-section for self-annihilating dark matter for a wide range of dark matter masses, including those inaccessible to the Large Hadron Collider (LHC). The study of distant extragalactic sources at very high energies offers the opportunity to look for energy-dependent variation of the speed of light due to quantum-gravity induced fluctuations, and the possibility to probe physics at the Planck scale and constrain LIV (Lorentz Invariance Violation) effects. The study of axion-like particles (ALPs) is another avenue of exploration for VHE instruments, as gamma rays may couple to other light particles such as ALPs, under the influence of intergalactic magnetic fields. The substantial increase in sensitivity that CTA offers will allow these fundamental physics topics to be addressed. A discovery in any of these areas would have a major impact in the field.

Dark Matter

It is now well established that dark matter (DM) exists in our universe with evidence for DM seen in spiral galaxies, galaxy clusters, elliptical galaxies, galaxies with low surface brightness and dwarf spheroidal galaxies. The existence of DM in the universe was first proposed by Zwicky in the 1930’s to explain the dynamics of the Coma cluster where the observed luminous matter could not sufficiently account for gravitational stability. Fig. 1 is an image of the Bullet cluster showing hot X-ray emitting gas overlaid with the deduced dark matter distribution in the cluster, calculated from gravitational lensing observations. The nature of DM is one of the major open questions for physics. Modern standard cosmology rests on the cold dark matter (CDM) paradigm, however, as of yet no clue has been found as to its particle content. Among the prominent particle candidates for DM are the Weakly Interacting Massive Particles (WIMPs), which are expected to self-annihilate to produce prompt or secondary gamma-ray emission for a wide range of DM masses.

WIMPs encompass a large variety of non-baryonic candidates with a mass typically between few tens of GeV and a few TeV and an annihilation cross-section of the order of the weak interaction. WIMPs are well motivated DM candidates in extensions of the Standard Model of particle physics (SUSY, Kaluza-Klein). CTA is expected to reach the benchmark value of the (velocity weighted) cross-section of ($\sim 3 \times 10^{-26}$ cm^3 s^{-1}) for WIMPs produced thermally in the early Universe, for a wide range of DM masses, including those inaccessible to the Large Hadron Collider (LHC). Current IACTs, such as H.E.S.S., MAGIC and VERITAS, have attempted to reach this value but have been limited by their sensitivities.

Different complementary approaches are required to establish and corroborate a DM signal and to extrapolate from a discovery to understanding the properties of DM in the universe. The four searches to carry out for non-gravitational signatures of DM in the form of WIMPs are: direct detection, indirect detection, collider experiments, and astrophysical probes sensitive to non-gravitational interactions of DM. The LHC is investing major effort in attempting to create DM directly in the laboratory and in detecting its virtual traces on Standard Model signals. Direct detection experiments measure the recoil energy of nuclei in a well-shielded detector when hit by a passing DM particle. Examples of some underground direct-detection experiments include CDMS-Si, CRESST, and EDELWEISS-II, XENON100, LUX, and CDMS II-Ge). Controversial evidence of the detection of an annual modulation signal (due to our motion around the Sun) of DM with mass around 10 GeV has been presented by DAMA/LIBRA and more recently by CoGeNT. CTA will complement these studies using indirect detection techniques for DM. Fig. 1 (right) shows the phase space of the regions available for different search techniques for various dark matter masses. In order to understand the nature of DM, these different techniques are complementary and essential. Note that CTA has the potential to discover candidates which escape direct detection and collider bounds. If signatures of DM do appear in direct-detection experiments or at the LHC, gamma-ray observations will provide a complementary approach to identify it, while the typical cutoff of the energy spectrum will allow for a precise mass determination. If such experiments do not detect DM, for example for the case of heavy DM candidates, CTA may be the only way to look for such particles over the next decade.

The Galactic Center will be an essential DM target for CTA, given that it is a nearby source. However, the large astrophysical gamma-ray background has to be well characterized and understood. Dwarf spheroidal galaxies (dSphs) are also very important targets [1,4]. These are gravitationally bound objects with large mass to light ratios, that are believed to contain up to O(1000) times more mass in DM than in visible matter, making them widely discussed as potential targets for indirect DM detection. Although these are attractive targets with no gamma-ray background, their DM distribution can be uncertain, and the need to understand J-factors will be important. The dwarf spheroidal galaxies (dSphs) of the Local Group could give a clear and unambiguous detection of DM. Other targets will include the Large Magellanic Cloud, and Clusters of galaxies. Fig. 2 (left) shows the sensitivity of CTA to a WIMP annihilation signature as a function of WIMP mass, for nominal parameters and for observations of multiple targets. Fig. 2 (right) shows the sensitivity predictions for observations in the Galactic Halo excluding the central region of Galactic latitude $b < 0.3^\circ$. The quest for DM requires a deep and uniform exposure over several degrees around the central black hole Sgr A* to allow for both spectral and spatial morphological studies, a deep understanding of the instrumental and observational systematics, and precise determinations of the standard astrophysical emissions. The expected CTA energy and angular resolutions are key ingredients to disentangle a DM signal from standard astrophysical background.

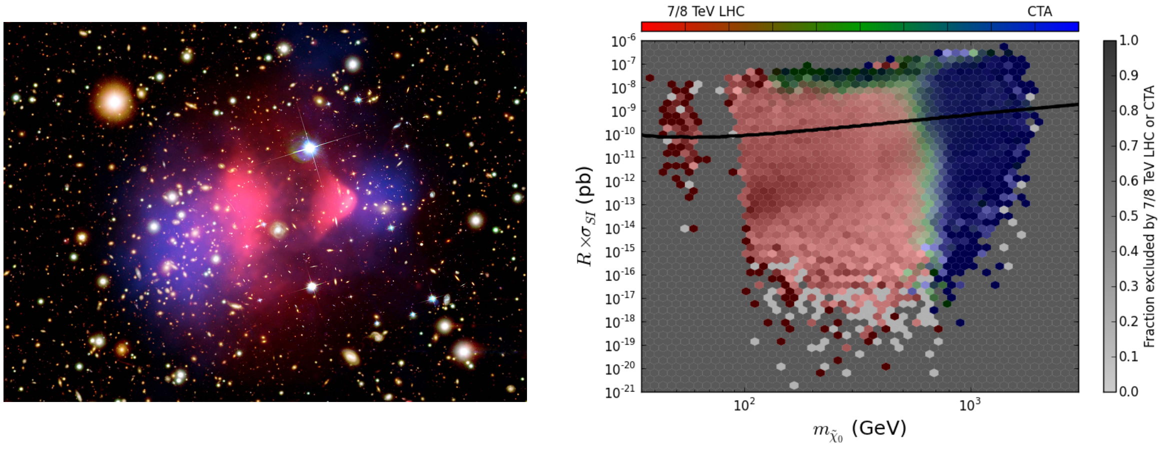

Figure 1: Left: Composite image of the Bullet Cluster [2]. Hot X-ray emitting gas is shown in red and the blue hue shows the dark matter distribution in the cluster deduced from gravitational lensing. Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al. Right: Comparisons of models from the phenomenological minimal supersymmetric model (pMSSM) surviving or being excluded by future direct-detection, indirect-detection and collider searches in the neutralino mass-scaled spin-independent cross-section plane. The spin-independent XENON1T exclusion is shown as a solid black line. The models accessible to CTA (blue) and LHC (red) are shown. Figures from [1] and [3].

To summarize, there are several reasons why CTA will have a much greater potential for indirect DM detection than the current generation of VHE telescopes: 1) CTA's extended energy range will allow searches for WIMPs with lower mass, 2) the improved sensitivity in the entire energy range will improve the probability of detection of DM , 3) the increased field of view with a homogeneous sensitivity as well as the improved angular resolution will allow for more efficient searches for extended sources and spatial anisotropies, and 4) the improved energy resolution will increase the chances of detecting a possible spectral feature in the a DM induced photon spectrum. CTA will indeed reach the canonical velocity-averaged annihilation cross-section of ($\sim 3 \times 10^{-26}$ cm^3 s^{-1}) for a DM mass in the range $\sim$ 200 GeV to 20 TeV — something which is not possible with current instruments for any exposure time. Together with the constraints from Fermi-LAT on DM lighter than a few hundred GeV, this will seriously constrain the WIMP paradigm for CDM in the case of non-detection. Models with a large photon yield from DM annihilation will be constrained to even smaller cross-sections. In conclusion, the WIMP paradigm, either through detection or non-detection will be significantly impacted upon during the first years of operation of CTA.

Search for Lorentz Invariance Violation

Relativity and quantum mechanics are two foundations of modern physics. Testing both concepts in their extremes might provide access to new physics. One paradigm of relativity is that the group of Lorentz transformations is scale invariant (Lorentz invariance, LI) with the practical consequence that the speed of light is constant. If, however, space time has quantum char-

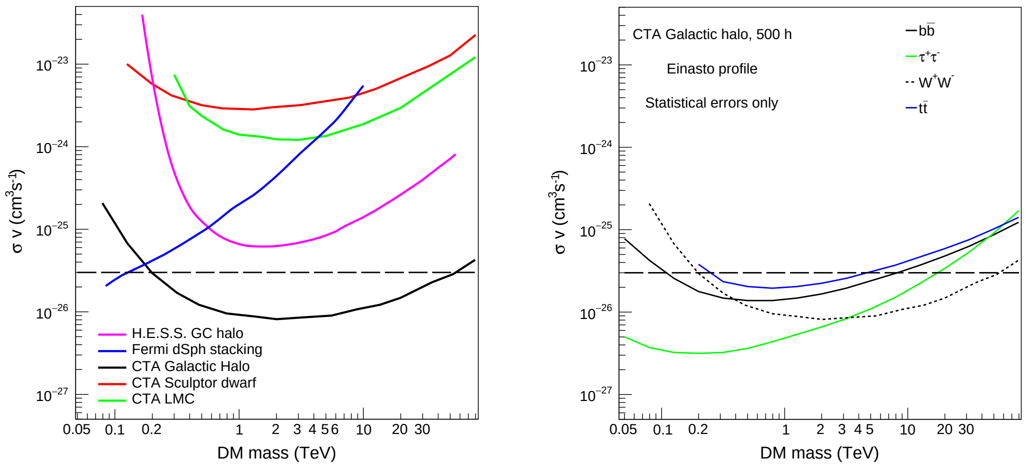

Figure 2: Left: CTA sensitivity to a WIMP annihilation signature as a function of WIMP mass, for nominal parameters and for the multiple CTA observations as described in Chapter 4 of [1]. The constraints are for W^+W^- annihilation channel in all cases. The dashed horizontal line indicates the likely cross-section for a WIMP which is a thermal relic of the Big Bang. Right: CTA sensitivity for $<\sigma v>$ from observation of the Galactic halo for different annihilation modes as indicated. Figures from [1].

acteristics at small scales, that might not be the case anymore. The natural scale at which quantum effects would become relevant and need to be looked for is the Planck scale of 1.2×10^{19} GeV or 1.6×10^{-35} m. These scales can be probed most sensitively with observations of astrophysical objects in very-high energy gamma rays. A prominent method is to search for an energy dependent dispersion in the arrival time of gamma rays from a pulsar or of gamma rays emitted during a brief outburst from an AGN or GRB [5]. Reviews of this and other methods can be found in [6, 7]. A summary of how to test LI with astrophysics observations [8] was adapted for this section.

Assuming that all gamma rays in such an outburst are emitted simultaneously, a linear or quadratic modification of the speed of light with energy dependent terms results in a dispersion in the arrival times at the observer. Such a modification is allowed in models that attempt to combine the concepts of quantum mechanics and gravity (quantum gravity). If the modification is linear in energy, it has been shown that $\mathscr{CPT}$ is violated [9,10]. Thus, if $\mathscr{CPT}$ is preserved and LI violated, the quadratic is expected to dominate. Furthermore, might the modification of the dispersion relation be direction dependent in which case a sample of about 20 LIV constraining observations at different positions in the sky would place stringent constraints on the parameters of the standard model extension [11]. Experiments like CTA are well suited to deliver a sufficient number of constraints.

Sensitivity to LI effects improves with distance to the source, a shorter duration of the gamma-ray outburst, and higher gamma-ray energies. Most important when testing for a quadratic modification of the dispersion relation is sensitivity to the highest gamma-ray energies, which is achieved by observing – with high sensitivity instruments like CTA – sources that emit gamma rays up into the TeV range like blazars, gamma-ray bursts and pulsars.

Observations of objects from these source class already provide some of the most stringent constraints that reach the Planck scale assuming a linear dependence of dispersion on energy [12,13,14,15]. The most constraining observations assuming a quadratic dependence come from the observations of GRBs and pulsars. It can be expected that these constraints will significantly improve in future gamma-ray observations with deeper exposures of pulsars, the detection of brighter and faster flares from blazars, as well as the detection of higher energy gamma rays from GRBs in the VHE band. The MAGIC Collaboration detected the very first GRB with a Cherenkov telescope only recently, after 15 years of operation. Extrapolating from observations with the *Fermi*-LAT, a detection rate as high as 1.5 GRB/year and as low as one per decade can be expected for CTA [16].

CTA will improve the sensitivity in the VHE band ten times over existing instruments; variable sources will be resolved on sub-minute time scale well into the TeV band. It can thus be expected that existing constraints on LI will dramatically improve in the future. Tests of LIV with individual objects are ultimately limited by source intrinsic effects that could either hide or fake an energy dependent dispersion. In some observations this is already the case, *e.g.* the observation of a shift in an AGN flare [17,18] or the low statistics at high energies paired with a rich structure at lower energies as seen in GRBs [12]. These limitations can be overcome by a) a better understanding of the source engine, b) testing with as many different source classes as possible, and c) using sources at as many different distances as possible. The last of these allows unambiguous separation of source intrinsic and propagation effects, although in the case of pulsars where an LIV-like effect is observed a long-term observation program can also differentiate between a source intrinsic and a propagation effect [19]. Another interesting topic is the effect of LIV on the gamma-ray horizon, see for example [20,21]. Gamma-ray instruments like CTA will be key in these studies.

Axion-like Particles

Apart from the search for annihilation/decay signals from dark matter, there is the exciting possibility of detecting axion-like particles (ALPs). Blazars and gamma-ray bursts have been identified as the most promising (bright and distant) target classes for these searches. High statistics measurements of GRBs and blazars over a wide energy range will allow CTA to probe this possibility significantly better than is possible with current IACTs.

Axions are a proposed solution to the strong-CP problem of quantum chromodynamics and also well motivated candidates to constitute a part or all of CDM. ALPS would not have the correct properties (i.e. mass and coupling) to explain the strong-CP problem, but they could potentially be an important component of the dark matter. ALPS are expected to convert into photons (and vice versa) as they traverse cosmic magnetic fields. In the case of a very distant AGN, the ALP/photon coupling can result in a detectable enhancement of the TeV photon flux (which competes with the absorption on the EBL), dependent on the ALP mass. The search for ALPs by CTA will complement dedicated laboratory experiments and studies using indirect astrophysical tests and X-ray telescopes.

In conclusion, each of the above studies could lead to a very major discovery, and alone worth the effort of constructing and operating CTA. Even a non-detection would significantly impact theoretical models. The major step in sensitivity that CTA represents brings such effects within reach and could well allow further issues in fundamental physics to be addressed.

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