On the Detectability of Dwarf Galaxies with the Cherenkov Telescope Array

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Abstract: The nature of dark matter is one of the greatest unsolved mysteries in science. Observations with the current generation of imaging atmospheric Cherenkov telescopes have taken the indirect search for dark matter to competitive levels. With a factor of 5-10 improvement in sensitivity, the Cherenkov Telescope Array (CTA) will improve the chances of detecting a dark matter signal. Assuming a hypothetical dark matter particle that generates observable γ-ray photons in the CTA energy range, we compute the detectability of dark matter subhalos as a function of the particle mass and its annihilation cross section. A wide range of subhalo astrophysical factors is considered, as well as different annihilation channels.

Keywords: HE 3.4 Direct and indirect dark matter searches, HE 3.6 New experiments and instrumentation.

1 Introduction

The existence of an additional non-baryonic particle component appears to be indispensable to accommodate a number of astrophysical observations, including gravitational lensing and galactic rotation curves [1]. An unequivocal detection of this so-called *dark matter* (DM) is one of the most important pursuits in astroparticle physics. Indirect searches for a DM signal from pair annihilation or particle decays are being performed through γ-ray observations of astrophysical objects with high dark matter density [2, 3, 4]. Unfortunately, no reliable DM smoking gun has been detected to date. Here, we explore the prospects for detecting a DM signal with observations of subhalos around the Milky Way with the upcoming Cherenkov Telescope Array (CTA).

1.1 The Cherenkov Telescope Array (CTA)

CTA is a global initiative to build the next generation ground-based γ-ray observatory [5]. When compared to current facilities such as H.E.S.S., MAGIC or VERITAS, a factor of 5-10 improvement in sensitivity is expected in the 100 GeV to some tens of TeV (or Very High Energy, VHE) energy domain. In addition CTA sensitivity will extend to both lower and higher energies. The observatory will consist of two arrays, one in each hemisphere. The Southern hemisphere array will be mainly dedicated to Galactic sources and the central part of our Galaxy, whereas the Northern one will complement the Southern, and be dedicated to northern extragalactic objects notably active galactic nuclei, gamma-ray bursts, and starburst galaxies.

Apart from this wide variety of astrophysical objects, CTA will allow a deep exploration of an energy window where DM signatures are expected, via DM particle annihilation or decay as γ-ray by-products. Therefore, a dedicated study of CTA response to possible DM signals is required.

Throughout this paper, we rely on the CTA design concepts summarized in [5], which has defined a number of possible array configurations and studied their sensitivities. The arrays considered thus far are composed principally of 3 types of telescopes: *large* (23 m diameter), *medium* (around 12 m) and *small* (6-7m). Apart from sizes, these telescope types also differ in other essential parameters, such as field of view or camera pixel diameter. Differences between arrays are due to the number of detectors of each kind that are used, and their spatial layout. Within the design study each considered array has been assigned a letter. Although in our study we have considered all the configurations, the results presented in this work concern only one of them (configuration E) that extends over a surface of $\approx$ 3 km^2 and it is characterized by a balanced sensitivity over the whole energy range.

1.2 Dark Matter targets and signatures

Despite bold efforts, no DM signal has been detected so far from any of the most promising DM targets including dwarf spheroidal (dSph) galaxies[6], the Galactic Center [4], and clusters of galaxies [7]. The null outcome is partially due to sensitivity limitations with the current generation of instruments. Yet, it also reflects the density and distance of the regions probed thus far.

High-resolution simulations indicate that DM halos must exhibit a wealth of substructure on all resolved mass scales [8]. Some of these subhalos would correspond to "classical" dwarf galaxies. Nevertheless, the low end of dark matter subhalos might not have attracted enough baryonic matter to ignite star-formation and would therefore be "invisible" to routine astronomical observations except for some ultra-faint dwarf galaxies. A fraction of these DM subhalos might become prominent at VHE due annihilating weakly interacting massive particles (WIMP) [9]. Such Galactic DM subhalos offer an intriguing sample where to search for a dark matter signature given that these might be out of the Galactic Plane and virtually free of astrophysical background.

A γ-ray signal from DM particle annihilation in the VHE domain would be characterized by a distinctive spectral shape that might include features such as lines, internal bremsstrahlung, as well as a characteristic cut-off at the DM particle mass. A genuine indicator of DM detection would be the detection of this distinct cut-off in several sources, given the universality of the DM spectrum. In the super-symmetric extension of the standard model (SUSY) the *neutralino* emerges as a natural DM particle candidate and the spectral cut-off is conveniently located within CTA energy range [10]. It is clear that even if one could capture a well measured spectrum, it might not be sufficient to reveal all the properties of the DM particle. However, a detection at VHE would provide valuable information for subsequent searches.

2 Detection prospects of dark matter subhalos with CTA

In order to quantify the detection prospects of DM subhalos with CTA one must compare the assumed annihilation γ-ray spectrum from DM annihilation with the expected CTA sensitivity.

2.1 γ-ray flux from dark matter subhalos

The hypothetical differential spectrum from DM annihilation in a galactic DM subhalo can be described as the product of two terms:

$$\phi(E, \Delta\Omega) = \phi^{PP}(E) \times J(\Delta\Omega), \tag{1}$$

The first term, so-called particle physics factor, depends on the particle physics model usually written as:

$$\phi^{PP}(E) = \frac{1}{4\pi} \frac{\langle \sigma_{\text{ann}} v \rangle}{2m_\chi^2} \sum_{i=1}^{n} B_i \frac{dN_i^\gamma}{dE}, \tag{2}$$

where $\langle \sigma_{\text{ann}} v \rangle$ is the thermally averaged annihilation cross section, m_χ is the DM particle mass, $\frac{dN_i^\gamma}{dE}$ is the photon spectrum per annihilation through channel i, and B_i is the i channel branching ratio. The second term, or the so-called astrophysical factor, consists on the integration of the DM density squared along the line of sight, considering a solid angle $\Delta\Omega$:

$$J(\Delta\Omega) = \int_{\Delta\Omega} \int_{l.o.s.} \rho^2(r(s, \Omega))\, ds\, d\Omega. \tag{3}$$

There are many unknown variables in the former expressions. For simplicity, we make a number of assumptions to build a set of reasonable DM spectra. First, the DM particle is considered to be a weakly interacting massive particle (WIMP) whose freeze-out in standard cosmology implies an annihilation cross section of $\langle \sigma_{\text{ann}} v \rangle \sim 3 \times 10^{-26} cm^3 s^{-1}$ [11]. Specifically, we examine a *neutralino* in the minimal Super Gravity (mSUGRA) model that is the preferred DM particle attending to the simulation results from [6]. For the photon spectra per annihilation, the analytical expressions from [12] for the channels $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, and $\mu^+\mu^-$ respectively were used. Throughout, branching ratios B_i of 100% are fixed. For the sake of simplicity we assume that the annihilation proceeds entirely through each of the considered channel.

We have considered a range of possible masses for the DM particle m_χ, that spans from 50 GeV to 10 TeV. The lower limit corresponds to a conservative energy threshold for CTA. It is also motivated by the current experimental lower limits from accelerator data [13]. The upper limit is justified by theoretical arguments (see [11]). Fig. 1 shows spectra for different annihilation channels for a potential 1 TeV WIMP mass and an astrophysical factor $J = 8 \times 10^{20}$ GeV^2 cm^{-5}.

In order to be considered statistically significant with CTA, we require a detection of a gamma-ray signal that exceed 5 standard deviations (5σ) over the background events [5]. In this work, statistical significances are calculated using Eq. 17 in [14]. The excess rate R_{exc} over a certain energy threshold E_{th} can be computed from the effective area of the instrument $A_{eff}(E)$ and the differential spectrum of the source $\phi(E)$ as:

$$R_{exc} = \int_{E_{th}}^{\infty} \phi(E) A_{eff}(E)\, dE \tag{4}$$

the estimated detection time for a certain source depends on the above formula and the background rate of the instrument. As it was previously mentioned, the considered effective area and background rate correspond to the CTA candidate configuration E.

3 Results

In order to survey the CTA capabilities to gamma-rays from DM annihilations at a specific subhalo object, we evaluate the statistical significance of the DM signal as a function of the DM particle mass m_χ and the astrophysical factor J, considering four different annihilation channels, namely $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, and $\mu^+\mu^-$.

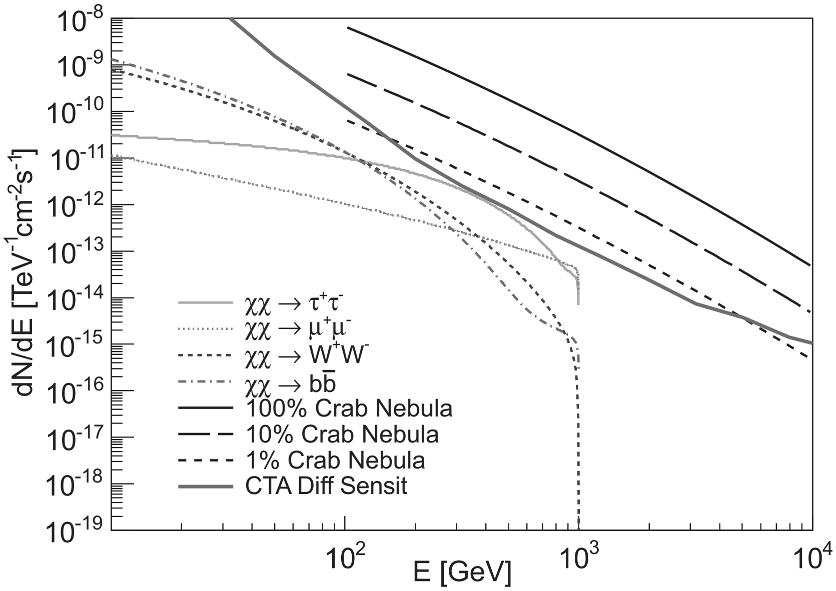

Figure 1: DM spectra for $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, and $\mu^+\mu^-$ channels. We assume an astrophysical factor $J = 8 \times 10^{20}$ GeV^2 cm^{-5} and m_χ = 1 TeV. The lines indicate the 100%, 10% and 1% Crab Nebula differential flux. Also shown is the differential sensitivity expected for CTA.

We have chosen two ways to present our results. In the first one we calculate the astrophysical factor J required to reach a statistical significance of 5σ assuming an effective observation time of 50 hours. In the second one we compute the so called *b*oost factor for a set of well known dwarf spheroidal galaxies.

3.1 Astrophysical factors

Results for the first method are shown in Fig. 2 as a function of WIMP mass for each of the 4 channels considered. As illustrated, the lines mark to the minimum astrophysical factor J_{min} necessary for a 5σ detection with CTA for each annihilation channel. In order to put these values in context, we note that known dwarf galaxies span a range between 4×10^{17} GeV^2 cm^{-5} for the Carina dSph and 1.8×10^{19} GeV^2 cm^{-5} for Segue 1 ultra-faint dwarf galaxy [15].

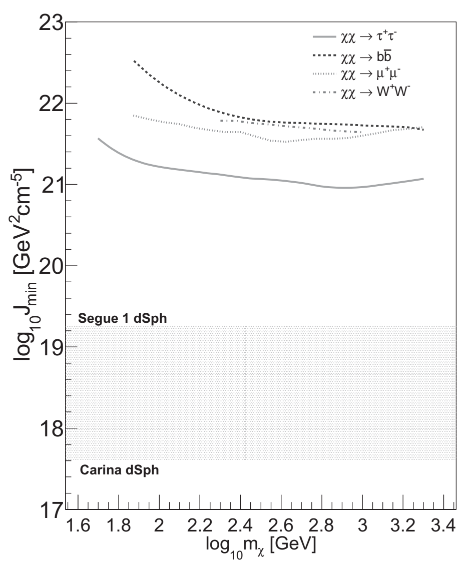

Figure 2: Astrophysical factor J as a function of WIMP mass m_χ. The lines depict the minimum value J required for a 5σ detection with CTA for the respective annihilation channel. The shaded region illustrates the current estimated values from Carina to the ultra-faint Segue 1.

3.2 Boost Factors

A different way to evaluate the prospects of DM detection is by means of the *boost factor* B_F. The approach is justified by the fact that one current conjecture in this field is that the actual signal due to dark matter might be enhanced with respect to classical calculations. This intrinsic boost in the flux could be provided by the effect of substructures within the subhalos, which enhances the astrophysical factor [16] and/or by the *Sommerfeld effect* which enhances the particle physics term [17].

We simply estimate the minimum boost required by a set of well known dwarf galaxies in order to allow for a 5σ detection in 50 hours of observation time with CTA. We compute the value of this minimum B_F as the ratio of the minimum astrophysical factor J_{min} to the measured astrophysical factor J_{obs} from observations/model ling, for a particular WIMP mass. Fig. 3 shows the minimum B_F for a 1 TeV WIMP mass annihilating to $\tau^+\tau^-$ for a set of 8 dwarf galaxies.

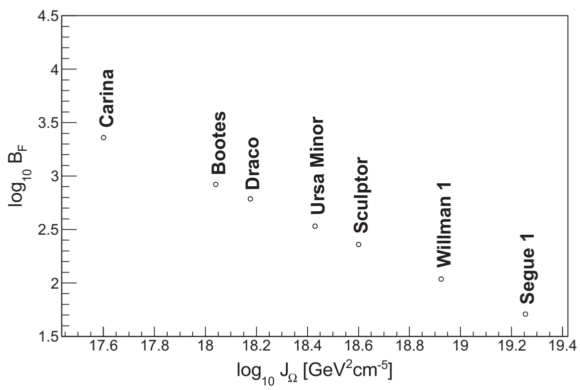

Figure 3: Minimum boost factor B_F as a function of astrophysical factor J for a set of 8 well-studied dSph galaxies, for a putative 1 TeV WIMP mass annihilating to $\tau^+\tau^-$. The minimum requirement is a 5σ detection in 50 hours by CTA. The least strict boost is for the ultra-fain Segue 1 that would only require a factor of 50.

4 Discussion and Conclusions

We have presented a preliminary study of the prospects of DM detection with CTA. In particular, DM annihilation could be realized for subhalos with astrophysical factors $J \geq 8 \times 10^{20}$ GeV^2 cm^{-5} assuming a *neutralino* with a mass around 1 TeV. At present, Segue 1 appears to be one of the most intriguing DM targets especially given the 1σ error bars of its astrophysical factor [15]. However, there is consensus that further work is required to try to calculate J directly from stellar dynamics [18]. From our results, it is obvious that the astrophysical community must continue to search for objects with extreme astrophysical factors *i.e.* either less distant or subhalos with enhanced density profiles. Our knowledge of the Galactic halo will certainly improve with upcoming Southern optical surveys that will scan for such subhalos prior or concurrent with CTA.

Potentially, boost factors $B_F \geq 50$ would alleviate the strict astrophysical factor requirements needed for a 5σ detection with CTA even down to some of the "classical" dwarf galaxies in our current sample. However, our unfamiliarity with the boost regime obliges us to be cautiously optimistic. It must be noted that longer observation times, larger annihilation cross sections, galaxy stacking and improved data analysis with CTA will allow us to improve these estimates even further.

We close by emphasizing that the results presented should be considered very conservative limits from the observational point of view, as further studies and design improvements are being introduced into the final CTA configuration. Specifically, the CTA dark matter prospects taking into account candidate arrays with augmented effective areas will be discussed in an upcoming publication. Nonetheless, albeit preliminary this study clearly illustrates the valuable impact that CTA could make on indirect dark matter searches over the upcoming years.

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