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Dark matter searches in dwarf spheroidal galaxies with the Cherenkov Telescope Array

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Dark matter (DM) is one of the major components in the Universe. However, at present its existence is still only inferred through indirect astronomical observations. DM particles can annihilate or decay, producing final-state Standard Model pairs that subsequently annihilate into high-energy γ-rays. The dwarf spheroidal galaxies (dSphs) in the Milky Way DM halo have long been considered optimal targets to search for annihilating DM signatures in GeV-to-TeV γ-ray spectra due to their high DM densities (hence high astrophysical factors), as well as the expected absence of intrinsic γ-ray emission of astrophysical origin. For such targets, it is important to compute the amount of DM in their halos in a consistent way to optimize the γ-ray data analysis. Such estimates directly affect the observability of DM signals in dSphs, as well as the DM constraints that can be derived in case of null detection. In this contribution, we present the results on the sensitivity of the Cherenkov Telescope Array (CTA) for DM annihilation and decay searches using planned observations of the Milky Way dSphs. We select the most promising targets among all presently known dwarf satellites, providing new determinations of their expected DM signal. This study shows an improvement of approximately an order of magnitude in sensitivity compared to current searches in similar targets. We also discuss the results in terms of cuspy and cored DM models, and investigate the sensitivity obtained by the combination of observations from different dSphs. Finally, we explore the optimal strategies for CTA observations of dSphs.

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1. Introduction

The problem of establishing the nature of dark matter (DM; [1]) is one of the major open challenges in modern astrophysics. Several efforts on the side of elementary particles – e.g., weakly interacting massive particles, (WIMPs; e.g., [2]) or axion-like particles (ALPs; e.g., [3]) – have been made to identify plausible DM candidates. However, the parameter space covered by such candidates ranges over several orders of magnitude in masses and cross sections (e.g., [4]). The current framework for the astronomical searches for DM signals is based on the possibility that DM particles annihilate or decay [5] into Standard Model (SM) pairs that subsequently produce final-state γ-ray photons [6, 7].

The concordance cosmological model predicts that the formation of visible astrophysical structures has been guided by the gravitational potential of previously formed DM overdensities. In particular, the dwarf spheroidal galaxies (dSphs; [8]) are highly DM-dominated and relatively nearby environments with respect to other cosmological DM reservoirs [9, 10]. Therefore, they configure as one of the primary targets for observations aimed at detecting potential observable signals from particle DM. Nearby dSphs have already been the subject of extensive studies with currently operating imaging atmospheric Cherenkov telescopes (IACTs; [11, 12]), and are also optimal targets for next-generation IACTs such as the Cherenkov Telescope Array (CTA; [13, 14]). In this contribution, we present the most updated CTA sensitivities to DM searches in dSph halos, based on novel derivations of their expected DM content. The dSph astrophysical factors for DM annihilation $J_{\rm ann}$ and decay $J_{\rm dec}$ [9] estimated in this way are in turn used to compute the expected DM γ-ray signal intensities and to rank such targets in view of their observation.

2. Astrophysical factors for dwarf spheroidal galaxy halos

The γ-ray flux produced by annihilating or decaying DM can be written as:

$$\frac{d\Phi_\gamma}{dE_\gamma\, d\Omega} = \begin{cases} \dfrac{\langle\sigma v\rangle}{8\pi m_{\rm DM}^2} \; \sum_i {\rm BR}_i \dfrac{dN_\gamma^{(i)}}{dE_\gamma} \cdot \dfrac{dJ_{\rm ann}}{d\Omega} \\ \dfrac{1}{4\pi m_{\rm DM}} \; \sum_i \dfrac{1}{\tau_i} \dfrac{dN_\gamma^{(i)}}{dE_\gamma} \cdot \dfrac{dJ_{\rm dec}}{d\Omega} \end{cases} \tag{1}$$

where $\langle\sigma v\rangle$ is the thermally-averaged DM annihilation cross section in case of annihilating DM and τ_i is the particle lifetime for DM decaying into the i-th SM channel, $m_{\rm DM}$ is the DM particle mass, dN_γ/dE_γ is the number of photons produced during one interaction at a given energy E_γ with a given branching ratio ${\rm BR}_i$ for the i-th channel. The astrophysical factor $J_{\rm ann}$ and $J_{\rm dec}$ are built on the target DM density, integrated over the line of sight (l.o.s.) to the dSph and the source extension $\Delta\Omega$:

$$J_{\rm ann}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\rm l.o.s.} \rho_{\rm DM}^2(\ell, \Omega)\; d\ell\, d\Omega \tag{2}$$

$$J_{\rm dec}(\Delta\Omega) = \int_{\Delta\Omega} \int_{\rm l.o.s.} \rho_{\rm DM}(\ell, \Omega)\; d\ell\, d\Omega \tag{3}$$

Since both $J_{\rm ann}$ and $J_{\rm dec}$ linearly increase the corresponding signal model, it is of utmost relevance to clearly assess the astrophysical factors for the DM halos of interest in order to infer DM

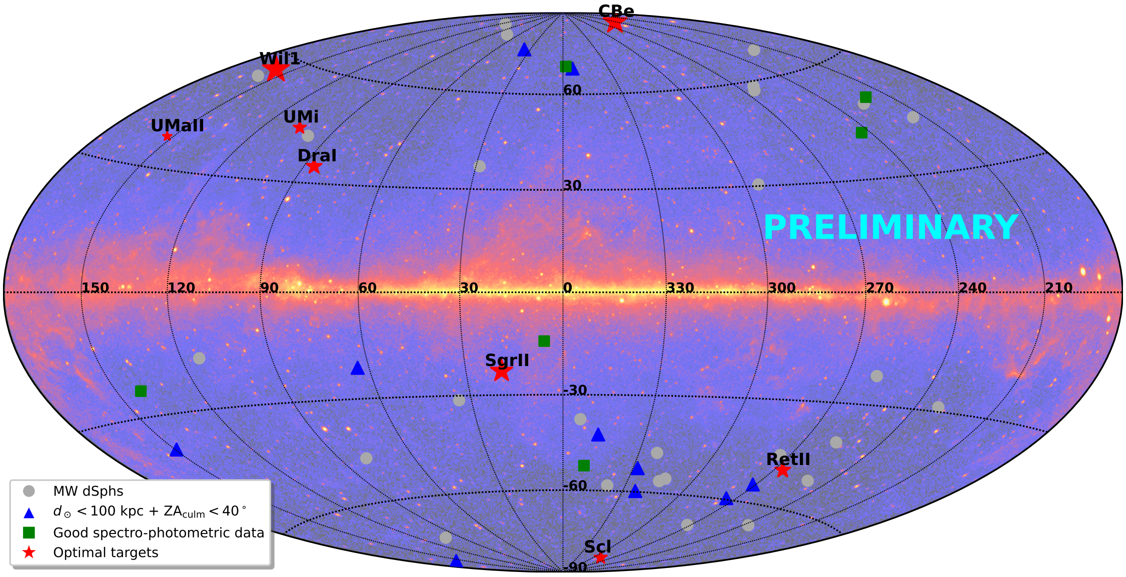

Figure 1: Sky distribution of known dSphs, superimposed to the *Fermi*-LAT γ-ray background (credits: NASA/DOE/*Fermi*-LAT Coll.). The adopted symbols correspond to targets passing incrementally stringent selection cuts (see legend). The optimal targets (*red stars*) are highlighted with symbols of increasing size, proportional to the value of their $\log J_{\rm ann}(0^\circ.1)$.

properties (in case of a positive signal detection) or to provide robust constraints to the particle DM parameters (in case of a null detection). The literature features several methods and assumptions for deriving the DM astrophysical factors for dSphs [10, 15, 17–19]; here, we provide our own estimates based on a common framework of settings. Such novel calculations are particularly relevant to influences the choice of the optimal targets to be observed with CTA.

Our derivation of the dSph astrophysical factors is based on the procedure described in [15], that makes use of the publicly available CLUMPY code [16]. CLUMPY allows to perform a MC dynamical analysis of the DM halos around a dSph that is treated as a steady-state, collisionless systems in spherical symmetry and with negligible rotation, in which the contribution of the stellar component to the total mass can be also neglected. Under such assumptions, the MC analysis relies on the solution of the second-order spherical Jeans equation [20]:

$$\frac{1}{n^*(r)}\left\{\frac{d}{dr}\left[n^*(r)\overline{v_r^2}\right]\right\} + 2\beta_{\rm ani}(r)\frac{\overline{v_r^2}}{r} \simeq -\frac{GM_{\rm DM}(r)}{r} \tag{4}$$

where $n^*(r)$ is the stellar number density, $\overline{v_r^2}$ is the square velocity dispersion and $\beta_{\rm ani}(r) = 1-\overline{v_\theta^2}/\overline{v_r^2}$ is the velocity anisotropy of the dSph. Feeding CLUMPY with such quantities in appropriate forms – i.e. either fixed input, sets of discrete input values over which performing the MC, or sets of free parameters that describe the adopted radial profiles [21] – we are able to solve Eq. 4 and thus obtain the DM density profiles $\rho_{\rm DM}(r)$ along the dSph radial coordinate r.

First, we select all of the dSphs whose expected DM signal is relatively strong and can be integrated over the entire CTA energy window: to this aim, we choose targets that are within 100 kpc distance and culminate at zenith angles ZA < 40° if observed from one of the CTA sites (La

	Einasto		Burkert	
Name	$\log J_{\rm ann}(0^\circ.1)$	$\log J_{\rm dec}(0^\circ.1)$	$\log J_{\rm ann}(0^\circ.1)$	$\log J_{\rm dec}(0^\circ.1)$
Coma Berenices (CBe)	$18.7^{+0.4}_{-0.5}$	$17.6^{+0.6}_{-0.3}$	$18.7^{+0.6}_{-0.5}$	$17.8^{+0.7}_{-0.5}$
Draco I (DraI)	$18.3^{+0.3}_{-0.2}$	$17.3^{+0.1}_{-0.1}$	$18.1^{+0.1}_{-0.3}$	$17.3^{+0.1}_{-0.1}$
Reticulum II (RetII)	$18.3^{+0.3}_{-0.3}$	$17.3^{+0.4}_{-0.3}$	$18.4^{+0.7}_{-0.6}$	$17.4^{+0.9}_{-0.4}$
Sculptor (Scl)	$18.2^{+0.3}_{-0.2}$	$17.2^{+0.1}_{-0.1}$	$17.9^{+0.1}_{-0.1}$	$17.2^{+0.1}_{-0.1}$
Sagittarius II (SgrII)	$18.6^{+1.0}_{-0.8}$	$17.4^{+0.8}_{-0.7}$	$19.4^{+1.1}_{-1.1}$	$18.0^{+1.0}_{-1.0}$
Ursa Major II (UMaII)	$18.1^{+0.7}_{-0.7}$	$17.3^{+0.3}_{-0.2}$	$17.8^{+0.7}_{-0.8}$	$17.3^{+0.7}_{-0.5}$
Ursa Minor (UMi)	$18.2^{+0.1}_{-0.1}$	$17.6^{+0.1}_{-0.1}$	$16.2^{+0.3}_{-0.3}$	$16.5^{+0.4}_{-0.2}$
Willman 1 (Wil1)	$18.9^{+0.4}_{-0.4}$	$17.3^{+0.4}_{-0.3}$	$18.9^{+0.5}_{-0.4}$	$17.4^{+0.7}_{-0.3}$

Table 1: Astrophysical factors for DM annihilation and decay of the selected 8 optimal dSphs, computed at $0^\circ.1$ for both the Einasto and Burkert DM density profiles. All the values of $J_{\rm ann}$ are given in logarithmic GeV^2 cm^{-5} and all those of $J_{\rm dec}$ in logarithmic GeV cm^{-2}.

Palma for CTA North and Paranal for CTA South, respectively). Then, we restrict our calculations to those objects that have spectro-photometric data samples containing more statistics than the number of free parameters in the Jeans analysis, in order to obtain meaningful results. For such targets, we compute the expected $J_{\rm ann}$ and $J_{\rm dec}$ from the posterior distributions of the parameters describing their DM density profiles, both for a cuspy (Einasto) [22] and a cored shape (Burkert) [23]:

$$\rho_{\rm DM}^{\rm (Ein)} = \rho_s \exp\left\{-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right\} \tag{5}$$

$$\rho_{\rm DM}^{\rm (Bur)} = \frac{\rho_s}{\left(1+\frac{r}{r_s}\right)\left[1+\left(\frac{r}{r_s}\right)^2\right]} \tag{6}$$

Finally, we select as optimal dSphs for each hemisphere those sources that exhibit $J_{\rm ann}(0^\circ.1) \gtrsim 10^{18}$ GeV^2 cm^{-5} for integration angles of $0^\circ.1$; we report the values of $J_{\rm ann}$ and $J_{\rm dec}$ for such sources in Tab. 1. In Fig. 1, we show the sky positions in Galactic coordinates of the optimal dSphs, along with those that have not passed all of the selection cuts; in Fig. 2, the profiles of $J_{\rm ann}$ and $J_{\rm dec}$ (Einasto DM profile only) as a function of the instrumental integration angle $\alpha_{\rm int}$ are shown for those dSphs – Coma Berenices (CBe), Draco I (DraI), Reticulum II (RetII) and Sculptor (Scl) – that represent the best trade-off between the expected signal intensity and the uncertainties on the astrophysical factor values.

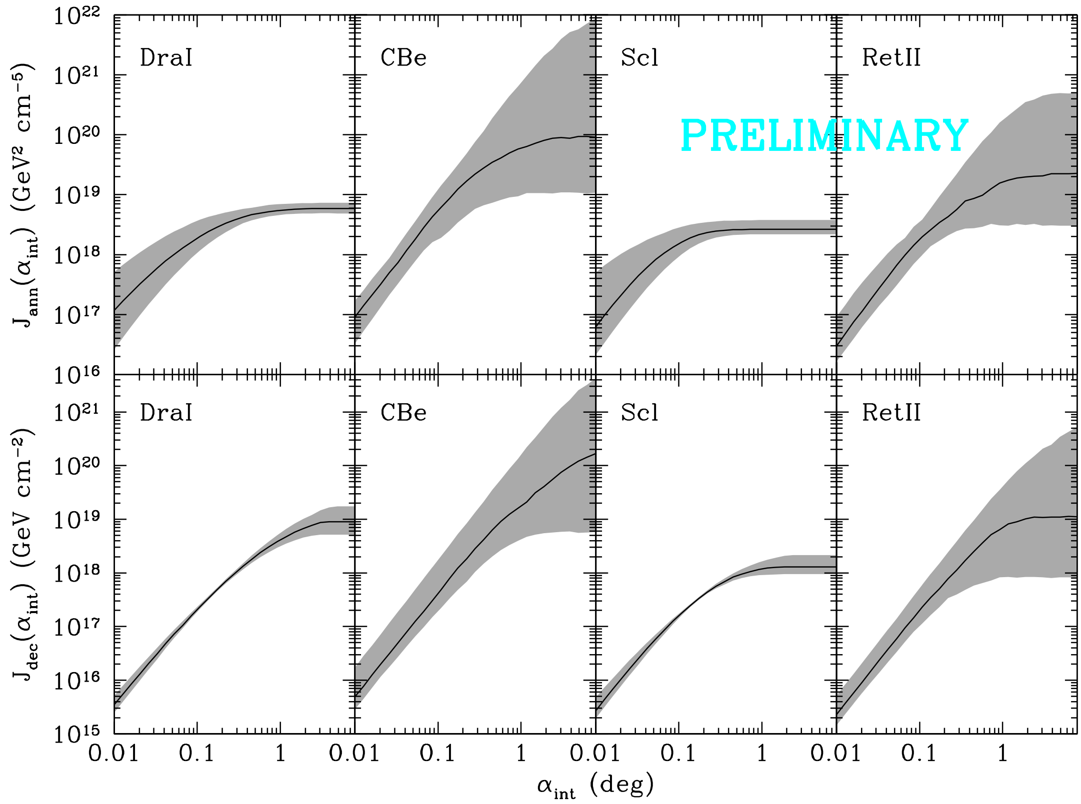

Figure 2: *Top panels:* DM annihilation astrophysical factor profiles $J_{\rm ann}(\alpha_{\rm int})$ as functions of the integration angle $\alpha_{\rm int}$ (*black solid lines*), along with the corresponding uncertainties at 68% confidence level (*grey shaded areas*), for some of the optimal dSphs reported in Tab. 1 (Einasto DM density profile only). *Bottom panels:* DM decay astrophysical factor profiles $J_{\rm dec}(\alpha_{\rm int})$ (*black solid lines*) and corresponding uncertainties at 68% confidence level (*grey shaded areas*) for the same targets.

3. Sensitivity of CTA to γ-rays from dark matter self-interaction

We then use the astrophysical factors computed with CLUMPY for the four optimal dSphs reported above to predict the CTA sensitivity to DM signals. To this end, we make use of the official CTA analysis code `GammaPy` [24] coupled with the CTA instrument response functions (IRFs)[1]. For a given modeled target flux and a set of IRFs and observational parameters, `GammaPy` builds a maximum likelihood estimator over the parameters of interests, and estimates its uncertainty via the likelihood profiling in both spatial and energy bins. The combined likelihood for having n_{ij} counts in all energy (N_E) and spatial bins (N_P) is:

$$\mathcal{L}(\vec{\alpha};\nu|\mathbf{D}) = \mathcal{L}\left[\vec{\alpha}|n_{ij}(\nu)\right] = \prod_{i=1}^{N_E}\prod_{j=1}^{N_P}\frac{\mu_{ij}^{n_{ij}}\,e^{-\mu_{ij}}}{n_{ij}!} \tag{7}$$

[1]Available at https://zenodo.org/record/5499840#.ZGTfjdZBwe0.

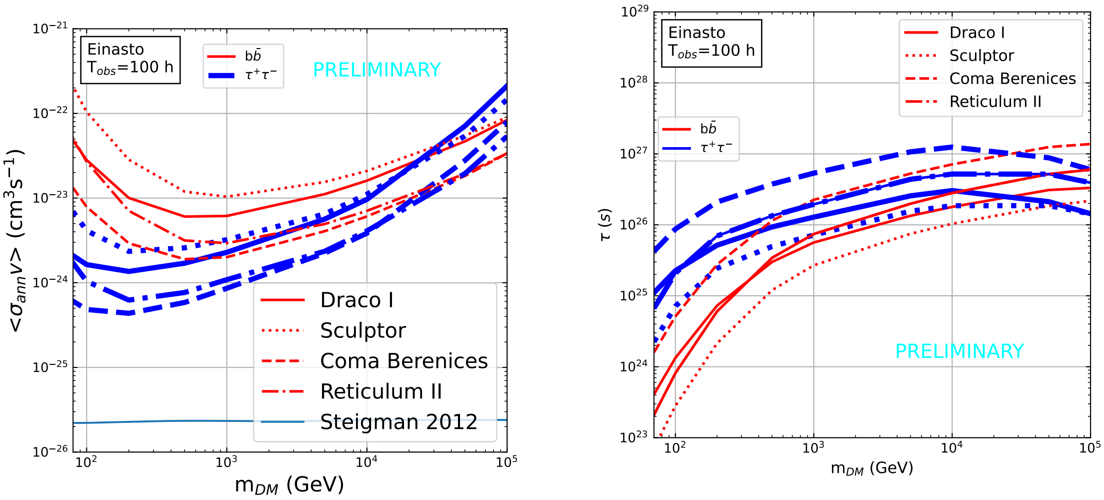

Figure 3: *Left panel:* upper limits on annihilating DM cross sections for the four selected dSphs – CBe (*dashed lines*), DraI (*solid lines*), RetII (*dot-dashed lines*) and Scl (*dotted lines*) – with the Einasto DM density profile derived by CLUMPY, computed assuming 100 h of observation for annihilation in the two pure DM channels $b\bar{b}$ (*thin red lines*) and $\tau^+\tau^-$ (*thick blue lines*). The thermal-relic cross section limit [25] (*cyan line*) is also indicated. *Right panel:* lower limits on the particle lifetime for models of DM decaying into the same channels.

where μ_{ij} is the expected Poissonian mean count for each bin, ν are the nuisance parameters and **D** is the simulated data set. Since this likelihood analysis produces no significant detection of DM signals for any target, we compute the CTA sensitivity to annihilation cross sections $\langle \sigma v \rangle$ and decay lifetimes τ over the range of DM particle masses 0.1 – 100 TeV.

In Fig. 3 we report the upper limits to $\langle \sigma v \rangle$ and lower limits to τ as a function of $m_{\rm DM}$ for the dSphs with the highest astrophysical factors according to Tab. 1 (Einasto DM density profile only), assuming 100% annihilation in either the $b\bar{b}$ or $\tau^+\tau^-$ SM channels. Since CTA will invest a total of ~500-h observing time on the DM searches in dSphs, likely observing each target for $\gtrsim$100 h, we also compute the prospects for the scenario in which we combine ~600-h observations of the two overall best targets, showing them in Fig. 4 for the DM annihilation case. All of the obtained cross-section limits sit between $O(10^{-24}) - O(10^{-22})$ cm^3 s^{-1} for the $b\bar{b}$ channel and $O(10^{-25}) - O(10^{-23})$ cm^3 s^{-1} for the $\tau^+\tau^-$ channel, whereas the lifetime limits may exceed $\gtrsim 10^{27}$ s for $m_{\rm DM} \gtrsim$ 10 TeV.

4. Summary and outlook

This work presents the limits on the particle DM parameter space that CTA can obtain in the search for signals from WIMP annihilation or decay in the halos around dSphs. Since these constraints are strongly affected by uncertainties related to the determination of the DM amount in dSphs based on the astronomical knowledge of their stellar content, the programming of deep spectro-photometric surveys on presently known objects or targets of future discovery is of paramount importance to reduce such biases and thus obtain a final set of optimal dSphs to be pointed at.

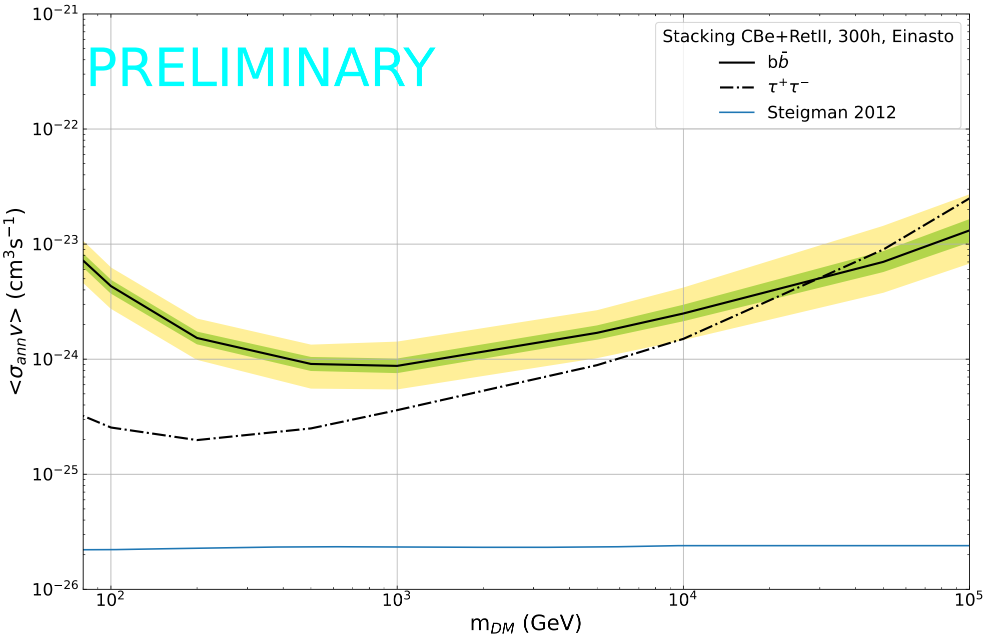

Figure 4: Combined limits from the two best dSphs – CBe (*solid line*) and RetII (*dot-dashed line*) – observed for 300 h each for both the $b\bar{b}$ and $\tau^+\tau^-$ channels, with the uncertainty on the stacked cross-section limit due to photon statistics at 68% (*green band*) and 95% confidence level (*yellow band*) reported for the $b\bar{b}$ channel.

Also, not all the dSphs residing in the MW halo have already been discovered. Based on N-body simulations carried out in the framework of the Aquarius Project [26], we expect 124^{+40}_{-27} satellite galaxies with V-band absolute magnitude $M_V > 0$ in a MW-like halo [27]; only roughly half of this number of dSphs has presently been discovered. Since the detection of fainter targets requires surveys that go ~4 mag deeper than the current ones, this task will be accessible to future facilities like the "Vera C. Rubin Observatory" [28] to potentially provide up to ~60 new dSph candidates. Such considerations highlight further the relevance of future campaigns aimed at characterizing the stellar population of dSphs, in order to expand the sample of potential CTA targets and achieve more accurate determinations of their astrophysical factors.

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