

Search for Dark Matter Subhalos in the High-Energy Gamma-ray Band with *Fermi* and the Cherenkov Telescope Array

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We discuss the potential for the detection of dark matter and the characterization of its particle nature via the observation of dark matter subhalos. Specifically, we discuss the search for dark matter Galactic subhalos in the gamma-ray band with the Large Area Telescope on-board the *Fermi* gamma-ray Space Telescope, and the future generation of imaging atmospheric Cherenkov telescopes, best represented by the planned Cherenkov Telescope Array.

Introduction

The concordance cosmological model, thoroughly validated by observations, requires 83% of the total mass density in the Universe to be non-baryonic [1]. The nature of the so-called dark matter (DM) is one of the major open questions currently in Physics, and on consideration that many plausible theories involve new, exotic particles, the answer may come from the confluence of Particle Physics and Astrophysics. Weakly interacting massive particles (WIMPs) with masses in the GeV-TeV range are well motivated DM particle candidates. WIMPs could self annihilate or decay into Standard Model particles, and thus the nature of DM could be revealed by the detection of these by-products, photons amongst them [2].

A gamma-ray signal from WIMP annihilation would have a very distinctive spectral shape: features such as annihilation lines [3], internal bremsstrahlung [4], as well as a characteristic cut-off at the DM particle mass, are expected. The spectrum of WIMP annihilation or decay must be universal, so even if one can detect all the previously mentioned features in a single measured spectrum, an ultimate confirmation of the DM origin of the signal would be the detection of the same spectral shape in different gamma-ray sources [5–8].

Regions where high DM density is foreseen are the best candidates for detection in the gamma-ray light of DM annihilation, since the expected flux is proportional to the square of the DM density integrated along the line of sight. No clear DM signal has been detected so far in any of the most promising targets, including dwarf spheroidal galaxies [9–12], the Galactic Center region [13, 14], or galaxy clusters [15–17]. Yet, other regions of high DM density potentially exist in the Galaxy: N-body cosmological simulations have uncovered how the cold DM distribution evolves from almost homogeneous initial conditions into a hierarchical and highly clustered state at present [18, 19]. High resolution simulations of Milky Way-like DM halos indicate that the halos should not be smooth but must exhibit a wealth of substructure down to even the smallest scales resolved in the simulations [20–22]. These subhalos could be too small to have accumulated enough baryonic matter to start star formation and would therefore be essentially invisible to astronomical observations [23, 24]. Some of these subhalos could be massive enough and close enough that they could be observed as bright gamma-ray emitters due to the annihilation of DM particles [25]. Since gamma-ray emission from DM annihilation or decay is expected to be steady from any given subhalo, such hypothetical sources would be found in deep sky surveys [26], and most likely would be among the *Fermi*-Large Area Telescope (LAT) detected sources as unassociated sources with no conventional counterpart at any other wavelength. As already mentioned, the smoking gun for DM detection could be a very distinct cut-off close to the DM particle mass. These subhalos could be detected by *Fermi*-LAT, although the distinctive cut-off would most likely be located at too high an energy (see, e.g. the *neutralino* mass lower limit of > 46 GeV [27]) to be detected within a reasonable time (if at all). Therefore the complementarity between *Fermi*-LAT and imaging atmospheric Cherenkov telescopes (IACTs) emerges naturally. In the following, we assume the DM to be composed of WIMPs with masses larger than the previously mentioned mass lower limit, in such a way that the DM annihilation spectral cut-off would lie in the very high energy (VHE, > 50 GeV) gamma-ray band.

Searches for DM subhalos in the *Fermi*-LAT data have already been conducted by the LAT team based on the first year of sky survey data, looking for spatially extended, unassociated sources [28]. Searches for DM subhalo

candidates in both *Fermi*-LAT First and Second Source Catalogs (1FGL and 2FGL catalog, respectively) have also been presented [29, 30], triggering IACT follow-up observations [31, 32]. Additionally, the feasibility of DM subhalo searches with wide-field IACTs has been studied [33].

Unassociated high-energy gamma-ray sources as DM subhalo candidates

The LAT, on board the *Fermi* Gamma-ray Space Telescope, has detected a large number of Galactic and extragalactic point sources of high-energy gamma rays above 100 MeV. The 2FGL catalog lists 1873 high energy sources of gamma rays corresponding to 24 months of scientific data taking [34]. A large fraction of the high latitude sources are associated with known sources, such as blazars. The sources at low Galactic latitudes are largely pulsars, or other supernova products. However, roughly ~ 400 of the 1873 high energy sources listed in the 2FGL catalog are still unassociated [35]. The 2FGL catalog lists source positions with good angular resolution, and flux and spectral measurements for these sources, but none of them have clear counterpart associations at other wavelengths. Thus, these sources remain unassociated and are termed *unassociated Fermi objects* (UFOs).

It is quite likely that many of the UFOs will be identified with known source types in the future with further observations. At the moment, the error boxes of the sources are still large enough to possibly harbor several likely candidates. While a systematic counterpart search of the ~ 400 UFOs individually is clearly unfeasible, it may be possible to characterize the sources that are the best dark matter (DM) subhalo candidates, and use the gamma-ray measurements and observations at other wavebands to identify these targets as astrophysical sources. Alternatively, ruling out a standard astrophysical explanation for the gamma-ray emission would eventually identify DM subhalos and lead to claims of indirect DM detection. In order to do this in the most efficient way, one has to select the most likely candidates for DM subhalos in the list of UFOs, and carry out follow up observations at other frequencies, to look for an astrophysical explanation.

DM subhalos are expected to be faint gamma-ray sources with apparent sizes comparable to the point spread function of IACTs such as VERITAS, H.E.S.S. or MAGIC. The best UFO candidates are those that best resemble a gamma-ray signal originating from the annihilation of DM particles in subhalos. Among the 2FGL candidates, the best possible targets for DM subhalo searches are likely to satisfy the following criteria: (a) location at high Galactic latitudes, (b) steady gamma-ray flux, (c) hard spectrum and (d) no obvious counterpart.

The expected gamma-ray flux due to DM annihilation can be factored into two terms: the so-called astrophysical and particle physics factors. The latter factor is universal, and only depends on the DM particle model. On the contrary, the astrophysical factor is proportional to the DM density squared integrated along the line of sight, and is thus source dependent. When trying to place upper limits on the DM annihilation cross section, the uncertainty in the range of astrophysical factor values one could expect from the population of DM subhalos is a major drawback. The number of subhalos as a function of their masses (known as subhalo mass function), as well as their galactic radial distribution, and inner structures, vary from one simulation to another. Consequently, any upper limit that could be derived from the absence of DM subhalos in the gamma-ray sky would not be model independent and would thus require certain assumptions on the former parameters (see, e.g., [33]). On the other hand, this very same uncertainty is what makes these objects so appealing, since there is the possibility of finding subhalos with astrophysical factors large enough to produce detectable gamma-ray fluxes within the sensitivity range of present and future IACTs. Recent work [36] suggests that in Milky Way-like galaxies a number of the subhalos should have astrophysical factors comparable to, or larger than, those of the Milky Way dwarf galaxies (often interpreted as the largest halo substructures). Consequently, deep observations with IACTs on promising unassociated LAT sources must be encouraged.

Prospective studies with CTA

The next generation of IACTs is best represented by the planned Cherenkov Telescope Array [37]. The expected performance of the instrument has been extensively studied through detailed Monte Carlo simulations [38] (the point source sensitivity of the instrument is shown in Fig. 1 for reference). The capabilities of CTA for DM detection have been presented in [39], where the detection prospects for the most promising targets are studied.

Fig. 2 illustrates the expected sensitivity of CTA to generic, point-like sources showing DM annihilation-like spectral shapes. Consequently, such prediction applies to any DM subhalo that could be considered a point-like source for CTA. The sensitivity is provided in terms of the minimum value of the astrophysical factor required for a 5σ detection after 100 hours of observations. The astrophysical factor of the dwarf spheroidal galaxy Segue 1, the highest among this

type of objects, is shown for reference. Two possible annihilation channels are shown: annihilation to $b\bar{b}$ quarks, as an example of a *soft* photon spectrum [40], and annihilation to $\tau^+\tau^-$ leptons, as an example of a *hard* photon spectrum. The projected sensitivity relies on the performance inferred from the aforementioned Monte Carlo studies, which do not take into consideration the US contribution to the array elements. The inclusion of the US medium-size telescopes, most likely using the novel Schwarzschild-Couder design, would provide a significant sensitivity improvement of the instrument in the energy range from 100 GeV to 10 TeV, a region most sensitive to DM searches (as shown in Fig. 2). Such an effect can be quantified as a factor of 2 to 3 improvement over the mentioned energy range [41], consequently boosting the capability of the instrument for DM searches. A more detailed study of this improvement can be found in an accompanying White Paper [42].

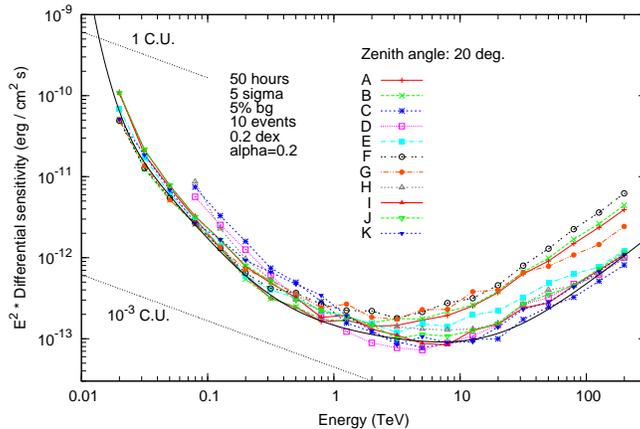


FIG. 1. Expected point source differential sensitivity for 50 hours observation time at 20° zenith angle. Eleven different array layouts for CTA of similar costs, as described in [38], are considered. The solid black line depicts an approximation of the best performance of any of these arrays at any energy. The sensitivity is provided in Crab Units (C.U.), where $1 \text{ C.U.} = 2.79 \times 10^{-7} \times (E/\text{TeV})^{-2.57} \text{ m}^{-2}\text{s}^{-1}\text{TeV}^{-1}$. Figure extracted from [38].

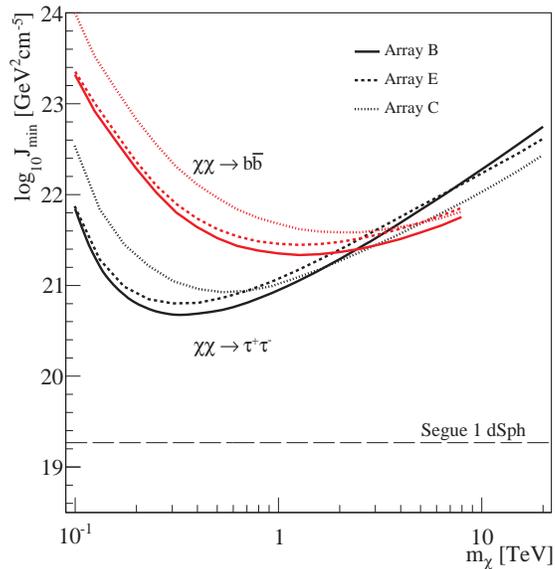


FIG. 2. Minimum value of the astrophysical factor required for a 5σ detection with CTA as a function of the DM particle mass. An observation time $T_{obs} = 100$ hours and an observation zenith angle of 20° are assumed. The results are computed for DM particles annihilating into $b\bar{b}$ (red lines) and $\tau^+\tau^-$ (black lines) and assuming a canonical annihilation cross-section $\langle \sigma v \rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$. The sensitivities of three different array layouts shown in Fig. 1 have been considered (B, C and E). The astrophysical factor for Segue 1 is shown for reference. Figure extracted from [39].

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