Searching for Dark Matter signatures in dwarf spheroidal galaxies with the ASTRI mini-array in the framework of Cherenkov Telescope Array

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Abstract. The nature of Dark Matter (DM) is an open issue of modern physics. Cosmological considerations and observational evidences indicate a behaviour beyond the Standard Model for feasible DM particle candidates. Non-baryonic DM is compatible with cold and weakly interacting massive particles (WIMPs) expected to have a mass in the range between ~10 GeV and ~100 TeV. Indirect DM searches with imaging atmospheric Cherenkov telescopes may play a crucial role in constraining the nature of the DM particle(s) through the study of their annihilation in very high energy (VHE) gamma rays from promising targets, such as the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way. Here, we focus on indirect DM searches in dSphs, presenting the preliminary prospects of this research beyond the TeV mass region achievable with the ASTRI mini-array, proposed to be installed at the Cherenkov Telescope Array southern site.

1. Introduction

Evidence of Dark Matter (DM) existence in our Universe (27% of total energy content) spans from kpc scales to Gpc ones, through its gravitational effect [1]. Although DM particles have not been detected yet, considerations coming from cosmological arguments allow us to do some hypothesis of its non-baryonic nature as a weakly interacting massive particle (WIMP) in thermal equilibrium with the primordial plasma. The interactions (annihilation/decay) that determine the relic abundance of DM also lead to consider the annihilation of WIMP pairs to Standard Model (SM) particles in the present epoch. In the standard thermal history of the early universe the WIMP self-annihilation cross-section has a natural value of $\langle\sigma v\rangle = 3 \times 10^{-26}$ $\mathrm{cm^{-3}s^{-1}}$ [2]. Particular models for WIMPs, such as the *neutralino* in SuperSymmetry, give prediction for gamma-ray energy spectra from the annihilations, which are crucial inputs, together with the DM distribution in the observed target, to achieve prospects for the sensitivity of indirect searches [3]. The goal of the present study is to provide preliminary comparative expectations on indirect DM searches with the ASTRI mini-array in the Cherenkov Telescope Array framework, taking into account continuum gamma-ray signatures coming from typical DM annihilation channels.

Here, we concentrate on simulations for observations of Segue 1, an optimal dwarf spheroidal galaxy (dSph) target.

2. Indirect Dark Matter searches

The indirect detection experiments aim at searching for a flux of annihilation products created in astrophysical environments where DM annihilation may be occurring at an appreciable rate [4]. In particular, the indirect DM searches carried out by imaging atmospheric Cherenkov telescopes (IACTs) look for photons as final state of energy in the WIMP mass range (∼10 GeV up to ∼100 TeV). The flux expected from a DM-dominated region depends respectively on the so-called *particle physics* and astrophysical (or J) factors: $d\phi/dE = d\phi^{\rm PP}/dE \times J(\Omega)$. In particular:

$$\frac{d\phi^{\rm PP}}{dE} = A\frac{dN_\gamma}{dE} \quad , \quad J(\Omega) = \frac{1}{4\pi}\int_\Omega \int_{\rm los} \rho^2(l)dld\Omega$$

where $d\phi^{\rm PP}/dE$ depends exclusively on the DM particle model parameters ($A = \langle\sigma v\rangle/2m^2_{\rm dm}$ takes into account the DM particle mass ($m_{\rm dm}$) and the annihilation cross-section ($\langle\sigma v\rangle$), while dN_γ/dE is the expected average annihilation gamma-ray spectrum per annihilation reaction), and $J(\Omega)$ is the integral along the *line of sight* of the squared DM density profile of the given target integrated within an optimized aperture angle. The products of DM annihilation are thought to come from decay and/or hadronization of the primary SM particles: quarks, leptons, and bosons (each channel is expected to have its own branching ratio).

3. Targets for indirect Dark Matter searches

Among the regions of the sky where DM is expected to be predominant and very-highly concentrated, our attention is devoted to the local universe. In this respect, the Galactic Center (GC) and the dSphs are the most promising targets. Despite the uncertainties in drawing unambiguously the GC density profiles (an open and arduous debate remains between core and cusp behaviour in its central region), the large amount of expected DM content in the GC and its proximity make that target very interesting to look for DM annihilation signals. However, the strong background in very high energy gamma rays makes hard to separate the searched signal from the gamma rays of astrophysical origin. On the other hand, despite a ∼100 times lower J-factors than that of the GC (in the most optimistic scenario), the dSphs are believed to be the smallest (size ∼1 kpc) and faintest ($10^2 - 10^8\ L_\odot$) astronomical objects whose dynamic is dominated by DM ($\frac{M}{L}$ ∼1000 $\frac{M_\odot}{L_\odot}$ for the ultra-faint ones), and they are free from gamma-ray astrophysical backgrounds [5]. Furthermore, ongoing photometric and spectroscopic studies (such as LBT) together with several optical surveys (such as DES, PanSTARSS, VLT, ATLAS), devoted to deeply explore large areas of the sky, are increasing the pool of new dSphs in the Local Group and our knowledge to better constrain the values of the J-factors. The small distance of dSphs from us ($\leq$100 kpc for most of them) is another reason to be preferential targets in this research. On the bases of the Dark Energy Survey (DES) 2-years data [6], some of new discovered satellites in the southern hemisphere could be already considered among the most promising targets to be observed for the first time by the next generation of IACTs. In this respect, the study focused on dSphs presented here looks forward the growth of available dSphs sample in the southern hemisphere in order to select new optimal dSph candidates and provide prospects for them.

4. The ASTRI mini-array in the framework of CTA

The Cherenkov Telescope Array (CTA) is the next-generation international ground based gamma-ray observatory [7]. It will make use of telescopes of three different sizes (large, medium, small) in order to cover the wide energy range from few tens of GeV up to few hundreds of TeV.

The expected CTA sensitivity will be one order of magnitude better than current IACTs in the whole energy window and will give the possibility to fruitfully address several galactic, extragalactic, and fundamental physics science cases [8]. The full sky coverage will be assured by two CTA arrays, one in each Earth hemisphere.
In the framework of CTA, the Italian National Institute for Astrophysics (INAF) is developing a dual-mirror, small-sized, end-to-end prototype (ASTRI SST-2M), inaugurated on September 2014 at Mt. Etna (Italy), and a mini-array – in synergy with institutes from Brazil and South-Africa – composed of nine ASTRI SST-2M telescopes, proposed to be installed at the southern CTA site [9, 10]. In order to study the expected performance and the scientific capabilities of the ASTRI mini-array, dedicated full Monte Carlo (MC) simulations have been performed [11]. According to the preliminary results, the expected sensitivity of the mini-array (for the default telescopes' relative distance of 257 m) is expected to be better than the H.E.S.S. one above ~10 TeV (see Fig. 1), allowing us to deal with few interesting galactic and extragalactic science cases in the early phases of CTA [9].

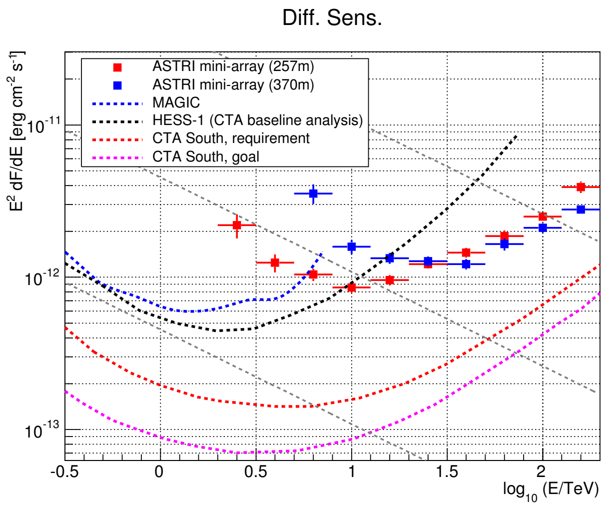

Figure 1. ASTRI mini-array expected differential sensitivity (blue and red points, for two different telescopes' relative distances) compared to the MAGIC [12], H.E.S.S. [13], and CTA (requirements and goal) ones (blue, black, red, and magenta dashed lines, respectively). Plot taken from [11].

5. Prospects for Dark Matter searches with the ASTRI mini-array

The goal of the study presented here is to provide first preliminary comparative expectations on indirect DM searches with the ASTRI mini-array with respect to achieved results by MAGIC [14] and prospects for CTA-North. For this purpose, specific analysis tools from the CTA Consortium and the MAGIC Collaboration have been considered. The instrument response functions (IRFs) used in our analysis have been produced by means of dedicated CTA-MC simulations/analysis [15, 16] (for the ASTRI mini-array and CTA-North) and provided by the MAGIC Collaboration [12] (for MAGIC). For the computation of the constrains on DM models, we have made use of the *full likelihood* analysis by [17], which allows to take advantage of the a priori knowledge of the annihilation spectral shapes to improve the sensitivity. The computation of DM annihilation/decay spectra extended up to 100 TeV have been produced with a code based on PYTHIA 8.135 simulation program [18]. In order to present the evaluation of the performance for different mini-array configurations, we have also considered a possible step-forward configuration with four additional medium size telescopes (MSTs) beside the ASTRI mini-array (hereafter dubbed as ASTRI mini-array+4MSTs). The IRFs for this latter configuration have been achieved as well from a dedicated CTA-MC simulation/analysis [15, 16]. As for the target selection, in this preliminary analysis we have considered the Segue 1 dSph as a benchmark target for all the considered instruments in order to be able to compare the

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sensitivity prospects of the ASTRI mini-array with the results already achieved by MAGIC with 160 hours of Segue 1 survey [14].
In Fig. 2 and 3 the prospects for the ASTRI mini-array and for the ASTRI mini-array+4MSTs configuration are shown for the annihilation channels $b\bar{b}$ and $\tau^+\tau^-$, considering 160 hours of observation of the dSph Segue 1. In the same plots, the results for MAGIC and CTA-North (for the same target and the same exposure time) are also shown. It is worth noting that the exclusion limits curve shown for MAGIC has been computed using our analysis and is compatible with the one published in [14]. In the same plots, also the Fermi-LAT limits achieved from the combined analysis of 15 dSphs (6-years observations) [19] are shown. From this preliminary DM constraints comparison study, rather interesting scenarios for the ASTRI mini-array (with respect current IACTs) in exploring WIMP parameter space are obtained for masses above few TeV, particularly in the $\tau^+\tau^-$channel. The prospects improve considerably when the array configuration with additional four MSTs is considered, due to the much lower energy threshold of such a configuration (~80 GeV) with respect the ASTRI mini-array one (~1.5 TeV).

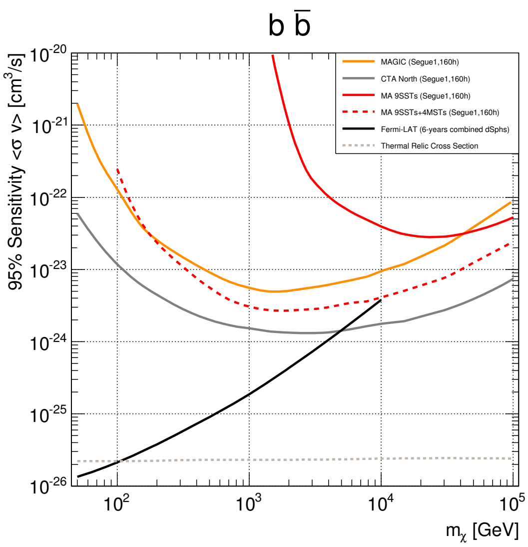

Figure 2. Comparison of sensitivities to DM searches for $b\bar{b}$ annihilation channel in 160 hours of observations of Segue 1 dSph with the ASTRI mini-array (red line), ASTRI mini-array+4MSTs (dashed red line), and CTA-North (grey line). Also shown the MAGIC limits (at 95% CL, orange line) achieved in 160 hours of observations of Segue 1 dSph, and the Fermi-LAT limits (at 95% CL, black line) achieved from the combined analysis of 15 dSphs (6-years observations). The thermal relic cross section values are taken from [20].

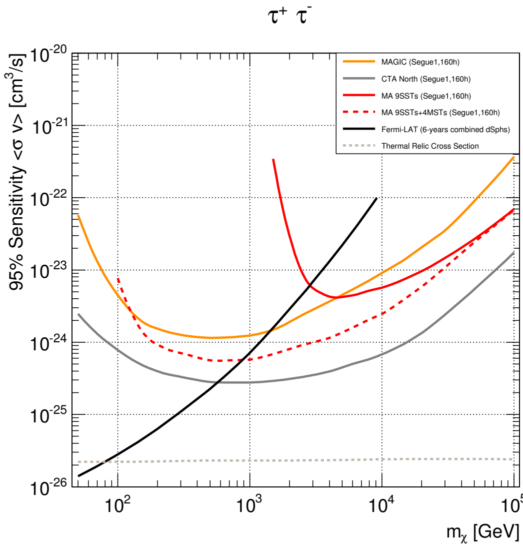

Figure 3. Comparison of sensitivities to DM searches for $\tau^+\tau^-$ annihilation channel in 160 hours of observations of Segue 1 dSph with the ASTRI mini-array (red line), ASTRI mini-array+4MSTs (dashed red line), and CTA-North (grey line). Also shown the MAGIC limits (at 95% CL, orange line) achieved in 160 hours of observations of Segue 1 dSph, and the Fermi-LAT limits (at 95% CL, black line) achieved from the combined analysis of 15 dSphs (6-years observations). The thermal relic cross section values are taken from [20].

6. Conclusions and outlook

The study of indirect DM search prospects with the ASTRI mini-array presented here is based on the assumption of 160 hours of observations of Segue 1, taken as benchmark target for all the considered instruments, and is meant to provide preliminary comparative indications on the capabilities of the ASTRI mini-array in this research field. The results show that the ASTRI mini-array may offer an opportunity to carry on indirect DM searches on dSphs, before the start of full CTA operations, with a sensitivity slightly better than current IACTs for leptonic annihilation channels beyond few TeV mass region. If additional four MSTs are considered (beside the ASTRI mini-array) in the array configuration, the prospects become especially promising, with an expected sensitivity better than the current operating IACTs above a few hundreds of GeV for all considered annihilation channels. In this respect, it is worth saying that the inclusion of some MSTs after the deployment of few SSTs in the southern CTA site can be considered indeed a natural realistic step towards the gradual realization of the final CTA-South. In order to provide more robust and realistic prospects for the ASTRI mini-array (and for some additional "mixed" configurations), some major improvements in the whole analysis chain are already on-going: the optimization of the IRFs calculation for different array configurations (based on more refined MC simulations and analysis); the optimization of the analysis threshold (a crucial issue for any indirect DM study); the identification of new optimal targets (on the bases of actual observability from the southern hemisphere and of the J-factor values); the inclusion of new DM annihilation/decay channels (such as virtual internal bremsstrahlung (VIB) and gamma-ray boxes) as final states. Finally, the prospects for indirect DM searches with the GC as primary target are under evaluation and represent a natural development of this study.

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