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Latest results on searches for dark matter signatures in galactic and extragalactic selected targets by the MAGIC Telescopes

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Abstract. Discovering the nature of Dark Matter (DM) is one of the fundamental challenges of the modern physics. Indirect searches of DM are devoted to look for non-gravitational signals of its presence in the highly DM dominated cosmic regions. Within the weakly interacting massive particles (WIMPs) scenario, we expect very high energy (VHE) gamma-ray emissions resulting from annihilation and/or decay of DM particles. Since the beginning of operations, the Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes are carrying out deep observations of several promising DM targets, with the aim of detecting such signals or alternatively setting stringent constrains to DM particle models in the TeV mass region. In this contribution we present the latest indirect DM search results achieved by MAGIC on several targets, such as dwarf satellites – where MAGIC reached the strongest constraints on DM annihilation searches above few hundreds of GeV –, galaxy clusters, and the Galactic Center.

1. Introduction

The nature of Dark Matter (DM) is still unknown although its presence in the Universe as the dominant gravitational mass component (85% of the universal matter) [1] is well established from galactic to cosmological scales. In our Standard Cosmological Model (ΛCDM), the DM settles the baryonic matter in galaxies and galaxy clusters within the DM halos and sub-halos formed in the early Universe according to a hierarchical scenario of galaxy formation and evolution. The Supersymmetric extension of the Standard Model (SM) of particles provides a suitable scenario to explain the character of DM as a weakly interacting massive particle (WIMP) with masses from tens of GeV up to ∼100 TeV [2]. Within these mass ranges a weak annihilation cross-section naturally leads to a DM relic abundance in agreement with cosmological observations. The DM relic abundance is empirically estimable in terms of its density parameter Ω_{DM}=0.27; this number sets the approximate value of thermal averaged annihilation cross-section before nucleosynthesis: $\langle\sigma v\rangle = 3 \times 10^{-26}$ cm^{-3}s^{-1}. Through annihilation and decay DM particles can convert their rest mass in SM particles [3]. In particular, the gamma rays produced in such

processes can be caught by current gamma-ray instruments like the Fermi-LAT in space, the ground-based Cherenkov telescopes MAGIC, VERITAS, and H.E.S.S., and the new-generation water Cherenkov detector HAWC. Each of these instruments is carrying on indirect DM searches, looking for a signal coming from regions expected to be DM dominated, as the Galactic Center (GC) and halo, the galaxy clusters, and the dwarf spheroidal satellite galaxies (dSphs) of the Milky Way (MW). In these regions WIMPs annihilation and decay rate are considered till today not negligible [4].
The expected DM annihilation/decay flux is proportional to the product of two parameters. The first one is the so-called *particle physics* factor (Eq. 1), which contains all the information of specific DM particle model, i.e. the DM particle mass, cross-section, lifetime, branching ratio, and what ends up generating very specific spectral features expected; the second one is the *astrophysical* (or J) factor (Eq. 2), which accounts for all the astrophysical related quantities, such as the DM distribution and the distance to the source:

$$\frac{d\phi^{\rm PP}}{dE} = A\frac{dN_\gamma}{dE} \quad , \tag{1}$$

$$J(\Omega) = \frac{1}{4\pi}\int_\Omega\int_{\rm los}\rho^k(l)dld\Omega \quad . \tag{2}$$

In Eq. 1, $A = \langle\sigma v\rangle/2m_{\rm dm}^2$ and $A = \tau_{\rm dm}^{-1}/m_{\rm dm}$ for annihilation and decay, respectively; $\langle\sigma v\rangle$ is the thermal averaged annihilation cross section of the DM particle; $m_{\rm dm}$ and $\tau_{\rm dm}$ are the mass and lifetime of the DM particle, respectively; N_γ is the number of gamma rays produced per annihilation or decay reaction, and E is the energy. In Eq. 2, ρ is the DM density, with exponent $k = 2$ for annihilation and $k = 1$ for decay. The integrals run over the line of sight (l) and the observed sky region (Ω).
In this contribution, we describe in more detail MAGIC observations of the Perseus Cluster and the Segue 1 dSph, reporting the results achieved by MAGIC and by a joint analysis with six years Fermi-LAT dSphs data. Finally, we provide some information on the on-going analysis of data from the GC observational campaign.

2. Indirect Dark Matter searches with MAGIC

The MAGIC telescopes are located at the Roque de los Muchachos Observatory (28.8° N, 17.9° W; 2200 m above the sea level) in the Canary Island of La Palma (Spain). MAGIC is a system of two 17 m diameter telescopes able to detect Cherenkov light produced by the atmospheric showers initiated by cosmic particles entering the Earth atmosphere. The stereoscopic system is able to detect cosmic gamma rays in the very high energy (VHE) domain, i.e. in the range between ∼50 GeV and ∼50 TeV. Thanks to its large reflectors and high-quantum-efficiency and low-noise camera PMTs, MAGIC has reached a sensitivity of less than 0.7% of the Crab Nebula flux, for energies above ∼ 300 GeV in 50 hours of observations [5].
MAGIC is carrying on deep campaigns for DM indirect searches on several selected sky regions. To this end, optimized analysis tools for DM searches have been developed, such as the *full likelihood* analysis [6] based on the full exploitation of the spectral information of the recorded events for the computation of the constrains on DM models. Depending on a given model, the sensitivity gain achieved from the use of this approach is about a factor of two with respect to more conventional methods (e.g. [7]).
In fact assuming that DM properties are universal and do not depend on the observed target, the results from different sources can be combined through an overall likelihood function, providing more sensitive DM model constraints. In this respect, the *full likelihood* method allows a straightforward combination of independent results obtained from different targets and by different instruments.

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2.1. Dark Matter search in the Segue 1 dSph and combined analysis with Fermi-LAT dSphs observations

Among the known satellite galaxies of the MW, the ultra-faint galaxy Segue 1 shows most of the features that make dSphs one of the optimal objects to be observed for indirect DM searches. Indeed, Segue 1 is considered one of the most DM-dominated known systems with an estimated mass-to-light ratio of $\sim 3400 \frac{M_\odot}{L_\odot}$ [8]. It is a quasi-point-like source for MAGIC, although it is located at only ∼23 kpc, and is free of astrophysical gamma-ray sources.
Segue 1 was observed by MAGIC between January 2011 and February 2013 for a total time of 158 hours, which makes these observations the deepest exposure of any dSph by any Cherenkov telescope, so far. The analysis of observational data showed no significant gamma-ray excess above the background. Using the *full likelihood* analysis the 95% confidence level upper limits on the velocity-averaged annihilation cross section ($\langle\sigma v\rangle$) and lower limits on the DM particle lifetime were derived, assuming different annihilation and decay channels: quark-antiquark, lepton-antilepton and gauge bosons pairs [9]. For leptonic annihilation channels MAGIC achieved the strongest limits above a few hundreds GeV from any dSph observation, till now. Moreover the Segue 1 results were combined with those of 6-years Fermi-LAT observations of 15 dSphs processed with the latest (Pass 8) data analysis [10]. The joint analysis has allowed to achieve limits on the annihilation cross-section for DM particle masses between 10 GeV and 100 TeV, the widest range so far explored. In the intermediate mass range (from few hundred of GeV to few tens of TeV), where Fermi-LAT and MAGIC achieve similar sensitivities, the improvement of the combined result with respect to the individual ones reaches a factor of ∼2 [11]. The results achieved by MAGIC with the Segue 1 survey reached a remarkable reward with the inclusion, among other results concerning DM searches, in the Particle Data Group (PDG) [12] to constrain the parameter space of the neutralino particle, one of the most studied candidates in the Supersymmetric extension of the SM.

2.2. Dark Matter search in the Perseus Cluster

Galaxy Clusters are the most massive gravitationally bound systems known up to date in the Universe. This, with the fact that 80% of their mass is believed to be constituted of DM, makes them very promising objects of indirect searches. MAGIC has achieved the deepest observational campaign on any galaxy cluster so far performed in the VHE range of the electromagnetic spectrum, with a data taking of almost 300 hours of the Perseus Cluster, between 2009 and 2015. The interest in observing the Perseus Cluster is motivated by different research fields. This observational campaign allowed MAGIC to reach several results: the discovery and modeling of two radio-galaxies NGC 1275 [13] and IC 310 [14]; strong limits in cosmic-ray acceleratio, and hints in cosmic-ray acceleration mechanism close to black holes. Here, we present the preliminary results on DM decaying searches achieved with the Perseus Cluster observations.
During the 6-year observational campaigns, MAGIC has undergone through several hardware upgrades and, therefore, different data samples have to be analyzed using different instrumental response functions (IRFs, mainly effective area and energy migration tables). The analysis details will be addressed in the upcoming related publication (in preparation), where it will be shown how the correct IRFs for each period are computed. Also, for the first time a new tool has been developed that takes into account the expected spatial distribution of events DM originated coming from the source as an input for a correct calculation of each data period IRF. This is the first time that a dedicated DM optimization is applied in a MAGIC analysis, taking into account the inferred DM spatial distribution of the source. The preliminary results of the analysis reported here refers to a small sample of collected data (∼12 hours) and focus on the decaying DM scenario for particle masses between 100 GeV and 20 TeV [15]. The results have been achieved by a *full likelihood* approach taking advantage of morphological and spectral information of the DM source.

Perseus is a galaxy cluster located at 77.7 Mpc (z=0.0183) distance. Assuming, in the case of DM decay, a Navarro-Frank-White profile [16] for the DM density distribution ρ, 90% of the expected signal comes from a region of 1° around the center of the cluster. In order to properly evaluate the optimal integral region $\Delta\Omega$ in the Perseus Cluster J-factor computation, the aperture angle must be optimized considering also that the irreducible background from primary charged cosmic rays will also increase under larger solid angles. Therefore, we have optimized the signal region through a quality-factor (Q-factor) that is proportional (for a given integration radius) to the ratio between the expected number of gamma rays from DM decay and the square-root of the number of background events. In this way, the sensitivity for a given target is optimized by the value of aperture angle that maximizes Q.
We found no statistically relevant excess in the otimized region. By fixing a DM mass and a decay channel, we derived, from our null detection, lower limits on the DM decay lifetime using Eq. 1. For the decay channels we used the analytical computation based on PYTHIA by [17]. The limits have been computed for two pure decay channels: $b\bar{b}$ and $\tau^+\tau^-$, for several DM masses in the range from 160 GeV to 200 TeV. The limits achieved with a subset of 12.4 hours of Perseus Cluster data provide a lower limit on the DM decay lifetime of 10^{24} s at 100 GeV and 10^{26} s at 1 TeV. These results are ∼3 times better than those obtained with the Segue 1 campaign. The Perseus Cluster decay results are the strongest (even vs Fermi-LAT) above certain mass value.
These preliminary results confirm the clusters of galaxies as optimal targets for decaying DM indirect searches. This is due the typically high J-factor for decay DM in galaxy clusters with respect to those normally obtained for dSphs. It is foreseen that the MAGIC results achieved with the full ∼300 hours of Perseus Cluster data set will be the most stringent results obtained with any IACT for the DM decaying scenario.

2.3. DM search in the Galactic Center
The GC is believed to be the nearest strongly DM-dominated region to us [18]. Although the GC observability is not the most favourable one from the MAGIC site (the target culminates at ∼58° in zenith and, thus, the energy threshold for such observations is several hundreds of GeV), MAGIC collected data on the GC in order to contribute to understanding the gamma-ray emission from the center of the MW.
The on-going analysis to achieve limits to the DM content at the GC refers to the data taken from March 2013 to July 2014 for a total effective time of 28 hours, within a zenith range from 58° to 70°. Assuming an Einasto DM density profile we studied the gamma-ray emission from the GC above an energy threshold of 300 GeV. Upper limits to the DM self-annihilation cross-section for different annihilation channels are derived using optimized analysis methods for extended sources. The experience already achieved with the Perseus Cluster data analysis will be employed to try to disentangle this crowded region of high energy γ-rays emissions, in order to allow MAGIC to add a new piece in the puzzle of dark matter searches at the GC, and complete the results previously obtained with the H.E.S.S. telescopes above several TeV.

3. Conclusion and outlook
In this contribution we reported the results achieved by MAGIC in some DM search campaigns on galactic and extragalactic targets, namely the limits achieved in the thermally averaged DM annihilation cross section from Segue 1 data and the lower limits on the DM decay lifetime obtained with a subset of Perseus Cluster data. In the on-going analysis of Perseus Cluster and GC data a *full likelihood* method will be used to combine results taken under different experimental conditions (through the use of different IRFs). The results on DM searches in the GC and Perseus Cluster will be available in dedicated upcoming publications.
The analysis approach aimed at optimizing the discrimination of the expected DM signal

coming from annihilation/decay could be the basis of a global DM search that combines the observations of all gamma-ray instruments. In this respect, a partial but relevant result has been already reached by combining the results from MAGIC Segue 1 and Fermi-LAT 6-years dSphs observations.
Currently the MAGIC telescopes performances are better than ever and new results are continuously produced in VHE γ-ray astronomy topics. In the next future the MAGIC DM search program will continue on several selected targets aiming at a continuous study and development of specific optimized analysis tools for expected DM signal The program will look also toward a global DM search including results coming from different regions and different instrument.
MAGIC Collaboration has planned to operate the telescopes for the next years, before starting new generation of the Cherenkov Telescope Array observatory, concentrating the efforts on the most challenging searches. In particular, looking toward a global DM search, the results achievable by MAGIC could be included in a joint study involving different targets and γ-ray current and future instruments.

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