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Upper limits on the WIMP annihilation cross section from a joint analysis of dwarf spheroidal satellite galaxy observations with the MAGIC telescopes

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Dwarf spheroidal galaxies (dSphs) are among the best candidates to perform indirect searches for DM, having the highest known mass-to-light ratio and being free of astrophysical gamma-ray emitting sources. The Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes, located on the Canary Island of La Palma, have observed a fair amount of optimal dSphs in the recent years. This is the outcome of diversifying the observation strategy in order to avoid possible biases in target selection and to improve previous results. In this contribution we will report on new MAGIC results obtained from 52.1 hours of observation of the Draco dSph in 2018 and 49.5 hours of the Coma Berenices dSph in 2019. We will also present the results of a joint analysis of Draco and Coma Berenices dSphs with other dSphs observed by MAGIC so far. The selected dataset accounts for 354.4 hours of good quality data, resulting in one of the largest dSphs samples ever collected by an array of Cherenkov telescopes. This allows us to derive the most constraining limits from dSphs, among Cherenkov telescopes, on the WIMP annihilation cross section for different annihilation channels in the WIMP mass range 70 GeV to 100 TeV.

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1. Introduction

Dark Matter (DM) is assumed to be present in all the Universe and to be gravitationally bound in overdensity structures, the so-called *DM halos*. Following the hierarchical bottom-up structure formation scenario [1], these halos usually host astrophysical objects, such as galaxies or clusters of galaxies. The dwarf spheroidal galaxies (dSphs) satellite of the Milky Way are one of the best targets to perform indirect DM searches. These objects are almost free of conventional astrophysical background and are relatively close to us, orbiting our Galaxy.
Indirect DM searches with Imaging Atmospheric Cherenkov Telescopes (IACTs), such as the Florian Göebel Major Atmospheric Gamma Imaging Cherenkov (MAGIC) telescopes [2], select the objects to study on the basis of their DM content and vicinity to the Earth. These criteria make dSphs one of the targets most investigated, in particular in the case of searches for DM annihilation.
The Weakly Interacting Massive Particle (WIMP) [3] is the DM particle candidate preferred for IACTs searches, having a mass in the range 10 GeV to 100 TeV[4] and emitting gamma rays among the products of annihilation/decay. Thus, models of WIMP DM annihilation/decay and the DM distribution are the main ingredients taken into account when performing DM searches with IACTs.
The MAGIC telescopes are a system of two IACTs operating simultaneously, in the so-called *stereo mode*, placed in the Observatorio del Roque de los Muchachos, on the Canary Island of La Palma (Spain). Since their first light, they observed dSphs in search for a gamma-ray signal of WIMP DM annihilation, but no hint of DM has been found yet. In this proceeding, we present the data samples of the new targets observed by MAGIC in the multi-year dSphs diversification program and the results of the analysis of the single dSphs, followed by the results of the analysis of a combined data sample, in which dSphs previously observed by MAGIC are also included.

2. Dwarf spheroidal galaxies data samples

The new MAGIC multi-year dSphs observation diversification program aims to detect hints of DM signals from promising dSphs targets in the Northern Hemisphere, or, in case of no detection, to improve the current limits on the velocity-averaged cross-section of WIMPs. This is done by differentiating the targets and accumulating data, in order to have a larger data sample that permits to reduce the systematic uncertainties and improve the results.
For this purpose, the two dSphs Draco and Coma Berenices were observed in 2018 and 2019 for a total effective time of 52.1 h and 49.5 h respectively. The dSphs were selected after a ranking of the dSphs presented in [5], taking into account the DM content, its uncertainty, and their distance from us, excluding the dSphs previously observed by MAGIC.
The DM analysis has been performed independently for each data sample acquired, as described in Section 3. In addition, previously observed Segue 1 and Ursa Major II dSphs data samples have been combined to the new data, resulting in a total amount of 354.4 h of good quality data. The results of the analysis on this overall data sample, together with the other results, are presented in Section 4. In Table 1, the effective observation time of the dSphs included in the combined data sample is presented. The order in which the dSphs are listed follows the year of observation, from the oldest observation to the newest one.

Table 1: dSphs effective observation times (after data quality selection).

Target	T_{obs} [h]
Segue 1	157.9
Ursa Major II	94.8
Draco	52.1
Coma Berenices	49.5

3. DM likelihood analysis

When searching for a DM annihilation signal with IACTs, the measured quantity is the flux of gamma rays emitted by the target of interest. This flux can be written as the product of two terms, a particle physics (PP-) factor, containing the particle physics properties of the considered DM particle candidate, and an astrophysical (or J-) factor, containing information of the DM spatial distribution of the target:

$$\frac{d\Phi(\Delta\Omega)}{dE} = \frac{1}{4\pi}\frac{\langle\sigma_{\text{ann}}v\rangle}{2m_{\text{DM}}^2}\frac{dN}{dE} \times \int_{\Delta\Omega} d\Omega' \int_{\text{l.o.s.}} dl\,\rho^2(l,\Omega'). \tag{1}$$

On the right-hand-side of the equation, one can find the geometrical factor $\frac{1}{4\pi}$, the PP-factor, described by the velocity-averaged cross-section $\langle\sigma_{\text{ann}}v\rangle$, the DM mass m_{DM} and the gamma-ray spectrum $\frac{dN}{dE} = \sum_{i=1}^{n} \text{Br}_i \frac{dN_i}{dE}$ of n possible annihilation channels weighted by the corresponding branching ratios Br_i, and the J-factor, written as the integral over the solid angle $\Delta\Omega$ and the line-of-sight of the squared DM density ρ of the target.
In order to compute the velocity-averaged cross-section of a WIMP particle, after the standard data reduction achieved by the MAGIC analysis software MARS [6], a binned likelihood analysis is performed on the data. The likelihood function, per target t and pointing direction i, as a function of the dataset $\mathcal{D}$, is expressed as:

$$\begin{aligned}
&\mathcal{L}_{ti}(\langle\sigma_{\text{ann}}v\rangle; \boldsymbol{\nu}|\mathcal{D}) = \mathcal{L}(\langle\sigma_{\text{ann}}v\rangle; J_t, \{b_{tij}\}_{j=1,\dots,N_{\text{bins}}}, \tau_{ti}|(N_{\text{ON},tij}, N_{\text{OFF},tij})_{j=1,\dots,N_{\text{bins}}})\\
&= \prod_{j=1}^{N_{\text{bins}}}\left[\frac{(g_{tij}(\langle\sigma_{\text{ann}}v\rangle, J_t) + b_{tij})^{N_{\text{ON},tij}}}{N_{\text{ON},tij}!} e^{-(g_{tij}(\langle\sigma_{\text{ann}}v\rangle, J_t)+b_{tij})} \times \frac{(\tau_{ti}b_{tij})^{N_{\text{OFF},tij}}}{N_{\text{OFF},tij}!} e^{-\tau_{ti}b_{tij}}\right]\\
&\times \mathcal{T}(\tau_{ti}|\tau_{\text{obs},ti}, \sigma_{\tau,ti}) \times \mathcal{J}(J_t|\log_{10} J_{\text{obs},t}, \sigma_{\log_{10} J,t}),
\end{aligned} \tag{2}$$

where $\boldsymbol{\nu}$ is the set of nuisance parameters, J is the J-factor value, b is the expected number of background events, τ is the OFF/ON acceptance ratio, N_{ON} and N_{OFF} are the number of observed events in the ON region and the OFF region, respectively, and g the expected number of signal events.
The likelihood function is written as the product of a Poisson function for N_{ON}, one for N_{OFF}, a Gaussian function for the τ parameter (with mean value τ_{obs} and variance σ_τ^2) and a Gaussian function for the J parameter (with mean $\log_{10} J_{\text{obs}}$ and variance $\sigma^2_{\log_{10} J}$). All these functions are expressed in terms of j, that runs over the number of energy bins N_{bins}.
The flux of gamma rays, that is described as a function of the parameter of interest for the study

$\langle\sigma_{\text{ann}} v\rangle$, is included in the expression of g as follows:

$$g_j(\langle\sigma_{\text{ann}} v\rangle, J) = T_{\text{obs}} \int_{E'_{\text{min},j}}^{E'_{\text{max},j}} dE' \int_0^{\infty} dE \frac{d\phi(\langle\sigma_{\text{ann}} v\rangle, J)}{dE} A_{\text{eff}}(E) G(E'|E) \tag{3}$$

where T_{obs} is the effective observation time (as reported in Table 1), A_{eff} the collection area and $G(E'|E)$ the probability density function for an event to migrate from the true energy E to the estimated energy E'.
The likelihood analysis is implemented in the gLike tool [7] and cross-checked using the independent software package LklCom [8]. It has to be noticed that the entire analysis considers the spatial distribution of DM of each target and, thus, the respective gamma-ray emission distribution with respect to the center of the target. This has been done thanks to the use of the Donut Monte Carlo tool [9].

4. Results and discussion

The DM analyses performed on Draco and Coma Berenices dSphs did not show any evidence for gamma rays emitted from the targets. Consequently, we computed upper limits (UL) at the 95% CL on the velocity-averaged annihilation cross-section. The case of Segue 1 and Ursa Major II is similar, as presented in [9, 10].
A DM analysis was then performed on the combined data sample of 354.4 h. UL at the 95% CL have been set also in this case. Figure 1 shows the individual limits for the four dSphs and the limit obtained for the combined data set.
Even if the limits derived with the combined data sample are driven by the Segue 1 contribution, we stress that the weight of the systematic uncertainties related to the latter is reduced due to the

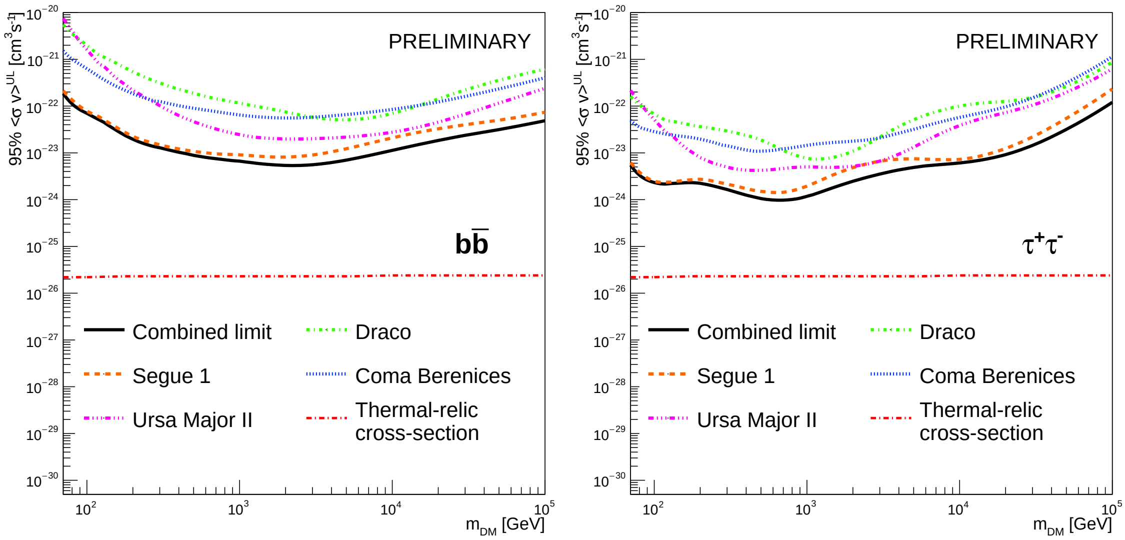

Figure 1: 95 % CL ULs on the WIMP velocity-averaged annihilation cross-sections for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels, for the single dSphs (Segue 1-orange, Ursa Major II-violet, Draco dSph- light green, Coma Berenices dSph-blue) and for the data combination (solid black line).

data combination.
The ULs presented are the most stringent ones within the MAGIC collaboration and very competitive with respect to other experiments, in particular in the TeV regime, such as Fermi-LAT, H.E.S.S., VERITAS and HAWC.

5. Conclusions

The MAGIC collaboration performed a multi-year observational diversification program to search for DM signals in dSphs, which are among the most promising targets for indirect DM searches. The program had the scope to diversify the dSph targets, in order to avoid possible biases in target selection, and accumulate dSphs data, allowing the improvement of previous results. For this reason, Draco dSph and Coma Berenices dSph were observed in 2018 and 2019, respectively. After the data analysis of both targets, no hint of DM signals were found and ULs at the 95% CL on the velocity-averaged annihilation cross-section of WIMPs were set. In a second step, the data of these two dSphs were combined to the data of previously observed Segue 1 and Ursa Major II dSphs. This has been done in order to mitigate the effects from target related systematic uncertainties and improve the UL values obtained per each DM mass. The limits computed by the combination of 354.4 h of good quality data are about a factor 2 more stringent than the previously published MAGIC results and are the most constraining among current Cherenkov telescopes in the WIMP mass range from 70 GeV to 100 TeV.

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