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Draco Observation with the MAGIC Telescope

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Abstract: The nearby dwarf spheroidal galaxy Draco with its high mass to light ratio is a promising target for indirect dark matter (DM) searches. It is located at a distance of about 82 kpc, at the edge of the Milky Way. The dwarf galaxy is enclosed by a DM halo where the DM particle may annihilate and produce an observable gamma-ray flux. Among the different DM particle candidates the lightest supersymmetric (SUSY) particle, the neutralino, is most favored. The neutralino annihilation produces mainly a continuous emission with a characteristic cut-off at the neutralino mass. Accelerator experiments provide a lower mass limit of 45 GeV, thus the cut-off is expected to be between 45 GeV and several TeV. We computed the DM annihilation flux from Draco for different SUSY models and DM halo profiles.
The MAGIC telescope at the Canary Islands has the lowest trigger threshold of all ground based VHE observatories and is therefore best suited to search for these signals.

Introduction

One of the main questions of cosmology is the nature of dark matter (DM). In 1933, Zwicky estimated the total mass needed to keep galaxy clusters together [1]. The visible mass was far too low to provide a sufficiently strong potential and a different kind of *dark* matter was claimed. Recent supporting experimental evidence for DM comes from Hubble-ACS [2]. Today, the total amount of DM can be estimated by using data from the cosmic microwave background [3], from large scale structure data, from data on the Lyman α absorption line and from the Big Bang nucleosynthesis. From this one can extract the different contribution Ω_i to the total energy density Ω_{tot} of the universe:

$$\Omega_{\text{tot}} = 1.02 \pm 0.02$$
$$\Omega_\Lambda = 0.73 \pm 0.04$$
$$\Omega_{\text{matter}} = \Omega_{\text{DM}} + \Omega_{\text{baryons}} = 0.27 \pm 0.04$$
$$\text{with } \Omega_{\text{DM}} = 0.23 \pm 0.04$$
$$\text{and } \Omega_{\text{baryons}} = 0.044 \pm 0.004$$

Ordinary matter (called *baryonic* matter) accounts for less than 5% of the universe. The vast majority is dark matter (Ω_{DM}=23%) and the dark energy (Ω_Λ=73%). DM itself could come as *cold* DM (consisting of non-relativistic particles) and *hot* DM (consisting of ultra-relativistic particles at the time of recombination). Today, hot DM is disfavoured by large scale structure formation to be the main participant to DM. For cold DM, so-called WIMPs (Weakly Interacting Massive Particles) are the favored candidates. Among those, the lightest neutralino (χ_1^0), a linear combination of the neutral superpartners of the W^3, B^0 and the neutral Higgs bosons in the SUSY framework, is the most studied candidate.

If the neutralino is the lightest supersymmetric particle (LSP) and R-parity is conserved then it must be stable. Nevertheless, it may annihilate with other neutralinos producing either a continuous γ spectrum mainly by hadronisation or the decay into a $\tau^+\tau^-$-pair. Also line emission is possible: $\chi_1^0\chi_1^0 \rightarrow$ Zγ or $\gamma\gamma$, even though it is loop suppressed. The continuous γ-spectra will be determined by SUSY parameters, while cosmological properties (i.e. DM distribution) will only provide a scaling factor.

The Draco Dwarf Galaxy

Draco is a dwarf spheroidal galaxy accompanying the Milky Way at a galactocentric distance of about 82 kpc. It is characterized by a high mass to light ratio: M/L $>$ 200. According to L. Mayer et al. [4] dwarf spheroidal galaxies are highly DM dominated as the initial gas content of these galaxies has been stripped away by a combination of ram pressure and tidal shocks, as the UV background heated the gas and it was only loosely bound to the core of the galaxy.

In general, the DM distribution of the halo of a spheroidal galaxy is modelled by a power law: $\rho_{\mathrm{DM}}(r) = Cr^{-\alpha}$, where the parameter $\alpha \geq 0$ describes the shape of the innermost DM distribution. The main models are the *cusp profile* for $\alpha \geq 1$ and the *core profile* with a central flat region where $\alpha = 0$. All models with $\alpha > 0$ demand a small core of constant density, because the annihilation rate cannot be greater than the infall of other particles to the central annihilation region [5]. Whether Draco is affected by tidal stripping or not is the topic of an ongoing debate and for example discussed in [6, 7, 8, 9]. For the outermost parts of the halo, here an exponential cut-off is assumed to be appropiate for Draco [10]:

$$\rho_{\mathrm{DM}} = Cr^{-\alpha} \exp\left(-\frac{r}{r_b}\right)$$

with the following values for the different profiles:

profile	C	$r_b (kpc)$	α
cusp	$3.1 \times 10^7\, M_\odot\, \mathrm{kpc}^{-2}$	1.189	1
core	$3.6 \times 10^8\, M_\odot\, \mathrm{kpc}^{-3}$	0.238	0

Table 1: The different parameters cusp and core DM density profile considered

Expected γ-Ray Flux From Neutralino Self-Annihilation

The expected γ-ray flux above an energy E_0 is calculated by:

$$\begin{aligned}\Phi_\gamma(E>E_0) = & \frac{N_\gamma(E>E_0)\langle\sigma v\rangle}{8\pi m_\chi^2} \times \\ \times \frac{1}{\Delta\Omega}\int_{\Delta\Omega} B(\Omega)\, d\Omega \times & \int_{\mathrm{los}} \rho^2\left(\Omega, \Psi, s\right)\, ds\end{aligned} \tag{1}$$

where

$\rho(r)$	DM density profile derived for Draco
N_γ	photon yield per annihilation with $E > E_0$
m_χ	neutralino mass
$\langle\sigma v\rangle$	thermally averaged annihilation cross-section
$\Delta\Omega$	solid angle for MAGIC angular resolution
$B(\Omega)$	Point Spread Function (PSF) of the telescope
Ψ	Pointing angle. Ψ=0 corresponds to center of Draco.
los	the line of sight.

The factor

$$J(\Psi) = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} B(\Omega)\, d\Omega \int_{\mathrm{los}} \rho^2\left(\Omega, \Psi, s\right)\, ds,$$

which denotes the integration of ρ^2 along the line of sight smeared out with the point spread function of the telescope, is shown in figure 1 for the cusp and the core profile. When pointing directly to the center of Draco the two models cannot be distinguished.

Models with a relic neutralino density smaller than the measurements of WMAP [3], meaning models with $\Omega_\chi h^2 < 0.094$[1], need to be rescaled since particles other than neutralinos could contribute to cold DM additionally:

$$\rho = \rho_{\mathrm{tot}} \times \left(\frac{\Omega_\chi h^2}{\Omega_{\mathrm{WMAP}}}\right) \tag{2}$$

1. $h = 0.7$

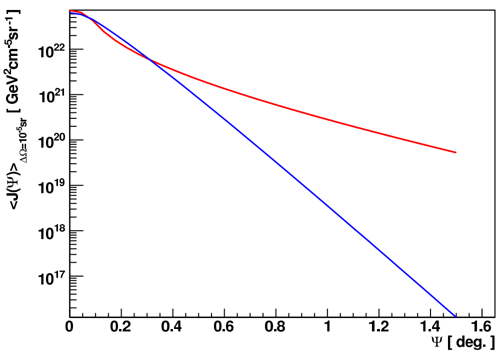

Figure 1: The factor $J(\Psi)$ for the cusp (red) and the core (blue) profile. See text for further explanations.

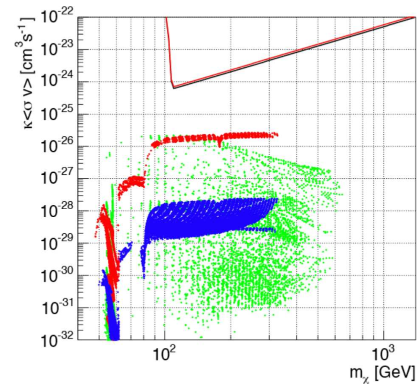

Figure 2: The thermally averaged Neutralino annihilation cross section for different mSUGRA models. The red and the black line denote the sensitivity curve of the MAGIC telescope for a cuspy and a core DM density profile.

With the numbers given in table 1 the integral over DM density squared reaches values of about $6 \cdot 10^{22}\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$. The gamma yield per annihilation N_γ ranges between 10^{-4} and 1 for an assumed energy threshold of 100 GeV. We simulated within the mSUGRA framework [11, 12, 13, 14] models in the following natural region: $\tan\beta < 50$, $m_0 < 6\,\mathrm{TeV}$, $m_{1/2} < 4\,\mathrm{TeV}$, $-4\,\mathrm{TeV} < A_0 < 4\,\mathrm{TeV}$ and $\mu = +1$. For these models, the annihilation into $\tau^+\tau^-$ produces most of the photons. All models accounting for the WMAP boundary ($0.094 < \Omega_\chi h^2 < 0.13$) of the relic density lead to χ_1^0 masses from 45 GeV up to 700 GeV, approximately.

The thermally averaged cross-section $< \sigma v >$ used in the formula 1 reaches values of $3 \cdot 10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$, if the limits on the relic density given by WMAP are respected. In figure 2 the values for $\kappa\,\langle\sigma v\rangle$, where κ is the normalization factor in equation 2, are plotted for different mSUGRA models. Also included is the sensitivity curve of the MAGIC telescope.

Observation

Among all the Imaging Air Cherenkov Telescopes (IACT) MAGIC is the largest single dish facility in operation (see e.g., [15, 16] for a detailed description). The observatory is located on the Canary Island La Palma (28.8°N, 17.8°W, 2200 m a.s.l.), the 17-m diameter tessellated reflector of the telescope consists of 964 0.5 $\times$ 0.5 m^2 diamond-milled aluminium mirrors, mounted on a light weight frame of carbon fiber reinforced plastic tubes. The Cherenkov light produced by high energetic particles hitting the atmosphere within a field-of-view of $3.5°$ is reflected and focussed on the MAGIC camera. It consists of 576 enhanced quantum efficiency photomultiplier (PMT), from where the analog signals are transported via optical fibers to the trigger electronics and are read out by a 2GSamples/s FADC system. The trigger region of the camera has a diameter of $2.0°$, which results in a trigger collection area of about $10^5\,\mathrm{m}^2$ for γ-rays at small zenith angles (ZA). The collection area is even larger for higher ZA but so is the trigger threshold. At La Palma, Draco culminates at about $30°$ ZA. As this dwarf spheroidal galaxy is located well above the galactic plane no stars brighter than 11^{th} magnitude are found in its vicinity.

With 6.7 hours of observations performed in 2007, a preliminary 2σ upper flux limit on steady emission from the direction of Draco of $1.1 \cdot 10^{-11}\,\mathrm{photons\,cm}^{-2}\,\mathrm{sec}^{-1}$ for photon energies above $160\,\mathrm{GeV}$ was found.

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