SAGITTARIUS DWARF GALAXY OBSERVATIONS BY H.E.S.S.: SEARCH FOR A DARK MATTER SIGNAL

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Abstract. The Sagittarius Dwarf spheroidal galaxy has been observed in June 2006 with the H.E.S.S. array of Imaging Atmospheric Cherenkov Telescopes. The dwarf spheroidal galaxies are one of the most promising targets for the search for a WIMP annihilation signal with high energy gamma rays in final state. Eleven hours of high quality data were analysed after selections and modelling of the Sagittarius Dwarf halo profile following to the latest set of its structural parameters. The data allowed to put constraints on the velocity-weighted annihilation cross section in Supersymmetric and Kaluza-Klein scenarii.

1 Introduction

The observations of the rotation curves in spiral galaxies and the velocity dispersion in elliptical ones, the X-ray emission and peculiar velocities of galaxies in the clusters of galaxies, the gravitational arcs, all these observations establish the existence of cosmological dark matter (DM). The present cosmological paradigm postulates that approximately 20% of the overall mass-energy budget of the Universe is composed of non-luminous and non-baryonic matter. On the galatic scales, it constitutes 90% of the gravitationnal mass, for which the microscopic nature remains one of the major mysteries in physics. This DM is usually assumed to be composed of stable, massive, collisionless particles. Weakly-interacting massive particles (WIMPs), with masses of few 100 GeV and velocity-weighted cross sections $\sim 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$, are preferred candidates for this cold dark matter (CDM), since they freeze-out with the appropriate thermal abundance in the early Universe. Such WIMPs are predicted by models of particle physics (Bertone et al. 2005).

Two CDM candidates, deriving from two differents theories, are privileged: the lightest neutralino $\tilde{\chi}$ provided by R-parity conserving, a supersymmetric extension of the Standard Models (Jungman et al. 1996) and the lightest Kaluza-Klein particle (LKP) (Servant & Tait 2003) for the extra dimension theories, which is most often the first KK mode of the hypercharge gauge boson, $\tilde{B}^{(1)}$. In both cases, a continuum of γ from WIMPs annihilations, with a spectrum shape different from an astrophysical source is expected. For MSSM models it is due to hadronization and decay of the cascading annihilation products, predominantly neutral pion (π^0) generated in quark and bosonic jets, whereas in KK scenarii, $\tilde{B}^{(1)}$ preferentially annihilate in charged leptons which radiatively produce VHE γ.

The H.E.S.S. array of Imaging Atmospheric Cherenkov Telescopes (IACTs), designed for high sensitivity in the 100 GeV - 10 TeV energy regime, is a suitable experiment to detect VHE γ-rays and investigate their possible origin.

2 CDM targets for indirect detection

The limited field of view of IACTs and their present sensitivity allow for a search for CDM particles in specific classes of objects. As the γ-ray flux produced by WIMPs annihilation is proportional to the DM density and inversely proportional to the squared distance which separates the source from the observer, IACT experiments should look at close regions of space where large concentration of WIMPs are expected. In these conditions, the most promising target is the Galactic Center (GC) which contains most of DM. However, other standard sources

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may produce VHE γ-rays, like the supernova remnant Sgr A East, are also present in this region. Though the possibility that a part of the VHE γ-ray signal comes from WIMPs annihilation can not be excluded. The particle mass required to match the data is unlikely high (Aharonian et al. 2006a). Other objects, like galaxy cluster, which present also a very high density of CDM, are interesting targets. M87, the Virgo cluster, has also been the subject of advanced work. But the flux measured by H.E.S.S. (Aharonian et al. 2006b), is considerably higher than the one predicted from WIMPs annihilations only. In that case again, a DM component in the VHE γ-ray signal can not be excluded.

The spheroidal dwarf galaxies (dSph) are another kind of targets for the CDM search through indirect gamma detection, probably the most promising. They are indeed objects widely dominated by CDM, as discussed in (Wilkinson et al. 2005), which shows that the range of DM amount lies between 10 and 100 times the luminous mass for this kind of object. In addition, contrary to the GC, astrophysical background is low there, since they contain poor amounts of stellar gas and dust. At last, as the observed flux is proportionnal to the distance from the source, we must highlight here that at least 4 dSph are present in the 100 kpc around the GC.

Sagittarius dSph has been discovered quite recently, in 1994 (Ibata et al. 1995), due to its position, behind the GC. Nevertheless, as it is situated on the edge of the galactic plane, we expect low background contamination from the diffuse emission revealed by H.E.S.S. (Aharonian et al. 2006c). Sgr dSph is a nucleated dSph, which spatial position (l=5.6°, b=-14.0°) coincides with the globular cluster M54. The mass to luminosity ratio, proof of CDM presence, is quite high, since it rises to around 50 in the external part of the galaxy. The luminous density profile of Sgr dSph, obtained in (Monaco et al. 2006), shows two components. The first one of a radius of 1.6 kpc is well adjusted by a King profile. The second is a compact one, a “cuspy” profile of 1.5 pc of radius. It is in this region where we expect to observe a signal from DM annihilation. Due to the distance of Sgr dSph, the size of the signal region is smaller than the *point spread function* (PSF) of H.E.S.S. and will be considered as point-like in this analysis.

3 H.E.S.S. observations of Sagittarius dwarf spheroidal galaxy (Sgr dSph)

H.E.S.S. (High Energy Stereoscopic System) is an array of 4 Imaging Cherenkov Telescopes located in Namibia at an altitude of 1800m above sea-level. The great surface of collection, 107 m^2 for each telescope, in association with the stereoscopic technic of reconstruction and the fine pixellisation of the cameras (960 PMTs per camera) confer to H.E.S.S. unequaled performances in the VHE range of the gamma astronomy. The total field of view of H.E.S.S. is 5°, allowing so far to study extended sources. The stereoscopic measurement allows improvement of the reconstruction of the incoming direction and energy of the primary gamma. This also leads to an excellent rejection of the hadronic background due to charged cosmic rays. The energy threshold of the experiment is now 160 GeV at zenith=0.

The γ-rays data obtained with H.E.S.S. on the Sgr dSph galaxy consist in 25 runs which go through the selection criteria described in (Aharonian et al. 2006d). It corresponds to 11 hours of good quality observations, done in June 2006. During this period, the zenithal angle range of observations have varying from 7 to 43°, with an average value of 19°.

After the calibrations of the raw showers obtained with the PMTs signals, 2 event reconstructions procedures have been used. The first one is based on the intrinsic parameters caracterising the gamma showers, which are known as Hillas moments (Aharonian et al. 2005). The second one, referred hereafter as “Model Analysis”, is based on a pixel-by-pixel comparison of the shower image with a template generated by a semi-analytical shower parametrization (de Naurois et al. 2003). For this analysis, the separation between gamma candidates and hadrons is done using a combination of the Hillas moments and a Model goodness-of-fit parameter, obtained via a minimisation of a likelihood function. The typical order of magnitude for the energy resolution obtained with both analyses is around 15%. An additionnal cut on the primary interaction depth is used to improve the background rejection.

In both cases, no signal was found at the nominal position of the Sgr dSph or in the field of view of the camera, as we can see in figure 1. This is confirmed by figure 2 which presents the θ^2 distribution of the observed γ-ray events relative to the target position.

These results lead to upper limit on the number of gamma that can have been emitted by the Sgr dSph. A 95 % confidence level (CL) upper limit of $N_\gamma^{95\% C.L.} = 56\ \gamma$ has been derived, using the Feldman and Cousins method (Feldman & Cousins 1998).

With this result and knowing the effective area of H.E.S.S. for the used configuration, we have been able to

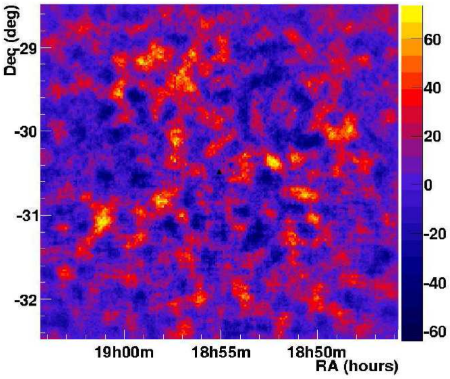

Fig. 1. Sky map of the γ-ray candidates with an oversampling radius of 0.14°. No excess is observed at the target position (RA = 18h54m40s, Dec = -30d27m05s) in equatorial coordinates (J2000) marked with a black triangle. Other spots in the field of view are not significant.

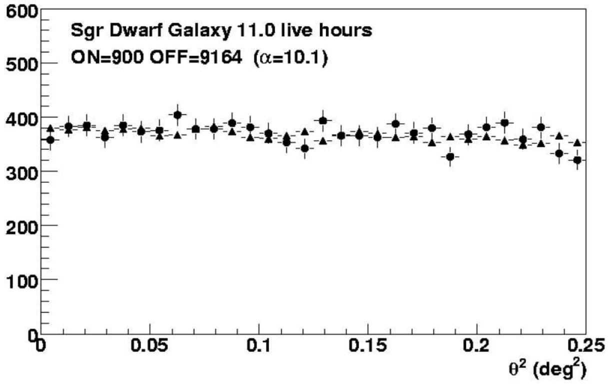

Fig. 2. θ^2 radial distribution of the ON and OFF events for γ-ray like events from the target position (RA = 18h54m40s, Dec = -30d27m05s) (black filled circles). Estimated background calculated as explained in the text is shown (black crosses). No excess is seen at small θ^2 value.

compute a 95 % CL flux limit:

$$\Phi_\gamma(E_\gamma > 250 \text{ GeV}) < 3.6 \times 10^{-12} cm^{-2} s^{-1} (95\% \text{ CL}).$$

4 γ-rays predictions for CDM annihilation

The formula that gives the γ-ray flux prediction for the annihilation of WIMPs can be expressed as the product of two terms. The first term is the particle physic model, whereas the second one is the astrophysical term which relies on the DM density profile of the source.

$$\frac{d\Phi}{dE}(\Delta\Omega, E) = \frac{1}{4\pi} \frac{<\sigma v>}{{m_{DM}}^2} \frac{dN_\gamma}{dE_\gamma} \times \bar{J}(\Delta\Omega)\Delta\Omega \tag{4.1}$$

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In the astrophysical term, J is the integral along the line of sight ($l.o.s$) of the squared density of the DM distribution in the object and $\bar{J}$ is its averaged over the solid angle of the integrated region, which is $\Delta\Omega = 2 \times 10^{-5}$ sr for H.E.S.S.:

$$\bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} PSF * \int_{l.o.s} \rho^2(r[s]) ds d\Omega \tag{4.2}$$

Two different modelisation of the dark matter halo of the Sgr dSph have been considered. The first one, is a cuspy Navarro Frenck White (NFW) model, (Navarro et al. 1997). In this model, the density of dark matter is given by the following equation:

$$\rho_{NFW}(r) = \frac{A}{r(r + r_s)^2} \tag{4.3}$$

where A is a factor of normalisation and r_s is the scale radius. The value of those parameters which appeared in table 5 have been derived from those used for Draco in (Evans et al. 2004).

The other type of halo considered to describe Sgr dSph is a core model, as discuss in (Evans et al. 2004).

$$\rho_{core}(r) = \frac{v_a^2}{4\pi G} \frac{3r_c^2 + r^2}{(r_c^2 + r^2)^2} \tag{4.4}$$

where v_a is the radial scale velocity and r_c is the core radius. In this case, these values were obtained by resolving the Jean's equation with the most recent values of the luminosity profile of Sgr dSph core, assuming the following form:

$$\nu(r) = \frac{\nu_0 r_c^{2\alpha}}{(r_c^2 + r^2)^\alpha} \tag{4.5}$$

From the data of (Monaco et al. 2006), the estimated values of those parameters are: $\alpha = 2.69 \pm 0.10$ and $r_c = 1.5$ pc. This r_c value is only an upper limit. Assuming a velocity dispersion independant from the position and taking the value given in (Zaggia et al. 2004) of the central velocity dispersion of Sgr dSph $\sigma = 8.2 \pm 0.3$ km s^{-1}, we find a value of $v_a = \sqrt{\alpha}\sigma = 13.4$ km s^{-1}. As the determined region of this core profile is very small, the value of $\bar{J}$, calculated via the equation 4.2, is very large as reported in table 5. The last column of this table indicates the amount of expected signal in the region of integration of the solid angle of H.E.S.S..

With the result on number of γ obtained in the previous section, we can compute constraints on the velocity-weighted cross section of DM annihilation. Indeed, from equation 4.1, we find the following relation:

$$< \sigma v >_{min}^{95\%CL} = \frac{4\pi}{T_{obs}} \frac{m_{DM}^2}{\bar{J}(\Delta\Omega)\Delta\Omega} \frac{N_\gamma^{95\%CL}}{\int_0^{m_{DM}} A_{eff}(E_\gamma)\frac{dN}{dE_\gamma}dE_\gamma} \tag{4.6}$$

where T_{obs} is the observation time of the source and A_{eff} is the effective area.

Depending on the considered distribution of the CDM in the halo of Sgr dSph, the constraints have been calculated and compared to the predictions for phenomenological MSSM (pMSSM) models provided by the DarkSUSY4.1 program (Gondolo et al. 2004) as shown in figure 3. Here, the grey points correspond to randomly generated models of the pMSSM space parameters described in table 5. The blue points are those satisfaying WMAP constraints on the CDM relic density. As shown in figure 3, 11 hours of observations cannot constraints any pMSSM model in case of a NFW cuspy profile (green line), whereas some models, corresponding to large cross-sections, are exluded for a core profile (red line). The same exercise can be reproduced in case of KK models, for which the LKP is the hypercharge boson $\tilde{B}^{(1)}$. In this case, the differential γ spectrum is parametrized using Pythia simulations and branching ratios from (Servant & Tait 2003). The $< \sigma v >$ predictions are preformed using the formula given in (Baltz & Hooper 2005). For KK models, $< \sigma v >$ depends analytically on the mass of the WIMP, as shown in figure 4. As previously discussed, given the large value of $\bar{J}$ in the case of a core profile, some KK models compatible with WMAP observations can be excluded whereas in case of NFW halo profile, no exclusions can be done.

5 Conclusion

The observations of Sgr dSph galaxy with H.E.S.S. reveal no significant γ-rays excess at the nominal target position. The halo of the Sgr dSph has been modeled using the latest data of its structure parameters allowing to put constrains on the velocity-weighted annihilation cross section of the CDM particle in the framework of the supersymmetric and Kaluza-Klein models.

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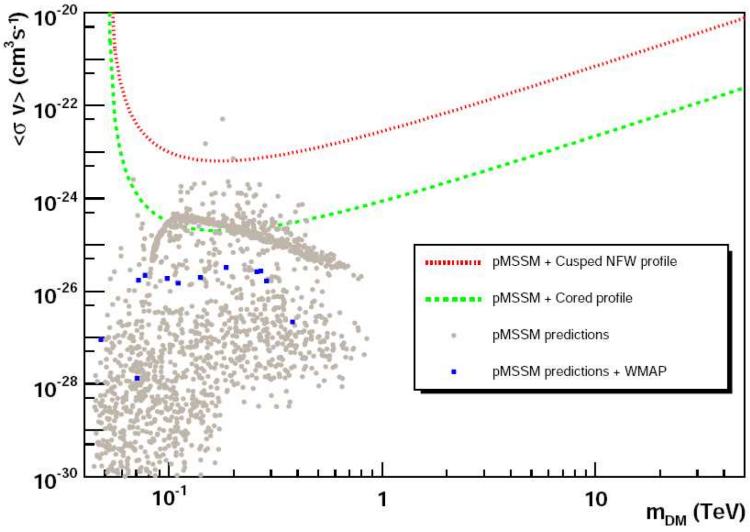

Fig. 3. Upper limits at 95% C.L. on $< \sigma v >$ versus the DM particle mass in the case of a cusped NFW (red dotted line) and a cored (green dashed line) DM halo profiles respectively. The pMSSM parameter space was explored with DarkSUSY 4.1 (Gondolo et al. 2004), each point on the plot correponsding to a specific model (grey point). Amongst these models, those satisfaying in addition the WMAP constraints on the CDM relic density are overlaid as blue square. The limits in case of neutralino dark matter from pMSSM are derived using the parametrisation from reference (Bergström et al. 1998) for a higgsino type neutralino annihilation γ profiles.

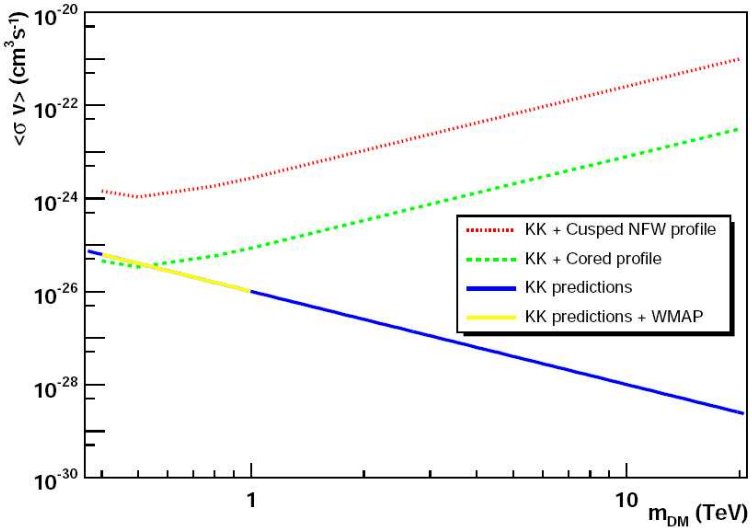

Fig. 4. Upper limits at 95% C.L. on $< \sigma v >$ versus the DM particle mass in the $\tilde{B}^{(1)}$ Kaluza-Klein scenarii for a cusped NFW (red dotted line) and a cored (green dashed line) DM halo profiles respectively. The blue line corresponds to Kaluza-Klein models (Servant & Tait 2003). Overlaid (yelow line) are the KK models satisfaying WMAP constraints on the CDM relic density.

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Halo type	Parameters	$\bar{J}$ ($10^{24}\mathrm{GeV}^2\mathrm{cm}^{-5}$)	Fraction of signal in $\Delta\Omega = 2\times10^{-5}$ sr
Cusped NFW halo	$r_s = 0.2$ kpc A = 3.3 $\times 10^7 M\odot$	2.2	93.6%
Cored halo	$r_c = 1.5$ pc $v_a = 13.4$ km s^{-1}	75.0	99.9%

Table 1. Structural parameters for a cusped NFW (r_s, A) and a cored (r_c, v_a) DM halo model, respectively. The values of the solid-angle-averaged l.o.s integrated squared DM distribution are reported in both cases for the solid angle region $\Delta\Omega = 2\times10^{-5}$ sr.

pMSSM parameter space region
100 GeV $\leq \mu \leq$ 30 TeV
100 GeV $\leq M_2 \leq$ 50 TeV
50 GeV $\leq M_A \leq$ 10 TeV
100 GeV $\leq m_0 \leq$ 1 TeV
-3 $\leq A_t \leq$ 3
-3 $\leq A_b \leq$ 3
1.2 $\leq tan\beta \leq$ 60

Table 2. Region of the pMSSM parameter space randomly scanned to generate the models. A set of free parameters in the considered ranges corresponds to a pMSSM model.

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