

Indirect dark matter searches with H.E.S.S.

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Abstract. The annihilations of WIMPs produce high energy gamma-rays in the final state. These high energy gamma-rays may be detected by IACTs such as the H.E.S.S. array of Imaging Atmospheric Cherenkov telescopes. Besides the popular targets such as the Galactic Center or galaxy clusters such as VIRGO, dwarf spheroidal galaxies are privileged targets for Dark Matter annihilation signal searches. H.E.S.S. observations on the Sagittarius dwarf galaxy are presented. The modelling of the Dark Matter halo profile of Sagittarius dwarf is discussed. Constraints on the velocity-weighted cross section of Dark Matter particles are derived in the framework of Supersymmetric and Kaluza-Klein models. The future of H.E.S.S. will be briefly discussed.

PACS. 98.70.Rz Gamma-rays : observations – 95.35.+d Dark Matter

1 Introduction

H.E.S.S. (High Energy Stereoscopic System) is an array of four Imaging Atmospheric Cherenkov Telescopes (IACTs) located in the Khomas Highlands of Namibia at an altitude of 1800 m above sea level. Each telescope has an optical reflector of 107 m² composed of 382 round mirrors [1]. The Cherenkov light is emitted by charged particles from electromagnetic showers initiated by the interaction of the primary gamma-rays in the Earth's upper atmosphere. The light is collected by the reflector which focuses it on a camera made of 960 fast photomultiplier tubes (PMTs) with individual field of view of 0.16° in diameter [2]. Each PMT is equipped with a Winston cone to maximize the light collection and limit the background light. The total field of view of the H.E.S.S. instrument is 5° in diameter. The stereoscopic technique allows for an accurate reconstruction of the direction and energy of the primary gamma-rays as well as for an efficient rejection of the background induced by cosmic ray interactions. The energy threshold is about 100 GeV at zenith and the angular resolution is better than 0.1° per gamma-ray. The point source sensitivity is $2 \times 10^{-13} \text{cm}^{-2} \text{s}^{-1}$ above 1 TeV for a 5σ detection in 25 hours [3].

The H.E.S.S. instrument is designed to detect very high energy (VHE) gamma-rays in the 100 GeV - 100 TeV energy regime and investigate their possible origin. Scenarios beyond the Standard Model of particle physics predict plausible WIMP (weakly interacting massive particle) candidates to account for the Cold Dark Matter. Among these are the minimal supersymmetric extension of the Standard Model (MSSM) or universal extra dimension (UED) theories. With R-parity conservation, SUSY models predict the lightest

SUSY particle (LSP) to be stable. In various SUSY breaking scenarios, the LSP is the lightest neutralino $\tilde{\chi}$. In Kaluza-Klein (KK) models with KK-parity conservation, the lightest KK particle (LKP) is stable [4], the most promising being the first KK mode of the hypercharge gauge boson, $\tilde{B}^{(1)}$. The annihilation of WIMPs in galactic halos may produce gamma-ray signals detectable with Cherenkov telescopes (for a review, see [5]). Generally, their annihilations will lead to a continuum of gamma-rays with energy up to the WIMP mass resulting from the hadronization and decay of the cascading products, mainly from π^0 's generated in the quark jets. The gamma-ray flux from DM particle annihilations of mass m_{DM} in a spherical halo can be expressed as:

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi} \frac{\langle\sigma v\rangle}{m_{DM}^2} \frac{dN_\gamma}{dE_\gamma} \times \bar{J}\Delta\Omega \quad (1)$$

which is a product of a particle physics term containing the velocity-weighted cross section $\langle\sigma v\rangle$ and the differential gamma-ray spectrum dN_γ/dE_γ , and an astrophysics term \bar{J} given by:

$$\bar{J} = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{l.o.s} \rho^2 ds \quad (2)$$

This term corresponds to the line-of-sight-integrated squared density of the DM distribution which is averaged over the solid angle integration region spanned by the H.E.S.S. point spread function (PSF).

Plausible astrophysical targets have been proposed to search for DM, from local galactic objects to extragalactic objects such as galaxy clusters. This paper reports on three recent results on targets relevant to indirect dark matter search: the Galactic Center, the center of the VIRGO cluster (M87) and the Sagittarius dwarf spheroidal galaxy.

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2 The Galactic Center

H.E.S.S. observations towards the Galactic Center have revealed in 2004 a bright point-like gamma-ray source, HESS J1745-290 [6], coincident in position with the supermassive black hole Sgr A*, with a size lower than 15 pc. Diffuse emission along the Galactic plane has also been detected [7] and correlates well with the mass density of molecular clouds from the Central Molecular Zone, as traced by CS emission [8]. According to recent detailed studies [9], the source position is located at an angular distance of $7.3'' \pm 8.7''$ (stat.) $\pm 8.5''$ (syst.) from Sgr A*. The pointing accuracy allows to discard the association of the VHE emission with the center of the radio emission of the supernovae remnant Sgr A East but the association with the pulsar wind nebula G359.95-0.04 can not be ruled out.

From 2004 data set, the energy spectrum of the source is well fitted in the energy range 160 GeV - 30 TeV to a power-law spectrum $dN/dE \propto E^{-\Gamma}$ with a spectral index $\Gamma = 2.25 \pm 0.04$ (stat.) ± 0.1 (syst.). No deviation from a power-law is observed leading to an upper limit on the energy cut-off of 9 TeV (95% C.L.). The VHE emission from HESS J1745-290 does not show any significant periodicity or variability from 10 minutes to 1 year [10].

Besides plausible astrophysical origins (see e.g. [11] and references therein), an alternative explanation is the annihilation of DM in the central cusp of our Galaxy [12]. The spectrum of HESS J1745-290 shows no indication for gamma-ray lines. The observed γ -ray flux may result from secondaries of DM annihilation such as $b\bar{b}$, etc. When $E^2 d\Phi/dE$ is plotted as a function of the γ -ray energy E_γ , the WIMP annihilation is characterized by a plateau for E_γ much lower than the WIMP mass m_{DM} . A rapid decrease is observed when $E_\gamma \sim m_{DM}$. The spectrum extends up to masses of

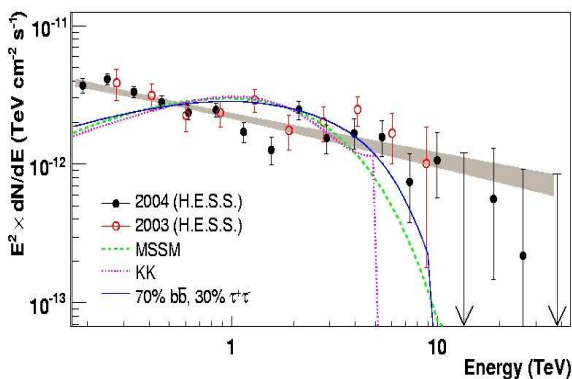


Fig. 1. Spectral energy density $E^2 \times dN/dE$ of γ -rays from HESS J1745-290 for 2003 (red empty circles) and 2004 (black filled circles) datasets of the H.E.S.S. observation of the Galactic Center. The shaded area shows the best power-law fit to the 2004 data points. The spectra expected from the annihilation of a MSSM-like 14 TeV neutralino (dashed green line), a 5 TeV KK DM particle (dotted pink line) and a 10 TeV DM particle annihilating into 70% $b\bar{b}$ and 30% $\tau^+\tau^-$ in final state (solid blue line) are presented.

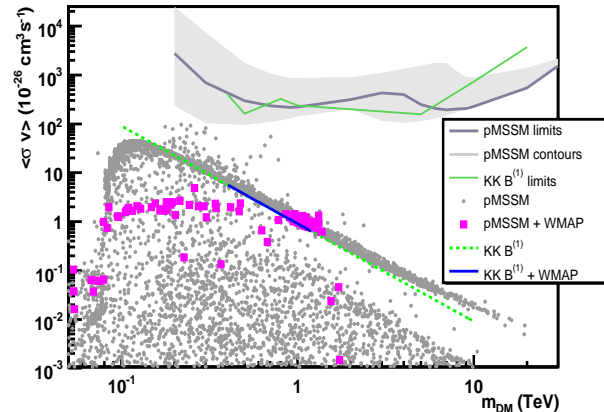


Fig. 2. Exclusion limit for the Galactic Center on $\langle\sigma v\rangle$ versus the WIMP mass for a NFW profile. The limits are derived from H.E.S.S. data in the case of pMSSM and KK dark matter models. The predictions for pMSSM (grey points) and KK (green dashed line) models are plotted. Those satisfying in addition the WMAP constraints on the relic cold dark matter density are superimposed for pMSSM (pink boxes) and KK (blue solid segment) models.

about 10 TeV which requires large neutralino masses (>10 TeV). They are unnatural in phenomenological MSSM scenarios. The Kaluza-Klein models provide harder spectra which still significantly deviate from the measured one. Non minimal version of the MSSM may yield flatter spectrum with mixed 70% $b\bar{b}$ and 30% $\tau^+\tau^-$ final states [13]. Even this scenario does not fit to the measured spectrum. The hypothesis that the spectrum measured by H.E.S.S. originates only from DM particle annihilations is highly disfavored. The observed signal may be produced by the superposition of a DM annihilation signal and a power-law astrophysical background spectrum. In this case, using a NFW profile, constraints on the velocity-weighted annihilation cross-section $\langle\sigma v\rangle$ can be derived. Fig. 2 shows the 99% confidence level limits on $\langle\sigma v\rangle$ from H.E.S.S. data in the case of pMSSM and KK DM models. Predictions from pMSSM models calculated with DarkSUSY4.1 [14] and KK models from [4] are shown as well as those satisfying cosmological constraints. The limits on $\langle\sigma v\rangle$ derived from H.E.S.S. data for both DM models are $\mathcal{O}(10^{-24})\text{cm}^3\text{s}^{-1}$. With a NFW profile, no $\langle\sigma v\rangle$ from SUSY or KK DM models can be ruled out.

3 The VIRGO galaxy cluster

Astrophysical systems such as the VIRGO galaxy cluster [15] have also been considered as targets for DM annihilations. The elliptical galaxy M87 at the center of the VIRGO cluster has been observed by H.E.S.S. It is an active galaxy located at 16.3 Mpc which hosts a black hole of $3.2 \times 10^9 M_\odot$. From 2003 to 2006, H.E.S.S. detected a 13σ signal in 89 hour observation time at a

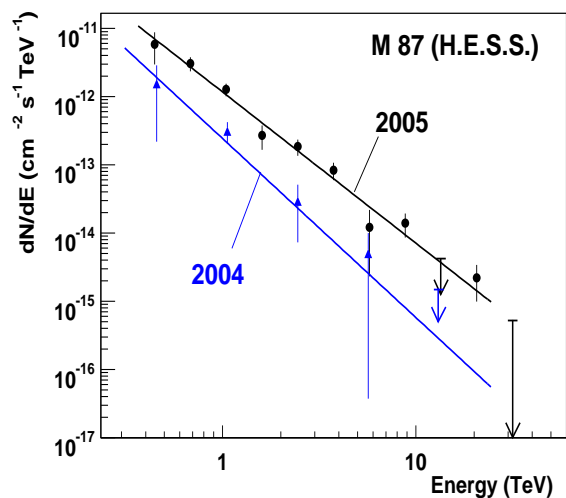


Fig. 3. Differential energy spectrum of M87 from ~ 400 GeV up to 10 TeV from 2004 and 2005 data. Corresponding fits to a power-law function $dN/dE \propto E^{-\Gamma}$ are plotted as solid lines. The data exhibit indices of $\Gamma = 2.62 \pm 0.35$ for 2004 and $\Gamma = 2.22 \pm 0.15$ for 2005.

location compatible with the nominal position of the nucleus of M87 [16]. With the angular resolution of H.E.S.S., the VHE source is point-like, with an upper limit on the size of $3'$ at 99% confidence level. Given the distance of M87, this corresponds to a size of 13.7 kpc.

Fig. 3 shows the energy spectrum for 2004 and 2005 data. Both data sets are well fitted to a power-law spectrum with spectral indices $\Gamma = 2.62 \pm 0.35$ (2004) and $\Gamma = 2.22 \pm 0.25$ (2005). The 2005 average flux is found to be higher by a factor ~ 5 the the average flux of 2004. The integrated flux above 730 GeV shows a yearly variability at the level of 3.2σ [16]. Variability at the day time scale has been observed in the 2005 data at the level of 4σ . This fast variability puts stringent constraints on the size of the VHE emission region. The position centered on M87 nucleus excludes the center of the VIRGO cluster and outer radio regions of M87 as the gamma-ray emission region. The observed variability at the scale of ~ 2 days requires a compact emission region below $50 R_s$ where $R_s \sim 10^{-15}$ cm is the Schwarzschild radius of the M87 supermassive black hole [16].

The short and long term temporal variability observed with H.E.S.S. excludes the bulk of the TeV gamma-ray signal to be of DM origin.

4 The Sagittarius dwarf spheroidal galaxy

Nearby dwarf spheroidal galaxies are known to be among the best targets to search for DM signals, considered as the most extreme DM-dominated environments. Unlike the Galactic Center, those galaxies are expected to have reduced astrophysical backgrounds. The Sagittarius (Sgr) dwarf galaxy is a Galaxy satellite of the Local Group. It was recently discovered [17] in the di-

rection of the Galactic Center. The center of Sgr is located at 24 kpc from the Sun. The visible mass profile is difficult to measure because of the contamination of foreground galactic stars. The central velocity dispersion has been measured by various groups [18]. Sagittarius dwarf has been observed in 2006 by H.E.S.S. with an averaged zenith angle of 19° . A total of 11 hours of high quality data is available after standard selection cuts. The target position is chosen at the location of the Sgr luminous cusp, coincident with the center of the globular cluster M54 [19]. The pointing position is thus (RA = $18^{\text{h}}55^{\text{m}}59.9\text{s}$, Dec = $-30^{\circ}28'59.9''$) in equatorial coordinates (J2000.0). The annihilation signal from Sgr is expected to come from a region of 1.5 pc, thus much smaller than the H.E.S.S. PSF so that a point-like signal has been searched for. No significant gamma-ray excess is detected at the nominal target position. We thus derived an upper limit at 95% C.L. on the observed number of gamma-rays using the Feldman & Cousins method [20]. A 95% confidence level upper limit on the gamma-ray flux is also derived :

$$\Phi_\gamma(E_\gamma > 250\text{GeV}) < 3.6 \times 10^{-12} \text{cm}^{-2}\text{s}^{-1} \quad (3)$$

assuming a power-law spectrum of spectral index $\Gamma = 2.2$. In order to constraint on the velocity-weighted annihilation cross section, a modelling of the Sgr DM halo has been carried out. Dynamic models have been studied in [21]. Two plausible models of the mass distribution of the DM halo have been studied: a NFW profile used as a reference model and a cored isothermal profile. For the NFW profile, the structure parameters are extracted from [21]. In case of the cored model, the velocity dispersion is assumed to be independent of the position and equal to the central velocity dispersion $\sigma = 8.2 \pm 0.3 \text{km s}^{-1}$ as reported in [18]. The velocity dispersion tensor is taken isotropic as in [21]. The mass density profile of stars is extracted from [19]. The cored profile has a small core radius due to a cusp in the luminous profile. The value of \bar{J} is found to be larger for the cored profile than for the NFW profile [22].

Fig. 4 presents the constraints on the velocity-weighted annihilation cross section in the case of a cored (green dashed line) and cusped NFW (red dotted line) profiles in the solid angle integration region $\Delta\Omega = 2 \times 10^{-5}\text{sr}$. Predictions for phenomenological MSSM (pMSSM) models are displayed (grey points) as well as those fulfilling in addition the WMAP constraints on the CDM relic density (blue points). The pMSSM models are calculated with DarkSUSY4.1 [14]. In the case of a cusped NFW profile, the H.E.S.S. observations do not set severe constraints on the velocity-weighted cross section. For a cored profile, due to a higher central density, stronger constraints are derived and some pMSSM models can be excluded in the upper part of the pMSSM scanned region. In the case of KK dark matter, the differential gamma-ray spectrum is parametrized using Pythia [23] simulations and branching ratios from [4]. Predictions for the velocity-weighted annihilation cross section of $B^{(1)}$ dark matter particle are performed using the formula given in [24]. In this case, the ex-

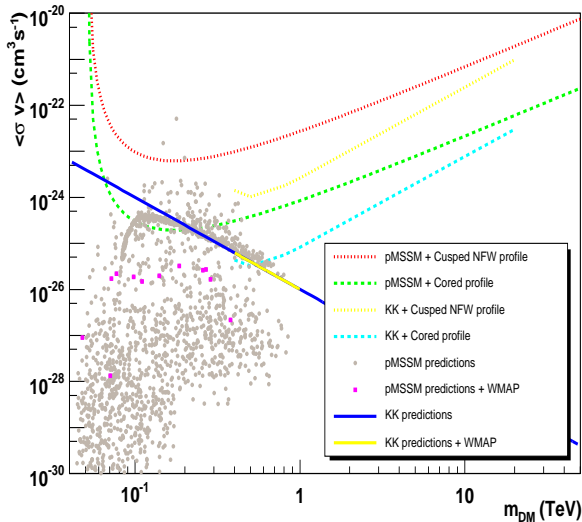


Fig. 4. Upper limits at 95% C.L. on $\langle\sigma v\rangle$ versus the dark matter particle mass in the case of a NFW and cored DM halo profile for the Sagittarius dwarf galaxy. The limits are derived from H.E.S.S. data in the case of pMSSM and KK dark matter models. The predictions in pMSSM and KK models are also plotted with in addition those satisfying in addition the WMAP constraints on the relic cold dark matter density.

pression for $\langle\sigma v\rangle$ depends analytically on the $B^{(1)}$ mass square. The KK models are also shown (solid blue line) as well as those satisfying the WMAP constraint on the cold dark matter density (solid yellow line). The sensitivity of H.E.S.S. in the case of Kaluza-Klein models where the hypercharge boson $B^{(1)}$ is the LKP, is also displayed on Fig. 4 for a cored (light blue solid line) and a cusped NFW (yellow solid line) profile respectively using the value of \bar{J} computed in section 3.2. With a NFW profile, no Kaluza-Klein models can be tested. In the case of a cored profile, some models providing a LKP relic density compatible with WMAP constraints can be excluded. From the sensitivity of H.E.S.S., we exclude $B^{(1)}$ masses lying in the range 300 - 500 GeV.

5 Conclusion

The H.E.S.S. collaboration has studied potential targets for DM annihilations. The TeV γ -ray energy spectrum measured by H.E.S.S. in the Galactic Center region is unlikely to be interpreted in terms of WIMP annihilations. Constraints on the velocity-weighted annihilation cross-section have been derived in the case of a NFW DM halo profile. Neither pMSSM nor KK models can be ruled out. The detection of a temporal variability of the VHE signal from the M87 nucleus in the VIRGO galaxy cluster excludes the bulk of the gamma-ray signal to come from DM annihilations. H.E.S.S. observed the Sagittarius dwarf spheroidal galaxy and no significant gamma-ray excess has been detected.

Two DM halo modellings of Sgr have been investigated to derive constraints on the velocity-weighted annihilation cross-section. Some models can be ruled out in the case of a cored profile.

Dark matter searches will continue and searches with H.E.S.S. 2 will start in 2009. The phase 2 will consist of a new large 28 m diameter telescope located at the center of the existing array. With the availability of the large central telescope H.E.S.S. 2, the analysis energy threshold will be lowered down to less than 80 GeV and will allow to explore more supersymmetric models.

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