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Dark matter annihilation as possible origin of the very high energy γ-radiation from the Galactic center measured by H.E.S.S.

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The H.E.S.S. Cherenkov telescope system has detected a steady and spatially extended signal of very high energy γ-radiation from the direction of the Galactic center. In this contribution we assume that this radiation originates either partially or entirely from the annihilation of dark matter particles. We present constrains on their mass, density profile and annihilation cross section under these two different assumptions.

1. Introduction

The rotational curves of spiral galaxies, including ours, yielded the first indication that most of the matter present is not directly visible. Model calculations about the primordial nucleosynthesis show that only 4% ($\Omega_{\rm B} = 0.04$) of the critical density of the universe is composed of baryonic matter, whereas the recent measurements of the cosmic microwave background fluctuations with WMAP [1] indicate a matter density of $\Omega_{\rm M} = 0.27$. The R-parity conserving supersymmetric and supergravitational extension (mSUGRA) of the standard model of elementary particle physics provides a candidate for dark matter particles: the lightest supersymmetric particle called neutralino χ. Another possible candidate is predicted by Kaluza Klein (KK) theories, the $B^{(1)}$ [2]. Both particles ($\chi, B^{(1)}$) are neutral, stable, and could naturally match the measured matter density. Besides direct measurements of dark matter in underground experiments, indirect detections via measurement of the secondary particles produced in the copious self-annihilation in deep gravitational potential wells has been suggested. One product of the self-annihilation of dark matter particles is high energy γ-radiation. Regions of high mass accumulations such as the Galactic center (GC) could produce a detectable very high energy (VHE) γ-ray flux [3]. In this paper we discuss the results of the observations of the GC with the H.E.S.S. Cherenkov telescope array [4] in 2003 and 2004 in terms of a dark matter annihilation signal.

2. γ-rays from dark matter annihilation

Since the neutralino and the $B^{(1)}$ are Majorana particles, they can annihilate producing photons with energies up to the particle masses. As the dark matter particles are neutral the direct productions of photons are loop processes with low probability, leading to monoenergetic γ-rays. The detection of such a γ-ray line would be a direct proof of dark matter annihilation and provide direct measurement of the particle mass. However, most of the high energy photons are produced in decays of secondaries from the annihilation processes. These photons have a continuous energy spectrum up to the mass of the dark matter particle and are not easily distinguished from other production channels for VHE γ-rays. The calculation of the γ-ray flux leads to the formula

$$\Phi(E) = 2.8 \cdot 10^{-10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \cdot \frac{dN_\gamma}{dE}\Big(\frac{\langle\sigma v\rangle}{\mathrm{pb}\,c}\Big)\Big(\frac{100\,\mathrm{GeV}}{m_{\chi,\,B^{(1)}}}\Big)^2 \bar{J}(\Delta\Omega)\Delta\Omega \qquad (1)$$

where $\langle\sigma v\rangle$ denotes the mean of the annihilation cross section multiplied with the velocity of the particles and dN_γ/dE the energy spectrum per annihilation. The factor $\bar{J}(\Delta\Omega)\Delta\Omega$ is the integral of the squared dark matter density ϱ^2 over the line of sight (los) and the considered solid angle matching usually the detector resolution

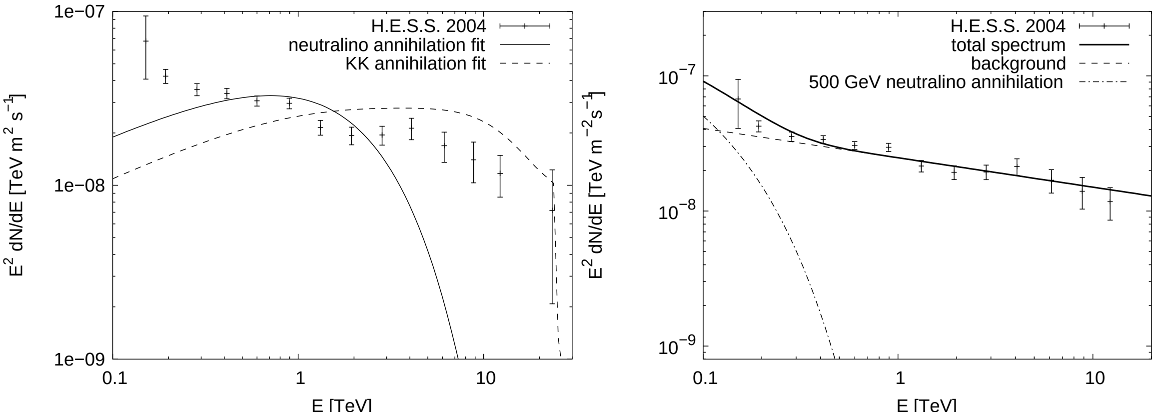

Figure 1. Left: Spectral energy distribution of the γ-radiation from Sgr A* as measured by H.E.S.S. together with fits of annihilation radiation only (hypothesis 1). The used neutralino annihilation spectrum is from [9] and the KK annihilation spectrum from [10]. For the $B^{(1)}$ such high masses are lager than anticipated. Right: Again the measured Sgr A* spectral energy distribution together with a power law plus an annihilation spectrum of a $500\,\mathrm{GeV}$ neutralino (hypothesis 2).

$\Delta\Omega$.

$$\bar{J}(\Delta\Omega)\Delta\Omega = \frac{1}{(0.3\,\mathrm{GeV/cm^3})^2 \cdot 8.5\,\mathrm{kpc}} \cdot \int d\Omega \int_{\mathrm{los}} dl\ \varrho^2 \qquad (2)$$

3. The center of our Galaxy

In N-body simulations of galaxy formation it is predicted that the central regions of galaxies contain large amounts of dark matter. However, the spatial resolution of the simulations is limited and potentially important dark matter enhancing processes are not considered [5]. The central region of our Galaxy is as a result of its proximity ($\approx$ 8 kpc) a target for the indirect search for dark matter. The factor $\bar{J}(\Delta\Omega)\Delta\Omega$ depends strongly on the largely unknown density profile. We consider here the results of simulations from Navarro, Frenk and White (NFW) predicting $\rho(r) \propto r^{-1}$ [6] and Moore et al. predicting $\rho(r) \propto r^{-1.5}$ [7]. Besides there are other possible VHE γ-radiation sources in the central region of our Galaxy.

The GC region containing the supermassive black hole Sgr A*, was observed with the H.E.S.S. telescopes in 2003 and 2004 and high energy γ-radiation above $200\,\mathrm{GeV}$ was detected without indications for variability. [8].

In the following, two different assumptions are used to derive conclusions on dark matter annihilation from the observed signal:

1. The flux results solely from dark matter annihilation as discussed in [9] and [10] exploring the consistency of the required mass density and cross section with other observations.
2. Only a part of the signal originates from dark matter annihilation, whereas the remaining part is produced by other processes and sources.

With hypothesis 1 we can derive mass and cross section of the the dark matter particle and the density profile of the dark matter halo in the central region of our Galaxy. With hypothesis 2 we can either constrain particle properties assuming a density profile or the factor $\bar{J}(\Delta\Omega)\Delta\Omega$ assuming in turn a range of cross sections.

3.1 Hypothesis 1: 100 % dark matter annihilation radiation

Density profile: The density profile of the dark matter in the inner part of the halo can be approximated by $\varrho \sim r^{-\alpha}$. Instead of the integration over the solid angle $\Delta\Omega$ in equation 1 we convolute the line of sight

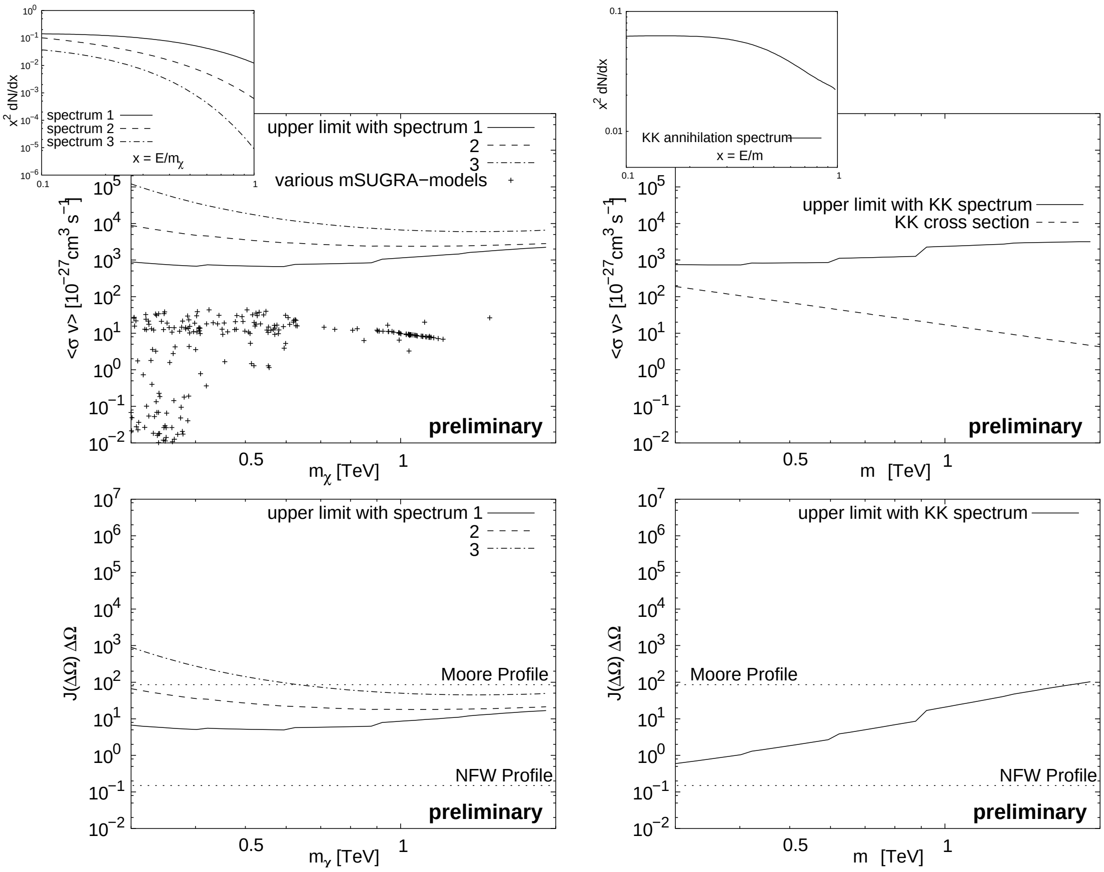

Figure 2. Upper limits on the cross section assuming an NFW profile (top) and on $\bar{J}(\Delta\Omega)\Delta\Omega$ assuming a cross section (bottom) for neutralinos (left) and KK particles (right). The small pictures show the used photon spectral energy distribution per annihilation. In mSUGRA the number of photons per annihilation depends on the used parameter set. Three spectra (power law with exponential cutoff) are used. The mSUGRA model cross sections are calculated with DarkSUSY 4.1 [13]. The KK annihilation spectrum and its cross section is described in [10].

integral with the point spread function of the detector (the H.E.S.S. experiment) [9]. The result is the expected luminosity profile of the dark matter halo as seen by the detector. The best fit is obtained with $\alpha = 1.01 \pm 0.02$, which is similar to the profile suggested by NFW.

Energy spectrum: The energy spectrum measured by H.E.S.S. reaches up to more than $10\,\mathrm{TeV}$. This would require a very massive dark matter particle close to the unitarity limit [11]. The favored mass range of the dark matter particles is below $1\,\mathrm{TeV}$ [12] in the considered models, but such high masses, not violating the unitarity limit, cannot be ruled out completely.

In Figure 1 (left) the spectral energy distribution measured by H.E.S.S. is shown together with fits of a neutralino annihilation spectrum parameterized according to [9] and a $B^{(1)}$ annihilation spectrum from [10]. Clearly, the expected curvature of the predicted energy spectra is not matching the data which is in reasonable agreement with a power law type function.

3.2 Hypothesis 2: Background and dark matter annihilation radiation

In GC region other processes may produce γ-radiation above $100\,\mathrm{GeV}$. This may result in a background to a hypothetical annihilation radiation. In Figure 1 (right) the measured spectral energy distribution is drawn together with an example of a power law background plus an annihilation spectrum of a $500\,\mathrm{GeV}$ neutralino. The background spectrum is assumed a priori to follow a power law. The strength of the annihilation radiation (equation 1) for a given particle mass $m_{\chi,\,B^{(1)}}$ is proportional to $A = \langle\sigma v\rangle \cdot J(\Delta\Omega)\Delta\Omega$. Fitting the assumed background plus the fixed annihilation component we get a function $\chi^2(A)$, which provides the upper limits on A. With this limits we can produce upper limits either on the cross section $\langle\sigma v\rangle$ of the annihilation by assuming a density profile or on $\bar{J}(\Delta\Omega)\Delta\Omega$ with a fixed cross section. In Figure 2 these upper limits are shown as function of the particle mass for neutralino dark matter and for KK dark matter. With an NFW profile no cross section neither from supersymmetric models (calculated with DarkSUSY 4.1 [13]) nor with KK dark matter can be ruled out. With a mean cross section for neutralinos or the expected cross section for KK particles a profile suggested by Moore can be ruled out for all considered neutralino masses.

4. Conclusion

We have investigated if part or all of the high energy radiation from the GC observed by H.E.S.S. could be attributed to dark matter annihilation. While the observed luminosity profile is consistent with the expectations from an NFW profile, the energy spectrum can't be reconciled by either a neutralino annihilation spectrum or with a spectrum produced by KK dark matter. Considering an additional background we can exclude a high line of sight integral of the squared density. For an NFW profile no model, neither mSUGRA nor KK dark matter, can be ruled out. Further studies are in progress [14].

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