The γ-radiation from the Galactic center observed by H.E.S.S. and the possible dark matter interpretation

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Abstract: With the H.E.S.S. system of four Cherenkov telescopes a signal of very high energy γ-radiation from the direction of the Galactic center has been detected. The interpretation of the signal due to dark matter annihilation is discussed and limits on the annihilation cross sections and density profiles are given. This is an update including recent observations of the Galactic center region with H.E.S.S.

Introduction

The nature of the dark matter particles is still one of the outstanding problems of astrophysikcs. A possible candidate for a dark matter particle is provided by the R-parity conserving supersymmetric extension of the standard model of particle physikcs e.g. the neutraline χ. Another possible candidate is predicted by Kaluza Klein (KK) theories, the $B^{(1)}$ [1]. Both particles 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 [2]. With the H.E.S.S. Cherenkov telescope array [3] the galactic center has been observed in 2003 and 2004 [4]. High energy γ-radiation has been observed with high significance. This radiation has been investigated in the framework of dark matter annihilation [5, 6, 7].

γ-rays from dark matter annihilation

Since the χ and the $B^{(1)}$ are Majorana particles, they can annihilate producing photons with energies up to the particle masses. Whereas the direct production of photons leading to monoenergetic γ-rays are loop suppressed most of the high energy photons are produced in decays of secondarys 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 astrophysical processes for VHE γ-rays. The calculation of the γ-ray flux leads to the formula

$$
\begin{aligned}
\Phi(E) &= 2.8 \cdot 10^{-10}\,\mathrm{cm}^{-2}\mathrm{s}^{-1} \\
&\quad \times \frac{dN_\gamma}{dE}\left(\frac{\langle\sigma v\rangle}{\mathrm{pb\,c}}\right)\left(\frac{100\,\mathrm{GeV}}{m_{\chi,\mathrm{B}^{(1)}}}\right)^2 \\
&\quad \times \bar{J}(\Delta\Omega)\Delta\Omega \\
\bar{J}(\Delta\Omega)\Delta\Omega &= \frac{1}{(0.3\,\mathrm{GeV/cm^3})^2 \cdot 8.5\,\mathrm{kpc}} \\
&\quad \times \int d\Omega \int_{\mathrm{los}} dl\, \varrho^2 \qquad (1)
\end{aligned}
$$

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 photon energy spectrum

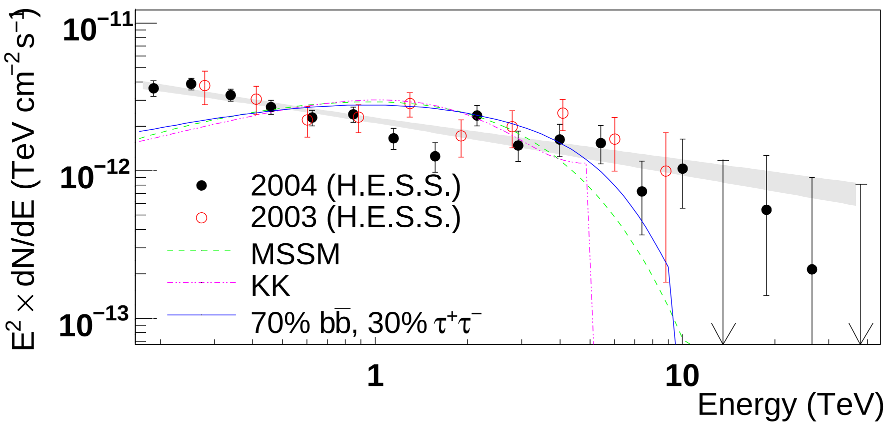

Figure 1: (Color online) Spectral energy density $E^2 \times \mathrm{d}N/\mathrm{d}E$ of γ-rays from the GC source, for the 2004 data (full points) and 2003 data [8] (open points). Upper limits are 95% CL. The shaded area shows the power-law fit $\mathrm{d}N/\mathrm{d}E \sim E^{-\Gamma}$. The dashed line illustrates a typical spectrum of neutralino DM annihilation for best fit neutralino masses of 14 TeV. The dotted line shows the distribution predicted for KK DM with a mass of 5 TeV. The solid line gives the spectrum of a 10 TeV DM particle annihilating into $\tau^+\tau^-$ (30%) and $b\bar{b}$ (70%).

per annihilation. The solid angle $\Delta\Omega$ denotes the resolution of the detector or the investigated solid angle. ρ denotes the dark matter density along the line of sight (los).

The center of our Galaxy

The GC region containing the supermassive black hole Sgr A*, was observed with the H.E.S.S. telescopes in the years 2003 and 2004. High energy γ-radiation above $200\,\mathrm{GeV}$ was detected with a significance of 37.9 standard deviations (in 2004) without indications for variability. Further data have been collected in 2005 and 2006 not yet included in this analysis.

The central region of our Galaxy is due to its proximity ($\approx\ 8.5$ kpc) and the expectation of high mass concentration a target for the indirect search for dark matter. The scaling factor $\bar{J}(\Delta\Omega)\Delta\Omega$ depends strongly on the not well known density profile. We consider the results of N-body-simulations from Navarro, Frenk and White (NFW) predicting $\rho(r)\ \propto\ r^{-1}$ [9] and Moore et al. predicting $\rho(r) \propto r^{-1.5}$ [10].

The measured spectrum can be described by a powerlaw

$$\Phi(E) = \Phi_0 \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-\Gamma} \qquad (2)$$

with an index of $\Gamma = 2.25 \pm 0.04_{\mathrm{stat}} \pm 0.10_{\mathrm{syst}}$. The integral flux above 1 TeV is $(1.87 \pm 0.10_{\mathrm{stat}} \pm 0.30_{\mathrm{syst}}) \cdot 10^{-12}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

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

1. The flux results solely from dark matter annihilation as discussed in [5] and [11] exploring the consistency of the required mass density and cross section with other observations. This hypothesis explores the mass and cross section of the dark matter particle and the density profile of the dark matter halo in the central region of our Galaxy.

2. Only a part of the signal originates from dark matter annihilation, whereas the remaining part is produced by other processes and sources. This hypothesis can constrain either particle properties assuming a density profile of the factor $\bar{J}(\Delta\Omega)\Delta\Omega$ assuming in turn a range of cross sectons.

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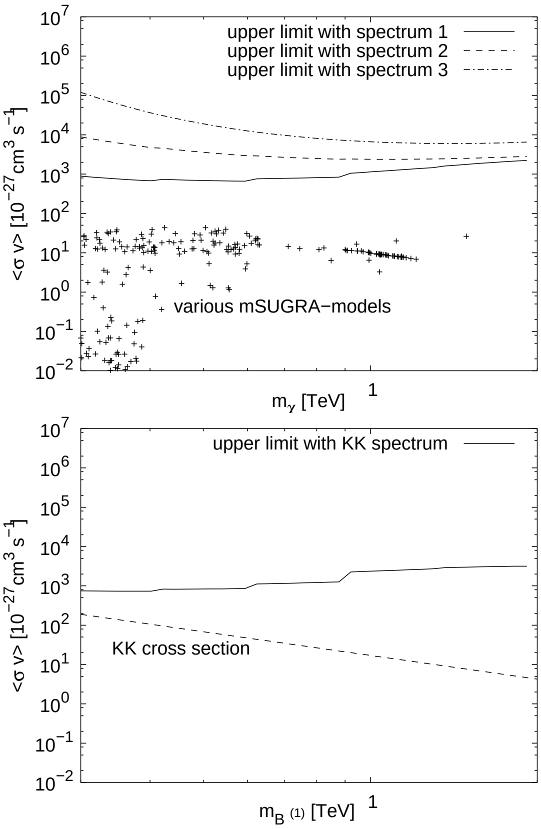

Figure 2: Upper limits (99% CL) on the annihilation cross section for neutralinos (upper panel) and KK particle (lower panel) as function of the dark matter particle mass.

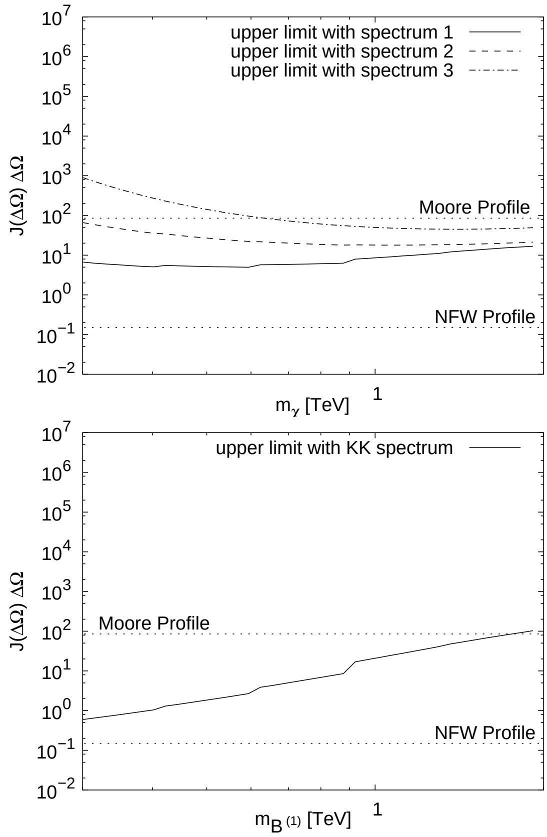

Figure 3: Upper limits on $\bar{J}(\Delta\Omega)\Delta\Omega$ assuming a cross section for neutralinos (upper panel) and KK particles (lower panel) as function of the dark matter particle mass.

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 integral with the point spread function of the detector (the H.E.S.S. experiment). In the Galactic center region are molecular clouds which lead to a diffuse radiation of γ-radiation [12] which has been substracted for this investigation. The remaining signal from the Galactic Center is compatible with a point source. For α a lower limit of 1.2 with a confidence level of 95% was derived [7]. This is not compatible with an NFW profile, but to a Moore profile.

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 [13]. The favored mass range of the dark matter particles is below $1\,\mathrm{TeV}$ [14] in the considered models, but such high masses, not violating the unitarity limit, cannot be ruled out completely.

In Figure 1 the spectral energy distribution measured by H.E.S.S. is shown together with fits of a neutralino annihilation spectrum parameterized according to [5] and a $B^{(1)}$ annihilation spectrum from [11]. 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. With nonminimal SUSY models flatter spectra can be obtained, but they also don't fit the measured spectrum well, too. Hypothesis 1 can therefore be ruled out.

Hypothesis 2: Background and dark matter annihilation radiation

In the GC region other processes may produce γ-radiation above $100\,\mathrm{GeV}$. This may result in a γ-ray background to a hypothetical annihilation. The strength of the annihilation radiation (equation 1) for a given particle mass $m_{\chi,\mathrm{B}^{(1)}}$ is proportional to $A = \langle\sigma v\rangle \cdot J(\Delta\Omega)\Delta\Omega$. Fitting the assumed background (a power law) 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 the figures 2 and 3 these upper limits are shown as functions of the particle mass for neutralino dark matter and for KK dark matter. In the supersymmetric scenario the number of photons per annihilation depends on the parameter set used. Three spectra which are encompassing all probabilities are used. The mSUGRA model cross sections are calculated with DarkSUSY 4.1 [15]. The KK annihilation spectrum and its cross section is described in [11]. With an NFW profile no cross section neither from supersymmetric models (calculated with DarkSUSY 4.1 [15]) 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.

Conclusion

We have investigated wether part or all of the high energy γ-radiation from the GC observed by H.E.S.S. could be attributed to dark matter annihilation. The energy spectrum can't be reconciled by either a neutralino annihilation spectrum or with a spectrum produced by KK dark matter only. Considering an additional background we can exclude a large line of sight integral of the squared density. For an NFW profile still no model, neither mSUGRA nor KK dark matter, can be ruled out.

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