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Is the unidentified TeV γ-ray source HESS J1303-631 a dark matter clump?

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Abstract: The H.E.S.S. collaboration found several so far unidentified TeV γ-ray sources without any known counterpart in other wavelengths. One of the best studied (as well as the first one discovered by H.E.S.S.) is HESS J1303-631 which was serendipitiously found in the same field of view of the initially observed binary system PSR B1259-63 / SS 2883. The possibility that HESS J1303-631 is a nearby (< 1 kpc) clump of dark matter is investigated based on its morphological and spectral properties.

Introduction

Using cosmological N-body simulations [1] the observed large-scale structure of galaxy clusters in the universe is best reproduced by a large fraction of cold dark matter (CDM), i.e. particles moving with velocities $v \ll c$ and not interacting electromagnetically with other matter. The simulations result however in a more complex substructure in the halos of galaxies than observed (i.e. in globular clusters). This can be described by a clumpy density structure of the dark matter (DM), referred to as DM clumps. The neutralino χ [2] and the Kaluza-Klein particle $\mathrm{B}^{(1)}$ [3] are discussed as possible candidates of DM particles. Depending on the type of the DM particles, a detectable γ-ray flux possibly up to GeV/TeV energies can be expected by annihilation processes, making a dark matter clump visible (mainly) at very high energies.

The possible interpretation of the unidentified TeV γ-ray source HESS J1303-631 as a dark matter clump is investigated in this paper based on its energy spectrum and angular emission profile.

The unidentified GeV/TeV γ-ray source HESS J1303-631

The H.E.S.S. collaboration operates an array of four Cherenkov telescopes [4] located in Namibia. The telescopes measure cosmic γ-rays in the energy range between $100\,\mathrm{GeV}$ and several $10\,\mathrm{TeV}$ by recording the Cherenkov light emitted from an air shower which develops when a particle (hadron or photon) enters the Earth's atmosphere. The stereoscopic observation together with a corresponding hardware trigger assures that an air shower is recorded by at least two of the four telescopes, allowing for an angular and energy resolution per event of $\delta\Theta < 0.1^\circ$ and $\Delta E/E \leq 15\%$, respectively, as well as an improved cosmic ray (CR) background suppression.

The TeV γ-ray source HESS J1303-631 was discovered serendipitously close to the galactic plane with a statistical significance of more than $30\,\sigma$ [5, 6] in the field of view of the initially observed binary system PSR B1259-63 (which was also detected). The data were taken in 2004 and 2005. An intrinsic extension of the emission region of HESS J1303-631 of $\sigma_{\mathrm{J1303,intr}} = (0.16 \pm 0.02)^\circ$ was found. The energy spectrum can be described by a power-law and the integral photon flux Φ_γ above an energy of $380\,\mathrm{GeV}$ was calculated to be $\Phi_\gamma = 1.3 \cdot 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. No temporal variations of the integral photon flux were found in the data.

A counterpart of HESS J1303-631 at other wavelengths (i.e. radio oder X-rays) could not be identified at the corresponding sky position of the TeV γ-ray excess, although dedicated X-ray observations

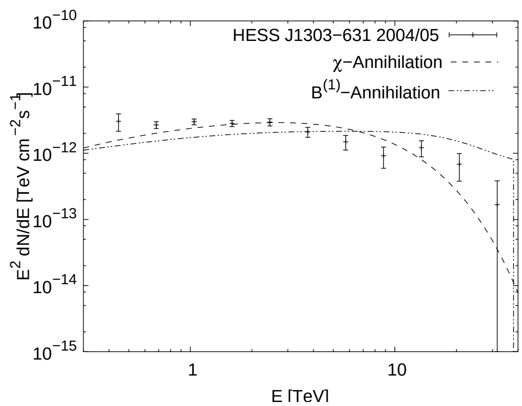

Figure 1: The spectral energy distribution (SED) $E^2 \mathrm{dN}/\mathrm{dE}$ of HESS J1303-631, adopted from [5]. Also shown are the fitted SEDs from Neutralino (χ) as well as Kaluza-Klein particle ($\mathrm{B}^{(1)}$) annihilations. A large particle mass of $\approx 40\,\mathrm{TeV}$ would be required for both types of particles.

with Chandra [7] and XMM-Newton had been performed. Thus, HESS J1303-631 was (at the time of its discovery) the second unidentified TeV γ-ray source following TeV J2032+4130 discovered in the Cygnus region by HEGRA [8, 9]. Recently, the discovery of a possible (extended) counterpart at X-ray energies of TeV J2032+4130 was reported based upon XMM observations [10]. More unidentified TeV γ-ray sources have been discovered in the H.E.S.S. galactic plance scan [11, 12].

HESS J1303-631 as a clump of dark matter?

A GeV/TeV γ-ray source showing no strong emission in other wavebands fulfills the expectations of a hypothetical clump of dark matter. Therefore, it is tried to describe the properties of HESS J1303-631 – i.e. the morphology (angular distribution) and energy spectrum – by a clump of dark matter.

Figure 1 shows the measured spectral energy distribution of HESS J1303-631 together with a fit of a neutralino as well as a $B^{(1)}$ annihilation spectrum. The masses for both particles were set to a relatively high value of $40\ \mathrm{TeV}$ each[1], leaving the cross section and particle density as free parameters for the fits, effectively scaling the spectra. The fits result in $\chi^2/\mathrm{d.o.f.} = 29/9 = 3.2$ for the neutralino and $\chi^2/\mathrm{d.o.f.} = 91/9 = 10$ for the Kaluza-Klein annihilation spectrum. Only the neutralino spectrum is a marginally acceptable description of the HESS J1303-631 spectrum.

For the angular distribution of excess events (see Fig. 2) a rotational symmetry is assumed. The expected angular profile $\varrho(r)$ of a dark matter clump is parametrized according to Zhao [13]:

$$\varrho(r) = \varrho_0 \cdot \frac{r_c^\gamma}{r^\gamma} \cdot \frac{(r_c^\alpha + r_s^\alpha)^{(\beta-\gamma)/\alpha}}{(r^\alpha + r_s^\alpha)^{(\beta-\gamma)/\alpha}} \tag{1}$$

The parameters γ and β are the exponents of a local power-law in the inner ($r \ll r_s$) and outer ($r \gg r_s$) region, respectively, whereas α describes the reciprocal width of the transition zone. The parameters ϱ_0 and r_c are scaling parameters. To avoid the singularity for the numerical integration we use $r \to \sqrt{r^2 + r_{\min}^2}$, whereas $r_{\min}$ is a-priori set to $10^{-10}\ \mathrm{pc}$. The NFW profile is obtained for $\gamma = 1$ and $\beta = 3$, whereas the Moore profile is obtained for $\gamma = 1.5$ and $\beta = 3$. Note, that in the following investigations also negative values of γ were allowed, which corresponds to a shell-like structure of the dark matter accumulation.

For a range of the outer exponent β from 3 to 17 and the inverse width $\alpha = 1$ various combinations of the parameters γ and r_s/D are tested (α has a negligible effect on the fit results). D is the distance of the clump to the observer. The obtained luminosity profile is folded with the point spread function (PSF) of the H.E.S.S. experiment and then fit to the measured angular profile of HESS J1303-631. If necessary, the density ϱ_0 is scaled such that the obtained luminosity profile matches the one measured from HESS J1303-631. Figure 2 shows the measured excess from HESS J1303-631 together with the best fit Zhao luminosity profile as well as the expectation of an NFW profile. It can be seen that an NFW profile does not describe the measured excess well. The same is true for a Moore profile (not shown in Fig. 2).The parameters of the best fit Zhao profile are $\gamma = -0.8$ and $r_s/D = 0.035$, with $\alpha = 1$ and $\beta = 17$.

1. Lower particle masses result in even worse fit qualities.

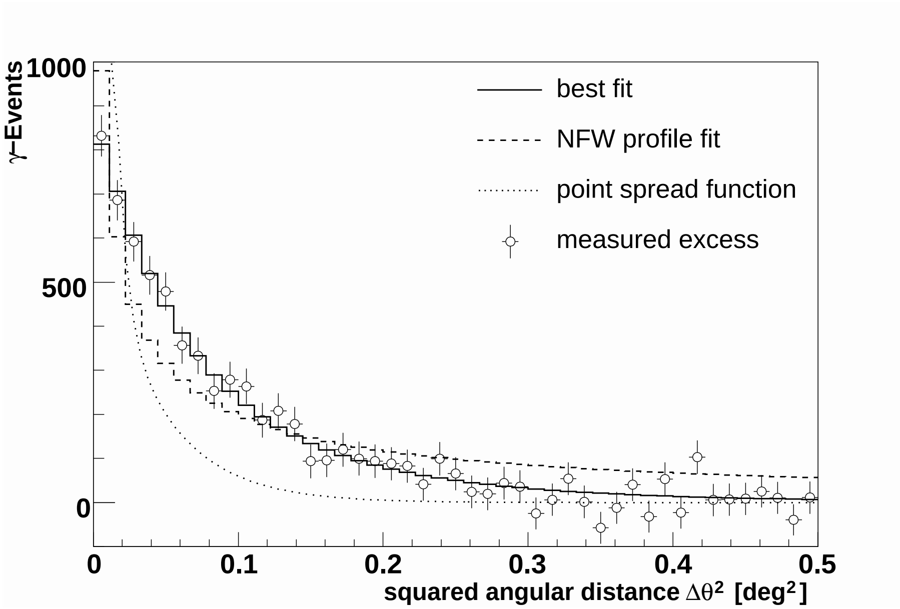

Figure 2: Distribution of excess events from HESS J1303-631 (data points) as a function of squared angular distance $\Delta\theta^2$, measured with respect to the source mean position. The solid histogram shows the best fit of an dark matter angular emission profile according to Zhao folded with the H.E.S.S. point spread function (PSF), which is also shown in the histogram. The dashed line repesents the fit of an NFW profile (also folded with the PSF).

For $\alpha = 1$ and $\beta = 17$ the values of χ^2 in the r_s/D vs γ plane are shown in Fig. 3. The χ^2 is the sum of the squared residuals of the individual θ^2 bins.

A small β ($\beta < 7$) leads to a tail in the luminosity profile but for large values of β ($\beta > 13$) the distribution of χ^2 in the γ and r_s/D plane is almost independent of β. The 99% confidence upper limit of γ is 0.5 and is not compatible with the expectations ($\gamma > 1$) obtained from N-body simulations (NFW or Moore).

Assuming a dark matter annihilation origin (using the best fit angular profile), one would require a mass of the dark matter clump of

$$M_{\mathrm{clump}} = 8.64 \cdot 10^5\,\mathrm{M}_\odot \cdot \left(\frac{D}{100\,\mathrm{pc}}\right)^{2.5} \cdot \left(\frac{m_{\mathrm{DM}}}{40\,\mathrm{TeV}}\right)^2 \cdot \left(\frac{N_\gamma\langle\sigma v\rangle}{2\cdot 10^{-26}\,\mathrm{cm}^3/\mathrm{s}}\right)^{-1} \cdot \left(\frac{\Phi_\gamma}{1.3\cdot 10^{-11}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}}\right)^{0.5} \qquad (2)$$

in order to reach the photon flux measured from HESS J1303-631. Here, D is the distance of the clump, m_{DM} is the mass of the dark matter particle, N_γ is the number of photons per annihilation above the energy threshold and $\langle\sigma v\rangle$ is the annihilation cross section.

Summary and Conclusion

The hypothesis that HESS J1303-631 is a dark matter clump has been investigated based on the energy spectrum and the luminosity profile. It turns out that the energy spectrum cannot be described well by a χ or $\mathrm{B}^{(1)}$ annihilation spectrum (which would require very high DM particle masses anyhow). The angular profile of HESS J1303-631 is fit by a Zhao parameterisation folded with the H.E.S.S. point spread function, for which various pairs of γ and r_s/D are tested. As a result, the measured angular profile can neither be described by an NFW nor by a Moore profile. In total it seems unlikely that the GeV/TeV γ-ray

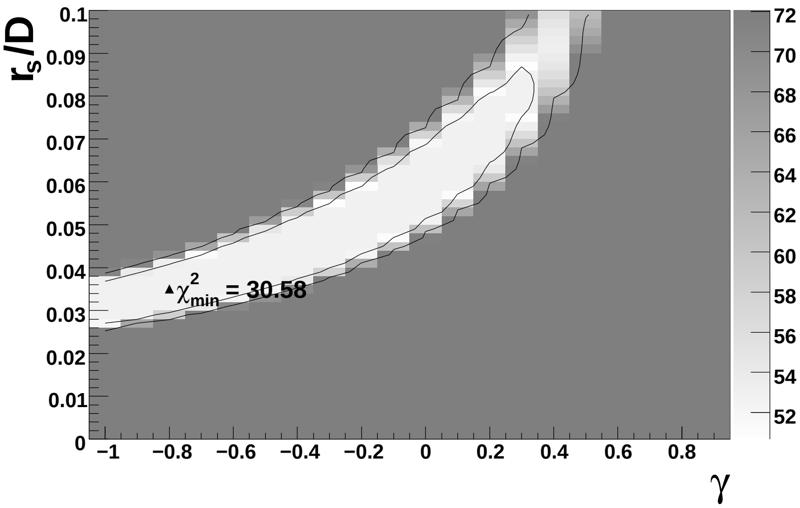

Figure 3: Distribution of χ^2 (for 43 degrees of freedom) in the γ and $r_{\rm s}/D$ plane of the Zhao parameterisation of the angular profile. The set of parameters yielding the best fit ($\chi^2_{\rm min}$) is found around $\gamma \approx -0.8$ and $r_{\rm s}/D \approx 0.035$. The contour lines show the allowed 90% and 99% confidence levels of the fit. The expectations are $\gamma = 1$ ($\gamma = 1.5$) for an NFW (Moore) profile.

emission measured from HESS J1303-631 is due to annihilation of dark matter. The other unidentified TeV γ-ray sources discovered so far do not have the same characteristics and are at present under investigation.

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