

PROBING DARK MATTER WITH AGN JETS

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We study the possibility of detecting a signature of particle dark matter in the spectrum of gamma-ray photons from active galactic nuclei (AGNs) resulting from the scattering of high-energy particles in the AGN jets off of dark matter. In the context of the Minimal Supersymmetric Standard Model (MSSM), we present the lowest-order calculation for a process where a photon is emitted in DM-electron scattering, where the electrons belong to the AGN jet. We find that such a process is dominated by a resonance whose energy is dictated by the particle spectrum in the dark matter sector. The resulting gamma-ray spectrum exhibits a very characteristic spectral feature, consisting of a sharp break to a hard power-law behavior. Although the normalization of the gamma-ray flux depends strongly on assumptions on the AGN jet geometry, composition and particle spectrum, we show that for realistic parameter space choices and for a prominent nearby AGN (Cen A) the detection of this effect is possible. We compare our predictions with actual gamma-ray observations carried out with the Fermi and H.E.S.S. telescopes.

1 Introduction

The innermost regions of active galactic nuclei (AGNs) correspond to locations where the highest dark matter densities in the universe are believed to exist. This remarkable feature, and the fact that AGNs are well-known sources of high-energy particles, naturally leads to the question of whether anything could happen and be observed as AGN jets traverse high-density dark matter regions. One possibility, first cleverly suggested some time ago by Bloom and Wells, Ref. ¹, is that for AGN jets pointing off of our line-of-sight, an isotropic photon emission might result from the scattering of the high energy electrons in the jet off of dark matter particles. The estimates of Ref. ¹, unfortunately, lead to rather pessimistic conclusions. With the advent of the Fermi Large Area Telescope and with the amazing recent results from ground-based Cherenkov Telescopes, most notably H.E.S.S., we deem it timely to re-consider the original proposal of Bloom and Wells.

The best target for this study is Centaurus A, an AGN that is 3.5 Mpc away and whose jets are at angle of about 68° with respect to the line of sight. The jets are believed to consist of ultra-relativistic protons and electrons. Here we will restrict our attention to the electrons and study their scattering off of the dark matter close to the core, with photons emitted in the final state. Those photons we hope to detect. The quantity of interest is therefore the following flux

$$\frac{d\Phi_\gamma}{dE_\gamma} = \int dE_{e[p]} \left(\frac{1}{M} \frac{d^2\sigma_{e[p]+\chi\rightarrow\gamma+\dots}}{d\Omega dE_\gamma} \right)_{\cos\theta_0} \left(\frac{1}{d_{\text{AGN}}^2} \frac{d\Phi_{e[p]}^{\text{AGN}}}{dE_{e[p]}} \right) \delta_{\text{DM}}. \quad (1)$$

The integrand is the product of three factors: the first one depends upon the DM particle model and involves the cross section for electron- χ (where χ generically indicates the DM particle) or

proton- χ into any final state that contains a photon, divided by the DM particle mass M (the cross section is computed at a scattering angle θ_0 between the direction of the AGN jet and the line of sight); the second factor depends upon the target AGN; the third factor involves the DM density profile.

For a more comprehensive discussion see Ref. ².

2 The calculation

2.1 Dark matter profile

Let us start from the last factor in the integrand above

$$\delta_{\text{DM}} \equiv \langle \rho_{\text{DM}} R_{\text{DM}} \rangle = \int_{r_{\text{min}}}^{r_0} \rho_{\text{DM}}(r) dr. \quad (2)$$

The region we are interested in is very close to the core, where the commonly used dark matter profiles, such as Navarro, Frank and White (NFW) for example, can be at best extrapolated. We prefer to use the theoretically motivated profile suggested by Gondolo and Silk ³. Working under the assumptions that the dark matter particles are collisionless and that the central black hole grew adiabatically by accretion of gas, stars and DM, they found that DM would form a dense spike. Their profile reads

$$\rho_{\text{DM}}(r) = \rho_{\text{sp}}(r) = \frac{\rho'(r) \rho_{\text{core}}}{\rho'(r) + \rho_{\text{core}}}, \quad (3)$$

where

$$\rho_{\text{core}} \simeq M_\chi / (\langle \sigma v \rangle_0 t_{\text{BH}}) \quad \rho'(r) = \rho_R g_\gamma(r) \left(\frac{R_{\text{sp}}}{r} \right)^{\gamma_{\text{sp}}}. \quad (4)$$

In the equation above, $\rho_R = \rho_0 \left(\frac{R_{\text{sp}}}{r_0} \right)^{-\gamma}$, $g_\gamma(r) \simeq \left(1 - \frac{4R_S}{r} \right)^3$, $R_{\text{sp}} = \alpha_\gamma r_0 \left(\frac{M_{\text{BH}}}{\rho_0 r_0^3} \right)^{\frac{1}{3-\gamma}}$, $\gamma_{\text{sp}} = \frac{9-2\gamma}{4-\gamma}$. ρ_{DM} vanishes for $r < 4R_S$, which sets the lowest possible value for r_{min} . We set $\alpha_\gamma = 0.1$ and $\gamma = 1$. We normalize the profile by requiring that the dark matter mass enclosed in 10^5 Schwarzschild radii (R_S) does not exceed the uncertainty in the measured black hole mass. We obtain a value for δ_{DM} that ranges from 10^8 to $10^{11} \text{ M}_\odot/\text{pc}^2$, depending on the choice of the annihilation cross section $\langle \sigma v \rangle_0$ and the age of the black hole t_{BH} .

2.2 Electron energy distribution

We adopt the commonly used blob geometry to model the jet: the electrons move isotropically in the blob frame with a power law energy distribution, and the blob itself moves with respect to the central black hole with a moderate bulk Lorentz factor $\Gamma_B = (1 - \beta_B^2)^{-1/2} \sim 3$. In this section, primed quantities refer to the blob rest frame, while unprimed quantities refer to the black hole rest frame. We use a broken power law energy distribution

$$\frac{d\Phi_e^{\text{AGN}}}{d\gamma'}(\gamma') = \frac{1}{2} k_e \gamma'^{-s_1} \left[1 + \left(\frac{\gamma'}{\gamma'_{\text{br}}} \right)^{s_2-s_1} \right]^{-1} \quad \text{for } \gamma'_{\text{min}} \leq \gamma' \leq \gamma'_{\text{max}}, \quad (5)$$

with $s_1 = 1.8$, $s_2 = 3.5$, $\gamma'_{\text{min}} = 8 \times 10^2$, $\gamma'_{\text{br}} = 4 \times 10^5$, $\gamma'_{\text{max}} = 10^8$. The constant k_e can be evaluated from the kinetic power of the jet, $L_e = 3 \times 10^{43} \text{ erg/s}$. After boosting this distribution to the black hole frame we find

$$\frac{1}{d_{\text{AGN}}^2} \frac{d\Phi_e^{\text{AGN}}}{dE_e} = \frac{1}{d_{\text{AGN}}^2} \int_{0.9}^1 \frac{d\mu}{\Gamma_B(1 - \beta_B \mu)} \frac{d\Phi_e^{\text{AGN}}}{d\gamma'}(\gamma \Gamma(1 - \beta_B \mu)). \quad (6)$$

where $\mu \equiv \cos \theta$, θ is the polar angle in the black hole frame.

2.3 Differential cross section

In the context of the MSSM, where the dark matter candidate is the lightest neutralino, we compute the following diagrams

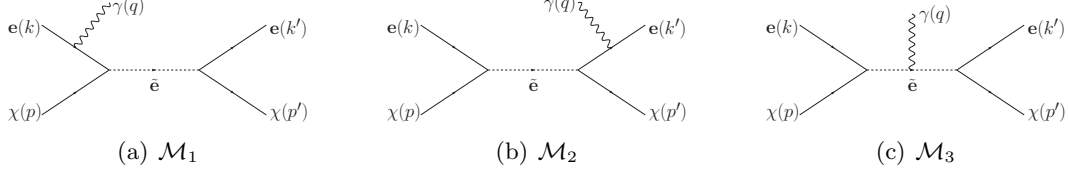


Figure 1: Feynman diagrams for the process $e(k) + \chi(p) \rightarrow e(k') + \chi(p') + \gamma(q)$.

Defining $s = (p + k)^2$, $s' = (p' + k')^2$, $\Pi_s = \frac{1}{s - M_{\tilde{e}}^2 - i\sqrt{s}\Gamma}$, $\Pi_{s'} = \frac{1}{s' - M_{\tilde{e}}^2 - i\sqrt{s'}\Gamma}$, we find the differential cross section

$$\begin{aligned} \left(\frac{d^2\sigma}{dE_\gamma d\Omega} \right)_{\cos\theta_0} &= \frac{1}{(2\pi)^5} \frac{1}{32E'_N} 2e^2(a_L^4 + a_R^4) |\Pi_s|^2 \\ &\times [E_\gamma (M_\chi + E(1 - \cos\theta_0)) \\ &\quad - |\Pi_{s'}|^2 \left(s' - M_{\tilde{e}}^2 + \frac{\sqrt{s'}\Gamma^2}{\sqrt{s} + \sqrt{s'}} \right) 4EM_\chi (EM_\chi - E_\gamma (M_\chi + E(1 - \cos\theta_0)))] \\ &\times \pi \ln \left(\frac{4E'^2}{m_e^2} \right), \end{aligned} \quad (7)$$

where E_γ is the photon energy, E, E', E'_N the energies of the initial electron, final electron, final neutralino respectively, and m_e is the electron mass.

There are two important points to notice in the result above:

1. when the selectron goes on-shell ($\sqrt{s} = M_{\tilde{e}}$) we have a resonance;
2. we have a log enhancement when the photon is collinear with the final electron.

These enhancements constitute the biggest improvement from the original work of Bloom and Wells.

3 Results

Now we have all the ingredients to compute the photon flux of eq. (1). The results are shown in Fig. 2, where we show lines correspondent to two different choices of the jet luminosity, that we still consider conservative, and we use the most conservative value for δ_{DM} . The Fermi data are from Ref. ⁴, the HESS data are from Ref. ⁵. The spectral feature is evident: one starts with a hard power-law behavior and then gets to a sudden drop. The break occurs where the photon energy is high enough that the incoming electron energy has to be beyond the resonance, $\sqrt{s} > M_{\tilde{e}}$. As soon as we loose the resonant enhancement, the signal drops.

There are still some astrophysical uncertainties such as the jet geometry, dark matter distribution and particle spectrum that need better understanding, and we hope that Fermi will be able to collect more data in the region between 10 and 200 GeV in the near future. Because the feature of the process we studied is so characteristic, its detection should be possible.

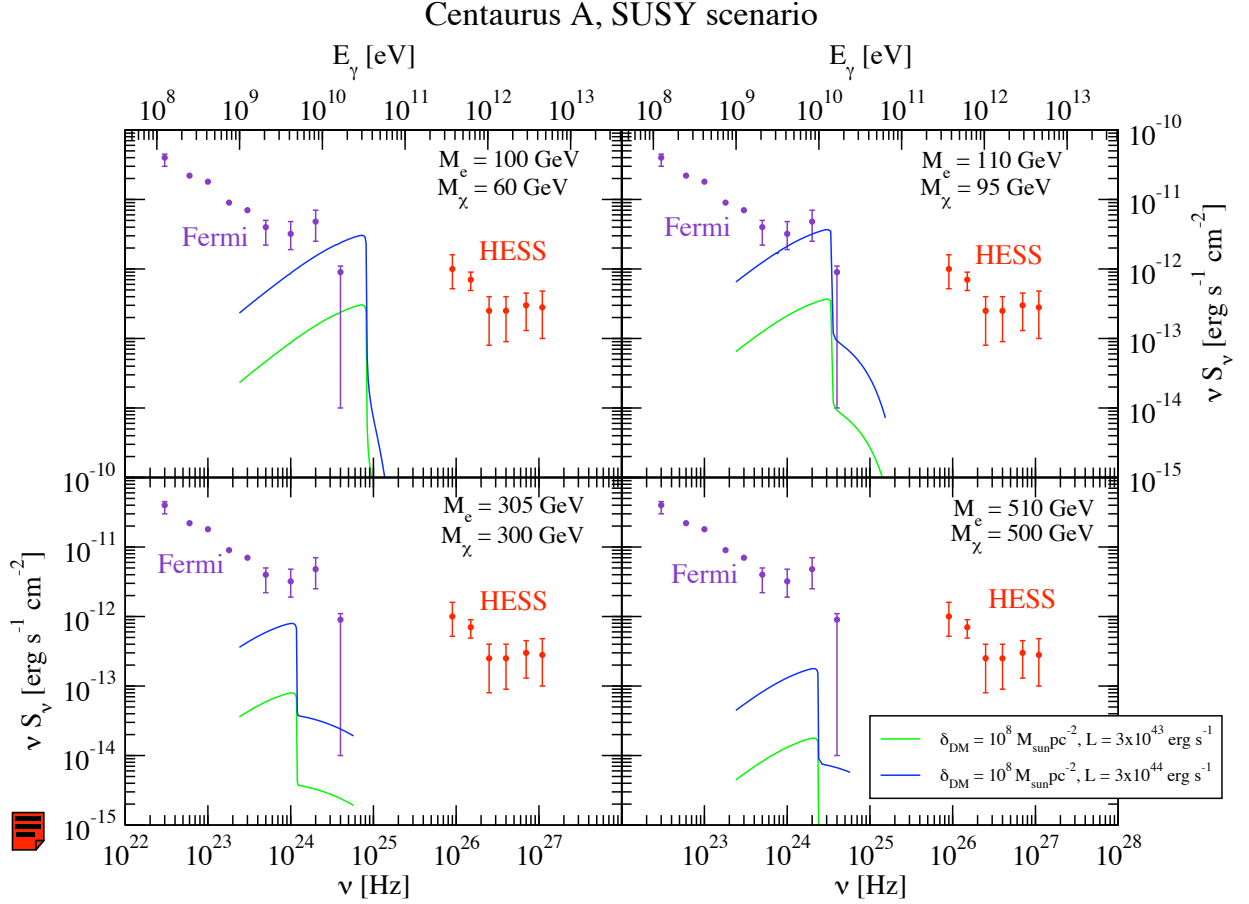


Figure 2: We show the spectral energy distribution νS_ν (equivalent to $E_\gamma^2 \times \frac{d\Phi_\gamma}{dE_\gamma}$) versus the photon energy for CenA, for four different choices of the masses in a supersymmetric scenario. The two lines correspond to two reasonable choices of the jet luminosity.

References

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