Multi-GeV photons from electron–dark matter scattering near Active Galactic Nuclei

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Abstract

Active Galactic Nuclei (AGN) may emit highly collimated and intense jets of relativistic electrons which upscatter ambient photons. These electrons can also scatter off the cold dark matter halo of the galaxy to produce high energy photons which have a more isotropic signature than the up-scattered photons from QED processes. We propose to look for these high energy photons coming from AGN as a method to detect dark matter. As a primary example we work out the expected signal from electrons scattering off the lightest supersymmetric partner into a photon plus selectron. Using the optimistic side of astrophysical uncertainties, we still find the signal from M87 or Centaurus A, two close-by AGN, smaller than the sensitivities expected of the currently proposed photon detectors. However, long running photon detectors and future detectors of higher sensitivity might be able to distinguish a signal from AGN sources. In order to have confidence that new physics sources are discernible, we also emphasize the importance of multi-wavelength studies of AGN with varying jet axis orientation to the earth.

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Astrophysics observations and cosmological arguments point to the necessity for a substantial amount of cold dark matter in the universe [1]. It is even possible that the invisible cold dark matter constitutes nearly critical density ($\rho_c = 3H^2/8\pi G$) in the standard $\Omega = 1$ big-bang cosmology. Dark matter detection to date has only been accomplished by witnessing gravitational effects (rotation curves of galaxies, Hubble flow distortions, gravitational lensing, etc.). Since the dark matter is probably not electrically charged or color charged [2], its most likely non-gravitational interactions are due to the weak force. Hence, the hypothesis of stable weakly interacting massive particles (WIMPs) has been considered [1]. We will use the bino (superpartner of the hypercharge gauge boson) as the lightest supersymmetric partner (LSP) in our example scattering process.

Experimental effort is now underway on many fronts [3] to see dark matter via its weak interactions. Cryogenic table top experiments which measure nuclear recoil of ambient LSPs interacting with Silicon, Germanium, and other elements are progressing. One can also search for neutrino yields from the annihilation of captured LSPs in the core of the sun or earth. And searches are underway to look for positrons, electrons, protons and antiprotons from the annihilations of LSPs in the galactic halo.

Here, we propose another idea to search for LSPs: photons originating in the final state of electron-LSP scattering near the center of Active Galactic Nuclei (AGN). The principle property of an AGN of the Blazar type [4] which makes this idea potentially feasible is the high energy and high flux electron beams which are thought to be emanating from their

centers [5,4]. The high energy jets are thought to arise from a highly relativistic shock wave traveling along the perpendicular axis of an accretion disk associated with a massive black hole at the center ($10^6 - 10^9$ $M_\odot$). Shock waves generated by the central engine accelerate electrons and positrons which in turn produce high energy photons mainly through inverse Compton scattering of the UV radiation from a thermal distribution of photons originating external to the electron/positron jet in the accretion disk [5]. Other processes that could be important include inverse Compton scattering of synchrotron radiation, and pair annihilation of the electrons and positrons into high energy photons. We will loosely call all these processes "up-scattering" of high energy electrons and positrons into high energy photons.

The lab frame, which is the accretion disk frame, or equivalently our observation frame on earth (for close-by AGN), has a distribution of electrons which scales roughly as E^{-2}, and is highly collimated with a beaming factor (solid angle fraction) of about 10^{-3} [5]. Since the upscattered radiation can be measured, the coefficient out in front of the assumed E^{-2} can be measured to obtain an estimate of the electron/positron flux ejected from the AGN.

The total power of the AGN in photon radiation is approximately $\Delta F_\gamma = 10^{47} f - 10^{49} f$ ergs/s in the energy range of $100\,\mathrm{MeV} < E_\gamma < 5\,\mathrm{GeV}$ [6], where f is the beaming factor (fraction of solid angle) of the electron beam. We shall take $f \simeq 10^{-3}$ in accordance with [5]. Since the hadronic component of the AGN jet is probably less important [4] to the photon radiation than the electron/positron constituents, we will make the approximation that all the photon radiation power is converted from the electron jet (often we use "electron"

to mean both electrons and positrons). This enables us to estimate the intensity and energy distribution of the electron beam. We find the approximate value by using [5] the same energy profile for the electrons as the photons:

$$\frac{df}{dE_e} = n_0 \left(\frac{m_e}{E_e}\right)^2.$$ (1)

We can estimate the value of n_0 to be

$$n_0 \simeq \frac{\Delta F_\gamma}{m_e^2} \frac{1}{\log 5\,\mathrm{GeV}/100\,\mathrm{MeV}} \simeq 10^{55}/\,\mathrm{GeV}/s.$$ (2)

Given this normalization, and given this distribution between 1 MeV to 10 TeV, the total amount of energy ejected from the AGN is about one solar mass per year. It might be that much more energy is ejected from the AGN, and that all the electron beam is not transmitted into photons, in which case the above estimate for n_0 would be too low. However, it should also be kept in mind that there are other models of high energy photon jets from AGNs which do not require such intense beams of electrons [7].

If all the electron power went into merely up-scattering photons through simple QED processes, then there would be no electrons left to interact with dark matter. Below it will become apparent that the penetration depth of the electrons is not crucial unless it is less than a few parsecs from the central engine, since almost all the electrons have to interact with the LSPs within about ten parsecs of the accretion disk in order for a signal to be viable at all. Together with the observation that a relatively small fraction of the electrons do scatter off the LSPs, we are free to use Eq. 1 as our particle beam source which interacts with the

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dark matter. Although there are some reasons to believe that the electrons could upscatter the photons far away from the central engine [8], the reader should keep in mind that a detailed model description of the electron/photon beam will involve a distance dependent attenuation factor for the electron beam. Current models are not precise enough to calculate the attenuation so we have assumed optimistically that it is negligible.

The dark matter target distribution must also be modeled [9,10]. Several differing proposals are in the literature. Here, we choose to model the dark matter distribution after Ref. [11] which postulates that $\rho \sim r^{-1.8}$. We choose this model over the more traditional distributions of $\rho \sim 1/(r^2 + r_c^2)$, where r_c is a hard-core density radius which smoothes ρ near $r = 0$, for two reasons: (1) The lack of a hard-core density radius in this model is becoming more and more observed in numerical simulations [10], and (2) large enhancements of ρ near $r \sim 0$ are needed for our proposed signal to be interesting. That is, without a cusp in the dark matter distribution [12], or equivalently, without $r_c \lesssim$ few parsecs, our resulting signal flux of photons would be too low to be detected.

To be explicit, we use the dark matter distribution

$$\rho(r) = \rho_a \left(\frac{a}{r}\right)^{1.8} \tag{3}$$

where a is some arbitrary distance from the center of the galaxy and ρ_a is the local density at that distance. For numerical purposes we will use $a = 8$ kpc and $\rho_a = 0.3\,\text{GeV}/\text{cm}^3$, in accord with the density profile of our galaxy. It is important to estimate the minimum radius size, r_{min}, at which this density function breaks down. The different physics sources

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that could disrupt this density profile are given in Ref. [11], and it was determined that a central black hole would yield the largest r_{min} of $\sim 1\,pc$ (for $M \sim 10^8 M_\odot$). The assumption of a black hole at the center of the galaxy is quite applicable to our AGN study, and we adopt the black-hole hypothesis as the origin of r_{min}. The capture radius of dark matter is then between about 0.01 pc to 10 pc depending on black hole mass, dark matter density, etc. For numerical purposes we will use both 1 pc and 1 kpc.

We now have modeled both the target (dark matter distribution) and the source (high energy electron beam), and so we can estimate the flux of photons originating from $e^\pm \chi \to \tilde{e}_R^\pm \gamma$ scattering. Our notation identifies the bino with χ and the right-handed selectron (superpartner of the right-handed electron) as $\tilde{e}_R$. Feynman diagrams for the process are given in Fig. 1.

Before setting up the differential flux, it is instructive to summarize some basic relativistic kinematics and notation. For close-by AGN, the lab frame of the electron/LSP collision is the observer frame. Thus E_e is the incident electron energy, making the center of mass energy equal to

$$s = m_\chi(m_\chi + 2E_e), \tag{4}$$

and the resulting photon energy in the lab frame is

$$E_\gamma = \frac{s - m_{\tilde{e}_R}^2}{2m_\chi}. \tag{5}$$

In the c.m. frame (primed quantities) the electron and photon energies are

$$E_e' = \frac{s - m_\chi^2}{2\sqrt{s}} \quad E_\gamma' = \frac{s - m_{\tilde{e}_R}^2}{2\sqrt{s}}. \tag{6}$$

Relativistic transformations of four vectors in the lab frame to the bino/electron c.m. frame are carried out by

$$\beta = \frac{E_e}{E_e + m_\chi}. \tag{7}$$

The angle $x = \cos\theta$ with respect to $\hat{z}$ (jet axis) in the lab frame is related to the angle $x' = \cos\theta'$ in the c.m. according to

$$x = \frac{\beta + x'}{1 + \beta x'}. \tag{8}$$

In the c.m. frame the differential cross-section for $e\chi \to \tilde{e}\gamma$ scattering in the limit that $\sqrt{s} \gg m_\chi, m_{\tilde{e}_R}$ simplifies to

$$\frac{d\sigma}{d\Omega'} \simeq \frac{\alpha^2}{2\cos^2\theta_W} \frac{1}{s} \left(\frac{1 + \cos\theta'}{1 - \cos\theta'} \right), \tag{9}$$

where $\alpha = 1/137$ is the QED coupling constant, and θ_W is the weak mixing angle. (Due to finite electron mass and selectron width there is no singularity in the cross-section as $\theta' \to 0$.) We keep the masses of χ and $\tilde{e}_R$ in our numerical work. To cast this in the lab frame we use Eq. 8 to substitute x for x' and to calculate dx'/dx as a function of x.

The total differential $e^\pm\chi$ scattering flux observed at the earth can be parameterized as

$$\frac{dF}{dE_e} = \frac{\# \text{ events}}{cm^2 sec\,\text{GeV}} = \frac{1}{d_{AGN}^2} \left[\frac{d\sigma}{d\Omega} \right]_{x_0} \frac{d\mathcal{L}}{dE_e}, \tag{10}$$

where $x_0 = \cos\theta_0$ is the fixed angle between the jet axis and the axis which points from the AGN to the earth. Also, d_{AGN} is the distance to the AGN and $d\mathcal{L}/dE_e$ is the effective luminosity given by

$$\frac{d\mathcal{L}}{dE_e} = \frac{df}{dE_e}\frac{\langle\rho_\chi l_\chi\rangle}{m_\chi}. \tag{11}$$

The factor $\langle\rho_\chi l_\chi\rangle$ is the average of the r dependent dark matter density function times the

effective length that the electrons pass through, and is defined as

$$\langle\rho_\chi l_\chi\rangle = \int_{r_{min}}^{r_{max}} dr\,\rho(r) \simeq r_{min}\rho_a\left(\frac{a}{r_{min}}\right)^{1.8} \simeq r_{min}\rho(r_{min}) \tag{12}$$

where the latter approximation is for $r_{max} \gg r_{min}$.

There is a one-to-one correspondence between the electron energy E_e and the photon

energy E_γ given by

$$E_e = \frac{m_{\tilde{e}}^2 - m_\chi^2 + 2m_\chi E_\gamma}{2m_\chi}. \tag{13}$$

Since $dE_e/dE_\gamma = 1$ the differential photon flux is given simply by substituting E_e of Eq. 13

into Eq. 10. The integral photon flux is then

$$F(E_\gamma) = \#\text{ photons cm}^{-2}\text{ sec}^{-1} = \int_{E_\gamma}^{\infty} dE_\gamma''\frac{dF}{dE_\gamma''}. \tag{14}$$

Figure 2 shows the results for the AGN M87 which is approximately 12 Mpc away, and

has a jet axis oriented at 42 ± 5 degrees to us [13,14]. We also show the result for Centaurus

A, which is ~ 2.5 Mpc away and is oriented at ~ 68 degrees [15]. The supersymmetric

model used to construct Fig. 2 is a pure bino LSP with mass 60 GeV, and a right-handed

selectron with mass 100 GeV. The upper solid line is with $r_{min} = 1\,pc$ and the bottom solid

line is with $r_{min} = 1\,kpc$. The top dashed line is the the 5σ sensitivity of the proposed space

based gamma ray telescope GLAST [16], and the lower right line is the expected sensitivity

of the proposed ground based gamma ray telescope array VERITAS [17]. For GLAST, the sensitivity corresponds to one year scanning mode in which the instrument is always pointed outward from the earth (approximately 30% duty cycle). For VERITAS, the sensitivity is for one week observing time on the source. As we can see, the signal is lower than the present sensitivities of these proposed photon detectors.

The AGN beam as modeled in [5] has a non-zero gamma ray flux at large angles from the jet axis. For Centaurus A the flux at 68 degrees off jet axis (i.e., earth direction is 68 degrees from jet axis) is expected to be negligible; the electron/positron beam is highly collimated, dramatically decreasing the overall flux normalization and especially decreasing the gamma ray energy cut-off from ordinary QED processes with higher observing angle. However, for M87 whose jet axis is only 42 ± 5 degrees with respect to the earth direction, the intrinsic background is substantial and swamps the expected flux from electron/bino scattering up to approximately 150 GeV. In the figure we have plotted this background estimate using the same photon beam flux used earlier in deriving the dark matter signal, and we have also assumed a 45 degree jet axis orientation for easier comparison with ref. [5]. Measuring gamma ray fluxes from intermediate angle ($10° \lesssim \theta \lesssim 50°$ off jet axis) AGN such as M87 are still useful because they can increase our understanding of AGN jets, and possibly the model of ref. [5] in particular. Multi-wavelength measurements of the photon flux from a number of AGN with different jet axis orientations is highly desirable to more fully characterize the AGN beams including determination of the angle of the jet axis to the earth using radio

measurements. Such measurements will allow deeper understanding of AGN beams and possibly allow us to have confidence that new physics is discernible.

Although we typically chose parameters such as r_{min} and n_0 which gave maximal contribution to the signal, there are many astrophysical uncertainties involved in the calculation that could make the signal perhaps larger or smaller than we have estimated here. Summing over all large angle Blazar sources will of course help increase the signal over the diffuse background. Such techniques have already been shown to have a significant impact on sensitivity in the X-ray region [18].

We have focused on the case of a pure bino dark matter candidate. Certainly other particles are around, even within supersymmetry, that yield good dark matter candidates. These candidates could of course have much different scattering amplitudes than the bino. For example, the higgsino dark matter candidates discussed in [19] would not allow a direct coupling of the higgsino to an electron and selectron. One useful final state is a chargino and a neutrino produced from t channel W exchange. The decay chain from the chargino then can include a photon from $\chi_2^0 \to \chi_1^0 \gamma$. Such decays could lead to structure in the photon energy spectrum, providing an additional signature. In any event, the final cross-section will have electroweak strength and should not be significantly different than the bino case studied above.

We have found that our estimate of the signal for electron-bino scattering into photons from a single AGN source is too low to be discerned by currently proposed experiments,

but future detectors of much higher sensitivity might be able to see a signal. The limit on sensitivity to the photon signal of the most sensitive of the currently proposed experiments – ground based Cherenkov telescope arrays – is largely due to the difficulty of subtracting pseudo-backgrounds primarily from electron showers in the atmosphere. Therefore, if a signal does exist it might be possible to reach the sensitivities required by the continuing progress to eliminate these backgrounds, and dramatically extend the observing time on candidate sources. Obviously this presents great challenges.

ACKNOWLEDGMENTS

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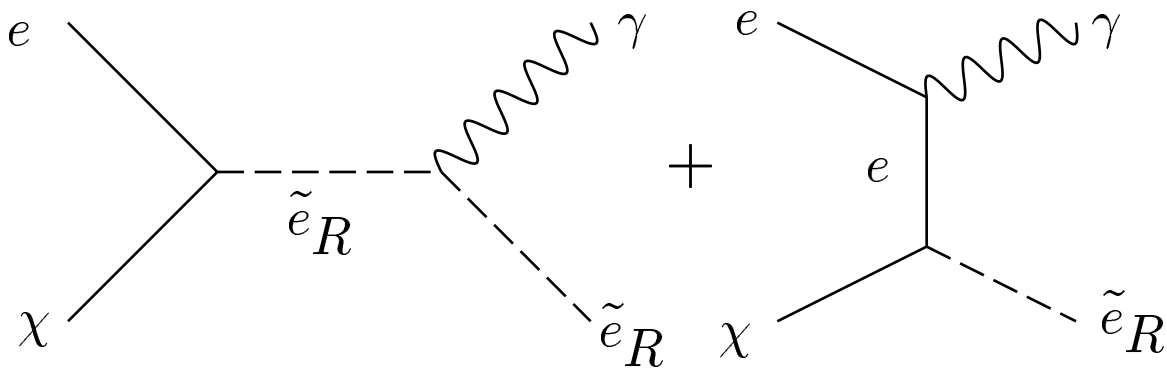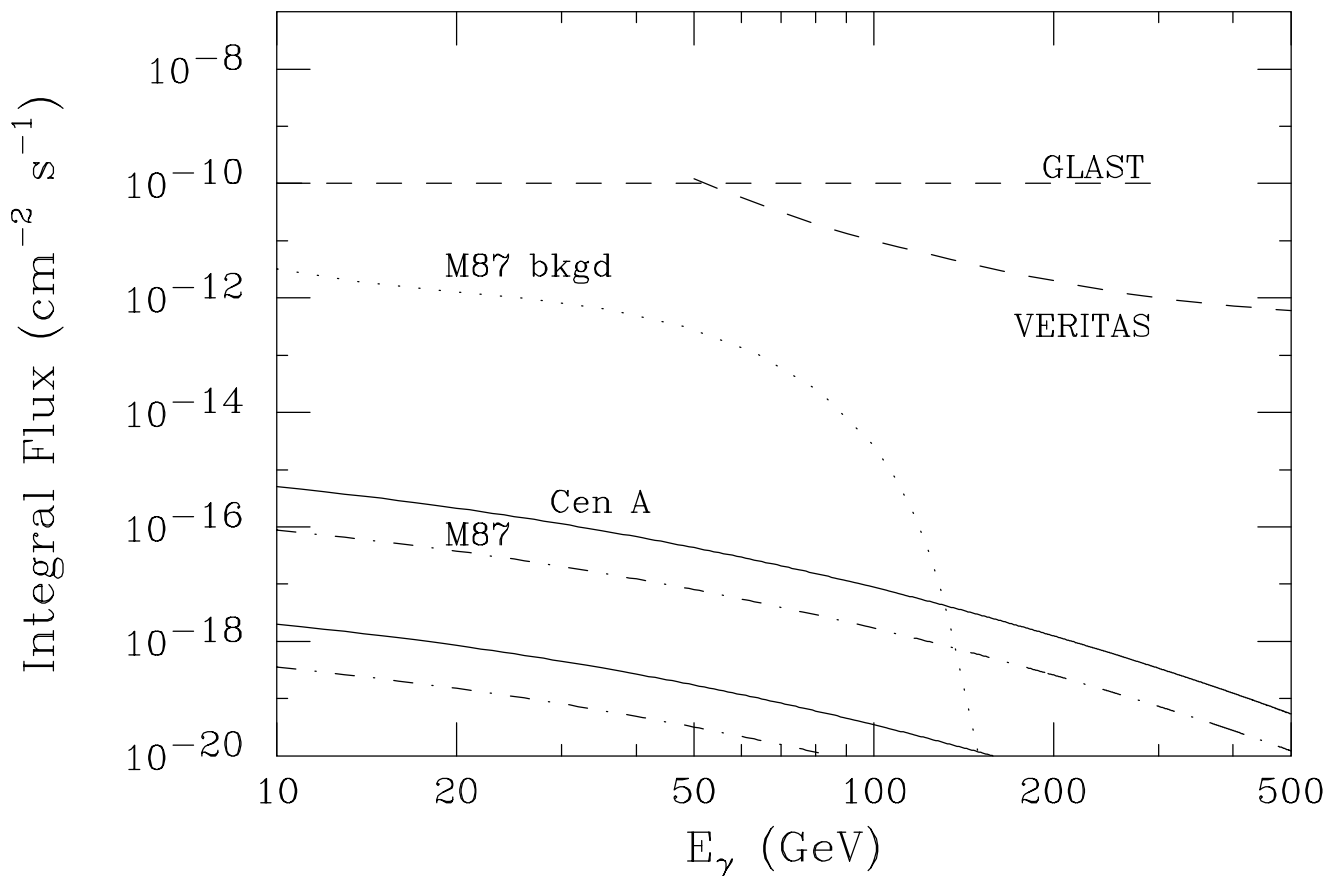FIG. 1. Feynman diagrams contributing to $e^{\pm}\chi \to \gamma\tilde{e}_R$ scattering.

FIG. 2. Integral flux of photon signal from the Centaurus A and M87 Active Galactic Nuclei. The top solid (dash-dot) line corresponds to $r_{min} = 1$ pc in the dark matter density profile for Centaurus A (M87), and the bottom line corresponds to $r_{min} = 1$ kpc. The dashed lines represent the sensitivity of the different photon detectors GLAST (one year scanning mode) and VERITAS (one week on source). The dotted line represents an estimate of the background flux from the M87 jet. Gamma ray jet background from Centaurus A is expected to be negligible. See the text for further discussion.