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Gamma Ray Lines From Dark Matter Annihilation*

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Abstract

If direct annihilation of dark matter particles into a pair of photons occurs in the galactic halo, a narrow γ-ray line can be discovered at future γ-ray detectors sensitive to the GeV region. The signals predicted by different dark matter candidates are analyzed.

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I. γ-Ray Line Signal And Background

It is possible that the dark matter (DM) which exists in the galactic halos consists of some elementary particle, remnant of the early history of the Universe. If this is true, these particles may be detectable directly through their elastic collisions with nuclei or indirectly through observation of their annihilation products[1]. Limits on some popular DM particle candidates have already been placed. Since annihilation rates are proportional to the square of the DM number density, the indirect limits come from search of energetic neutrinos produced in the annihilation in the body of the Sun or Earth, where large DM density enhancements are likely. Although annihilation in the galactic halo occurs at a much smaller rate, it allows the observation in a wider variety of channels, through detection of antiprotons, positrons, neutrinos and photons.

A particularly interesting possibility is the annihilation in the halo of DM particles into a pair of photons[2-5]. This process generates a gamma ray line with energy $E_\gamma = m_{DM}$ and energy spread due only to Doppler effect, $\Delta E_\gamma / E_\gamma \simeq v_{DM}/c \simeq 10^{-3}$, where m_{DM} and v_{DM} are respectively the mass and the average velocity in the halo of the DM particle. The extremely clean signature with a narrow line which would stand out against the diffuse gamma ray background justifies the interest in this process, even if the rate is expected to be rather small.

In fact, the relevant region of the gamma ray spectrum, with energies in the range of GeV, will be measured for the first time by the Energetic Gamma Ray Experiment Telescope (EGRET) on the Gamma Ray Observatory (GRO) satellite[6] which will be launched in 1990. Larger devices with excellent angular and energy resolution such as ASTROGAM[7] have recently been proposed. EGRET is able to detect gamma radiation in the energy range between 20 MeV and 30 GeV with an energy resolution of 15% and an effective acceptance geometry factor of 900 cm^2 sr. Note that a good energy resolution is an essential parameter for high efficiency in detecting gamma ray lines against a diffuse radiation spectrum. ASTROGAM is designed to detect gamma rays in the energy range between 1 GeV and 1 TeV, with energy resolution of about 1% and an effective acceptance geometry factor of 7000 cm^2 sr.

The flux of monochromatic photons produced in the dark matter annihilation is[8]:

$$\frac{d\phi}{d\Omega} = \frac{N_\gamma}{4\pi}\frac{< \sigma_\gamma v >}{m_{DM}^2}\int_0^\infty dr \rho_{DM}^2(r). \tag{11}$$

N_γ is the number of photons generated in each process (=2), $\rho_{DM}(r)$ is the dark matter energy density at a distance r in the line of sight and $< \sigma_\gamma v >$ is the average of the annihilation cross section into a pair of photons times the relative velocity of the annihilating particles. For a spherical isothermal galactic halo of core radius a and local dark matter density ρ_o, the DM energy density is:

$$\rho_{DM}(R) = \rho_o \frac{r_o^2 + a^2}{R^2 + a^2} \quad , \tag{12}$$

where R is measured for the centre of the galaxy and r_o is the distance solar system - centre of the galaxy. Replacing eq. (2) in eq. (1), one finds:

$$\frac{d\phi}{d\Omega} = \frac{N_\gamma}{8\pi}\frac{\rho_o^2}{m_{DM}^2} < \sigma_\gamma v > J(b,\ell) \tag{13}$$

where b and ℓ are respectively the galactic latitude and longitude (b=ℓ=0 corresponds to the centre of the galaxy). Also:

$$J(b,\ell) = \frac{\sqrt{r_o^2 + a^2}}{(1-\delta)^{3/2}}\left[\frac{\pi}{2} + \sqrt{\delta(1-\delta)} + \arcsin\sqrt{\delta}\right] \tag{14}$$

$$\delta \equiv \frac{r_o^2}{r_o^2 + Q^2}\cos^2 b \cos^2 \ell \tag{15}$$

Using $r_o = 8.5$ kpc, $a = 5.6$ kpc, $\rho_o = 0.3$ GeV/cm^3 and measuring $< \sigma_\gamma v >$ in units of 10^{-26} cm^3/sec, at high galactic latitudes ($b \simeq 90°$), eq. (3) becomes

$$\frac{d\phi}{d\Omega} = \frac{< \sigma_\gamma v >_{26}}{(m_{DM}/GeV)^2} \cdot 110 \frac{events}{year \text{ sr cm}^2} \tag{16}$$

The event rates at EGRET and ASTROGAM are:

$$R_{EGR} = \frac{<\sigma_\gamma v>_{26}}{(m_{DM}/GeV)^2}\, 1 \cdot 10^5 \frac{events}{year} \tag{17}$$

$$R_{AST} = \frac{<\sigma_\gamma v>_{26}}{(m_{DM}/GeV)^2}\, 8 \cdot 10^5 \frac{events}{year} \tag{18}$$

The astrophysical parameters a, r_o and especially ρ_o involve large uncertainties in eqs. (7-8). Note that the rate could be substantially larger in the direction $b=\ell=0$, if there is a large concentration of DM near the galactic center[9]. Before studying the predictions on $<\sigma_\gamma v>$ from the various DM candidates, let us briefly discuss the sources of background.

The estimate of the background should rely upon extrapolation from the 100 MeV region, where measurements have been made by the COS-B and SAS-2 satellites, and upon theoretical calculations. The main source of background is photons from π° decay, where the pions are produced in baryonic cosmic ray interactions with the interstellar medium (ISM). Additional contributions to diffuse γ radiation in the GeV region come from cosmic ray electrons Compton scattering with microwave blackbody photons or from their bremsstrahlung in the interaction with the electric fields of ISM atoms. At high galactic latitudes, the photon flux is predicted to be[10]:

$$\frac{d\phi}{dE_\gamma} = 24 \left(\frac{E_\gamma}{GeV}\right)^{-2.7} \mathrm{year^{-1} sr^{-1} cm^{-2} GeV^{-1}}. \tag{19}$$

Contributions to extra-galactic gamma rays may come from intergalactic cosmic-ray interactions, superposition of unresolved extra-galactic sources or matter-antimatter annihilation in a baryon symmetric Universe. However, their origin is very uncertain and an estimate of this background seems difficult. Therefore, eq. (9) will be taken as reference background, bearing in mind that the extra-galactic contribution could increase the observed flux. On the other hand, the background may be much smaller than (9) in directions at high galactic latitudes where the column density of interstellar medium is lower. Therefore, the background estimates are very uncertain.

However, the line signal can be identified over the diffuse background once it is larger than the statistical uncertainty on the measurement of the background itself in the relevant energy region[4].

II. Predictions for Specific DM Candidates

A. Neutrino

A stable heavy neutrino, either Dirac (with no cosmic asymmetry) or Majorana, gives rise to a relic energy density consistent with $\Omega \simeq 1$, if $M_\nu \simeq 10\ GeV$. Let us then consider such a neutrino as the constituent of the galactic halo and, in the case of Dirac, assume an equal neutrino and antineutrino density. The process $\nu\bar{\nu} \rightarrow \gamma\gamma$ occurs at one-loop level either through a box diagram involving the associated charged lepton and the $W^\pm$ gauge boson or through an effective $Z^\circ\gamma\gamma$ coupling. Since the new charged lepton must be heavy, the dominant contribution comes from the effective $Z^\circ\gamma\gamma$ coupling involving a loop of fermions, yielding a cross section, in the non-relativistic limit[3]:

$$< \sigma_\gamma v >= \frac{\alpha^3 G_F^2 m_\nu^2 N}{2\pi^3} \left| \sum_f C_f Q_f^2 T_f D_Z J\left(\frac{m_\nu^2}{m_f^2}\right) \right|^2 \tag{21}$$

where C_f, Q_f and T_f are the color factor (3 for quarks, 1 for leptons), the electric charge and third component of weak isospin ($\pm$ 1/2 for up and down quarks) of the fermion running inside the loop. Also:

$$D_Z \equiv \frac{m_Z^2 - 4m_\nu^2}{m_Z^2 - 4m_\nu^2 - i\Gamma_Z m_Z} \tag{22}$$

$$J(x) = \begin{cases} 1 - \frac{1}{x}(\arcsin\sqrt{x})^2 & for\ x < 1 \\ 1 - \frac{1}{x}(\frac{\pi}{2} + i\log(\sqrt{x} + \sqrt{x+1}))^2 & for\ x > 1 \end{cases} \tag{23}$$

Finally, N=1, 1/4 for a Majorana and Dirac neutrino respectively.

If all fermions were degenerate in mass, the sum in eq. (10) would vanish, because of the anomaly cancellation in the standard model. Even if the cancellation is not exact (mainly due to the top quark contribution), plugging eq. (10) into eq. (8), one predicts less than 1 event per year at ASTROGAM. The signal from DM neutrinos is too small to be observed.

B. Neutralino

A very promising DM candidate is the neutralino (χ), a neutral Majorana fermion predicted by low energy supergravity models. Its relic energy density is close to the critical density of the Universe, in a wide region of supersymmetric parameters[11]. Let us then assume that the galactic halo consists of neutralinos and consider the annihilation process $\chi\chi \to \gamma\gamma$. A large number of Feynman diagrams can contribute to the process at one loop level. The higgsino component of χ will mainly annihilate through Z° with the rate given in eq. (10), replacing m_ν with m_χ and N with the relevant higgsino coupling. As previously discussed, this rate is too small to be detected. The gaugino component of χ will annihilate into a pair of photons through a box diagram involving the matter fermions and their scalar supersymmetric partners ($\tilde{f}$). In the limit of pure photino, the cross section is[3]:

$$< \sigma_\gamma v >= \frac{\alpha^4}{\pi} m_\chi^2 \left| \sum_f \frac{C_f Q_f^4}{m_{\tilde{f}}^2} J\left(\frac{m_\chi^2}{m_{\tilde{f}}^2}\right) \right|^2 \tag{24}$$

where the sum runs over both left and right sfermions. The contributions of other diagrams involving chargino and Higgs boson exchange have been discussed in ref. 5. Although in some region of parameters these terms provide the leading contribution, they never give rise to rates much larger than eq. (13). Therefore, the result in eq. (13) can be considered as a reasonable estimate of the total cross section.

Apparently, the counting rate in eqs. (7-8) is now almost independent of m_χ, since the cross section eq. (13) scales like m_χ^2. This is however not true, if one consistently requires that χ has a sizable relic density[4,5]. In fact, if the total χ annihilation cross section (and therefore Ω_χ) is kept fixed, the rates (7-8) decrease for large χ masses approximately as m_χ^{-2}.

The predicted rates at ASTROGAM and GRO as function of the neutralino mass are shown in fig. 1-3, for χ relic density $\Omega h^2 = 0.25$ and 0.025 (h is the Hubble constant in units of 100 km/Mpc/sec, $1/2 \lesssim h \lesssim 1$). The mass of the sfermions are determined for each m_χ by fixing the value of Ωh^2. For the lines of the figures labeled "not split," all squarks and sleptons are assumed degenerate in mass. For the lines labeled "split," a common squark mass, $M_{\tilde{q}}$, and a common slepton mass, $M_{\tilde{\ell}}$, are taken with the assumption $M_{\tilde{q}} = 3M_{\tilde{\ell}}$, as generally predicted in supersymmetric model with radiative symmetry breaking. Also shown are the region corresponding to squark or slepton masses excluded by either the CDF limit[12] or the ASP limit[13] on single photon events. As a result, no more than tens of events per year can be expected at ASTROGAM. At GRO, the smaller signal and larger background make the process unobservable.

C. Sneutrino

If the sneutrino ($\tilde{\nu}$), the scalar partner of the neutrino, is the lightest supersymmetric particle, it is a possible DM candidate. However, due to the large annihilation rate in $\tilde{\nu}\tilde{\nu} \rightarrow \nu\nu$, a sizable sneutrino relic density is not easy to be achieved[14]. Moreover, the present limits on DM disfavor the sneutrino as constituent of the galactic halo[1]. Nevertheless, the case of a light sneutrino DM candidate is not ruled out.

If present in the halo, the sneutrino can annihilate $\tilde{\nu}\tilde{\nu}^* \rightarrow \gamma\gamma$, with a dominant contribution given by a box diagram involving the associated charged lepton and the fermionic partner (χ^+) of the W. This leads to a cross section of order

$$< \sigma_\gamma v > \sim \frac{\alpha^4}{\pi \sin^4 \theta_W} \frac{m_{\tilde{\nu}}^2}{m_{\chi^+}^4} \tag{25}$$

Thus, requiring that χ^+ does not largely deplete the relic abundance of $\tilde{\nu}$'s, we can expect that a few GeV sneutrino could produce some tens of events per year at ASTROGAM.

D. Luxino and magnino

We have seen that the rates for gamma ray lines from halo annihilation of the most popular DM candidates are rather low. This is true primarily for two reasons. First, the number density of DM particles in the halo is low, and the annihilation rate is proportional to the density squared. Second, the cross section for annihilation of neutral particles into two photons typically occurs only at the loop level, and it is suppressed by a factor of α^2/π^2 with respect to the dominant annihilation channel. In turn, the total annihilation cross section of a DM particle can be determined (at "freeze-out") by requiring a cosmologically relevant relic abundance:

$$< \sigma v >_{ann} \sim \frac{10^{-26}}{\Omega h^2} \frac{cm^3}{sec} \tag{26}$$

where some dependence upon the "p" versus "s" wave annihilation has been left out.

As a way around this, one can consider a class of particles, called luxinos, whose main annihilation channel in the early Universe is into two photons. Assuming this, eqs. (15) and (7) predict

$$R \simeq \frac{10^5}{\Omega_\ell h^2}\left(\frac{GeV}{m_\ell}\right)^2 \frac{events}{year} \tag{27}$$

at GRO and a rate about eight times larger for ASTROGAM. Here m_ℓ and Ω_ℓ are the luxino mass and relic energy. This substantial rate should be visible above background by the EGRET detector. A specific model for a luxino, invisible in direct DM detection experiments via nuclear recoil, as has been suggested in ref. 5.

It is also interesting to mention that the magnino (m°), the particle proposed in ref. 15 to solve the solar neutrino problem, has an annihilation rate in the early Universe $m^\circ\overline{m}^\circ \rightarrow \gamma\gamma$ which is of the same order of $m^\circ\overline{m}^\circ \rightarrow f\bar{f}$. Therefore, if magninos and antimagninos are both present in the halo, a rate of order (16) is expected.

Finally, signals even larger than (16) can be obtained by relaxing the condition that the relic density of the DM particle is determined by the "freeze-out" annihilation, eq. (15). For instance, the DM particle density can be generated by the late decay of a long-lived particle, leaving almost unconstrained the annihilation cross section.

E. Technicolor dark matter

Technicolor theories, where the Higgs sector is replaced by a sector of strong interacting fermions, have a natural DM candidate[16]. In fact, the lightest technibaryon (LT) is stable since technicolor and extended technicolor interaction conserve technifermion number. Let us then assume that the LT is neutral and that the same mechanism giving rise to a cosmic baryon asymmetry (ε_B) produces a technibaryon asymmetry (ε_{TB}) of the same order. The relic density of LT is then

$$\rho_{TB} = \frac{\varepsilon_{TB}}{\varepsilon_B}\frac{m_{LT}}{m_P}\rho_B \simeq 10^{-3}\rho_B \quad , \tag{28}$$

since the LT mass (m_{LT}) is about $\Lambda_{TC}/\Lambda_{QCD} = 10^3$ times larger than the mass of the proton (m_P). Therefore, technicolor nicely explains the hierarchy between luminous and dark matter approximately in the correct range[16].

The population of antitechnibaryons is exponentially suppressed and no annihilation in the galactic halo can be expected from technicolor DM. However, the same interaction that violates baryon and technibaryon number and generates the cosmic asymmetry, will mediate the LT decay with lifetime $\tau_{LT} \simeq \left(\frac{m_P}{m_{LT}}\right)^5 \tau_P \simeq 10^{-15}\tau_P$, where τ_P is the proton lifetime. This produces a diffuse flux of galactic and extra-galactic photons, with typical energy $E_\gamma \simeq 10^{11-12}$ eV,

$$\frac{d\phi}{d\Omega} \simeq N_\gamma \, \frac{TeV}{m_{LT}} \, \frac{year}{\tau_{LT}} \, 10^{19}\mathrm{cm}^{-2}\mathrm{sr}^{-1}\mathrm{year}^{-1} \tag{29}$$

where N_γ is the number of photons per decay. The flux of eq. (18) could be observed at ASTROGAM even for parameters corresponding to a proton lifetime completely unaccessible to experiments.

Therefore, technicolor DM, which is rather elusive in direct searches via nuclear recoil, can very well be tested by studies of gamma rays in the region $E_\gamma \simeq 10^{11-12}$.

III. Conclusions

Detection of gamma ray lines in the GeV region would be a "smoking-gun" for direct DM particle annihilation into a pair of photons. Unfortuntely the signal from supersymmetric DM is only at the border of observability in future detectors, while the signal from heavy neutrinos is far too low. Nevertheless, new non-standard DM candidates (luxinos) can give very large rates, observable at GRO. Technicolor DM predicts a diffuse gamma ray spectrum in the TeV region, which could be observed by ASTROGAM.

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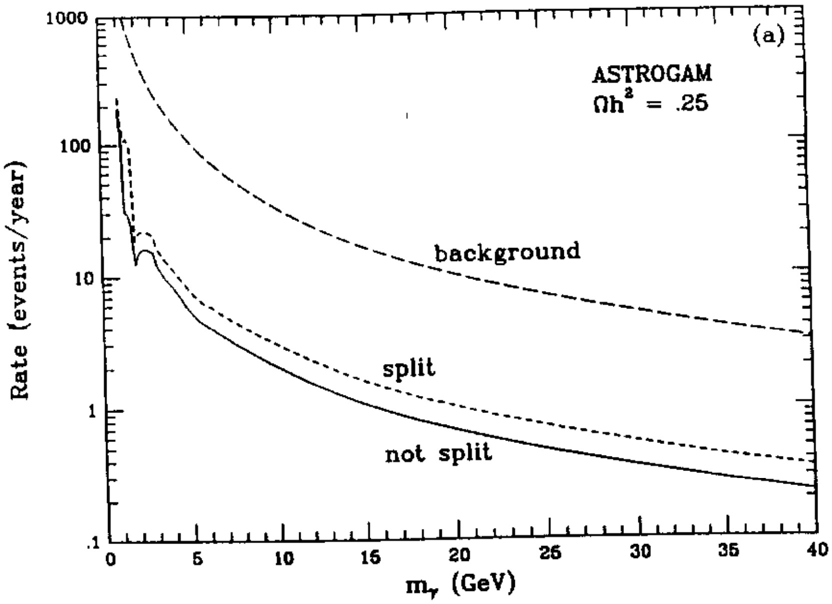

Fig. 1

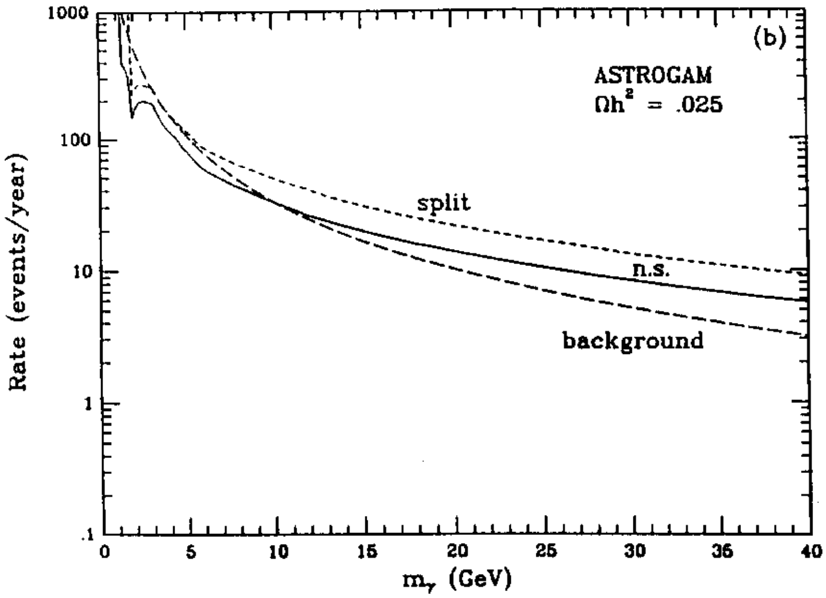

Fig. 2

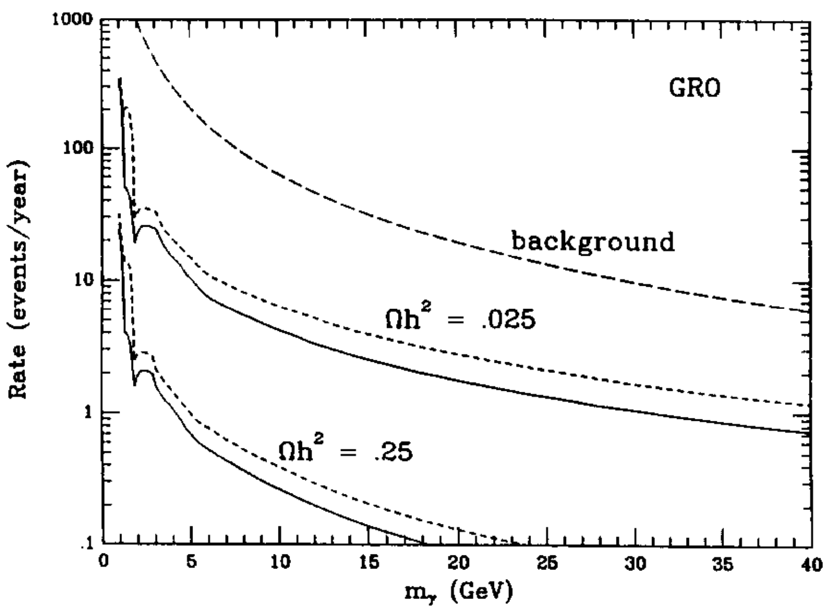

Fig. 3

Fig. 1-3. Photon counting rates at ASTROGAM and GRO EGRET from annihilation of galactic photons, assuming $\Omega h^2 = 0.25$ and 0.025. Using the experimental bounds on sfermion masses from ASP and CDF detectors, light photinos as dark matter can be excluded as indicated by vertical bars.