# Gamma Rays from Dark Matter

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**Abstract.** I give a brief review of high energy gamma-ray signatures of dark matter. The decay of massive $X$-particles and subsequent hadronization have been suggested as the origin of the highest energy cosmic rays. Propagation over cosmological distances to Earth (as would be the case in some topological defect origin models for the $X$-particles) results in potentially observable gamma-ray fluxes at GeV energies. Massive relic particles on the other hand, would cluster in galaxy halos, including that of our Galaxy, and may give rise to anisotropic gamma ray and cosmic ray signals at ultra high energies. Future observations above 100 Gev of gamma rays due to WIMP annihilation in the halo of the Galaxy may be used to place constraints on supersymmetry parameter space.

## INTRODUCTION

In this brief review I shall discuss possible high energy (HE) gamma-ray signatures of dark matter and how they may arise. I shall concentrate on gamma-ray signatures at high energies, and mainly on Cold Dark Matter (CDM) as this appears to make up most of the matter in the Universe. Observational constraints currently favor a so-called "ΛCDM" cosmological model [1] in which the various contributions to the closure parameter, $\Omega \approx 1$, are $\Omega_\Lambda \sim 0.7$ (cosmological constant), $\Omega_m \sim 0.3$ (CDM), $\Omega_b \sim 0.045$ (baryonic), $\Omega_\nu \gtrsim 10^{-3}$ (neutrinos). Hot dark matter would consist of neutrinos with mass in the range 1–10 eV, and these will not be discussed further. CDM candidates could be broadly classified into axions, weakly interacting massive particles (WIMPs) and supermassive particles (wimpzillas). Axions are predicted to explain the absence of strong CP violation. If they exist, axions with mass in the range $10^{-5}$–$10^{-3}$ eV would have been produced copiously in the early universe and could in principle make up all the CDM, but would probably not have HE gamma-ray signatures.

Topological defects (TD) such as monopoles, cosmic strings, monopoles connected by strings, etc., may be produced at the post-inflation stage of the early Universe. In the process of their evolution the constituent superheavy fields (particles) may be emitted through cusps of superconducting strings, during annihilation of monopole-antimonopole pairs, etc. These particles, collectively called

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X-particles, can be superheavy Higgs particles, gauge bosons and massive supersymmetric (SUSY) particles. These are generally very short-lived, and their decay followed by a hadronization cascade could produce an observable gamma-ray signal. Signals of TD origin would be affected by interactions/cascading during propagation over cosmological distances to Earth.

There could be also superheavy quasi-stable particles with lifetimes larger (or much larger) than the age of the Universe. These particles could be produced by many mechanisms during the post-inflation epoch, and survive until the present epoch. One interesting process is the "gravitational production of super-heavy particles", in which no interaction of X-particle is required. Also, string theories predict the existence of other super-heavy particles ("cryptons") which are metastable and could in principle form part of the CDM (see refs. [2,3]). As with any other kind of CDM, super-heavy quasi-stable X-particles would cluster in galactic halos. The same clustering would also occur for some TD, such as monopolonium, monopole-antimonopole pairs connected by a string, and vortons. The gamma-ray signals from all these objects would reach us relatively attenuated.

Perhaps the most promising WIMP CDM candidate is the lightest SUSY particle (LSP) with mass 20–1000 GeV. SUSY solves the problem of the Higgs mass $m_H \to \infty$ in the Standard Model. It is postulated that every particle has a SUSY partner with spin $\frac{1}{2}$ lower. It is also postulated that "R-parity" is conserved, normal particles having $R = +1$, SUSY particles having $R = -1$, and in an interaction or decay the product of $R$ being conserved. An important implication of R-parity is that the LSP must be stable. The LSP is therefore a strong candidate for CDM and, if it exists, would be the lightest of four neutralinos: $\tilde{\chi}_1$, $\tilde{\chi}_2$, $\tilde{\chi}_3$, $\tilde{\chi}_4$. Each neutralino is supposed to be a mixture of $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}^0$ and $\tilde{h}^0$. Annihilation of WIMPs could produce an observable HE gamma-ray signal.

## FRAGMENTATION FUNCTIONS

If particles make up CDM they are probably WIMPS ($\chi$) (e.g. neutralinos or heavy neutrinos) which would therefore cluster in the halos of galaxies where they would annihilate.

TD which accumulate in galaxy halos (monopolonia, monopole-antimonopole-pairs and vortons) could also produce a galactic signal through the annihilation/emission and decay of short lived "X-particles" which would in turn decay promptly into Standard Model states, while TD such as cosmic strings, necklaces, etc., are extragalactic, and could produce an extragalactic signal through the decay of short-lived X-particles. Super-heavy quasi-stable particles ($\tau \gg t_0$) would decay similarly but these would be clustered as CDM in galactic halos.

The annihilation (WIMP) and decay ($X$ particle) channels are then

$$\chi\bar{\chi} \to \gamma\gamma \text{ or } \gamma Z \qquad (\gamma\text{-ray lines})$$

$$\left\{ \begin{array}{c} \chi\bar{\chi} \\ X \end{array} \right\} \rightarrow \left\{ \begin{array}{c} W^+W^- \\ Z^0Z^0 \\ \bar{q}q \\ e^+e^- \\ \text{etc.} \end{array} \right\} \rightarrow \text{ hadrons} \rightarrow \ (\gamma\text{-ray continuum})$$

In the second case, each decay particle or annihilation product could gives rise to a jet of hadrons, e.g.

$$\left\{ \begin{array}{c} \chi\bar{\chi} \\ X \end{array} \right\} \rightarrow q\bar{q} \rightarrow \ 2 \text{ jets} \rightarrow \left\{ \begin{array}{l} \gamma\text{−rays} \\ \text{neutrinos} \\ \text{nucleons } (\sim 5\%) \\ \text{electrons} \end{array} \right.$$

Energy spectra of the emerging particles, the "fragmentation functions", were first calculated by Hill [4]. More recent calculations use PYTHIA/JETSET [5] or HERWIG Monte Carlo event generators to obtain the fragmentation functions. Each jet has energy $m_X/2$, and so one defines a dimensionless energy for the cascade particles, $x = 2E/m_X$. The fragmentation function for "species a" is then defined as $dN_a/dx$. A very flat spectrum of particles results, and this can be crudely approximated by

$$\frac{dN_a}{dx} \propto x^{-1.5} \qquad (\sim 32\% \ \pi^+, \pi^0 \,\text{and}\, \pi^-; \sim 4\% N)$$

where the particle energies extend up to $\sim m_X/2$. More sophisticated treatments used the Modified Leading Logarithm Approximation (MLLA) which is valid only for $x \ll 1$, and in more recent QCD calculations used PYTHIA/JETSET or HERWIG Monte Carlo event generators to obtain the fragmentation functions. The fragmentation functions due to Hill [4], those based on the MLLA [6], and the crude $x^{-1.5}$ approximation for large $x$ are compared in Fig. 1.

Initially, the inclusion of the production of SUSY particles [7] was done by putting 40% of the cascade energy above threshold for production of SUSY particles into LSP, thereby steepening the fragmentation functions for normal particles at high energy. In a recent paper Birkel and Sarkar [8] have shown using the HERWIG Monte Carlo that even without inclusion of SUSY production there is a significant dependence on $m_X$, such that for high $m_X$ the fragmentation functions are steeper, as a direct consequence of the well known Feynman scaling violation in QCD [9]. Fragmentation functions of Birkel and Sarkar [8] have been added to Fig. 1, and are well below previous QCD calculations for GUT scale $X$-particles. Sarkar [9] notes, however, that the HERWIG event generator overestimated production of nucleons by a factor ~2–3, and that new calculations by Rubin [10] address this issue and also include more correctly SUSY particle production. Very recent calculations by Berezinsky and Kachelriess [11] (added to Fig. 1) have also used new improved treatments of SUSY particle production, and result in only $\sim$ 5–12% of the cascade energy going into LSP.

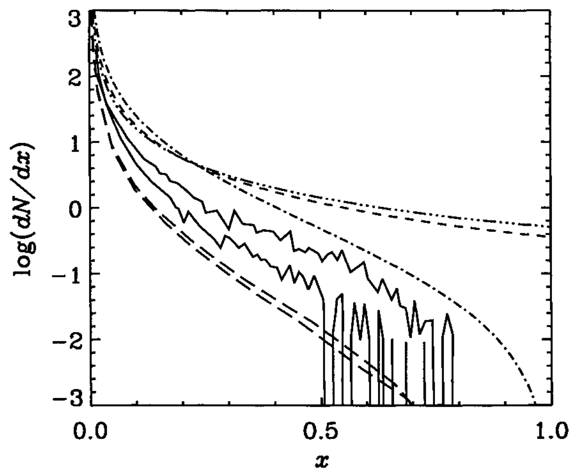


**FIGURE 1.** Fragmentation functions for hadronization of nucleons due to Hill [4] (dot-dashed curve), the MLLA approximation [6] (short dashed curve), the crude $x^{-1.5}$ approximation (dot-dot-dot-dashed curve), Monte Carlo results of Birkel and Sarkar [8] for $m_X = 10^3$GeV (upper solid curve) and $m_X = 10^{11}$GeV (lower solid curve), compared with recent results of Berezinsky and Kachelriess [11] for $m_X = 10^{12}$GeV (upper long dashed curve) and $m_X = 10^{14}$GeV (lower long dashed curve).

## Propagation over cosmological distance

Because of the flat spectrum of particles (including gamma-rays and protons) extending up to GUT scale energies, topological defect models [12–14] have been invoked to try to explain the ultra high energy cosmic rays (UHE CR) for various assumed $m_X$. Propagation of the spectra of all particle species over cosmological distances is necessary to predict the cosmic ray and gamma-ray spectra expected at Earth.

For propagation of energetic particles of energy $E$, mass $m$ and velocity $\beta c$, through isotropic radiation the reciprocal of the mean free path for collisions with photons is given by

$$x_{\rm int}(E)^{-1} = \frac{1}{8E^2\beta}\int_{\varepsilon_{\rm min}}^{\infty} d\varepsilon \frac{n(\varepsilon)}{\varepsilon^2}\int_{s_{\rm min}}^{s_{\rm max}(\varepsilon,E)} ds\,(s - m^2c^4)\sigma(s), \tag{1}$$

where $n(\varepsilon)$ is the differential photon number density, and $\sigma(s)$ is the relevant total cross section for a center of momentum frame energy squared given by $s = m^2c^4 + 2\varepsilon E(1-\beta\cos\theta)$ where $\theta$ is the angle between the directions of the energetic particle and soft photon, $s_{\rm min} = (\sum_{\rm final} m_{\rm final}c^2)^2$, $\varepsilon_{\rm min} = (s_{\rm min} - m^2c^4)/[2E(1+\beta)]$, and

$s_{\max}(\varepsilon, E) = m^2c^4 + 2\varepsilon E(1+\beta)$. For photon-photon pair production by gamma-rays, $m = 0$, $\beta = 1$, $\sum_{\rm final} m_{\rm final} = 2m_e$. For inverse Compton scattering, $m = m_e$, $\sum_{\rm final} m_{\rm final} = m_e$. For Bethe-Heitler pair production, $m = m_p$, $\sum_{\rm final} m_{\rm final} = 2m_e + m_p$, and for pion photoproduction, $m = m_p$, $\sum_{\rm final} m_{\rm final} = m_\pi + m_p$.

The "attenuation length" or "energy-loss distance", $x_{\rm loss}(E)$, is of greater interest and is defined by either $x_{\rm loss}(E) = x_{\rm int}(E)/K(E)$ where $K(E)$ is the mean inelasticity of the interaction (fraction of initial energy lost), or $x_{\rm loss}(E) = E/(-dE/dx)$ for continuous energy loss processes, e.g. synchrotron radiation. For photon-photon pair production $K(E) = 1$. The inelasticity is calculated using a Monte Carlo event generator for inverse Compton interactions [15,16], Bethe-Heitler pair production [17], and for pion photoproduction [17,18]. The radiation fields used here are the infrared [19], microwave, and radio [20] backgrounds. The energy loss distance of electrons, protons, and gamma-rays is shown in Fig. 2.

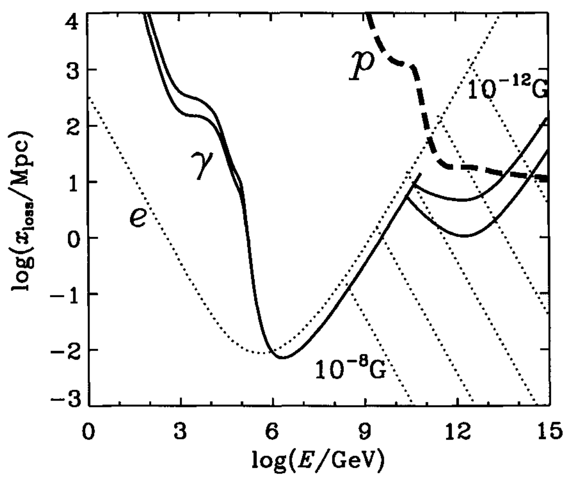


**FIGURE 2.** Energy loss distance, i.e. mean free path divided by inelasticity, of electrons "$e$", protons "$p$", and gamma-rays "$\gamma$". The following processes are included: for electrons inverse Compton scattering in the cosmic microwave background and sychrotron radiation in magnetic fields $10^{-12}, 10^{-11}, \ldots 10^{-8}$ G; for gamma-rays photon-photon pair production in the cosmic infrared [19], microwave and radio [20] backgrounds; for protons Bethe-Heitler pair production and pion photoproduction in the cosmic microwave background.

As can be seen from Fig. 2 the Universe is very far from being transparent above 100 GeV. Also, protons with energies above about $3 \times 10^{11}$ GeV can travel only about 25 Mpc before losing a substantial fraction of their energy, so that a cut-off was expected at $\sim 10^{11}$ GeV in the cosmic ray energy spectrum if the UHE CR originate in sources at cosmological distances, the "GZK cut-off" [21,22]. However, UHE CR have been observed above this energy [23,24] and are difficult to explain by conventional cosmic ray acceleration scenarios, making topological defect and superheavy CDM models an attractive possibility.

Protheroe and Meyer [25] have analyzed the consequences of a recent determination of the far-infrared background intensity. They find that the Universe would become nearly opaque to 20 TeV gamma rays at distances above $\sim 10$ Mpc. Using this to correct the gamma ray flux from Markarian 501 observed by HEGRA would lead to an unacceptably high luminosity for this source, $L_{501} \sim 10^{49}$ erg/s. They consider three possibilities: (i) the IR data is still contaminated by foreground emission; (ii) the 20 TeV events are due to Bose-Einstein condensates of lower energy photons [26]; (iii) Lorentz Invariance (LI) violation. If LI violation is the explanation, then the consequences of this are: (a) the Universe becomes transparent to photons above 100 TeV [27]; (b) the Universe also becomes transparent to protons – no GZK cut-off [28] — and so we should see spectra from TDs unattenuated. In this review, I shall adopt a conservative view, i.e. possibility (i), and not consider the new far-infrared data further or the possible consequences of it being correct, but the other possibilities should nevertheless be borne in mind.

## Calculating CR and $\gamma$-ray fluxes

I give below a qualitative description of how the particle fluxes arising from massive $X$-particle decay are calculated. In the case of massive relic particles clustering in halos of galaxies, there are assumed to be two components to the flux observed at Earth: (i) the flux due to $X$-particle decay in the halo of our galaxy, and (ii) the flux due to $X$-particle decay elsewhere in the Universe (mainly in halos of other galaxies). The fluxes can be estimated as follows

$$I_i^{h,u}(E) \approx \frac{1}{4\pi} \frac{n_X^{h,u}}{\tau_X} R_i^{h,u}(E) W_i(E) \qquad \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{eV}^{-1}$$

where $n_X^h m_x = \zeta_x \rho_{\mathrm{CDM}}^h$ is the density of $X$ particles in the halo, $n_X^u m_x = \zeta_x \Omega_{\mathrm{CDM}} \rho_{\mathrm{crit}}$ is the density of $X$ particles in the Universe, $n_X$ being the number density of $X$ particles, $\zeta_x$ is fraction of CDM in $X$ particles, and $\tau_X$ is the mean decay time of $X$-particles. $W^i(E)$ is energy spectrum for particle $i$ resulting from $X$-particle decay and subsequent cascading and is obtained from the fragmentation function. $R_i^{h,u}(E)$ is effective size of emission region for particle $i$ produced in our Galaxy's halo ($h$) or elsewhere in the Universe ($u$).

$$R_i^{h,u}(E) \approx \begin{cases} \text{size of halo for halo intensity} \\ \text{attenuation length for extragalactic intensity} \end{cases}$$

In the case of $X$-particles from topological defects distributed uniformly throughout the Universe, only the component $I_i^u(E)$ is calculated.

Sophisticated calculations take account of all cascading processes taking place during propagation over cosmological distances [14,13]. In even quite low magnetic fields synchrotron radiation by electrons dominates over inverse Compton scattering, and Protheroe and Johnson [17] using a sophisticated hybrid Monte-Carlo numerical calculation pointed out the importance of including pair-synchrotron cascades in UHE CR propagation. Following their approach, Protheroe & Stanev [14] showed that the $\gamma$-ray flux for many TD models of UHE CR exceeded that observed at 100 MeV energies for $B \gtrsim 10^{-9}$ G. I show in Fig. 3 their result for $m_X = 10^{14}$ GeV and $B = 10^{-9}$ G (solid curves) together with other calculations for $m_X = 10^{14}$ GeV to be discussed later. The flux of observable particles $(p, n, \gamma)$ was normalized to the observed UHE CR flux. Protheroe & Stanev concluded that for higher intergalactic magnetic fields and $m_X = 10^{14}$ GeV, or higher $m_X$ and $B = 10^{-9}$ G, the 100 MeV gamma ray flux would exceed that observed. Given that GUT scale $X$-particle masses were expected (i.e. $m_X \gtrsim 10^{16}$ GeV), and extragalactic fields are probably higher than $10^{-9}$ G it seemed in 1996 that UHE CR could not be explained with a TD origin.

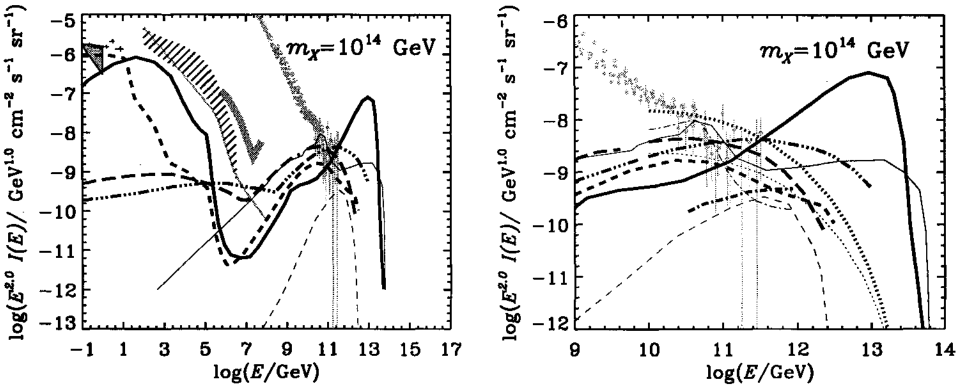


**FIGURE 3.** Models with $m_X = 10^{14}$ GeV. Thick curves are for gamma-rays, thin curves are for protons. Preditions are from: Protheroe & Stanev [14] TD (solid curves); Sigl et al. [29] TD $X \to \nu\nu$ (short dashed curves); Blasi [30] super-heavy relic halo population, SUSY-QCD and $\pi\mu e$ synchrotron (gamma rays only, long dashed curve), QCD and $\pi\mu e$ synchrotron (gamma rays only, dot-dot-dot-dashed curve). The right panel gives more detail at UHE energies and also includes the following results: Berezinsky et al. [32] super-heavy relic halo population, SUSY-QCD (dotted curves), necklaces SUSY-QCD (dot-dashed curves). Cosmic ray data are taken from the survey of Gaisser and Stanev [33]. Gamma ray data at 0.1–10 GeV are from [34,35], gamma-ray upper limit (thick line at $10^6$–$10^8$ GeV) is from [36], cosmic ray electron inverse Compton gamma ray prediction (shaded band at $10^2$–$3 \times 10^6$ GeV) is from ref. [37], and cosmic ray $\pi^0$ gamma ray prediction at $10^2$–$10^8$ GeV (thin curve) is from ref. [38].

## Recent calculations for TD and massive relic particles

Since 1996, recent theoretical work has suggested that $m_X$ can be significantly below the GUT mass, possibly in the range $10^{12}$–$10^{16}$ GeV. New fragmentation functions have been obtained using Monte Carlo jet hadronization codes, and attempts have been made to account for production of SUSY particles in these cascades. Also, new channels for $X$-particle decay have been considered, as well as different types of TD. Some recent calculations have considered an extragalactic magnetic field to be extremely low, $B \ll 10^{-9}$ G. Interactions of UHE $\nu$ with big-bang $\nu$ have been shown to be potentially important. Perhaps, the most interesting is the possibility of having relic massive particles that cluster in Galaxy halos. Having such a nearby potential source of UHE CR means that the propagation effects for UHE CR and gamma-rays are minimal, thereby giving a plausible explanation to the super-GZK cosmic ray events.

The main differences in the input to the various calculations are due to: (1) the mass of the decaying $X$-particles, (2) the origin of the massive particles - whether they are uniformly distributed through the Universe (e.g. from cosmic strings, etc.), or are clustered in galaxy halos (massive relic particles), and (3) the fragmentation functions determined by the $X$-particle decay channel, and the particle theory used (QCD, or SUSY-QCD). For example, Berezinsky, Blasi & Vilenkin [32] have made calculations for "Necklaces" producing $X$-particles of various masses $m_X = 10^{14}, 10^{15}, 10^{16}$ GeV, and have used SUSY-QCD with 40% of the energy going into LSP [7].

In none of the models is there an absolute prediction of what the rate of injection of primary cosmic rays is. The predicted fluxes are usually normalized to fit the highest energy cosmic rays, without violating limits and observations of the diffuse gamma-ray flux at GeV to PeV energies, and then some parameter describing the injection rate of energy from $X$-particle decay is determined. One such parameter is $\zeta_X t_0/\tau_X$, where $\zeta_X$ is the fraction of CDM in massive $X$-particles, and $\tau_X/t_0$ is the mean decay time of $X$-particles in units of the Hubble time. For example, Berezinsky et al. [6] have made, predictions for several models, their preferred model having $m_X = 10^{14}$ GeV. For $m_X = 10^{13}$ GeV, using QCD and MLLA, a halo radius $R_{\rm halo} = 100$ kpc and $\Omega_{\rm CDM}h^2 = 0.2$ and find $\zeta_X t_0/\tau_X = 5 \times 10^{-11}$. Birkel & Sarkar [8] used the HERWIG QCD event generator to get fragmentation functions, and for $m_X = 10^{12}$ GeV find $\zeta_X t_0/\tau_X \sim 1.5 \times 10^{-10}$ about 3–5 times higher than Berezinsky et al. They suggest that suitable particles with $m_X \sim 10^{12}$ GeV could be Cryptons with a decay time $\tau_X \sim 10^{20}$ yr which would give a unique signature in the ratio of UHE neutrinos to UHE CR.

Also affecting the results, particularly for gamma-rays, are the assumed values of the intergalactic magnetic field and the cosmic infrared and radio background fields adopted. It seems to me that in many cases, unrealistically low magnetic fields have been used (e.g. $\leq 10^{-10}$ G). This is a problem particularly for the models where the $X$-particles decay uniformly throughout the Universe rather than in galaxy halos because the UHE CR must propagate over cosmological distances to Earth, and

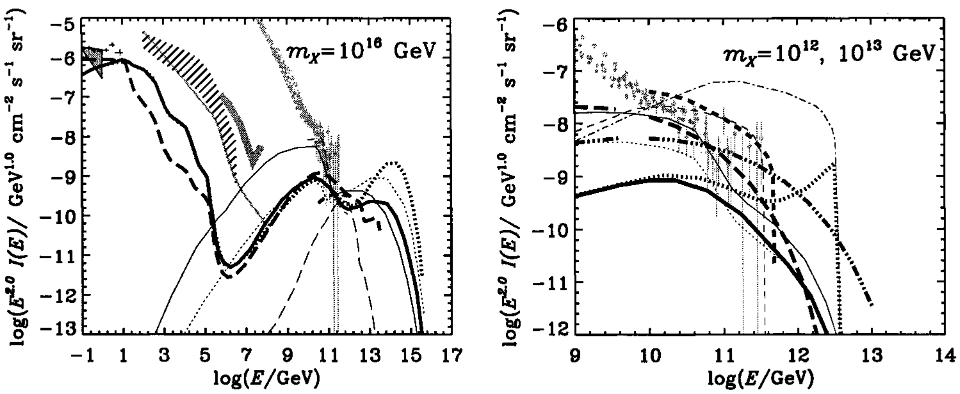


**FIGURE 4.** (a) Models with $m_X = 10^{16}$ GeV. Thick curves are for gamma-rays, thin curves are for protons. Predictions are from Sigl et al. [29]: TD $X \to \nu\nu$ (long dashed curves), TD $X \to q+q$ QCD (dotted curves), TD $X \to q+q$ SUSY-QCD (solid curves). (b) Models with $m_X = 10^{12}$ and $10^{13}$ GeV. Thick curves are for gamma-rays, thin curves are for protons. Predictions are from: Sigl et al. [29] TD $m_X = 10^{13}$ GeV, $X \to q+q$ QCD (solid curves), TD $m_X = 10^{13}$ GeV, $X \to q+l$ QCD (dotted curves); Blasi [30] $m_X = 10^{13}$ GeV super-heavy relic halo population, SUSY-QCD and $\pi\mu e$ synchrotron (gamma rays only, long dashed curve), QCD and $\pi\mu e$ synchrotron (gamma rays only, dot-dot-dot-dashed curve); Birkel and Sarkar [8] super-heavy relic halo population QCD $m_X = 10^{13}$ GeV (protons only, dot-dashed curve) and $m_X = 10^{12}$ GeV (short-dashed curve). Other data and limits are as in Fig. 3.

then pair-synchrotron cascading in realistic magnetic fields ($\geq 10^{-9}$ G) can give rise to excessive GeV gamma-ray production at GeV energies.

In the case of decay of massive relic particles clustering in galaxy halos being the origin of the highest energy cosmic rays, there may well be a problem with the predicted anisotropy of cosmic rays from our Galaxy's halo being too high [39], although this is far from certain [40,41]. Although there are a variety of possible dark matter halo distributions, the conclusions regarding anisotropy seem rather insensitive to the model chosen. Berezinsky, Blasi & Vilenkin [32] have made calculations for superheavy relic particles, and note that clustering in the halo implies an anisotropy towards the Galactic center, and an anisotropy towards Virgo.

An interesting idea due to Blasi [30] concerns the case of relic particles clustered in the halo decaying via $X \to \bar{q}q$. He notes that since the fragmentation functions have $f_\pi \gg f_N$, the UHE CR could be $\pi^0$ $\gamma$-rays. In this case, electrons from $\pi\mu e$ decay would synchrotron radiate $\gamma$-rays which might be detectable at $E > 300$ TeV. However, it is not certain whether the highest energy cosmic rays can be gamma-rays (see e.g. ref. [31]).

Sigl et al. [29] have made a series of calculations for the case of emission from topological defects (no halo clustering). An innovation in their calculations is to include $\nu\nu$ interactions during propagation. They consider three decay modes: $X \to q + q$, $q + l$, or $\nu + \nu$ and $X$-particle masses in the range $10^{13}$–$10^{16}$ GeV. Interestingly, the $\nu\nu$ interactions during propagation result in UHE CR protons even for the case of $X \to \nu + \nu$.

Gamma-ray signals and their associated cosmic ray fluxes for the models discussed above are shown in Figs. 3 and Figs. 4. Fragmentation functions for various different assumptions gives rise to a relatively large range of model predictions. With the improvements in the accuracy of calculations of the fragmentation functions [11,10,9], the current large spread in the predicted gamma ray fluxes should hopefully decrease.

Bhattacharjee, Shafi and Stecker [42] point out that TDs such as monopoles and cosmic strings associated with phase transitions in some SUSY theories can be sources of Higgs bosons of mass $\sim 1$ TeV as well as gauge bosons of mass $\gg 1$ TeV. These TD-produced TeV scale Higgs may contribute significantly to the gamma ray background above a few GeV. The topic of gamma-ray cascading over cosmological distances from TeV to GeV energies in the infrared background had been discussed earlier [43], and in the context of using the observed background at GeV energies to constrain energy injection at TeV and higher energies [14,44].

## NEUTRALINO ANNIHILATION

The case of neutralino annihilation in CDM halos has been discussed for several years [45,46]. Assuming the CDM to be neutralinos and considering the annihilation channels $\chi\bar{\chi} \to \gamma +$ anything, one expects a gamma-ray flux above energy $E$ of

$$I_\gamma^{\rm SUSY}(>E) = \frac{1}{4\pi}\frac{\langle\sigma v\rangle N_\gamma(>E)}{m_\chi^2}\int \rho_\chi^2 ds$$

where $\sigma$ is the annihilation cross section, and $v$ is neutralino velocity. $\rho_\chi$ is the mass density in neutralinos, assumed to be clustered in galaxy halos. Because the density is squared in the case of annihilations, the emission is very strongly peaked towards the center of the galaxy being observed, Baltz et al. [47] suggest looking for $\gamma$-rays from nearby galaxies. They also point out that if the CDM is clumped, the gamma-ray flux could be enhanced by $\sim \times 40$ (based on estimate of the fraction of the halo in clumps). They assume, $\langle\sigma v\rangle N_\gamma(>100\ \text{GeV}) = 10^{-25}$ cm$^3$ s$^{-1}$, $m_\chi = 1$ TeV, use the Lund Monte Carlo for the fragmentation functions, and find potentially observable fluxes above 100 GeV from within a few arc-minutes of M87. They note, however that a large background from cosmic ray electrons is expected, and that an enormous collecting area is required.

Strausz [48] suggests that neutralino annihilation just outside the Sun by neutralinos trapped by the Sun's gravitational potential may give a signal above 100 GeV potentially detectable by GLAST or MILAGRO.

Looking for gamma-rays from neutralino annihilation gives a way of potentially exploring the SUSY parameter space. The minimal supersymmetric standard model (MSSM) has many free parameters, but reasonable choices for most leave 7 remaining free. A model, i.e. a set of 7 parameters, is sampled by the Monte Carlo method, and the model is rejected if it is already excluded by other data. For each model, the product of the annihilation cross section with the fragmentation function for gamma-rays above energy $E$, i.e. $\langle \sigma v \rangle N_\gamma(>E)$ is worked out and plotted against $m_\chi$. Future $\gamma$-ray observations of such a CDM signal could in principle limit the SUSY parameter space.

Berezinsky, Bottino and Mignola [49] noted that neutralino annihilation for the case of a power-law galactic halo CDM density profile would produce a potentially observable flux of gamma-rays from the galactic center (GC) because of the cusp in $\rho^2$ expected at the GC. More recently, Bergstrom, Ullio and Buckley [50] have studied this process in detail, exploring the SUSY parameter space. They calculate $\langle \sigma v \rangle N_\gamma(>E)$ for a range of models as described above, and from this obtain the expected GC $\gamma$-ray flux for each model. Fluxes for some of the models may be detectable with future atmospheric Cherenkov telescopes, but for most models the predicted flux is below the sensitivity of any planned telescope.

## GEV GAMMA RAYS FROM GALACTIC HALO

The recent discovery of a diffuse galactic halo in GeV gamma-rays by Dixon et al. [51] (see also Chary and Wright [52]) has led to several possible dark matter explanations. For example, Gondolo [53] suggests this may be due to annihilation of relic WIMPS with mass $\sim$ 2–4 GeV corresponding to $\Omega_\chi \sim 0.1$. Fargion et al. [54] suggest that it could be due annihilation of heavy relic neutrinos, $N$, with mass in the range $m_Z/2$ to $m_Z$ followed by inverse Compton scattering of electron pairs or decay of $\pi^0$ produced as a result of $N \rightarrow q\bar{q}$. They conclude that the predicted halo flux is consistent with that observed. De Paolis et al. [55] suggest that cold $H_2$ clouds may be clumped in dark clusters (possibly MACHOs) in the galactic halo. Cosmic ray interactions would then produce a $\gamma$-ray intensity at GeV energies which would be anisotropic. For all of these possibilities, there would be an important background due to inverse Compton scattering from CR electrons which it might be possible to disentangle by examining the energy spectrum of the halo component.

## CONCLUSION

Most of the Matter in the Universe is CDM, and if it consists of neutralinos, or massive relic particles they should cluster in galaxy halos. In the case of massive relic particles, their decay would produce UHE gamma-ray and CR signals weakly anisotropic towards the GC, and the UHE CR spectrum would not have a GZK cut-off. WIMP annihilation gamma-ray signals would be strongly anisotropic towards the GC. Detection of such signal by GLAST and future atmospheric Cherenkov telescopes would constrain SUSY models. If CDM consists of particles associated with Topological Defects distributed uniformly throughout the Universe, then UHE CR are subject to the GZK cut-off. In this case $\gamma$-ray signals result from a pair-synchrotron cascade in background radiation and extragalactic magnetic fields. The magnetic fields used in some cascade calculations may have usually been unrealisticly low, and the infrared and radio radiation fields are subject to uncertainties. Absolute fluxes for TD models are not predictable, but detection of UHE gamma ray signals can be used to constrain models. Currently, predictions for the case of massive relic particles and TD models suffer from uncertainties in the fragmentation functions as illustrated by the spread in Fig. 1, but work is underway to improve this [11,9].

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