Supersymmetric Dark Matter and the Extragalactic Gamma Ray Background

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We argue that the annihilation of cosmological neutralinos with a thermally averaged total annihilation cross section \( \langle \sigma v \rangle = 3.05^{+0.67}_{-0.57} \times 10^{-26} \text{cm}^3\text{s}^{-1} \) and rest mass \( m_\chi = 515^{+110}_{-75} \) GeV could be the main source of the observed extragalactic gamma ray background at energies of a few GeV. Based on the assumption that neutralinos provide the bulk of the cold dark matter, the extragalactic continuum gamma ray intensity due to neutralino annihilations is computed using results of high-resolution N-body structure formation simulations.

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INTRODUCTION

The extragalactic gamma-ray background (EGB) has been a challenge to both theory and experiment, ever since the seminal paper by Morrison in 1958. Diffuse, isotropic gamma-ray background radiation results either from the emission of numerous sources too faint to be resolved, or from weakly interacting massive particles ("WIMPs") that have survived as a fossil record of the early Universe. The EGRET spark chamber detector on board the Compton Gamma Ray Observatory successfully completed an all-sky survey above 30 MeV after collecting data from 1991 until 2000. Careful subtraction of the foreground plays an equally important role to determine the extragalactic background as in the case of other cosmological precision measurements, e.g. the measurements of the microwave background and its anisotropies. The discovery of a residual galactic gamma ray halo at GeV-energies prompted improvements of the foreground model used in the analysis of the EGRET data. A new determination of the intensity of the EGB in the energy range of 30 MeV–50 GeV has been accomplished using an improved numerical code (GALPROP) for modeling this galactic gamma-ray foreground, including an Inverse-Compton (IC) component. The EGB spectrum has two components: a steep-spectrum power law with index \( \alpha = -2.3 \) and a strong bump at a few GeV. The first analysis of the EGB did not reveal as clearly this spectral structure. Guided by the observation that the net spectral index of \( -2.1 \pm 0.03 \) was tantalizingly close to the mean spectral index of the resolved extragalactic EGRET sources (all but one are blazars), it was concluded that faint, unresolved blazars were responsible for up to 25% or 100% of the background, respectively. Physically related sources (such as radio galaxies) or gamma ray bursts could also contribute to the EGB. Whatever astrophysical scenario may be considered, however, an universal multi-GeV bump resulting from the superposition of the spectra of a large, diverse population of sources remains conspicuous.

By contrast, the observed energies of the excess bump appear naturally in the context of models involving weakly interacting, self-annihilating cold dark matter. MeV-scale dark matter particles have recently been discussed as a source of the galactic positronium halo. The Lee-Weinberg criterion for thermal freeze-out during the hot Big Bang, however, renders weakly interacting particles with masses much larger than that of the proton natural candidates for the cold dark matter. Independently, supersymmetry calls for a new stable particle with weak interactions and a mass scale close to \( E_F = (1/\sqrt{2G_F})^{1/2} \approx 246 \) GeV, probably the lightest neutralino \( (\chi^0) \). Neutralinos can indeed provide cosmologically relevant amounts of cold dark matter, choosing from the large parameter space available in the Minimal Supersymmetric Standard Model (MSSM). The annihilation of the Majorana neutralinos in dark matter halos - starting from the freeze-out in the hot Big Bang and continuing until the present day - produces electromagnetic radiation (along with \( \nu, p, e \)) from the decay chains of short-lived heavy leptons or quarks. Annihilation lines would only arise from the loop-level processes \( \chi \chi \rightarrow \gamma \gamma \) and \( \chi \chi \rightarrow Z^0\gamma \), and thus their intensities are generally expected to be rather small. The continuum gamma-ray energies are kinematically lowered by factors of the order of ten. Owing to progressive structure evolution, the strongest contribution to the gamma-ray intensity from neutralino annihilation is expected from small-mass halos at moderate redshifts \( z < 1 \). Hence it follows that redshift convolution would affect the shape of the spectrum only little. Obviously, the number of dark matter halos must be much larger than any possible astrophysical gamma-ray source population, and hence the main signature of cosmological neutralino annihilation should actually be a rather narrow bump in the EGB at about \( \sim 10 \) GeV. In this Letter, we show that the observed bump in the EGB could well be a signature of dark matter annihilation, and that there exists an allowed range of neutralino candidates in the cosmologically constrained MSSM naturally explaining this feature when combined with a steep astrophysical power-law spectrum component.
GAMMA RAYS DUE TO COSMOLOGICAL NEUTRALINO ANNIHILATION

For an observed halo at redshift \(z\) and energy \(E\), annihilation will dominantly lead to jet fragmentation, producing continuum gamma rays with differential energy distribution \(df(E(1+z))\). The extragalactic gamma-ray intensity due to neutralino annihilation is then given by

\[
\Phi_\gamma(E) = c/(4\pi H_0) \times 1/2 \langle\sigma v\rangle_\chi \Omega M_\rho \rho_{crit}/m^2_\chi \times \int_0^{z_{max}} (1+z)^3 \times \kappa(E,z) \times \Gamma(z) \times df(E(1+z)) / \xi(z) \, dz
\]

where \(\rho_{crit}\) is the critical density. Since we consider contributions from annihilations at high redshifts, gamma-ray attenuation is included via the attenuation function \(\kappa(E,z)\). For \(0 < z \leq 5\) we use the attenuation derived from the star formation history [19], whereas for \(z > 5\) the absorption derived from interactions with the cosmological relic radiation field [20] is employed. \(\Gamma(z)\) denotes the intensity multiplication function obtained from high-resolution simulations of structure formation [18]. The range of integration is limited to 0 \(\leq z \leq 20\); gamma rays from higher redshifts are negligible. The parameter \(\xi(z)\) is given by \(\xi(z)^2 = \Omega_M (1+z)^3 + \Omega_K (1+z)^2 + \Omega_\Lambda\). 

In this work, we employ the cosmological "concordance model" of a flat, dark energy and dark matter dominated Universe with the parameters \((\Omega_{DM}, \Omega_{M}, \Omega_K, \Omega_\Lambda) = (0.23, 0.27, 0, 0.73)\). For the dimensionless Hubble-Parameter \(h\) we use the value 0.71 [22]. The annihilation induced intensity scales quadratically with the local overdensity and thus strongly depends on the amount of structure present in the dark matter. The intensity enhancement due to structure formation is sensitive to the predominant density profile of the dark matter halos. High resolution N-body simulations generally yield an "universal" dark matter halo profile \(\rho(t) = \rho_0/[(t/r_0)^\gamma][1 + (t/r_0)^\gamma]^{(3-\gamma)/\alpha}\), where \(\rho_0\) and \(r_0\) denote scale density and radius. For the center of our galaxy, observations could not yet demonstrate whether such a "cusped" dark matter halo exists. Mounting evidence of the existence of \(r^{-\gamma}\)-type halo profiles, however, comes from X-ray observations of Abell clusters [20] and from the Lyman-\(\alpha\)-forest at high redshifts [21]. For our calculations, we will employ the Moore et al. profile \((\alpha = \gamma = 1.5\) and \(\beta = 3)\) [22] and a lower mass cutoff for the halos/subhalos of \(10^6\) solar masses.

The resulting intensity enhancement \(\Gamma(0) = 1.5 \times 10^7\) is well within the range of values possible for different scenarios of structure formation history.

MODELING THE ANNIHILATION COMPONENT

We compare the EGB intensity due to neutralino annihilations with EGRET data [4], depending on the parameters \(\langle\sigma v\rangle_\chi\) and \(m_\chi\). The EGRET data points in the energy range 50 MeV–300 MeV are very well described by a power law, the best-fit spectrum is \(7.4 \times 10^{-7} \times (E/GeV)^{-2.33}\). Adding the annihilation spectrum to this steep power law (presumably due to faint, unresolved active galactic nuclei), best fit values for the cross-section and neutralino mass are \(\langle\sigma v\rangle_\chi = 3.05 \pm 0.85 \times 10^{-25}\) cm\(^3\) s\(^{-1}\) and \(m_\chi = 515^{+110}_{-70}\) GeV (Fig. 1). To verify that correspondingly high values for \(\langle\sigma v\rangle_\chi\) can actually be obtained within the MSSM framework while producing cosmologically interesting amounts of neutralinos we use the DarkSusy [23] numerical routines to scan the MSSM parameter space. In Fig. 1, we plot valid models that have been found in a promising region of the parameter space described in Table 1. Obviously, there are numerous models within the MSSM which can, in fact, produce the required type of signature in the EGB, even if the intensity enhancement due to structure formation is smaller than assumed here.

The models we plot are required to thermally produce 0.025 \(\leq \Omega_\chi h^2 \leq 0.15\). Among these models, many have a resulting \(\Omega_\chi h^2\) in the right ballpark for being the dominant constituent of the dark matter. For models producing less than \(\Omega_\chi = 0.23\) an additional, non-thermal source of neutralinos, e.g. from the decay of heavier relic particles, might be considered. In this venue, an interesting possibility arises from the Anomaly Mediated Symmetry Breaking (AMSB) scenario, which has been shown to naturally produce very high (\(O(10^{-24})\) cm\(^3\) s\(^{-1}\)) values for \(\langle\sigma v\rangle_\chi\) [24]. For a MSSM-neutralino with a mass of 520 GeV and \(\langle\sigma v\rangle_\chi = 3.10 \times 10^{-25}\) cm\(^3\) s\(^{-1}\) the value of \(\chi^2/\nu\) is 0.74, which is excellent. The MSSM parameters and resulting EGB spectrum for this model are shown in Fig. 2. This neutralino is a very pure gaugino (gaugino fraction 0.996) and thermally produces the correct relic density of \(\Omega_\chi h^2 \approx 0.1\). In this scenario the mass of the lightest Higgs boson \(H_2\) is 118.32 GeV.

<table>
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<th>Abs[(\mu)]</th>
<th>Abs[m_\chi]</th>
<th>m_\chi</th>
<th>tan (\beta)</th>
<th>m_S</th>
<th>(A_t)</th>
<th>(A_b)</th>
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<td>1500 GeV</td>
<td>50</td>
<td>3000 GeV</td>
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<td>-1</td>
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TABLE I: Limits of the region of the MSSM parameter space that have been scanned with DarkSusy for cosmologically interesting neutralino models not excluded by current accelerator limits; (higgsino mass parameter \(\mu\); gaugino mass parameter \(m_\chi\); mass of the cp-odd higgs \(m_A\); ratio of the higgs vacuum expectation values \(\tan \beta\); scalar mass parameter \(m_S\) and the trilinear soft-breaking parameters for the third generation squarks \(A_t\) and \(A_b\) )
component with the hardest spectral index determined from EGRET data of resolved sources, to see how well the new result for the EGB can be matched. Evaluating $\Phi_{\nu}^{\text{AGN}} \propto \int d\nu n(z)(1+z)^2[(E(1+z)/E_b)^{-2.33} + (E(1+z)/E_b)^{-1.5}] \times \kappa(E,z)$ with the source density in the comoving frame $n(z) \propto (1+z)^{m}$ in the redshift range $0.03 \leq z \leq 1.5$, we obtain a coarse, rescaled version of the SS96-model, in which the amplitude and break energy $E_b$ were chosen to minimize $\chi^2/\nu$. Details of the luminosity evolution are unimportant for this test. The result of fitting this straw person’s model to the new EGB data is a value of 1.05 compared to the 0.74 of the SUSY-model (Fig. 2). We have also tested the extreme case of no $z$-evolution (homogeneous space density) to avoid the smearing of the spectral features by the $(1+z)$-factors without much improvement. It should be noted that the astrophysical model not only fits worse than the neutralino model, but requires an universal break or crossing energy $E_b$ of the order of (1–10) GeV. No robust physical mechanism is known keeping this energy fixed in a diverse source population. Moreover, the fraction of sources with hard spectra at an energy of 1 GeV at any time would have to be about 25% - considerably more than the fraction of the hard-spectrum sources in the EGRET catalog [25]. The blazar model also predicts $\sim 1000$ sources with a $> 300$ GeV flux of the order of

**FIG. 1:** Results of the $\chi^2$-test of the neutralino annihilation hypothesis against the measured EGB. The dots represent MSSM neutralinos created by scanning the parameter space described in Table I; for models that do not thermally produce $\Omega_\chi = \Omega_{\text{DM}}$ the value of $\langle \sigma v \rangle_\chi$ is rescaled by a factor $\Omega_\chi/\Omega_{\text{DM}}$. The rectangle denotes the 520 GeV-neutralino further explored in Fig. 2

**FIG. 2:** Extragalactic gamma-ray background: spectrum as determined from EGRET data by Strong et al. (solid circles); the upper limit in the (60–100) GeV range is from Sreekumar et al.; steep power law background component (dashed), Stecker & Salamon blazar model (dot-dashed), straw person’s blazar model (dotted line), neutralino annihilation spectrum (thin solid line), and combined annihilation plus steep power law background spectrum (thick solid line)

**COMPARISON WITH ASTROPHYSICAL BACKGROUND MODELS**

The total, omnidirectional flux emitted by the resolved extragalactic sources amounts to roughly 10% of the EGB intensity. All but one of the resolved sources are blazars, i.e. radio galaxies at cosmological distances seen close to their jet axes. Relativistic motion with bulk Lorentz factor $\Gamma > 1$ commonly found in the extragalactic jets of radio galaxies leads to a Lorentz-boosted forward radiation pattern. Obviously, misoriented jets, low values of the bulk Lorentz factor, low jet power, etc. must correspond to weaker, but more numerous, gamma-ray sources. These faint sources with fluxes below the EGRET detection limit contribute an unknown fraction of the EGB intensity [2]. In order to explain the weak concave behavior of the EGB intensity above 1 GeV, as it had emerged from the first analysis of the EGRET data [1], these authors assumed a two component nature of the variable blazar spectra: a steep power law as a stationary emission component, and a flatter power law as a flaring component. The predicted EGB intensity does not agree with the strong bump feature evident in the new determination of the EGB (Fig. 2). Constructing a straw person’s model with the same redshift evolution, we modify the assumptions of Stecker & Salamon (SS96) by adopting steeper spectra for the quiescent (faint) component, and adding a flatter (flaring) spectral
a typical Whipple-source, whereas the steeper power law would imply \( \sim 40 \) sources (we mimicked source evolution and gamma attenuation by assuming the same source distribution in \( z \) as in the straw person’s blazar model). The first number seems worryingly large in view of the \( \sim 10 \) confirmed sources, in spite of excessive observation campaigns on candidate sources from radio and X-ray catalogues \cite{26}. The new-generation Cherenkov telescopes H.E.S.S., MAGIC, VERITAS, and the GLAST observatory will tell the story.

**DISCUSSION**

We have arrived at the conclusion that the observed EGB spectrum is in agreement with the annihilating neutralino dark matter scenario. Best-fit values for the thermally averaged annihilation cross section and neutralino mass are \( \langle \sigma v \rangle = 3.05^{+0.85}_{-0.70} \times 10^{-25} \text{cm}^3\text{s}^{-1} \) and \( m_\chi = 515^{+110}_{-75} \text{GeV} \). The rather high scale for the mass ladder of the supersymmetric particles might render their direct detection by the LHC experiments difficult \cite{27}. The EGB spectrum can also be fitted acceptably with blazar models of the Stecker & Salamon type, but these run into several worrying difficulties. A universal spectral break at GeV energies is required by conspiracy, the models predict a higher fraction of hard-spectrum sources at GeV energies than observed with EGRET, and the models imply a considerably higher number of low-redshift blazars expected above 300 GeV than discovered with imaging air Cherenkov telescopes. The extragalactic radio intensity implied by the neutralino annihilation scenario is not larger than the intensity due to normal and radio galaxies \cite{25}. Should a dark matter cusp \cite{25} exist in the central region of the Milky Way, the Galactic Center would exhibit a gamma luminosity of \( 5.0 \times 10^{35} \text{ergs/s} \) above 1 GeV from within \( 10^{-3} \text{sr} \). However, the already detected strong TeV-emission (probably due to supernova remnants) \cite{26} will make background suppression in gamma-ray observations of the Galactic Center difficult. The galactic neutralino population would give rise to a faint galactic gamma-ray halo with intensity \( \sim 10^{-7} \text{ph cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) above 1 GeV. Present data do not allow to confirm or disconfirm such a non-IC halo component, but for the galactic component commonly attributed to Inverse Compton radiation also neutralino annihilation has been proposed as a source \cite{3, 31}. A robust calculation using DarkSusy shows that the corresponding galactic antipton flux is compatible with the BESS measurements \cite{32}. External galaxies such as M87 should also be interesting targets for gamma-ray observations \cite{33}. For the MAGIC telescope at an energy threshold of 50 GeV and the halo profile from \cite{33}, the annihilation component in the gamma spectrum of M87 would be detectable with 5\( \sigma \) in 250 hours of observation time.

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