Supersymmetric Dark Matter and the Extragalactic Gamma Ray Background

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We trace the origin of the newly determined extragalactic gamma-ray background from EGRET data to an unresolved population of blazars and neutralino annihilation in cold dark matter halos. Using results of high-resolution simulations of cosmic structure formation, we calculate composite spectra and compare with the EGRET data. The resulting best-fit value for the neutralino mass is $m_\chi = 515^{+110}_{-75}$ GeV (systematic errors ~30%).

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The origin of the extragalactic gamma-ray background (EGB) has been discussed since the seminal paper on gamma-ray astrophysics by Morrison in 1958 [1]. 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 completed an all-sky survey above 30 MeV, collecting data from 1991 until 2000 [2]. Subtraction of the foreground plays an equally important role in determining the extragalactic gamma-ray 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 [3] 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 the numerical code GALPROP for modeling the galactic gamma-ray foreground, now including an inverse-Compton component [4]. The EGB spectrum has two components: a steep-spectrum power law with index $\alpha = -2.33$ and a strong bump at a few GeV. The first analysis of the EGB [5] did not reveal as clearly this spectral structure. Guided by the observation that the net spectral index of -2.10 ± 0.03 was tantalizingly close to the mean spectral index of the resolved extragalactic EGRET sources (all but Centaurus A and the Large Magellanic Cloud are blazars), it was then concluded that faint, unresolved blazars were responsible for up to 25% or 100% of the background, respectively [6–8]. Physically related sources (such as radio galaxies), large-scale structures [9], or gamma-ray bursts [10] could also contribute to the EGB. Whatever astrophysical scenario may be considered, however, a universal multi-GeV bump resulting from the superposition of the spectra of a large, diverse population of sources remains suspicious. By contrast, the observed energies of the excess bump appear naturally in the context of models involving weakly interacting, annihilating cold dark matter. MeV-scale dark matter particles have recently been discussed as a source of the galactic positronium halo [11]. 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 [12]. Independently, supersymmetry calls for a new stable particle with weak interactions and a mass scale close to $E_F = (1/\sqrt{2}G_F)^{1/2} \simeq 246$ GeV, probably the lightest neutralino (χ_1^0) [13]. 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 ν, p, e) from the decay chains of short-lived heavy leptons or quarks. Annihilation lines [14] would only arise from the loop-level processes $\chi\chi \to \gamma\gamma$ and $\chi\chi \to Z^0\gamma$, 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 10 [15]. 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 10 GeV [16]. In this Letter, we show that the observed bump in the EGB could well be this signature of dark matter annihilation, and that there exists an allowed range of neutralino candidates in the cosmologically constrained minimal supersymmetric standard model (MSSM) naturally explaining this feature when combined with a steep astrophysical power-law spectrum component.

Modeling the annihilation component.—With the differential gamma-ray energy distribution from jet fragmentation and π^0 decay df, observed energy E and redshift z, the extragalactic gamma-ray intensity due to WIMP annihilation can be written as $\Phi_\gamma(E) = c/4\pi H_0 \times 1/2\langle\sigma v\rangle_\chi \Omega_{\rm DM}^2 \rho_{\rm crit}^2/m_\chi^2 \times \int_0^{z_{\rm max}}[(1+z)^3\kappa(E,z)\Gamma(z) \times \Psi df_{E(1+z)}]/\xi(z)dz$, [14,16,17] where $\rho_{\rm crit}$ is the critical density. Since we consider contributions from annihilations at high redshifts, gamma-ray absorption is included via the attenuation function $\kappa(E,z)$. For $0 \le z \le 5$ we use the attenuation derived from star formation history [18], whereas for $z > 5$ the absorption from interactions with

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the cosmological relic radiation field [19] is employed. 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 $(\Omega_{\rm DM}, \Omega_M, \Omega_K, \Omega_\Lambda) = (0.23, 0.27, 0, 0.73)$. For the dimensionless Hubble-Parameter h we use the value 0.71 [20]. The annihilation induced intensity scales quadratically with the dark matter density and thus strongly depends on the amount of structure present in the dark matter. This dependence is included via the function $\Gamma \equiv 1/(\bar{\rho}^2 V) \int_v \rho^2 dV$ ($\bar{\rho}$: mean density over volume V), which we use as z-dependently evaluated for cosmological volumes in [21]. Generally speaking, $\Gamma(z)$ therefore is the "enhancement factor" between a structured universe and a completely homogeneous dark matter distribution. This enhancement due to structure formation is sensitive to the predominant density profile of the dark matter halos, and therefore subject to some uncertainty. Most high-resolution N-body simulations yield a universal dark matter halo profile $\rho(r) = \rho_S/\{(r/r_S)^\gamma[1+(r/r_S)^\gamma]^{(\beta-\gamma)/\alpha}\}$, where ρ_S and r_S denote scale density and radius. Mounting evidence of the existence of this type of dark matter density profile and the validity of the paradigm of hierarchical structure formation comes from x-ray observations of Abell clusters [22] and from observations of the Lyman-α forest at high redshifts [23]. For our calculations, we will employ the Navarro-Frenk-White (NFW) profile ($\alpha = 1$, $\beta = 3$, and $\gamma = 1$) [24,25] and a lower mass cutoff for the halos or subhalos of 10^5 solar masses as the baseline case. For the mass-dependent concentration parameter $c(M_{\rm halo}, z_{\rm formation}) \equiv r_{\rm virial}/r_S$ the results presented in [26] are used. This scenario yields a present-day enhancement of the flux of 2×10^6, compared to a completely structureless universe [21].

If a substantial fraction of the dark matter halos has steeper inner slopes, like the Moore *et al.* profile [27], the overall intensity enhancement might well be a constant factor of 2–25 larger than assumed here (depending on the inner cutoff radius in case of a singular inner slope $\propto r^{-1.5}$ or steeper) [21]. Even steeper inner slopes can arise from adiabatic compression by baryons [28]. To account for this uncertainty, in this paper we will work with the NFW case of $\Gamma(0) = 2 \times 10^6$, while keeping in mind that the intensity could be additionally boosted by a factor $\Psi = \mathcal{O}(1 \ldots 10)$. Substantial clumping of the dark matter on mass scales below 10^5 solar masses [29] might result in further enhancement of the intensities. We compare the EGB intensity due to WIMP annihilations with EGRET data [4], depending on the neutralino parameters $\langle\sigma v\rangle_\chi$ and m_χ. The EGRET data points in the energy range 50–300 MeV are very well described by a power law, presumably due to faint, unresolved active galactic nuclei. The best-fit spectrum is $7.4 \times 10^{-7} \times (E/\mathrm{GeV})^{-2.33} ph\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\mathrm{sr}^{-1}\ \mathrm{GeV}^{-1}$. A steeper spectrum than that of the resolved EGRET sources is in fact not unexpected due to the flux-spectral-index relation [30]. Adding the annihilation spectrum to this steep power law, best-fit values for the cross section times Ψ and neutralino mass are $\langle\sigma v\rangle_\chi \times \Psi = (2.6 \pm 0.6) \times 10^{-24}\ \mathrm{cm}^3\,\mathrm{s}^{-1}$ and $m_\chi = 515^{+110}_{-75}$ GeV [Fig. 1(a)]. The inferred neutralino mass is independent from the details of cosmic structure evolution. To verify that correspondingly high values for $\langle\sigma v\rangle_\chi$ can be obtained within the MSSM framework while producing cosmologically interesting amounts of neutralinos, we use the DARKSUSY [15] numerical routines to scan the MSSM parameter space. In Fig. 1(b), we plot valid models that have been found in the region of the parameter space described in Table I. In this "m_A resonance region," annihilation resonantly proceeds via $\chi\chi \rightarrow A \rightarrow f\bar{f}$, allowing for a high annihilation cross section while still

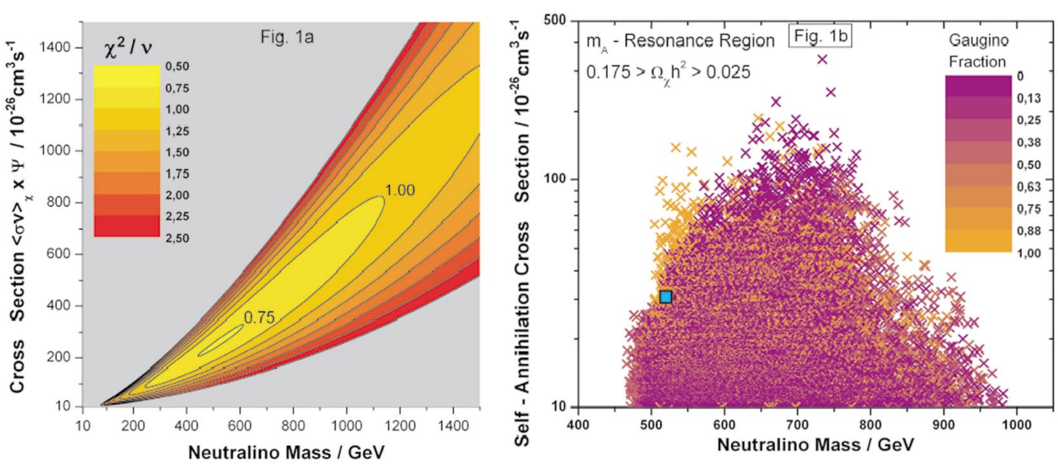

FIG. 1 (color). (a) Results of the χ^2 test of the neutralino annihilation hypothesis against the measured EGB. The annihilation cross section times Ψ is normalized to the NFW-profile case [$\Gamma(0) = 2 \times 10^6$] (b) Scatter plot of MSSM neutralinos created by scanning the parameter space described in Table I; the rectangle denotes the 520 GeV neutralino further explored in Fig. 2.

TABLE I. Limits of the region of MSSM parameter space that have been scanned with DARKSUSY for cosmologically interesting neutralino models not excluded by current accelerator limits (Higgsino mass parameter μ, gaugino mass parameter m_2, mass of the cp-odd Higgs boson m_A, ratio of the Higgs vacuum expectation values $\tan\beta$, scalar mass parameter m_S, and trilinear soft-breaking parameters for the third generation squarks A_t and A_b).

$\|\mu\|$	$\|m_2\|$	m_A	$\tan\beta$	m_S	A_t	A_b
500 GeV	2500 GeV	1000 GeV	5	1000 GeV	0.1	−2.5
1000 GeV	1000 GeV	1500 GeV	50	3000 GeV	1	−1

producing the correct relic density [31]. There is considerable spread among models. In a number of cases, the observed EGB signature can be produced even if Ψ is close or equal to unity. The models we plot are required to thermally produce $0.175 > \Omega_\chi h^2 > 0.025$. For models producing substantially less than $\Omega_\chi h^2 = 0.1$ an additional, nonthermal source of neutralinos, e.g., from the decay of heavier relic particles, might be considered. For a MSSM neutralino with a mass of 520 GeV, $\langle\sigma v\rangle_\chi = 3.1 \times 10^{-25}\ \mathrm{cm^3\,s^{-1}}$, and a moderate Ψ of 8 the value of χ^2/ν is 0.74, which is excellent. The MSSM parameters and resulting EGB spectrum for this model are shown in Fig. 2. This neutralino is gauginolike (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 GeV. WIMPs with similar mass and cross section, but in other respects different parameters, might, however, equally be a possibility.

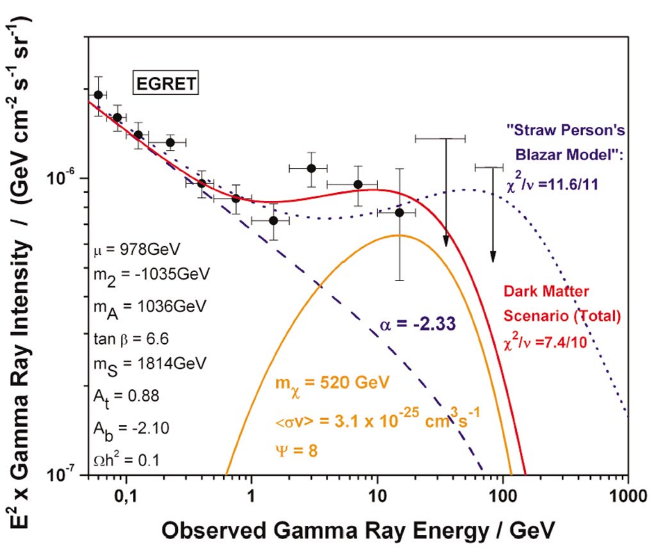

FIG. 2 (color). Extragalactic gamma-ray background: spectrum as determined from EGRET data by Strong *et al.* (data points) [the upper limit in the (60–100) GeV range is from Sreekumar *et al.*], steep power-law component (dashed line), straw person's blazar model (dotted line), neutralino annihilation spectrum (orange solid line), and combined steep power law plus annihilation spectrum (red solid line).

Comparison with astrophysical background models.—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 [5], a two component nature of the variable blazar spectra was assumed: a steep power law as a stationary emission component, and a flatter power law as a flaring component [7,8]. Constructing a straw person's model with the same redshift evolution, we modify the assumptions of Stecker and Salamon (SS96/98) by adopting steeper spectra for the quiescent (faint) component, and adding a flatter (flaring) spectral component with the hardest spectral index determined from EGRET data for a single source, to see how well the new result for the EGB can be matched. Evaluating $\Phi_\gamma^{\rm AGN} \propto \int dV_c n(z)(1+z)^2 \times [(E(1+z)/E_b)^{-2.23} + (E(1+z)/E_b)^{-1.5}] \times \kappa(E,z)$ with the source density in the comoving frame $n(z) \propto (1+z)^{3.4}$ in the redshift range $0.03 \le z \le 1.5$, we obtain a coarse, rescaled version of the SS96/98 model, in which the amplitude and break energy E_b were chosen to minimize χ^2/ν. Details of the luminosity evolution are unimportant for this test, and the original SS96/98 curve can be reproduced accurately by choosing appropriate values for the parameters. The result of fitting this straw person's model to the new EGB data is a value of 1.05 (Fig. 2). It should be noted that, while the astrophysical model can in principle produce an acceptable fit to the data, this requires a sharp spectral break at an energy E_b of ~5 GeV. Blazars, however, have continuously varying spectral properties (spectral index, peak energies, etc.). A sharply bimodal distribution of the gamma-ray spectral index—as required here—seems unnatural, and the physical origin of the universal crossing energy thus mysterious. Moreover, the fraction of sources with hard spectra at an energy of 1 GeV at any time would have to be about 20%—considerably more than the fraction of the hard-spectrum sources in the EGRET catalog [32]. The blazar model also would imply ~1000 sources with a >300 GeV flux of the order of a typical Whipple source, whereas the steeper power law alone corresponds to ~40 sources. The first number seems worryingly large in view of the ~10 confirmed sources, in spite of excessive observation campaigns on candidate sources from radio and x-ray catalogues [33]. Source-intrinsic cutoffs well below 100 GeV could, however, remedy this problem. The new-generation Cherenkov telescopes HESS, MAGIC, VERITAS, and the GLAST observatory will tell the story.

Discussion.—We have arrived at the conclusion that the neutralino dark matter scenario is in agreement with the observed EGB spectrum. The best-fit value for the neutralino mass is $m_\chi = 515^{+110}_{-75}$ GeV (notable systematic errors of ~30% can be inferred from the systematic uncertainties of the EGRET EGB determination [4]; they will be substantially reduced by GLAST). The strength of the observed signature can be explained by a combination of NFW-type dark matter halo profiles and an annihilation cross section of the order obtainable within the MSSM framework. The rather high scale for the mass ladder of the superpartners might render direct detection of all but the lightest of these particles by the CERN LHC difficult [34]. For present elastic-scatter experiments, the WIMP-nucleon cross sections for the majority of these models are out of reach ($\sigma_{\chi-p} < 10^{-7}$ pb), but could be accessible by next-generation detectors. For the EGB spectrum to be fitted acceptably with two component blazar models, these seem to run into several worrying difficulties: A universal spectral crossing energy of a few GeV is required by conspiracy, the models predict a higher fraction of hard-spectrum sources at GeV energies than observed by EGRET, and the models possibly imply a higher number of low-redshift blazars above 300 GeV than discovered with imaging air Cherenkov telescopes. The combination of astrophysical sources and WIMP annihilation presented above is an interesting alternative scenario that should be probed by the next generation of gamma experiments. For the ~520 GeV neutralino previously discussed, the galactic neutralino population would give rise to a faint galactic gamma-ray halo with intensity $\sim 10^{-7} ph\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}$ above 1 GeV. Present data do not allow to confirm or rule out such a halo component, but for a galactic GeV-component commonly attributed to inverse-Compton radiation also neutralino annihilation has been proposed as a source [3,35]. A robust calculation using DARKSUSY shows that the corresponding galactic antiproton flux is not incompatible with the BESS measurements [36]. If the astrophysical background can be characterized, gamma rays due to neutralino annihilation from the galactic center or external galaxies like M87 [37] could possibly be detected with low-threshold gamma-ray telescopes. For a NFW profile and the neutralino presented in Fig. 2, the galactic center would exhibit a gamma-ray luminosity of 5×10^{35} ergs/s above 1 GeV ($F_{E>50\ \mathrm{GeV}} = 8 \times 10^{-11} ph\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) from within 10^{-3} sr. Note that in this scenario the high EGB intensity corresponds to a moderate flux from the galactic center due to the intricate effects of clumping of the dark matter (cf. [38]). For the MAGIC telescope at an energy threshold of 50 GeV and the halo profile from [39], the annihilation component in the gamma-ray spectrum of M87 would be detectable at 5σ in 250 hours of observation time.

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