FERMILAB-CONF-07-359-A

30TH INTERNATIONAL COSMIC RAY CONFERENCE

Dark matter annihilation bound from the diffuse gamma ray flux

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Abstract: An upper limit on the total annihilation rate of dark matter (DM) has been recently derived from the observed atmospheric neutrino background. It is a very conservative upper bound based on the sole hypothesis that the DM annihilation products are the least detectable final states in the Standard Model (SM), neutrinos. Any other decay channel into SM particles would lead to stronger constraints. We show that comparable bounds are obtained for DM masses around the TeV scale by observations of the diffuse gamma ray flux by EGRET, because electroweak bremsstrahlung leads to non-negligible electromagnetic branching ratios, even if DM particles only couple to neutrinos at tree level. A better mapping and the partial resolution of the diffuse gamma-ray background into astrophysical sources by the GLAST satellite will improve this bound in the near future.

Introduction

One promising way to detect dark matter (DM) is indirectly, via its possible annihilations (or decay) products. The DM annihilation products—barring baroque models with additional stable and relatively light particles—are Standard Model (SM) particles, although with model-dependent branching ratios. Using atmospheric neutrino data, the authors of Ref. [1] derived a conservative observational upper bound to the thermally averaged annihilation cross section $\langle\sigma_{\rm ann}v\rangle$ of a DM candidate, assuming that it annihilates into the least detectable final states in the SM, namely neutrinos (hence the *conservative* bound). In general, realistic dark matter models with large annihilation cross sections (see e.g. [2]) must require extremely tiny branching ratios in electromagnetic (and hadronic) channels, to avoid overshooting the diffuse gamma ray background [3, 4].

Interestingly, supermassive relic particles only coupled to neutrinos have already been invoked in exotic scenarios explaining the origin of ultra-high energy cosmic rays. The restriction on their coupling is needed to escape existing constraints from gamma rays (see e.g. [5]). However, even if the particle only couples to neutrinos at tree level, electroweak jet cascading imply that non-negligible electromagnetic branching ratios are present, ruling out these models [6]. For masses well above the Z boson mass m_Z, the suppression of higher-order processes is not effective, and the strongest conservative constraint comes from the contribution to the diffuse gamma ray flux. In this paper, which summarizes the research reported in [7], we extend the argument to annihilating dark matter, showing that this mechanism coupled with diffuse gamma radiation data still provides interesting observational constraints on the dark matter annihilation rate into standard model particles for masses $m_X \gtrsim 100\,$GeV.

The astrophysical input

The overall diffuse gamma-ray radiation can be qualitatively divided into a galactic and an extragalactic contribution. Since the latter is not simply the isotropic part of the flux, the separation of these two components can be done at present only assuming a specific model for the production of secondaries by cosmic rays in the galactic disk and halo. (However, a measurement of the cosmological Compton-Getting effect that should be achievable for GLAST would provide a model-

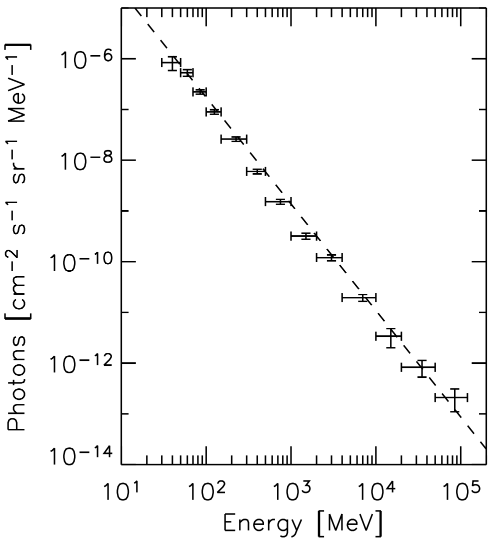

Figure 1: EGRET data for the diffuse extragalactic gamma ray flux, according to [4], and the older fit of the original analysis in [3].

independent way to separate the two contributions [8]). For our purposes here, a detailed analysis is not required, and thus we employ a fit of the galactic diffuse flux proposed in [9] and calibrated on EGRET data around the GeV [10].

The analysis team of the CGRO/EGRET satellite data additionally provides the intensity spectrum for the isotropic diffuse flux [3]

$$I(E) = k_0 \left(\frac{E}{0.451 \mathrm{GeV}}\right)^{-2.10\pm0.03} , \quad (1)$$

valid from $E \sim 10$ MeV to $E \sim 100$ GeV, where $k_0 = (7.32 \pm 0.34) \times 10^{-6} \mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}\mathrm{GeV}^{-1}$. The reanalysis of the data performed in [4], based on a revised model for the galactic propagation of cosmic rays, deduced an extragalactic spectrum significantly lowered with respect to Eq. (1) at intermediate energies, while closer to the original result of Eq. (1) at the lowest and highest energy points. In Fig.1, we show the points according to this reevaluation, together with the fit of Eq. (1). To derive our constraint, we shall ask that the photon flux from DM annihilations, integrated in each of the energy bins of Fig. 1 and in the whole energy range covered by EGRET, remains below the sum of the upper limit for the extragalactic flux plus the galactic emission. To be conservative, we shall compare the DM photon flux to the background profiles along the curve $l = 0$, since the galactic background is maximum at this longitude.

In [1], the expected dominating diffuse neutrino flux was estimated from the integrated extragalactic contribution. Unfortunately, this flux strongly depends on the degree of clumpiness of DM, and a robust estimate is difficult to achieve. Although in [1] a relatively modest value of 2×10^5 for the enhancement due to the clumpiness of DM was used, even values lower by a factor of $\mathcal{O}(10)$ are possible. To be more conservative, we use the diffuse flux due to the smooth DM distribution in the halo of our Galaxy since: (i) its normalization and distribution is better known (within a factor ~ 2). (ii) It is truly a lower limit for the DM annihilation flux [11]. Substructure in our halo is expected to augment it by orders of magnitude (see e.g. the parametric study [11] for our Galaxy or the study [12] for dwarf galaxy satellites). Also, an additional contribution from the diffuse extragalactic background may further enhance the actual emission.

The differential flux of photons from dark matter annihilations is (assuming self-conjugated particles)

$$I_{\rm sm}(E,\psi) = \frac{\mathrm{d}N_\gamma}{\mathrm{d}E} \, \frac{\langle\sigma_{\rm ann} v\rangle}{2\, m_X^2} \int_{\rm l.o.s.} \mathrm{d}s \, \frac{\rho_{\rm sm}^2[r(s,\psi)]}{4\pi}, \quad (2)$$

where $r(s,\psi) = (r_\odot^2 + s^2 - 2\, r_\odot\, s \cos\psi)^{1/2}$, ψ is the angle between the direction in the sky and the Galactic Center (GC), $r_\odot \approx 8.0\,$kpc is the solar distance from the GC, and s the distance from the Sun along the line-of-sight (l.o.s.). Particle physics enters via the DM mass m_X, the annihilation cross section $\langle\sigma_{\rm ann} v\rangle$, and the photon differential energy spectrum $\mathrm{d}N_\gamma/\mathrm{d}E$ per annihilation. Concerning the DM halo profile, we adopt a Navarro-Frenk-White profile [13]

$$\rho_{\rm sm}(r) = \rho_\odot \left(\frac{r_\odot}{r}\right) \left(\frac{r_\odot + a}{r + a}\right)^2 , \quad (3)$$

where we choose $\rho_\odot = 0.3\,$GeV/cm^3 as the dark matter density at the solar distance from the GC,

Table 1: The branching ratio $R = \sigma(XX \to \bar{\nu}\nu Z)/\sigma(XX \to \bar{\nu}\nu)$ as function of m_X.

m_X/GeV	100	300	1000	3000	10^4
R/%	0.01	0.02	0.87	1.9	3.4

and $a = 45$ kpc as the characteristic scale below which the profile scales as r^{-1}. The galactic halo DM flux has a significant angular dependence, with possibly large fluxes from the galactic center region. However, the DM profile in the inner regions of the Galaxy is highly uncertain. To be conservative, we shall only use the NFW profile for $r > 1$ kpc, a region where numerical simulations of DM halos have reached convergence and the results are robust [14, 15]. Of course, other choices for the profile are possible, but all of them agree in the range of distances considered here, differing primarily in the central region of the halos. Since here we are focusing on the galactic diffuse emission rather than that from the GC, the residual uncertainties which are introduced through the choice of profile (a factor ~ 2) are negligible for our discussion.

Gamma emission from DM annihilation into neutrinos

By assumption, the DM particles X couple at tree-level only to neutrinos. Hence the only possible $2 \to 2$ annihilation process is $XX \to \bar{\nu}\nu$ with an unspecified intermediate state that has negligible couplings to SM particles. Then the dominant $2 \to 3$ and $2 \to 4$ processes are the bremsstrahlung of an electroweak gauge boson that subsequently decays: $XX \to \bar{\nu}\nu Z, \nu e^{\pm} W^{\mp}$ and $XX \to \bar{\nu}\nu \bar{f} f$. If we denote by Q^2 the momentum transferred squared, the branching ratio $R = \sigma(XX \to \bar{\nu}\nu Z)/\sigma(XX \to \bar{\nu}\nu)$ depends generally on the details of the underlying $2 \to 2$ process only for $Q^2 \sim m_X^2$. One can distinguish three different regimes of this process:

i) the Fermi regime $m_X \lesssim m_Z$ with $R \sim [\alpha_2/(4\pi)]^2 (m_X/m_Z)^4$,

ii) the perturbative electroweak regime $m_Z \lesssim m_X \lesssim \alpha_2/(4\pi) \ln^2(m_X/m_Z) \sim 10^6$ GeV where R grows from $\mathcal{O}(\alpha_2/(4\pi))$ to $\mathcal{O}(0.1)$,

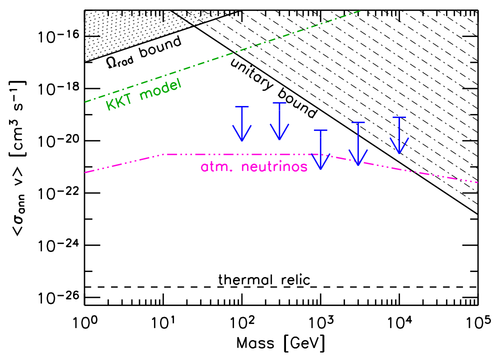

Figure 2: Bounds on $\langle\sigma_{\rm ann} v\rangle$ versus m_X from diffuse γ rays (blue arrows), atmospheric neutrino data [1] (magenta line) together with the expectation for a thermal relic (for s-wave annihilation), the KKT model and the unitary limit. See the text for details.

iii) the non-perturbative regime where large logarithms over-compensate the small electroweak coupling α_2 [6].

Here, we consider regime *ii*) and can use therefore standard perturbation theory for the evaluation of R. The dominant source of photons are π^0 produced in q jets from W and Z decays. The resulting differential photon energy spectrum $\mathrm{d}N_\gamma/\mathrm{d}E$ has been simulated using HERWIG [16]. Numerical values of R are given in Tab. 1.

The obtained bound from the EGRET limit is shown in Fig. 2 with arrows together with the limit from Ref. [1] using atmospheric neutrino data. The upper extreme of the arrow indicates the bound obtained by comparing the emissions at the highest galactic latitudes ($b = \pi/2$, $l = 0$), while the lower extreme is the bound coming from the inner Galaxy emission ($b = 1/8$, $l = 0$). The length of the arrow thus quantifies the improvement due to our simple, angular-dependent analysis. Indicated are also the required value for a standard thermal relic with an annihilation cross section dominated by the s-wave contribution, $\langle\sigma_{\rm ann} v\rangle \approx 2.5 \times 10^{-26}\mathrm{cm}^3$/s, the unitary limit $\langle\sigma_{\rm ann} v\rangle \leq 4\pi/(v\, m_X^2)$ for $v = 300$ km/s, appropriate for the

Milky way, and the constraints on the cosmological relativistic energy density from [17].

Conclusions

We have shown that, even if dark-matter particles annihilate at tree-level only into neutrinos, diffuse gamma-ray data provide interesting constraints on their annihilation cross section because of electroweak bremsstrahlung. These bounds are comparable or better than the atmospheric neutrino bound from Ref. [1] in the mass range between $\sim 100\,\mathrm{GeV}$ and the onset of the stronger unitary bound around 10 TeV. Any appreciable branching ratio at tree level in electromagnetically interacting particles would lead to much stronger constraints from gamma-rays, but they are not as conservative as the bounds derived here or in Ref. [1]. A major improvement in the gamma-ray bound is expected from the GLAST satellite [18], to be launched by the beginning of 2008. In particular, GLAST should resolve most of the diffuse flux of astrophysical origin, and map both the galactic and extragalactic diffuse emission with much higher accuracy, thereby improving the bound derived here.

Acknowledgements: We are grateful to Mike Seymour, Brian Webber and John Beacom for helpful comments. PS acknowledges support by the US DOE and by NASA grant NAG5-10842.

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