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 argue here that for $m_X \gtrsim 100\,\mathrm{GeV}$ comparable bounds may be obtained in the future from observations of the diffuse gamma ray flux by the GLAST satellite, because electroweak bremsstrahlung leads to non-negligible electromagnetic branching ratios, even if DM particles only couple to neutrinos at tree level.

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 rates (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 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 $m_X \gtrsim 100\,\mathrm{GeV}$.

The astrophysical input

The analysis team of the CGRO/EGRET satellite data provided the intensity spectrum for the diffuse (unresolved) 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

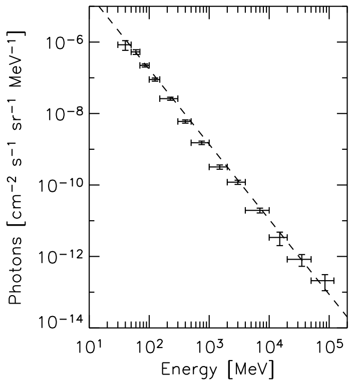

Figure 1: EGRET data for the diffuse extragalactic gamma ray flux, according to [4], and the older fit of the original analysis in [3].

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 DM flux, integrated in each of the EGRET energy bins, remains below the corresponding EGRET value calculated assuming the upper limit for the flux, in the whole range detected by EGRET.

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 [7]. Substructure in our halo is expected to augment it by orders of magnitude (see e.g. the parametric study [7] for our Galaxy or the study [8] for dwarf galaxy satellites). Also, an additional contribution from the diffuse extragalactic background may further enhance the actual emission. Since the Galactic halo flux has a significant angular dependence, we shall compare the experimental data with its value in the direction perpendicular to the galactic plane, where the astrophysical foregrounds are minimal. Note that we do not consider the flux from the inner regions of the Galaxy, which is highly uncertain. In summary, we estimate that our bound might be conservative by more than two orders of magnitude.

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

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

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), $r_\odot \approx 8.0\,{\rm kpc}$ 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 ${\rm d}N_\gamma/{\rm d}E$ per annihilation. Concerning the DM halo profile, we adopt a Navarro-Frenk-White profile [10]

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

where we choose $\rho_\odot = 0.3\,{\rm GeV/cm^3}$ as the dark matter density at the solar distance from the GC, and $a = 45\,{\rm kpc}$ as the characteristic scale below which the profile scales as r^{-1}. Other choices for the profile are possible, but differ primarily in the central region. 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

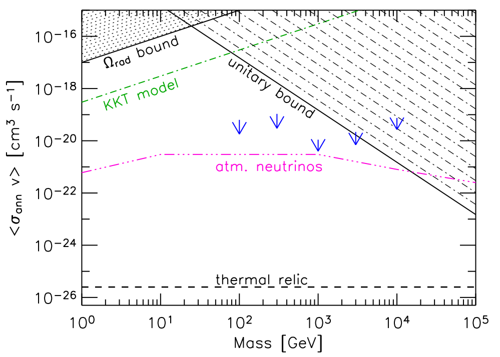

Figure 2: Bounds on $\langle\sigma_{\rm ann}v\rangle$ versus m_X from diffuse γ rays (blue arrows), atmospheric neutrino data [1] (magenta line) together with the expectation for a thermal relic (for s-wave annihilation), the KKT model and the unitary limit.

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 $\mathcal{O}(R) = [\alpha_2/(4\pi)]^2(m_X/m_Z)^4$,

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 $\mathcal{O}(0.1)$,

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

Here, we consider regime *ii*).

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 [9].

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. Indicated are also the required value for a standard thermal relic with an annihilation cross section dominated by the s-wave contribution, $\langle\sigma_{\rm ann}v\rangle \approx 2.5\times10^{26}\mathrm{cm}^3$/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 [11].

Conclusions

We have shown that, even for DM with tree-level couplings only to neutrinos, gamma ray data provide interesting constraints on the annihilation cross section, due to electroweak bremsstrahlung. While the atmospheric neutrino bound [1] is at present more stringent, a major improvement in the gamma ray bound is expected from the GLAST satellite [12], to be launched this year. 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. Together with an improved analysis of the data, it is not unrealistic to expect the bound derived here to tighten by one order of magnitude or more, possibly providing the most stringent and robust observational constraint to DM annihilation in the mass range above $\sim 100\,$GeV. On the other hand, neutrinos will probably continue to provide the only robust constraint for $m_X \lesssim m_Z$, as discussed in [1].

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