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Model-independent dark matter annihilation bound from the diffuse gamma ray flux

M. Kachelrieß[1] and P. D. Serpico[2]
[1]Institutt for fysikk, NTNU, N–7491 Trondheim, Norway
[2]Center for Particle Astrophysics, Fermi National Accelerator Laboratory, Batavia, IL 60510-0500, USA

An upper limit on the total annihilation cross section of dark matter (DM) has been recently derived from the observed atmospheric neutrino background. 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 partly resolution of the diffuse gamma-ray background into astrophysical sources by the GLAST satellite will improve this bound in the near future.

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I. INTRODUCTION

One promising way to detect dark matter (DM) is indirectly via its 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 an observational upper bound on the annihilation cross section $\langle\sigma_{\rm ann}v\rangle$ of any DM candidate, assuming that it annihilates only into the least detectable final states in the SM, namely neutrinos. Allowing only couplings to neutrinos might be not only a conservative assumption needed to derive this bound, but could be realized in nature: Possible DM candidates, like the majoron, with this property exist. Moreover, the bound on the diffuse gamma ray background from EGRET observations [2, 3, 4] translates into extremely restrictive limits on the branching ratios in electromagnetic and hadronic DM annihilations channels. Therefore, models with high annihilation rates proposed to solve the "cusp problem" of conventional cold DM (see e.g. [5]) and DM masses m_X above $\mathcal{O}$(GeV) are likely to require either fine-tuning or should couple the DM particle only to neutrinos.

The latter possibility has already been invoked in exotic scenarios explaining the origin of ultra-high energy cosmic rays. Reference [6] proposed that supermassive relic particles decay only into neutrinos, thereby contributing to the ultra-high energy cosmic ray flux through the Z burst mechanism and escaping at the same time constraints from the diffuse gamma-ray background. However, the authors of Ref. [7] showed that electroweak jet cascading leads a non-negligible electromagnetic branching ratio and rules out these models.

In this work, we extend this argument to annihilating dark matter of lower mass, showing that this mechanism combined with the limit on the diffuse gamma radiation by the EGRET satellite provides competitive observational constraints on $\langle\sigma_{\rm ann}v\rangle$ for masses around the TeV scale. Future observations of the diffuse gamma ray flux by the GLAST satellite should improve these bounds. We also find that the strongest and most robust way to constrain $\langle\sigma_{\rm ann}v\rangle$ is to use the DM signal associated with the galactic halo, instead of the diffuse flux from cosmologically distributed dark matter. We comment on the possibility to improve the neutrino bounds as well by exploiting the strongly peaked angular distribution expected from annihilations in the galactic dark matter halo. In Sec. II, we discuss the properties of dark matter relevant here, while Sec. III is devoted to the data used to derive the bound. The bound is presented and commented upon in Sec. IV. In Sec. V, we discuss possible improvements and finally conclude.

II. THE DARK MATTER INPUT

In Ref. [1], the expected dominating contribution to the diffuse neutrino flux was estimated from the integrated extragalactic contribution to dark matter annihilations. Unfortunately, this flux strongly depends on the shape of dark matter halos and their degree of clumpiness. A robust estimate is thus difficult to achieve. Although in Ref. [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 photon flux from 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 [8]. Substructure in our halo is expected to augment it up to orders of magnitude (see e.g. the parametric study [8] for our Galaxy or the study [9] for dwarf galaxy satellites). Note that the contribution from the diffuse extragalactic photon background from DM annihilations further enhances the total DM emission. By neglecting both the substructure in our halo and the extra-galactic contribution, we are being conservative.

The differential flux of photons from dark matter annihilations is [19]

$$I_{\rm sm}(E,\psi)=\frac{{\rm d}N_\gamma}{{\rm d}E}\,\frac{\langle\sigma_{\rm ann}v\rangle}{2\,m_X^2}\int_{\rm l.o.s.}{\rm d}s\,\frac{\rho_{\rm sm}^2[r(s,\psi)]}{4\pi}\,, \tag{1}$$

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.). In terms of galactic latitude b and longitude l, one has

$$\cos\psi=\cos b\cos l\,. \tag{2}$$

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 for the smooth DM mass density $\rho_{\rm sm}$ 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}. 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 $r>1\,{\rm kpc}$, a region where numerical simulations of DM halos have reached convergence and the results are robust [11, 12]. 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.

III. THE DIFFUSE GAMMA RAY BACKGROUNDS

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-independent way to separate the two contributions [13]). A significant fraction of the quasi-isotropic component, especially in the GeV range, may be due to high-latitude galactic emission coming from processes in the magnetized halo of the Milky Way. For our purposes here, a detailed analysis is not required, and thus we employ a fit of the galactic diffuse flux proposed in [14] and calibrated on EGRET data around the GeV [2],

$$I_{\rm gal}(E)=N_0(l,b)\times 10^{-6}\left(\frac{E}{\rm GeV}\right)^{-2.7}\ {\rm cm^{-2}s^{-1}sr^{-1}GeV^{-1}}\,, \tag{4}$$

where the arguments are in degrees, $-180^\circ\leq l\leq 180^\circ$ and $-90^\circ\leq b\leq 90^\circ$,

$$N_0(l,b)=\begin{cases}\frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+[b/(1.1+0.022\,|l|)]^2}}+0.5\,, & |l|\geq 30^\circ\\ \frac{85.5}{\sqrt{1+(l/35)^2}\sqrt{1+(b/1.8)^2}}+0.5\,, & |l|\leq 30^\circ\end{cases}\,. \tag{5}$$

The EGRET collaboration derived the intensity of the extragalactic gamma-ray flux as [3]

$$I_{\rm ex}(E)=(7.32\pm 0.34)\times 10^{-6}\left(\frac{E}{0.451{\rm GeV}}\right)^{-2.10\pm 0.03}\ {\rm cm^{-2}s^{-1}sr^{-1}GeV^{-1}}\,, \tag{6}$$

valid from $E\sim 10$ MeV to $E\sim 100$ GeV.

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. (6) at in-

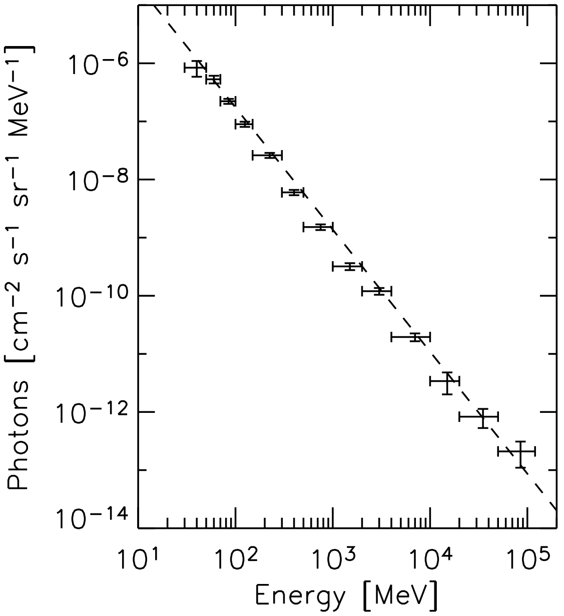

FIG. 1: EGRET data for the diffuse extragalactic gamma ray flux, according to [4], and the older fit of the original analysis in [3].

termediate energies, while closer to the original result of Eq. (6) at the lowest and highest energy points. In Fig. 1, we show the points according to this reevaluation, together with the fit of Eq. (6). 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 estimated according to the fit of Eq. (4). 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 (see Eq. (4)).

IV. GAMMA-RAY EMISSION FROM DM ANNIHILATION INTO NEUTRINOS

By assumption, the DM particles X couple on 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 $XX \to \bar{\nu}\nu \bar{f} f$. The branching ratio $R = \sigma(XX \to \bar{\nu}\nu Z)/\sigma(XX \to \bar{\nu}\nu)$ depends generally only for $Q^2 \sim m_X^2$ on the details of the underlying $2 \to 2$ process. 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 $m_Z \lesssim m_X \lesssim \alpha_2/(4\pi) \ln^2(m_X/m_Z)^2 \sim 10^6\,\mathrm{GeV}$ where R grows from $\mathcal{O}(\alpha_2/(4\pi))$ to $\mathcal{O}(0.1)$, and *iii*) the non-perturbative regime where large logarithms over-compensate the small electroweak coupling α_2 [7]. Here, we consider regime *ii*) and can use therefore standard perturbation theory for the evaluation of R. Numerical values of R are given in Tab. 1.

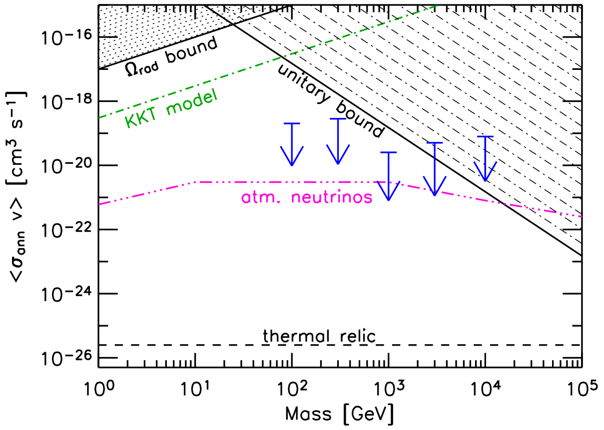

FIG. 2: Bounds on $\langle\sigma_{\rm ann} v\rangle$ versus m_X from diffuse γ rays (blue arrows), atmospheric neutrino data [1] (magenta line) together with the expectation for a thermal relic (for s-wave annihilation), the KKT model and the unitary limit. See the text for details.

The dominant source of photons are π^0 produced in quark jets from W and Z decays. The resulting differential photon energy spectrum $\mathrm{d}N_\gamma/\mathrm{d}E$ has been simulated using HERWIG [15].

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

TABLE I: 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

for a standard thermal relic with an annihilation cross section dominated by the s-wave contribution, $\langle\sigma_{\rm ann}v\rangle \approx 2.5\times10^{-26}{\rm cm}^3/{\rm s}$, the unitary limit $\langle\sigma_{\rm ann}v\rangle \leq 4\pi/(v\,m_X^2)$ for $v = 300\,{\rm km/s}$, appropriate for the Milky way, and the constraints on the cosmological relativistic energy density from [16].

V. DISCUSSION AND CONCLUSION

In this paper 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 $\sim 100\,{\rm GeV}$ 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 Re. [1]. A major improvement in the gamma-ray bound is expected from the GLAST satellite [17], 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. On the other hand, our results also suggest that the neutrino bound may be tightened as well by considering the DM annihilation in the galactic halo and taking into account the strong angular dependence on the halo signal.

As a further application of our results, we note that the electroweak higher-order corrections discussed here also contribute to increase the robustness of the bounds on strongly interacting dark matter from the Earth's heat flow in Ref. [18]. Above the TeV scale, electroweak bremsstrahlung put a lower bound of $\mathcal{O}(1\%)$ on the energy released in other-than-neutrino channels, thus guaranteeing that an appreciable energy is release by annihilations in the interior of the Earth even for models with tree-level annihilations in neutrinos only.

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