Gamma-ray and radio constraints of high positron rate dark matter models annihilating into new light particles

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The possibility of explaining the positron and electron excess recently found by the PAMELA and ATIC Collaborations in terms of dark matter (DM) annihilation has attracted considerable attention. Models surviving bounds from, e.g., antiproton production generally fall into two classes, where either DM annihilates directly with a large branching fraction into light leptons, or, as in the recent models of Arkani-Hamed *et al.*, and of Nomura and Thaler, the annihilation gives low-mass (pseudo)scalars or vectors ϕ which then decay into $\mu^+\mu^-$ or e^+e^-. While the constraints on the first kind of models have recently been treated by several authors, we study here specifically models of the second type which rely on an efficient Sommerfeld enhancement in order to obtain the necessary boost in the annihilation cross section. We compute the photon flux generated by QED radiative corrections to the decay of ϕ and show that this indeed gives a rather spectacular broad peak in $E^2 d\sigma/dE$, which for these extreme values of the cross section violates gamma-ray observations of the Galactic center for DM density profiles steeper than that of Navarro, Frenk and White. The most stringent constraint comes from the comparison of the predicted synchrotron radiation in the central part of the Galaxy with radio observations of Sgr A*. For the most commonly adopted DM profiles, the models that provide a good fit to the PAMELA and ATIC data are ruled out, unless there are physical processes that boost the local antimatter fluxes more than 1 order of magnitude, while not affecting the gamma-ray or radio fluxes.

There have recently been indications of a very interesting enhancement in the amount of cosmic ray electrons and positrons detected near the Earth, both seen by PAMELA in the ratio of positrons to the sum of electrons and positrons between a few GeV and 100 GeV [1], and by ATIC in the sum of electrons and positrons at several hundred GeV to 1 TeV [2]. While these so far unexplained excesses might be due to standard astrophysical processes [3], positrons also constitute one of the promising channels in which to search for dark matter (DM; for reviews, see [4]), and these new experimental findings have therefore already triggered a large number of theoretical analyses trying to explain the data as being induced by DM annihilation or decay (see, e.g., Ref. [5] and references therein for supersymmetric DM, Ref. [6] for alternative DM scenarios and Ref. [7] for decaying DM scenarios). In general, these analyses seem to point at the need for DM particles with masses in the TeV range that annihilate, with a very large rate, dominantly into charged light leptons.

The bremsstrahlung process, falling like E_γ^{-1}, is generally regarded in particle physics as having a "soft" spectrum. In the astrophysical context, this is, however, on the contrary a quite hard spectrum, since most of the background γ-ray spectra like those from acceleration near supernova remnants usually fall like E_γ^{-2} or faster. Gamma rays from DM generally feature a spectrum that is somewhere in between these two at low energies ($E_\gamma^{-1.5}$) and drops even faster close to the DM particle mass [8] (for

important exceptions see, however, [9]). If the DM particles χ annihilate directly into a pair of charged leptons, the photon distribution from the process $\chi\chi \to \ell^+\ell^-\gamma$, for $m_\chi \gg m_\ell$, is to a good approximation of the Weizsäcker-Williams form (see, e.g., [10]):

$$\frac{d(\sigma v)}{dx} = (\sigma v)_{\ell\ell} \frac{\alpha_{\rm em}}{\pi} \frac{((1-x)^2 + 1)}{x} \ln\left[\frac{4m_\chi^2(1-x)}{m_\ell^2}\right],$$
(1)

where $x = E_\gamma/m_\chi$ and $(\sigma v)_{\ell\ell}$ is the annihilation rate for the lowest order process $\chi\chi \to \ell^+\ell^-$ (note that the above approximation also breaks down when there is a symmetry that suppresses the annihilation into two-body, but not into three-body final states [11]).

This case has recently been treated by [12–14]. (The last of these references also briefly treats, but leaves for a more detailed calculation, the kind of processes we will compute here.) It was found that the gamma rays produced in DM models with these annihilation modes lead to rather severe constraints. Even more stringent bounds on this type of DM models that try to explain the PAMELA and ATIC data arise from the synchrotron radiation produced by the resulting population of electrons and positrons, in realistic models of the DM density distribution and for a wide variety of assumptions about the magnetic field in the inner Galaxy [13,15].

It remains to consider another possibility, where DM annihilates into a new type of light (sub-GeV) particles ϕ that in turn dominantly decay into light leptons (see [16] for a general account of this idea). The advantage of this type of models is that the strongly constrained decay into hadronic modes (see, e.g., [17]) is kinematically forbidden and that Sommerfeld enhancements in the limit of the small galactic DM velocities expected today allow for the very large annihilation cross sections that are needed to explain the PAMELA/ATIC results, but which at first seem to be at odds with the cross sections required to get the right thermal relic density for the DM. Another interesting feature of the Arkani-Hamed *et al.* model [16] is that it encompasses ideas that have been proposed to explain the Wilkinson Microwave Anisotropy Probe (WMAP) haze [18] and the International Gamma-Ray Astrophysics Laboratory excess [19]. As pointed out in [16,20], one may basically distinguish between scalar and vector ϕ and whether or not $m_\phi \lesssim 2m_\mu$ (in which case it dominantly decays into e^+e^-). For $m_\phi \gtrsim m_\pi$, even decays into pions should be taken into account (which we neglect here). While $m_\phi \gtrsim 10$ MeV is roughly needed not to be in conflict with big bang nucleosynthesis, one has to require $m_\phi \gtrsim 100$ MeV in order to get Sommerfeld enhancements of the order 10^3–10^4 that are needed to explain the PAMELA/ATIC result with these types of DM models. Based on this discussion, we adopt the four benchmark settings $A1$–$A4$ summarized in Table I.

While [16] describes a rather general setup, [21] introduces a concrete realization of this idea; the proposed model has the appealing feature of containing a "standard" Peccei-Quinn axion and can be embedded in a fully realistic supersymmetric scenario. Here, DM annihilates into a scalar s and a pseudoscalar a, $\chi\chi \rightarrow sa$. With a mass scale of 360 MeV $\lesssim m_a \lesssim 800$ MeV, the latter mostly decays into muons, which subsequently decay into electrons or positrons. The benchmark models for this setup $N1$–$N5$ are also given in Table I.

For the first a particle created in the $\chi\chi$ annihilation, we analytically compute the photon multiplicity $(dN/dE_\gamma)^{(a)}$ from $a \rightarrow \mu^+\mu^-\gamma$ in the rest frame of a. We then make a Lorentz boost back to the DM frame, i.e., the Galactic rest frame, to get

$$\left(\frac{dN}{dE_\gamma}\right)^{(\text{DM})} = \frac{1}{2\beta\gamma} \int_{E/(\gamma(1+\beta))}^{E/(\gamma(1-\beta))} \frac{dE'}{E'} \left(\frac{dN}{dE'_\gamma}\right)^{(a)}, \quad (2)$$

with $\gamma = (m_\chi/m_a)[1 - (m_s^2 - m_a^2)/(4m_\chi^2)]$ since the annihilation takes place essentially at rest (typical galactic velocities are 10^{-3}). Axions resulting from $s \rightarrow aa$ we treat in a similar way, boosting them first to the s frame and from this to the DM frame. Since s may have a mass up to 50 GeV, the gamma-ray spectrum may even receive important contributions from its decay into bottom quarks or tau leptons, a possibility which we will shortly return to. (Bremsstrahlung from electrons in the muon decay will give γ's of lower energies and will thus not be important for our constraints.)

Summing up all these contributions, we arrive at the total photon spectrum in the DM frame that we show in Fig. 1 for the models $N1$–$N5$ in Table I. We also include the corresponding spectra obtained in the Arkani-Hamed *et al.* setup (models $A1$–$A4$) and, for comparison, the case of 1 TeV DM particles directly annihilating into e^+e^- or $\mu^+\mu^-$. Please note that, from Eq. (2), the quantity dN/dx for the models listed in Table I is independent of m_χ as long as $m_\chi \gg m_a, m_s$; the direct annihilation of DM into leptons, on the other hand, *does* contain a logarithmic dependence on m_χ. Let us mention that while Eq. (1) provides a rather good approximation to our analytic results for photons radiated from e^+e^- pairs, it overestimates the photon yield from muons (especially when the mass of the decaying particle is close to m_μ like, e.g., in model $AH4$).

Once a DM profile $\rho(r)$ is assumed, it is straightforward to estimate the corresponding gamma-ray flux from a solid angle $\Delta\Omega$ towards the Galactic center:

TABLE I.   Our benchmark scenarios.

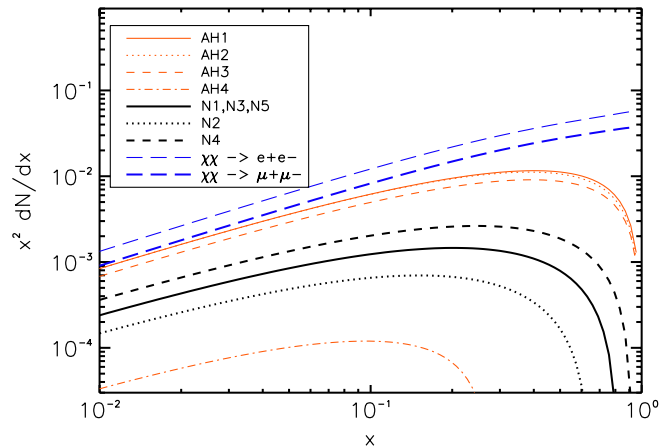| | Arkani-Hamed *et al.* type | | | | Nomura-Thaler type | |
	m_ϕ [GeV]	Type	e^+e^-	$\mu^+\mu^-$		m_s [GeV]	m_a [GeV]
$AH1$	0.1	Scalar	100%	$\cdots$	$N1$	5	0.5
$AH2$	0.1	Vector	100%	$\cdots$	$N2$	20	0.36
$AH3$	0.25	Vector	67%	33%	$N3$	20	0.5
$AH4$	0.25	Scalar	$\cdots$	100%	$N4$	20	0.8
					$N5$	50	0.5

FIG. 1 (color online).   The various possible photon spectra that can arise from DM annihilating to new light particles which in turn decay into charged leptons. For the models $N1$–$N5$, we neglect here the decay of s to tau leptons or bottom quarks—see Fig. 2 for an example of how this changes the spectra. For comparison, we also indicate the spectrum from DM directly annihilating to charged leptons.
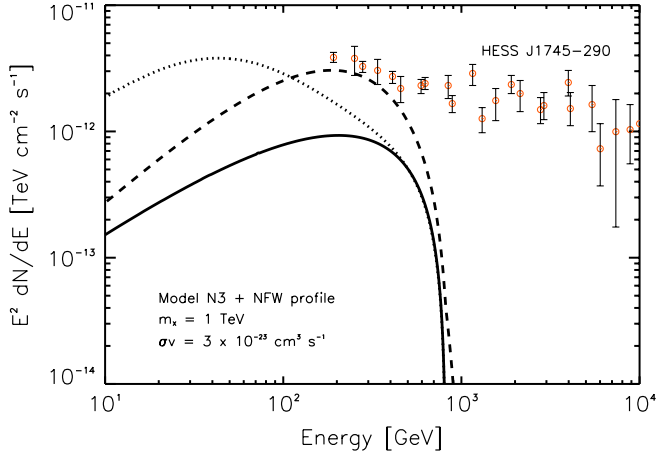
FIG. 2 (color online). The total gamma-ray spectrum dN/dE_γ, for an NFW halo, from a 1 TeV DM particle annihilating into a pseudoscalar a (decaying to muons) and a scalar s which decays to aa (solid line) or only in 95% of the cases into aa and in 5% into $b\bar{b}$ (dotted line) or $\tau^+\tau^+$ (dashed line). The masses for a and s are those of model $N3$ of Table I, so the solid line corresponds to the $N3$ line shown in Fig. 1.

$$\frac{d\Phi_\gamma}{dE} = \frac{1}{8\pi}\frac{\sigma v}{m_\chi^2}\frac{dN_\gamma}{dE}\int d\lambda \int_{\Delta\Omega} d\Omega \rho^2(\lambda), \qquad (3)$$

where λ is the line of sight distance. In Fig. 2, we compare the resulting flux to the gamma-ray data from the Galactic center taken by the HESS telescope [22], which has an angular resolution of about $0.1°$, and thus $\Delta\Omega = 10^{-5}$ sr. We here show the spectrum for model $N3$ and, for comparison, the case where s decays not only to axions but with a branching ratio of 5% to $\bar{b}b$ or $\tau^+\tau^-$ (which is the typical case for the model presented in [21]). By comparison with Fig. 1, it is straightforward to arrive at the corresponding spectra for the other models in Table I. We have here adopted a so-called Navarro-Frenk-White (NFW) profile [23], with the same parameters as in Ref. [13]. Note that the gamma-ray spectra in this case are consistent with the HESS data, unlike the case of the annihilation modes discussed in [13], for the same density profile. Assuming a profile $\rho(r) \propto r^{-1.2}$, as needed to explain the WMAP haze (see Ref. [18]), the constraints become much more stringent. However, at the same time they become much more sensitive to the dependence of σv on the velocity dispersion of DM, which inevitably increases in the vicinity of the supermassive black hole at the Galactic center. As we shall see soon, however, it is possible to derive even tighter constraints without making assumptions on the small-v behavior of σv.

Before that, however, let us note that another potential source of gamma rays from DM annihilations are dwarf galaxies, like the Sagittarius dwarf galaxy, observed by HESS [24]. The HESS observations put an upper bound on the integrated gamma flux above 250 GeV of $\Phi_\gamma < 3.6 \times 10^{-12}$ cm^{-2} s^{-1}. Assuming an NFW (isothermal) profile in

the Sagittarius dwarf galaxy, this can be translated to the limit $\sigma v < 7.4 \times 10^{-22}(2.2 \times 10^{-23})$ cm^3 s^{-1} for model $N3$. For the other models in Table I, the limits differ by a factor of a few as indicted by the spectra in Fig. 1. For other dwarf galaxies, the limits are similar: using a conservative estimate of the line of sight integral from Ref. [25], the limits on the gamma flux from Willman 1 as observed by Magic [26], e.g., translate to $\sigma v < 1.3 \times 10^{-21}$ cm^3 s^{-1}. However, the uncertainties from dynamical constraints [25] are large and improved future data might result in better constraints. As one typically needs a boost of order 10^3 to explain the PAMELA data, we note that the limits derived here are very close to the required σv. This means that for some models, like $AH1$–$AH3$, the more optimistic scenarios for the halo profile of, e.g., the Sagittarius dwarf are excluded.

A rather stringent constraint on the rate of injection of high energy $e^\pm$ in the Galaxy comes from the analysis of the synchrotron radiation produced by these particles as they propagate in the Galactic magnetic field. Although observations of different targets and at different wavelengths provide interesting constraints [27], the most stringent ones come from radio observations of the Galactic center, where the DM density is highest [15,27,28].

The synchrotron luminosity generated by a distribution of electrons and positrons produced by a DM distribution with profile $\rho(r)$ in a magnetic field $B(r)$ is

$$\nu L\nu = 2\pi \frac{\sigma v}{m_\chi^2}\int dr\, r^2 \rho^2(r) E_p Y_e(E_p), \qquad (4)$$

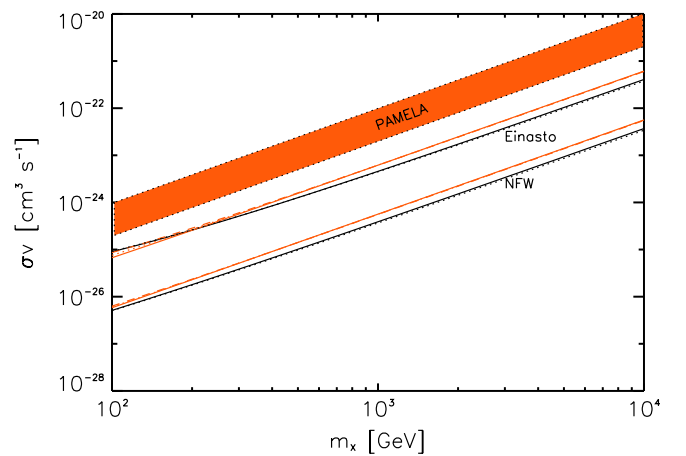where $\qquad E_p = \nu^{1/2}[0.29(3/4\pi)(e/m_ec^2)^3 B(r)]^{-1/2},$

FIG. 3 (color online). Exclusion plot in the σv vs mass plane. The two sets of curves give the maximum annihilation cross section compatible with radio observations of Sgr A* for Einasto and NFW profiles. The color code of the curves is the same as in Fig. 1. The shaded region, corresponding to the range of annihilation cross sections that provide a good fit to the PAMELA and ATIC data, appears to be in conflict with observations, unless the DM profile is more shallow than Einasto.

$Y_e(E) = \int_E^{m_\chi} dE' dN_e/dE'$ and we have adopted the mono-chromatic approximation for the synchrotron emission, assuming $P(\nu, E) = (8\pi/9\sqrt{3})\delta(\nu/\nu_c - 0.29)$, with $\nu_c = (3eBE^2)/(4\pi m_e^3 c^6)$, for its spectrum.

By comparing the predicted synchrotron radiation with radio observations, we can set limits on the annihilation cross section for any given annihilation channel, following a procedure similar to Ref. [13]. The most stringent constraint comes from the upper limit on the radio emission from a cone with half-aperture of $4''$ towards Sgr A* at $\nu = 0.408$ GHz [29], which we translate in Fig. 3 to the σv vs mass plane. Let us stress that the σv plotted in Fig. 3 is the *effective* annihilation cross section, including both Sommerfeld enhancements and boosts due to substructures. The only way to avoid our constraints would thus be to boost the local antimatter fluxes by more than 1 order of magnitude without affecting the gamma-ray or radio fluxes. Although this theoretical possibility cannot be ruled out (e.g., Ref. [30]), it appears to be unlikely for a realistic distribution of substructures in the Milky Way halo. Numerical simulations seem to indicate that the boost factors due to substructure are rather small [31]. How big the boost factors could be is still under debate and recent simulations [31] indicate that locally they are at most a factor of a few. A recent study [32] develops a model that

indicates that the local boost could be about a factor of 10. The details of the mechanism giving such large boosts are yet to be presented, however. For more discussion about boost factors, see Ref. [13].

The two sets of curves give the maximum annihilation cross section compatible with radio observations of Sgr A* for two different DM profiles: Einasto and NFW. The shaded region, corresponding to the range of annihilation cross sections that provide a good fit to the PAMELA and ATIC data, appears to be in conflict with observations, unless the DM profile is more shallow than expected in current models of structure formation. However, if the DM interpretation of the PAMELA data was corroborated by additional evidence, then our result can be interpreted as a hint of the shallowness of the DM profile.

Profiles steeper than NFW—like the $\rho(r) \propto r^{-1.2}$ needed to explain the WMAP haze [18]—are ruled out by a rather larger margin. This confirms the dramatic importance of the multiwavelength approach to DM studies [13,15,27,28], especially for DM models tailored to explain anomalies in astrophysical observations.

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