

Cosmic Neutrino Bound on the Dark Matter Annihilation Rate in the Late Universe

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Abstract. How large can the dark matter self-annihilation rate in the late universe be? This rate depends on $(\rho_{DM}/m_\chi)^2 \langle \sigma_{Av} \rangle$, where ρ_{DM}/m_χ is the number density of dark matter, and the annihilation cross section is averaged over the velocity distribution. Since the clustering of dark matter is known, this amounts to asking how large the annihilation cross section can be. Kaplinghat, Knox, and Turner proposed that a very large annihilation cross section could turn a halo cusp into a core, improving agreement between simulations and observations; Hui showed that unitarity prohibits this for large dark matter masses. We show that if the annihilation products are Standard Model particles, even just neutrinos, the consequent fluxes are ruled out by orders of magnitude, even at small masses. Equivalently, to invoke such large annihilation cross sections, one must now require that essentially no Standard Model particles are produced.

(This proceedings article is based on J. F. Beacom, N. F. Bell and G. D. Mack, “General Upper Bound on the Dark Matter Total Annihilation Cross Section,” astro-ph/0608090 [1].)

1. Dark Matter Disappearance

The self-annihilation cross section is a fundamental property of dark matter. For thermal relics, it sets the dark matter mass density, $\Omega_{DM} \simeq 0.3$, and in these and more general non-thermal scenarios, also the annihilation rate in gravitationally-collapsed dark matter halos today [2]. There are two general constraints that bound the rate of dark matter *disappearance*. (Throughout, we mean the cross section averaged over the halo velocity distribution, i.e., $\langle \sigma_{Av} \rangle$, where $v_{rms} \sim 10^{-3}c$.) We assume that the dark matter is its own antiparticle.

The first is the unitarity bound, developed for the early universe case by Griest and Kamionkowski [3], and for the late-universe halo case by Hui [4]. In the plane of $\langle \sigma_{Av} \rangle$ and dark matter mass m_χ , this allows only the region below a line $\langle \sigma_{Av} \rangle \sim 1/m_\chi^2$. The unitarity bound has some possible exceptions [3, 4, 5]. The second is provided by the model of Kaplinghat, Knox, and Turner (KKT) [6], in which significant dark matter annihilation is invoked to resolve a conflict between predicted (sharp cusps) and observed (flat cores) halo profiles. (In contrast to using dark matter elastic self-scattering, as in Ref. [7].) Since this tension may have been relaxed [2], we reinterpret this type of model as an upper bound, allowing only the region below a line $\langle \sigma_{Av} \rangle \sim m_\chi$. That the KKT model requires $\langle \sigma_{Av} \rangle$ values $> 10^7$ times larger than the natural scale for a thermal relic highlights the weakness of the unitarity bound in the interesting GeV range. However, there have been no other strong and general bounds to improve upon these. (Following Refs. [4, 6], we assume that the dark matter is somehow not a thermal relic, and hence ignore early-universe constraints, which would prohibit such large cross sections.)

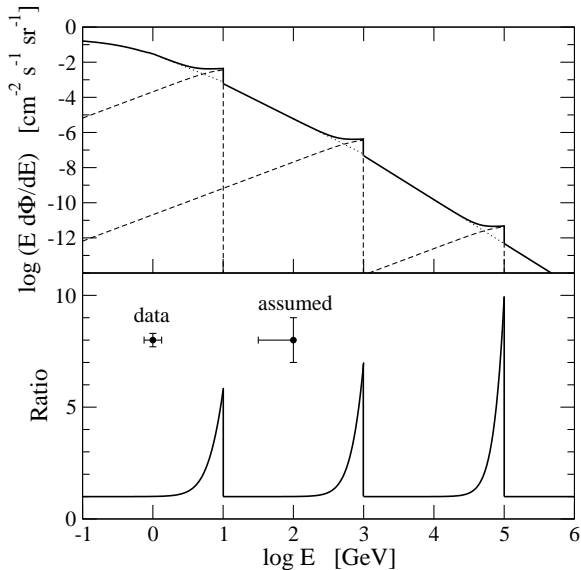


Figure 1. Upper: Diffuse $\bar{\nu}\nu$ annihilation signal for $m_\chi = 10, 10^3, \text{ and } 10^5$ GeV, added to the atmospheric background, both as $(\bar{\nu}_\mu + \nu_\mu)$ and versus neutrino energy. As noted, the signals are most accurate for $E_\nu > m_\chi/3$. **Lower:** Ratio of this sum and background. The $\langle\sigma_{Av}\rangle$ values at each example m_χ are chosen to be detectable by our conservative criteria; the data and assumed uncertainty scales are also indicated. Figure taken from Ref. [1].

While these bound the *disappearance* rate of dark matter, they say nothing about the *appearance* rate of annihilation products, instead assuming that they can be made undetectable. To evade astrophysical limits, the branching ratios to specific final states can be adjusted in model-dependent ways. However, a model-independent fact is that the branching ratios for all final states must sum to 100%. A reasonable assumption is that these final states are Standard Model (SM) particles, as it is assumed the dark matter is the lightest stable particle in the Beyond-SM sector; we generalize below.

2. Neutrino Appearance

We assume that annihilation proceeds to SM particles, and express the cross section in terms of branching ratios to “visible” and “invisible” final states, such as gamma rays and neutrinos, respectively. If the branching ratio to a specific final state were known, then a bound on that appearance rate would yield a bound on the total cross section, inversely proportional to this branching ratio. However, the branching ratios are model-dependent, and any specific one can be made very small, making that bound on $\langle\sigma_{Av}\rangle$ very weak, e.g., KKT require a stringent $Br(\gamma) < 10^{-10}$ to avoid exceeding the cosmic diffuse gamma-ray background [6].

KKT [6] and Hui [4] assume invisible final states, but do not specify them. Among SM final states, it is clear that all but neutrinos will produce many more gamma rays than $Br(\gamma) \sim 10^{-10}$. Quarks and gluons hadronize, unavoidably producing pions, where $\pi^0 \rightarrow \gamma\gamma$; the decays of weak bosons and tau leptons also produce π^0 . It has been shown recently that the stable final state e^+e^- is not invisible, since it produces gamma rays either through electromagnetic radiative corrections [8] or energy loss processes [9]; the final state $\mu^+\mu^-$ immediately produces e^+e^- by its decays. Thus the only possible “invisible” SM final states are neutrinos. Of final states with only neutrinos, we focus on $\bar{\nu}\nu$. Similar bounds could be derived for $\bar{\nu}\nu\nu\nu$, but we assume that these are either suppressed and/or that the Rube Goldberg-ish Feynman diagrams required would contain charged particles, and hence gamma rays through radiative corrections.

To derive our bound on the *total* annihilation cross section, we assume $Br(\bar{\nu}\nu) = 100\%$. This is *not* an assumption about realistic outcomes, but it is the right way to derive the *most conservative* upper bound, if only SM final states are possible. Why is this a bound on the total cross section, and not just on the partial cross section to neutrinos? Because if even a small fraction of the final states were not neutrinos, they would produce gamma rays, and those flux bounds are so much more stringent that the assumed cross section would be ruled out. Therefore,

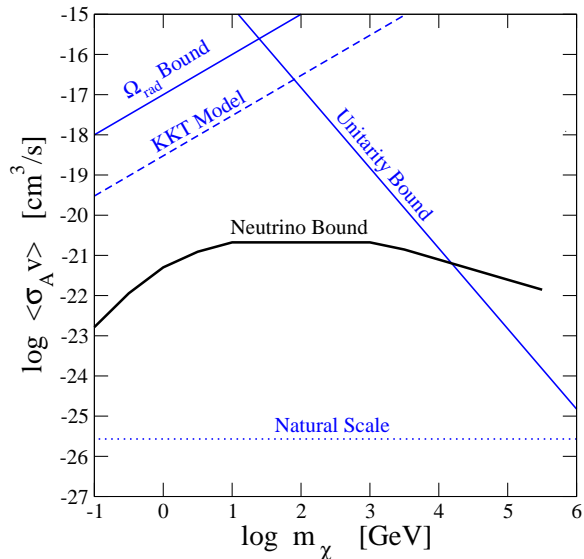


Figure 2. Upper bounds on the dark matter total annihilation cross section in galaxy halos as a function of the dark matter mass, calculated as discussed in the text. Figure taken from Ref. [1].

while setting this bound using neutrinos can be too conservative, it can never overreach. It is beyond our scope to set a more stringent bound using either direct gamma rays (probing $\langle \sigma_A v \rangle$ near the natural scale [2]), or those produced via radiative corrections [10]; this would require specifying the branching ratios for these final states.

3. Neutrino Signal and Background

To bound the neutrino appearance rate, we use the cosmic diffuse neutrino flux from dark matter annihilations in all halos in the universe as the signal. Since this is isotropic and time-independent, it is challenging to detect above the background caused by the atmospheric neutrino flux. Our calculations depend on the average value of density squared in the late (clustered) universe, and for this, we follow the calculations of Refs. [11, 12, 13]. The formalism is summarized in Ref. [1], along with a detailed discussion of the atmospheric neutrino backgrounds [14, 15, 16, 17, 18, 19] and how large of a signal perturbation is allowed.

The predicted neutrino spectra are shown in Fig. 1. These results can be simply checked, following some basic principles. We plotted our spectra as $E d\Phi/dE$ to make these points obvious, and to make estimating the integrals over energy a trivial multiplication by $d \log E$. First, since the annihilation rate scales as $n^2 = (\rho_{DM}/m_\chi)^2$, the energy-integrated fluxes should scale as $1/m_\chi^2$, and they do. Second, since the redshift history is independent of dark matter mass, the spectral shapes for different masses should be the same ($E d\Phi/dE$ at each energy is proportional to the number of annihilations at the corresponding redshift), up to the $1/m_\chi^2$ normalization above, and they are. Third, the fluxes should be dominated by annihilation at low redshift, and they are. Fourth, one can estimate the energy-integrated fluxes by multiplying the annihilation rate density by several Gyr and $c/4\pi$, and this comes out right.

4. Conclusions

We have shown that the dark matter total annihilation cross section in the late universe, i.e., the dark matter *disappearance* rate, can be directly and generally bounded by the least detectable SM states, i.e., the neutrino *appearance* rate. This can be simply and robustly constrained by comparing the diffuse signal from all dark matter halos to the terrestrial atmospheric neutrino background. Our final bound on $\langle \sigma_A v \rangle$ is shown in Fig. 2. Over a very large range in m_χ , it is much stronger than the unitarity bound of Hui [4]. It strongly rules out the proposal of Kaplinghat, Knox, and Turner [6] to modify dark matter halos by annihilation. The only

exception unique to our bound is if one postulates truly invisible non-SM final states, such as sterile neutrinos. However, the annihilations would have to proceed to *only* those states. For a cross section above our bound, its ratio to our bound yields a conservative constraint on the branching ratio to SM final states that one would have to require to invoke that cross section.

Annihilation flattens halo cusps to a core of density $\rho_A \sim m_\chi / (\langle \sigma_{Av} \rangle H_0^{-1})$ [6]. Our bound implies that for all $m_\chi > 0.1$ GeV, this density is $\rho_A > 5 \times 10^3$ GeV/cm³, which only occurs at radii < 1 pc in the Milky Way for an NFW profile, and perhaps not at all for less steep profiles. While modeling is needed to confirm this, we expect that dark matter annihilation cannot have any macroscopic effect on galactic halos, and that it is unlikely that such a strong statement could be made any other way (for example, an argument that we made based on the radiation density [20] is too weak). Detailed analyses by the Super-Kamiokande and AMANDA Collaborations should be able to improve our bound by a factor 10–100 over the whole mass range. Halo substructure or mini-spikes around intermediate-mass black holes could increase the signal by orders of magnitude [13, 21]. The sensitivity could thus become close to the natural scale for thermal relics, making it a new tool for testing even standard scenarios.

Acknowledgments

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