Dark matter annihilation in the Milky Way halo

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Dark matter annihilation in the Milky Way halo

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Abstract. To constrain the particle properties of dark matter using their annihilation products, robust predictions of the annihilation rates are critical. Since the annihilation rate scales as the dark matter density squared, a precise knowledge of the distribution of dark matter is required. Given the popular galactic center contains large uncertainties in the dark matter density, we focus on the signal arising from the whole Milky Way halo. This is less sensitive to uncertainties in the dark matter distribution, and in terms of flux it is larger than the cosmic signal for halos flatter than NFW. We apply this to a dark matter model in which the principal annihilation products are neutrinos. Being the least detectable Standard Model particle, the neutrino defines a strong and general upper bound on the total annihilation cross section. We show that using the Milky Way halo signal improves previous limits by 1–2 orders of magnitude.

(This article is based on H. Yuksel, S. Horiuchi, J. F. Beacom, S. Ando, “Neutrino Constraints on the Dark Matter Total Annihilation Cross Section,” arXiv:0707.0196 [1].)

1. Introduction
High-energy particles from the annihilation of dark matter provide indirect means to probe the particle properties of dark matter. Since the annihilation rate scales as the dark matter density squared, annihilation signatures including gamma rays and neutrinos, which point to the site of production, have been searched for in regions where the dark matter density is expected to be high. Among the many possibilities, the galactic center (GC) remains an attractive site for its closeness and for the expected dark matter cusp. However, the precise annihilation rate strongly depends on the assumed dark matter halo profile; this uncertainty manifests itself as an uncertainty of a few orders of magnitude in size in the enhancement of the annihilation rate (often called the “boost factor”). Given that one places constraints on dark matter properties by assuming a particular dark matter particle make up and a particular dark matter density profile, uncertainties in the boost factor are carried directly to uncertainties in the particle constraints.

Regarding the choice of dark matter particle, there is an entire “zoo” of possible candidates; see a recent review by Bertone, Hooper, and Silk [2]. If the branching ratio to a specific final state were known, a bound on the appearance rate of that state would yield a bound on the total annihilation cross section. However, branching ratios are dependent on the choice of dark matter particle, and for each candidate, there can be different models producing different branching ratios. Any limit on the total annihilation cross section is therefore very weak (specific).

Recently, Beacom, Bell, and Mack have shown that neutrinos can be used as probes to place a strong upper limit on the total dark matter annihilation cross section provided dark matter doesn’t annihilate dominantly to new and truly dark particles [3]. We extend on this so-called “neutrino bound”, both in terms of robustness and magnitude, by keeping to a conservative
analysis of the Milky Way halo. We first show that a large field of view centered around the GC dramatically reduces the spread in boost factor between different profiles, and highlight an isotropic component of the galactic halo that is as large as the truly cosmic component for halos flatter than NFW. We then use the halo components for the neutrino bound, showing that previous bounds are improved upon by 1-2 orders of magnitude.

2. Milky Way halo components

We first discuss the annihilation signal flux for a generic dark matter particle. Detailed derivations can be found in [5, 6]; a summary of appropriate material is also presented in [7, 1].

Due to the cusp, the average boost factor within a cone of half-angle \( \psi \) centered on the GC is very high for small angles. The left of Fig. 1 shows the boost factor \( J(\psi) \) (thin lines) and its average \( \bar{J} \bar{\Delta} \bar{\Omega} \) (thick lines) as functions of \( \psi \) and \( \Delta \Omega / 4\pi = (1 - \cos \psi) / 2 \) respectively, for three halo profiles (Moore, NFW and Kravtsov in order of dotted, dashed and solid lines). Note that the left (right) half is presented in log (linear) scale. Constraints on the dark matter total self-annihilation cross section from components of the Milky Way halo as defined in the text (shaded regions excluded). The constraint from the cosmic signal (dotted line) and the unitarity bound [4] (dot-dashed) are shown.

**Figure 1.** Left.—\( J(\psi) \) (thin lines) and \( J\Delta \bar{\Omega} \) (thick lines), plotted against \( \psi \) and \( \Delta \Omega / 4\pi = (1 - \cos \psi) / 2 \) respectively, for three halo profiles (Moore, NFW and Kravtsov in order of dotted, dashed and solid lines). Note that the left (right) half is presented in log (linear) scale. Right.—Constraints on the dark matter total self-annihilation cross section from components of the Milky Way halo as defined in the text (shaded regions excluded). The constraint from the cosmic signal (dotted line) and the unitarity bound [4] (dot-dashed) are shown.

Interestingly, the boost factor of the Halo Isotropic is essentially profile independent - \( \langle J_{\text{Moore}} J_{\text{NFW}} J_{\text{Kra}} \rangle \approx (0.3, 0.4, 0.55) \). In addition, for halo profiles that are at least as flat as the NFW, the predicted flux of annihilation products in this isotropic component is as large as the truly cosmic flux from all dark matter halos, under the assumption of halo universality. For example, the ratio of the Halo Isotropic to truly cosmic flux for a Kravtsov profile is \( \approx 2 \).
3. Bounds on the total annihilation cross section from neutrinos
We assume that dark matter annihilation proceeds to Standard Model (SM) particles, and explain the neutrino bound in this section. Of the many possible high energy particles produced in dark matter annihilation, neutrinos, being the hardest to detect of the SM particles, provide the weakest bound on the total annihilation cross section. One may naively expect that they cannot therefore produce any meaningful constraints. However, it has recently been shown that this is not the case, and surprisingly strong flux limits can be derived from recent high-statistics data [3]. Due to the difficulty of neutrino detection, we may interpret the neutrinos as bounding all SM final states, and hence constraining the total annihilation cross section. This is because dark matter with even the slightest branching ratio to particles other than the neutrino will yield a stronger, but particle specific, constraint through that particle (or secondary particle, most often photons). Note that the neutrino bound can be evaded if the final states are dominated by new and truly dark non-SM particles, in which case all dark matter annihilation searches will be more challenging.

On the right of Fig. 1 we show our neutrino bounds, placed considering the Milky Way halo components. We assume a NFW profile, and a signal detection criteria of double the atmospheric neutrino background flux. The null detection over background then yields the bounds shown in the figure. Energy bins of $\Delta \log_{10} E = 0.3$ and $\Delta \log_{10} E = 0.5$ were used for the halo and cosmic neutrino signals, respectively. The already strong previous bound is improved on by 1–2 orders of magnitude, depending on which Milky Way component is utilized.

4. Discussion
Can neutrinos be the only final state? We do not stress this is a realistic assumption, but that it enables us to place robust limits on the total annihilation cross section, which are at the same time strong. The upper limits shown on the right of Fig. 1 have been placed using components of the Milky Way halo, and are 1–2 orders stronger than those placed using the cosmic signal from all extragalactic halos. Advantages of the halo components include: (i) the Halo Isotropic is robust to uncertainties in the halo profile, (ii) for profiles cuspier than NFW the Halo Angular becomes stronger than in Fig. 1 (iii) for profiles flatter than NFW the Halo Isotropic becomes more important relatively, (iv) high energy photons from cosmic dark matter are attenuated, and thus neutrinos may not necessarily be the hardest to detect Standard Model particle (the halo components do not have this concern).

Here we showed the neutrino bound using large energy bins and a conservative detection criteria of 100% as large as the atmospheric neutrino background. The atmospheric neutrino background has been measured with high statistics over six orders of magnitude in energy, and shows zenith dependency. A detailed analysis, including zenith dependency (see also [11]), tighter energy bins and detection criteria, and inclusion of electron neutrinos, should be performed. A complementary study [12] has in fact discussed angular dependence, as well as gamma-rays from Z bremsstrahlung [13]. Charged-lepton pairs accompanying $\nu \bar{\nu}$ pairs may also provide competitive and complementary constraints. A comprehensive study including the points above will yield further stringent limits.

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