Gamma-rays From Neutralino Annihilation in Milky Way Substructure: What Can We Learn?

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Abstract. We estimate the probability of detecting gamma-rays from the annihilation of neutralino dark matter in the substructure of the Milky Way. We characterize substructure statistically based on Monte Carlo realizations of the formation of a Milky Way-like halo using semi-analytic methods that have been calibrated against N-body simulations. We find that it may be possible for the upcoming GLAST and VERITAS experiments, working in concert, to detect gamma-rays from dark matter substructure if $M_\chi < \sim 100$ GeV, while for $M_\chi > \sim 500$ GeV such a detection seems unlikely. We investigate the effects of the underlying cosmological model and find that the probability of detection is sensitive to the primordial power spectrum of density fluctuations on small (galactic and sub-galactic) scales. We conclude that the lack of such a detection reveals little about the supersymmetric parameter space due to the uncertainties associated with the properties of substructure and cosmological parameters.

1 Introduction

In the currently popular ΛCDM cosmological model, the Universe is composed of ~ 4% baryonic matter and ~ 26% cold, collisionless dark matter (CDM), and is made flat by a cosmological constant ($\Lambda$) [1]. The growth of structure is seeded by a nearly scale-invariant spectrum of density fluctuations, supposedly generated during an early epoch of inflation. Within this framework, structure forms hierarchically, with small objects collapsing first and subsequently merging into larger structures over time. This paradigm for structure formation predicts the presence of a large number of self-bound subhalos within Milky Way-sized halos (e.g., [2]) and it is possible that these substructures may give rise to a gamma-ray signal due to annihilations of dark matter particles in their dense inner regions [4]. This is based on the assumption that the dark matter is a weakly-interacting massive particle (WIMP) that annihilates into photons. Such a WIMP candidate is provided by supersymmetry (SUSY). In the most popular SUSY models, R-parity conservation guarantees that the lightest SUSY particle (LSP) is stable. Additionally, a large region of SUSY parameter space provides an LSP with the requisite relic abundance to serve as the CDM. In the constrained minimal supersymmetric extension to the standard model (MSSM), this particle is typically the lightest neutralino, or lightest mass eigenstate formed from the two CP-even Higgsinos, the $W^3$ino and the Bino.

In this Proceeding, we explore the idea that neutralino annihilations in Milky Way (MW) substructure may teach us about SUSY and/or structure formation. In particular, we estimate the probability that the gamma-ray signal from neutralino annihilations in substructure will be detected by the upcoming GLAST and VERITAS experiments, assuming the the majority of the CDM is in the form of neutralinos. Further, we investigate the type of information that may be gleaned from such a gamma-ray detection, or lack thereof. The results that we summarize here are based on the work of Ref. [3], to which we refer the reader for details.
2 Milky Way Substructure

To begin with, we describe the matter density profiles of halos using the result of Navarro, Frenk, and White (NFW) [5]: \(\rho(r) = \rho_s (r/r_s)^{-1}(1 + r/r_s)^{-2}\). This description of CDM halos is supported by the most recent numerical studies [6]. To estimate the properties of substructure in the MW, we adopt the simple, semi-analytic model described in Ref. [7]. We first generate Monte Carlo realizations of the merger history of a Milky Way-sized host halo using the extended Press-Schechter formalism [8]. We then track the orbit of the subhalo in the host potential in order to determine whether or not the subhalo is destroyed by tidal forces and to estimate its final position. This model produces substructure radial distributions, mass functions, and velocity functions that are in approximate agreement with the results of high-resolution N-body simulations. This method allows us to account approximately for known correlations between the density structure and collapse histories of subhalos, to model substructure in a simple way that is inherently free of resolution effects, and to generate statistically significant results for a variety of input parameters by examining a large number of realizations of MW-like host halos.

3 The Gamma-ray Signal From Substructure

We calculate the number of gamma-ray photons originating from neutralino annihilations in the central regions of subhalos by assuming the best-case-scenario for detection. We choose to fix the annihilation cross section into all intermediate states that subsequently decay and/or hadronize to yield photons to \(\langle |v|\rangle_h = 5 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}\) and the annihilation cross section into the 2-photon and \(Z^0\)-photon final states to be \(\langle |v|\rangle_{\gamma\gamma, \gamma Z^0} = 10^{-28} \text{ cm}^3 \text{ s}^{-1}\). These values are representative of the maximum achievable cross sections within the context of the constrained MSSM. We include the contributions from the cosmic ray electron [9], hadron [10], and the diffuse gamma-ray backgrounds [11] in our calculation of competing backgrounds. We adopt a liberal definition of a detection at a significance of \(S > 3\) and note that due to detector specifications, the significance is a function of threshold energy and neutralino mass. In accord with our strategy of optimizing the likelihood for detecting the gamma-ray signal from substructure, we concentrate on observations at a threshold energy and neutralino mass where the significance is maximized. Using the specifications of the atmospheric Čerenkov telescope (ACT) VERITAS\(^1\), we find that the significance is maximized at a neutralino mass of \(M_\chi \simeq 500 \text{ GeV}\), with a threshold energy of \(E_{\text{th}} \simeq 50 \text{ GeV}\). We take GLAST\(^2\) as an example of a space-based detector. In this case, the significance is maximized at a neutralino mass just above experimental bounds, \(M_\chi \simeq 40 \text{ GeV}\), and at a threshold \(E_{\text{th}} \simeq 4 \text{ GeV}\).

4 Results

Our first results deal with the likelihood of a detection by the VERITAS instrument. Figure 4 shows results for the most optimistic case for VERITAS, namely, \(M_\chi = 500 \text{ GeV}\) observed above a threshold of \(E_{\text{th}} = 50 \text{ GeV}\). We have assumed a generous exposure time of \(t_{\text{exp}} = 250 \text{ hours}\). In Fig. 4, we show the cumulative number of visible subhalos in the entire sky as a function of an adopted lower mass cut-off, \(M_{\text{min}}\). In practice, there is likely a cut-off in CDM substructure at some low mass, well beyond the regime where N-body simulations can probe. Our results indicate that reducing \(M_{\text{min}}\), adding more low-mass subhalos, does not necessarily lead to a dramatic increase in the number of visible subhalos. Our model suggests that the number of detectable subhalos per mass interval scales as \(dN_{\text{total}}/\ln M \sim M^{-0.02}\) at low mass. We find that with \(M_{\text{min}} = 10^4 \text{ M}_\odot\), we expect \(N_{\text{total}} \sim 17\) detectable subhalos, with fewer than \(N_{\text{total}} \sim 25\) detectable at 95%. This means that, on average, an ACT like VERITAS will have to survey \(\sim 1/20\) of the sky to find one subhalo. Considering the small field of view of VERITAS and the fact that ACTs can, on average, observe \(\sim 6\) hours per night, the prospects for detection must rely heavily on serendipity, even in the best of circumstances. Note that for neutralino masses higher or lower than \(M_\chi \sim 500 \text{ GeV}\), there are fewer detectable subhalos.

If we are to learn about SUSY and/or structure formation from such experiments, we must investigate the sensitivity of these results to cosmological parameters. In Figure 4, we show the results of

\(^1\)http://veritas.sao.arizona.edu
\(^2\)http://glast.gsfc.nasa.gov
Figure 1: Left: The cumulative number of subhalos on the entire sky with mass $M \geq M_{\text{min}}$ that are detectable at $S \geq 3$ by VERITAS after an exposure time of 250 hours. The neutralino mass is $M_\chi = 500\text{ GeV}$ and $E_{\text{th}} = 50\text{ GeV}$, yielding the highest probability for detection. The solid line represents the mean over 100 model realizations in the $\Lambda$CDM cosmological model with scale-invariant primordial power spectrum. The dashed line represents the mean over 100 realizations in a $\Lambda$CDM model with a running power law power spectrum, $dn/d\ln k = -0.03$ with $n(k = 0.05\text{ Mpc}^{-1}) \simeq 0.93$ and $\sigma_8 \simeq 0.84$. In both cases, the error bars correspond to the 64% range of the predictions (symmetric about the median). The down arrows indicate that more than 18% of the realizations had zero visible halos in the corresponding mass bin. Right: The cumulative number of visible subhalos detectable at $S \geq 3$, with mass $M \geq M_{\text{min}}$, after a one year exposure with GLAST in standard $\Lambda$CDM. The threshold energy is $E_{\text{th}} = 3\text{ GeV}$. Solid lines represent the mean over 100 model realizations for a neutralino with mass $M_\chi = 40\text{ GeV}$, while dashed lines represent a neutralino with $M_\chi = 100\text{ GeV}$. The error bars are as in the left panel.

a calculation based on a $\Lambda$CDM model with a nonstandard power spectrum. We show a model with a running power law index, $dn/d\ln k = -0.03$, as suggested by the recent analysis of the WMAP team[1]. In this case, the mean number of visible subhalos is reduced by more than an order of magnitude. This can be explained by examining the effects of reduced small-scale power on the properties of substructure populations [7] and shows that predictions for the gamma-ray signal from WIMP annihilations in substructure are sensitive the power spectrum on sub-galactic scales.

We now turn our attention to the space-based GLAST detector. In Figure 4, we show the number of subhalos that would be detectable after a year long exposure with GLAST. The most optimistic number of detectable subhalos is $N_{\text{total}} \sim 14$, corresponding to roughly two subhalos per GLAST field of view; however, one must be cautious. Consider the energy scales involved in this calculation. The optimum neutralino mass for a GLAST detection is at the lower limit of current experimental searches, $M_\chi \sim 40\text{ GeV}$. Increasing the neutralino mass results in fewer visible halos due to the limited effective area of GLAST and a rapidly decreasing subhalo luminosity.

A key ingredient in this calculation is the matter distribution in the very central regions of subhalos. In the absence of any other effect, subhalos may exhibit a central, constant density core established by the competition between the rate of neutralino annihilations and the rate of infalling material. Due to the significant uncertainty in the mass densities achieved in the central regions of dark matter halos, we investigate the effect of the size of the core region on subhalo detectability. In Figure 4, we show how our results vary as a function of core radius, parameterized by $\beta = r_c/r_{c,0}$, where $r_{c,0}$ is the core radius assigned by equating the annihilation rate inside the core to the rate of material infall (see [3]), and $r_c$ is a new core radius defined as a multiple of $r_{c,0}$. Clearly, the precise choice of the core radius affects our results only weakly over many orders of magnitude. Notably, making $\beta < 1$
Figure 2: Left: The cumulative number of subhalos with mass $M \geq M_{\text{min}}$ as a function of $M_{\text{min}}$ for different values of the core parameter $\beta = \tilde{r}_c/\tilde{r}_{c,0}$. The solid, long-dashed and dash-dotted lines correspond to means over all realizations in a ΛCDM cosmological model for $\beta = 10^{-2}$, $10^7$ and $5 \times 10^7$ respectively. Error bars are as in Figure 4. Right: The cumulative number of visible subhalos with a mass $M \geq M_{\text{min}}$ for the standard ΛCDM cosmological model (solid), a model with a spectral index of primordial fluctuations $n = 1.1$ ($\sigma_8 \simeq 1.2$; long-dashed), and a model where the density profiles of subhalos are described by the Moore et al. profile (short-dashed).

...does not have a significant effect on $N_{\text{total}}$. Eventually, when $\beta \gtrsim 5 \times 10^7$, the number of detectable subhalos decreases significantly as the angles subtended by typical subhalo cores become comparable to the detector resolution.

In general the luminosity and therefore detectability of a subhalo is given by integrating the square of the mass density of the subhalo along the line-of-sight to the subhalo. It is of interest to test the robustness of our results by investigating the change in $N_{\text{total}}$ when different mass density profiles are assumed. For this purpose, we show in Figure 4 the number of detectable objects when the Moore et al. profile [12] (with $\rho(r) \propto r^{-3/2}$ at small radii) is assumed. As expected, the number of detectable subhalos increases dramatically (a factor of $\sim 10$).

5 Conclusions

We investigated the possible detection of the MW substructure via the detection of gamma-rays from neutralino annihilations in otherwise dark subhalos. We chose the most optimistic SUSY parameters in order to maximize the probability of detection. We also employed a realistic, yet still optimistic from the standpoint of predicting observable signals from substructure, model for the population of subhalos in the MW. Our main results were:

\* If the neutralino is relatively light ($M_\chi \lesssim 100$ GeV), then GLAST and VERITAS, working in concert, may be able to detect the gamma-ray signal. In this case, GLAST with its large field of view can be used to identify sources in the sky and direct subsequent VERITAS observations, which can search for line-emission at $E = M_\chi$, the smoking gun of neutralino annihilations. For example, if $M_\chi \sim 75$ GeV, then, in the case of optimal coupling to photons, there will be $\sim 1$ detectable subhalo per GLAST field of view, on average. In this case, subsequent, directed observations with VERITAS should be able to confirm the line-emission feature after an exposure time of $t_{\text{exp}} \sim 450$ hr.

\* For neutralino masses in the range $100$ GeV $\lesssim M_\chi \lesssim 500$ GeV, detection requires an instrument with a large effective area, like VERITAS; however, such a detection must rely on serendipity due to...
the small number of potentially detectable objects and VERITAS' comparably small field of view.

For $M_\chi > \sim 500$ GeV it seems unlikely that gamma-rays from neutralino annihilations in dark subhalos will be detectable with VERITAS or GLAST.

What can be learned by the lack of such a detection? The lack of such a detection certainly will not lead to a bonanza of constraints on the MSSM or SUSY in general. Even after choosing the optimal MSSM parameters for detection, the likelihood of a detection is small for most of the viable range of $M_\chi$. Moreover, the number of detectable objects depends upon the uncertain shape of density profiles in the innermost regions of dark matter halos. These uncertainties can significantly influence our predictions. Moreover, there are additional uncertainties that are not associated with our lack of knowledge of density profiles and subhalo populations. The predictions of the expected gamma-ray flux are strongly dependent upon poorly-constrained cosmological parameters. We showed in Fig. 4 that adopting the best-fitting power spectrum from the WMAP group reduces the probability of detection by more than an order of magnitude relative to a model with a standard, scale-invariant primordial power spectrum.

Of course, a detection would yield a great deal of information. First and foremost, it would be evidence for neutralino (or some other WIMP that annihilates into photons) dark matter, it would suggest the presence of dark subhalos within the MW, it would indicate that such subhalos do achieve extremely high densities in their central regions, and it may also yield information about the survival rates and accretion histories of dark matter subhalos. Nevertheless, it will be difficult to “measure” SUSY from such a detection. As we demonstrated above, cosmological parameters play a role in predicting the gamma-ray signal and, as we show in Fig. 4, adopting a “blue tilted” power spectrum with $n = 1.1$, COBE-normalized to $\sigma_8 \simeq 1.2$, can boost the expected number of detectable subhalos by a factor of $\sim 3$. Such uncertainties must be marginalized over and a model similar to the one we presented here may be able to play an important role in this regard. Further, the flux from a particular subhalo depends upon subhalo distance and there is no obvious way to determine reliably the distance to an otherwise dark subhalo. Our model attempts to take this uncertainty into account by calculating “likely” realizations of the substructure population of the MW.

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