The observability of gamma-rays from neutralino annihilations in Milky Way substructure

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We estimate the probability of detecting gamma-rays from the annihilation of neutralino dark matter in dense, central regions of Milky Way substructure. We characterize Galactic substructure statistically based on Monte Carlo realizations of the formation of a Milky Way-like halo using a semi-analytic method that has been calibrated against the results of high-resolution N-body simulations. We find that it may be possible for the upcoming experiments GLAST and VERITAS, working in concert, to detect gamma-rays from dark matter substructure if the neutralino is relatively light ($M_{\chi} \lesssim 100$ GeV), while for $M_{\chi} \gtrsim 500$ GeV such a detection would be unlikely. We perform most of our calculations within the framework of the standard ΛCDM cosmological model; however, we also investigate the robustness of our results to various assumptions and find that the probability of detection is sensitive to poorly-constrained input parameters, particularly those that characterize the primordial power spectrum. Specifically, the best-fitting power spectrum of the WMAP team, with a running spectral index, predicts roughly a factor of fifty fewer detectable subhalos compared to the standard ΛCDM cosmological model with scale-invariant power spectrum. We conclude that the lack of a detected gamma-ray signal gives very little information about the supersymmetric parameter space due to uncertainties associated with both the properties of substructure and cosmological parameters.

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I. INTRODUCTION

A standard cosmology (ΛCDM) has emerged in which the Universe is spatially flat and its energy budget is balanced by ~4% baryonic matter, ~26% cold, collisionless dark matter (CDM), and roughly 70% dark energy or a cosmological constant (Λ) [1, 2, 3]. The growth of structure is seeded by density fluctuations supposedly generated during an early epoch of inflation [4]. The primordial power spectrum of fluctuations is expected to have a nearly scale-invariant form, $P(k) \propto k^n$, $n \simeq 1$. CDM dominates the baryons in the matter budget, and luminous galaxies form within halos of CDM, where the dark matter potential wells trap and compress baryons so that they may cool and condense. In this paradigm, structure forms hierarchically: small mass objects collapse first and merge into larger objects over time [5]. Many of the small halos subsumed by objects that grow to become present day galactic halos survive as gravitationally self-bound substructure or "subhalos." In fact, CDM theory predicts that halos similar to that of the Milky Way (MW) should host hundreds of subhalos that are apparently about the same size as the observed satellite galaxies of the MW [6]; however, there are only eleven known satellite galaxies within ~300 kpc of the MW (see Ref. [7] for a census of the Local Group). This discrepancy has been dubbed the "dwarf satellite problem" (DSP).

The robustness of the DSP is uncertain and some authors have argued that the observed MW satellites may correspond directly to the eleven or so most massive subhalos observed in simulations [8]. Alternatively, others have proposed solutions to the DSP that fall into two very broad categories. In the first, the number of subhalos of the appropriate size and density structure is reduced such that all such subhalos host luminous satellite galaxies. This outcome can be achieved either by changing the properties of the dark matter [9] or by modifying the spectrum of density fluctuations that seed structure growth [10, 11]. In the second class of solutions, MW-like halos do play host to hundreds of subhalos of the size expected to host its dwarf satellites, but luminous galaxies do not form in ~90% of these subhalos and they remain dark and undetectable. In this case, baryons do not cool and condense in subhalos, perhaps because they are heated by the photo-ionizing background [12, 13], by supernova feedback [14], or some other feedback mechanism. Efforts to detect non-luminous substructure in galactic halos through lensing effects [15], tidal streams [16], or any other method therefore promise to distinguish between these alternatives. As such, these observations may provide a crucial test of the ΛCDM paradigm and reveal important information about structure growth and galaxy formation.

If the standard CDM paradigm is correct, then galactic halos should be teeming with substructure and if the dark matter is in the form of a supersymmetric particle
species produced in the early Universe, then it is possible for this substructure to be lit up by the annihilations of the dark matter particles into gamma-rays. Supersymmetry (SUSY) is the most popular extension of the Standard Model (SM) of particle physics (for a review of SUSY, see Ref. [17]) with several intriguing properties, one of the most cosmologically significant of which is that it admits natural CDM candidates. In the most popular models, especially from the standpoint of building SUSY grand unified theories, the conservation of R-parity guarantees that the lightest supersymmetric particle (LSP) is stable. Moreover, there is a large swath of SUSY parameter space in which the LSP is weakly-interacting and may be produced in the early Universe with an appropriate relic density to serve as the CDM. In the simplest models that meet accelerator constraints, the LSP is the lightest neutralino ($\chi$), or the lightest mass eigenstate formed from the superposition of the two CP-even Higgsinos, the W$^3$ino, and the Bino (for a review of SUSY that focuses on SUSY dark matter, see Ref. [18]).

Several authors have considered the possibility of direct detection of neutralino dark matter from the gamma-ray flux produced by neutralino annihilations in the Galactic center [15]. Assuming that the Milky Way resides within a standard NFW-like halo, the flux from the Galactic center may be considerably larger than that from substructure (by perhaps as much as a factor of $\sim 10^3$) [23]; however, there are large uncertainties in the dark matter density structure of Galaxy-sized halos, largely due to the unknown effect of baryons on the dark matter distribution [27]. In order to mitigate these uncertainties and to test the CDM paradigm, it may be advantageous to consider annihilations in CDM substructure. Other authors have considered this possibility [24, 25, 26, 27], usually with an eye toward constraining the minimal supersymmetric standard model (MSSM) parameter space. Generally, these studies have used overly optimistic prescriptions for the spatial distribution and density profiles of CDM subhalos that are not supported by detailed studies of structure formation in ΛCDM cosmologies.

In this paper, we study neutralino annihilation in halo substructure using a rather different approach. We use a semi-analytic method to estimate the properties of the subhalo population. Past studies of neutralino annihilation in substructure [21, 22, 23, 24, 25] did not account for the fact that the density structure of the subhalos and the spatial distribution of substructure of a given mass depend upon their accretion histories. The semi-analytic model we use allows us to account for these correlations, albeit in an approximate way. In addition, the model allows us to generate statistically significant results for a variety of input parameters by examining a large number of realizations of MW-like halos. Thus we can estimate the likelihood of observing gamma-rays from neutralino annihilations in dark subhalos. In this sense, our approach is aimed more toward serving as a guide for observations and is complementary to the recent numerical study of Stoehr et al. [27]. We demonstrate that observations of this kind will likely not yield meaningful constraints on SUSY and explicitly show how predictions for the expected flux and the number of observable subhalos are rather sensitive to uncertainties regarding the background cosmology. In particular, we show that the likelihood of directly observing subhalos via neutralino annihilations is very sensitive to the initial power spectrum of density perturbations on sub-galactic scales.

The outline of this manuscript is as follows. In Section II we review the properties of dark matter halos observed in N-body simulations and discuss our modeling of halo substructure. In Section III we calculate the expected flux from CDM subhalos, describe the various backgrounds that this signal must overcome and outline conditions for detectability. In Section IV we present our results on the detectability of substructure via gamma-rays from neutralino annihilations. Lastly, we summarize and draw conclusions from this work in Section V.

Throughout most of this work, we assume the standard ΛCDM cosmological model (e.g., [1, 2]) with $\Omega_M = 0.3$, $\Omega_L = 1 - \Omega_M = 0.7$, $\Omega_L h^2 = 0.02$, $h = 0.72$, and a standard, scale-invariant primordial power spectrum of initial density fluctuations, $P(k) \propto k^n$ with $n = 1$. We also consider the consequences of adopting a primordial power spectrum with a running power law index $dn/d\ln k = -0.03$, normalized to $\sigma_8 = 0.84$ as advocated by the recent analysis of the Wilkinson Microwave Anisotropy Probe (WMAP) team [1].

II. THE STRUCTURE AND SUBSTRUCTURE OF DARK MATTER HALOS

In this Section, we discuss the density structure of dark matter halos as well as the properties and characteristics of halo substructure based on our semi-analytic model. The size of a halo can be quantified by its virial Mass $M_v$, virial radius $R_v$, or equivalently its virial velocity $V_v^2 \equiv GM_v/R_v$. The virial radius is defined as the radius within which the mean density is $\Delta_{\text{vir}}$ times the mean matter density of the universe $\rho_M$, so that $M_v = 4\pi\rho_M\Delta_{\text{vir}}(z)R_v^3/3$. The virial overdensity can be estimated using the approximation of spherical top-hat collapse. We compute $\Delta_{\text{vir}}(z)$ using the approximate fitting formula of Bryan and Norman [28]:

$$\Delta_{\text{vir}}(z) \approx (18\pi^2 + 82x - 39x^2)/\Omega_M(z),$$

where $x = 1 - \Omega_M(z) = \Omega_M(1 + z)^3/\Omega_M(1 + z)^3 + \Omega_L$ and $\Omega_M(z)$ is the ratio of the mean matter density to critical density at redshift $z$. In the ΛCDM cosmology that we adopt, $\Delta_{\text{vir}}(z = 0) \approx 337$ and $\Delta_{\text{vir}}(z) \rightarrow 178$ at high redshift, approaching the standard CDM ($\Omega_M = 1$) value. For reference, the virial radius can be written in terms of $M_v$ as $R_v = 13.6h^{-1}\text{ kpc } M_v^{1/3}(\Omega_M\Delta_{\text{vir}}(z)/337)^{-1/3}(1 + z)^{-1}$, where $M_\odot = M_v/10^9h^{-1}\text{ M}_\odot$.

The matter density profiles of CDM halos have been studied extensively in numerical simulations. The spherically-averaged density profile proposed by Navarro,
Frenk, and White 24 (hereafter NFW)

\[
\rho(r) = \rho_s \left( \frac{r}{r_s} \right)^{-1} \left( 1 + \frac{r}{r_s} \right)^{-2},
\]

seems to represent best the structure of halos in the most recent studies of high-resolution numerical simulations 30 and seems to be further buttressed by other theoretical considerations 31 32. These studies rule out the singular isothermal sphere with \( \rho(r) \propto r^{-2} \) and begin to disfavor the very steep profile with \( \rho(r) \propto r^{-1.5} \) proposed by Moore et al. 33 as faithful representations of the predictions of CDM on small scales. In fact, Power et al. 34 observe that the inner profiles of halos become increasingly shallow with decreasing radius all the way down to the minimum radius at which their convergence criteria are met. Therefore, even the assumption of the NFW profile is likely to overestimate gamma-ray flux from dark matter annihilation because this flux is very sensitive to the dark matter density at radii below the resolution limits of present N-body simulations. A definitive resolution of this issue awaits further numerical work. In most of this study, we assume the NFW profile with inner power law \( \rho \propto r^{-1} \), but we also explore the effect of adopting the steeper profile of Moore et al. 33 on our results.

The relative concentration of an NFW halo of a given mass is determined by the NFW scale radius \( r_s \) or equivalently, the NFW concentration parameter \( c_v \equiv R_v/r_s \). This is related to the characteristic NFW density by

\[
\rho_s = \rho_M \Delta_v c_v^2/3 f(c_v), \quad \text{where} \quad f(x) \equiv \ln(1+x) - x/(1+x).
\]

Numerical studies have shown that the concentrations of dark matter halos are set by their mass accretion histories 24 34 35 36. In particular, the concentration parameter of a halo of a given mass is strongly correlated with a suitably-defined epoch of formation for typical halos of that mass (see Refs. 24 34 36 for details). The important point is that the structural parameters of the NFW profiles that describe halo substructure are essentially fixed by the choice of cosmology and are not set by, for example, requiring a subhalo of a given mass at a given galacto-centric radius to be compact enough to resist tidal stripping as has been supposed in previous studies (e.g., as in Ref. 24). Moreover, because of this correlation between subhalo concentration and halo formation epoch, the structural parameters of halos depend strongly upon cosmological parameters such as the linear, rms amplitude of density fluctuations smoothed over spheres of radius 8 \( h^{-1}\)Mpc, \( \sigma_8 \), and the power law index of the primordial power spectrum, \( n \) 37 (of course, if the normalization of the power spectrum is fixed on large scales by measurements of the cosmic microwave background anisotropy, for instance, a change in \( n \) implies a specific shift in \( \sigma_8 \)). As we discuss below, the gamma-ray flux from CDM annihilations in substructure is quite sensitive to the density of the inner regions of halos. This implies that the probability of detecting gamma-ray flux from neutralino annihilations in substructure can be a strong function of cosmological parameters, even in highly-idealized calculations like those that we present here.

In order to account for the correlations between halo mass, redshift, and concentration we adopt the simple, semi-analytic prescription of Bullock et al. 35 (B01) in our modeling of substructure. We use this model to set the concentrations of all substructure halos as described below. The B01 model reproduces the mean \( c_v - M_v \) relation observed in N-body simulations and provides an estimate of the statistical scatter. The model has been tested successfully against standard ΛCDM simulations, tilted ΛCDM simulations, simulations of so-called “standard” CDM (i.e., \( \Omega_M = 1 \)), scale-free power law CDM models 36 38, and warm dark matter cosmologies 39 for halos in the mass range \( 10^{12} \lesssim M_v/M_\odot \lesssim 10^{14} \). In addition, recent results from new simulation data together with a re-analysis of older simulations suggest that the B01 model accurately represents the mean \( c_v - M_v \) relation all the way down to \( M_v \sim 10^7 M_\odot \) and also supports the universality of the NFW profile 40 41.

The first step in our calculation is to estimate the spatial distribution and structural properties of substructure in the MW halo. The properties of substructure in CDM halos are determined through an endless competition between subhalo accretion and destruction due to tidal forces and dynamical friction. Several authors have studied substructure distributions in simulated CDM halos 2 42 43 44, typically in cluster-sized halos. In this study, we adopt a complementary, semi-analytic approach to estimate the properties of the substructure population as described in Ref. 11 (hereafter ZB03). We give a brief summary of the model below, see Ref. 11 for further detail.

First, we generate the merger histories of MW-sized host halos using the extended Press-Schechter formalism 45. In particular, we employ a modified version of the merger tree algorithm proposed by Somerville and Kolatt 46. This allows us to generate a list of masses and accretion redshifts for all halos above a given mass threshold \( M_{\text{min}} \), that merged into the present day MW-like halo during its formation. Second, we assign each subhalo an NFW concentration at the accretion event. To do this, we use the Bullock et al. 35 model to calculate the mean value of the logarithm of the concentration parameter, \( \langle \log(c_v) \rangle \), for the mass of each subhalo at the time of accretion. We then compute the actual value of \( c_v \) that we assign to each subhalo by selecting \( c_v \) randomly from a log-normal distribution with standard deviation \( \sigma(\log(c_v)) = 0.14 \). Bullock et al. 35 determined this to be a good approximation for the statistical scatter of \( c_v \) at fixed mass in their simulations. Finally, we track the subhalo’s orbit in the potential of the host from the time of accretion until today, in a manner similar to that of Taylor and Babul 47 in order to determine whether or not the subhalo is destroyed by tidal forces once incorporated into the parent halo. Using this model we construct 100 statistical realizations of a MW-sized halo with \( M_v = 1.4 \times 10^{12} M_\odot \), using a minimum subhalo mass...
of $M_{\text{min}} = 10^5 \, M_\odot$, and ten realizations of a MW-sized halo with $M_{\text{min}} = 10^4 \, M_\odot$.

This technique yields an estimate of the substructure population of MW-sized halos that is in approximate agreement with the radial distributions, mass functions, and velocity functions of high-resolution N-body simulations [11]. This method offers improvement over some previous estimates of substructure populations in studies of neutralino annihilation in substructure because we account for the known correlations between mass accretion history and the structure of both the host and its subhalos and we are able to study a statistically significant number of hosts. Like previous numerical studies [12, 13, 14], this method reveals a core-like behavior in the radial distribution of subhalos themselves for radii $r \lesssim 30 - 70$ kpc, with the exact value depending upon the subhalo mass cut one considers. This is the well-known result that subhalos are anti-biased with respect to the dark matter due to tidal effects. The distribution of subhalos only follows the $\rho \propto r^{-3}$ behavior of the mean dark matter distribution at fairly large halo-centric radii. In addition, our method complements N-body work. First, it suffers from no inherent resolution effects such as the issue of “overmerging,” which may cause simulations to underestimate the amount of substructure near the centers of Galaxy-sized halos [12]. If resolution issues are not a problem in numerical simulations, then this method provides an overestimate of gamma-ray flux from subhalos. This is a conservative approach in the context of this paper. Second, our method allows us to generate a large number of MW halo realizations so that we may estimate the probability of observing gamma-rays from neutralino annihilations in otherwise dark substructure, given the scatter in the subhalo distribution in any given host, and demonstrate the effects of cosmological parameters on the probability of detection.

With the gross properties of the subhalo distribution in place, another issue that must be dealt with is the distribution of matter in the very central regions of subhalos. This is where most of the luminosity due to annihilations originates because the annihilation rate scales as the square of the mass density (see below). There will be some limit to the central density of the halo. The densities achieved in the inner regions of halos may be limited simply due to the fact that neutralinos in very dense regions will annihilate, so something closer to a nearly constant density core might be expected. In this case, the core size is set by a competition between mass in-fall and neutralino annihilation, so a simple approximation for the core radius $r_{c,0}$ follows from equating the annihilation rate to the rate of in-falling material,

$$M_\chi/\rho_c(r_{c,0}) \langle |\sigma v| \rangle \sim \sqrt{R_h/GM_\odot}, \quad (2)$$

and solving for $r_{c,0}$. In Eq. (2), $M_\chi$ is the mass of the neutralino and $\langle |\sigma v| \rangle$ is the thermally-averaged total cross section times relative velocity for neutralino annihilation. We assume that the density at all points interior to $r_{c,0}$ is given by the NFW profile density at that point, $\rho_c = \rho(r_{c,0})$. In actuality, most of the gamma-ray luminosity arises from the inner core regions, which are orders of magnitude smaller than has been reliably probed by N-body simulations, so there is little justification for assuming that an NFW profile holds at such small radii [3, 22, 30]. Moreover, there are many other phenomena that could significantly affect the density structure of halos on these scales. Effects that rely on the presence of large baryonic components in the satellite halos are probably negligible for the vast majority of subhalos that are otherwise dark. Other effects, such as that of tides and heating due to rapid encounters with the disk of the host and/or other subhalos are likely to be more important [14, 15]. In these cases, the net result is generally to make subhalos more diffuse in their centers than our model predicts, so we feel that our prescription gives the largest justifiable overestimate for the gamma-ray luminosity of subhalos. Nevertheless, due to the uncertainties in the density structure of subhalos at very small radii, in the following Sections we investigate the effect of adopting core radii given by $r_c = \beta r_{c,0}$, where $r_{c,0}$ is the core radius given by the solution to Eq. (2). We allow $\beta$ to vary between $10^{-2}$ and $10^{0}$.

Figure 1 shows the relevant substructure properties de-
rived from 100 realizations of MW-like host halos. In the left panel of Figure 1 we show the relationship between the quantity $\rho^2 r^3$ [as we discuss below, this combination is roughly proportional to the gamma-ray luminosity of the subhalo, see Eq. (1)] and subhalo mass for the surviving subhalos in our model. In the right panel of Figure 1 we fix the mass range to $10^5 < M/M_\odot < 5 \times 10^5$ and plot the product $\rho^2 r^3$ as a function of the distance of the subhalo from the sun, $d$. In both panels, we also show the values of $\rho^2 r^3$ that we computed using the method of Ref. [22]. Notice that our modeling, which is calibrated against N-body work, suggests that subhalos are typically further away from the sun and less luminous than was assumed by Ref. [22]. The subhalo population that we present here is a more faithful representation of the predictions of the CDM paradigm of structure formation. Yet, we still expect that all of the simplifying assumptions that we have made go in the direction of an over-estimate of the gamma-ray signal from neutralino annihilations.

III. THE GAMMA-RAY SIGNAL FROM ANNIHILATIONS IN SUBSTRUCTURE

In this Section, we outline our method for calculating the emitted flux of gamma-rays from neutralino annihilations in MW subhalos, and compare this with the gamma-ray background to determine a detectability threshold.

A. Gamma-rays from a subhalo

The number of photons with energy greater than a threshold energy $E_{\text{th}}$, arising from neutralino annihilations in a subhalo can be written as

$$N_s = \frac{1}{4\pi} \int_{E_{\text{th}}}^{M_\chi} \frac{dR_{\text{ SUSY}}(E)}{dE} \mathcal{L}_{\text{halo}}(E) A_{\text{eff}}(E) t_{\text{exp}} dE,$$

where

$$\mathcal{L}_{\text{halo}}(E) = \int_{0}^{2\pi} d\phi \int_{0}^{y_{\text{max}}(E)} dy \int_{\text{LOS}} \frac{\rho^2}{D^2} d(\text{LOS})$$

contains all of the information about the subhalo, and

$$\frac{dR_{\text{ SUSY}}}{dE} = \sum_{i=\gamma\gamma, \gamma Z, h \gamma} \frac{dN_{\gamma i}}{dE} \langle \sigma v \rangle_i,$$

contains all of the particle physics information. In Equations (3)-(5), $D$ is the distance to the differential line-of-sight (LOS) element over which the integral is performed. The energy-dependent angular resolution of the detector is $\sigma_0(E)$ and $d$ is the distance to the center of the subhalo. The quantity $y_{\text{max}}(E)$ represents a projected length scale on the subhalo defined by the angular resolution of the detector and given by $y_{\text{max}}(E) = \sigma_0(E)d$.

The energy-dependent effective area of the detector is $A_{\text{eff}}(E)$ and $t_{\text{exp}}$ is the exposure time. As discussed above, for $r < r_c$, the density is constant, given by $\rho(r) = \rho(r_c) = \rho_c =$ const., while for $r > r_c$, $\rho(r)$ is given by Eq. (1).

The neutralino mass is $M_\chi$, the thermally-averaged cross section times the relative velocity of the annihilating neutralinos into a final state $i$ is $\langle \sigma v \rangle_i$, and $dN_{\gamma i}/dE$ is the number of photons in the energy interval $E$ to $E + dE$ that result from neutralino annihilations into final state $i$.” The summation runs over the different final states that lead to gamma-rays.

Neutralino annihilations may yield photons in three ways: (1) by the direct annihilation into a two-photon final state ($\gamma\gamma$); (2) by the direct annihilation into a photon and a $Z^0$ boson ($\gamma Z^0$); and (3) through annihilation into an intermediate state that subsequently decays and/or hadronizes, yielding photons ($h$). The first two processes are easy to deal with because the result is a mono-energetic line emission at energies of $E_{\text{th}}^{\gamma\gamma} = M_\chi$ for the $\gamma\gamma$ final state and $E_{\text{th}}^{\gamma Z^0} = M_\chi [1 - (M_{Z^0}/2M_\chi)^2]$ for the $\gamma Z^0$ final state. In these instances,

$$\frac{dN_{\gamma i}}{dE} = \frac{n_k}{E} \delta \left[ 1 - \frac{E_{\text{th}}}{E} \right],$$

with $n_{\gamma\gamma} = 2$ for the $\gamma\gamma$ final state, and $n_{\gamma Z^0} = 1$ for the $\gamma Z^0$ final state. The theoretical cross sections for these processes span many orders of magnitude and vary depending upon the composition of the neutralino. In the context of the constrained MSSM, the highest values these cross sections attain are $\sim 10^{-28} \text{cm}^3\text{s}^{-1}$ when the neutralino is primarily composed of higgsinos, while mostly gaugino neutralinos have the lowest, roughly $\sim 10^{-32} \text{cm}^3\text{s}^{-1}$. In order to maximize the probability of detecting gamma-rays from halo substructure, we choose the most optimistic set of SUSY parameters, thus we fix the cross sections for annihilation directly into photons to $\langle \sigma v \rangle_{\gamma\gamma} = \langle \sigma v \rangle_{\gamma Z^0} = 10^{-28} \text{cm}^3\text{s}^{-1}$ for all values of $M_\chi$.

The much more complicated case of decay and hadronization of the annihilation products leads to continuum emission. The resultant spectrum for the most important annihilation channels can be well-approximated by

$$\frac{dN_{\gamma h}}{dE} = \frac{\alpha_1}{M_\chi} \left( \frac{E}{M_\chi} \right)^{-3/2} \exp \left[ -\alpha_2 \frac{E}{M_\chi} \right],$$

where ($\alpha_1, \alpha_2$) = (0.73, 7.76) for $WW$ and $Z^0Z^0$ final states, ($\alpha_1, \alpha_2$) = (1.0, 10.7) for $b\bar{b}$, ($\alpha_1, \alpha_2$) = (1.1, 15.1) for $t\bar{t}$, and ($\alpha_1, \alpha_2$) = (0.95, 6.5) for $u\bar{u}$. The cross sections associated with these processes also span many orders of magnitude, from roughly a few $\times 10^{-26} \text{cm}^3\text{s}^{-1}$ to as little as six orders of magnitude smaller. Again, we choose the most optimistic possible value and fix the cross sections to all of these final states to $\langle \sigma v \rangle_h = 5 \times 10^{-26} \text{cm}^3\text{s}^{-1}$, independent of the neutralino mass.
B. Background photons

In order to detect the signal from neutralino annihilations in substructure, it must be significantly larger than the contaminating noise of the gamma-ray background. There are two contributions to this background: (1) the observed background due to cosmic ray hadrons and electrons which will contribute to the background for atmospheric Čerenkov telescopes (ACTs); and (2) the diffuse gamma-ray background supposedly coming from astrophysical sources. The total contribution to the gamma-ray count from background photons above the threshold energy \( E_{\text{th}} \) is

\[
N_B = \int_{E_{\text{th}}}^{\infty} \frac{dN_B}{dE} \, dE,
\]

where the number of observed background photons per unit energy interval can be written as

\[
\frac{dN_B}{dE} \simeq 2.67 \phi_B(E) \left( \frac{A_{\text{eff}}(E)}{\text{cm}^2} \right) \left( \frac{\sigma_\theta(E)}{\text{arcmin}} \right)^2 \left( \frac{t_{\exp}}{\text{yr}} \right) \frac{1}{\text{GeV}},
\]

with

\[
\phi_B(E) = 6.4 \times 10^{-2} \left( \frac{E}{\text{GeV}} \right)^{-3.3} + 1.8 \left( \frac{E}{\text{GeV}} \right)^{-2.75} + 1.4 \times 10^{-6} \left( \frac{E}{\text{GeV}} \right)^{-2.20}.
\]

The three background contributions to \( \phi_B \) are as follows. The first term corresponds to the electron background \cite{19}, the second term is due to hadronization of cosmic rays \cite{50}, and the third term accounts for the diffuse gamma-ray emission measured by the Energetic Gamma-Ray Experiment Telescope (EGRET) \cite{51}. All three of these background contributions are relevant for ACTs, while for space-based gamma-ray detectors the only relevant background is the diffuse background due to astrophysical sources. A fourth source of background photons can be the diffuse emission from neutralino annihilations in the smooth component of the MW halo itself; however, the flux in this case is more than an order of magnitude smaller than all the aforementioned backgrounds and we therefore neglect it in this work.

C. The Detectability of Substructure

We now discuss the conditions for detecting substructure through neutralino annihilations and the probability for observing such a signal. The background count follows Poisson statistics, so it exhibits fluctuations of amplitude \( \sim \sqrt{N_B} \). The quantity called the \textit{significance} \( S = N_s/\sqrt{N_B} \) therefore describes the likelihood of misinterpreting fluctuations in the background as the desired signal from neutralino annihilation. In order to minimize the likelihood of counting background fluctuations, one must demand that the significance be greater than some predetermined requirement, \( S \geq \nu \). We adopt the very liberal detection criterion \( \nu = 3 \). Note that both the background and the source photon counts are directly proportional to the exposure time, so that \( S \propto \sqrt{t_{\exp}} \).

The next issues that need to be addressed are the optimal threshold energy for observation and the neutralino mass at which the probability for detection is maximized. These are important considerations because the significance is a function of threshold energy and neutralino mass for a fixed exposure time, subhalo distance, and subhalo structure, \( S \equiv S(E_{\text{th}}, M_\chi) \). For example, at a fixed neutralino mass, the function \( d\sigma_{\text{easy}}/dE \) is generally a decreasing function of energy while at fixed energy it is a decreasing function of the neutralino mass. For ACTs and space-based gamma-ray detectors, \( A_{\text{eff}}(E) \) increases with energy while \( \sigma_\theta(E) \) decreases with energy. The background contribution \( \phi_B(E) \) is a decreasing function of energy. We would like to investigate the best-case-scenario for detection, so we choose to observe at a neutralino mass and above a threshold energy where the function \( S(E_{\text{th}}, M_\chi) \) is maximized. Generally, \( S(E_{\text{th}}, M_\chi) \) peaks in the continuum part of the spectrum. As a result, it is most fruitful to look for evidence of the continuum signal and then use follow-up observations of the line-emission to confirm that the signal is, indeed, due to neutralino annihilations.

For definiteness, we consider specific examples for maximizing the detectability of neutralino annihilations in subhalos by both an ACT and a space-based gamma-ray detector. For the ACT, we adopt the specifications of the

![FIG. 2: Left: The significance \( S(E_{\text{th}}, M_\chi) \) for VERITAS as a function of threshold energy for neutralino masses \( M_\chi = 100 \text{ GeV} \) (long-dashed), \( M_\chi = 500 \text{ GeV} \) (solid) and \( M_\chi = 5 \text{TeV} \) (dot-dashed) neutralinos normalized to the peak value of the \( M_\chi = 500 \text{ GeV} \) neutralino case. Right: The significance for the GLAST experiment for masses \( M_\chi = 40 \text{ GeV} \) (solid), \( M_\chi = 100 \text{ GeV} \) (dashed) and \( M_\chi = 500 \text{ GeV} \) (dotted), normalized to the \( M_\chi = 40 \text{ GeV} \) case. For VERITAS, the significance is maximized at the instrumental threshold of \( E_{\text{th}} = 50 \text{ GeV} \) for a \( M_\chi = 500 \text{ GeV} \) neutralino, while for GLAST it is maximized at an energy threshold of \( E_{\text{th}} = 3 \text{ GeV} \), for a neutralino of mass \( M_\chi = 40 \text{ GeV} \).](attachment:image.png)
Very Energetic Radiation Imaging Telescope Array System (VERITAS) \[54\]. In this case \( S \), and thus the likelihood of detection, is maximized for a \( M_\chi = 500 \text{ GeV} \) neutralino observed above the VERITAS energy threshold of \( E_{\text{th}} = 50 \text{ GeV} \). We adopt the specifications of the Gamma-ray Large Area Space Telescope (GLAST)\[55\] for the space-based gamma-ray detector. For this experiment, \( S \) is maximized for a neutralino mass just above the present experimental bounds \[57\], \( M_\chi \approx 40 \text{ GeV} \), for gamma-rays observed above an energy threshold of \( E_{\text{th}} = 3 \text{ GeV} \). Other choices of \( M_\chi \) and threshold energy result in smaller values of the significance.

In Figure 2 we show the detectability condition normalized to our choices for the maximum probability of detection. The flattening (VERITAS) and eventual drop-off (GLAST) in the significance at low energies is due to the combined effects of the decreasing effective area of the detectors as well as an increased background photon flux. The lower significance at higher neutralino masses results from the suppression of flux due to the \( M_\chi^{-2} \) term in Equation (6). In principle, a similar set of values of the threshold energy and neutralino mass can be obtained for any detector given its design characteristics.

\[ L \sim \rho_s^2 \chi_c^3 \left[ \gamma + \int_{r_c}^{y_{\text{max}}} \rho_s^2 d^3 r \right] \sim C \rho_s^2 \chi_c^3, \quad (11) \]

where \( C = r_c^{-1} \gamma^{-1}_{\text{max}} \) is a constant that depends on the core radius through \( r_c = r_c/r_s + 1/(1 + r_c/r_s)^3 \) and \( y_{\text{max}} \) through \( y_{\text{max}} = 1/(1 + y_{\text{max}}/r_s)^3 \). Our model yields a relationship between luminosity and subhalo mass, \( L \sim M_{\text{sub}}^{0.52} \), that is close to what one would expect just from the simple scalings \( \rho_s \sim c_s^3, \quad r_s \sim M^{1/3} c_s^{-1}, \) and \( c_s \sim M^{-0.07} \), which is the approximate scaling of concentration with mass given by the B01 model on the small mass scales that we consider in this calculation \[32\]. Knowing how the luminosity of a subhalo scales with mass allows us to derive a scaling relationship for the number of visible halos above some flux threshold. The number of objects visible above a particular threshold is given by the number of objects that are contained within a volume of radius \( d \sim L^{1/2} \), such that the observed flux is higher than the imposed threshold. In this case, the number of objects above this threshold per logarithmic mass interval is \( dN(N_s > \nu \sqrt{N_B})/\text{dln} M \sim (dn/\text{dln}M) L^{3/2} \). Simulations, as well as our simple, semi-analytic model, show that \( dn/\text{dln}M \sim M^{-0.8} \). Using the result that \( L \sim M_{\text{sub}}^{0.52} \), the number of visible halos per logarithmic mass interval is then \( dN(N_s > \nu \sqrt{N_B})/\text{dln} M \sim M^{-0.02} \) on small mass scales. The dependence on minimum mass cut is weak: making the mass cut small does not necessarily lead to a marked increase in the number of visible subhalos.

We find that with a lower mass cut at \( M_{\text{min}} = 10^4 \text{ M}_\odot \), we expect \( N_{\text{total}} \approx 17 \) subhalos to be detectable at \( S > 3 \). As we discussed above, considering lower mass cuts does not increase the number of detectable objects appreciably. Even in this best-case-scenario, the 68\% range only extends up to \( N_{\text{total}} \approx 22 \) (so 84\% of the realizations had fewer detectable subhalos) and the 95\% range extends to \( N_{\text{total}} \approx 25 \). This means that, on average, a detector like VERITAS would have to survey \( 1/20 \) of the entire sky to find one subhalo; this amounts to one subhalo per \( \sim 170 \) VERITAS fields of view. Considering the small field of view of VERITAS and the fact that ACTs can, on average, observe only \( 6 \) hours per night, such a detection must rely heavily on serendipitous discovery, even under the most favorable of circumstances. Note that for neutralinos masses higher or lower than \( M_\chi \sim 500 \text{ GeV} \), the total number of subhalos detectable at \( S > 3 \) would be smaller.

If the direct detection of substructure via particle annihilations (or lack of such a detection) is to yield any constraint on SUSY and/or information about structure/galaxy formation, it is necessary to investigate the influence of the background cosmology on the expected number of visible subhalos. As an example, in Figure 6 we show the results of a calculation based on a cosmology with \( \Omega_M = 1 - \Omega_\Lambda = 0.3 \), but with a nonstandard primordial power spectrum of density fluctuations. In this particular case, we consider a power spectrum

\[ 1 \text{ URL } \url{http://glast.gsfc.nasa.gov} \]
with a running power law index $dn/d\ln k = -0.03$, with $n(k = 0.05 \text{ Mpc}^{-1}) = 0.93$, and $\sigma_8 = 0.84$, as suggested by the recent analysis of the WMAP data [1]. Note that the statistical significance of this result is weakened if additional uncertainties in the mean flux decrement in the Ly-$\alpha$ forest are considered [24]; Nevertheless it is of interest to investigate the consequences of such a power spectrum. In this alternative model the mean number of visible subhalos is reduced by a factor of $\sim 50$. This effect can be understood by examining the influence of reduced small-scale power on the average properties of CDM substructure [11, 24, 35]. In models with reduced small-scale power, low-mass objects form later, and as a result have lower concentrations than objects of the same mass in the standard model. The reduced concentrations of typical subhalos and the fact that the subhalos are consequently more susceptible to tidal disruption, and therefore typically exhibit a larger core in their radial distribution within the host, results in a large reduction in the number of potentially detectable subhalos relative to the predictions of the standard model.

FIG. 3: The cumulative number of subhalos with mass $M \geq M_{\text{min}}$ that are detectable at a significance $S \geq 3$ by VERITAS on the entire sky as a function of $M_{\text{min}}$. As discussed in the text, the neutralino mass is $M_\chi = 500 \text{ GeV}$ observed above the VERITAS threshold energy of $E_{\text{th}} = 50 \text{ GeV}$, yielding the highest possible detection efficiency. The exposure time is set to a generous $t_{\text{exp}} = 250 \text{ hours}$. The solid line represents the mean over all model realizations, down to the minimum mass threshold of $10^4 \text{ M}_\odot$, in the standard $\Lambda$CDM cosmological model with scale-invariant primordial power spectrum.

The dashed line represents the same region for a standard $\Lambda$CDM model with a “running” power law spectrum of primordial fluctuations with $d\ln n/dk = -0.03$ as suggested by the WMAP team [1]. The down arrows indicate that more than 16% of the realizations had zero detectable subhalos in the corresponding mass bin.

The error bars demarcate the 68 percentile range (symmetric about the median) determined from the model realizations. The dashed line represents the same region for a standard $\Lambda$CDM model with a “running” power law spectrum of primordial fluctuations with $d\ln n/dk = -0.03$ as suggested by the WMAP team [1]. The down arrows indicate that more than 16% of the realizations had zero detectable subhalos in the corresponding mass bin.

We now turn our attention to the detectability of substructure with GLAST. In Figure 4 we exhibit the number of subhalos that are detectable at $S > 3$ after a year long exposure with GLAST. Here the most optimistic number of detectable subhalos is $N_{\text{total}} \sim 19$ at the upper limit of the 68% range. This amounts to $\sim 2$ objects per field of view, on average; however, it is necessary to exercise caution. Consider the energy scales involved in this calculation. The optimum neutralino mass for a GLAST detection is at the lower limit of current experimental bounds, $M_\chi \sim 40 \text{ GeV}$ [27]. The factor $dN_{\text{sup}}/dE$ in Eq. 3 is proportional to $M_\chi^{-2}$ and because of its small effective area, GLAST cannot compensate for this rapidly decreasing function of $M_\chi$. Consequently, the number of halos that are observable drops dramatically as $M_\chi$ is increased. This is shown by the bottom set of (dashed) lines in Fig. 4.

Due to the uncertainty in the density structure of the inner regions of halos, it is of interest to investigate the sensitivity of our results to the choice of core radius. In Figure 5 we show how our results on the number of detectable subhalos vary with core radius. We parameterize the variation in core radius by $\beta \equiv r_c/r_{c,0}$, where $r_{c,0}$ is the core radius assigned according to our standard procedure of solving Eq. 3, and $r_c$ is the new core radius defined as a multiple of $r_{c,0}$. Clearly, the particular choice of the core radius affects our results only weakly as a shift in core radius of nine orders of magnitude changes the number of detectable subhalos by less than 40%. This robustness is easily understood. As we discussed previ-
This behavior is valid up to approximately constant as the core radius is changed. Long as \( r \) \( \sim r_c \) nearer the typical range of \( r \) increases appreciably mean that the number of potentially detectable subhalos in N-body simulations. In this case, our results suggest the luminosity of a subhalo can be approximated by \( L \sim \rho_{\chi}^3 \beta \left( r_c - y_{\max} \right) \) [see Eq. (11)]. For a fixed subhalo mass at a fixed distance (i.e., \( y_{\max} = \text{const.} \)), \( r_c' = 1 \) as long as \( r_c < r_s \) and so the expected luminosity remains approximately constant as the core radius is changed. This behavior is valid up to approximately \( \beta \sim 10^7 \). At this point, \( r_c' \) starts to deviate from 1, the core size comes nearer the typical range of \( y_{\max} \) values, and the constant \( C \) decreases. Given the spatial distribution of the subhalos in our model, this behavior becomes noticeable at roughly \( r_c/r_s \sim 10^{-3} \). These scales are beyond the current resolution limits of the inner parts of subhalos in N-body simulations. In this case, our results suggest that the presence of smaller cores does not necessarily mean that the number of potentially detectable subhalos increases appreciably.

V. DISCUSSION AND CONCLUSIONS

We considered the detection of otherwise dark CDM substructure from the gamma-ray products of neutralino annihilations in the center of subhalos. In order to demonstrate several important points, we chose the most optimistic SUSY parameters so that we maximized 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 analysis allowed us to estimate the likely range in the number of detectable subhalos, given the statistical fluctuations in subhalo populations from host to host. The simplifying assumptions of our model should only lead to overestimates of the core densities of subhalos and underestimates of the typical distance to the nearest subhalo and, if anything, we expect that the actual number of detectable subhalos should be smaller than the results that we presented here.

We found it unlikely that an ACT similar to VERITAS will be able to detect neutralino annihilations in dark subhalos due to the small number of potentially detectable subhalos and the relatively small field of view of such a detector. On the other hand, we found that if the mass of the neutralino is near the low end of the viable range, \( M_{\chi} \lesssim 75 \text{ GeV} \), the GLAST detector, with its much larger field of view (~ 2 steradians) will have a significantly higher probability of detecting such objects. In our best-case-scenario of a neutralino of mass \( M_{\chi} = 40 \text{ GeV} \) and an observing threshold of \( E_{\text{th}} = 3 \text{ GeV} \), we found, on average, two subhalos visible at \( S > 3 \) per GLAST field of view. Our results indicate that the best strategy is to locate gamma-ray signals with GLAST and then point detectors like VERITAS at the location of these signals in order to pinpoint them, observe the shape of the gamma-ray spectrum, and search the energy spectrum for the line-emission at \( E = M_{\chi} \), which is a “smoking gun” of neutralino annihilation in substructure. As an example, we found that for a neutralino of mass \( M_{\chi} \sim 75 \text{ GeV} \), there will be \( \sim 1 \) detectable subhalo per GLAST field of view, on average, assuming the maximum cross section for annihilation into photons, and that a directed VERITAS exposure should confirm the line-emission feature.

FIG. 5: The cumulative number of detectable subhalos with mass \( M > M_{\min} \) as a function of \( M_{\min} \) for different values of the quantity \( \beta = r_c/r_s \) (see text). The neutralino mass, exposure time, threshold energy and instrument specifications are as in Fig. 3. Note that over a change of nine orders of magnitude in \( \beta \), the total number of visible halos is nearly independent of the core size.

FIG. 6: The number of subhalos that are detectable by VERITAS at \( S > 3 \) as a function of the minimum mass cut-off \( M_{\min} \), after adopting a Moore profile rather than a NFW profile to describe the substructure (short-dashed) or allowing a positively tilted primordial power spectrum with \( n = 1.1 \) and COBE normalized to \( \sigma_8 \simeq 1.2 \) (long-dashed). The solid line represents the prediction of our fiducial “standard” model of NFW halos and a scale-invariant power spectrum with \( \sigma_8 \simeq 0.95 \). The error bars are as in Figure 3.
after an exposure time of $t_{\text{exp}} \sim 450$ hr. If the neutralino mass were to be in the range, $100 \lesssim M_{\chi} / \text{GeV} \lesssim 500$, we found that a detection would require an instrument with a large effective area, such as VERITAS; however, such a detection would have to rely on serendipity because of the comparably small field of view of such detectors. Unfortunately, for $M_{\chi} \gtrsim 500$ GeV we found that it is unlikely that neutralino annihilations in dark subhalos will be detectable.

As we mentioned earlier, our results are rather sensitive to the assumed form of the subhalo density profile. To illustrate the significance of this, we have repeated our calculations assuming the density profile of Moore et al. 

$$\rho(r) = \rho_0 (r/r_M)^{-3/2} (1 + r/r_M)^{-3/2},$$

with $\rho(r) \propto r^{-3/2}$ at small radii. Our results are presented in Figure 6. Adopting the steeper Moore et al. profile increases the number of detectable subhalos by approximately an order of magnitude. If subsequent studies reveal that the number of detectable subhalos by approximately a factor of $\sim 50$ relative to the same cosmological model

$$\chi \sim 10^{-2},$$

with $1 < \eta < 1.5$ intermediate between the Moore et al. and NFW profiles, then the number of detectable subhalos should lie between the solid and short-dashed lines in Fig. 6.

Suppose that gamma-rays are not observed from halo substructure. Our results demonstrate that the lack of such a detection doesn’t lead to a bonanza of constraints on SUSY in general, or the constrained MSSM in particular, because the number of subhalos that are detectable via gamma-rays depends sensitively on the properties of the substructure. Even after choosing the optimal parameters for detection (i.e., the largest couplings to photons) the likelihood of a detection is small for most of the viable mass range of the neutralino. Additionally, as we have shown, the likelihood depends upon the density profiles in the innermost regions of dark matter halos. The work of Power et al. 

shows no evidence that density profiles approach the NFW inner power law of $\rho \propto r^{-1}$. Rather, they find that the power law may become ever shallower with decreasing radius. Moreover, there are additional uncertainties that are not associated with our lack of knowledge of density profiles and subhalo populations. The predictions of the number of potentially detectable subhalos are strongly dependent upon poorly-constrained cosmological parameters. We showed in Fig. 6 that adopting the best-fitting power spectrum from the WMAP group reduces the probability of detection by a factor of $\sim 50$ relative to the same cosmological model with a standard, scale-invariant primordial power spectrum.

Of course, a detection of gamma-rays from substructure would yield a plethora of information. First and foremost, it would be strong evidence for neutralino (or some other WIMP which annihilates into a photon final state) dark matter, it would indicate the presence of numerous, otherwise dark subhalos surrounding the MW and disfavor models with reduced small-scale power

[10, 11], and it would indicate that such subhalos achieve high densities in their central regions. If future detections yield surface brightness profiles for substructure, then the dark matter distribution of the subhalos could be inferred which would be an important addition to the studies of mass density profiles

[29, 30, 59]. If a large number of subhalos are found then that would give us information on the survival of the very inner regions of accreted subhalos and provide an insight into the accretion history of the MW halo. However, we must exercise caution: if substructure in the Milky Way halo is found via annihilation into high-energy photons, it will still be difficult to “measure” supersymmetric parameters. First, as we have already mentioned, the expected number of detectable subhalos is sensitive to cosmological parameters. In Fig. 6 we show the number of subhalos that are detectable by the VERITAS instrument in the case where the power spectrum has a “blue tilt,” with $n = 1.1$, and is normalized to the Cosmic Background Explorer measurements of cosmic microwave background anisotropy

[60], yielding $\sigma_8 \approx 1.2$. In this case the SUSY parameters are fixed, yet the number of detectable halos is boosted by a factor of $\sim 3$ due to the increase in small-scale power. Although spectra with such large values of $\sigma_8$ seem to be disfavored (e.g.,

[61]), uncertainties like these must be marginalized over in analyses of the SUSY parameter space and calculations similar to the one presented here may be helpful in this regard. Second, the observed flux of gamma-rays from a particular subhalo depends upon the distance to that particular subhalo. This is a significant problem, for there is no obvious way to determine reliably the distance to an otherwise dark subhalo. In our approach, we have attempted to marginalize over such uncertainties by calculating “likely” realizations of substructure in the MW and the most likely number of observable subhalos, assuming a maximum annihilation cross section to photons. Therefore, if a large number of subhalos are observed, it is likely that the neutralino annihilation cross section is large. Such a large cross section would imply a neutralino with a large higgsino component, a region of the supersymmetric parameter space which will be more easily explored in forthcoming experiments. If, on the other hand, SUSY is discovered in the upcoming runs of the Large Hadron Collider

2 (LHC), and the mass and couplings of the neutralino are subsequently measured, this information would provide the framework within which a calculation along the lines of the one presented in this manuscript could be used to study the properties and distribution of CDM substructure.

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