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GLAST and Dark Matter Substructure in the Milky Way

Michael Kuhlen*, Jürg Diemand†,** and Piero Madau†,‡

*School of Natural Science, Institute for Advanced Study, Einstein Lane, Princeton, NJ 08540, USA
†Department of Astronomy and Astrophysics, UC Santa Cruz, 1156 High Street, Santa Cruz, CA, USA
**Hubble Fellow
‡Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85740 Garching, Germany

Abstract. We discuss the possibility of GLAST detecting gamma-rays from the annihilation of neutralino dark matter in the Galactic halo. We have used "Via Lactea", currently the highest resolution simulation of cold dark matter substructure, to quantify the contribution of subhalos to the annihilation signal. We present a simulated allsky map of the expected gamma-ray counts from dark matter annihilation, assuming standard values of particle mass and cross section. In this case GLAST should be able to detect the Galactic center and several individual subhalos.

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INTRODUCTION

One of the most exciting discoveries that the *Gamma-ray Large Area Space Telescope* (GLAST) could make, is the detection of gamma-rays from the annihilation of dark matter (DM). Such a measurement would directly address one of the major physics problems of our time: the nature of the DM particle.

Whether or not GLAST will actually detect a DM annihilation signal depends on both unknown particle physics and unknown astrophysics theory. Particle physics uncertainties include the type of particle (axion, neutralino, Kaluza-Klein particle, etc.), its mass, and its interaction cross section. From the astrophysical side it appears that DM is not smoothly distributed throughout the Galaxy halo, but instead exhibits abundant clumpy substructure, in the form of thousands of so-called subhalos. The observability of DM annihilation radiation originating in Galactic DM subhalos depends on their abundance, distribution, and internal properties.

Numerical simulations have been used in the past to estimate the annihilation flux from DM substructure [1, 2, 3, 4], but since the subhalo properties, especially their central density profile, which determines their annihilation luminosity, are very sensitive to numerical resolution, it makes sense to re-examine their contribution with higher resolution simulations.

DM ANNIHILATION IN SUBSTRUCTURE

Here we report on the substructure annihilation signal in "Via Lactea", the currently highest resolution simulation of an individual DM halo. Details about this simulation, including the properties of the host halo and its substructure population, can be found in [4, 5]. To briefly summarize: The central halo is resolved with ~ 200 million high resolution DM particles, corresponding to a particle mass of $M_p = 2 \times 10^4\,\mathrm{M}_\odot$. At $z = 0$ the host halo has a mass of $M_{200} = 1.8 \times 10^{12}\,\mathrm{M}_\odot$, and it underwent its last major merger at $z = 1.7$. In total we resolve close to 10,000 subhalos, which make up 5.3% of the host halo mass. The subhalo mass function is well approximated by a powerlaw $dN/d\ln M \propto M^{-1}$ over three orders of magnitude down to the resolution limit of about 200 particles per subhalo ($\sim 4 \times 10^6\,\mathrm{M}_\odot$). This power law slope corresponds to equal mass in substructure per decade, and it implies that the total subhalo mass fraction has not yet converged. Future simulations with even lower particle masses will presumably find an even larger subhalo mass fraction. A limitation of this present simulation is that it completely neglects the effects of baryons. Gas cooling will likely increase the DM density in the central regions of the host halo through adiabatic compression [6]. However, because of their shallower potential wells, the DM distribution in galactic subhalos is unlikely to be significantly altered by baryonic effects.

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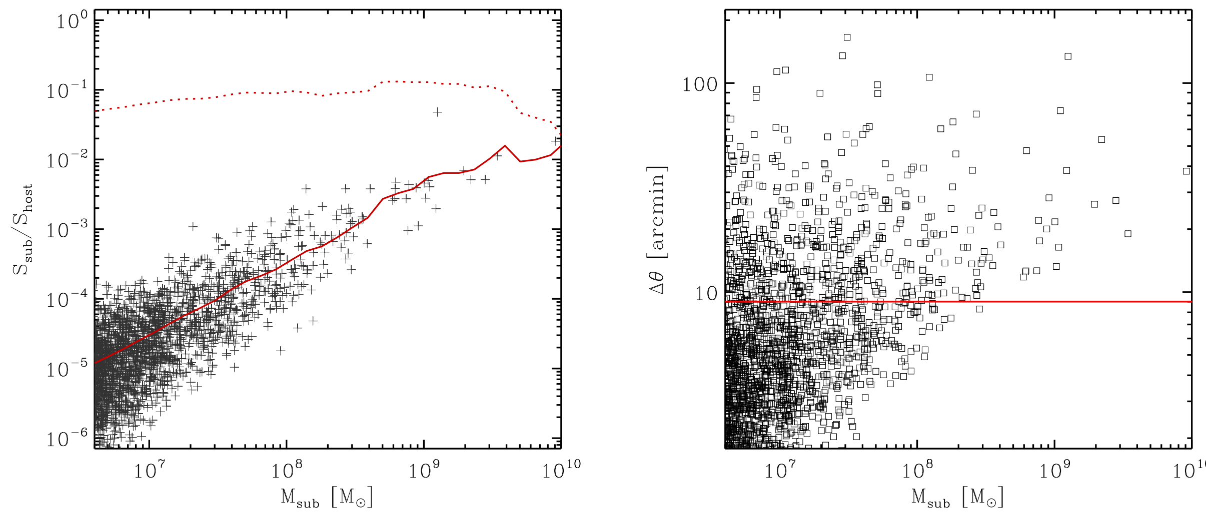

FIGURE 1. *Left panel*: The annihilation signal of individual subhalos (*crosses*) in units of the total luminosity of the spherically averaged host halo. The curves are the average (*solid*) and total (*dotted*) signal in a sliding window over one decade in mass. *Right panel*: The angular size subtended by $2.0r_s$ for a fiducial observer located 8 kpc from the halo center vs. the subhalo tidal mass. For an NFW density profile $\sim 90\%$ of the total luminosity originates within r_s. The expected GLAST 68% angular resolution at > 10 GeV of 9 arcmin is denoted by the solid horizontal line.

We approximate the annihilation luminosity of an individual subhalo by

$$S_{\mathrm{sub,i}} = \int_{V_i} \rho_{\mathrm{sub}}^2 dV_i = \sum_{j\varepsilon\{P_i\}} \rho_j m_p, \tag{1}$$

where ρ_j is the density of the j^{th} particle (estimated using a 32 nearest neighbor SPH kernel), and $\{P_i\}$ is the set of all particles belonging to halo i. In the left panel of Figure 1 we plot S_{sub} normalized by S_{host}, the total luminosity of the spherically averaged host halo.

We find that the subhalo luminosity is proportional to its mass. Given our measured substructure abundance of $dN/d\ln M_{\mathrm{sub}} \propto M_{\mathrm{sub}}^{-1}$, this implies a total subhalo annihilation luminosity that is approximately constant per decade of substructure mass, as the Figure shows (dotted line). We measure a total annihilation luminosity from the host halo that is a factor of 2 higher than the spherically-averaged smooth signal, obtained by integrating the square of the binned radial density profile. About half of this boost is due to resolved substructure, and we attribute the remaining half to other deviations from spherical symmetry. Similar boost factors may apply to the luminosity of individual subhalos as well (see next section).

The detectability of DM annihilation originating in subhalos depends not only on their luminosity, but also on the angular size of the sources in the sky, which we can constrain by "observing" the subhalo population in our simulation. For this purpose we have picked a fiducial observer position, located 8 kpc from the halo center along the intermediate axis of the triaxial host halo mass distribution. In the right panel of Figure 1 we plot the angular size $\Delta\theta$ of the subhalos for this observer position. For an NFW density profile with scale radius r_s, about 90% of the total annihilation luminosity originates within r_s. We define $\Delta\theta$ to be the angle subtended by $r_{\mathrm{Vmax}}/2.16$, where r_{Vmax} is the radius of the peak of the circular velocity curve $V_c(r)^2 = GM(<r)/r$, which is equal to $2.16r_s$ for an NFW profile. GLAST's expected 68% containment angular resolution for photons above 10 GeV is 9 arcmin. We find that (553, 85, 20) of our subhalos have angular sizes greater than (9, 30, 60) arcmin. In the following section we consider the brightness of these subhalos and discuss the possibility of actually detecting some of them with GLAST.

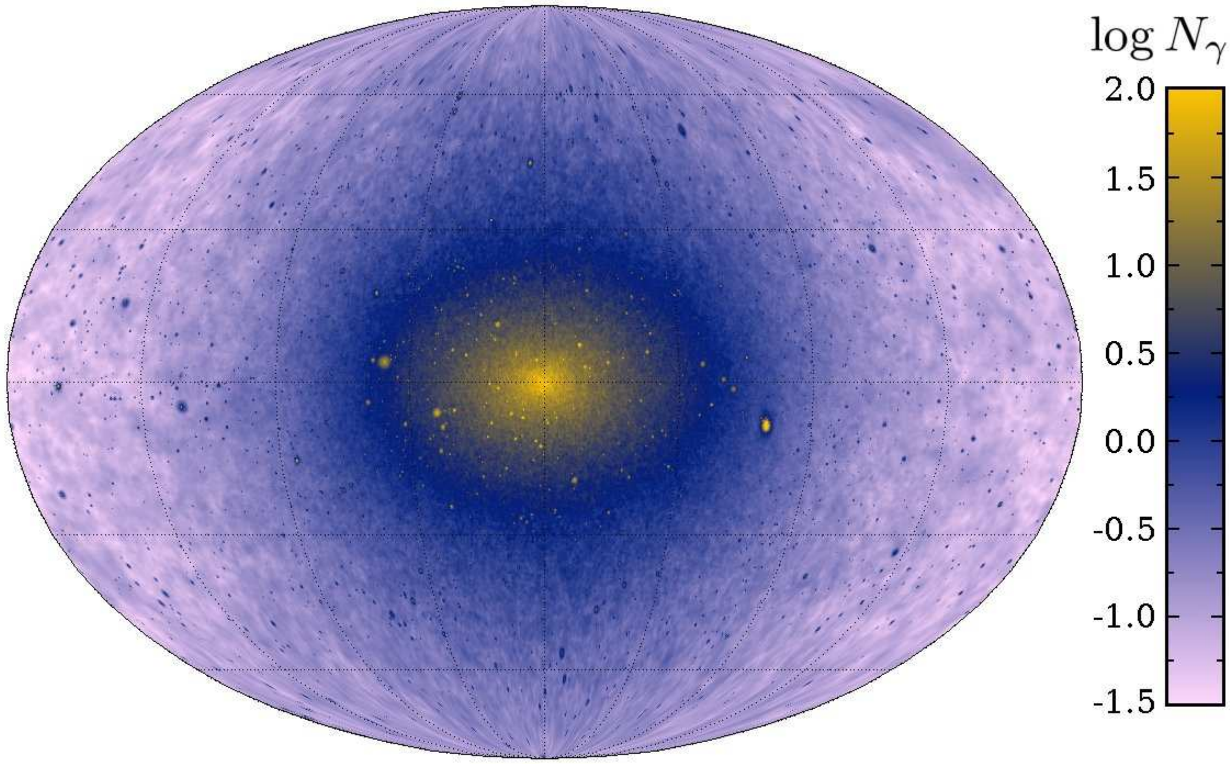

FIGURE 2. Simulated GLAST allsky map of neutralino DM annihilation in the Galactic halo, for a fiducial observer located 8 kpc from the halo center along the intermediate principle axis. We assumed $M_\chi = 46$ GeV, $\langle \sigma \mathrm{v} \rangle = 5 \times 10^{-26}$ cm^3 s^{-1}, a pixel size of 9 arcmin, and a 2 year exposure time. The flux from the subhalos has been boosted by a factor of 10 (see text for explanation). Backgrounds and known astrophysical gamma-ray sources have not been included.

DM ANNIHILATION ALLSKY MAP

Using the DM distribution in our Via Lactea simulation, we have constructed allsky maps of the gamma-ray flux from DM annihilation in our Galaxy. As an illustrative example we have elected to pick a specific set of DM particle physics and realistic GLAST/LAT parameters. This allows us to present maps of expected photon counts.

The number of detected DM annihilation gamma-ray photons from a solid angle $\Delta\Omega$ along a given line of sight (θ, ϕ) over an integration time of $\tau_{\rm exp}$ is given by

$$N_\gamma(\theta,\phi) = \Delta\Omega\ \tau_{\rm exp} \frac{\langle \sigma \mathrm{v} \rangle}{M_\chi^2} \left[\int_{E_{\rm th}}^{M_\chi} \left(\frac{dN_\gamma}{dE} \right) A_{\rm eff}(E) dE \right] \int_{\rm los} \rho(l)^2 dl, \qquad (2)$$

where M_χ and $\langle \sigma \mathrm{v} \rangle$ are the DM particle mass and velocity-weighted cross section, $E_{\rm th}$ and $A_{\rm eff}(E)$ are the detector threshold and energy-dependent effective area, and dN_γ/dE is the annihilation spectrum.

We assume that the DM particle is a neutralino and have chosen standard values for the particle mass and annihilation cross section: $M_\chi = 46$ GeV and $\langle \sigma \mathrm{v} \rangle = 5 \times 10^{-26}$ cm^3 s^{-1}. These values are somewhat favorable, but well within the range of theoretically and observationally allowed models. As a caveat we note that the allowed M_χ-$\langle \sigma \mathrm{v} \rangle$ parameter space is enormous (see e.g. [7]), and it is quite possible that the true values lie orders of magnitude away from the chosen ones, or indeed that the DM particle is not a neutralino, or not even weakly interacting at all. We include only the continuum emission due to the hadronization and decay of the annihilation products ($b\bar{b}$ and $u\bar{u}$ only, for our low M_χ) and use the spectrum dN_γ/dE given in [8].

For the detector parameters we chose an exposure time of $\tau_{\rm exp} = 2$ years and a pixel angular size of $\Delta\theta = 9$ arcmin, corresponding to the 68% containment GLAST/LAT angular resolution. For the effective area we used the curve published on the GLAST/LAT performance website [9] and adopted a threshold energy of $E_{\rm th} = 0.45$ GeV (chosen to maximize the significance, see below). The fiducial observer is located 8 kpc from the center along the intermediate principle axis of the host halo's ellipsoidal mass distribution.

Lastly, we applied a boost factor of 10 to all subhalo fluxes. The motivation for this boost factor is twofold: First, we expect the central regions of our simulated subhalos to be artificially heated due to numerical relaxation, and hence less dense and less luminous than in reality. Secondly, we expect the subhalo signal to be boosted by its own substructure. We in fact observe sub-subhalos in the most massive of Via Lactea's subhalos [4], and this sub-substructure, and indeed sub-sub-substructure, etc., will lead to a boost in the annihilation luminosity analogous to the one for the whole host halo, discussed in the previous section. An analytical model [10] for subhalo flux boost factors gives boosts from a few up to ~ 100, depending on the slope and lower mass cutoff of the subhalo mass function.

Figure 2 shows the resulting allsky map in a Mollweide projection. The coordinate system has been rotated such that the major axis of the host halo ellipsoid is aligned with the horizontal direction, which would also correspond to the plane of the Milky Way disk, if its angular momentum vector were aligned with the minor axis of the host halo. The halo center (at $l = 0^\circ$, $b = 0^\circ$) is the brightest source of annihilation radiation, but the most massive subhalo (at around $l = +70^\circ$, $b = -10^\circ$) is of comparable brightness. Additionally a large number of individual subhalos are clearly visible, especially towards the halo center ($-90^\circ < l < +90^\circ$, $-60^\circ < b < +60^\circ$).

In order to quantify the detectability of individual subhalos (given our assumptions) we include diffuse Galactic and extragalactic backgrounds, and convert our photon counts N_γ into significance $S = N_s/\sqrt{N_b}$, where N_s and N_b are the source and background counts, respectively. For the extragalactic background we use the EGRET measurement [11] and for the Galactic background we follow [12] and assume that it is proportional to the Galactic H I column density [13]. Whereas the extragalactic component is uniform over the sky, the Galactic background is strongest towards the center and in a band of $b \pm 10^\circ$ around the Galactic disk.

We consider all objects with $S > 5$ to be detectable by GLAST. With our choice of parameters the halo center could be significantly detected, with $S > 100$. The number of subhalos with $S > 5$ depends strongly on the applied boost factor. Without boosting the subhalo fluxes, only the most massive halo is detectable. Applying a boost factor of 5 (10), we find that 29 (71) subhalos satisfy the $S > 5$ threshold for detectability. Note that subhalos below our current resolution limit might also be detectable. Their greater abundance reduces the expected distance to the nearest neighbor, and this may compensate for their lower intrinsic luminosities (see Koushiappas' contribution in these Proceedings).

In conclusion we find that with favorable particle physics parameters, GLAST may very well detect gamma-ray photons originating from DM annihilations, either from the Galactic center or from individual subhalos. This would be a sensational discovery of great importance, and it is worth including a search for a DM annihilation signal in the data analysis.

ACKNOWLEDGMENTS

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REFERENCES

1. Calcaneo-Roldan, C., & Moore, B. 2000, PhRvD, 62, 123005
2. Stoehr, F., White, S. D. M., Springel, V., Tormen, G., & Yoshida, N. 2003, MNRAS, 345, 1313
3. Diemand, J., Kuhlen, M., & Madau, P. 2006, ApJ, 649, 1
4. Diemand, J., Kuhlen, M., & Madau, P. 2007, ApJ, 657, 262
5. Diemand, J., Kuhlen, M., & Madau, P. 2007, submitted to ApJ, (astro-ph/0703337)
6. Blumenthal, G. R., Faber, S. M., Flores, R., & Primack, J. R. 1986, ApJ, 301, 27
7. Colafrancesco, S., Profumo, S., & Ullio, P. 2006, A&A, 455, 21
8. Bergström, L., Ullio, P., & Buckley, J. H. 1998, Astroparticle Physics, 9, 137
9. `http://www-glast.slac.stanford.edu/software/IS/glast_lat_performance.htm`
10. Strigari, L. E., Koushiappas, S. M., Bullock, J. S., & Kaplinghat, M. 2006, submitted to Phys. Rev. D (astro-ph/0611925)
11. Sreekumar, P., et al. 1998, ApJ, 494, 523
12. Baltz, E. A., Briot, C., Salati, P., Taillet, R., & Silk, J. 2000, Phys. Rev. D, 61, 023514
13. Dickey, J. M., & Lockman, F. J. 1990, ARAA, 28, 215