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Indirect detection of clumps inside the Milky Way with GLAST-like satellites: a closer look

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Abstract: Within the Cold Dark Matter scenario of structure formation, assuming the Dark Matter is composed by common candidates such as supersymmetric particles, the smallest bound structures have masses as low as $10^{-6}M_{\odot}$. High-resolution N-body experiments have shown that a large fraction of these small structures survive hierarchical clustering and can be found within the halo of our own Galaxy. These clumps are expected to boost up significantly the expected annihilation signal and, if sufficiently luminous might also be detected individually as bright spots in the γ-ray sky. In this work we perform a thorough analysis of the prospects for indirect detection of these objects with GLAST-like experiments, exploring different prescriptions for the formation and evolution of Dark Matter clumps, and allowing the subhalos shape parameters to vary within the range currently allowed by numerical simulations. Our results confirm that the subhalos significantly contribute to the diffuse Galactic annihilation signal. The signal preferentially comes from the top-massive subhalos rather than from the smallest ones. However, the possibility to detect individual subhalos with an experiment like GLAST is rather small but in the most optimistic, yet not unrealistic, cosmological scenarios.

Introduction

The upcoming launch of the GLAST satellite focuses our attention on the γ-ray energy band which will be observed, and we study the feasibility of a Dark Matter (DM) indirect detection with GLAST. Details on the DM Indirect Detection can be found in [1].

A large amount of uncertainties arises when computing the predicted annihilation flux. This is due to the unknown nature of the DM and to its unknown distribution inside the halos.

The smooth radial DM distribution is poorly constrained in the innermost regions around the halo center, where neither experiments nor numerical simulations have enough resolution to allow any conclusive modeling. The NFW density profile [2] is usually found to be consistent with numerical simulations. Extrapolated at small distances from the halo center, it predicts a $\rho(r) \propto r^{-1}$ behaviour.

A feature of the hierarchical formation scenario in the Cold DM model is the prediction that each halo at $z = 0$ is the result of the merging of a number of progenitors. The smallest halos ever accreted onto the present day halo have a mass of $10^{-6}M_{\odot}$, if the DM particle is a Weak Intracting Massive Particle (WIMP) [3] such as a Supersymmetric or a Universal Extra Dimension Particle Candidate. High resolution N-body experiments (see, i.g. [4]) have shown that the mass function of subhalos is well approximated by a power law $dn(M)/dln(M) \propto M^{-1}$ and that their distribution traces the mass of the parent halo. When scaled to the Milky Way (MW), they predict the existence of $\sim 10^{16}$ subhalos in the mass range $[10^{-6}, 10^{10}]M_{\odot}$.

A number of papers have investigated the possibility of detecting a population of Galactic subhalos (see, i.g. [5, 6, 7, 8, 9, 10]) with different results depending on the model chosen for the DM density both of subhalos in the Milky Way and inside the subhalos. Some of them claimed for the possibility of detecting a large number of small mass halos through γ-ray detection as well as through their proper motion in the sky [10].

Unfortunately, constraints on the scale parameters of the NFW profiles of each subhalo are very poor.

In this paper we derive a prediction for the γ-ray flux expected from the population of subhalos inside the MW, and we study its detectability with a GLAST-like experiment. We assume different models for the subhalo concentration parameter, which result in more or less concentrated NFW subhalos.

γ-ray flux from subhalos

The γ-ray annihilation flux can be written as $\Phi_\gamma = \Phi^{\rm PP} \times \Phi^{\rm cosmo}$, which factorizes the particle physics and cosmological contributions. We define

$$\Phi^{\rm PP}(E_\gamma) = \frac{1}{4\pi}\frac{\sigma_{\rm ann}v}{2m_\chi^2} \times \sum_f B_f \int_E \frac{dN_\gamma^f}{dE_\gamma} dE. \quad (1)$$

and we adopt $m_\chi = 40$ GeV, $\sigma_{\rm ann}v = 10^{-26}{\rm cm}^3{\rm s}^{-1}$, a 100% branching ratio in $b\bar{b}$, and integrate above 3 GeV. We refer to [11] for further details. On the other hand, $\Phi^{\rm cosmo}$ includes cosmological factors as well as geometrical details such as the angular resolution $\Delta\Omega$ of the instrument and the pointing angle ψ:

$$\Phi^{\rm cosmo}(\psi, \Delta\Omega) = \int_M dM \int_c dc \int\int_{\Delta\Omega} d\theta d\phi$$

$$\int_{\rm l.o.s} d\lambda[\rho_{sh}(M, R(R_\odot \lambda, \psi, \Delta\theta, \phi)) \times P(c) \times$$

$$\times \Phi^{\rm cosmo}_{halo}(M, c, r(\lambda, \lambda', \psi, \theta', \phi')) \times J] \quad (2)$$

where

$$\Phi^{\rm cosmo}_{halo}(M, c, r) = \int\int_{\Delta\Omega} d\phi' d\theta' \int_{\rm l.o.s} d\lambda'$$

$$\left[\frac{\rho_\chi^2(M, c, r(\lambda, \lambda', \psi, \theta'\phi'))}{\lambda^2} \times J\right]; \quad (3)$$

ρ_χ is the NFW density profile inside the halo, whose scale parameters are a function of the concentration parameter $c(M, z)$. $P(c(M, z))$ is the lognormal probability for a given value c with width=0.24. J is the Jacobian determinant, R is the distance from the MW center and r is the distance from each halo center. ρ_{sh} is the subhalo distribution inside the MW taken from [8]:

$$\rho_{sh}(M, R) = AM^{-2}\frac{\theta(R - r_{min}(M))}{(R/r_s^{MW})(1 + R/r_s^{MW})^2}, \quad (4)$$

where r_s^{MW} is the scale radius of our Galaxy and $\theta(R - r_{min}(M))$ accounts for the effect of tidal disruption, according to the Roche criterion. We refer to [12] for the complete definition of symbols.

We use Eq.3 when deriving the contribution from each subhalo as well as the one coming from the smooth MW halo.

Eq.2 is used to derive the expected diffuse γ-ray foreground coming from unresolved halos. The resulting flux is then normalized not to exceed the EGRET extragalactic background far from the Galactic plane.

Ten Monte Carlo realizations of the closest and brightest subhalos have been realized in order to study the possibility of detecting an annihilation flux from a resolved subhalo.

As already pointed out in the Introduction, the $c(M, z)$ relation is not well established. We have used the following 6 different models when deriving the flux predictions for both the diffuse and the resolved halo flux:

B_{z_0}: uses $c(M, z = 0)$ as computed in [13], extrapolated to $c(M = 10^{-6}M_\odot, z = 0)$ = 80 [4].

$B_{z_0,5\sigma}$: uses $c(M, z = 0)$ as computed in [13], extrapolated to $c(M = 10^{-6}M_\odot, z = 0)$ = 400, corresponding to a 5 σ density peak fluctuation.

B_{z_f}: as B_{z_0} but computed at the collapse redshift as derived from [13], extrapolated to $z_f(M = 10^{-6}M_\odot)$ = 70 [4] through the relation $c(M, z = 0) = (1 + z_f) \times c(M, z_f)$.

$B_{z_f,5\sigma}$: as $B_{z_0,5\sigma}$ but computed at the collapse redshift.

ENS_{z_0}: as B_{z_0} but with $c(M, z = 0)$ computed according to [14].

ENS_{z_f}: as B_{z_f} but with $c(M, z = 0)$ computed according to [14].

The $c(M, z = 0)$ curves are shown in Fig.1. Further details can be found in [12].

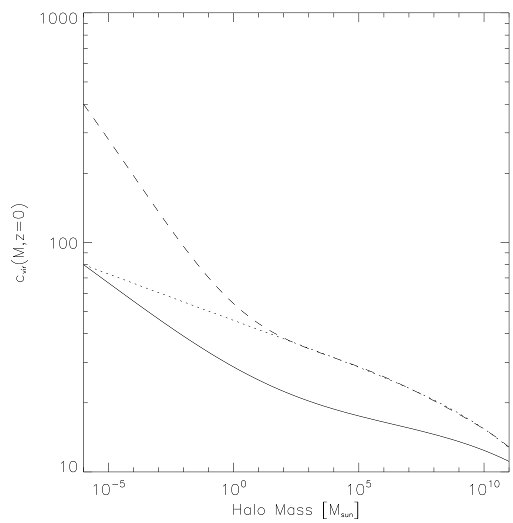

Figure 1: Concentration parameters as a function of halo mass at $z = 0$ computed for the ENS$_{z_0}$(solid), B$_{z_0}$(dashed) and the B$_{z_0,5\sigma}$(dotted) model described in the text.

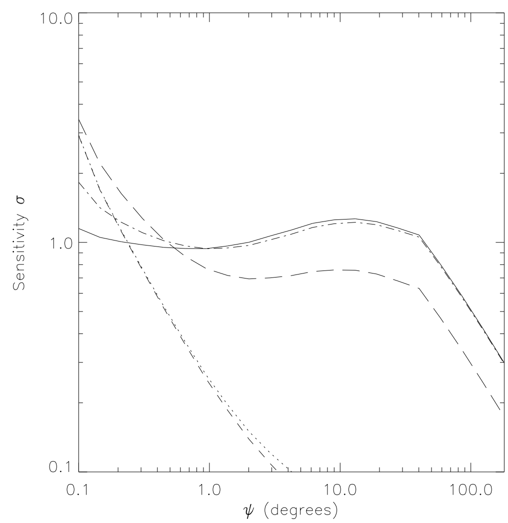

Figure 2: Sensitivity curves for the smooth subhalo contribution obtained along l=0. Results for the B$_{z_0}$(dotted), ENS$_{z_0}$(short dashed), B$_{z_0,5\sigma}$(long dashed), B$_{z_f}$and ENS$_{z_f}$(solid), B$_{z_f,5\sigma}$(dot-dashed) models are shown.

Experimental sensitivity

We define the experimental sensitivity σ as the ratio

$$\sigma \equiv \frac{n_\gamma}{\sqrt{n_{\rm bkg}}}$$
$$= \frac{\sqrt{T_{obs}} \int A_\gamma^{\rm eff}(E,\theta_i)[d\phi_\gamma^{\rm signal}/dEd\Omega]dEd\Omega}{\sqrt{\int \sum_{\rm bkg} A_{\rm bkg}^{\rm eff}(E,\theta_i)[d\phi_{bkg}/dEd\Omega]dEd\Omega}} \quad (5)$$

Here, T_{obs} =1 yr, $A^{\rm eff} = 10^4 cm^2$ independent from both energy and incident angle, and the background is taken from [15] and [16]. While computing the sensitivity for the single halo, the smooth MW and subhalo annihilation foregrounds have been included in the background term. Fig.2 shows the sensitivity curves for the diffuse subhalo + MW foreground for the models described in Sec.2. Such a signal would be detectable only toward the Galactic Centre for the $z = 0$ models which are not affected from the normalization imposed by the EGRET data. Unfortunately, the astrophysical uncertainties in modeling the expected background in that region are very high.

We have then computed the 3-σ detection probability for each one of the simulated halos, as the probability $P(c_{3\sigma})$ of having a concentration parameter $c_{3\sigma}$ whose corresponding flux would result in a 3-σ level detection. The sum of the detection probabilities of all the simulated halos gives us the number of subhalos detectable at 3-σ in 1 yr for the given model. The result is shown in Fig.3, where the number of detectable halos as a function of the subhalo mass is plotted for all the concentration parameter models. The sum of detectable halos integrated over the mass is greater than 1 in all cases but the B$_{z_f,5\sigma}$and ENS$_{z_0}$. Yet, the only detectable subhalos would have a mass greater than $10^7 M_\odot$.

Conclusion

We have derived the expected γ-ray flux from the annihilation of DM in galactic subhalos. We have computed the smooth MW halo and unresolved subhalos components as well as the contribution from resolved halos. We have shown that detection of an annihilation signal with a GLAST-like

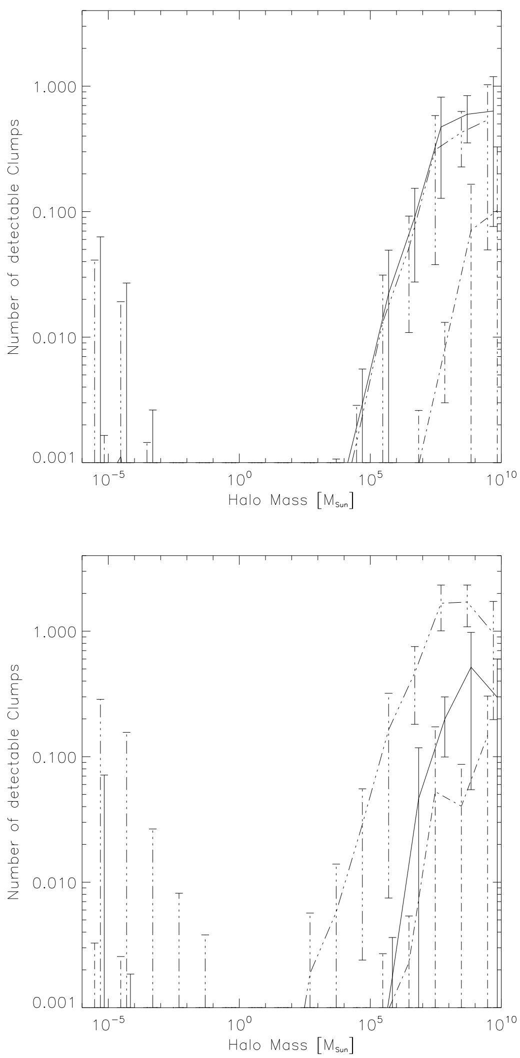

Figure 3: Upper panel: Number of detectable subhalos in a 50 degrees cone of view towards the GC for the models B_{z_0}(solid), $B_{z_0,5\sigma}$(long dot-dashed) and ENS_{z_0}(short dot-dashed), given the lognormal distribution $P(c)$ for the concentration parameter. Lower panel: the same as the upper panel for the models ENS_{z_f}(solid), B_{z_f}(long dot-dashed) and $B_{z_f,5\sigma}$(short dot-dashed).

satellite as a diffuse emission would be possible only toward the Galactic Centre, where astrophysical uncertainties would make it difficult to disentangle from the poorly known astrophysical background. On the other hand, even in the most optimistic models, only a handful of subhalos with masses in the range $[10^7, 10^9]M_\odot$ could be detected individually.

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