Detecting the dark matter via the proper motion of $\gamma$–rays from microhalos

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Abstract. I discuss the prospects for detecting the dark matter via the proper motion of sub–solar mass dark matter halos in the vicinity of the solar neighbourhood. Microhalos that survive tidal disruption could exhibit proper motion of order few arcminutes per year. For dark matter particles that couple to photons, such as the lightest supersymmetric or Kaluza-Klein particles, microhalos could be detected via their $\gamma$-ray photon emission from annihilations. A detection of proper motion of a microhalo in the $\gamma$-ray part of the spectrum contains not only information about the particle physics properties of the dark matter particle, but also provides an insight into hierarchical structure formation at very early times.

Keywords: Dark matter, Galactic halos, Gamma-ray sources

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INTRODUCTION

Even though the presence of dark matter has been firmly established in recent years, the nature of the dark matter particle remains an outstanding problem in particle physics. The idea that the dark matter particle may perhaps be detected indirectly via the detection of potential annihilation products is promising. One particularly interesting aspect of indirect demodulation is the detection of $\gamma$-rays from dark matter annihilations because it will be readily tested with the Gamma-ray Large Area Telescope (GLAST) in the next few years.

The presence of sub–solar mass subhalos (microhalos) in the Milky Way can be probed by searching for the proper motion of $\gamma$-rays emitted from dark matter annihilations [1, 2]. Such a detection is of profound importance. First and foremost, it will be a detection of dark matter. In addition, it will provide information on the survival rate of microhalos in the solar neighborhood, and will place bounds on the mass of the dark matter particle, its annihilation cross section and its kinetic decoupling temperature [1].

PROPER MOTION OF MICROHALOS AND EXPECTED PHOTON FLUX

In the Cold Dark Matter (CDM) paradigm, the first bound structures form at high redshifts. The minimum mass is set by the rms dark matter particle velocities dictated at kinetic decoupling at a temperature $T_d$ [3, 4, 5, 6, 7, 8]. For the particular case of supersymmetric (SUSY) dark matter, this scale is $M_{\text{min}} \approx 10^{-4}(T_d/10\text{MeV})$ [9]. The abundance of microhalos in the solar neighborhood is still under debate [10, 11, 12, 13, 14, 15, 16]. As such, it can be parametrized by assuming that a certain fraction of the local dark matter density ($\rho \approx 10^{-2}M_\odot \text{pc}^{-3}$) is in microhalos in a logarithmic mass interval [1],

$$\frac{dN}{d\ln M_m dD} \approx 2 \left( \frac{\xi}{0.002} \right) \left( \frac{10^{-6}M_\odot}{M_m} \right) \left( \frac{D}{0.1\text{pc}} \right)^2$$

In this parameterization, $\xi$ takes the maximum value of $\xi = 1$ when all of the local dark matter density is in objects in the logarithmic interval $M_m$. We can get an estimate on the range of values it may take by considering the subhalo mass function of dark matter halos. The subhalo mass function has been studied in numerical simulations and found to be described by $dN/d\ln M \sim M^{-1}$, normalized in a way such that for a Milky Way size halo, 10% of the mass of the halo is in subhalos of mass greater than $10^7 M_\odot$. Preliminary results from N-body simulations [10, 11], as well as approximate analytical arguments find that this mass function is preserved down to microhalo scales, with the exception that on sub–solar mass scales the survival probability is reduced to only $10 – 20\%$ due to early rapid merging processes as well as potential interactions with stars [14, 15, 16]. In this case, the value of $\xi$ as defined above reduces to $\xi \approx 0.002$. 

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orbit configuration of the spacecraft \cite{19}), the sensitivity threshold for GLAST is an exposure time of 10 years (assuming the sky will be exposed uniformly for 5 years). For this particular example, the mass of the dark matter particle was assumed to be \(10 \times 10^5\) cm\(^{-2}\) s\(^{-1}\) and with a velocity distribution function \(f(v)\) (assumed to be described by a Maxwell-Boltzmann, see \cite{1})). The expected flux of \(\gamma\)-rays from a microhalo of mass \(M_m\) at a distance \(D\) depends on the annihilation cross section \(\langle \sigma v \rangle\) and mass \(M_\chi\) of the dark matter particle, the density profile of the microhalo, as well as the redshift at which the microhalo collapsed, \(z_{\text{form}}\). Assuming an Navarro-Frenk-White profile \cite{17} and a spectrum given in \cite{18} the number of photons per unit area and time with energy greater than 3 GeV can be written as:

\[
\frac{dN_{\gamma}(>3\text{GeV})}{dA dt} \approx 4 \times 10^{-10} \text{cm}^{-2}\text{s}^{-1}\left(\frac{M_m}{10^{-6} M_\odot}\right) \left(\frac{0.05 \text{pc}}{D}\right)^2 \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3\text{s}^{-1}}\right) \left(\frac{40\text{GeV}}{M_\chi}\right)^2 \left(\frac{1+z_{\text{form}}}{1+70}\right)^3
\]

### DETECTING PROPER MOTION OF \(\gamma\)-RAYS WITH GLAST

In order to detect the proper motion of microhalos that may be present in the solar neighborhood, it is necessary to survey the whole sky in the \(\gamma\)-ray part of the spectrum. This is where GLAST is ideal in performing a search for the proper motion of nearby microhalos. GLAST will survey the whole sky with an integral sensitivity of \(\sim 2 \times 10^{-3}\) cm\(^2\) s\(^{-1}\) for photons with energy above a few GeV. Assuming an effective area of \(2 \times 10^3\) cm\(^2\) and an exposure time of 10 years (assuming the sky will be exposed uniformly for \(5.3 \times 10^6\) seconds per year based on the orbit configuration of the spacecraft \cite{19}), the sensitivity threshold for GLAST is \(\sim 20\) photons.

The left panel of Fig. 1 shows the number of photons expected from microhalos as a function of distance for the same effective area and exposure time as mentioned above. For this particular example, the mass of the dark matter particle was assumed to be \(M_\chi = 40\text{GeV}\), with an annihilation cross-section of \(\langle \sigma v \rangle = 10^{-26}\) cm\(^3\) s\(^{-1}\). This particular choice of parameters represents an optimistic scenario for supersymmetric dark matter. The shaded area in Fig. 1
shows the radius of the volume needed in order to enclose at least 1 microhalo for different values of the parameter \(\xi\). The lower limit comes from assuming that \(\xi = 1\), while the upper bound corresponds to \(\xi = 0.002\). As can be gleaned from Fig. 1, within reasonable distance (e.g. within the shaded area), the number of photons on Earth in a 10 year exposure is between 100-1000 for microhalos with masses \(M_m \geq 10^{-5}M_\odot\). This number is well above the sensitivity threshold for GLAST, suggesting that GLAST will be able to perform a search for microhalos in the solar neighborhood. If the fraction of the local dark matter density in microhalos of mass less than \(10^{-2}M_\odot\) is more than 0.2\%, then there should be at least one microhalo potentially detectable with GLAST at a high signal-to-noise ratio. The dot-dashed lines show the distance where the maximum proper motion is greater or equal to 1 & 9 arcminutes. The single photon angular resolution of GLAST is better than \(\mu_0 \approx 9\) arcminutes for photons of energy above few GeV. However, the localization of a source which emits \(N_\gamma\) photons is improved by a factor of \(1/\sqrt{N_\gamma}\) thus placing a proper motion threshold of detection of \(\mu_{th} = \mu_0/\sqrt{N_\gamma}\). The solid lines show the threshold at which microhalos will be resolved as extended objects in GLAST (assuming a PSF of 9 arcminutes). In this case, the prospects for proper motion detection are much better because the excess photon flux from adjacent resolution bins in extended objects could be used to better localize the position of the source \([20]\).

The right panel of Fig. 1 shows the number of microhalos per logarithmic mass interval that will be detectable based on the integral sensitivity of GLAST as a function of microhalo mass and the particle physics properties of the dark matter particle. Here, \(\xi = 0.002\), and the quantity \(N_\gamma(\sigma v)/M_\gamma^2\) is left as a free parameter (where \(N_\gamma = \int_{M_\odot}^{M_\gamma} dN_\gamma/dE\)). The particular case of an optimistic choice of parameters for supersymmetric dark matter is shown with the dashed line. However, it should be emphasized that the quantity \(N_\gamma(\sigma v)/M_\gamma^2\) can attain higher values than the optimistic case of supersymmetry, e.g. Kaluza–Klein dark matter \([21][22]\). The solid lines represent iso-number contours of the number of microhalos detected that will also exhibit proper motion greater than \(\mu_0\). Such a detection can place constraints on the properties of the dark matter particle. More specifically, the detection of at least 1 microhalo with proper motion places a bound on the mass of the lightest supersymmetric particle to be less than 600 GeV, and its kinetic decoupling temperature to be \(T_d = [1 -- 10] \text{MeV}\) (see \([23]\) for more details on the range of values of \(T_d\) for supersymmetric dark matter).

The potential detection of microhalos in the solar neighborhood has profound consequences in our understanding of the nature of the dark matter particle. It is therefore essential that GLAST includes a search for proper motion of \(\gamma\)-rays in the data analysis. Such an analysis can benefit significantly if the lifetime of GLAST is maximized, thus increasing the baseline for proper motion detection.

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