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CAN ASTROPHYSICAL GAMMA RAY SOURCES MIMIC DARK MATTER ANNIHILATION IN GALACTIC SATELLITES?

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ABSTRACT

The nature of the cosmic dark matter is unknown. The most compelling hypothesis is that dark matter consists of weakly interacting massive particles (WIMPs) in the 100 GeV mass range. Such particles would annihilate in the galactic halo, producing high-energy gamma rays which might be detectable in gamma ray telescopes such as the GLAST satellite. We investigate the ability of GLAST to distinguish between the WIMP annihilation spectrum and the spectrum of known astrophysical source classes. Focusing on the emission from the galactic satellite halos predicted by the cold dark matter model, we find that the WIMP gamma-ray spectrum is unique; the separation from known source classes can be done in a convincing way. We discuss the follow-up of possible WIMP sources with Imaging Atmospheric Cerenkov Telescopes. Finally we discuss the impact that Large Hadron Collider data might have on the study of galactic dark matter.

Subject headings: dark matter — elementary particles — Galaxy: halo — gamma rays: theory

1. INTRODUCTION

It is now firmly established that the majority of matter in the universe is non-baryonic. Evidence for this standard cosmology includes the microwave background anisotropies (Spergel et al. 2006) and the power spectrum of density fluctuations on galactic scales (Tegmark et al. 2006). The "dark matter" is of unknown composition, but indirect evidence from particle physics and cosmology indicates that it is likely to consist of weakly interacting massive particles (WIMPs) in the mass range 30 GeV to 3 TeV. Such particles would be expected to annihilate in galactic halos, albeit at a very low rate. In most models for WIMPs, a significant fraction of the annihilation radiation is expected to be high energy gamma rays coming from the decays of the π^0 meson, which is produced copiously in any energetic interaction involving hadrons.

In the cold dark matter (CDM) paradigm (Blumenthal et al. 1984; Peebles 1984), it is well known that structure forms hierarchically: the dark halos of galaxies such as the Milky Way are expected to contain large numbers of sub-halos. For halos made of WIMPs, the sub-halo mass spectrum is expected to extend down to $10^{-6}M_\odot$ (Green et al. 2005; Diemand et al. 2005). While the brightest source of WIMP annihilation radiation is expected to be the galactic center (where the WIMPs are most concentrated), detecting this signal may be problematic due to the astrophysical gamma ray sources in the galactic plane and at the galactic center. WIMP annihilation in the sub-halos is particularly interesting because of the expectation that many sub-halos will be at high galactic latitude, avoiding the locations of astrophysical galactic gamma ray sources.

Many authors have discussed the possibility of annihilations in galactic substructure (Bergström et al. 1999; Baltz et al. 2000; Calcáneo-Roldán & Moore 2000; Tasitsiomi & Olinto 2002; Stoehr et al. 2003; Taylor & Silk 2003; Evans et al. 2004; Aloisio et al. 2004; Koushiappas et al. 2004); In this Letter, we will illustrate that the spectrum of gamma rays from WIMPs annihilating to hadrons is unique. No known astrophysical source class can mimic the spectrum. This means that the detection of a compact high latitude source with a WIMP annihilation spectrum will provide strong evidence that the dark matter in the Galaxy actually consists of particles in the 100 GeV mass range. Such a detection (e.g. by the GLAST satellite) would provide a crucial piece of the dark matter puzzle.

We outline the hadronic gamma ray spectrum in §2. In §3 we describe simulations of the substructure in the Milky Way and relate these to the detectability of the gamma rays from WIMP annihilations. The astrophysical sources that might mimic an annihilation signal are outlined in §4. Finally, the we discuss the implications of a WIMP detection in §5.

2. GAMMA RAYS FROM HADRONIC INTERACTIONS

The galactic environment is rich in high energy particles. In this section we will concern ourselves with the hadrons, which include protons and all atomic nuclei. When relativistic hadrons interact, such as when cosmic ray protons impinge on the interstellar medium (ISM), the collisions are typically inelastic. The energy lost is mostly emitted as π^+,π^0,π^- mesons in roughly equal numbers. The decay of the π^0 mesons provides most of the gamma rays from hadronic interactions.

The π^0 has a mass m_π = 135.0 MeV. It has two common decay modes: $\pi^0 \to 2\gamma$ (98.8%) and $\pi^0 \to e^+e^-\gamma$ (1.2%) with rare modes contributing less than 0.01%. The π^0 is a pseudoscalar particle, thus it decays isotropically. The photons emitted in $\pi^0 \to 2\gamma$ have energies of $E_0 = m_\pi/2 = 67.5$ MeV in the π^0 rest frame. When boosted to the lab frame, the photon energies are $E_\pm = E_0\gamma(1\pm\beta\cos\Theta)$. This is simply the formula for the doppler shift of photons of energy E_0 and angle Θ relative to the boost axis. The isotropy of the decay implies that $\cos\Theta$ is uniformly distributed, and thus the spectrum dN/dE is constant between the minimum and maximum energies $E_{\rm min,max} = E_0\gamma(1\pm\beta)$. If we consider the spectrum dN/dE as a function of $\ln E$, it is symmetric about $\ln E_0$, because $E_{\rm max}/E_0 = E_0/E_{\rm min}$. The observed spectrum from a source will have this property if the pion distribution is isotropic, true for both WIMP annihilation and cosmic ray interactions with the ISM.

The photon spectrum from a single pion energy must be convolved with the pion spectrum. We consider the process $\chi\chi \to b\bar{b}$, the annihilations of pairs of self-conjugate

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dark matter particles to pairs of b quarks. The dark matter particles are non-relativistic, thus the quarks produced are nearly monochromatic, with energy $E_q = m_\chi$. The individual quarks each form "jets" of hadrons, mostly π mesons. In figure 1 we plot the photon spectra from annihilations to b quark pairs for several dark matter particle masses, as calculated by DarkSUSY (Gondolo et al. 2004) which uses results from Pythia (Sjöstrand et al. 2006). The spectrum is universal: even $\chi\chi \rightarrow W^+W^-$ or Z^0Z^0 gives similar results. Only the $\chi\chi \rightarrow \tau^+\tau^-$ channel differs appreciably (Fornengo et al. 2004; Hooper & Taylor 2006), but this is difficult to arrange for WIMPs from supersymmetry, so we will neglect it.

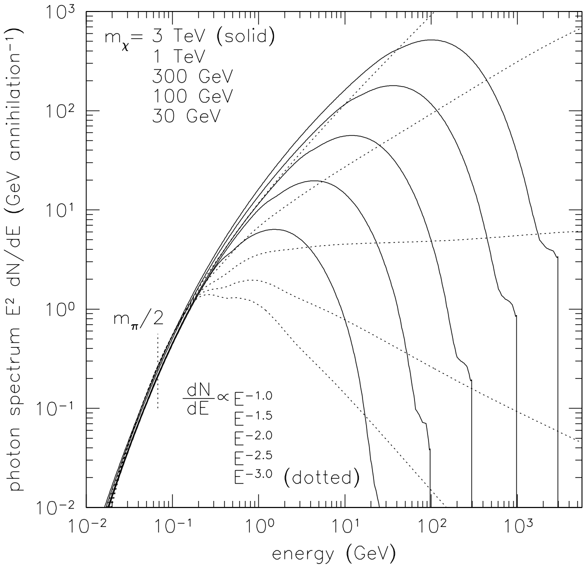

FIG. 1.— Spectrum of photons from hadronic processes. Solid lines depict annihilations to b quark pairs for several WIMP masses. The peak in the spectrum occurs at an energy of $E_{\rm peak} \approx m_\chi/25$. At low photon energies the spectrum is nearly independent of WIMP mass in both shape and magnitude. Dotted lines depict pp interactions for several proton spectra. The pp photon spectra are normalized to be equal at an energy of E_0 = 67.5 MeV (vertical dotted line), where their spectral slopes are guaranteed to be equal.

Astrophysical hadronic interactions universally involve protons and nuclei. The pion spectrum coming from pp collisions at a single energy is very similar in shape to the spectrum coming from quark pairs. Astrophysical proton sources typically have power-law spectra, in almost every case at least as steep as $dN/dE \propto E^{-2}$. In figure 1 we show the spectrum of photons from several power-law proton sources. What this illustrates is that power-law proton beams can *not* mimic the gamma ray spectrum from WIMP annihilations.

3. DETECTABILITY OF GALACTIC DARK MATTER SATELLITES

The GLAST satellite (Atwood 1994; Bloom 1996; Gehrels & Michelson 1999) is well suited to measuring gamma rays from dark matter annihilations. It has an effective area of ≈1 m^2, an solid angle acceptance of roughly 1/4 of the sky, and a point spread function (PSF) of 0.4° at 1 GeV energy. It will measure gamma ray energies between 20 MeV and 300 GeV. Most data will be taken in survey mode, mapping the sky with equal coverage with a large duty cycle. The exposure towards any point on the sky will reach roughly 3×10^{11} cm^2 s over a 5 year mission.

We have estimated the number of Milky Way dark matter satellites observable by GLAST. The dark matter calculation was performed with the semi-analytic method of Taylor & Babul (2004, 2005a,b). The satellite mass distribution has the expected $dN/dM \propto M^{-2}$ (Ghigna et al. 1998), cutting off below $10^6 M_\odot$ due to computational limitations. The dark matter satellite distribution is roughly spherically symmetric about the galactic center and extends well beyond the solar orbit, thus the dark matter satellites are located mostly out of the galactic plane. Individual sources have NFW density profiles (Navarro et al. 1997), with central r^{-1} cusps. Satellites with steeper profiles, e.g. (Moore et al. 1999), would be easier to detect. We find that the brightest sources have masses in the $10^6 - 10^7 M_\odot$ range. These brightest sources have tidal radii of order 100 pc, typically corresponding to 1° on the sky. We note that most of these objects are severely stripped. They have scale radii r_s that are much larger than their tidal truncation radii, thus they have nearly pure r^{-1} density profiles out to the tidal radius r_t.

The surface brightness in gamma rays is proportional to the J parameter, defined in Bergström et al. (1998). For a stripped NFW clump, at a fixed angular distance from its center, $J \propto M^2/r_t^4/D$, where r_t is the tidal radius and D is the distance. If the mass spectrum of clumps is $dN/d\ln M \propto M^{-\alpha}$ and the tidal radius $r_t \propto M^\beta$, the surface brightness of the nearest clump ($D \propto M^{\alpha/3}$) is $J \propto M^{2-4\beta-\alpha/3}$. Our simulations indicate that $\alpha \approx 1$ and $\beta \approx 1/2$, thus $J \propto M^{-1/3}$. Lower mass clumps are thus brighter. However, their angular size $\theta \propto r_t/D \propto M^{\beta-\alpha/3} \propto M^{1/6}$. The total flux is proportional to $(1/D^2)\int \rho^2 dV \propto M^{2-3\beta-2\alpha/3}$; for our parameters flux $\propto M^{-1/6}$. Clumps with masses smaller than those we simulated are brighter, but they are also likely to be smaller than the GLAST PSF, and thus only detectable as point sources. These results are sensitive to the values of α and β, thus is is difficult to extrapolate to smaller mass objects.

As a fiducial case, we assume a WIMP mass of 100 GeV and an annihilation cross-section to $b\bar{b}$ of $\langle\sigma v\rangle = 1.6 \times 10^{-26}$ cm^3 s^{-1}, giving 14.2 photons per annihilation above 1 GeV. In addition, we consider WIMP masses of 30 and 200 GeV, with 4.9 and 21.9 photons above 1 GeV, respectively. Assuming a 5 year GLAST mission, and integrating a 1° radius around the source, the number of background counts is 375 (based on the EGRET extragalactic background (Sreekumar et al. 1998)). The typical brightest clump has $\langle J\rangle = 1400$ averaged in 1° circle. For an example of such an object take $2 \times 10^6 M_\odot$, 3 kpc distant, tidal radius 50 pc, thus subtending 1° on the sky. The number of signal counts above 1 GeV within 1° for 30, 100, 200 GeV WIMPs is 3450, 900, 345, respectively. The resulting number of dark matter satellites as a function of detection significance is shown in figure 2.

4. ASTROPHYSICAL SOURCES

A pure dark matter galactic satellite has three distinguishing characteristics in the gamma rays: hadronic spectrum from monochromatic quarks (and essentially no emission at other wavelengths), spatial extent, and lack of variability. We will focus on the energy spectrum, but we note that a satellite with an NFW profile has a surface brightness in annihilation gamma rays proportional to $1/r$, meaning equal flux in equal width annuli. With the 0.4° PSF of GLAST above 1 GeV, and the typical 1° size of the clumps, we expect that the spatial extent should be detectable with some confidence.

In figures 3-5 we plot the spectrum of the typical brightest clump ($\langle J\rangle = 1400$) with 30, 100, and 200 GeV WIMPs together with fits for several astrophysical source classes.

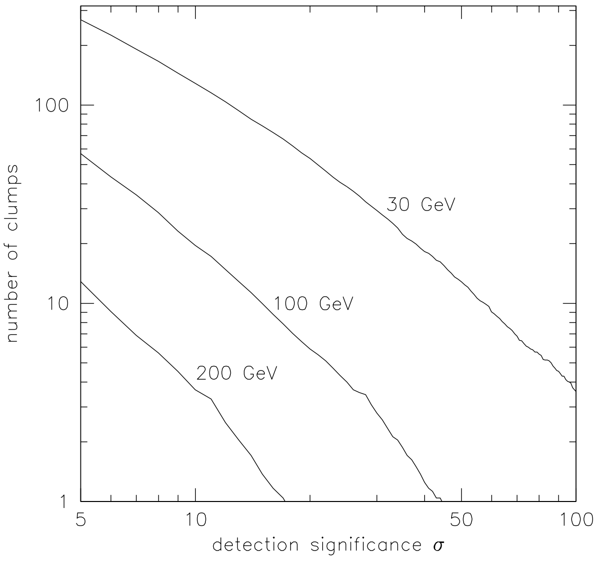

FIG. 2.— The number of detectable clumps is plotted against the detection threshold. Curves for 30, 100, and 200 GeV WIMPs are shown. The typical brightest clump would have a significance of 170, 44, 18 sigma, respectively, for counts above 1 GeV.

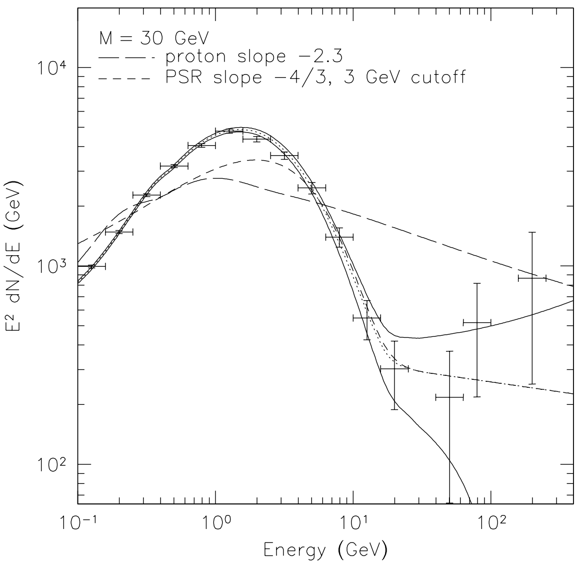

FIG. 3.— Comparison of astrophysical sources with annihilation of 30 GeV WIMPs. The dotted line represents the WIMP spectrum from a single clump with $\langle J \rangle = 1400$ within 1°, and solid lines denote the 1σ error band. The long dashed line indicates the best fit proton power law, and the short dashed line indicates the best fit pulsar cutoff with a low energy power law slope of -4/3. None of the fits are acceptable, including a pure power law (not shown). This source would have had ∼50 counts above 100 MeV detected by EGRET, just above the limit of the third EGRET catalog (Hartman et al. 1999).

4.1. *Molecular Clouds*

The gamma ray spectrum from molecular clouds is generated by cosmic ray protons. The observed gamma ray spectrum is thus a function of the cosmic ray spectrum impinging upon the cloud. These spectra are exactly what is plotted with dotted lines in figure 1. The long dashed lines in figures 3-5 show the best fit molecular cloud spectra. In each case, the molecular cloud hypothesis is ruled out at high confidence. However, because the gamma rays from molecular clouds are expected to be extended and non-variable, it would be comforting to rule out counterparts in other frequencies, especially the radio where CO emission could be visible.

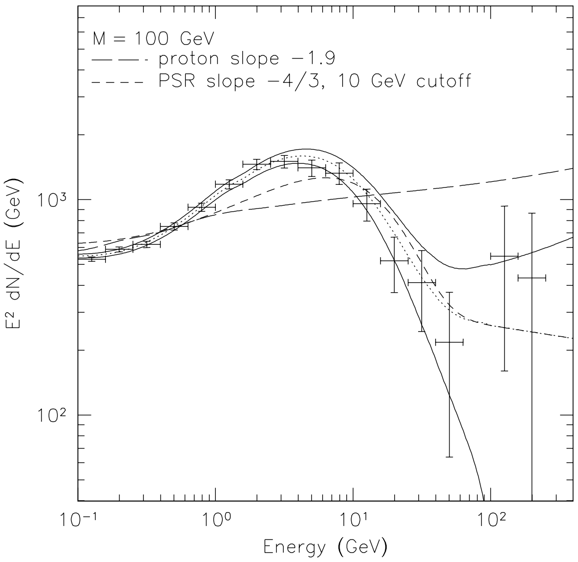

FIG. 4.— Annihilation of 100 GeV WIMPs. The curves are the same as in figure 3. Again, none of the fits are acceptable, including a pure power law.

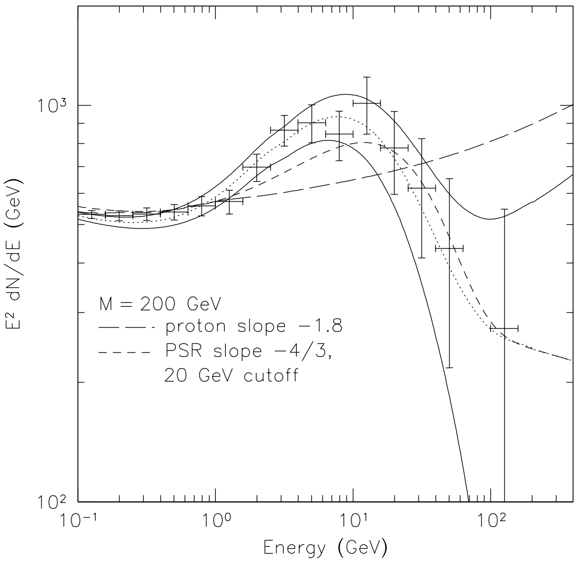

FIG. 5.— Annihilation of 200 GeV WIMPs. The curves are the same as in figure 3. In this case, the pulsar fit is allowed at the 8% level, but the others are unacceptable, including a pure power law.

4.2. *Gamma Ray Pulsars*

Gamma ray pulsars are potentially the most problematic of the astrophysical sources. Their spectra can be parameterized as (Nel & de Jager 1995)

$$\frac{dN}{dE} \propto E^{-\Gamma}\, e^{-(E/E_c)^{\alpha}}. \tag{1}$$

The few known examples have $\Gamma > 4/3$. In fact, most models for gamma ray pulsars require this (e.g. the outer gap model (Romani 1996)), but $\Gamma \to 2/3$ is in principle possible.

The short dashed lines in figures 3-5 show the best fit gamma ray pulsar spectrum. For 30 GeV and 100 GeV, the usual ($\Gamma = 4/3$) spectrum is ruled out. In the 200 GeV case, the usual spectrum is consistent at the 8% level. This case has a considerably lower flux, thus disentangling the possibilities is more difficult. If the low energy slope $\Gamma \to 1$, the spectra become nearly impossible to disentangle for any WIMP mass.

Gamma ray pulsars tend to have multi-wavelength counterparts and also tend to be near the galactic plane. A notable exception is 3EG J1835+5918 which is located at high latitude, but has a faint X-ray counterpart (Halpern, et.al. 2002). The well known radio quiet gamma ray pulsar Geminga is located within 5° of the galactic plane (and could therefore be excluded as a high latitude dark matter candidate).

The variability of the pulsar is difficult to determine in a blind search of the period-period derivative plane. Pulsars are point sources. To mimic the diffuse emission from a galactic satellite, a cluster of pulsars would be required, none of which could have any counterpart in other wavelengths.

4.3. *Other Source Classes*

Plerions will typically have multi-wavelength counterparts, especially in X-rays, and are located close to the galactic plane. They are compact sources in X-rays ($\sim 1'$), but at GLAST energies they may be detected as extended sources.

Supernova remnants will have a power-law gamma ray spectrum. In each case, the best-fit power law is convincingly ruled out. Furthermore, supernova remnants will have multi-wavelength counterparts and are likely to be located near the galactic plane.

Blazars will have a power-law gamma ray spectrum. Furthermore, blazars are variable point sources with counterparts, whereas dark matter satellite annihilations are non-variable, extended sources without counterparts.

5. DISCUSSION

We have shown that the brightest dark matter satellites should be distinguishable from other astrophysical sources, given the capabilities of the GLAST satellite. In any case, such sources would be compelling targets for further study in a multiwavelength campaign. In particular, the dark matter sources are excellent targets for Imaging Atmospheric Cerenkov Telescopes (IACTs).

The mass of the WIMP must be above the IACT analysis threshold, at the present time around 100 GeV. The sensitivity of IACTs is limited by the the residual charged particle background. If this background could be eliminated, then the ultimate sensitivity would be limited only by the isotropic extragalactic diffuse gamma ray background, as it is for GLAST.

A follow-up campaign of 500 hours with an IACT of 0.2 km^2 on our brightest clump, taking the 100 GeV model, can provide a 5σ detection of the direct annihilation to two photons, $\chi\chi \to \gamma\gamma$, for a branching ratio of $B = 1.2\%$. This assumes 99% rejection of hadronic backgrounds and 15% energy resolution. If the hadron rejection were improved by a factor of 10, the electron background dominates: here the line sensitivity would extend to $B = 0.005$. If the electron background could also be eliminated, the extragalactic gamma-ray background would limit the line sensitivity to $B = 0.0003$. The expected branching ratio is typically $B \sim 0.001$. Obviously, there is no astrophysical background that could produce a line at these energies, and thus the existence of particle dark matter would be demonstrated.

The Large Hadron Collider (LHC) may discover a candidate WIMP, and measure its mass at the 10% level on a timescale that matches the GLAST program. A simple estimate shows that GLAST can constrain the mass at the 25% level, for a 100 GeV WIMP. If the GLAST and LHC mass estimates match, the WIMP hypothesis would be greatly strengthened. With strong evidence for particle dark matter in hand, especially including accelerator measurements of cross sections (Baltz et al. 2006), it would become possible to consider mapping the galactic dark matter in the gamma ray sky.

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