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VERITAS Search for VHE Gamma-ray Emission from Dwarf Spheroidal Galaxies

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ABSTRACT

We present results from the VERITAS gamma-ray telescope array observations of the dwarf spheroidal galaxies Draco, Ursa Minor, and Willman 1. The observations were made to search for gamma-rays from the dwarf galaxies indicating a possible signature of self-annihilating weakly interacting massive particles (WIMPs) which may constitute astrophysical dark matter (DM). The observations and analysis of the data are summarized. No signal of significance is observed and we present 95% confidence upper limits on the possible gamma-ray flux from each source. The flux limits range from $(0.3-2.2)\times10^{-12}$ph cm^{-2}s^{-1} for gamma-rays above 200 GeV. Limits on the product of the total self-annihilation cross section and velocity of the WIMP, $\langle\sigma v\rangle$, are given using conservative smooth density profile estimates of the astrophysical contribution to the gamma-ray flux. These limits are approximately 3 orders of magnitude above the expectation for heavy WIMP annihilation with no boost factor from halo sub-structure.

Subject headings: gamma rays: observations — dark matter — galaxies: dwarf

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1. Introduction

The existence of astrophysical non-baryonic dark matter (DM) has been established by its gravitational affect on galaxy rotation (Rubin 1980) and velocity dispersion on objects from dwarf galaxies (Walker *et al.* 2007) through large galaxy clusters (Zwicky 1937). Additional evidence of DM existence comes from cosmic microwave background measurements (Spergel *et al.* 2007) and gravitational lensing of galaxies by foreground galaxy clusters. At present though, all evidence for the existence of dark matter is solely inferred from its gravitational effects on baryonic matter. The particle nature of dark matter is yet to be revealed through direct detection in Earthbound dedicated dark matter search detectors or through its production in particle accelerators. Indirect dark matter searches provide a third approach to discover the particle nature of dark matter. From a variety of astrophysical targets, indirect searches look for evidence of a flux of "normal" matter (electrons, positrons, gamma-rays, etc.) that could be produced by the annihilation of dark matter particle pairs. In this paper, we report on an indirect dark matter search carried out using the VERITAS gamma-ray telescope array located in southern Arizona, USA. Gamma-rays are posited to be produced either directly as pairs from the self-annihilation of weakly interacting massive particles (WIMPs), or as secondary decay products from the primary particles produced in WIMP annihilation. The former would produce a monoenergetic source of gamma-rays equal to the WIMP mass and would constitute essentially definitive evidence for particle dark matter. The latter mechanism would produce a spectrum of gamma-ray energies with a cutoff at the WIMP mass. The spectrum is expected to exhibit non-power law behavior in contrast to the usual power law spectrum of very high energy (VHE) gamma-rays produced by supernova remnants, active galactic nuclei (AGN) blazars, compact binary objects, and other known VHE gamma-ray sources. Moreover, a DM gamma-ray signal should exhibit little or no time variability.

WIMPs are a credible candidate for constituting the majority or entirety of dark matter because such a particle is predicted in some extensions to the Standard Model of Particle Physics, e.g. supersymmetry (neutralinos) and theories of large extra dimensions (Kaluza-Klein particles). Both neutralinos and K-K particles are predicted to have a mass in the range of a few tens of GeV to possibly a few tens of TeV. As previously stated, primary or secondary gamma-rays produced in WIMP annhilation would have energies comparable to this mass. Ground-based imaging air Cherenkov telescope arrays such as VERITAS, MAGIC, HESS, and CANGAROO are sensitive to precisely this energy regime and, thus, are effective instruments to carry out an indirect search for evidence of dark matter annihilation.

The VERITAS search reported in this paper targets three dwarf spheroidal (dSph) galaxies that are satellites of the Milky Way: Draco, Ursa Minor, and Willman 1. The high mass-to-light ratios of dSph galaxies make them particularly good targets for a dark matter search. Moreover, the relative proximity of these Milky Way satellites provides one of the best expected fluxes of DM annihilation gamma-rays. The general lack of active or even recent star formation in the dSph galaxies means there is little background from normal astrophysical sources such as has been observed in the Milky Way Galactic Center (Aharonian *et al.* 2006).

2. Apparatus and Observations

2.1. The VERITAS Telescope Array

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12m imaging Cherenkov telescopes located at the Whipple Observatory base camp (31°57′N 111°37′W) in southern Arizona at an altitude of 1268m above sea level (Weekes 2002). For an energy range of ∼200 GeV - 30 TeV the array has an effective area $> 3 \times 10^4 \mathrm{m}^2$ near the zenith, an energy resolution of 10-20%, and an event-by-event angular resolution of 0.14°. Signals from the 499 photomultiplier tubes (PMTs) that constitute the camera of each telescope are split such that each signal is digitized by a 500 MHz flash ADC (FADC) and also presented to a constant fraction discriminator (CFD) for trigger generation. VERITAS has a 3 level trigger:

Level 1 A single pixel trigger with a standard threshold setting of 50mV (∼ 4 photoelectrons).

Level 2 A telescope trigger requiring any 3 adjacent (PMTs) within a 5ns coincidence window.

Level 3 A path length corrected array trigger requiring any 2 telescopes within 100ns.

For a triggered event, 24 FADC samples for each PMT are recorded, i.e. a 48ns window. Further technical description of VERITAS can be found in Hays, Maier, and Weinstein (2007).

2.2. Dwarf Galaxy Observations

The three dSph galaxies forming the subject of this paper have been studied both observationally (Aliu *et al.* 2008; Albert *et al.* 2008; Bellazzini *et al.* 2002; Driscoll *et al.* 2007;

Kleyna *et al.* 2001; Martin *et al.* 2007; Willman *et al.* 2005; Wood *et al.* 2008), and theoretically (Bringmann *et al.* 2008; Kleyna *et al.* 1999; Strigari *et al.* 2007, 2008). In particular, searches for VHE gamma-rays from Draco have been done by the STACEE (Driscoll *et al.* 2007) and MAGIC (Albert *et al.* 2008) collaborations and from Willman 1 by the MAGIC collaboration (Aliu *et al.* 2008). Dwarf spheroidal galaxies typically have stellar velocity dispersions implying a high mass-to-light (M/L) ratio indicative of their dynamics being dominated by dark matter. Moreover, the stellar populations are typically low-metallicity with ages of many Gyr. The lack of recent star formation implies the galaxies have not undergone mergers or accretions since their early star formation epochs. In the case of Ursa Minor, the central region structure may indicate that it has undergone some tidal disruption due to interaction with the Milky Way (Bellazzini *et al.* 2002) and have a $M/L \sim 10$. Draco appears to be an undisturbed system (Ségall *et al.* 2007) with a $M/L \gtrsim 100$ (Odenkirchen *et al.* 2001). Willman may be one of the most dark matter dominated dwarf galaxies (Strigari *et al.* 2008) with $M/L \sim 500 - 700$.

Observations of the Draco, Ursa Minor, and Willman 1 dSph galaxies were performed in 2007 and 2008 during which VERITAS operated as first a three telescope array and, later, as a completed four telescope array. Specifically, Ursa Minor was observed for 26 hours in February-May, 2007, Draco for 22.3 hours in April-May, 2007, and Willman 1 for 13.7 hours in December, 2007-February, 2008. Draco and Ursa Minor have a mix of three and four telescope data [1], while Willman 1 was observed only in 4-telescope mode. Observational data are acquired in "wobble" mode in which the source is positioned at an offset from the camera center. For the dwarf galaxy data, the offset was 0.5° and the offset direction was alternated between north, south, east, and west. Observations were made with varying atmospheric conditions during moonless periods of the night. All data except runs with some error condition or of very short length ($\lesssim$ 5 min.) were processed through the VERITAS software analysis packages. Only data with good observational atmospheric conditions (good weather) are used for signal and background event extraction. For wobble mode, signal and background estimation can be performed within the same data set (Berge *et al.* 2007). Background regions are defined within the field of view at the same average radius with respect to the camera center as that of the targeted dwarf galaxy.

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[1] technical problems after the start of 4-telescope operation caused most observations after March, 2007 to also be in 3-telescope mode

3. Analysis

Event data were analyzed by two independent analysis packages [2]. We describe here the analysis path followed for the standard VERITAS analysis package, VEGAS (Cogan *et al.* 2007). Hardware dependent quantities are first calculated in a calibration phase and the calibrations then applied. A "cleaning" of the data is performed to remove isolated noise pixels. Individual telescope events are reconstructed and characterized by a second moment analysis that calculates the standard Hillas parameters (Hillas 1985). Individual telescope events are combined in a stereo reconstruction of the event giving location of the shower core on the sky and its intersection with the ground with respect to the array, i.e. the impact parameter. Selections based on the individual telescope Hillas parameters and the stereo reconstructed event parameters are applied. In the final stage of analysis, signal and background regions are defined for each run, run-by-run signal and background counts are estimated, and the run-by-run events and statistics are combined to provide an overall result for the target. We describe below, the selection of events, the background estimation techniques used, the extraction of signal and background counts, and the calculation of significance and, because of the absence of any significant signal, upper limits on the gamma-ray flux from the targeted dwarf galaxies. Details of the early stages of the analysis are given in Holder *et al.* (2006).

During the second stage of the analysis in which calibrations are applied to the event data, parametrized shower images based on the second moment analysis are calculated for each telescope. A subsequent stage selects for stereo reconstruction events containing at least two telescope images comprised of 5 or more phototubes having summed digital counts greater than 400 ($\sim$ 75 photoelectrons). The image distance from the center of the camera is required to be less than $1.43°$. Due to physical constraints at the Whipple basecamp, the initial configuration of the four telescope array has telescopes designated T1 and T4 spaced a distance of 35m apart. Because this separation does not give effective stereo reconstruction, events containing only T1 and T4 images are removed. The gamma-ray energy, mean scaled width (msw), and mean scaled length (msl) are estimated using multi-parameter lookup tables based on Monte Carlo simulations of a source whose flux is 3% that of the Crab Nebula. Selections for the mean scaled width and length were optimized for the same assumed 3% Crab signal and applied to the data. The requirements are $0.05 \leq msw \leq 1.16$ and $0.05 \leq msl \leq 1.36$. As is detailed below, the absence of a significant signal from any of the dwarf galaxies vindicates use of cuts optimized for a source which is a small fraction of the Crab

[2]The VERITAS standard package is the VERITAS Gamma-ray Analysis Suite (VEGAS). The secondary analysis for this paper was performed using a package that provides a set of tools for both simulation and analysis of VERITAS data and is called ChiLA

Nebula flux. It was also verified that cuts germane to a flux nearer to that of the Crab do not change the conclusion of the absence of a statistically significant signal from any of the observations.

The background in the source region is estimated using the "reflected region" model. Circular regions of angular size 0.115° with offset equal to that of the purported source from the observation position are defined. The VERITAS field of view allows 11 such background regions to be used for the chosen ring angular size. The absence of bright stars within any of the three dwarf galaxy pointings allows all 11 regions to be used in the background count estimation.

4. Results

The signal region is defined by a circular region of angular size 0.115° centered on the known location of the target galaxy. As stated above, 11 background regions of the same size and offset from the camera center are used for background estimation. The significance of any signal is estimated using the Li and Ma method (Li 1983). No excess of significance above background was found in any of the observations. Therefore, we calculate 95% confidence upper limits on the flux of gamma-rays from each of the three dSph galaxies. The upper limits of the flux are calculated using the profile likelihood ratio statistic developed by Rolke *et al.* (2005). This method has been shown to be robust for the case of an unknown background in the signal region. To verify correct statistical coverage for the 95% confidence limit, we simulated 100,000 experiments each with a total background similar to that from the sum of the 11 background regions defined for the wobble method (c.f. Table 1) and for signal values ranging from 0-25 events in the signal region. The mean background count was varied in steps of 100 from 3000 to 3800. For each mean background value, we stepped through each of the 26 signal count values and generated 100,000 Monte Carlo "experiments". For each Monte Carlo experiment a total background count was generated according to a Poisson distribution with mean set to the mean background. A second Poisson random value was generated using a distribution with mean equal to the chosen signal value. Given the randomly generated background and signal counts, an upper limit was generated using the unbounded Rolke profile method. The fraction of experiments in which the signal value exceeded the upper limit was determined for each background/signal combination. We found as demanded that 5% of the experiments had a generated signal larger than the upper limit over the range 1-25 signal counts. The coverage for 0 signal is actually $\sim 97\%$. The discontinuity is an artifact of the method due to the non-existence of a maximum likelihood estimator at either zero signal or background counts.

The average effective area is calculated from a sample of simulated gamma-ray showers using a lookup table. The effective area is quoted for an energy threshold of 200 GeV. Table 1 summarizes the results for each of the three dwarf galaxies.

5. Limits on WIMP Parameter Space

Following the formalism of Wood *et al.* (2008) the differential flux of gamma-rays from WIMP annihilation is given by

$$\frac{d\phi(\psi,\Delta\Omega)}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\left[\frac{dN(E,m_\chi)}{dE}\right]\int_{\Delta\Omega} d\Omega \int \rho^2(\lambda,\psi,\Omega)\,d\lambda, \tag{1}$$

where $\langle\sigma v\rangle$ is the thermally averaged product of the total self-annihilation cross section and the speed of the WIMP, m_χ is the WIMP mass, $dN(E,m_\chi)/dE$ is the differential gamma-ray yield per annihilation, $\Delta\Omega$ is the observed solid angle, ρ is the DM mass density, ψ is the angle between the dwarf galaxy center and the Earth line-of-sight direction, and λ is the line-of-sight distance. For the purpose of setting limits in the WIMP parameter space $(m_\chi, \langle\sigma v\rangle)$, we re-express equation 1 as an inequality with the upper limit on the detected gamma-ray rate R_γ(95% C.L.) inserted and perform the integration over the product of the differential gamma-ray yield and effective area:

$$\begin{aligned}\frac{\langle\sigma v\rangle}{3\times10^{-26}\mathrm{cm^3s^{-1}}} &< R_\gamma(95\%\ \mathrm{C.L.})\left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2 \\ &\times\left(\frac{1.45\times10^4\mathrm{GeV}}{J}\right)\left\{\phi_{1\%}\int_{200\ \mathrm{GeV}}^{\infty}A(E)\left[\frac{dN(E,m_\chi)/dE}{10^{-2}\mathrm{GeV^{-1}}}\right]dE\right\}^{-1}\end{aligned} \tag{2}$$

where $\phi_{1\%} = 6.64\times10^{-12}\mathrm{cm^{-2}s^{-1}}$ is 1% of the integral Crab Nebula flux above 100 GeV as extrapolated from the power-law fit of $3.2\times10^{-11}(E/1\ \mathrm{TeV})^{-2.49}\mathrm{cm^{-2}s^{-1}}$ (Hillas 1998), $A(E)$ is the energy dependent effective area, and J represents the dimensionless astrophysical factor given by

$$J(\psi,\Delta\Omega) = \left(\frac{1}{\rho_c^2 R_H}\right)\int_{\Delta\Omega} d\Omega \int \rho^2(\lambda,\psi,\Omega)\,d\lambda. \tag{3}$$

The above integral is normalized to the product of the square of the critical density, $\rho_c = 9.74\times10^{-30}\mathrm{g\ cm^{-3}}$ and the Hubble radius, $R_H = 4.16$ Gpc to produce a dimensionless J. Various parametrizations of the DM mass density profile have been put forward (Navarro *et al.* 1997; Kazantzidis *et al.* 2004; de Blok *et al.* 2001; Burkert 1995). The most conservative approach to the density profile is the assumption of a smooth distribution with either an inner core (asymptotically $\propto r^{-1}$) or a steeper power-law inner cusp. Substructure of the DM halo can lead to significantly higher local densities resulting in a "boosted" astrophysical factor, J (Strigari *et al.* 2007). We provide limits on the WIMP parameter space based on the assumption of a smooth NFW profile (Navarro *et al.* 1997). The astrophysical factor, J, is then given by

$$J(\psi,\Delta\Omega)=\left(\frac{2\pi\rho_s^2}{\rho_c^2R_H}\right)\int_{\cos(0.115^\circ)}^{1}\int_{\lambda_{min}}^{\lambda_{max}}\left(\frac{r(\lambda)}{r_s}\right)^{-2}\left[1+\left(\frac{r(\lambda)}{r_s}\right)\right]^{-4}d\lambda\,d(\cos\theta),\qquad(4)$$

where ρ_s, r_s are the scale density and radius, respectively. The integration over the line of sight involves the galactocentric distance, r, i.e. the radial distance from the dwarf galaxy center to the observation point within the galaxy halo. In terms of the line of sight distance, λ, and the distance from Earth to the dwarf galaxy center, R_{dSph}, r is given by

$$r=\sqrt{\lambda^2+R_{dSph}^2-2\lambda R_{dSph}\cos\theta}.\qquad(5)$$

The integration limits, λ_{min} and λ_{max} are given by $R_{dSph}\cos\theta\pm\sqrt{r_t^2-R_{dSph}^2\sin^2\theta}$, where r_t is the tidal radius of the dSph galaxy. For the tidal radius we used a value of 7 kpc as was used by Sánchez-Conde *et al.* (2007). As noted in (Sánchez-Conde), r_t depends strongly on the profile used and values considerably less than 7 kpc are appropriate for an NFW profile, e.g. for Draco, Evans *et al.* (2004) use 1.6 kpc while Strigari *et al.* (2007) use 0.93 kpc. In practice, since almost all the contribution to $J(\psi,\Delta\Omega)$ comes from $r \ll r_t$, any $r_t \gtrsim 1kpc$ gives essentially the same J. Furthermore, the uncertainty added by the choice of ρ_s, r_s renders the dependence of J on r_t negligible in comparison. For Draco and Ursa Minor, we use for ρ_s, r_s, the midpoints of the range from Strigari *et al.* (2007). For Willman, we use values given in Bringmann *et al.* (2008). The parameters used in our J calculations and the resulting values of J are given in Table 2; the J values in parentheses are those used in deriving $\langle\sigma v\rangle$ limits from eq. 2.

Figure 1 shows $\langle\sigma v\rangle$ limits as a function of neutralino mass using eq. 2. Also plotted are values from MSSM models that are consistent with the relic DM density (see Wood *et al.* (2008) for details on the MSSM models allowed). As noted above, we have assumed a smooth NFW profile with no boost from DM halo substructure. The limits indicate that a boost factor of ~ 1000 would be necessary to produce a signal within our present sensitivity. Strigari *et al.* (2007) find a maximum boost factor of $\mathcal{O}(100)$ and one may consider present generation IACTs are, thus, about an order of magnitude in sensitivity away from constraining DM structure models. However, other effects such as inclusion of internal bremsstrahlung in neutralino annhilation calculations (Bringmann *et al.* 2008) and the possibility of a velocity-dependent (Sommerfeld) enhancement (Robertson & Zentner 2009; Pieri *et al.* 2009) could further boost the gamma-ray flux from neutralino annihilation.

Table 1: Summary Results of Dwarf Galaxy Observations

Quantity	Draco	Ursa Minor	Willman I
Exposure (s)	66185	68080	49255
Signal Region (events)	305	250	326
Total Background (events)	3667	3084	3602
Number Backgrd. Regions	11	11	11
Significance[a]	-1.51	-1.77	-0.08
95% c.l. (counts)[b]	8.7	3.3	36.7
Effective Area (m^2)	12518	16917	33413
Energy Threshold (GeV)[c]	200	200	200
Flux Limit 95% c.l. ($cm^{-2}s^{-1}$)	1.05×10^{-12}	0.29×10^{-12}	2.23×10^{-12}

[a]i and Ma method (Li 1983)

[b]Rolke method (Rolke *et al.* 2005)

[c]see text

Table 2: Parameters used for the astrophysical factor, J calculation. The scale density and radius, ρ_s, r_s, for the Draco and Ursa Minor dwarf galaxies are from the ranges in Strigari *et al.* (2007); values in parentheses are the central values from Strigari and are used for the J calculation. For Willman, values from Bringmann *et al.* (2008) are used. The tidal radius, r_t was set to 7 kpc for all calculations but the value of J is negligibly changed for r_t as low as 0.9 kpc. The J values in parentheses are the ones used in the actual calculation of limits for Figure 1.

Quantity	Draco	Ursa Minor	Willman I
$R_d Sph$ kpc	80	66	38
r_t kpc	7	7	7
ρ_s $M_\odot/\mathrm{kpc}^3$	$2 - 10(4.5) \times 10^7$		4×10^8
r_s kpc	0.4-1.12(0.79)		0.18
J[a]	1.8-9.2(4)	4-20(7)	(22)

[a]J is expressed as a dimensionless value normalized to the critical density squared times the Hubble radius, $3.832 \times 10^{17} \mathrm{GeV}^2 \mathrm{cm}^{-5}$.

6. Conclusions

We have carried out a search for very high energy gamma-rays from three dwarf spheroidal galaxies, Draco, Ursa Minor, and Willman I, as part of an indirect dark matter search program on the VERITAS IACT array. The dwarf galaxies were chosen for their large mass-to-light ratio and proximity to Earth. The absence of active star formation in dSph galaxies assures a low background flux from non-DM sources. No significant excess above background was observed from any of the three galaxies allowing us to set upper limits on the flux and subsequently limits on the cross section times velocity, $\langle\sigma v\rangle$, for neutralino pair annihilation as a function of neutralino mass. The $\langle\sigma v\rangle$ limits are at least two orders of magnitude above expectations of MSSM models assuming a smooth NFW dark matter density profile. The knowledge of the parameters determining the size of the astrophysical factor, J, produce about an order of magnitude uncertainty in J values while halo substructure, internal bremsstrahlung produced in the annihilation, and/or velocity dependent cross section enhancements could increase the astrophysical factor by $\times 100$ or more.

The observation time of any one of the galaxies in this study was somewhat minimal ranging from 14-26 hours. Future observations of other dwarf spheroidal galaxies by VERITAS are planned. In particular, SEGUE 1, Boötes 1, and Coma Berenices appear to be good candidates in terms of proximity and large mass-to-light ratio. SEGUE may be even more dark matter dominated that Willman I. The strategy to date has been to take 10-20 hours of observational data to determine if a signal of marginal significance might be present and warrant a follow-up. We would anticipate a similar strategy looking at additional dSphs. However, given no significant signal from the present observations and assuming no signal from newly targeted dSphs, the strategy would likely be altered to take deeper observations on 1-3 of the targeted dSphs over the course of several observing seasons. This will allow pushing the neutralino $\langle\sigma v\rangle$ limits lower by a factor of 2-3. There is probably some improvement to be had in background supression that might allow slightly lower limits. The uncertainty of the nature of dark matter and how it might cluster in galactic haloes make this a useful measurement. The successful observation of VHE gamma-rays from dark matter annihilation is a low probability but very high payoff pursuit.

Next generation IACT arrays now being planned such as the Advanced Gamma-ray Imaging System (AGIS) and the Cherenkov Telescope Array (CTA) [3] will provide an order of magnitude increase in sensitivity over current arrays such as VERITAS, MAGIC II, and HESS and may begin to constrain some models of both supersymmetric dark matter or

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[3]see presentations given at the 1^{st} Conference on Technology and Instrumentation in Particle Physics, Tsukuba, Japan, 2009; http://tipp09.kek.jp

Kaluza-Klein dark matter associated with models of anomalous extra dimensions. Along with observations by the Fermi Gamma-ray Space Telescope and new particle searches at the Large Hadron Collider, prospects for understanding the nature of dark matter over the next decade look to be promising.

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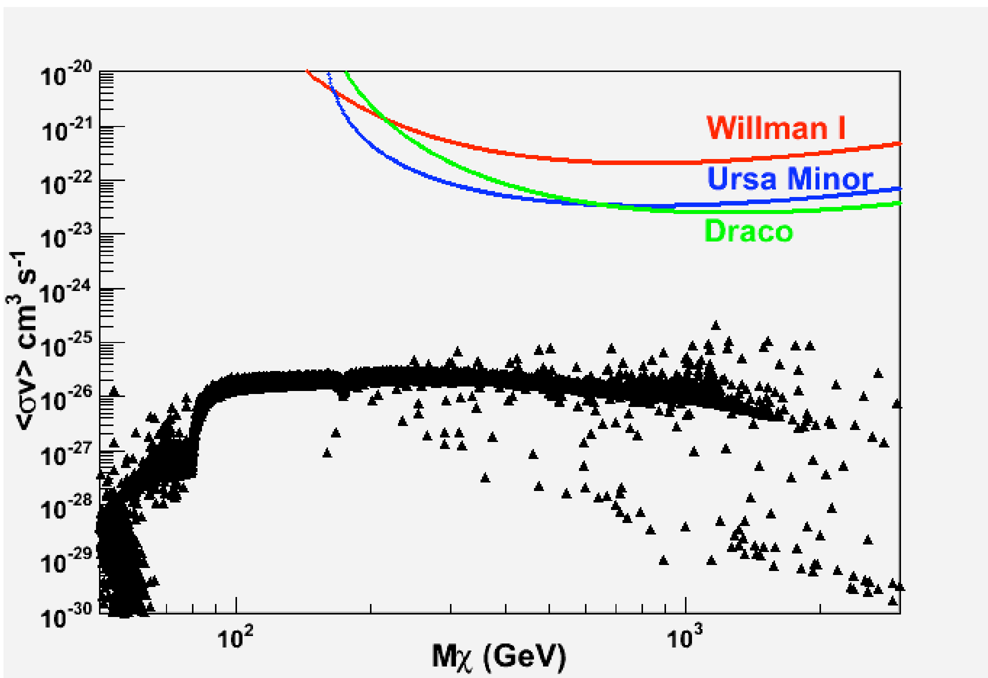

Fig. 1.— Upper limits on $\langle \sigma v \rangle$ as a function of neutralino mass, m_χ using eq. 2 using a composite neutralino spectrum (see Wood *et al.* (2008) and the values of J from Table 2. Black triangles represent points from MSSM models that fall within ± 3 standard deviations of the relic density measured in the 3 year WMAP data set (Spergel *et al.* 2007).