

INVESTIGATING NEUTRALINO ANNIHILATIONS USING DarksUSY

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ABSTRACT

Physicists do not fully understand the nature of dark matter although we infer its existence from experimental observation. This project is part of the dark matter detection searches with the Gamma-Ray Large Area Space Telescope (GLAST). We are investigating one of the Weakly Interacting Massive Particles (WIMP) candidates called the neutralino, a particle predicted by the Minimal Supersymmetric Standard Model. In particular, we ran a computer simulation called DarksUSY that predicts the signature that we expect to see in the data from GLAST that pertains to the detection of the neutralino in the galactic halo.

PROJECT DESCRIPTION

The primary objective of this project is to predict the flux of photons from the galactic halo due to neutralino annihilations using the DarksUSY simulation code¹ so that one can calculate the sensitivity of the GLAST detector for dark matter searches. The secondary objectives of this project are to:

1. Understand and document the DarksUSY simulation code;
2. Generate output from DarksUSY in a format useful for analysis in the GLAST framework; and
3. Develop a framework under which one can generate a large number of DarksUSY events (approximately one million) on the computer infrastructure at SLAC.

INTRODUCTION

THE MASS DENSITY PARAMETER Ω

The mass density of the universe has an important consequence because, according to standard cosmological theory, the value of this density determines whether the universe will expand or collapse. To quantify the state of the universe we define a mass density parameter $\Omega = \rho/\rho_{crit}$ where ρ is the mass density of the universe (homogenous on large scales) and $\rho_{crit} = 3H^2/8\pi G \sim 10^{-38}h^2 \text{ kg/m}^3$.² If Ω is less than one then the universe will continue to expand and is said to be open; if Ω is greater than one then the universe will eventually collapse and is said to be closed; if Ω is equal to one then the universe is delicately balanced between the previous two states and is said to be flat. So far Ω is observed to be very close to one (a flat universe).

Now that one understands Ω , one should analyze what contributes to Ω 's value. Ω is determined by two contributions: one due to the mass in the universe, Ω_M , and another due to what is labeled the cosmological constant, Ω_Λ . Ω_Λ is a result of solving Einstein's equation and can be thought of as a sort of "dark en-

ergy" that we cannot account for but whose existence we infer from observation. Ω_M is experimentally determined to be close to 0.3 while Ω_Λ is close to 0.7. The Ω_M term is subdivided into two terms: the first due to baryonic matter Ω_B and the second due to non-baryonic matter Ω_{NB} . It turns out that only around ten percent of matter in the universe is luminous and the remaining ninety percent consists of matter that we cannot see called dark matter. That is, $\Omega_{NB} \approx 90\%$ of $\Omega_M \sim 0.25$.

DARK MATTER

In the galaxy NGC 3198, experimental observation of gravitational effects indicates that more matter exists than what is visible.² The rotational velocity of stellar objects (see Figure 1) contradicts Newton's Laws which predict that $v^2 = GM/r$. There are observations from many other galaxies like NGC 3198 that exhibit similar behavior. One way to explain this phenomenon is to postulate there is invisible matter permeating the galaxy and the stellar objects therefore lie in a sphere of mass. In this way, one can assume that the M in Newton's Law is proportional to the radius r and therefore we find that $v^2 \propto GM$, which is a constant of r .

In recent years there has been increasing confidence that dark matter is not made up of ordinary matter and is instead non-baryonic. Among the non-baryonic candidates investigated today are axions and Weakly Interacting Massive Particles (WIMPs). One class of WIMP is the supersymmetric particles predicted by the Minimal Super-symmetric Standard Model (MSSM).⁴ The focus of this paper is on models in which the lightest and most stable of the supersymmetric particles called the neutralino exists.

MINIMAL SUPER-SYMMETRIC STANDARD MODEL (MSSM)

The MSSM was actually created by particle physicists to explain problems with the Standard Model:

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- Mass scale problem: The problem of explaining why particles have the masses that they do. In masses at the scales of the Standard Model (~ 100 GeV), one can explain the mass hierarchy by introducing the Higgs boson. Grand unified theories, however, introduce masses $\sim 10^{15}$ GeV for which the Higgs boson is an insufficient explanation. The MSSM accounts for masses at the $\sim 10^{15}$ GeV scale by introducing four new Higgs bosons.⁵
- Naturalness problem: Correction to the Higgs mass can diverge.⁵

The MSSM is the “minimum amount” of new physics that one must add to the Standard Model to account for these problems. The MSSM adds superpartners to some of the particles in the Standard Model: bosons get fermionic superpartners whose names are formed by attaching “-ino” to the end of the bosons’ name (e.g., photon goes to photino), whereas fermions get bosonic superpartners whose names are formed by adding an “s” to the beginning of the fermions’ name (e.g., quark goes to squark). In particular, the MSSM consists of the following³:

1. 4 neutralino mass eigenstates (χ_i^0), which all arise from the mixing between like-sign Higgsino and Gaugino fields;
2. 2 chargino mass eigenstates (χ_i^\pm);
3. spin 1/2 gluino (\tilde{g}) and spin 0 squarks (\tilde{q}), sleptons (\tilde{l}), and sneutrinos ($\tilde{\nu}$); and
4. 5 physical Higgs bosons.

The particles which the MSSM introduces are often called SUSY particles (Super-SYmmetric), hence the simulation’s name: DarkSUSY.

THE NEUTRALINO (χ_1^0)

In some MSSM models, the χ_1^0 neutralino is the Lightest SuperParticle (LSP) and is therefore stable in that it does not decay into other superparticles. Although there are three other

neutralino states (see above), in this paper when I refer to the neutralino I am referring to its lightest state, χ_1^0 . The χ_1^0 neutralino is a linear combination of Higgsino and Gaugino particles:

$$\chi_1^0 = a_{11}\tilde{B} + a_{12}\tilde{W}^3 + a_{13}\tilde{H}_1^0 + a_{14}\tilde{H}_2^0 \quad (1)$$

The a_{ij} coefficients give weight to the different quantum states that make up the neutralino. There is a quantity called the gaugino fraction which is defined as the following:

$$Z_g = |a_{11}|^2 + |a_{12}|^2 \quad (2)$$

The gaugino fraction is close to one if the neutralino is mainly in the gaugino states (\tilde{B} and \tilde{W}^3) and close to zero if the neutralino is mostly in the Higgsino states (\tilde{H}_1^0 and \tilde{H}_2^0). Although the χ_1^0 neutralino does not decay because it is stable, it does have the following three annihilation channels:

- Line processes

$$-\chi\chi \rightarrow \gamma\gamma$$

$$-\chi\chi \rightarrow Z\gamma$$

- Continuum process

$$-\chi\chi \rightarrow q\bar{q} \rightarrow \dots \rightarrow \gamma\gamma$$

The line processes are so-called because the gamma particles that result from the annihilation process have a well-defined energy, resulting in a spike in the gamma ray spectrum at a particular energy (see Figure 2). The continuum process, on the other hand, can produce gamma rays with a wide range of energies because of the many channels in which $q\bar{q}$ can annihilate and therefore continuum processes produce gamma ray spectrums which are spread out.

The neutralino is considered one of the favorite WIMP candidates for dark matter because the cross section neutralino annihilations (in times following the Big Bang but before freeze-out) is such that the neutralino could account for the non-baryonic con-

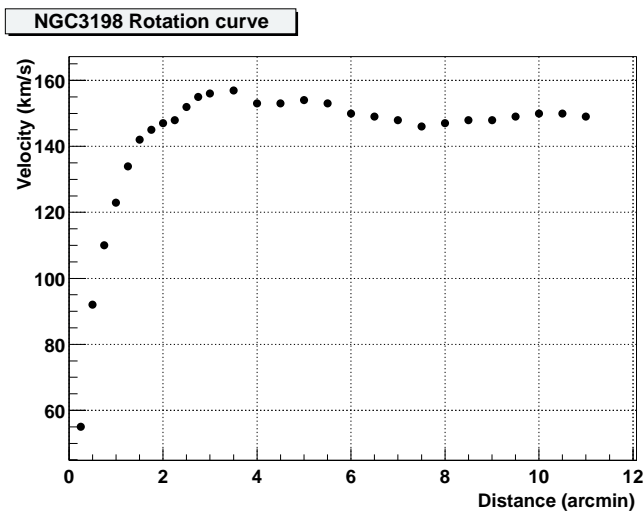


Figure 1. The velocity of stellar objects as a function of distance from the galactic center in the galaxy NGC 3198. Although Newton’s laws predict $v^2 = GM/r$ we see clearly that here this is not the case. Galactic rotation curves such as this one imply the existence of dark matter.³ Data points were extracted from Begeman.

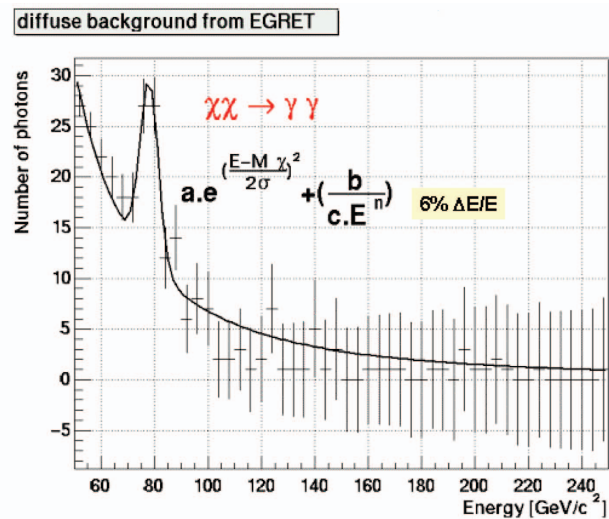


Figure 2. The flux versus the photon energy for a neutralino line process with background simulated from 50 to 250 GeV. The neutralino was generated with energy of 78 GeV, hence the spike at that energy.

tribution to dark matter. The neutralino contribution to Ω_M is given by the following equation⁴:

$$\Omega_\chi \sim \frac{10^{-10} \text{ GeV}^{-2}}{\langle \sigma_A v \rangle} \quad (3)$$

Notice that as σ_A —the cross section of neutralino annihilations—increases, the Ω_χ contribution decreases because the more neutralinos annihilate the less neutralinos there are to contribute to Ω_M . The quantity v is the relative velocity between neutralinos. For supersymmetric dark matter, $\langle \sigma_A v \rangle \sim \alpha^2/m_W^2$ $0.1 \sim 10^{-9\pm 1}$ (see reference 6) which implies that $\Omega_\chi \sim 10^{-1\pm 1}$. This range allows for Ω_χ to account for $\Omega_{NB} \sim 0.25$.

GLAST (GAMMA-RAY LARGE AREA SPACE TELESCOPE)

The measurement of dark matter is but one of the many purposes of the GLAST project. The main instrument of the GLAST is called the Large Area Telescope (LAT) and is designed to detect photons in the energy range of 20 MeV to 300 GeV. The energy range of 30 GeV to 300 GeV is a region in which no previous experiments have attempted to detect photons. We believe that we can detect neutralinos (χ) by means of the neutralino annihilation processes occurring in the galactic halo and we will use the

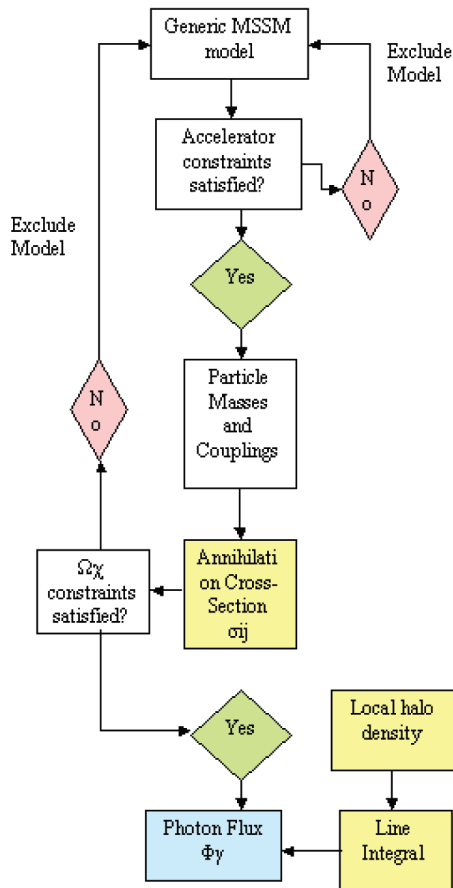


Figure 3. This flowchart summarizes the calculations involved in finding the photon flux due to the neutralino annihilation processes occurring in the galactic halo.

LAT to detect the annihilation processes for M_χ ranging from 50 GeV to ~ 300 GeV.

DarkSUSY SIMULATION

The DarkSUSY code calculates the photon flux Φ_γ that results from neutralino annihilations. This flux depends on the MSSM parameters, the model for the galactic halo density, and the neutralino annihilation cross-section. Figure 3 is a flowchart that summarizes the calculations needed to complete the flux calculation, starting with the random generation of an MSSM model, followed by the intermediate calculations and checks for model exclusion if it does not satisfy constraints, and ending with the calculation of Φ_γ if the model is allowed by constraints. The calculations shown in the flowchart are performed by the DarkSUSY code in the following six stages:

1. Generation of MSSM parameters;
2. calculation of the relic particle density;
3. calculation of the masses of particles introduced by the MSSM;
4. calculation of the photon fluxes for neutralino line processes;
5. calculation of the photon flux for the neutralino continuum process; and
6. calculation of the actual photon spectrum for the neutralino continuum process for each model.

The DarkSUSY code is modular and so each step may be submitted to the CPU or computer servers as a separate job. This is important, for example, if one does not want to tie up a computer network with one large job (the first step of the DarkSUSY simulation alone takes about 12 hours on the SLAC computer farms to generate one million models).

MSSM PARAMETERS GENERATION

We studied the way in which DarkSUSY excludes generated models. In particular we checked the accelerator constraints implementation and found that it is not up to date with the most recent particle physics developments. The code uses values from the Particle Data Group 2000⁷ and will have to be updated.

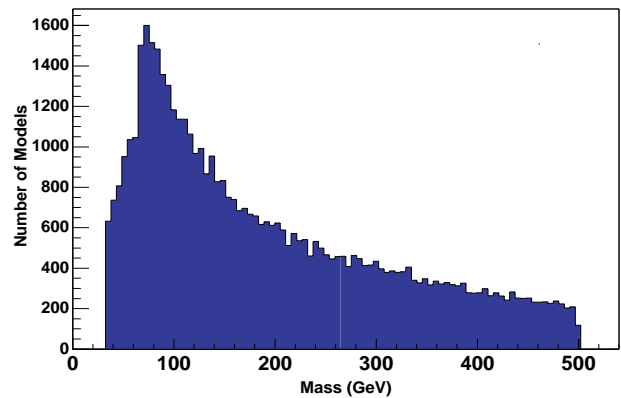


Figure 4. The number of models generated by the DarkSUSY simulation versus the value for the mass of the lightest neutralino χ_1^0 to which the models lead. The dark matter detection searches with GLAST will attempt to detect the annihilation process for $50 \text{ GeV} \leq M_\chi \leq 300 \text{ GeV}$.

In the calculation of the relic particle density, this project's task was to understand the connection between the variables in the code and the variables in the physics equations because it was not immediately evident to us to what the variables in the code corresponded. Specifically, we analyzed the use of the Boltzmann equation in calculating $Y = n/s$ where n is the neutralino density and s is the entropy of the halo.⁸ The value of Y is needed to calculate the density of relic neutralinos that formed in the galactic halo in primeval times immediately following the Big Bang and whose formation is subsequently frozen-out.

DarkSUSY must calculate the density in the galactic halo because it varies depending on the choice of halo model. We used the output of this stage of the calculation to modify the J integral in stage 4, where the DarkSUSY simulation calculates the flux for the line processes. We previously referred to the calculation of the halo density for different halo models. The following equation determines the choice of a halo model based on the value of (α, β, γ) :

$$\rho(r) \propto \frac{\rho_c}{\left(\frac{r}{a}\right)^\gamma \left[1 + \left(\frac{r}{a}\right)^\alpha\right]^{\frac{\beta-\gamma}{\alpha}}} \quad (4)$$

where r is the distance from the center of the halo, a is a parameter related to the core radius of the halo⁵, and ρ_c is the local halo density. A plot of the halo density for different halo models appears in Figure 5. The three models used in the DarkSUSY simulation are shown in the figure. The three models are the following: isothermal, $(\alpha, \beta, \gamma) = (2, 2, 0)$; Navarro-Frenk-White (NFW), $(\alpha, \beta, \gamma) = (1, 3, 1)$; and Moore, $(\alpha, \beta, \gamma) = (1.5, 3, 1.5)$.^{2,10,11}

MSSM PARTICLE SPECTRA CALCULATION

It was not immediately obvious to us which variables in the code corresponded to what masses of the MSSM particles. As a result, we interpreted the mass variables in the code and documented the names of the variables for future reference.

PHOTON FLUXES FOR LINE PROCESSES

The DarkSUSY simulation calculates the flux of photons from the galactic halo by means of the equation $F \propto \sigma J$, where σ is the cross-section of neutralino annihilations and $J \propto \int_{\text{line-of-sight}} \rho^2(l) dl(\hat{n})$, the line integral of the neutralino density in the galactic halo along the line of sight (i.e., the amount of neutralinos in the galactic halo).⁵

The calculation of flux due to line processes took the J integral averaged over a solid angle rather than as a function of the galactic coordinates and returned an average flux. This project was responsible for altering the code to take J as a function of galactic coordinates and thereby producing flux as a function of galactic coordinates.

The primary objective of this project was to produce the flux of photons from the galactic halo due to neutralino continuum processes in the galactic halo, which is handled in this step of the simulation. We wrote a subroutine that outputs a table of the photon spectrum which we used to plot a histogram (see Figure 5).

INPUT DATA FOR PHYSICS ANALYSIS TOOLS

After one runs all six stages of the DarkSUSY simulation, one obtains six different output files containing output for each stage. For data analysis software such as Root⁹, however, it is best to have one large output file that contains all the data that one wishes to plot so that one can apply cuts to the data. We wrote a new program specifically for the DarkSUSY output files that combines the data from all six files into one table. We used this program to plot the histograms of the DarkSUSY data that are found in this paper.

RESULTS

There are about 50 figures that we made using the DarkSUSY simulation that one could show in this section. Here we present a sample of some of the plots generated.

As mentioned above, we are detecting photons that result from neutralino annihilation processes such that $50 \text{ GeV} \leq M_{\tilde{\chi}} \leq 300 \text{ GeV}$. Accelerator constraints lead us to the lower limit around 40 GeV ⁷, hence we chose an arbitrary range from 50 GeV to 500 GeV for our generated models. Figure 3 is a plot of the neutralino mass for 50,000 models generated by DarkSUSY.

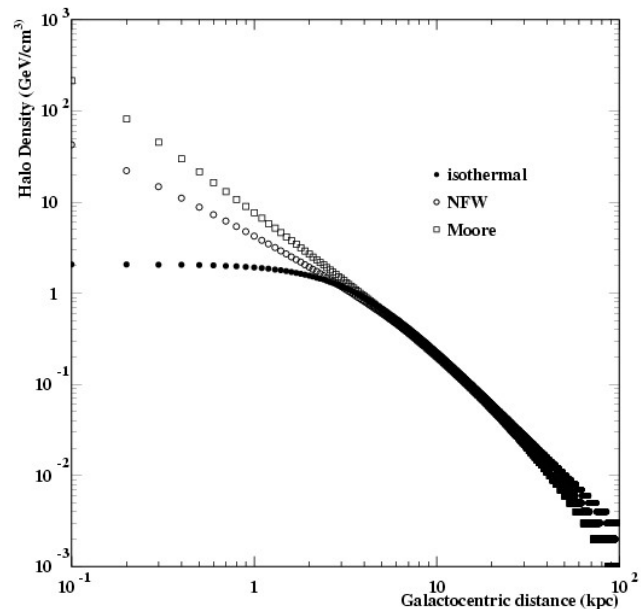


Figure 5. The galactic halo density versus the galactocentric distance for three different halo models since the prediction for the halo density depends on choice of halo model. The three halo models shown here (isothermal, NFW and Moore) are the models used in the DarkSUSY simulation.

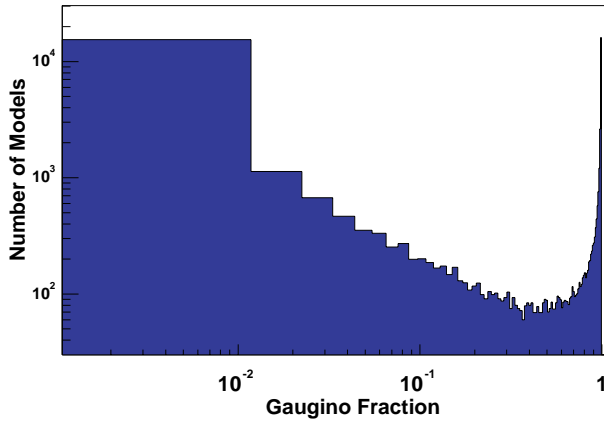


Figure 6. The number of models generated by the DarkSUSY simulation versus the value for the gaugino fraction. The gaugino fraction varies from 0 (Higgsino) to 1 (Gaugino).

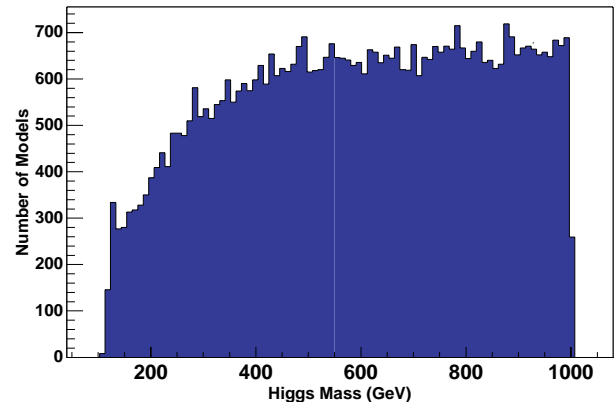


Figure 7. The number of models generated by the DarkSUSY simulation versus the value for the mass of the lightest Higgs boson to which the models lead. There are five Higgs bosons in the MSSM and the lightest one corresponds to the Higgs particle in the Standard Model.

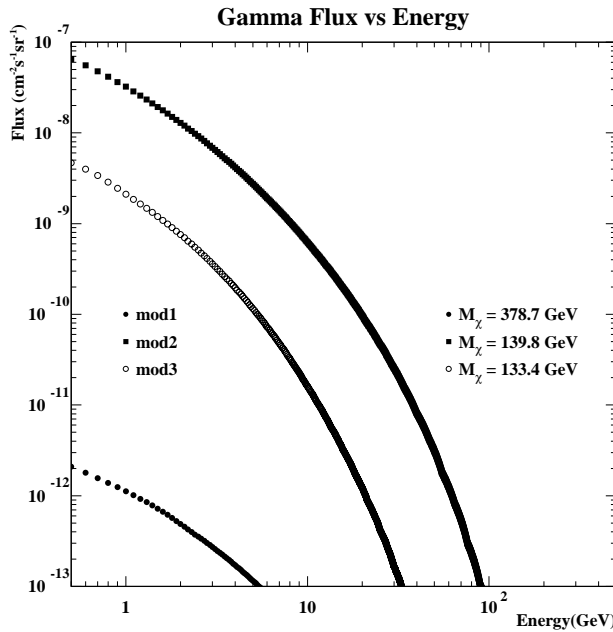


Figure 8. The flux of photons due to the neutralino continuum process in the galactic halo versus the photon energy for three distinct models generated by the DarkSUSY simulation. Shown to the right of the curves is the mass of the lightest neutralino that results from each of the three models shown here.

The gaugino fraction mentioned above, which varies from 0 (Higgsino) to 1 (Gaugino), is shown in Figure 6.

DarkSUSY generates a value for the Higgs mass for which the radiative corrections mentioned above sets an upper limit of 130 GeV.⁵ We used DarkSUSY's results for the mass of the lightest Higgs (recall that there are 5 Higgs particles in the MSSM, and the lightest Higgs corresponds to that of the Standard Model) to obtain the plot shown in Figure 7.

The photon flux due to the neutralino continuum process in the galactic halo versus the photon energy is, as mentioned above, the primary objective of this project. We succeeded in creating a

preliminary plot of the continuum photon spectrum for three models generated by DarkSUSY, which is shown in Figure 8. The next step is to analyze the graph shown in this paper and to make graphs that feature more than three models. After that, we will need to simulate the neutralino processes because the continuum process does not result in a definitive signal (since the photon spectrum for the continuum process has the same form as cosmic background radiation). We will detect the continuum process to get a hint of the neutralino's existence and then we will attempt to detect the line processes because its detection is more convincing proof.

CONCLUSION

We made a preliminary histogram that predicts the flux of photons from the galactic halo due to the neutralino continuum process, although we need to verify the values for the flux. Also, we understood and documented around 25% of the DarkSUSY code and began developing a framework under which we can generate the output from DarkSUSY in a useful format. We began estimating the time of execution of the DarkSUSY simulation so that we could develop a framework under which we could run the DarkSUSY simulation on the SLAC computer farms. This project will lead to the calculation of the GLAST sensitivity for the neutralino line and continuum processes.

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