Finding Dark Matter with GLAST: A discussion of "GLAST and Dark Matter Substructure in the Milky Way" (Kuhlen et al)

by

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Abstract

The work discussed in this paper is by Kuhlen et al. It was presented at the First GLAST Symposium, held in Stanford, California on 5-8 February 2007. The authors wanted to determine the feasibility of detecting substructure in the galactic dark matter signature using GLAST (Gamma-Ray Large Area Space Telescope) after it launches in June 2008. To frame their question more precisely, the authors examined the characteristics if a single type of dark matter – a WIMP (Weakly-Interacting Massive Particle) known as a neutralino. Using a new, high-resolution N-body simulation of the dark matter in the galaxy, they modeled the formation of substructure in the dark matter halo. Then, using background and spectral data from the CGRO (Compton Gamma-Ray Observatory) EGRET (Energetic Gamma-Ray Experiment Telescope), they computed detectability values for individual subhalos. Their work indicates that if neutralino parameters are within a certain favorable range, GLAST should be able to detect some substructure in the dark matter signal.

Dark Matter: WIMPs and MACHOs

The existence of dark matter has been postulated for many years, based on (among other things) the flatness of the outer regions of galactic rotation curves. In those data, Doppler measurements of star and gas velocities in the outer regions of galaxies were found to be much higher than predicted using Newtonian gravitational dynamics and a mass based on the visible material in the galaxy. These higher velocities required the presence of much more matter than was visually evident. The simplest solutions indicated that the dark matter was distributed in a spherical halo centered on the galaxy, and completely enclosing the visible galaxy. Later cosmological studies indicated that these halos probably formed prior to the galaxies, and provided the nucleus for the gravitational collapse which formed the galaxies.

A variety of forms have been suggested to explain the presence of dark matter. Two of the most popular are MACHOs (MAssive Compact Halo Objects) and WIMPs (Weakly-Interacting Massive Particles). The former were presumed to be large, dim bodies on at least a planetary size scale, such as brown dwarfs. Such bodies would in theory emit some form of electromagnetic radiation, but their inherent faintness and great distance would conspire to make these bodies essentially undetectable using traditional observations in the electromagnetic spectrum. The Optical Gravitational Lensing Experiment (OGLE) (http://sirius.astrouw.edu.pl/~ftp/ogle/) project was dedicated to searching for such bodies, and some indication of their presence was found, but the resulting estimates of halo mass were insufficient to provide the mass needed to explain the galactic rotation curves. The OGLE survey, on the other hand, has become a prolific source of detections of extrasolar planets, which create microlensing events identical to those produced by the presumptive MACHOs.

The WIMP concept provides a more plausible explanation for dark matter. WIMPs, as their name suggests, are only weakly coupled to normal matter and radiation. In fact, the coupling between WIMPs and radiation is essentially nil – the only impact that dark matter could have on radiation is the relativistic effects of large mass concentrations, such as gravitational lensing. On the other hand, the coupling between WIMPs and normal visible (baryonic) matter was that due to normal gravity. WIMPs also are excellent candidates to explain the early formation of dark matter halos. In these dark matter models (as we saw in class), the WIMPs can be treated as a pressureless fluid. Gravitational collapse of the dark matter to form the halo is resisted only by free-streaming and turbulent motions in the dark matter fluid. Therefore, the forces which counteract the collapse of a dark matter fluid are considerably weaker than for normal baryonic matter, and this difference provides a natural explanation for the formation of the dark matter halos as the precursors of galaxy formation.

For this study, the authors examined a type of WIMP called a *neutralino*. The neutralino is one of many possible WIMP particles. None of these particles have been directly detected (except for a recent possible detection of a modulated dark matter signal by the DAMA/LIBRA team (Bernabei et al, 2008)). The neutralino is a particle predicted by supersymmetry models of particle physics. In these models, each Standard Model particle has a supersymmetric "partner" particle, such as the "zino" for the Z boson, the "photino" for the photon, and the "higgsino" for the Higgs boson. The supersymmetric partners have the same quantum numbers as their Standard Model counterparts, but a spin differing by ½. These supersymmetric particles can combine in various proportions to form neutralinos. However, as none of these particles have been detected, their physical parameters, such as mass and interaction cross-section, are very poorly constrained, e.g. mass estimates for the neutralino range from 10 GeV to 1 TeV, with annihilation cross-sections of the order 10^{-26} cm^3s^{-1}, which is minuscule compared to the typical annihilation cross-section of an electron/positron pair of order 10^{-8} cm^3s^{-1} at energies of 65 GeV (Burkhard, 2002). The annihilation cross-section is of interest because the neutralino self-annihilates. More precisely, when neutralinos collide, they annihilate each other, forming gamma-rays of energy equivalent to the mass of the original neutralinos. This is the mechanism by which (the authors hope) GLAST will be able to detect the signature of neutralinos. This does not imply that the particle exists in neutralino and anti-neutralino form, and so the annihilation is not the same sort of event as occurs in matter-antimatter annihilation.

GLAST

The Gamma-Ray Large-Area Telescope (GLAST) is a gamma-ray observatory scheduled to be launched by NASA in early summer of 2008. The observatory is described in detail elsewhere (Ritz, et al, 2007). The spacecraft contains two instruments – the Large-Area Telescope (LAT), and the GBM (Gamma-ray Burst Monitor). The LAT will be used to perform an all-sky survey in the energy range 20 MeV-300+ GeV. The wide field of view of the instrument, combined with slow rocking during orbit, will result in total sky coverage, with 30 minute exposure time every 3 hours. The GBM will be used to detect gamma-ray bursts, and command the spacecraft to autonomously repoint as needed to ensure the burst is in the LAT field of view.

The LAT (illustrated in Figure 1) is a pair-conversion telescope. Incoming gamma-rays and high-energy cosmic rays strike the tungsten converter plates in the tracker tower and form electron-positron pairs. These particles then propagate downward through the tower, and tracked by the silicon-strip detectors. The particles are ultimately captured by the CsI crystal calorimeter module at the base of the LAT. The entire instrument is surrounded by a set of plastic scintillator tiles which form the anti-coincidence shield, allowing the instrument to reject events caused by photons and particles entering the tracker from outside the field of view of the instrument. Note that only of order 1% of the events detected by the LAT are expected to be gamma-ray photons; the large majority will be high-energy cosmic rays. Software on the spacecraft and in the ground processing system will allow investigators to discriminate between the two particle types, and measure there incident direction and energy.

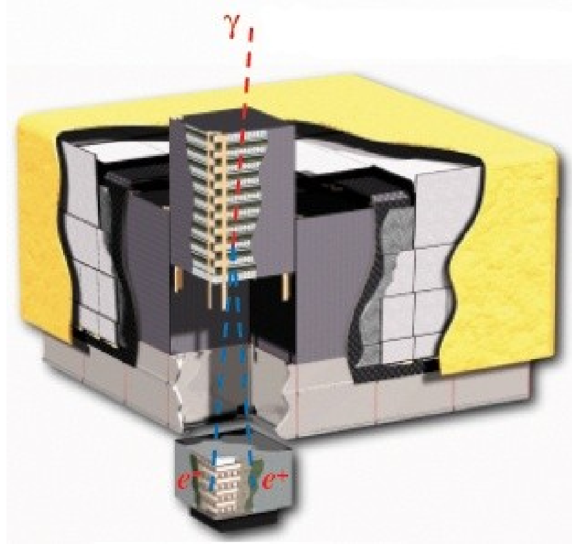

Figure 1: The Large Area Telescope (LAT). The incoming gamma ray strikes the converter plate and transforms into an electron-positron pair.

Modeling the Dark Matter Halo

To simplify the study, the authors considered only the dark matter component of the galaxy. The gravitational potential generated by the baryonic component of the galaxy is very small compared to that of the dark matter component, and this could be neglected with little effect. The authors used a recent high-resolution N-body simulation of the dark matter halo known as *Via Lactea*. This simulation modeled the halo using 2 x 10^8 dark matter particles, each of mass 10^4 M_0.

The simulation resulted in a single massive central halo surrounded by approximately 10^4 subhalos which ranged in size over 3 orders of magnitude (see Figure 2). The bulk of the mass was in the central halo, while the aggregate subhalos constituted approximately 5.6% of the total halo mass. An accurate visual analogy is a large central bubble surrounded by thousands of smaller bubbles, with a wide range of sizes. The resulting subhalo mass distribution is accurately described by:

$$(1) \quad \frac{dN}{dln(M)} \propto \frac{1}{M}$$

which is similar to the form of the Press-Schecter distribution discussed in class.

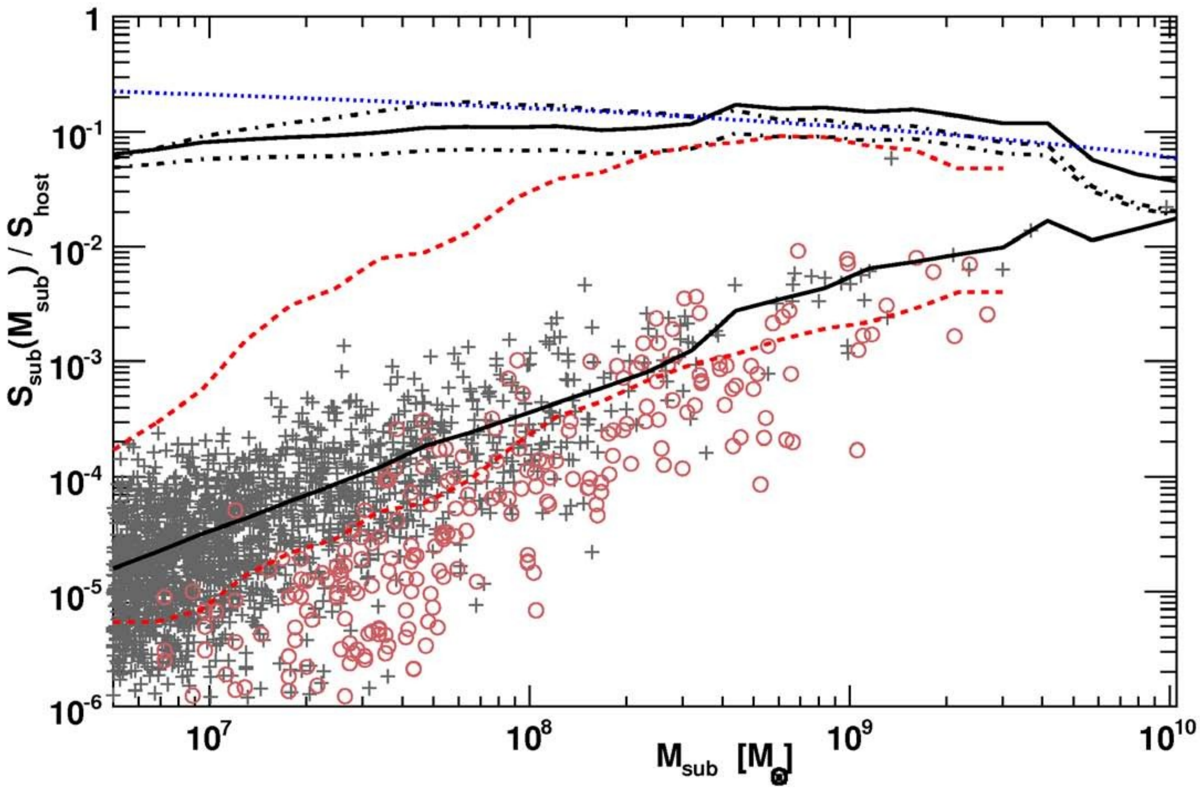

Figure 2: Neutralino subhalo mass and luminosity distribution.

Once subhalo masses were computed, the authors were able to model the gamma-ray flux due to neutralino self-annihilation in individual subhalos. The total number of gamma-ray photons N_γ detected from an individual subhalo at angular position (θ,ϕ) is described by:

$$(2) \quad N_\gamma(\theta,\phi)=\Delta\Omega\,\tau_{\exp}\frac{\langle\sigma v\rangle}{M_\chi^2}\int_{E_{th}}^{M_\chi}\left(\frac{dN_\gamma}{dE}\right)A_{eff}(E)\,dE\int_{los}\rho(l)^2\,dl$$

where $\Delta\Omega$ is the angular size of the subhalo as seen by the observer, τ_{exp} is the total exposure time (assumed to be 2 years), $<\sigma v>$ is the assumed annihilation cross-section (5×10^{-26} cm3 s^{-1}), M_χ is the assumed mass of the neutralino (46 GeV), E_{th} is the threshold energy for the LAT detector (assumed to be 0.45 GeV), dN_χ/dE is the gamma-ray photon spectrum produced by neutralino self-annihilation, A_{eff} is the effective area of the LAT detector as a function of gamma-ray energy, and $\rho(l)$ is the mass density of neutralinos along line-of-sight distance l. This equation arises from a standard linear radiative transfer model for an optically thin medium. The flux generated at any point is proportional to the square of the number density of neutralinos, since the flux arises from neutralino self-annihilation, which is a reaction with second-order kinetics. The squared mass density term is mapped to number density by the squared particle mass term in the denominator. The lines of sight for computing the photon counts are based on a galactocentric distance of 8 kpc, i.e. it models GLAST in orbit around the Earth. Since the location and size of each subhalo is known from the model results, the line-of-sight distance and angular size of each subhalo can be easily computed.

Application of equation (2) to the results of the *Via Lactea* model, using the parameters listed above, resulted in the all-sky gamma-ray map shown in Figure 3. The large central halo is the dominant feature, but significant substructure is seen as a result of the neutralino subhalos. This map accounts only for the predicted neutralino self-annihilation signal; no galactic or extragalactic background sources are shown. Since the distribution and intensity of the non-neutralino sources will limit the observability of the neutralino signal, the authors then applied an extragalactic background model based on the results of the EGRET instrument on the Compton Gamma-Ray Observatory, and a galactic background model which assumed the galactic signal was proportional the galactic HI column density. These background models can be summarized as:

$$(3)\ N_b = N_g + N_{eg}$$

where N_b is the total background photon count, N_g is the photon count due to the galactic background, and N_{eg} is the photon count due to the extragalactic background. The detectability S of a single subhalo was then computed as:

$$(4)\quad S = \frac{N_s}{\sqrt{N_b}}$$

where N_s is the total number of photons predicted for a single subhalo, from equation (2). A subhalo was deemed to be detectable by GLAST when S > 5.

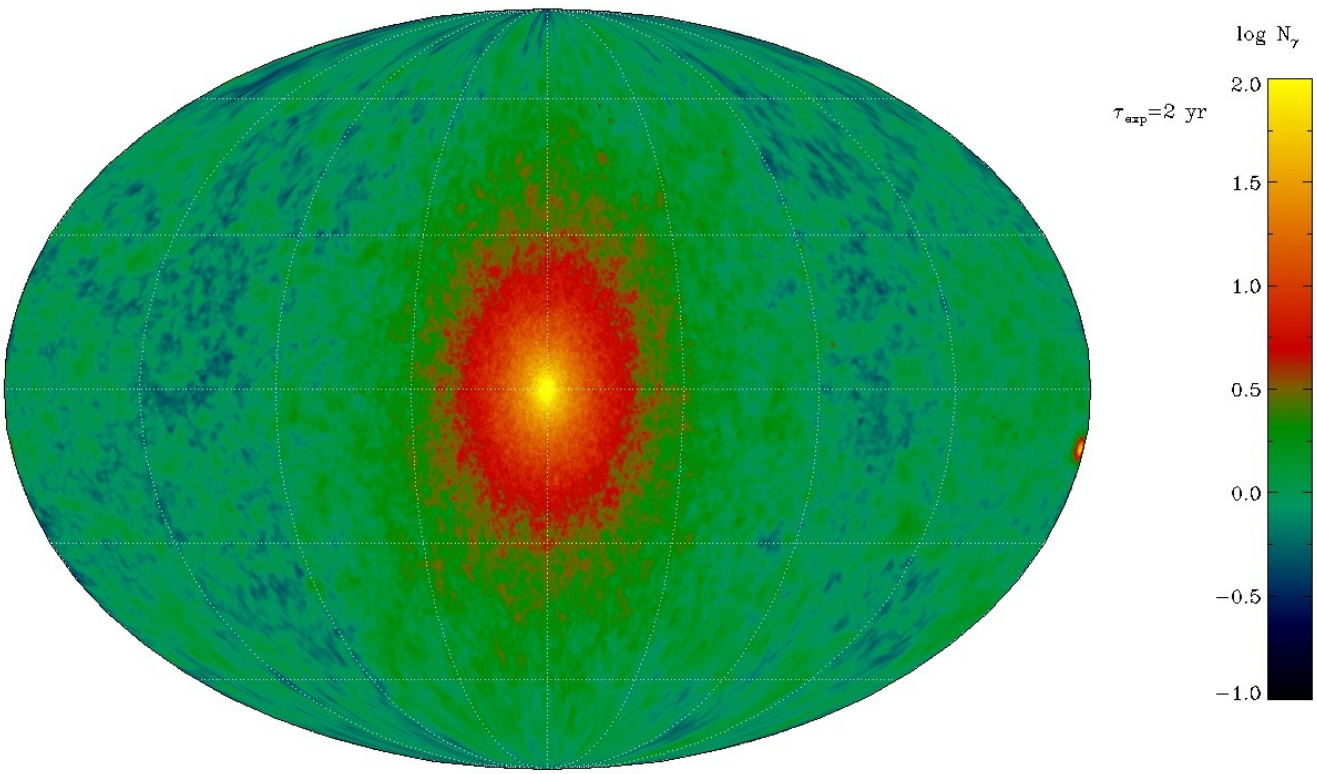

Figure 3: Simulated GLAST all-sky map of gamma-ray emission from neutralino self-annihilation (Mollweide projection, galactic plane horizontal across map center).

Using the selected values for the neutralino mass and annihilation cross-section, the authors determined that the central subhalo would be easily detected by GLAST (S > 100). However, detectability of individual subhalos will be difficult. Even after applying a numerical "boost factor" to the subhalo signals to account for "numerical heating" in the simulation, only a small fraction (< 1%) of the subhalos would be detectable by GLAST. The "numerical heating" effect artificially decreases the predicted density within a subhalo, and thus decreases the predicted signal. The boost factor is applied to the computed signal to counteract this effect. Boost factors of up to 10 were used, but (strangely) the angular size of the subhalos was not recomputed. Presumably the more concentrated density profile within a subhalo would result in a more compact neutralino distribution, and thus a smaller angular size for the target. This effect would to some extent offset the increased signal caused by the dependence of the photon count on the neutralino density. The boost factor arbitrarily subsumes these effects into a single value.

Note also that the detectability of a subhalo is strongly dependent on the neutralino parameters. The neutralino signal N_s from equation (2) is proportional to the annihilation cross-section $<\sigma v>$, but inversely proportional to the square of the neutralino mass M_χ. Since the possible range of masses for the neutralino range over 2 orders of magnitude, the resulting signal can vary over 4 orders of magnitude, for a fixed cross-section. Therefore, if the neutralino has 1/10 the mass (around 5 GeV), the signal will be approximately 100 times stronger than that predicted in this study. But if the neutralino has a mass in the upper portion of the mass range, the chance of detecting a subhalo rapidly drops to near zero; a mass increase by a factor of 10 would result in at most a single subhalo being detectable by GLAST.

Conclusion

The authors provide a useful example of how GLAST might be used to search for evidence of dark matter. GLAST will likely be able to detect the presence of the central massive dark matter halo (assuming it is composed of neutralinos), regardless of the specific neutralino parameters. However, the possibility of detecting substructure in the dark matter halo is strongly dependent on the physical parameters used for the neutralino. If such structure is detected, it can be used to place strong constraints on these parameters (neutralino mass and annihilation cross-section).

Note: All figures were taken from the original paper and its associated presentation slides.

References

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