Shedding Light on Dark Matter

can't actually be done – while these particles make up 82% of the matter in the Universe, they don't interact with light. So how do we know anything about these invisible particles? While the mere existence of dark matter particles is inferred from their gravitational pull on matter that we can see, we can go further and learn about the properties of these subatomic particles. The properties of subatomic particles have important effects on the formation of the first galaxies and present-day dwarf galaxies. Dark matter has been described as massive "cold" particles that decoupled from other particle species with little thermal velocity; however, if dark matter is composed of lighter "warm" particles, their thermal velocities allow them to stream out of the smallest over-dense regions in the early Universe thereby decreasing the density and preventing the collapse and formation of small galaxies. Using N-body simulations of the gravitational interaction of 200 million bodies, we can model Milky Way–sized galaxies with various particle masses. The number of small satellite galaxies in the simulated Milky Ways decreases with decreasing mass of the dark matter particle. Comparing the simulations to the number of satellite galaxies observed around the Milky Way sets a lower limit on the mass of the dark matter particle. Determining just how cold "cold dark matter" really is helps us to determine the composition of dark matter and thus understand galaxy formation. We still can't see dark matter, but we're finding out how to take its temperature.

Constraining the Very Small with the Very Large: Particle Physics and the Milky Way

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The majority of matter in the universe likely consists of one or more undiscovered particles that do not interact with light. The properties of this dark matter can be deduced from its gravitational interaction with visible matter. The early universe contained regions where the matter density was higher than average. These regions collapsed gravitationally to form galaxies. The velocities of dark matter particles in the early universe depend on the particle mass — less massive particles move faster and can stream out of the smallest dense regions, thereby decreasing their density and preventing gravitational collapse. In this way, the number of small satellite galaxies in massive galaxies can probe the unseen particle's mass. We have conducted N-body simulations of the gravitational interactions between 200 million bodies to model Milky Way–sized galaxies with various particle masses. Such simulations are computationally challenging because gravity is a long-range force and, in a direct approach, the complexity of the computation scales as N^2 for N bodies. We compare our simulations to the observed number of Milky Way satellites to derive a lower limit on the particle mass comparable to, and independent of, complementary astronomical methods.

INTRODUCTION

Cosmology has entered an age of precision where the major parameters such as the amount of matter and energy in the universe are known to within just a few percent. Of the matter in the universe, less than 18% is composed of the familiar protons and neutrons that make up the elements. The rest consists of an undiscovered particle that neither emits, absorbs, nor reflects light at a detectable level and is called "dark matter." The presence of dark matter is deduced from its gravitational interaction with the visible matter in galaxies and clusters. Simulations show the stars and gas of galaxies and clusters reside in extended spheroidal shaped halos of dark matter.

In the standard paradigm, the dark matter particle is "cold": it decoupled from the other particle species in the early universe with negligible thermal velocities. A cold particle would have a large mass, on the order of giga-electron volts (GeV) or more. Cold dark matter (CDM) is extremely successful at describing the large-scale features of matter distribution in the universe but has problems on small scales. Below the mega-parsec scale (Mpc = 3.3 million light years) CDM predicts numbers of satellite galaxies for Milky Way–sized hosts about an order of magnitude more than the number observed.

One proposed solution is the dark matter may be "warm" with a particle mass on the order of kilo-electron volts (keV). Warm dark matter (WDM) particles decouple in the early universe with relativistic velocities, enabling them to stream out of regions of higher density and erase density fluctuations on sub-Galactic scales. WDM thereby reduces the numbers of satellites. In this way, the satellite galaxies of the Milky Way can be used to probe the unseen particle's mass. Since the number of dark matter halos must be greater than or equal to the number of observed satellites, a census of observed Milky Way satellites combined with simulations of the satellite population of Milky Way–sized dark matter halos can set a lower limit on the particle mass.[1]

WARM DARK MATTER

The WDM particle is often assumed to be a thermal particle, meaning it was in thermal equilibrium with the other particle species at the time of its decoupling in the early universe. A candidate for a thermal WDM particle is the gravitino from supersymmetry theories of particle physics. In general, the dark matter particle may not have been in thermal equilibrium when it decoupled. This is the case for a sterile neutrino, a theoretical particle proposed as an explanation for the anomalous excess of oscillations observed between neutrinos and antineutrinos. Figure 1 shows the effects of WDM on the power spectrum of density fluctuations for several thermal particle masses and an 11 keV sterile neutrino. As the particle mass decreases, structures are erased on larger scales.

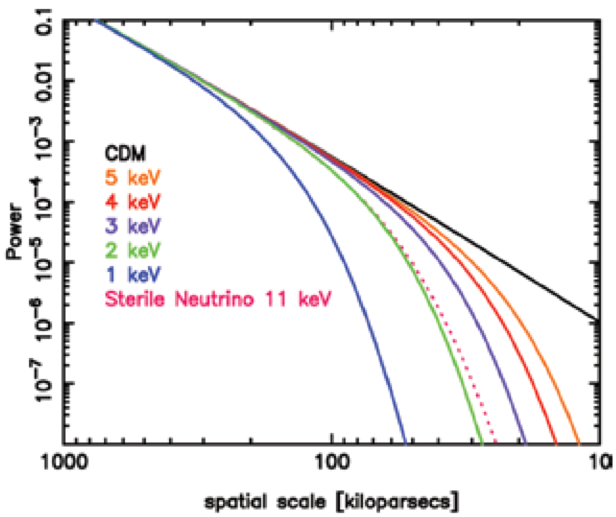

FIGURE 1
Power spectra of density fluctuations for CDM and WDM. As the particle mass decreases, the number of structures (power) decreases on larger scales.

SIMULATIONS

Dark matter can be treated as a collisionless gas. In the N-body method, the phase-space density of this gas is sampled with a finite number, N, of tracer particles. Solving the evolution of this gas from the early universe to the present requires calculating the gravitational force on every tracer particle and calculating its new position after a small time step from its acceleration and velocity. Since gravity is long ranged, the force on each particle is influenced by every other particle. A direct integration of forces would require N-1 force calculation for each particle, or on the order of N^2 computations for each time step. As the number of particles grows large, a direct approach to force calculation quickly becomes intractable. Algorithms have been developed requiring less computational resources and below we describe the methods used by the N-body code GADGET-2.

GADGET-2 separates the force on each particle into a short-range and a long-range term. A "particle mesh" method is used for calculating the long range force. The force is treated as a field quantity and approximated on a mesh. Densities are computed for each mesh cell and the gravitational potential and forces on the grid are calculated. Gravitational potentials and forces at the particle positions are obtained by interpolating the mesh values.

The short range force is calculated with a "tree" method. This method uses the principle that the individual forces from distant groups of particles can be treated as a single force from a massive particle. This reduces the number of force computations for a single particle from N-1 in the direct approach to on the order of log N. The particles are grouped hierarchically with a recursive subdivision of space. A "root" node is formed encompassing the whole simulation volume. The root node is subdivided into smaller daughter nodes. These daughter nodes are recursively subdivided, like branches of a tree, until all particles are in "leaf" nodes of no more than one particle per leaf. To calculate the force on a particle, the tree is "walked"; starting at the root node, it is decided if the node is small enough and far enough away to provide an accurate force estimate. If so, the walk is stopped along this branch; if not, the node is opened and the procedure repeated at the next level of branches. This is repeated until the forces from all other particles in the short range region have been accounted for.

GADGET-2 is also a massively parallel simulation code flexible for use on an arbitrary number of processors. The computational volume is decomposed into a set of domains, each assigned to one processor with each processor running a separate instance of the GADGET-2 code. Each domain is compact with a small surface-area-to-volume ratio that reduces communication times between processors necessary when calculating the forces on domain-bordering particles.

OUR SIMULATIONS

We employ a "zoom" technique in which we run a simulation of a 90 Mpc^3 cubic box with coarse mass resolution and identify dark matter halos with properties similar to the Milky Way. We chose a halo for resimulation at higher resolution by placing a smaller refinement region over the volume containing the halo's particles in the initial conditions, a box within a box. The refinement region has many more particles with much lower mass resolution than the original simulation. Our highest resolution simulations have over 200 million particles with a resolution of 9×10^4 solar masses. We ran high-resolution simulations for two separate Milky Way halos in CDM and WDM cosmologies with dark matter particle masses of 1, 2, and 4 keV. We ran each high-resolution simulation using 128 processor cores on the "Deepthought" parallel computing cluster at the University of Maryland, College Park. Each simulation took about 13 days to run, or about 4.5 years total CPU time per simulation.

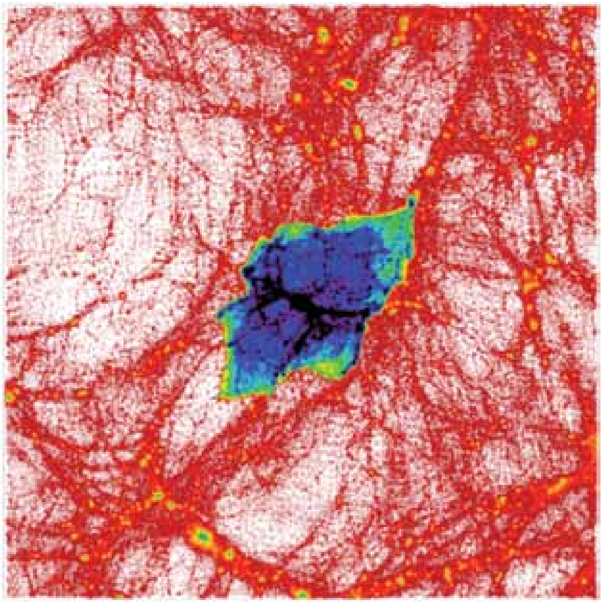

FIGURE 2
A 40 Mpc^3 cubic box centered on one of our simulated Milky Way halos. The image is color-coded by particle density showing the high mass resolution region embedded in the lower resolution simulation volume.

Figure 2 shows a 40 Mpc^3 region centered on one of our high-resolution halos at the end of the CDM simulation. The image is color-coded by particle density and shows the refinement region embedded in the larger, lower resolution simulation box. The Milky Way halo is at the center of the refinement region. Figure 3 shows portraits at 6 Mpc and 600 kpc of the same halo in the high-resolution CDM and WDM simulations. The number of small-scale halos decreases as the dark matter particle mass decreases, while the large-scale features remain generally unchanged.

Finding the gravitationally bound dark matter halos in large N-body simulations is also a nontrivial computational problem. For our simulations, we used the AHF halo finding software. AHF constructs a hierarchy of grids and calculates the particle density in each cell. If the cell density is higher than a threshold value, the cell is divided into a refined subgrid and the procedure repeated. A tree of nested grids is thus constructed that traces the density field. Halos are followed by stepping in density contours from high values to the background density. Substructures are identified by recursively walking the tree from coarse grids to fine. Like GADGET-2, AHF supports parallel computing through domain decomposition techniques, allowing it to run quickly even on large N simulations.

COMPARISON TO OBSERVATIONS

Before the Sloane Digital Sky Survey (SDSS), there were only 12 classically known satellite galaxies of the Milky Way. Sixteen new satellites have been discovered in the SDSS. We correct for the primary incompleteness of the SDSS, its sky coverage of 28.3%, and combined with the classic Milky Way satellites, this forms our observed data set.

The SDSS is a magnitude-limited survey, meaning satellites of a given luminosity and surface brightness are preferentially detected at closer distances. The num-

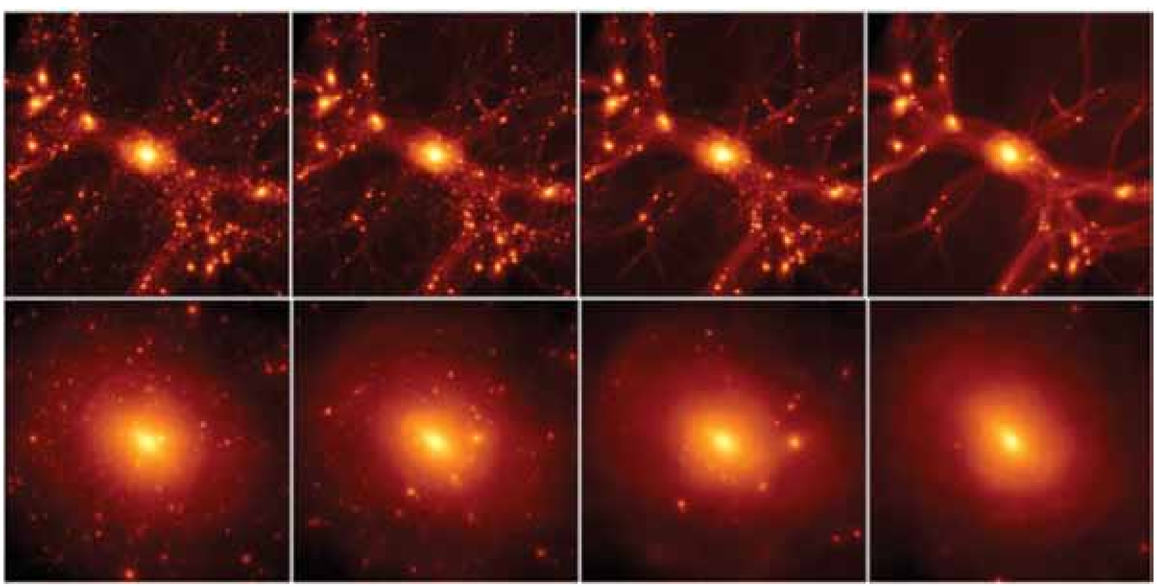

FIGURE 3
Portraits of the Milky Way halo at 6 Mpc (upper row) and 600 kpc (bottom row) for different cosmologies. From left to right the cosmologies are CDM, 4 keV WDM, 2 keV WDM, 1 keV WDM. As the dark matter particle mass decreases, the number of Milky Way satellites decreases.

ber of satellites within 50 kpc of the Milky Way center is most important for constraining the dark matter particle mass because the observations are most complete to this distance. Unfortunately, this is also the distance range where numerical destruction effects become important for the simulations. Satellites in simulations are destroyed artificially by extraneous tidal fields due to limitations of the simulation technique. This numerical destruction becomes dominant for satellites in the inner halo region. We calculate and correct the effects of numerical destruction using results of published high-resolution simulations found in the literature.

We count the number of satellites from 0 to 50 kpc in our high-resolution simulations. We consider the uncertainty in the simulated halo abundances due to halo-to-halo variation and, using the results of other published simulations, we conservatively set the scatter to 30% and interpolate the simulation results over the range m_{WDM} = 1–5 keV. We also consider an uncertainty in the number of observed satellites due to the incomplete sky coverage of the SDSS. In Fig. 4 we plot the difference in the number of observed and simulated satellites with 1σ and 2σ limits (shaded regions) from combining the uncertainties of the observed and simulated data sets. The number of satellites in simulation must be at least equal to the number of observed satellites; therefore, where this quantity equals zero, a lower limit on the dark matter particle mass is defined.

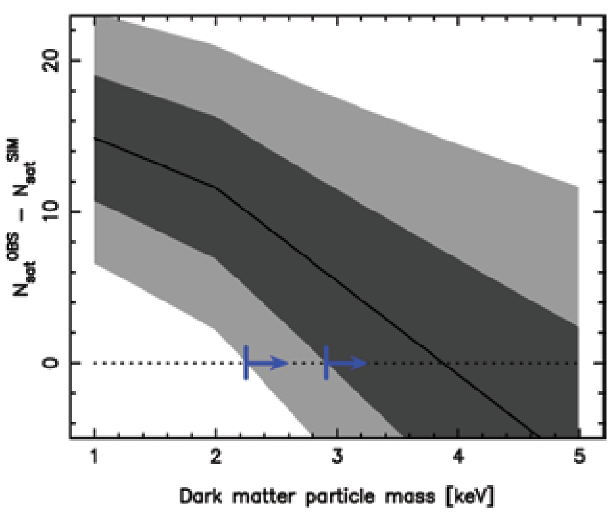

FIGURE 4
Number of observed Milky Way satellites minus the number of satellites in our simulations interpolated over WDM cosmologies with particle masses 1–5 keV. The dark and light shaded regions show the 1σ and 2σ ranges considering uncertainties in both the observed and simulated data sets. The arrowed lines show our lower limits on the dark matter particle mass at 1σ and 2σ confidence.

The arrowed lines indicate the lower limits at 1σ and 2σ, and we adopt m_{WDM} > 2.3 keV at 95% confidence.

COMPARISON TO OTHER METHODS

Our result can be compared to limits on the particle mass from modeling the Lyman-α absorption by neutral hydrogen along the line of sight in the spectra of distant quasars. Work using low-resolution spectra for SDSS quasars finds a limit of > 2 keV for a thermal WDM particle. Adding high-resolution spectra for a subset of quasars raises the limit to > 4 keV; however, the derived temperature of the intergalactic medium is higher than expected and also higher than that derived from high-resolution spectra taken with other instruments and from the widths of thermally broadened absorption lines. This could be explained by an unaccounted-for systematic error in the data that may also affect the derived mass limits.

Using a scaling relation for sterile neutrinos, we find a lower limit m_s > 13.3 keV. Sterile neutrinos are expected to radiatively decay to a lighter mass neutrino and an X-ray photon. X-ray observations of the diffuse X-ray background and dark matter halos in clusters, the Andromeda galaxy, dwarf spheroidal galaxies, and the halo of the Milky Way have all been used to set constraints on the sterile neutrino mass in the range m_s < 2.5–9.3 keV. These upper limits are well below the lower limits derived in this work and from Lyman-α observations and seem to rule out the standard production mechanisms. However, these mass limits, including the constraints set in this work, are model dependent and make assumptions about the dependence of the sterile neutrino mass on the mixing angle with active neutrinos, their cosmic density, and the initial conditions in the early universe when they were created. Depending on the assumptions made and the adopted production model, the relationship between mass, mixing angle, and cosmic density changes so that robust constraints cannot be placed on any one parameter.

SUMMARY

We conducted N-body simulations of the satellite populations of Milky Way–sized dark matter halos in CDM and WDM cosmologies. These simulations would not be possible with direct calculation techniques but are made possible by the use of algorithms that reduce the number of computations by many orders of magnitude, and by parallel programming methods that allow a problem requiring large numbers of calculations to be divided into smaller pieces and distributed to many processors running simultaneously. We have demonstrated how N-body simulations of the

Milky Way and its satellites can set limits on the dark matter particle mass comparable to complementary methods, but the methods are independent and almost certainly are subject to different systematic errors if any exist. Our limits are helped greatly by the discovery of many new satellites in the SDSS. Future surveys have the potential to discover many more satellites. Better constraints will result from the smaller uncertainty in the number of observed satellites achieved by improving the sky coverage and reducing luminosity corrections. In addition, there may exist a yet unknown population of even fainter satellites with luminosities and surface brightnesses that have been so far undetectable.

ACKNOWLEDGMENT

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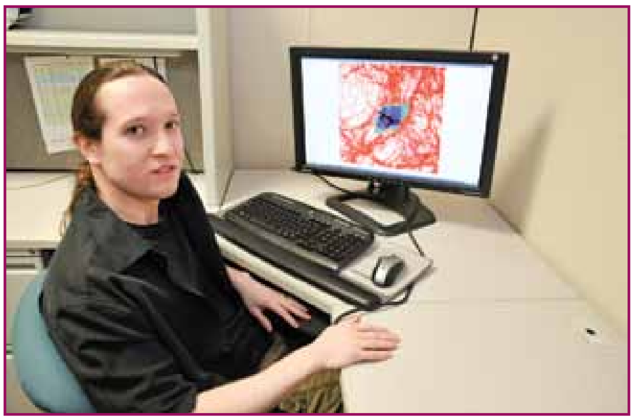
[Sponsored by NRL]

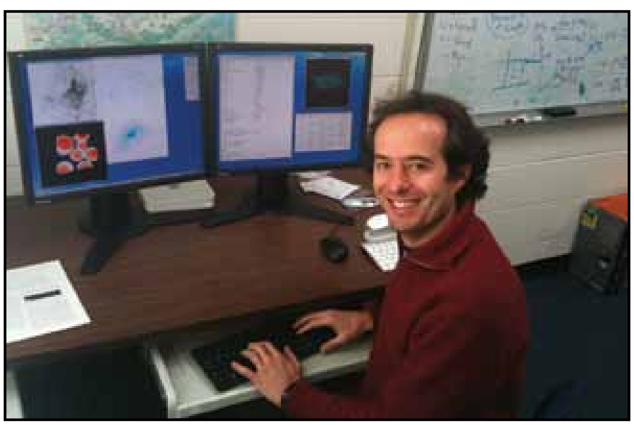
Reference

[1]E. Polisensky and M. Ricotti, "Constraints on the Dark Matter Particle Mass from the Number of Milky Way Satellites," *Phys. Rev. D* **83**, 043506 (2011), arXiv:1004.1459.

THE AUTHORS



EMIL POLISENSKY started working at NRL under an internship in the summers of 2002 and 2003. As an intern, he assisted in the research and development of antennas for low-frequency radio astronomy and helped build and analyze data from the NRL Long-Wavelength Test Array. He earned his M.S. degree in astronomy from San Diego State University in 2004 studying X-ray binaries and came to work at NRL full-time in the radio astronomy group of the Remote Sensing Division. His radio astronomy work has involved simulations of phased antenna array design, imaging with sparse arrays, and development of software to make model sky maps at frequencies below 100 MHz, which he uses to simulate the diurnal variation in power output from single antennas. Since 2006 he has been pursuing a Ph.D. at the University of Maryland under the Edison Program, conducting research in cosmology.



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