Dark Matter Spikes and Annihilation Radiation from the Galactic Center

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The annihilation rate of weakly interacting cold dark matter particles at the galactic center could be greatly enhanced by the growth of a density spike around the central supermassive black hole (SBH). Here we discuss the effects of hierarchical mergers on the central spike. Mergers between halos containing SBHs lead to the formation of SBH binaries which transfer energy to the dark matter particles, lowering their density. The predicted flux of annihilation photons from the galactic center is several orders of magnitude smaller than in models that ignore the effects of SBHs and mergers. Measurement of the annihilation radiation could in principle be used to constrain the merger history of the galaxy.

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The dark matter puzzle is one of the central challenges facing particle physics and cosmology [1]. A popular candidate for nonbaryonic cold dark matter (CDM) is the lightest supersymmetric particle, plausibly the neutralino χ [2,3]. The mass of the neutralino is constrained by accelerator searches and theoretical considerations of thermal freeze-out to lie in the range 30 GeV $\lesssim M_\chi \lesssim$ 10 TeV [4,5]. Neutralinos are generically found to decouple at a temperature that is roughly $M_\chi/20$, which means that they are nonrelativistic already at decoupling and hence behave like CDM.

Dark matter particles may be detected directly, via laboratory experiments [6], or indirectly, via their annihilation products [7]. Indirect schemes are typically based on searches for gamma rays from neutralino annihilations in the dark matter halo of the Milky Way (MW) galaxy [8–10]. Since the photon flux depends on the squared density of neutralinos integrated along the line of sight, the signal is greatly enhanced in directions where the dark matter is clumped. This includes the galactic center, where the density in a smooth halo would be maximum, as well as any lines of sight intersecting the centers of relic halos that orbit as subclumps in the MW halo [11,12]. The signal from the galactic center is further enhanced if there is a CDM "spike" associated with the central supermassive black hole (SBH). Adiabatic growth of a SBH at the center of a preexisting halo produces a power-law distribution of matter around the SBH, a spike, with density $\rho \sim r^{-\gamma}$, $2.2 \lesssim \gamma \lesssim 2.5$, $r \lesssim r_h \equiv GM_\bullet/\sigma^2$ [13]; $M_\bullet$ is the SBH mass and σ is the 1D velocity dispersion of the dark matter particles. For the MW SBH, $M_\bullet \sim (2\text{–}5) \times 10^6 M_\odot$ [14–16] and $r_h \sim 1$ pc. These spikes lead to predictions of higher-than-observed rates of γ-ray annihilation products [17].

One element missing from earlier discussions of dark matter spikes is the destructive effect of hierarchical mergers. A dark matter halo as massive as that of the MW, $M \sim 10^{12} M_\odot$, has almost certainly experienced a significant merger event since a redshift of $z \sim 2$. Furthermore, SBHs with masses of $\sim 10^9 M_\odot$ were present in at least some halos already at redshifts of 5–6 [18,19], and SBHs probably acquired most of their mass by a redshift of 2–3, the epoch of peak quasar activity [20]. In the CDM paradigm, big halos grow through the buildup of smaller ones [21]; if more than one of the progenitor halos carried a central SBH, a binary SBH will form following the merger [22]. Formation and decay of the SBH binary transfers energy to the background particles and lowers the density of matter in a region within a few $\times r_h$ around the binary [23,24], roughly the scale of the spike, before the SBHs coalesce due to emission of gravitational radiation [25]. In this Letter we compute the dark matter density profiles of merging CDM halos containing SBHs and show that the net result of including the SBHs is to substantially *lower* the predicted flux of annihilation photons compared with halos lacking SBHs. Our results are relevant also to models that relate the origin of ultrahigh energy cosmic rays to the decay of unstable superheavy relic particles in the galactic halo [26].

We first calculated the probability that the MW halo has experienced a major merger event by generating multiple realizations of the merger history of a halo of $10^{12} M_\odot$ using the algorithm described by Somerville and Kolatt [27], as applied to the standard ΛCDM cosmological model ($\Omega_0 = 0.3$, $\Lambda_0 = 0.7$). This algorithm accurately reproduces the merger histories of halos seen in N-body simulations of structure formation [28] although at a value of the scale factor that may differ as much as 20% from the true value [29]. We recorded all merger events such that the mass of the smaller of the subclumps involved in the merger was above a given limit $M_{\rm lim}$. From 600 of these realizations, we then computed the probability that a halo of $10^{12} M_\odot$ at redshift $z = 0$ had in its merger history at least one such event since a redshift of $z = 2$. Figure 1 shows this probability as a function of $M_{\rm lim}$. With 68% confidence, a halo the size of the MW has experienced at least one merger since $z = 2$ in which the mass of the smaller of the merging halos was above $2 \times 10^{11} M_\odot$, implying a

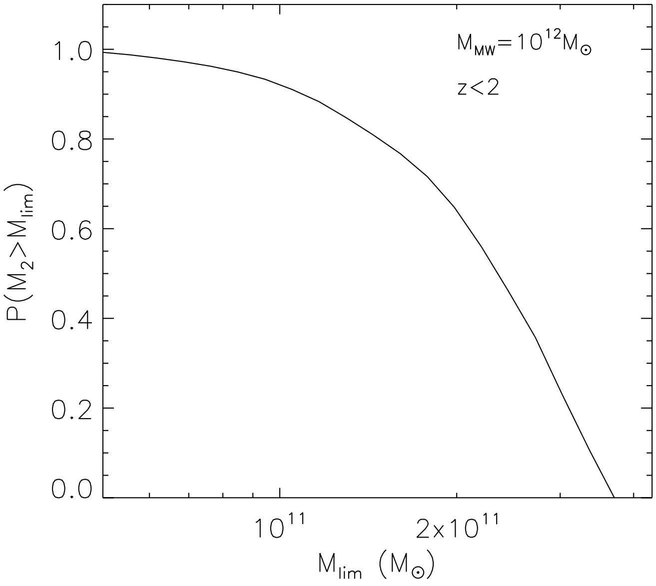

FIG. 1. Probability that the merger tree of a CDM halo of mass $10^{12}M_\odot$ at $z = 0$ contains at least one merger event between $z = 0$ and $z = 2$ in which the mass M_2 of the smaller subclump exceeded $M_{\rm lim}$.

mass ratio between subclumps of 4:1 or less. Mergers with mass ratios of 9:1 or less occurred with greater than 90% probability.

To investigate the detailed effects of mergers on dark matter spikes, we used an N-body code to simulate interactions between CDM halos containing central SBHs. N-body models were generated from the spherical density law

$$\rho_{\rm DM}(x) = \rho_0 x^{-1.5}(1 + x^{1.5})^{-1}, \qquad x \equiv r/r_{\rm DM}\,, \quad (1)$$

the "Moore profile" [30], one of a set of profiles found to accurately describe the halos generated in CDM structure formation simulations; $r_{\rm DM}$ defines the radius of transition between the inner cusp and the steeper outer falloff. Our choice of the Moore profile is conservative in the sense that other proposed fitting functions [31,32] have shallower central density cusps implying less prominent spikes. The Moore profile has a divergent mass; we truncated it spatially and generated velocities of the dark matter particles from a distribution function [33] which generates an isotropic velocity distribution near the center and increasingly circular orbits approaching the truncation radius. This procedure guarantees a state of detailed dynamical equilibrium in spite of the model's hard edge. Since the dependence of the central densities of CDM halos on halo mass is not well determined, we investigated two values of the central density ratio $\rho_1/\rho_2 = \{1, 1/3\}$ for one of the unequal-mass mergers, where ρ is defined as the asymptotic central density of the halos before growth of the SBH. A "black hole" was inserted into each N-body halo by slowly increasing the mass of a (Newtonian) central point particle from 0 to $M_\bullet$ (see Ref. [34]). We verified that the resulting density profile satisfied $\rho_{\rm DM} \sim r^{-2.4}$, $r \lesssim r_h$ as predicted by adiabatic theory ([13]; Fig. 2). Since the scale length of the MW halo is believed to be $r_{\rm DM} \sim 20$ kpc [35], the dark matter density profile is essentially scale-free, $\rho_{\rm DM} \sim r^{-1.5}$, at all radii of interest, and the mass chosen for the particle representing the MW SBH is fairly arbitrary. We tried two values, $M_\bullet/M_{\rm DM} = \{0.01, 0.03\}$; the larger value was preferred since it resulted in a lower amplitude of Brownian motion of the SBH particle [36]. The same mass ratio was adopted for the SBH in the smaller halo. The parameters of the N-body runs are given in Table I.

The mass scaling of our models was fixed by the measured mass of the MW SBH [14–16]; we assumed $M_\bullet = 3 \times 10^6 M_\odot$. The length scale was determined by assuming that the dark matter in the MW produces a circular rotation velocity of 90 km s^{-1} at the solar circle, $R_\odot = 8$ kpc [37] and that its density profile is $\rho_{\rm DM} \propto r^{-1.5}$ inward of $R_\odot$.

Simulated mergers of the halo models were carried out using a new, general-purpose N-body algorithm [38] that combines the elements of a hashed tree code with a quadrupolar expansion of force moments for the bulk dynamics, and the highly accurate Hermite predictor-corrector scheme for near-neighbor and massive-particle interactions. The code implements individual block time steps, individual stepping and softening criteria, and full functional parallelization. Interactions between SBH and dark matter particles were unsoftened. Calculations were carried out using 16 processors on the Rutgers Sun HPC-10000 computer. Integrations were terminated when the

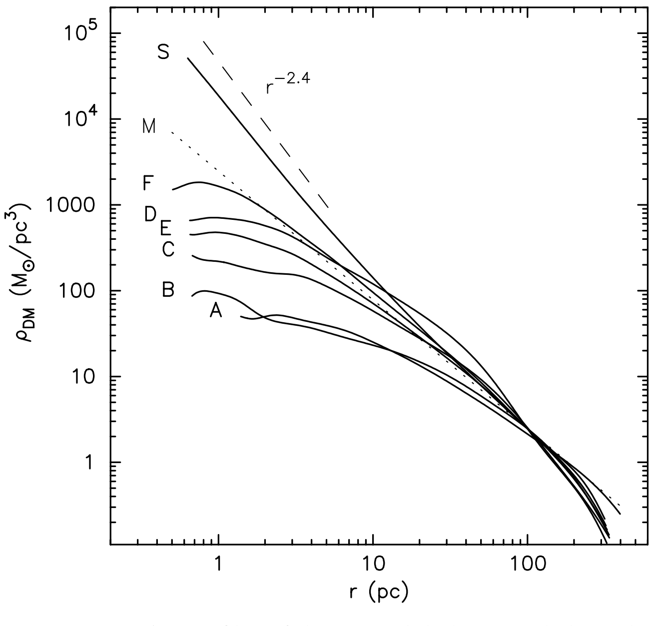

FIG. 2. Density profiles of the merged dark-matter halos. The origin is defined as the center of mass of the binary SBH; spherical symmetry is assumed. The curves labeled M and S are the density profiles of the large halo before and after growth of the SBH.

TABLE I. Parameters of the N-body integrations. M_1 (M_2) is the mass of the large (small) halo; ρ is the central halo density before growth of the SBH; $M_\bullet$ is the mass of the SBH particle; N is the combined number of DM particles in both halos; and $a_{\rm final}$ is the final separation of the BH binary.

Run	M_1/M_2	ρ_1/ρ_2	$M_\bullet/M$	N	$a_{\rm final}$(pc)
A	1	1	0.01	10^5	0.91
B	1	1	0.03	2×10^5	0.71
C	3	1	0.03	4×10^4	0.31
D	3	1/3	0.03	4×10^4	0.42
E	5	1	0.03	6×10^4	0.36
F	10	1	0.03	1.1×10^5	0.90

separation between the SBH particles was less than 1 pc (see Table I).

Figure 2 shows the effect of mergers on the dark matter density profiles. The steep, $\rho \sim r^{-2.4}$, density spikes are destroyed in each case by the transfer of kinetic energy from the binary SBH to the dark matter particles. (Mergers without central SBHs tend to preserve spike slopes [24,39].) The energy transfer takes place in two stages [24]: before the two SBHs form a binary system, dynamical friction acting on the individual SBHs causes their orbits to decay; and after formation of a bound pair, dark matter particles which pass the binary within a few times the binary's semimajor axis are ejected by the gravitational slingshot. The result is a lowered density out to a "core" radius r_c of $\sim$10–100 pc and a density profile that rises inward of r_c as a weak power law, $\rho \sim r^{-0.5}$. The amount of damage done to the preexisting spike increases with the mass of the secondary SBH, consistent with the expectation that the mass ejected by the binary is of order a few times M_2 [40]. Final mean dark matter densities within 100 pc are $(5-10)M_\odot$ pc^{-3} for all of the runs, rising inward to $\rho \sim 10^2 M_\odot$ pc^{-3} for the 1:1 mergers and $\sim 10^3 M_\odot$ pc^{-3} for the 10:1 merger.

The differential photon flux along a direction that makes an angle ψ with respect to the galactic center is

$$\frac{d\Phi_\gamma}{d\Omega} = \sum_i N_\gamma^i \frac{\sigma_i v}{4\pi M_\chi^2} \int_\psi \rho^2 \, dl \, , \qquad (2)$$

where Ω is the solid angle, ρ is the neutralino density, and σv is the annihilation cross section (independent of v for nonrelativistic particles); the sum is over all annihilation channels. $N_\gamma = 2$ for $\chi\chi \to \gamma\gamma$ and $N_\gamma = 1$ for $\chi\chi \to Z\gamma$ [10]. We are principally concerned with the final line-of-sight integral, $J(\psi) = \int_\psi \rho^2 \, dl$, which contains all of the information about the halo density profile. Following earlier authors [7,10], we write J in dimensionless form as

$$J(\psi) = \frac{1}{8.5 \text{ kpc}} \left(\frac{1}{0.3 \text{ GeV/cm}^3} \right)^2 \int_\psi \rho^2 \, dl \, , \qquad (3)$$

where the normalizing factors for length and density are roughly the radius of the solar circle and the local density of dark matter, respectively. Finally, we average the flux over the field of view assuming a circular aperture of size $\Delta\Omega$ centered at $\psi = 0$:

$$\langle J \rangle \equiv \frac{1}{\Delta\Omega} \int_{\Delta\Omega} J(\psi) \, d\psi \, . \qquad (4)$$

Figure 3 plots $\langle J \rangle$ as a function of $\Delta\Omega$ at the end of the N-body simulations. For a typical atmospheric Cherenkov telescope angular acceptance of $\Delta\Omega = 10^{-3}$ sr, $\langle J \rangle$ ranges from $\sim 10^{3.2}$ for the 1:1 merger to $\sim 10^{3.9}$ for the 3:1 mergers, compared with $\sim 10^{4.2}$ for the initial halo model without a SBH-induced spike (computed assuming an inner cutoff at the Schwarzschild radius of the SBH). Thus the addition of SBHs to CDM halos results in a net *decrease* in the annihilation flux compared with SBH-free models, if mergers are taken into account. The values of $\langle J \rangle$ in Fig. 3 are nevertheless large enough to allow testing of large parts of the neutralino parameter space using instruments like GLAST [41].

We note that the predicted flux is a strong function of the merger parameters when observed with $\Delta\Omega \lesssim 10^{-6}$ (Fig. 3), corresponding roughly to the sphere of influence of the MW SBH. This fact might allow the merger history of the MW to be inferred from measurements of the annihilation flux on different angular scales.

The addition of SBHs to CDM halos could result in even lower densities than shown in Fig. 2. Halos as massive as that of the MW are believed to have formed through a succession of mergers, and the damage done by binary SBHs would be to some extent cumulative, resulting in shallower

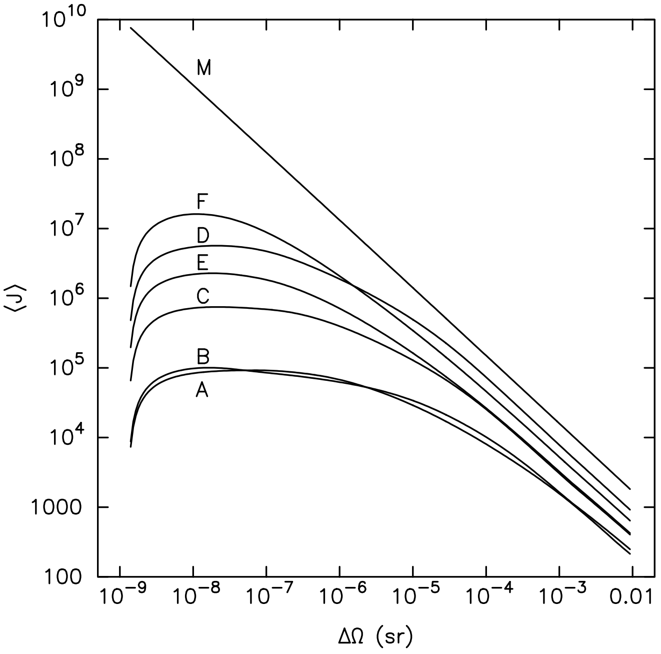

FIG. 3. Dimensionless integrated flux of the merger models as a function of the angular acceptance of the detector $\Delta\Omega$ [Eq. (4)]. The curve labeled M is the flux predicted by a Moore-profile halo without a SBH-induced spike (Fig. 2).

central profiles than found here [24,42]. In addition, binary SBHs may eventually coalesce due to emission of gravitational radiation [25]. The radiation so emitted carries linear momentum leading to a recoil of the SBH at a velocity $v_{\mathrm{recoil}} \sim 10^2 - 10^3$ km/s [43–45], and possibly even higher if the SBHs were rapidly spinning prior to coalescence [46]. Recoil velocities of this order would eject the coalesced SBH from the nucleus and its subsequent infall would displace dark matter particles (e.g., [47,48]). Quantitative evaluation of this effect will require more accurate estimates of v_{recoil} based on fully general-relativistic calculations of black hole mergers.

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