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GALAXY CORES AS RELICS OF BLACK HOLE MERGERS

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ABSTRACT

We investigate the hypothesis that the cores of elliptical galaxies and bulges are created from the binding energy liberated by the coalescence of supermassive binary black holes during galaxy mergers. Assuming that the central density profiles of galaxies were initially steep power laws, $\rho \sim r^{-2}$, we define the "mass deficit" as the mass in stars that had to be removed from the nucleus in order to produce the observed core. We use nonparametric deprojection to compute the mass deficit in a sample of 35 early-type galaxies with high-resolution imaging data. We find that the mass deficit correlates well with the mass of the nuclear black hole, consistent with the predictions of merger models. We argue that the level of damage done to stellar cusps by merging black holes is a lower limit on the damage expected for cusps of non-interacting dark matter.

Subject headings: black holes: binary black holes— galaxies: elliptical and lenticular, cD— galaxies: interactions— galaxies: nuclei

1. INTRODUCTION

Ferrarese *et al.* (1994) and Lauer *et al.* (1995) divide elliptical galaxies into two classes based on their nuclear properties, which Lauer *et al.* call "core" and "power-law" galaxies. Core galaxies exhibit a definite break in the surface brightness profile at some radius R_b; inward of this break, the logarithmic slope gently decreases in a manner that mimics a constant-density core. Power-law galaxies show essentially a single power-law profile throughout their inner regions, $\Sigma(R) \sim R^{-\Gamma}$, $\Gamma \approx -0.8 \pm 0.2$. The brightest galaxies, $M_V \lesssim -21$, are exclusively core galaxies while faint galaxies, $M_V \gtrsim -16$ always exhibit power laws; galaxies of intermediate luminosity can exhibit either type of profile (Gebhardt et al. 1996). While the two categories were initially seen as distinct, nonparametric deprojection revealed that even the "core" galaxies exhibit power laws in their central space densities, $\rho \sim r^{-\gamma}$, with $\gamma \lesssim 1$ (Merritt & Fridman 1995). Power-law galaxies have $1 \lesssim \gamma \lesssim 2.5$ (Gebhardt et al. 1996). Furthermore the distribution of de-projected slopes is essentially continuous as a function of galaxy luminosity in the larger samples now available (Ravindranath et al. 2001; Rest et al. 2001).

Here we assume that the steep central density cusps of faint ellipticals and bulges, $\rho \sim r^{-2}$, are characteristic of the earliest generation of galaxies, and ask: How do the low-density cores associated with bright galaxies form? An appealing hypothesis links cores to nuclear BHs: in a galactic merger, the BHs will fall to the center of the merger remnant and form a bound pair, releasing their binding energy to the surrounding stars (Ebisuzaki et al. 1990; Quinlan & Hernquist 1998). High-resolution N-body simulations verify that this process can convert a steep power-law cusp, $\rho \sim r^{-2}$, into a shallow power-law cusp, $\rho \sim r^{-1}$, within the radius of gravitational influence of the BHs (Milosavljević & Merritt 2001). Successive mergers would presumably lower the density of the core still more. In this model, power-law galaxies are those which have not experienced a major merger since the era of peak quasar activity, or which have re-generated their cusps via star formation (Milosavljević & Merritt 2001).

Preliminary tests of the cusp-disruption model were presented by Faber et al. (1997) and Milosavljević & Merritt (2001). The former authors plotted core properties (break radius, core luminosity) versus global properties in a sample of 19 early-type galaxies and noted a rough proportionality. Core properties should correlate more fundamentally with BH mass, since the mass of stars ejected by a decaying BBH is expected to be of order the BHs' mass. Milosavljević & Merritt (2001) used the new empirical relation between galaxy velocity dispersion and BH mass, the $M_\bullet - \sigma$ relation (Ferrarese & Merritt 2000), to estimate BH masses in the Faber et al. sample. They found that the break radius correlated poorly with $M_\bullet$ but that the "mass deficit" – the mass that would need to be removed from an initially r^{-2} density cusp in order to produce the observed profile – correlated well with $M_\bullet$.

In this paper we present the most careful test to date of the BBH merger hypothesis for the formation of galaxy cores. We use nonparametric deprojection (Merritt & Tremblay 1994) to compute the mass deficit in a sample of galaxies with high-resolution imaging data from HST (§2). We find a strong correlation between this mass and the mass of the nuclear BH; typical ejected masses are $\sim$ several $M_\bullet$ (§3). We argue (§4) that this result is consistent with the formation of cores via hierarchical mergers of galaxies containing pre-existing BHs. Cusps of non-interacting dark matter particles should behave in the same way as cusps of stars in response to heating by BBHs, and we argue that the damage done to stellar cusps by this mechanism represents a plausible lower limit on the damage done to dark matter cusps.

2. DATA AND METHOD

Our data set is drawn from a sample of 67 surface brightness profiles of early-type galaxies observed with HST/WFPC2 by Rest *et al.* (2001), and three additional

galaxies: NGC4472 and 4473, observed with WFPC1 by Ferrarese *et al.* (1994); and a WFPC2 F547M image of M87 (Jordán *et al.* 2002). The Rest et al. sample was selected from the set of all early-type galaxies with radial velocities less than 3400 km s^{-1}, absolute V-band magnitudes less than -18.5, and absolute galactic latitude exceeding 20 degrees. From this sample we excluded 13 galaxies for which central velocity dispersions were not available in literature; as discussed below, velocity dispersions were needed to compute BH masses in most of the galaxies. For specifics of the image-data reduction we refer the reader to the sources cited above. Surface brightness profiles used in this study were major-axis profiles. We applied a crude correction for the apparent ellipticity of the galaxies by multiplying the volume-integrated quantities, defined below, by $(1-\epsilon_{25})$, where ϵ_{25} is the ellipticity of the $\mu_B = 25$ mag arcsec^{-2} isophote.

The intrinsic luminosity profiles $\nu(r)$ were obtained by deprojecting the PSF-deconvolved surface brightness profiles $\Sigma(R)$ using the non-parametric MPL technique (Merritt & Tremblay 1994). We opted for one-step deprojection via maximization of the penalized likelihood functional

$$\mathcal{L}_\lambda[\nu] = \sum_i \frac{(\Sigma_i - P_i[\nu])^2}{(\Sigma_i^{err})^2} - \lambda \int_0^\infty \left[\frac{d^2 \log \nu}{(d \log r)^2}\right]^2 d \log r. \quad (1)$$

The first term compares the observed surface brightness data $\Sigma_i \equiv \Sigma(R_i)$ to the projections $P_i[\nu]$ of the intrinsic luminosity estimate ν given by the operator

$$P_i[\nu] = 2 \int_{R_i}^\infty \frac{\nu(r) r dr}{\sqrt{r^2 - R_i^2}}. \quad (2)$$

The second term in equation (1) is the penalty function which assigns zero penalty to any power-law $\nu(r)$; hence our estimate of ν is unbiassed if ν is an unbroken power law and should be minimally biassed if ν is approximately a power law. Relative strength of the penalty term is regulated through the parameter λ which was chosen by eye and equal for all galaxies; integrated quantities like the mass deficit defined below are only weakly dependent on λ.

Distances for 26 of the galaxies were drawn from the SBF survey (Tonry *et al.* 2001). For the remaining 34 galaxies we adopted distances computed assuming a pure Hubble expansion with $H_0 = 80$ km s^{-1} Mpc^{-1} corrected for Virgo-centric infall (Rest *et al.* 2001). Luminosity densities were converted to mass densities $\rho(r) = \Upsilon \nu(r)$ using the individual mass-to-light ratios Υ_V quoted in Magorrian *et al.* (1998) or their best-fit relation $\log(\Upsilon_V/\Upsilon_{\odot,V}) = -1.11 \pm 0.33 + (0.18 \pm 0.03) \log(L_V/L_{\odot,V})$ for galaxies not included in that study.

We define $\gamma \equiv -d \log \rho(r)/d \log(r)$ as the local, negative logarithmic slope of the deprojected density profile. Power-law galaxies are defined as those in which $\gamma \geq 2$ at all radii; typically the profiles of such galaxies show no clear feature that can be identified as a "break radius" and are unlikely candidates for cusp destruction by BBHs. In the remaining 35, "core" galaxies, the slope varies from $\gamma > 2$ at large radii to $\gamma < 2$ at small radii; the radius at which the slope crosses $\gamma = 2$ in the positive sense ($d\gamma/dr > 0$) is called here the "break radius" r_b (Figure 1). This definition has little in common with the more standard definition based on fitting of the *surface brightness* profile to an ad hoc parametric function. In a few galaxies the slope crosses $\gamma = 2$ in the positive sense at more than one radius. In such cases, we select the crossing to the right of the largest dip below $\gamma = 2$.

We define the *mass deficit* as the difference in integrated mass between the deprojected density profile $\rho(r)$ and a $\gamma = 2$ profile extrapolated inward from the break radius:

$$M_{\rm def} \equiv 4\pi(1-\epsilon) \int_0^{r_b} \left[\rho(r_b) \left(\frac{r}{r_b}\right)^{-2} - \rho(r)\right] r^2 dr. \quad (3)$$

Our choice of an r^{-2} density profile to characterize the "undisrupted" core is to a certain extent arbitrary; adiabatic growth of BHs can produce cusps with $1.5 \lesssim \gamma \lesssim 2.5$ depending on initial conditions, and the faintest ellipticals with measured cusp slopes exhibit a similar range of γ's (e.g. Gebhardt et al. 1996). To test the sensitivity of our results to the assumed initial profile, we repeated the analysis using fiducial slopes of $\gamma_0 = 1.75$ and 1.5. Values of $\gamma_0 > 2$ were found to exclude all but a few galaxies.

BH masses for a few of the galaxies in our sample are available from spatially-resolved kinematical studies 5 (Merritt & Ferrarese 2001). For all other galaxies we estimated $M_\bullet$ via the $M_\bullet - \sigma$ relation,

$$M_\bullet \approx 1.4 \times 10^8 M_\odot \left(\frac{\sigma_c}{200 \text{ km s}^{-1}}\right)^{4.8 \pm 0.5} \quad (4)$$

(Ferrarese & Merritt 2000), where σ_c is the central velocity dispersion corrected to an aperture of $r_e/8$ with r_e the effective radius. We used the aperature corrections of Jørgensen *et al.* (1995) to compute σ_c from published values of σ in Davies *et al.* (1987), Tonry & Davis (1981) and di Nella *et al.* (1995).

3. RESULTS

Results are given in Table 1 and Figure 2; Table 1 gives mass deficits only for $\gamma_0 = 2$ while Figure 2 shows $M_{\rm def}$ computed using all three values of the fiducial slope, γ_0=(2, 1.75, 1.5). In the first panel of Figure 2 we have also plotted "dynamical" estimates of $M_{\rm def}$ for a sample of galaxies from Gebhardt *et al.* (1996), using equation (41) from Milosavljević & Merritt (2001), $M_{\rm dyn} \equiv$

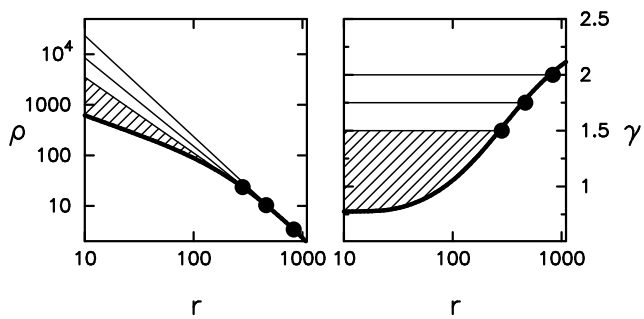

FIG. 1.— Definition of the mass deficit, illustrated using the profile of NGC5903. Left panel: density in $M_\odot$pc^{-3} as a function of radius in parsecs (thick line); hypothetical original density cusps for fiducial slopes $\gamma_0 = 2, 1.75, 1.5$ (thin lines). Dots indicate the corresponding break radii. Shaded region is the mass deficit. Right panel: the negative logarithmic derivative of the density profile, $\gamma \equiv -d \log \rho / d \log r$. Break radii are defined as the radii where $\gamma = \gamma_0$.

TABLE 1

Galaxy	D	M_B	r_b	γ_{min}	$\log M_\bullet$	$\log M_{\rm def}$	Galaxy	D	M_B	r_b	γ_{min}	$\log M_\bullet$	$\log M_{\rm def}$
N2549	12.6	-18.5	0.22	1.59	7.91	8.24	N4564	15.0	-18.9	0.11	1.69	7.76	8.09
N2634	33.4	-19.9	0.27	1.73	7.90	8.66	N4589	22.0	-20.0	0.18	1.05	8.22	8.79
N2986	26.8	-20.5	0.41	0.99	8.79	9.55	N5077	34.0	-20.4	0.54	1.15	8.78	9.57
N3193	34.0	-20.9	0.23	0.84	8.15	9.32	N5198	34.1	-20.0	0.11	0.92	8.09	8.63
N3348	38.5	-21.1	0.49	0.75	8.47	9.82	N5308	26.6	-19.7	0.10	1.84	8.37	7.54
N3414	25.2	-20.1	0.14	1.61	8.71	8.70	N5370	41.3	-19.0	0.32	1.56	7.49	8.69
N3613	29.1	-20.7	0.52	0.80	8.20	9.25	N5557	42.5	-21.2	0.44	0.87	8.64	9.62
N3640	27.0	-21.0	0.68	0.94	7.82	9.59	N5576	25.5	-20.3	0.24	1.37	8.00	9.20
N4121	28.3	-17.9	0.12	1.76	7.06	8.01	N5796	36.5	-20.7	0.18	1.18	8.60	9.08
N4128	32.4	-19.8	0.18	1.64	8.32	8.61	N5812	26.9	-20.3	0.25	1.71	8.15	8.78
N4168	30.9	-20.4	1.25	1.01	7.90	9.58	N5813	32.2	-21.1	0.43	0.31	8.40	9.59
N4291	26.2	-19.8	0.17	0.49	8.28	9.25	N5831	27.2	-19.9	0.22	1.42	7.72	8.75
N4365	20.4	-21.1	0.57	0.71	8.50	9.79	N5898	29.1	-20.4	0.33	1.34	8.30	9.26
N4472	16.3	-21.7	0.63	0.90	8.74	10.03	N5903	33.9	-20.9	0.78	0.77	8.41	9.58
N4473	15.7	-19.9	0.24	1.22	7.90	9.25	N5982	39.3	-20.9	0.45	0.49	8.71	9.60
N4478	18.1	-19.1	0.30	1.42	7.55	8.76	N6278	37.1	-19.7	0.10	1.53	7.64	8.43
N4486	16.1	-21.5	1.12	0.74	9.55	10.49	U4551	23.6	-18.7	0.24	1.36	8.02	8.44
N4503	17.6	-19.2	0.25	1.56	7.11	8.52	...	...	...	...	...	...	...

NOTE.—D is distance in Mpc; r_b is break radius in kpc; γ_{min} is the small-radius logarithmic slope; $M_\bullet$ and $M_{\rm def}$ are in solar masses.

$2(2-\gamma)/(3-\gamma)\sigma^2 R_b/G$; $M_{\rm dyn}$ depends on the density profile only through R_b, the break radius of the surface brightness profile. When calculated for the deprojected galaxies in our sample, $M_{\rm dyn}$ was consistent within the scatter with $M_{\rm def}$.

For $\gamma_0 = 2$, the mass deficits are clustered about a linear relation defined by $\langle\log(M_{\rm def}/M_\bullet)\rangle = 0.88$, 1.0, and 0.45, respectively, for Es and S0s; Es only; and S0s only, corresponding to $M_{\rm def} \sim (7.6, 10, 2.8)M_\bullet$. Decreasing γ_0 decreases $M_{\rm def}$ (cf. Fig. 1b) and $M_{\rm def}$ becomes negative/undefined in galaxies when the minimum pointwise slope γ_{min} approaches γ_0. We do not cite values of $\langle\log(M_{\rm def}/M_\bullet)\rangle$ for these low values of γ_0 since the mean depends strongly on which galaxies are defined as having "cores." However Figure 1b,c shows that $M_{\rm def}$ remains of order $M_\bullet$ or greater for many of the galaxies even when $\gamma_0 < 2$.

We note that in most galaxies the break radius defined via $\gamma(r_b) = \gamma_0 = 2$ is close to the radius at which the density profile exhibits a "visual" break, i.e. where the curvature is greatest. The break radius, however, is not a good predictor of the mass deficit; in particular, some galaxies with large break radii, $r_b \gg r_\bullet$, with $r_\bullet = GM_\bullet/\sigma^2$ the dynamical radius of the BH, have mass deficits below the mean. We speculate below that these large break radii may be produced by mechanisms other than BH mergers.

Although estimation of errors in Figure 2 is difficult, we believe that the scatter is at least partly intrinsic. Uncertainties in $\log M_\bullet$ are due primarily to uncertainties in σ and are of order $\log 2$. Uncertainties in $\log M_{\rm def}$ are also roughly $\log 2$ based on variances between the redshift-based and SBF distances. A scatter greater than that due to measurement uncertainties would be reasonable given the different merger histories of galaxies with given $M_\bullet$.

4. DISCUSSION

The mass ejected by a decaying BH binary is

$$M_{\rm ej} \approx J M_{12} \ln\left(\frac{a_h}{a_{gr}}\right) \qquad (5)$$

where $M_{12} = M_1 + M_2$ is the binary mass, a_h is the semi-major axis when the binary first becomes hard, and a_{gr} is the separation at which the evolution is dominated by the emission of gravitational radiation. The dimensionless mass-ejection rate J is approximately 0.5 for an equal-mass binary (Milosavljević & Merritt 2001) and decreases only slightly for $M_2 \ll M_1$ (Quinlan 1996). For decay in a power-law cusp, we can write

$$\frac{a_{gr}}{a_h} \approx A\,|\ln A|^{0.4}, \quad A = 9.85\left(\frac{M_1}{M_2}\right)^{0.2}\left(\frac{M_{12}}{2M_2}\right)^{0.4}\frac{\sigma}{c} \qquad (6)$$

(Merritt 2000). For $\sigma \approx 200$ km s^{-1}, the ejected mass is well approximated by

$$M_{ej} \approx 2.3\left(\frac{J}{0.5}\right)M_{12}\left[1 + 0.13\ln\left(\frac{M_2}{M_1}\right)\right], \quad M_1 \le M_2. \qquad (7)$$

Thus M_{ej}/M_{12} varies from ~ 2 when $M_1 = M_2$ to ~ 1 when $M_2 = 0.03M_1$.

If a BH and its host galaxy grew by cumulative mergers, the ejected mass will be greater than this. We consider two extreme cases. In a merger hierarchy where the galaxies at each level of the hierarchy are identical, a mass in stars of order M_{ej} is ejected at each stage, and the mass deficit in the final merger product will be $\sim 2NM_\bullet$ where N is the number of levels in the hierarchy and $M_\bullet$ is the final BH mass (Milosavljević & Merritt 2001). At the other extreme, if a BH grows by repeated accretion of much less massive BHs, equation (5) implies that the ejected mass is of order $N(N+1)\delta m/2$ where N is the number of accretion events and δm is the mass of each accreted BH. The mass deficit would then be $\sim NM_\bullet/2$. The latter number almost certainly overestimates the effect on the stellar density profile since (1) most of mass "ejected" when $M_2 \ll M_1$ has too low a velocity to escape the nucleus (Quinlan 1996); much of this mass would be redistributed in the vicinity of the BH; (2) very small accreted galaxies may not contain supermassive BHs; (3) the time required for a small BH to reach the nucleus may exceed the age of the universe (Merritt 2000).

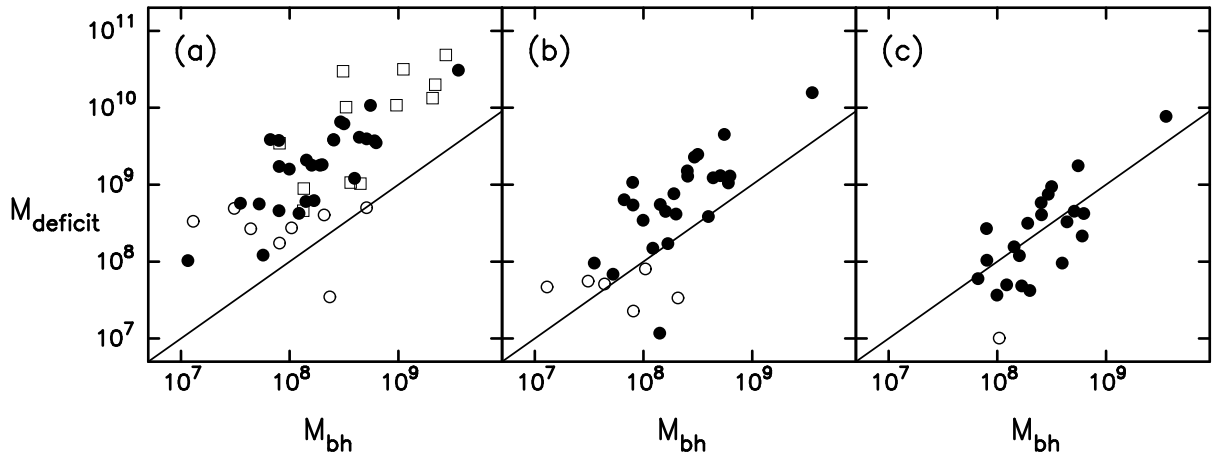

FIG. 2.— Mass deficit vs. BH mass for three different values of γ_0, the assumed logarithmic slope of the density cusp before energy input from BHs. (a) $\gamma_0 = 2$; (b) $\gamma_0 = 1.75$; (c) $\gamma_0 = 1.5$. Filled circles are elliptical galaxies, empty circles are lenticulars, and squares are dynamical estimates of $M_{\rm def}$ for the sample of galaxies considered in Milosavljević & Merritt (2001). Solid line is the $M_{\rm def} = M_\bullet$ relation.

We can summarize these arguments by saying that $M_{\rm def}$ should be of order $NM_\bullet$, where N is the number of "significant" merger events, i.e. mergers in which the infalling BH successfully coalesces with the larger BH. This prediction is consistent with Figure 2 if the initial cusp slope γ_0 is assumed to be greater than ~ 1.5. For $\gamma_0 = 2$, Figure 2 implies $N \approx 8$, and for $\gamma_0 = 1.75$, $N \approx 4$. We note that galaxies with masses $M \gtrsim 10^{11} M_\odot$, including most of the galaxies plotted on Figure 2, are believed to have undergone at least one major merger since a redshift of ~ 1 (Kauffmann, Charlot & Balogh 2001).

Our interpretation depends critically on the assumption that *all* of the change in γ can be attributed to the BHs, i.e. that cusp slopes remain unchanged following mergers in the absence of BHs. This is known to be the case in equal-mass mergers (Barnes 1999; Merritt & Cruz 2001), though in unequal-mass mergers, features can appear in the cusp density profile that are not due to the BHs (Merritt & Cruz 2001). We speculate that the break radii in some of the galaxies in our sample may be due to this process, particularly those galaxies (e.g. NGC 3640, 4168) where r_b greatly exceeds the radius of gravitational influence of the BH. N-body simulations of cumulative mergers with unequal BH mass ratios will be needed to assess this hypothesis.

Our interpretation of Figure 2 presents an interesting contrast to the model of van der Marel (1999), who proposed that cores (in the sense of constant-density regions) were present in *all* galaxies ab initio, and that power-law cusps were generated by the growth of the SBHs – roughly the opposite of our model in which SBHs destroy preexisting cusps. Van der Marel assumed that core mass correlated initially with bulge luminosity as $M_{\rm core} \sim L^{1.5}$ and that $M_\bullet \propto L$; hence $M_{\rm core} \propto M_\bullet^{1.5}$, consistent with the correlation in Figure 2 if we identify $M_{\rm core}$ with $M_{\rm def}$. We believe that this agreement is coincidental. Van der Marel's model ignores the effects of mergers which must alter any correlation set up at the time of galaxy formation. His model also requires an ad hoc postulate, the relation between initial core mass and galaxy luminosity, and leaves unanswered the question of how cores formed in the first generation of galaxies. Nevertheless van der Marel's model shows that the interpretation presented here is not unique.

If stellar cusps are destroyed by binary BHs, the same should be true of dark-matter cusps, like those predicted in CDM theories of structure formation (e.g. Navarro, Frenk & White 1996; Moore et al. 1998; Bullock et al. 2001). Destruction of dark matter cusps could be very efficient if supermassive BHs were present in dark matter halos at large redshifts (e.g. Fan et al. 2001; Haiman & Loeb 2001); furthermore, dark matter cusps would not be regenerated the way that stellar cusps might be via star formation following mergers. Thus we propose that the level of cusp destruction inferred here – an ejected mass of order $\sim$ several times $M_\bullet$ – represents a plausible lower limit on the damage expected for dark matter cusps at the centers of galaxies.

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