

Scaling Laws for Dark Matter Halos in Late-Type and Dwarf Spheroidal Galaxies

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Abstract. Dark matter (DM) halos of Sc–Im galaxies satisfy structural scaling laws analogous to the fundamental plane relations for elliptical galaxies. Halos in less luminous galaxies have smaller core radii r_c , higher central densities ρ_o , and smaller central velocity dispersions σ . If dwarf spheroidal (dSph) and dwarf Magellanic irregular (dIm) galaxies lie on the extrapolations of these correlations, then we can estimate their baryon loss relative to that of Sc–Im galaxies. We find that, if there had been no enhanced baryon loss relative to Sc–Im galaxies, typical dSph and dIm galaxies would be brighter by $\Delta M_B \simeq -4.0$ mag and $\Delta M_B \simeq -3.5$ mag, respectively. Instead, the galaxies lost or retained as gas (in dIm galaxies) baryons that could have formed stars. Also, dSph and dIm galaxies have DM halos that are more massive than we thought, with $\sigma \sim 30$ km s⁻¹ or circular-orbit rotation velocities $V_{\text{circ}} \sim 42$ km s⁻¹. Comparison of DM and visible matter parameter correlations confirms that, at $M_V \gtrsim -18$, dSph and dIm galaxies form a sequence of decreasing baryon-to-DM mass ratios in smaller dwarfs. We show explicitly that galaxy baryon content goes to (almost) zero at $V_{\text{circ}} \lesssim 42 \pm 4$ km s⁻¹, in agreement with V_{circ} as found from our estimate of baryon depletion. Our results suggest that there may be a large population of DM halos that are dark and undiscovered. This helps to solve the problem that the initial fluctuation spectrum of cold dark matter predicts more dwarf galaxies than we observe.

1. Introduction and Analysis Machinery

This paper summarizes Kormendy & Freeman (2014). That paper derives structural parameter correlations for DM halos in Sc–Im and dSph galaxies. We restrict ourselves to objects that contain only two main components, a baryonic disk or main body and a DM halo. For galaxies with well measured HI rotation curves $V(r)$, the derived DM parameters come from published maximum-disk decompositions of $V(r)$ into visible and dark components. The halo model used is the nonsingular isothermal. At absolute magnitude $M_B \gtrsim -14$, V is comparable to the velocity dispersion; then rotation curve decomposition is impossible. For these dwarf spheroidal (dSph) and dwarf Magellanic irregular (dIm) galaxies, we derive central DM densities using the Jeans equation.

We compare DM parameters with visible matter parameter correlations from Kormendy & Bender (2012). They show that the parameter correlations of Sph galaxies are continuous with the disks (but not bulges) of S0 galaxies. In essence, Sph galaxies are bulgeless S0s. Moreover, Sph and S+Im galaxies have similar structure at each M_V . Effective brightnesses decrease dramatically at $M_V > -18$; this is used in Figure 3 here.

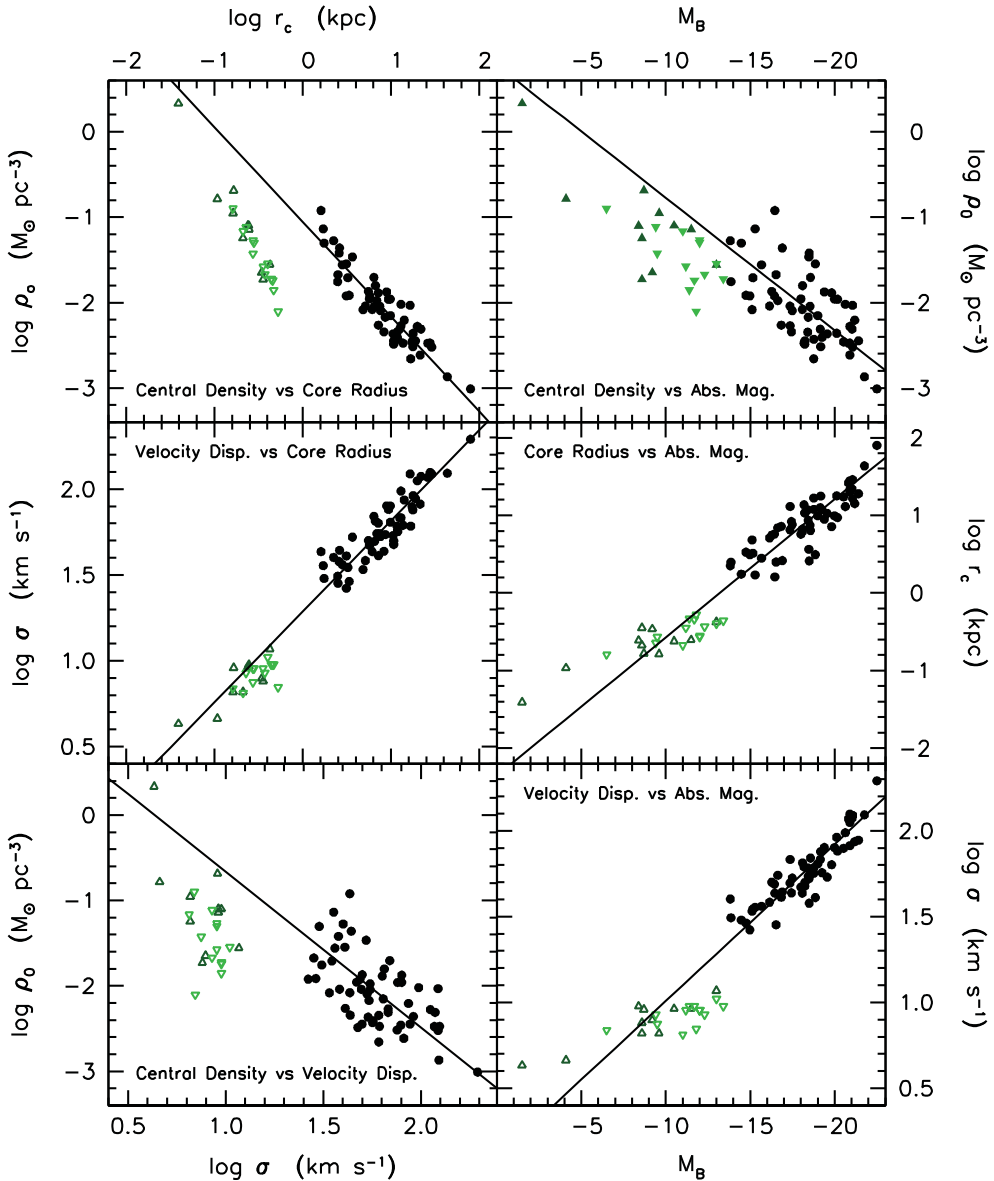


Figure 1. Dark matter parameter correlations for Sc–Im galaxies as derived from rotation curve decompositions using the nonsingular isothermal as DM model (black points and black line = symmetric least-squares fit). Also added are dSph galaxies (green triangles) and dIm galaxies (upside-down green triangles). For dSph and dIm galaxies, ρ_0 is a measure of the DM and therefore is plotted with filled symbols in the top-right panel. But r_c and σ are visible-matter parameters and so are plotted with open symbols in the other panels. From Kormendy & Freeman (2014).

2. DM Structural Parameter Correlations

Figures 1 and 2 show the main observational result of Kormendy & Freeman (2014): DM halos of Sc–Im galaxies satisfy well defined scaling laws. Halos in less luminous galaxies have smaller core radii, higher central densities, and smaller velocity dispersions. This confirms previous analyses of smaller samples (Kormendy 1988, 1990; Kormendy & Freeman 2004). Scaling laws provide new constraints on galaxy formation. For example:

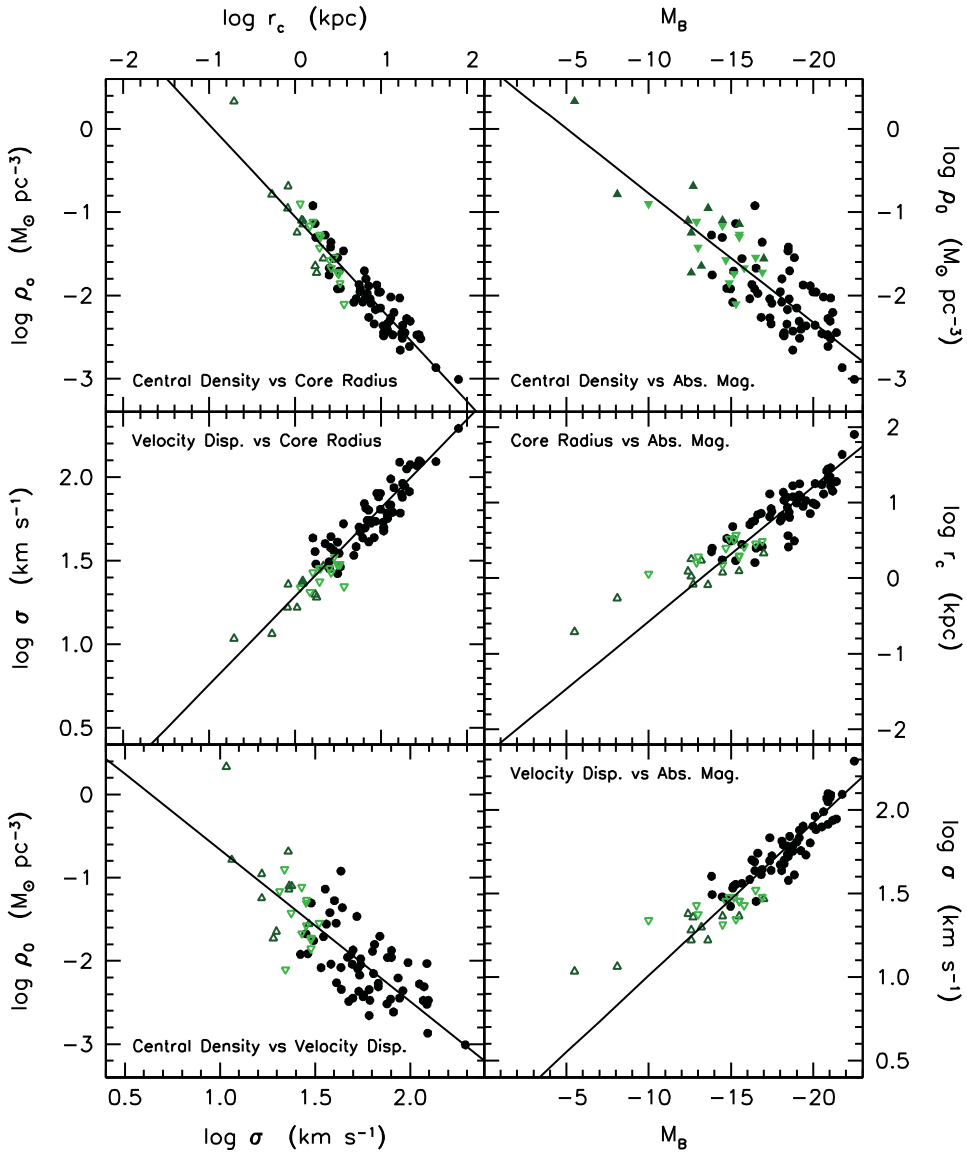


Figure 2. DM correlations for Sc–Im, dSph, and dIm galaxies (Figure 1) but with dSph and dIm galaxies shifted in M_B , $\log r_c$, and $\log \sigma$ (but not $\log \rho_0$) to move them onto the scaling laws for the Sc–Im galaxies. The goal is to estimate (1) the baryon loss from dwarf galaxies relative to that from Sc–Im galaxies and (2) the difference between the baryon and DM values of $\log r_c$ and $\log \sigma$. The shifts for dSph and dIm galaxies are, respectively, $M_B \rightarrow M_B - 4.0$ and $M_B \rightarrow M_B - 3.5$, $\log r_c \rightarrow \log r_c + 0.70$ and $\log r_c \rightarrow \log r_c + 0.85$, and $\log \sigma \rightarrow \log \sigma + 0.40$ and $\log \sigma \rightarrow \log \sigma + 0.50$. Note the interpretation of the shifts: $\Delta \log r_c$ gives us the ratio of DM core radius to visible matter core radius, and $\Delta \log \sigma$ gives us the ratio of DM velocity dispersion to visible matter velocity dispersion. From Kormendy & Freeman (2014).

Halo density depends on collapse redshift z_{coll} as $\rho_0 \propto (1 + z_{\text{coll}})^3$. Thus ρ_0 increases toward lower luminosities because fainter galaxies collapsed earlier. The DM correlations imply that dwarf galaxies formed at least $\Delta z_{\text{coll}} \simeq 7$ earlier than giant spirals. Correction for baryonic DM compression would make the “pristine” ρ_0 smaller for giant galaxies and would increase Δz_{coll} .

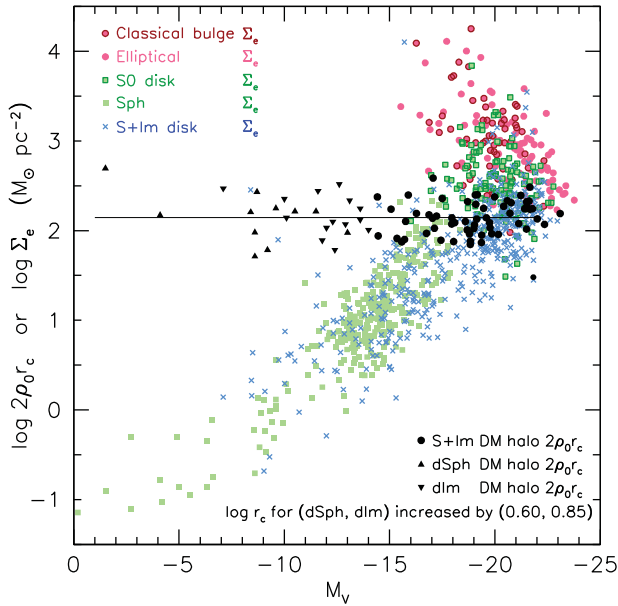


Figure 3. Comparison of DM halo parameters from Fig. 2 with visible matter galaxy parameters from Kormendy & Bender (2012). Central projected densities are plotted for DM halos; effective surface densities $\Sigma_e = \Sigma(r_e)$ are shown for visible components. Here r_e is the radius that encloses half of the light of the component. To convert surface brightnesses to stellar surface densities, we assume mass-to-light ratios $M/L_V = 8$ for ellipticals, 5 for bulges and S0 disks, and 2 for spiral galaxy disks, Im galaxies, and Sph galaxies. From Kormendy & Freeman (2014).

In Figure 3, smaller dwarfs have smaller stellar-to-DM ratios; these are probably associated with baryon loss. The correlations in Figure 1 provide a way to estimate this baryon loss and the properties of dwarf galaxy halos. The Jeans equation tells us the DM central density ρ_0 but not its core radius r_c or velocity dispersion σ . So the top-right panel in Figure 1 correctly shows an offset of dSph+dIm galaxies from the extrapolation of the fitted $\rho_0 - M_B$ correlation. But the smallest galaxies with rotation curve decompositions have DM densities similar to those of the biggest dwarfs with Jeans equation estimates. *We assume that dSph+dIm galaxies would lie on the extrapolation of the $\log \rho_0 - M_B$ correlation for bright galaxies except for the effects of their enhanced baryon loss.* The top-right panel of Figure 1 then tells us the ΔM_B shifts that bring dSph and dIm galaxies onto the fitted relation. The top-left and bottom-left panels tell us the shifts in $\log r_c$ and $\log \sigma$ that bring dSph+dIm galaxies onto those relations. These shifts are applied in Figure 2. In all panels, dSph and dIm galaxy halos lie on the correlations for more massive galaxies. The $\Delta \log \sigma$ shifts imply that almost-dark dwarfs are more massive than we thought. Their typical halo has $\sigma \sim 30 \text{ km s}^{-1}$. This corresponds to $V_{\text{circ}} \sim 42 \text{ km s}^{-1}$, in remarkably good agreement with the value of V_{circ} where galaxies get dim in Figure 4.

3. Comparison of Scaling Relations for Visible and Dark Matter

Figure 3 compares the central projected densities of DM halos with effective projected densities of stars. S+Im+Sph galaxies with $M_V \gtrsim -18$ form a sequence of decreasing baryon-to-DM density ratios at decreasing L_V . We suggest that they form a sequence of decreasing baryon retention (vs. supernova-driven winds: Dekel & Silk 1986) or decreasing baryon capture (after cosmic reionization) in smaller galaxies. For galaxies with present

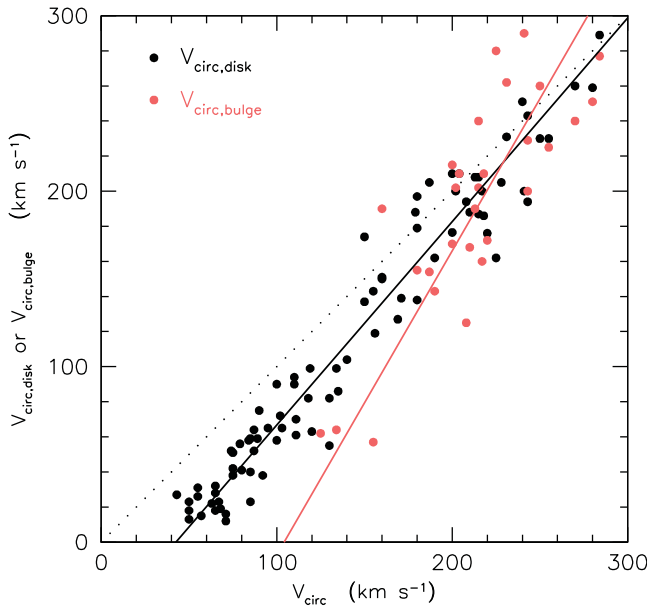


Figure 4. Maximum rotation velocity of the bulge $V_{\text{circ,bulge}}$ (red points) and disk $V_{\text{circ,disk}}$ (black points) given in bulge-disk-halo decompositions of galaxy rotation curves whose outer, DM test particle rotation velocities are V_{circ} . The dotted line indicates $V_{\text{circ,bulge}} = V_{\text{circ,disk}} = V_{\text{circ}}$. Every red point has a corresponding black point, but many galaxies are bulgeless, and then only a disk was included in the decomposition. This figure shows that the “rotation curve conspiracy”, $V_{\text{circ,bulge}} \simeq V_{\text{circ,disk}} \simeq V_{\text{circ}}$ for the halo (Bahcall & Casertano 1985; van Albada & Sancisi 1986; Sancisi & van Albada 1987), happens mostly for galaxies with $V_{\text{circ}} \sim 200 \text{ km s}^{-1}$. The lines are least-squares fits with each variable symmetrized around 200 km s^{-1} . The correlation for bulges is steeper than the one for disks; bulges disappear at $V_{\text{circ}} \sim 104 \pm 16 \text{ km s}^{-1}$. Disks disappear robustly at $V_{\text{circ}} = 42 \pm 4 \text{ km s}^{-1}$. From Kormendy & Freeman (2014).

$M_V \sim -10 \pm 3$, the baryon depletion is estimated by ΔM_B in the caption of Figure 2. If the stellar M/L_V is similar in dwarfs and Sc–Im systems, then ΔM_B measures the mass of stars in dwarfs relative to the mass of stars in Sc–Im galaxies with halos of similar ρ_o . This agrees with their mass-to-light ratios, $M/L_V \sim 10^2$. These dwarfs are almost dark, probably because they lost more baryons than the (also substantial) loss from Sc–Im galaxies. In dIm galaxies, some baryons are still in cold gas, but this effect is fairly small.

Also in Figure 3, projected (not volume!) DM density Σ_{DMo} is essentially independent of galaxy luminosity L_V . This is a well known result (Kormendy & Freeman 2004; Spano *et al.* 2008; Gentile *et al.* 2009; Donato *et al.* 2009; Plana *et al.* 2010). It implies a Faber–Jackson (1976) relation of the form DM mass $M_{DM} \propto \sigma^4$.

Finally, in Figure 3, bulges and elliptical galaxies have $\Sigma_e > \Sigma_{DMo}$, more so at lower L_V . Kormendy *et al.* (2009) and Kormendy & Bender (2012) suggest that they form a sequence of increasing dissipation in the formation of smaller galaxies.

Perhaps the most remarkable result in Kormendy & Freeman (2014) is shown in Fig. 4. It shows that rotation-curve decompositions reveal a robust, linear correlation between the maximum rotation velocity $V_{\text{circ,disk}}$ of baryonic disks and the outer circular velocity V_{circ} of test particles in their DM halos. It explicitly shows that $V_{\text{circ,disk}} \rightarrow 0 \text{ km s}^{-1}$ at $V_{\text{circ}} > 0 \text{ km s}^{-1}$. In fact, baryons become unimportant at $V_{\text{circ}} = 42 \pm 4 \text{ km s}^{-1}$. This $V_{\text{circ,disk}} = 0$ intercept agrees very well with the typical halo σ that we deduced in Section 2. Smaller galaxies are dim or dark. For example, the two extremely faint dSph galaxies in our sample, Segue 1 and Coma, have V_{circ} values of about 16 km s^{-1} .

4. Does There Exist a Large Population of Dark Galaxies?

From the above results, we conclude that the range of visible matter content of $\sigma \sim 30 \text{ km s}^{-1}$ DM halos is large. The ones with the most baryons rotate enough to allow rotation curve decomposition. The ones with the fewest baryons are barely discoverable. None of these galaxies “know” that they must retain $\sim 1\%$ of their baryons to be discoverable by us almost 14 billion years after they formed. Moreover, as luminosity decreases toward barely discoverable galaxies, these dwarfs become much more numerous as well as much more nearly dominated by DM. And baryon depletion processes should be more efficient in smaller galaxies. All this suggests that there may exist a large population of objects that are even darker – too dark to be discovered by current techniques. This would help to solve the problem that such objects are predicted by cold DM theory but not seen in Local-Group-like environments (Moore *et al.* 1999; Klypin *et al.* 1999).

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