ACDM is Consistent with SPARC Radial Acceleration Relation

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Abstract
Recent analysis of the Spitzer Photometry and Accurate Rotation Curve (SPARC) galaxy sample found a surprisingly tight relation between the radial acceleration inferred from the rotation curves and the acceleration due to the baryonic components of the disk. It has been suggested that this relation may be evidence for new physics, beyond $\Lambda\text{CDM}$. In this Letter, we show that 32 galaxies from the MUGS2 match the SPARC acceleration relation. These cosmological simulations of star-forming, rotationally supported disks were simulated with a WMAP3 $\Lambda\text{CDM}$ cosmology, and match the SPARC acceleration relation with less scatter than the observational data. These results show that this acceleration relation is a consequence of dissipative collapse of baryons, rather than being evidence for exotic dark-sector physics or new dynamical laws.

Key words: dark matter – galaxies: evolution – galaxies: kinematics and dynamics – gravitation

1. Introduction
For nearly a century, observations of kinematics in galaxies and clusters of galaxies have found large velocities inconsistent with the luminous matter within them. Even when thorough, comprehensive surveys of the baryonic mass within galaxies and clusters have been performed, most of the matter has been found to be missing. Zwicky (1937) presented observations of galaxy velocity dispersions in the Coma cluster, and proposed that the bulk of that cluster’s mass was some sort of dark matter (DM). Later, the groundbreaking observations of Rubin & Ford (1970) showed that this DM was also ubiquitous within disk galaxies like our own. Today, there is a wealth of evidence for cold DM, not just from galaxy kinematics, but from the formation of large-scale structure (Blumenthal et al. 1984), the cosmic microwave background power spectrum (Planck Collaboration et al. 2014), and the primordial abundances of elements after Big Bang nucleosynthesis (Walker et al. 1991). DM is now part of the standard cosmology, $\Lambda\text{CDM}$, in which most of the matter in our universe is in fact dark. Despite this, we still do not know the actual form that DM particles take. Both direct detection experiments and searches for DM annihilation have failed to conclusively observe these particles (Aprile et al. 2012), and as such, alternative explanations for the kinematics of galaxies have been proposed.

The Spitzer Photometry and Accurate Rotation Curves (SPARCs) sample, presented in Lelli et al. (2016a), is a new set of observations and derived mass models for a large number of rotation-dominated galaxies. By using 3.6 $\mu$m observations, the stellar mass can be estimated with great accuracy. The stellar mass is complemented with 21 cm observations of HI to get a measure of the gas mass within the disk. The recent paper by McGaugh et al. (2016) analyzed this sample and determined a relation between the observed radial acceleration determined from the rotation curve ($g_{\text{obs}}$) and the acceleration induced by the baryons observed in the disk ($g_{\text{bar}}$). McGaugh et al. (2016) found that for large values of $g_{\text{bar}}$, $g_{\text{obs}} \sim g_{\text{bar}}$, while for values of $g_{\text{bar}} \lesssim 10^{-10}$ m s$^{-2}$, the observed acceleration begins to rapidly outstrip the acceleration one would expect from the observed baryons. They find that the relation between $g_{\text{bar}}$ and $g_{\text{obs}}$ is well fit by

$$g_{\text{obs}} = \frac{g_{\text{bar}}}{1 - \exp(-\sqrt{g_{\text{bar}}/g_0})},$$

where $g_0 = 1.20 \pm 0.26 \times 10^{-10}$ m s$^{-2}$. In addition to the simple functional form, McGaugh et al. (2016) found a surprisingly low scatter in this relation, with residuals normally distributed with $\sigma = 0.11$ dex. The authors noted that this is the same functional form as the Modified Newtonian Dynamics (MOND; Milgrom 1983) acceleration law, which attempts to explain galaxy rotation curves without DM.

A correlation between the total acceleration seen in disk galaxies and the acceleration due only to baryons has been known for some time (Sancisi 2004; McGaugh 2004). Until recently, this has primarily been examined through the mass-discrepancy acceleration relation (MDAR): $g_{\bar{b}}$ versus $M_{\text{col}}/M_{\text{bar}}$. McGaugh et al. (2016) directly probes a more fundamental relation, the radial acceleration relation (RAR), with a number of improvements that reduce the observational uncertainties.

In discussing these results, McGaugh et al. (2016) offer three possible explanations for the tight relation:

1. The end point of galaxy formation with conventional (baryonic) physics.
2. New dark-sector physics coupling DM and baryons.
3. New dynamical laws (such as MOND Tensor-Vector-Scalar Gravity, TeVeS; Bekenstein 2004, etc.).

This is not the first set of observations that appear to be in discordance with $\Lambda\text{CDM}$. N-body simulations of halo formation have found DM halos follow a universal, “cuspy” density profile (Navarro et al. 1996). Yet, observations of dwarf galaxies in the local universe find flat, “cored” central densities (the “cusp-core problem”; Walker & Peñarrubia 2011). Meanwhile, DM-only simulations were finding that the local group should contain thousands of dwarfs, in contrast to the dozens actually observed (the “missing satellites problem”; Klypin et al. 1999). Many of these halos are large enough that suppression of star formation by reionization could not explain their absence from the observations (the “too big to fail” problem; Boylan-Kolchin et al. 2011).
A common feature in each of these conflicts is the comparison of observations to simulations of galaxy formation that rely purely on N-body, DM-only simulations. We now know that the impact of baryonic physics, chief among them the feedback from massive stars and black holes, can have a dramatic effect on the star formation history (e.g., Keller et al. 2015) and density profile of galaxies (Mashchenko et al. 2006). Multiple studies (Pontzen & Governato 2012; Sawala et al. 2016; etc.) have found these problems disappear when galaxies are simulated with gas dynamics, along with reasonable models for star formation, radiative cooling, and stellar feedback. This is what constitutes a modern theory of galaxy formation, the first of the three options offered to explain the RAR. Galaxies are formed through the gravitational collapse of collisional particles (gas) into a rotationally supported disk. Conservation of angular momentum, combined with star formation and feedback within that disk, leads to the observed scaling relations and galaxy properties we see today. Whether this can also reproduce the RAR has been yet to be demonstrated.

In this Letter, we show that the apparent tension between models of galaxy formation in ΛCDM and the SPARC observations also evaporates when the collapse of baryons is taken into account. We find that the $g_{\text{obs}} - g_{\text{bar}}$ relation for a set of pre-existing cosmological galaxy simulations, evolved in a conventional ΛCDM cosmology, matches the SPARC acceleration relation, with even tighter scatter than the observed sample.

2. The McMaster Unbiased Galaxy Simulations (MUGS2) Sample

The MUGS2 sample is an unbiased, statistically representative set of 18 cosmological zoom-in simulations of L* disk galaxies. These galaxies were simulated in a WMAP3 ΛCDM cosmology, with parameters $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.24$, $\Omega_{\text{bar}} = 0.04$, $\Omega_{\Lambda} = 0.76$, and $\sigma_8 = 0.76$. The MUGS2 $z = 0$ halo masses range from $3.7 \times 10^{11} M_\odot$ to $2.2 \times 10^{12} M_\odot$, with disk masses ranging from $1.8 \times 10^{10} M_\odot$ to $2.7 \times 10^{11} M_\odot$. For more details on the creation of the MUGS2 initial conditions, see the original MUGS paper, Stinson et al. (2010). For more information on the simulations themselves, see Keller et al. (2015, 2016).

MUGS2 was simulated using the modern smoothed particle hydrodynamics code GASOLINE (Wadsley et al. 2004; Keller et al. 2014). The simulations used metal line radiative cooling (Shen et al. 2010), as well as a simple Schmidt law for star formation. What sets MUGS2 apart from the original MUGS, aside from improved hydrodynamics, is the use of a physically motivated, first principles model for treating feedback from supernovae (SNe). Originally presented in Keller et al. (2014), the superbubble model captures the effects of thermal conduction and evaporation between a hot, SNe heated bubble and a surrounding shell of cold, swept-up interstellar medium (ISM). This model was derived to allow unresolved superbubbles to radiatively cool at realistic rates, with no free parameters, while automatically capturing the effects of clustered SNe.

In addition to the central spirals, we also include a number of dwarf companions from the MUGS2 sample. As with McGaugh et al. (2016), we exclude galaxies that are experiencing significant tidal interactions. Joshi et al. (2016) showed that tidal interactions on infalling galaxies can occasionally be seen out to 3 virial radii, we select galaxies between 3 and 5 virial radii from the central spiral. We exclude halos beyond 5 virial radii because our zoom-in simulations do not contain gas particles at these distances. In order to limit the effects of poor resolution, and to ensure that each radial bin contains sufficient baryonic resolution, we select only galaxies that contain 100 or more star particles. This gives us an additional 14 galaxies at $z = 0$, for a total of 32 galaxies. The stellar, gas, and total virial masses for each of our galaxies are shown in Table 1.

| Galaxy | $M_\text{gas}$ | $M_\text{vir}$ |
|--------|----------------|---------------|
| g158073 | $1.66 \times 10^7$ | $1.52 \times 10^8$ | $1.74 \times 10^{10}$ |
| g8893 | $2.14 \times 10^7$ | $1.06 \times 10^8$ | $1.10 \times 10^{10}$ |
| g15362 | $2.62 \times 10^7$ | $1.03 \times 10^8$ | $8.36 \times 10^{10}$ |
| g3021 | $3.24 \times 10^7$ | $3.93 \times 10^8$ | $2.49 \times 10^{10}$ |
| g1455 | $4.04 \times 10^7$ | $9.55 \times 10^8$ | $2.83 \times 10^{10}$ |
| g171241 | $4.76 \times 10^7$ | $2.83 \times 10^8$ | $3.54 \times 10^{10}$ |
| g27491 | $6.66 \times 10^7$ | $4.22 \times 10^8$ | $2.53 \times 10^{10}$ |
| g1536 | $1.19 \times 10^7$ | $3.75 \times 10^8$ | $5.29 \times 10^{10}$ |
| g1452 | $1.76 \times 10^7$ | $8.40 \times 10^8$ | $4.83 \times 10^{10}$ |
| g158007 | $3.04 \times 10^7$ | $1.09 \times 10^8$ | $5.50 \times 10^{10}$ |
| g1451 | $3.93 \times 10^7$ | $5.29 \times 10^8$ | $1.30 \times 10^{11}$ |
| g15807 | $7.54 \times 10^7$ | $1.68 \times 10^8$ | $8.17 \times 10^{10}$ |
| g4720 | $1.03 \times 10^8$ | $1.36 \times 10^9$ | $9.70 \times 10^{10}$ |
| g22437 | $1.94 \times 10^8$ | $8.22 \times 10^9$ | $1.53 \times 10^{11}$ |
| g7124 | $5.22 \times 10^8$ | $4.97 \times 10^9$ | $3.66 \times 10^{11}$ |
| g8993 | $7.36 \times 10^8$ | $9.10 \times 10^9$ | $5.80 \times 10^{11}$ |
| g5664 | $9.44 \times 10^8$ | $7.29 \times 10^9$ | $4.77 \times 10^{11}$ |
| g21647 | $1.18 \times 10^9$ | $1.01 \times 10^{10}$ | $7.44 \times 10^{11}$ |
| g422 | $1.51 \times 10^9$ | $1.24 \times 10^{10}$ | $7.62 \times 10^{11}$ |
| g28547 | $1.59 \times 10^9$ | $1.67 \times 10^{10}$ | $9.85 \times 10^{11}$ |
| g1536 | $1.86 \times 10^9$ | $1.04 \times 10^{11}$ | $6.49 \times 10^{11}$ |
| g24334 | $2.55 \times 10^9$ | $1.53 \times 10^{11}$ | $1.02 \times 10^{12}$ |
| g3021 | $3.63 \times 10^9$ | $1.51 \times 10^{11}$ | $9.78 \times 10^{11}$ |
| g19195 | $7.15 \times 10^9$ | $9.34 \times 10^{10}$ | $1.01 \times 10^{12}$ |
| g22437 | $9.03 \times 10^9$ | $7.31 \times 10^{10}$ | $8.52 \times 10^{11}$ |
| g22795 | $1.06 \times 10^{11}$ | $4.55 \times 10^{10}$ | $8.52 \times 10^{11}$ |
| g15784 | $1.30 \times 10^{11}$ | $1.14 \times 10^{11}$ | $1.31 \times 10^{12}$ |
| g4720 | $1.42 \times 10^{11}$ | $5.51 \times 10^{10}$ | $1.02 \times 10^{12}$ |
| g145 | $1.50 \times 10^{11}$ | $8.09 \times 10^{10}$ | $1.19 \times 10^{12}$ |
| g25271 | $1.56 \times 10^{11}$ | $7.87 \times 10^{10}$ | $1.25 \times 10^{12}$ |
| g27491 | $1.88 \times 10^{11}$ | $2.08 \times 10^{11}$ | $2.14 \times 10^{12}$ |
| g15807 | $2.14 \times 10^{11}$ | $1.75 \times 10^{11}$ | $2.03 \times 10^{12}$ |

Note. All masses are in solar masses. Subscript 0 denotes the central galaxy.
particles in the halo on those particles within the annulus. Only the in-plane component of the acceleration was used, to better follow McGaugh et al. (2016). For $g_{\text{obs}}$ (the observed acceleration), all particles (gas, stars, and DM) within the simulation were used. To calculate $g_{\text{bar}}$, we simply calculate the contributions from stars and gas, $g_*$ and $g_{\text{gas}}$, so that $g_{\text{bar}} = g_* + g_{\text{gas}}$. For each of $g_*$ and $g_{\text{gas}}$, we use a direct summation only on those particles (stars and gas, respectively). This process of direct summation to calculate gravity is equivalent to the numerical solution to Poisson’s equation used in McGaugh et al. (2016). The mass model in SPARC (Lelli et al. 2016a) included stellar masses estimated from 3.6 μm near-infrared observations and gas masses estimated using 21 cm observations of HI. These HI masses were converted to total gas masses using the simple equation $M_{\text{gas}} = 1.33M_{\text{HI}}$. Rather than using the total gas mass from our simulations, we follow the HI-based estimate from SPARC by calculating accelerations due to gas using $1.33M_{\text{HI}}$, rather than $M_{\text{gas}}$. This is especially important near the outskirts of the galaxy, where the contribution to the baryonic mass from ionized gas in the ISM and circumgalactic medium is most significant. The HI fraction is calculated using the radiative cooling code within GASOLINE, which relies on tabulated equilibrium cooling rates from CLOUDY (Ferland et al. 2013).

3. Results

3.1. $z = 0$ Acceleration Relation

The MUGS2 sample gives us 2100 acceleration data points, just over 3/4 the sample size of McGaugh et al. (2016). Figure 1 shows the $g_{\text{obs}} - g_{\text{bar}}$ relation for the MUGS2 sample, compared both to the pure baryonic acceleration and the RAR. It is clear these simulated galaxies follow the McGaugh et al. (2016) relation extremely well. As can be seen from the inset residual distribution, our simulated galaxies follow the SPARC RAR even more tightly than the actual observational data. The scatter in our results, with $\sigma = 0.06$ dex, is consistent with the McGaugh et al. (2016) estimates. They decomposed their scatter of 0.11 dex into different sources, and when all of the observational uncertainties are removed, the remaining intrinsic scatter gives a variance of $\sigma = 0.06$ dex, very close to the value presented here here. A reduced $\chi^2$ statistic of the SPARC relation fit to the $z = 0$ MUGS2 data finds a very good fit, with $\chi^2 = 1.25$. These simulation data are fit by Equation (1) at least as well as the original SPARC data.

3.2. Feedback and the Evolution of the Acceleration Relation

If the SPARC acceleration relation is in fact due to new physics, it would be surprising if the relation did not hold at all redshifts. This would not be the case if the relation was simply a consequence of galaxy evolution. In Figure 2, we show that the acceleration relation in the MUGS2 sample actually shows significant redshift dependence, and only settles to the Equation (1) relation near $z = 0$. For these data points, we scaled the thickness of the annuli by the cosmic scale factor $a$, so that $\delta r = 300/(1 + z)$ pc. This scaling ensures we are sampling primarily from the stellar disk, and not well beyond it. Omitting this scaling has little effect on these results, save for extending the points to very low values of $g_{\text{bar}}$ and removing points from the high $g_{\text{bar}}$ end. This evolution is a consequence of the huge impact that stellar feedback has on galaxies at $z \sim 2$. Keller et al. (2015) showed that SNe drive hot outflows from high-redshift galaxies with mass loadings of $M_{\text{out}}/M_* \sim 10$. This leads to disks at high redshift with baryon fractions depleted relative to those at low redshift. This feedback effect is clear when a single galaxy, g1536, is compared to the same galaxy simulated without SNe feedback. As Figure 3 shows, the redshift trend is nearly nonexistent without SNe feedback. Even at $z = 2$, the galaxy without feedback falls within the scatter of the SPARC observations, and within the scatter of the $z = 0$ MUGS2 relation. This tells us that we need not invoke feedback processes to explain the $z = 0$ SPARC RAR. Simple dissipational collapse of gas is...
sufficient to produce a similar relation. The evolution as a function of redshift is therefore dominated primarily by the stronger effect of feedback at higher redshift.

4. Discussion

This Letter is the first work to show that the RAR’s acceleration scale and tight scatter, as reported by McGaugh et al. (2016), can arise from fully self-consistent hydrodynamical simulations.

Efforts have been made in the past to explain related acceleration relations (the MDAR; the Baryonic Tully–Fisher, BTFR; McGaugh et al. 2000, etc.) with analytic arguments (van den Bosch & Dalcanton 2000; Kaplinghat & Turner 2002), existing scaling relations (Di Cintio & Lelli 2016), or hydrodynamical simulations (Santos-Santos et al. 2016). Analytic studies have found that the MOND-like scaling relations can arise as a consequence of exponential disks living within an NFW halo (van den Bosch & Dalcanton 2000), van den Bosch & Dalcanton (2000) showed that this can explain not only Tully–Fisher relation’s relatively tight scaling over a large range of masses and surface densities (McGaugh & de Blok 1998), but even explain the appearance of a characteristic acceleration in disk galaxy rotation curves (McGaugh 1999).

Subsequent studies have suggested that an even harder constraint for ΛCDM to match is the tight scatter in the MDAR (Wu & Kroupa 2015) or the RAR (Milgrom 2016). A semi-empirical model recently published by Di Cintio & Lelli (2016) showed that both the BTFR and the MDAR can arise as a result of galaxies that follow a handful of scaling relations both for the baryonic content of the galaxy, as well as the DM halo it resided within. Both their model matches to the MDAR and the BTFR did show slightly higher scatter than the Lelli et al. (2016b) observations (0.17 versus 0.11 (0.06 intrinsic) dex), which they suggest may be a result of the BTFR’s sensitivity to measuring radius.

The BTFR and MDAR were also examined using galaxies from the MaGICC (Stinson et al. 2013) and CLUES (Gottloeber et al. 2010) simulations by Santos-Santos et al. (2016). Their results also showed similar scatter to the MDAR reported in McGaugh (2014), with a scatter of σ ∼ 0.3 dex. This is significantly higher than the intrinsic scatter of 0.06 dex reported in McGaugh et al. (2016). This may be due to the use of a sample composed of simulations run using different subgrid physics prescriptions, which will naturally differ from one another. While matching the scatter of previous observations, which suffered from much higher observational uncertainties, matching both the fitting function and small intrinsic scatter of McGaugh et al. (2016) has never been done prior to this study.

Concurrently with the work presented here, Ludlow et al. (2016) presented a study using simulations from the EAGLE (Schaye et al. 2015) and APOSTLE (Sawala et al. 2016) projects. EAGLE and APOSTLE use a common set of subgrid physics. They found their simulations were fit well by McGaugh et al. (2016) functional form of the RAR with $g_s = 3 \times 10^{-10}$ m s$^{-2}$ (well outside the uncertainties reported in McGaugh et al. 2016 for the value of $g_s$). They also found that the $z = 0$ relation is only somewhat sensitive to the subgrid physics model (as we have found as well). The fact that their $g_s$ is larger than ours mean EAGLE galaxies are somewhat baryon-depleted compared to ours. This, coupled with the lack of redshift evolution, suggests that the EAGLE feedback model drives stronger outflows at low redshift compared to the superbubble model used in MUGS2.

The EAGLE subgrid physics model is complex and involves a number of different purely numerical parameters that were tuned to reproduce the observed stellar mass to halo mass relation (SMHMR) and size–mass relation, the details of which can be found in Crain et al. (2015). MUGS2 instead used a well-constrained, physically motivated model for SN feedback (Keller et al. 2014), with no free parameters beyond the energy available per SNe, and which captures the effects of thermal evaporation that are ignored in EAGLE. This allows us to better capture the real variation that occurs in the efficiency of outflows over cosmic time (Keller et al. 2015; Muratov et al. 2015). Perhaps the clearest conclusion that can be drawn from the results of this paper and those of Ludlow et al. (2016) is that the scatter in the RAR will be fairly small regardless of the details of baryonic process like cooling, star formation, and feedback. However, the actual value of $g_s$ is sensitive to these details, and the RAR may therefore be a useful new tool for constraining subgrid physics in galaxy simulations.

5. Conclusion

We have shown here that the SPARC RAR can be produced by conventional galaxy formation in a ΛCDM universe. While we have used a pre-existing set of simulations, MUGS2, we expect a larger sample designed to match SPARC should find similar results. Neither the particular functional form (Equation (1)) nor the small scatter about this relation requires anything beyond the dissipational collapse of baryons in a DM halo. We predict the fit observed at $z = 0$ will not hold at all redshifts: vigorous feedback at high redshift acts to scour protogalaxies of their baryons, reducing the baryon fraction of

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1. While this number is not reported in McGaugh (2014), we have confirmed this value with Dr. McGaugh in a private communication.
the disk, flattening the $g_{\text{obs}} - g_{\text{bar}}$ relation. Stellar feedback is an essential process if we are to produce realistic galaxies. In order for a single RAR to hold at all redshifts, feedback efficiencies would have to be so low as to produce galaxies with stellar masses and bulge fractions in conflict with the observed SMHMR, and the observed kinematics of local galaxies. If one wished to use Equation (1) to fit galaxies at all epochs, $g_i$ would need to have a significant redshift dependence. If, on the other hand, high-redshift observations of the $g_{\text{obs}} - g_{\text{bar}}$ relation found no evolution in shape, or a steeper slope at low $g_{\text{bar}}$, this would in fact constitute a serious disagreement with $\Lambda$CDM, as it would be difficult to produce the observed low cosmic star formation efficiency without strong outflows removing baryons from high-redshift disks.

As Figure 3 shows, the $z = 0$ SPARC relation is not a result of stellar feedback. While feedback does change the relationship at high redshift, its general form is reproduced by simple gas collapse and radiative cooling. This is one of the few apparent problems in $\Lambda$CDM that does not require feedback for its resolution!

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References

Aprile, E., Alfonsi, M., Arisaka, K., et al. 2012, PhRvL, 109, 181301
Bekenstein, J. D. 2004, PhRvD, 70, 083509
Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Natur, 311, 517
Boylan-Kolchin, M., Bullock, J. S., & Kaplinghat, M. 2011, MNRAS, 415, L40
Crain, R. A., Schaye, J., Bower, R. G., et al. 2015, MNRAS, 450, 1937
Di Cintio, A., & Lelli, F. 2016, MNRAS, 456, L127
Ferland, G. J., Porter, R. L., van Hoof, P. A. M., et al. 2013, RMxAA, 49, 137
Gottloeber, S., Hoffman, Y., & Yepes, G. 2010, arXiv:1005.2687
Joshi, G. D., Parker, L. C., & Wadsley, J. 2016, MNRAS, 462, 761
Kaplinghat, M., & Turner, M. 2002, ApJL, 569, L19
Keller, B. W., Wadsley, J., Benincasa, S. M., & Couchman, H. M. P. 2014, MNRAS, 442, 3013
Keller, B. W., Wadsley, J., & Couchman, H. M. P. 2015, MNRAS, 453, 3499
Keller, B. W., Wadsley, J., & Couchman, H. M. P. 2016, MNRAS, 463, 1431
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Knollmann, S. R., & Knebe, A. 2009, ApJS, 182, 608
Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016a, ApJ, 152, 157
Lelli, F., McGaugh, S. S., & Schombert, J. M. 2016b, ApJL, 816, L14
Ludlow, A. D., Benitez-Llambay, A., Schaller, M., et al. 2016, PhRvL, submitted (arXiv:1610.07663)
Mashchenko, S., Couchman, H. M. P., & Wadsley, J. 2006, Natur, 442, 539
McGaugh, S. 1999, in ASP Conf. Ser. 182, Galaxy Dynamics—A Rutgers Symp., ed. D. R. Merritt, M. Valluri, & J. A. Sellwood (San Francisco, CA: ASP), 528
McGaugh, S. 2014, Galax, 2, 601
McGaugh, S., Lelli, F., & Schombert, J. 2016, PhRvL, 117, 201101
McGaugh, S. S. 2004, ApJ, 609, 652
McGaugh, S. S., & de Blok, W. J. G. 1998, ApJ, 499, 41
McGaugh, S. S., Schombert, J. M., Bothun, G. D., & de Blok, W. J. G. 2000, ApJ, 533, L99
Milgrom, M. 1983, ApJ, 270, 371
Milgrom, M. 2016, arXiv:1609.06642
Muratov, A. L., Kereš, D., Faucher-Giguère, C.-A., et al. 2015, MNRAS, 454, 2691
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Pontzen, A., & Governato, F. 2012, MNRAS, 421, 3464
Power, C., Navarro, J. F., Jenkins, A., et al. 2003, MNRAS, 338, 14
Rubin, V. C., & Ford, W. K., Jr. 1970, ApJ, 159, 379
Sancisi, R. 2004, in IAU Symp. 220, Dark Matter in Galaxies, ed. S. Ryder et al. (San Francisco, CA: ASP), 233
Santos-Santos, I. M., Brook, C. B., Stinson, G., et al. 2016, MNRAS, 455, 476
Sawala, T., Frenk, C. S., Fattahi, A., et al. 2016, MNRAS, 457, 1931
Schaye, J., Crain, R. A., Bower, R. G., et al. 2015, MNRAS, 446, 521
Shen, S., Wadsley, J., & Stinson, G. 2010, MNRAS, 407, 1581
Stinson, G. S., Bailin, J., Couchman, H., et al. 2010, MNRAS, 408, 812
Stinson, G. S., Brook, C., Macciò, A. V., et al. 2013, MNRAS, 428, 129
van den Bosch, F. C., & Dalcanton, J. J. 2000, ApJ, 543, 146
Wadsley, J. W., Stadel, J., & Quinn, T. 2004, NewA, 9, 137
Walker, M. G., & Penarrubia, J. 2011, ApJ, 742, 20
Walker, T. P., Steigman, G., Kang, H.-S., Schramm, D. M., & Olive, K. A. 1991, ApJ, 376, 51
Wu, X., & Kroupa, P. 2015, MNRAS, 446, 330
Zwicky, F. 1937, ApJ, 86, 217