ON THE LACK OF EVOLUTION IN GALAXY STAR FORMATION EFFICIENCY

PETER S. BEHROOZI1, RISA H. WECHSLER1, AND CHARLIE CONROY2

1 Kavli Institute for Particle Astrophysics and Cosmology, Department of Particle Physics and Astrophysics, Physics Department, SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94305, USA
2 Department of Astronomy and Astrophysics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA

Received 2012 September 15; accepted 2012 December 7; published 2012 December 20

ABSTRACT

Using reconstructed galaxy star formation histories, we calculate the instantaneous efficiency of galaxy star formation (i.e., the star formation rate divided by the baryon accretion rate) from \( z = 8 \) to the present day. This efficiency exhibits a clear peak near a characteristic halo mass of \( 10^{11.7} M_\odot \), which coincides with longstanding theoretical predictions for the mass scale relevant to virial shock heating of accreted gas. Above the characteristic halo mass, the efficiency falls off as the mass to the minus four-thirds power; below the characteristic mass, the efficiency falls off at an average scaling of mass to the two-thirds power. By comparison, the shape and normalization of the efficiency change very little since \( z = 4 \). We show that a time-independent star formation efficiency simply explains the shape of the cosmic star formation rate since \( z = 4 \) in terms of dark matter accretion rates. The rise in the cosmic star formation from early times until \( z = 2 \) is especially sensitive to galaxy formation efficiency. The mass dependence of the efficiency strongly limits where most star formation occurs, with the result that two-thirds of all star formation has occurred inside halos within a factor of three of the characteristic mass, a range that includes the mass of the Milky Way.

Key words: dark matter – galaxies: abundances – galaxies: evolution

Online-only material: color figures

1. INTRODUCTION

Theorists have long predicted that galaxy formation is most efficient near a mass of \( \sim 10^{12} M_\odot \) based on analyses of supernova feedback, cooling times, and galaxy number counts (Silk 1977; Rees & Ostriker 1977; Dekel & Silk 1986; White & Rees 1978; Blumenthal et al. 1984). More recently, hydrodynamical simulations have indicated that the host dark matter halo mass strongly influences gas accretion onto galaxies (Birnboim & Dekel 2003; Kereš et al. 2005; Dekel & Birnboim 2006). For low halo masses, these simulations predict that gas accretes in cold filaments (“cold-mode accretion”) directly to the galaxy disk, efficiently forming stars. Above a transition halo mass of \( 10^{11}-10^{11.5} M_\odot \) (which is predicted to be redshift-independent for \( z < 3 \)), a shock develops at the virial radius which heats accreting gas (“hot-mode accretion”) and rapidly quenches star formation (Dekel & Birnboim 2006).

To test these predictions, we use previously generated statistical reconstructions of the galaxy–halo connection for all observable galaxies (Behroozi et al. 2012) to compare the average star formation rate (SFR) in galaxies to the average baryon accretion rate as a function of halo mass and time. This approach allows us to directly test for a characteristic mass scale in the efficiency of star formation in halos. We summarize the reconstruction method in Section 2, present our main results in Section 3, and conclude in Section 4. Throughout this work, we assume a Chabrier (2003) initial mass function, the Bruzual & Charlot (2003) stellar population synthesis model, and the dust model in Blanton & Roweis (2007). We additionally assume a flat, ΛCDM cosmology with parameters \( \Omega_M = 0.27 \), \( \Omega_\Lambda = 0.73 \), \( h = 0.7 \), \( n_s = 0.95 \), and \( \sigma_8 = 0.82 \).

2. STATISTICAL RECONSTRUCTIONS

To summarize our reconstruction technique (fully detailed in Behroozi et al. 2012), we link galaxies observed at different redshifts to halos in a dark matter simulation using an extremely flexible parameterization for the stellar mass–halo mass relation over cosmic time (\( SM(M, z) \)).3 Any choice of \( SM(M, z) \), applied to halo merger trees, will result in predictions for the galaxy stellar mass function, average specific SFRs of galaxies, and the cosmic SFR. We use a Markov Chain Monte Carlo method to constrain \( SM(M, z) \) to match observations of these quantities from \( z = 8 \) to \( z = 0 \). We calculate uncertainties from a wide range of statistical and systematic effects (including uncertainties from stellar population synthesis models, dust models, stellar population history models, the faint-end slope of the stellar mass function, scatter between stellar mass and halo mass, etc.; see Behroozi et al. 2010, 2012), mitigating potential biases from, e.g., limited observational constraints at high redshifts. Alternate initial mass functions are not modeled; these would primarily cause uniform normalization shifts in stellar masses and SFRs, which would not affect our conclusions. We use free priors on the functional form of \( SM(M, z) \), but we require non-negative SFRs in all galaxies, and we require that the stellar mass to halo mass ratio is always less than the cosmic baryon fraction.

We combine observational constraints from over 40 recent papers (see Behroozi et al. 2012 for a full list). These include results from the Sloan Digital Sky Survey and from PRIMUS (Moustakas et al. 2012), which self-consistently recover stellar mass functions from \( z = 1 \) to \( z = 0 \) over a wide area of the sky. At high redshifts, we include recent measurements of stellar masses and SFRs to \( z = 8 \) (Bouwens et al. 2011, 2012; McLure et al. 2011; Bradley et al. 2012). Notably, measurements of the cosmic SFR now agree with the evolution of the stellar mass to halo mass relation over wide redshift ranges (SM(\( M, z \)), which coincides with longstanding theoretical predictions for the mass scale relevant to virial shock heating of accreted gas. Above the characteristic halo mass, the efficiency falls off as the mass to the minus four-thirds power; below the characteristic mass, the efficiency falls off at an average scaling of mass to the two-thirds power. By comparison, the shape and normalization of the efficiency change very little since \( z = 4 \). We show that a time-independent star formation efficiency simply explains the shape of the cosmic star formation rate since \( z = 4 \) in terms of dark matter accretion rates. The rise in the cosmic star formation from early times until \( z = 2 \) is especially sensitive to galaxy formation efficiency. The mass dependence of the efficiency strongly limits where most star formation occurs, with the result that two-thirds of all star formation has occurred inside halos within a factor of three of the characteristic mass, a range that includes the mass of the Milky Way.

We combine observational constraints from over 40 recent papers (see Behroozi et al. 2012 for a full list). These include results from the Sloan Digital Sky Survey and from PRIMUS (Moustakas et al. 2012), which self-consistently recover stellar mass functions from \( z = 1 \) to \( z = 0 \) over a wide area of the sky. At high redshifts, we include recent measurements of stellar masses and SFRs to \( z = 8 \) (Bouwens et al. 2011, 2012; McLure et al. 2011; Bradley et al. 2012). Notably, measurements of the cosmic SFR now agree with the evolution of the stellar mass

---

3 Six parameters control the relation at \( z = 0 \) (a characteristic stellar mass, a characteristic halo mass, a faint-end slope, a massive-end shape, a transition region shape, and the scatter in stellar mass at fixed halo mass); for each of these parameters, two more variables control the evolution to intermediate (\( \sim 1 \)) and high (\( \geq 3 \)) redshifts.
3. RESULTS

3.1. Strong Mass Dependence for the Star Formation Efficiency

We show the main output of the method in Behroozi et al. (2012), the average SFR in dark matter halos as a function of virial mass (Bryan & Norman 1998) and time, in the top-left panel of Figure 1. The SFR depends strongly on time, yet there is also a distinct halo mass threshold, as may be seen by normalizing to the maximum SFR as a function of time (Figure 1, top-right panel). To understand the implications for gas physics in halos, it is necessary to consider the baryon accretion rate as well. We calculate this as the dark matter halo mass accretion rate (Behroozi et al. 2012) times the cosmic baryon fraction; see van de Voort et al. (2011) for a comparison with hydrodynamical simulations.

The baryon accretion rate increases with halo mass and lookback time, as shown in Figure 1, middle-left panel. This trend combines with trends in the SFR to reveal a clear picture of star formation efficiency (SFE) in halos (Figure 1, bottom panel). This efficiency, defined as the SFR divided by the baryon accretion rate, shows a prominent maximum near a characteristic mass of $10^{11.7} M_{\odot}$ (see also Figure 2). Indeed, the SFE over 90% of the history of the universe ($z < 4$) is strongly dependent on halo mass; by comparison, it has a weak dependence on time.

The peak in the SFE at $10^{11.7} M_{\odot}$ represents observationally constrained evidence for a characteristic mass for galaxy formation. This characteristic mass matches longstanding theoretical predictions in both its value and in its lack of evolution since $z = 3 - 4$. The steep efficiency cutoff above the characteristic mass (SFE $\propto M_b^{-4/3}$, where $M_b$ is halo mass) suggests that a strong physical mechanism prevents incoming gas from reaching galaxies in massive halos. Besides the effect of hot-mode accretion, this slope coincides with the mass and luminosity scaling for supermassive black holes ($L_{\text{BH}} \propto M_{\text{BH}}$; scalings for $M_{\text{BH}}$ vary from $M_{\text{BH}} \propto \sigma^4 \propto M_b^{5/3}$ to $M_{\text{BH}} \propto \sigma^5 \propto M_b^{2/3}$; Ferrarese & Merritt 2000; McConnell et al. 2011), which may prevent residual cooling flows in massive clusters from forming stars. Below the characteristic mass, the efficiency is not a perfect power law; between $M_b \sim 10^{10}$ and $\sim 10^{11.5} M_{\odot}$, the average slope is SFE $\propto M_b^{-2/3}$. This may seem to be consistent with semi-analytic galaxy formation models that use supernova feedback (most commonly scaling as $V_{\text{circ}} \propto M_b^{2/3}$; Hatton et al. 2003; Somerville et al. 2008; Lu et al. 2012) to expel most of the gas in low-mass halos. However, these models often assume that the expelled gas re-accretes onto the halo after a dynamical time (Lu et al. 2011); this extra incoming gas would result in a steeper mass dependence for the SFE at low halo masses.

3.2. Weak Time Dependence of the Star Formation Efficiency

The weak time dependence of the SFE is unexpected given the different environments of $10^{11.7} M_{\odot}$ halos at $z = 4$ and $z = 0$. At $z = 4$, the background matter density was $\sim 125$ times higher, mass accretion rates were $\sim 40$ times higher, galaxy–galaxy merger rates were $\sim 20$ times higher, and the UV background from star formation was $\sim 500$ times more intense than at the present day (Behroozi et al. 2012). None of these differences significantly influenced average SFE (unless they conspired to cancel each other out), strongly constraining possible physical mechanisms for star formation in galaxies and halos.

While the time dependence of the SFE is weak, it is not absent. As seen in Figure 1, the characteristic halo mass evolves from a peak of $10^{12} M_{\odot}$ at $z = 3$ to $10^{11.5} M_{\odot}$ at $z = 0$. The peak SFE also evolves around its average value of 0.35, reaching a maximum of 0.55 at $z = 0.8$ and a minimum of 0.22 at $z = 0$. However, observational constraints on SFRs and stellar masses are uncertain at the 0.3 dex level (Behroozi et al. 2010, 2012) especially for $z > 1$; these are larger than the observed deviations ($\pm 0.2$ dex) in the peak SFE. The variations in the characteristic mass are likely more significant; while observational biases can be stellar mass-dependent (Behroozi et al. 2012) in a way that changes the location of the peak halo mass, this effect ($< 0.1$ dex; Leauthaud et al. 2012) cannot account for the 0.5 dex change from $z = 3$ to $z = 0$. Nonetheless, these concerns do not alter the fact that the trends with mass (four decades of variation) in the SFE are stronger than the trends with time.

One way to eliminate the residual time dependence in the characteristic mass is to use a different mass definition. For example, using $M_{200b}$ (i.e., 200 times the background density) would cancel some of the evolution from $z = 1$ to $z = 0$. However, this would also raise the mass accretion rate at $z = 0$, which would increase evolution in the star formation efficiency’s normalization. Using the maximum circular velocity ($V_{\text{circ}}$) or the velocity dispersion ($\sigma$) instead would also lead to more evolution in the SFE (at fixed $V_{\text{circ}}$ or $\sigma$); due to the smaller physical dimensions of the universe at early times, both these velocities increase with redshift at fixed virial halo mass.

The nearly constant characteristic mass scale is robust to our main assumption that the baryon accretion rate is proportional to the halo mass accretion rate, because this mass scale is already present in the conditional SFE (Figure 1). A baryon accretion rate which scales nonlinearly with the dark matter accretion rate would change the width of the most efficient halo mass range, but it would not change the location. However, as discussed previously, the baryon accretion rate for small halos ($M_b < 10^{12} M_{\odot}$) can differ from the dark matter accretion rate through recooling of ejected gas; the changing virial density threshold can also introduce non-physical evolution in the halo mass which affects the accretion rate (Diemer et al. 2012). Properly accounting for these effects may change the low-mass slope of the SFE; we will investigate this in future work.

Note that the level of consistency seen in the SFE is not possible to achieve using other common specific ratios, e.g., the specific SFR (SFR to stellar mass ratio; Figure 1, middle-right panel) or the SFR to halo mass ratio. The stellar mass to halo mass ratio (i.e., the integrated formation efficiency) does show somewhat similar features (Conroy & Wechsler 2009; Behroozi et al. 2010, 2012; Yang et al. 2012; Leauthaud et al. 2012; Moster et al. 2012; Wang et al. 2012); however, the integrated efficiency is several steps removed from the actual
Figure 1. Top-left panel: star formation rate as a function of halo mass and cosmic time in units of $M_\odot$ yr$^{-1}$. The gray shaded band excludes halos not expected to exist in the observable universe. Top-right panel: conditional star formation rate as a function of halo mass and cosmic time, in units of the maximum star formation rate at a given time. Middle-left panel: baryonic mass accretion rate ($M_A$) in halos as a function of halo mass and time, in units of $M_\odot$ yr$^{-1}$. Middle-right panel: the star formation rate to stellar mass ratio, in units of yr$^{-1}$, as a function of halo mass and time. There is a roll-off toward higher halo masses; however, the normalization and characteristic mass are strongly redshift-dependent. Bottom panel: instantaneous star formation efficiency (star formation rate divided by baryonic mass accretion rate) as a function of halo mass and time.

(A color version of this figure is available in the online journal.)

physics of star formation. Galaxy stellar mass is influenced by stellar death, galaxy–galaxy mergers, and ejection of merging stellar mass into the intracluster light (Conroy & Wechsler 2009; Behroozi et al. 2012; Moster et al. 2012), complicating the interpretation of the integrated efficiency. Moreover, the shape of the integrated efficiency is influenced by star formation along the entire halo mass accretion history. Intuitively, the integrated efficiency tends to lag behind changes in the instantaneous SFE,
leading to a peak at a larger halo mass and a gentler falloff in the high-mass slope, as shown in Figure 2.

3.3. A Time-independent Model

Going further, it is interesting to approximate the SFE for individual halos as completely time-independent. In this case, the stellar mass formed at a given halo mass is

$$\text{SM} = \int_{0}^{t_{\text{final}}} \frac{f_{\text{bd}} dM_{h}}{dt} \frac{dSM}{f_{bd}dM_{h}} dt = \int_{0}^{M_{h,\text{final}}} \frac{dSM}{f_{bd}dM_{h}} f_{bd}dM_{h},$$

(1)

(where SM is the stellar mass, $M_{h}(t)$ is the halo mass accretion history, and $dSM/f_{bd}dM_{h}$ is the SFE). The total stellar mass formed then becomes a function of only the final halo mass ($M_{h,\text{final}}$) and not of time.

The specific choice of redshift for the instantaneous SFR does not matter greatly, as shown in Figure 1. We nonetheless marginalize the instantaneous SFR over time; the resulting functional form is shown in Figure 2. Using this as the time-independent efficiency, we calculate the total stars formed as a function of halo mass using Equation (1) and reduce the resulting value by 50%, corresponding to the stellar population remaining for a 6 Gyr old starburst (Conroy & Wechsler 2009). (For comparison, a 1 Gyr old starburst would have 60% of its original stars remaining.) This allows us to calculate the stellar mass to halo mass ratio, as shown in the left panel of Figure 3. Similarly, we may use halo mass accretion rates and number densities along with the same SFE to calculate the cosmic SFR (Figure 3, right panel).

The real universe is more complicated, of course; the stellar mass–halo mass relation must evolve weakly to accurately reproduce galaxy number counts (Conroy & Wechsler 2009; Moster et al. 2010, 2012; Behroozi et al. 2010, 2012; Leauthaud et al. 2012; Wang et al. 2012). However, integrating a time-independent SFE with respect to halo mass reproduces the $z = 0$ stellar–halo mass relation to within observational systematics over nearly five decades in halo mass ($10^{10}$–$10^{15} M_\odot$). Similarly, integrating the SFE times the mass accretion rate and number density of halos gives a precise match to the observed cosmic SFR from $z \sim 4$ to the present.

Furthermore, the prediction in time-independent SFE models of fixed stellar mass formed at a given halo mass is not far off from observational constraints at $z = 0$ (0.2 dex scatter in stellar mass at fixed halo mass; Reddick et al. 2012). The evolution in the median stellar mass–halo mass relation with time, corresponding to an evolution in the SFE, may then set a lower bound on the scatter in stellar mass at fixed halo mass at the present day. Conversely, the scatter in stellar mass at fixed halo mass today sets an upper bound on the possible evolution of the median stellar mass to halo mass ratios at earlier times.

When considering the cosmic SFR, the time-independent efficiency model may imply more success matching galaxy formation physics than is warranted. In fact, a model with an SFE of 7% independent of halo mass or time also matches the decline
in cosmic SFRs (Figure 3, right panel), but would not match the stellar mass to halo mass ratio or galaxy number counts. For that reason, the decline in the cosmic SFR since $z = 2$ is more related to declining dark matter accretion rates than changes in how galaxies form stars. This may explain past successes in reproducing the cosmic SFR with a variety of incompatible physical models (e.g., Hernquist & Springel 2003; Bouché et al. 2010; Krumholz & Dekel 2012; Davé et al. 2012)—the cosmic SFR for $z < 2$ alone is a poor discriminant between models. That said, the rise in the cosmic SFR from early times to $z = 2$ is much steeper than a mass-independent efficiency model predicts. Matching this rise is much more closely tied to galaxy formation physics, as it requires an increase in the average SFE with time. In the mass-dependent model, this is provided by an increasing number of halos reaching the characteristic mass.

3.4. Consequences for When and Where Stars Were Formed

The SFE leaves a distinct imprint on the star formation history of the universe: as halos pass through the characteristic mass ($10^{11.7} M_{\odot}$), they form most of their stars. Equivalently, most stars were formed in halos between $10^{11.5} M_{\odot}$ and $10^{12.2} M_{\odot}$ (Figure 4, left panel). Furthermore, because of the tight correlation between stellar mass and halo mass, most stars formed in galaxies with stellar masses between $10^{9.9}$ and $10^{10.8} M_{\odot}$ (Figure 4, right panel). This same narrow range of halo and stellar masses (which includes the stellar and halo masses of the Milky Way; Klypin et al. 2002; Flynn et al. 2006; Smith et al. 2007; Busha et al. 2011) is responsible for most star formation since at least $z = 4$, due to the constancy of the SFE with time. Given current observational limits (Figure 4, right panel), surveys have probed a stellar mass and redshift range corresponding to 90% of the star formation in the Universe.

4. CONCLUSIONS

As we have shown, the ratio of star formation to baryon accretion in galaxies falls off strongly on either side of a characteristic halo mass and appears to be only weakly correlated with time and environment. This would suggest a model for galaxy formation in which self-regulation after $z \sim 4$ is nearly perfectly efficient and is controlled by effects that correlate largely with the local gravitational potential: supernova feedback (Dekel & Silk 1986) and possibly metallicity effects (Krumholz & Dekel 2012) limit galaxy growth in low-mass halos, and hot-mode accretion as well as black hole feedback (Silk & Rees 1998) limit growth in high-mass halos. Quantitative understanding of how these and other physical feedback effects act to shape observed galaxy formation efficiency will remain a challenge for future research.

Support for this work was provided by an HST Theory grant; program number HST-AR-12159.01-A was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Incorporated, under NASA contract NAS5-26555. This research was also supported in part by the National Science Foundation under Grant No. NSF PHY11-25915, through a grant to KITP during the workshop “First Galaxies and Faint Dwarfs.” We thank Yu Lu, Tom Abel, James Bullock, Louis Strigari, Sandy Faber, Ari Maller, Surhud More, and Joel Primack for insightful discussions during the preparation of this work.

REFERENCES

Behroozi, P. S., Conroy, C., & Wechsler, R. H. 2010, ApJ, 717, 379
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2012, arXiv:1207.6105
Behroozi, P. S., Wechsler, R. H., & Wu, H.-Y. 2011, ApJ, 762, 109
Behroozi, P. S., Wechsler, R. H., Wu, H.-Y., et al. 2013, ApJ, in press (arXiv:1110.4370)
Bernardi, M., Shankar, F., Hyde, J. B., et al. 2010, MNRAS, 404, 2087
Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734
Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Natur, 311, 517
Bouché, N., Dekel, A., Genzel, R., Genel, S., et al. 2010, ApJ, 718, 1001
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2011, ApJ, 737, 90
Bouwens, R. J., Illingworth, G. D., Oesch, P. A., et al. 2012, ApJ, 754, 83
Bradley, L. D., Trenti, M., Oesch, P. A., et al. 2012, ApJ, 760, 108
Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000
Bryan, G. L., & Norman, M. L. 1998, ApJ, 495, 80
Busha, M. T., Marshall, P. J., Wechsler, R. H., Klypin, A., & Primack, J. 2011, ApJ, 743, 40
Chabrier, G. 2003, PASP, 115, 763
Conroy, C., & Wechsler, R. H. 2009, ApJ, 696, 620
Davé, R., Finlator, K., & Oppenheimer, B. D. 2012, MNRAS, 421, 98
Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2
Dekel, A., & Silk, J. 1986, ApJ, 303, 39
Diemer, B., More, S., & Kravtsov, A. 2012, arXiv:1207.0816
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, 9
Flynn, C., Holmberg, J., Portinari, L., Fuchs, B., & Jahreiß, H. 2006, MNRAS, 372, 1149
Hatton, S., Devriendt, J. E. G., Ninin, S., et al. 2003, MNRAS, 343, 75
Hernquist, L., & Springel, V. 2003, MNRAS, 341, 1253
Kereš, D., Katz, N., Weinberg, D. H., & Davé, R. 2005, MNRAS, 363, 2
Klypin, A., Zhao, H., & Somerville, R. S. 2002, ApJ, 573, 597
Klypin, A. A., Trujillo-Gomez, S., & Primack, J. 2011, ApJ, 740, 102
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Kravtsov, A., & Klypin, A. 1999, ApJ, 520, 437
Kravtsov, A. V., Klypin, A. A., & Khokhlov, A. M. 1997, ApJ, 111, 73
Krumholz, M. R., & Dekel, A. 2012, ApJ, 753, 16
Leauthaud, A., Tinker, J., Bundy, K., et al. 2012, ApJ, 744, 159
Lu, Y., Kereš, D., Katz, N., et al. 2011, MNRAS, 416, 660
Lu, Y., Mo, H. J., Katz, N., & Weinberg, M. D. 2012, MNRAS, 421, 1779
McConnell, N. J., Ma, C.-P., Gebhardt, K., et al. 2011, Nat, 480, 215
McLure, R. J., Dunlop, J. S., de Ravel, L., et al. 2011, MNRAS, 418, 2074
Moster, B. P., Naab, T., & White, S. D. M. 2012, MNRAS, 261
Moster, B. P., Somerville, R. S., Maulbetsch, C., et al. 2010, ApJ, 710, 903
Moustakas, J., et al. 2012, ApJ, submitted
Reddick, R. M., Wechsler, R. H., Tinker, J. L., & Behroozi, P. S. 2012, arXiv:1207.2160
Rees, M. J., & Ostriker, J. P. 1977, MNRAS, 179, 541
Silk, J. 1977, ApJ, 211, 638
Silk, J., & Rees, M. J. 1998, A&A, 331, L1
Smith, M. C., Ruchti, G. R., Helmi, A., et al. 2007, MNRAS, 379, 755
Somerville, R. S., Hopkins, P. F., Cox, T. J., Robertson, B. E., & Hernquist, L. 2008, MNRAS, 391, 481
van de Voort, F., Schaye, J., Booth, C. M., Haas, M. R., & Dalla Vecchia, C. 2011, MNRAS, 414, 2458
Wang, L., Farrah, D., Oliver, S. J., et al. 2012, arXiv:1203.5828
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Yang, X., Mo, H. J., van den Bosch, F. C., Zhang, Y., & Han, J. 2012, ApJ, 752, 41

The Astrophysical Journal Letters, 762:L31 (6pp), 2013 January 10

Behroozi, Wechsler, & Conroy