



## Implications of the remarkable homogeneity of galaxy groups and clusters

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# Implications of the remarkable homogeneity of galaxy groups and clusters

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## ABSTRACT

We measure the diversity of galaxy groups and clusters with mass  $M > 10^{13}h^{-1}M_{\odot}$ , in terms of the star formation history of their galaxy populations, for the purpose of constraining the mass scale at which environmentally-important processes play a role in galaxy evolution. We consider three different group catalogues, selected in different ways, with photometry and spectroscopy from the Sloan Digital Sky Survey. For each system we measure the fraction of passively-evolving galaxies within  $R_{200}$  and brighter than either  $M_r = -18$  (and with  $z < 0.05$ ) or  $M_r = -20$  (and  $z < 0.1$ ). We use the  $(u - g)$  and  $(r - i)$  galaxy colours to distinguish between star-forming and passively-evolving galaxies. By considering the binomial distribution expected from the observed number of members in each cluster, we are able to either recover the intrinsic scatter in this fraction, or put robust 95% confidence upper-limits on its value. The intrinsic standard deviation in the fraction of passive galaxies is consistent with a small value of  $\lesssim 0.1$  in most mass bins for all three samples. There is no strong trend with mass; even groups with  $M \sim 10^{13}h^{-1}M_{\odot}$  are consistent with such a small, intrinsic distribution. We compare these results with theoretical models of the accretion history to show that, if environment plays a role in transforming galaxies, such effects must occur first at mass scales far below that of rich clusters, at most  $M \sim 10^{13}M_{\odot}$ .

**Key words:** galaxies: clusters

## 1 INTRODUCTION

In the highly successful model of dark matter-dominated hierarchical galaxy formation, clusters of galaxies grow over time by accreting matter from their surroundings, with a well-defined distribution of halo masses ranging from isolated galaxies to large groups (e.g. Lacey & Cole 1994; Zhao et al. 2003; Berrier et al. 2009; McGee et al. 2009). If galaxy evolution is sensitive to the mass of the host dark matter halo, then differences in mass accretion history should be reflected in the population residing within groups and clusters (McGee et al. 2009). For example, the increase in the fraction of young galaxies in cluster cores as a function of redshift (e.g. Butcher & Oemler 1984; Margoniner et al. 2001) can be linked to a corresponding increase in infall rate (Ellingson et al. 2001; Kodama & Bower 2001; Haines et al. 2009), and the change in population with distance from the cluster centre can be used to infer a transformation timescale (e.g. Balogh et al. 2000).

Recently, McGee et al. (2009) have shown that the cluster-to-cluster scatter in galaxy populations is a potentially powerful indicator of “pre-processing” — environmentally-driven transformation that may have occurred in galaxies before they were accreted into the current structure (e.g. Zabludoff & Mulchaey 1998; Li et al. 2009). For example, if the only environmental effect on galaxies occurs at mass scales well below that of rich clusters, one

should expect a very homogeneous cluster population. On the other hand, if galaxies are transformed only once they are accreted into very massive systems, than the stochasticity of this process will lead to more diversity in present-day cluster populations. In fact, such an argument was recently invoked by Poggianti et al. (2006), who claim that an increase in diversity in groups with velocity dispersions below  $\sigma \sim 500\text{km/s}$  is evidence that transformations are likely occurring at those scales. However, the uncertainties on the fraction of galaxies with [OII] emission in a single system are large, and they increase with decreasing mass. Thus it is not clear whether or not the *intrinsic* scatter is such a strong function of mass.

With the advent of very large surveys of nearby galaxies, the populations of galaxy groups and clusters and their correlations with mass, X-ray properties and redshift are fairly well established (e.g. Fairley et al. 2002; De Propris et al. 2004; Popesso et al. 2004; Wake et al. 2005; Weinmann et al. 2006; Aguerri et al. 2007; Finn et al. 2008; Kimm et al. 2009; Hansen et al. 2009; Barkhouse et al. 2009; Lu et al. 2009). However, relatively little attention has been given to the variation between clusters. One important exception is Popesso et al. (2007b), who analyzed 79 X-ray clusters in the Sloan Digital Sky Survey (SDSS), and find a *r.m.s.* scatter of 0.19 in the fraction of blue galaxies. However, they do not have a large enough sample to study this as a function of cluster mass, which is crucial for identifying a putative transformation scale. Furthermore,

the measured *r.m.s.* includes a contribution from the statistical uncertainties on individual measurements, and thus is an upper limit on the intrinsic variation. Very recently, Haines et al. (2009) use *Spitzer* data of 30 X-ray luminous clusters at  $z < 0.3$  to measure the fraction of strongly star-forming galaxies ( $\gtrsim 8M_{\odot}\text{yr}^{-1}$ ), and find a remarkably small intrinsic scatter, consistent with zero once the trend with redshift is accounted for.

In this paper, we revisit the issue using three different samples of galaxy clusters, based on the SDSS. Our results are consistent with those of Poggianti et al. (2006) and Popesso et al. (2007b), but we take the extra step of measuring the intrinsic cluster-to-cluster variation, and comparing this with the model predictions of McGee et al. (2009). Throughout the paper we adopt a cosmology with  $\Omega_m = 0.3$ ,  $\Omega_{\Lambda} = 0.7$ , and parameterize the Hubble constant as  $H_0 = 100h\text{km s}^{-1}\text{Mpc}^{-1}$ .

## 2 SAMPLE SELECTION

For our purposes, we require a large, homogeneous sample of galaxy groups and clusters, together with a simple, reliable and sensitive measurement of the galaxy population within them. The SDSS (York et al. 2000), with its large size, homogeneous data, and highly complete spectroscopy, is particularly well-suited to this type of study. We use data from the DR6 spectroscopic sample, making use of the NYU-VAGC of Blanton et al. (2005). The data are unbiased for  $r \leq 17.77$ , and colours and luminosities are measured from Petrosian magnitudes, k-corrected to  $z = 0.1$  using KCORRECT (Blanton & Roweis 2007). We make no correction for spectroscopic completeness; this is a small correction with little dependence on luminosity or colour (e.g. Popesso et al. 2007b), so has no impact on these results.

There are many different ways to find galaxy clusters, usually based on either galaxy position (with or without redshifts, and possibly using colour information) or X-ray emission from the intracluster plasma. The ideal sample is complete, uncontaminated, and has a reliable, observable property that can be related to the total mass of the system. For our purposes, completeness is perhaps the most critical, as this allows us to put robust upper limits on the scatter we observe. We will use three different cluster catalogues for this analysis. The first, which we call the ‘‘Halo’’ catalogue, is taken from Yang et al. (2005), who use some prior information from theory and observation to associate every galaxy with a ‘‘halo’’. The mass is then given by rank-ordering the groups by their total luminosity or stellar mass (we use the latter), and associating that with a theoretical dark matter mass function. The second catalogue, also based on optical data, is from Berlind et al. (2006). We refer to this as the ‘‘FOF’’ catalogue, as it is a traditional friends-of-friends algorithm, with parameters calibrated to match numerical simulations. Masses for these systems are calculated from their velocity dispersions, assuming virial equilibrium. Finally, we consider an X-ray selected sample of clusters, which consist of all HIFLUGCS (Reiprich & Böhringer 2002) clusters in SDSS, and C4 (Miller et al. 2005) clusters cross-correlated with the *ROSAT* catalogue. For clusters in the HIFLUGCS sample, we use the masses measured by Reiprich & Böhringer (2002), under the assumption of hydrostatic, isothermal gas; these have typical uncertainties of 10–30 per cent. For the C4 clusters, we use the  $M - L_x$  relation of Reiprich & Böhringer (2002) to convert *ROSAT* luminosities to mass.

Galaxy properties are known to correlate strongly with both clustercentric radius, and the limiting luminosity or stellar mass of the galaxy sample Popesso et al. (e.g. 2007b). We will select all

galaxies<sup>1</sup> within the estimated projected virial radius  $r_{200}$ , determined from the cluster mass<sup>2</sup>. This is done in different ways for each sample. The X-ray sample uses  $r_{200}$  computed by Reiprich & Böhringer (2002) for the HIFLUGCS clusters, and the results of Popesso et al. (2007a), based on fitting a King profile to the galaxy distribution, for the *ROSAT*-matched C4 clusters. For the FOF group catalogue we calculate  $r_{200}$  from the velocity dispersions, using equation 8 in Finn et al. (2005). The masses of the Halo clusters from Yang et al. (2007) are measured by ranking the clusters by stellar mass and comparing to dark matter mass functions, but the mass calculated is for a radius with a *matter* overdensity of 180 which, for their choice of cosmology, corresponds to 43 times the critical density. Therefore their masses and radii are about 2.2 times larger than  $M_{200}$  and  $R_{200}$ , assuming a flat potential. We apply this correction to make them more comparable to the other two samples. However, we need not concern ourselves overmuch with ensuring complete consistency between samples; indeed, differences between them help show explicitly that our main conclusions are completely independent of these details. Both statistical and systematic uncertainties (e.g. projection of field galaxies along the line of sight, Popesso et al. 2007b) associated with this measurement will only lead to increase the scatter we measure; thus our upper limits will still be robust.

We will select galaxies based on luminosity, and will consider two versions of each sample. The main catalogue is limited to  $z < 0.05$ , and we use all galaxies brighter than  $M_r + 5 \log h = -18$ ; for comparison we consider a ‘‘bright’’ sample consisting of  $M_r + 5 \log h < -20$  galaxies, and including clusters out to  $z = 0.1$ . Our results on the scatter are comparable for both samples.

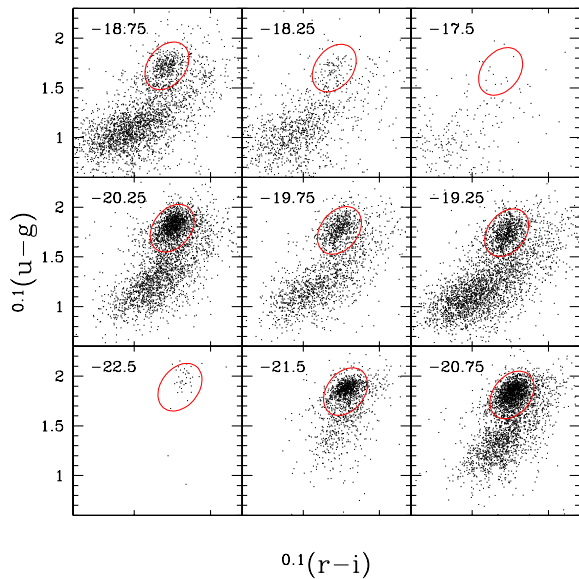
## 3 DEFINITION OF PASSIVE GALAXIES

We will take advantage of the well known fact that galaxies appear to primarily divide into two classes. One has predominantly red colours, and little star formation, while the other consists of blue and actively forming stars (e.g. Strateva et al. 2001; Baldry et al. 2004; Kimm et al. 2009; Pozzetti et al. 2009, and many others). Most simply, this distinction can be made using a colour-magnitude diagram to isolate red-sequence and blue-cloud galaxies (e.g. Baldry et al. 2004). However it is also known that a single optical colour cannot distinguish between dusty, star-forming galaxies, and truly old, passive galaxies (e.g. Popesso et al. 2007b). However, Wolf et al. (2005, 2009) have shown that this distinction can be reliably made using two colours: one bracketing the 4000Å break, and another at longer wavelengths. We show this for our full sample of SDSS galaxies, in Figure 1; each panel shows the  $(u - g)$  colour as a function of  $(r - i)$ , for galaxies within 0.1 magnitude of the  $r$ -band luminosity shown (all colours are k-corrected to  $z = 0.1$ ). The existence of two populations is remarkably clear, as is the fact that a cut in  $(u - g)$  colour alone would include galaxies from both populations.

We choose to select passive galaxies as those within the ellipse shown in Figure 1. The centre of the ellipse is a smooth function of  $M_r$ , but the orientation and size is kept fixed. These ellipses are not optimized in any rigorous way, but reasonable variations in definition have no influence on our results.

<sup>1</sup> Only clusters with full SDSS coverage at  $r < R_{200}$  are included in our analysis.

<sup>2</sup> We define  $R_{200}$  to be the radius within which the total matter density is 200 times the critical density of the Universe.



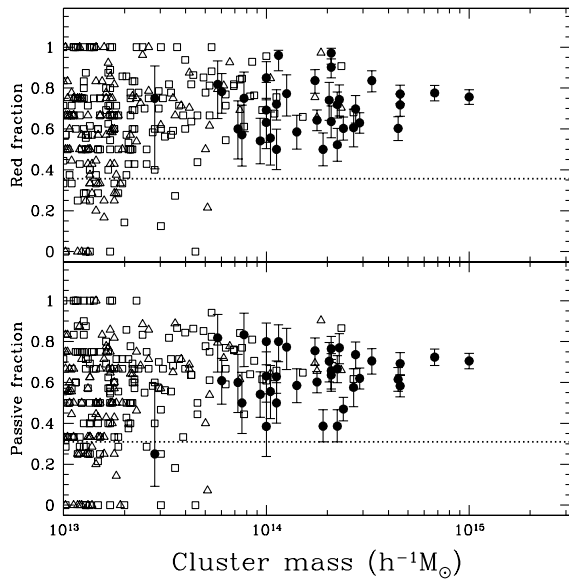
**Figure 1.** Colour-colour diagrams (k-corrected to  $z=0.1$ ) for a random subset of SDSS galaxies in our sample within 0.1 mag of the  $M_r$  magnitude indicated in the top-left corner ( $h = 1$ ). The galaxies are clearly separated into two populations, and we associate those galaxies within the red ellipses as “passive” galaxies, with little or no ongoing star formation. The ellipse is fixed in size and orientation, but the centre is a linear function of  $M_r$ .

For comparison we will also measure a simple “red fraction”, based on the  $(u - r)$  colour as a function of  $M_r$ . We fit the red sequence with a slope of  $-0.0818$ , and a colour  $(u - r) = 2.8$  at  $M_r + 5 \log h = -20$ , and choose red galaxies to be those that are up to 0.25 mag bluer than this line. Our results on the scatter of the red fraction are completely insensitive to the details of this choice.

## 4 RESULTS

In Figure 2 we show the fraction of passive galaxies in every cluster in the three catalogues, as a function of its mass, for the “main” sample ( $M_r + 5 \log h < -18$ ). Uncertainties on the fractions are computed using the full binomial distribution (Gehrels 1986). We see that both the Halo and X-ray samples of clusters are in good agreement where they overlap, despite the different selection criteria, and definitions of mass and radius. The passive fractions are systematically larger than the  $M_r + 5 \log h < -18$  sample as a whole (31%, shown as the horizontal line), on average. There is a weak trend with mass, such that the most massive clusters have larger passive fractions, on average. The passive fractions are systematically lower than the *red* fractions based only on the  $(u - r)$  colour (top panel), due to the contamination from dusty-spiral galaxies in the latter. However, the scatter from cluster-to-cluster is similar whether we consider the red or truly passive fraction.

The scatter in Figure 2 becomes very large at lower masses. This is very similar to the trends shown in Figs. 4b and Fig.6 of Poggianti et al. (2006), where they find the scatter in the fraction of galaxies with [OII]-emission increases sharply in systems with velocity dispersion below  $\sigma \sim 500$  km/s ( $M \sim 1 \times 10^{14} h^{-1} M_\odot$ ). However, the uncertainties on individual measurements are also much larger in these lower mass systems, since they have fewer



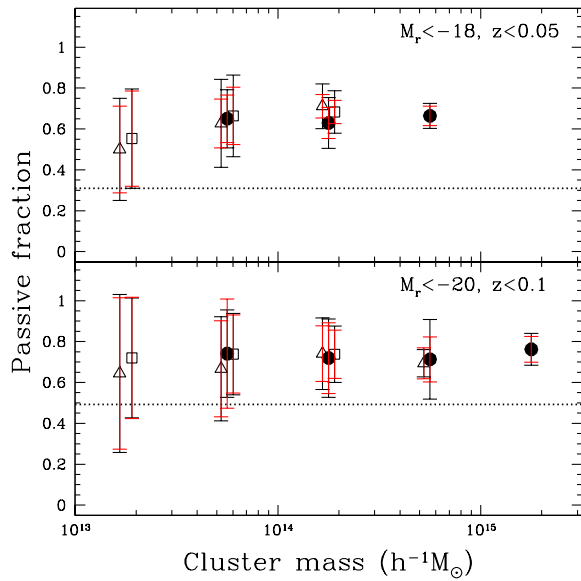
**Figure 2. Bottom panel:** The fraction of passive galaxies in each cluster within the optical Halo catalogue (Yang et al. 2005, open squares), the FOF catalogue (Berlind et al. 2006, open triangles) and the X-ray matched catalogue (filled circles). In all cases we use the main catalogue, with  $M_r + 5 \log h < -18$ . Passive galaxies are defined as those within the elliptical areas in the colour-colour diagram of Figure 1. The *dotted line* shows the passive fraction in the full SDSS sample (31%), considering  $M_r + 5 \log h < -18$  galaxies. Error bars are 68% confidence limits using the binomial probability distribution, and are shown only on the X-ray sample, for clarity; the uncertainties on individual points at low masses get very large. **Top panel:** Similar, but here we show the fraction of *red* galaxies, defined using only the  $(u - r)$  colour.

members. Our task now is to recover the intrinsic scatter from these observations.

In Figure 3 we show the average passive fraction as a function of mass, for both samples. The black “error bars” show the standard deviation in this fraction (they are not the error on the mean, which is much smaller). The red “error bars” show the standard deviation expected from statistical uncertainties alone, assuming *no* intrinsic variation. To compute this we treat the observed fraction for each cluster as randomly drawn from a binomial probability distribution defined by the number of galaxies in the cluster and with an expectation value given by the mean value in each mass bin. We neglect any error in the mean value itself, which is small.

This demonstrates that the variance in passive fraction is not much larger than expected due to the statistical uncertainties alone. The close agreement between all three samples also suggests that systematic uncertainties related to sample selection, and mass or radius definition, contribute much less to the observed variance than the statistical uncertainties.

For each mass bin we simulate the binomial distribution 10000 times, and compute the variance of each simulation. By adding in quadrature an assumed amount of intrinsic (Gaussian) variation, ranging from 0 to 0.25, we estimate the 5% and 95% confidence limits on this intrinsic scatter, and specifically the probability that it is non-zero. When the latter is greater than 95%, we measure the intrinsic scatter as the quadrature difference between the observed and predicted statistical standard deviations; otherwise, we report an upper limit. In Figure 4 we show these measurements and upper limits on the scatter, as a function of mass. Generally, the scatter is

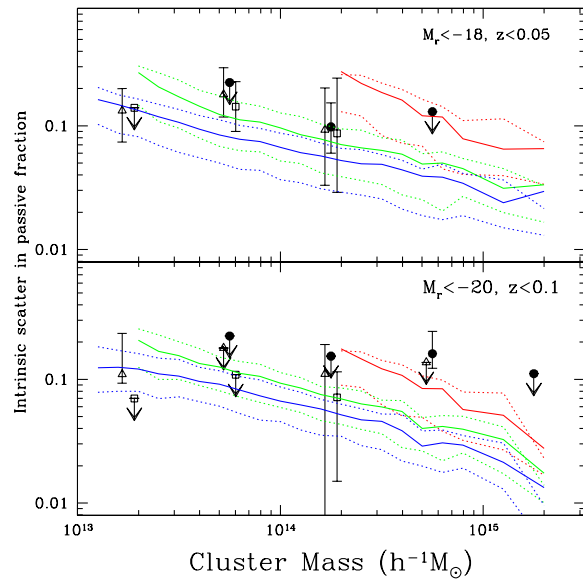


**Figure 3. Top panel:** The points show the *average* passive fraction among all clusters, in bins of equal mass; only points with at least five contributing clusters are shown. The *filled circles* represent the X-ray catalogue, while the *open squares* are the Halo catalogue of Yang et al. (2005) and the *open triangles* are the FOF catalogue of Berlind et al. (2006). Black “error bars” indicate the standard deviation within each bin (not the error on the mean). Red bars represent the standard deviation expected due to binomial sampling fluctuations alone, assuming no intrinsic scatter. The horizontal, *dotted line* indicates the passive fraction in the whole  $M_r < -18$  SDSS sample, 31%. The observed variance is typically very similar to that expected from the statistical uncertainties alone. **Bottom panel:** The same, for the  $M_r + 5 \log h < -20$  sample, which has more clusters but fewer galaxies per cluster. Here the horizontal, *dotted line* indicates the passive fraction in the brighter  $M_r < -20$  SDSS sample, 49%.

remarkably small, consistent with 0.1 or less. Importantly there is at most a weak trend with cluster mass: even at  $M \sim 10^{13} h^{-1} M_\odot$  the intrinsic variation is small. The fact that a large scatter is observed in these systems is due to the fact that the uncertainties associated with an individual group are large, limited by the number of members. With a large enough sample, however, it is possible to overcome these uncertainties and allows us to put interesting limits on the intrinsic scatter.

## 5 DISCUSSION AND CONCLUSIONS

We have shown that the fraction of passive galaxies in clusters has remarkably small scatter between systems, generally 0.1 or less. We can compare this directly with the predictions of McGee et al. (2009), who use the galaxy formation model of Font et al. (2008) to calculate the rate at which galaxies are accreted into groups and clusters, and the amount of time they spend within haloes of a given mass during their history. More specifically, McGee et al. (2009) show the fraction of galaxies that have been inside a halo of mass  $M > M_{\text{trunc}}$  for a time  $t \geq T_{\text{trunc}}$ . Under the assumption that such galaxies are the only ones that turn passive, we can compare those predictions with our results. Although these predictions make use of a semi-analytic model to trace galaxies, the results are determined primarily by the dark matter growth history, which is



**Figure 4.** We show the intrinsic  $1\sigma$  *r.m.s* scatter on the passive fraction from cluster to cluster, in mass bins with at least five clusters. The X-ray clusters are indicated with *filled circles*; the Halo clusters with *open squares*, and the FOF clusters with *open triangles*. Where the observed variance is significantly larger than the statistical uncertainty, we have represented the 95% confidence limits with error bars. In cases where we are unable to measure a significant intrinsic scatter, in light of the statistical uncertainties, we have placed the point at the 95% confidence upper limit, indicated with a downward arrow. Model predictions from McGee et al. (2009) are shown as the lines. Red, green and blue lines indicate  $\log(h M_{\text{trunc}}) = 14, 13$  and 12, respectively. In each case the solid line represents  $T_{\text{trunc}} = 3\text{Gyr}$ , with the dotted lines representing 1 Gyr (lower scatter) and 6 Gyr (higher scatter). *Top panel:* The main cluster samples, used throughout most of this sample, restricted to  $M_r + 5 \log h < -18$  and  $z < 0.05$ . *Bottom panel:* The larger, “bright” cluster sample, restricted to  $M_r + 5 \log h < -20$  and  $z < 0.1$ .

taken from the Millennium simulation (Springel et al. 2005), and are largely independent of the recipes used to model the galaxies.

We plot predictions from McGee et al. (2009) together with our data, in Figure 4. Note that the observed scatter will be affected by other systematic effects, such as field contamination and uncertainties in the mass and radius; thus all of our points are best thought of as strict upper limits on the true cluster population, which is what is being modeled. Lines are shown for three different  $M_{\text{trunc}}$  and three different  $T_{\text{trunc}}$ , as described in the caption. It is interesting first of all that the scatter predicted by the models is quite comparable to that observed, even in the lowest mass groups; there is no evidence that the variance in group properties significantly exceeds what would be expected from these simple infall-based models. The fact that these groups have passive fractions significantly greater than the global average, with a small intrinsic scatter, implies that  $M_{\text{trunc}} < 10^{13} h^{-1} M_\odot$ . That is, star formation in galaxies must be shutting down long before they enter cluster-sized haloes. Treating all the points as strict upper limits, even the scatter in the most massive systems puts interesting limits on these parameters. If star formation is only truncated upon accretion into clusters,  $M_{\text{trunc}} > 10^{14} h^{-1} M_\odot$ , then the timescale must be  $T \lesssim 1\text{Gyr}$  to be consistent with all the cluster samples presented here. Such a model, however, would predict greater scatter than observed at  $M = 2 \times 10^{14} h^{-1} M_\odot$ , and moreover that systems with

1  $M < M_{\text{trunc}}$  should resemble the field population, which is ruled  
2 out.

3 The results of Haines et al. (2009) potentially provide even  
4 stronger constraints. Their sample of clusters with masses of  $\sim 2$ –  
5  $20 \times 10^{14} M_{\odot}$  (Okabe et al. 2009; Zhang et al. 2008) has an *rms*  
6 of 0.03 after accounting for a trend with redshift, and is consistent  
7 with no intrinsic scatter. At face value, this suggests that not only  
8 must  $M_{\text{trunc}}$  be low, but  $T_{\text{trunc}}$  must also be small,  $\lesssim 1$  Gyr. How-  
9 ever, their star formation rate threshold is quite high, and this is  
10 probably why the average fraction of passive galaxies at the low-  
11 est redshifts in their sample is 0.95, substantially higher than in the  
12 present sample. This, together with the wider redshift range cov-  
13 ered, makes it difficult to directly compare with our results.

14 In conclusion, the fraction of passive galaxies and the variance  
15 in this fraction from system to system suggests that star formation is  
16 shut off in galaxies within groups with masses  $M \lesssim 10^{13} h^{-1} M_{\odot}$ ;  
17 thus, “pre-processing” is crucial to explain the observed properties  
18 of today’s clusters. These constraints can be significantly improved  
19 by increasing survey depth, so there are more members per cluster,  
20 and by increasing the volume surveyed so there are more contrib-  
21 uting clusters. Mass measurements with smaller statistical uncer-  
22 tainty (for example from X-ray observations with resolved temper-  
23 ature profiles) would also be helpful in reducing the scatter, as  
24 there is a small trend for the passive fraction to increase with mass.  
25 Perhaps most importantly, repeating the analysis at higher redshift  
26 will be valuable, as the scatter associated with large  $T_{\text{trunc}}$  mod-  
27 els is predicted to increase significantly with redshift McGee et al.  
28 (2009).

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