Halo histories versus galaxy properties at $z = 0$ – III. The properties of star-forming galaxies

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ABSTRACT

We measure how the properties of star-forming central galaxies correlate with large-scale environment, $\delta$, measured on $10 \, h^{-1}$ Mpc scales. We use galaxy group catalogues to isolate a robust sample of central galaxies with high purity and completeness. The galaxy properties we investigate are star formation rate (SFR), exponential disc scale length $R_{\text{exp}}$, and Sersic index of the galaxy light profile, $n_S$. We find that, at all stellar masses, there is an inverse correlation between SFR and $\delta$, meaning that above-average star-forming centrals live in underdense regions. For $n_S$ and $R_{\text{exp}}$, there is no correlation with $\delta$ at $M_\ast \lesssim 10^{10.5} \, M_\odot$, but at higher masses there are positive correlations; a weak correlation with $R_{\text{exp}}$ and a strong correlation with $n_S$. These data are evidence of assembly bias within the star-forming population. The results for SFR are consistent with a model in which SFR correlates with present-day halo accretion rate, $\dot{M}_h$. In this model, galaxies are assigned to haloes using the abundance-matching ansatz, which maps galaxy stellar mass onto halo mass. At fixed halo mass, SFR is then assigned to galaxies using the same approach, but $\dot{M}_h$ is used to map onto SFR. The best-fitting model requires some scatter in the $\dot{M}_h$–SFR relation. The $R_{\text{exp}}$ and $n_S$ measurements are consistent with a model in which both of these quantities are correlated with the spin parameter of the halo, $\lambda$. Halo spin does not correlate with $\delta$ at low halo masses, but for higher mass haloes, high-spin haloes live in higher density environments at fixed $M_h$. Put together with the earlier instalments of this series, these data demonstrate that quenching processes have limited correlation with halo formation history, but the growth of active galaxies, as well as other detailed galaxies properties, are influenced by the details of halo assembly.

Key words: galaxies: evolution – cosmology: observations.

1 INTRODUCTION

This is the third instalment of a series of papers focused on possible connections between the properties of present-day galaxies and the evolutionary histories of the haloes in which those galaxies formed. In each work, we select a sample of ‘central’ galaxies with which to make our comparisons. These galaxies live at the centre of distinct haloes – these galaxies could also be referred to as ‘field galaxies’ – and have not been subjected to the type of physical processes that transform galaxies that have been accreted as satellites onto groups and clusters. In Papers I and II, we investigated the quenched fraction of central galaxies in the SDSS, $f_Q$, comparing various measurements of this quantity to theoretical models. In these papers, we used the conditional abundance-matching framework of Hearin & Watson (2013) and Hearin, Watson & van den Bosch (2015) to construct models that match mean stellar age to various quantities that correlate with halo formation history. This model, which we refer to as the ‘age-matching model,’ predicts that red-and-dead galaxies live in the oldest haloes, while the most active star formers live in the youngest. In Paper I, we determined that such models predict a dependence of $f_Q$ on large-scale density that is inconsistent with observations. At fixed mass, halo clustering depends on halo age, an effect known as assembly bias (Wechsler et al. 2006; Gao & White 2007). Thus, the age-matching model predicts that quiescent central galaxies should predominantly live in dense regions, but will rarely be found in underdense regions. The measurements of Paper I shows essentially no correlation between $f_Q$ and density at...
the halo masses where the age-matching model predicts it to be the strongest.

In Paper II we explored $f_{\text{g}}$ through galactic conformity (see e.g. Kauffmann et al. 2013; Hearin et al. 2015), once again finding that halo formation has a limited, if any, role in determining whether a galaxy makes the transition from star forming to quiescence. In this paper, we narrow our sample to only looking at central galaxies that are actively star forming. Theoretical models of galaxy growth inside haloes usually assume some relationship between the properties of disky, active galaxies, and the dark matter halo that surrounds them. We will test several of these assumptions.

In some respects, the correlation between galaxy growth and halo growth is undeniable: larger galaxies live in larger haloes. The abundance-matching model has been used as a function of redshift to infer the details of this correlation (Conroy & Wechsler 2009; Behroozi, Wechsler & Conroy 2013a,b; Moster, Naab & White 2013). In all of these models, it is assumed that the baryonic accretion rate onto a halo is proportional to the dark matter accretion rate of that halo. Abundance matching tells one how much the galaxy within a given halo has grown, and with this information one can infer the efficiency of star formation over that time interval. For two haloes of the same mass today, the halo that grew the most over that time should have the highest star formation rate. Halo growth rate is tied to closely tied to assembly bias, thus this prediction of the abundance-matching ansatz creates testable predictions for the population of central galaxies.

In the canonical picture of galaxy formation in a CDM universe, the properties of disc galaxies are determined by the relationship between dark matter and baryons. Accreted baryons are converted into a disc of cold gas and stars that has an exponential scale length determined by the angular momentum of the dark matter halo, which is aligned and distributed proportionately with the baryonic material (Dalcanton, Spergel & Summers 1997; Mo, Mao & White 1998). Recent cosmological hydrodynamic simulations have found a clear connection between halo angular momentum and whether a galaxy is spiral or elliptical. Several studies have shown that halo angular momentum (or ‘spin’ for brevity) is another halo property that influences – or is influenced by – the clustering of the haloes: higher spin haloes live in more dense regions (Bett et al. 2007; Gao & White 2007), giving us the opportunity to test this theory observationally.

Although galactic bulges can form in a variety of processes, cosmological hydrodynamic simulations demonstrate that merger activity is one of the methods by which galaxies build up a central bulge (see e.g. Brooks & Christensen 2016 and citations therein). The merger rate of dark matter haloes depends on large-scale density such that more mergers occur in higher density environments. This dependence is not particularly strong – the merger rate increases by a factor of $\sim 2$ over roughly a factor of 10 in $\rho$ (Fakhouri & Ma 2009). But bulgeless, disc-dominated galaxies in the local universe have most likely experienced the lowest amount of merging in the galaxy population. If so, they should reside in the lowest densities within which such galaxies can be found, making it possible to detect this effect.

The key to all of these supposedly observable trends, as always, is having an unbiased sample of central galaxies. Galaxies that orbit within larger haloes as satellites have been subjected to a set of physical processes that are distinct from those that can act on central galaxies in the field. As in Papers I and II, we will use group catalogues to identify central galaxies within the full SDSS DR7. The tight correlation between stellar mass and halo mass implies that we can use stellar mass as a reasonable proxy for halo mass. This assumption is most valid at stellar masses at and below the knee in the stellar mass function, which is where we focus our efforts. Thus, a pure and complete set of central galaxies at fixed stellar mass is an effective way to examine a set of haloes at fixed dark matter mass. In this context, the search for assembly bias is much cleaner and more straightforward.

Throughout, we define a galaxy group as any set of galaxies that occupy a common dark matter halo, and we define a halo as having a mean interior density 200 times the background matter density. For all distance calculations and group catalogues, we assume a flat, ΛCDM cosmology of $(\Omega_m, \sigma_8, \Omega_b, n_s, h_0) = (0.27, 0.82, 0.045, 0.95, 0.7)$. Stellar masses are in units of $M_{\odot}$.

2 DATA, MEASUREMENTS, AND METHODS

2.1 NYU value-added galaxy catalogue and group catalogue

As in Papers I and II, we use the NYU Value-Added Galaxy Catalog (VAGC; Blanton et al. 2005a) based on the spectroscopic sample in Data Release 7 (DR7) of the Sloan Digital Sky Survey (SDSS; Abazajian et al. 2009). We use stellar masses from the kcorrect code of Blanton & Roweis (2007), which assumes a Chabrier (2003) initial mass function. Estimates of the specific star formation rates ($sSFRs$) of the VAGC galaxies are taken from the MPA-JHU spectral reductions1 (Brinchmann et al. 2004).

The group catalogues are created from volume-limited stellar mass samples. Details of the group finding process can be found in Tinker, Wetzel & Conroy (2011) and further tested in Campbell et al. (2015). In brief, the group finding algorithm used here is based on that of Yang et al. (2005), in which the full galaxy population can be decomposed into two distinct populations: central galaxies, which exist at the centre of a distinct dark matter halo, and satellite galaxies, which orbit within a larger dark matter halo. Each galaxy in the sample is given a probability of being a satellite galaxy, $P_{\text{sat}}$. In our fiducial sample, galaxies with $P_{\text{sat}} \geq 0.5$ are classified as satellites, while galaxies with $P_{\text{sat}} < 0.5$ are classified as centrals.

In this paper, we focus exclusively on central galaxies. Impurities and incompleteness are inevitable consequences of any group-finding process. Using our group finder, the purity of the full sample of central galaxies is around 90 per cent, with a completeness of 95 per cent. However, the purity of the sample of central galaxies has a strong correlation with $P_{\text{sat}}$. The vast majority of central galaxies have $P_{\text{sat}} < 0.01$, with many being exactly 0. Most incorrectly classified central galaxies – i.e. true satellite galaxies that are labelled as centrals by the algorithm – have $P_{\text{sat}}$ in the range $0.01 < P_{\text{sat}} < 0.5$. Thus, we can create a ‘pure’ sample of central galaxies by reducing the $P_{\text{sat}}$ threshold to $P_{\text{sat}} < 0.01$. This excludes roughly 15 per cent of classified centrals but reduces the impurity to 1 per cent. Our fiducial results in this paper will use samples of pure central galaxies in order to avoid any bias from including true satellite galaxies in the sample. In Appendix B we demonstrate that our fiducial results are largely unaffected by this choice.

In addition to focusing on central galaxies, we specifically want to investigate the properties of galaxies on the star-forming main

1http://www.mpa-garching.mpg.de/SDSS/DR7/
sequence (SFMS). The SFMS is characterized by a power-law dependence of star formation rate (SFR) and $M_*$, with a lognormal scatter of roughly 0.3 dex around the mean log SFR (Noeske et al. 2007). Dividing a sample of galaxies into star forming and quiescent usually involves splitting a bimodal distribution at the minimum between the two modes of the galaxy distribution. However, there are galaxies that are on either side of that division that are not canonical star-forming or quiescent objects, but rather in the process of migrating from the former to the latter. We call these transitioning galaxies. The relative height of this ‘green valley’ to the peaks containing information about the quenching time-scale of galaxies. Using this information, Wetzel et al. (2013) and Hahn, Tinker & Wetzel (2017) find that satellite galaxies and central galaxies typically spend ~2 and ~4 Gyr in this migration, respectively.

Identifying which galaxies are transitioning and which are merely below-average star formers is not possible with the dataset we use here. We thus require a procedure to statistically account for the fact that some fraction of the population is not on the canonical SFMS. Fig. 1 shows the distribution of specific star formation rate (sSFR ≡ SFR/$M_*$) for low- and high-mass central galaxies. The red curves show a lognormal fit to the distribution, but only using the data rightward of the mode of the distribution. We make the assumption that the true SFMS is a symmetric lognormal distribution. The area of the histogram above the red curve shows the fraction of galaxies that are assumed to be transitioning. In galaxies in this range of sSFRs are weighted by the ratio of the red curve to the total histogram. This procedure has two benefits: (1) the sample of galaxies has a true lognormal distribution of sSFRs, thus making it straightforward to create theoretical models that connect halo accretion rate to galaxy SFR (which we will discuss in Section 2.3. (2) If transitioning galaxies occupy any special environment, this will not impact our results. However, we show in Appendix B that, in fact, using all galaxies does not change our results.

In addition to SFR, we utilize two other properties of central galaxies in SDSS; their exponential scale lengths, $R_{\text{exp}}$, and the Sersic indices of their light profiles, $n_S$. We obtain the values of $R_{\text{exp}}$ from the NYU-VAGC. For $n_S$, we use updated values from the NASA-Sloan Atlas (NSA). 3 The value of $R_{\text{exp}}$ is the value of the exponential scale length in a pure exponential model fit to the galaxy magnitude profile. The value of $n_S$ is determined by fitting the magnitude profile to a Sersic function with the form $I(r) = A \exp\left[-(r/r_0)^{1/n_S}\right]$. For a purely exponential disc, $n_S = 1$, while for a purely de Vaucouleurs profile $n_S = 4$. In Blanton et al. (2005b), galaxies with blue $g - r$ colours exhibit $n_S$ values in the range 0.5–2.5. Since our sample of central galaxies all lie on the SFMS, the vast majority will have some disc component. The use of $n_S$ is a proxy for how bulge-dominated the galaxy is.

2The NSA is made publicly available by M. R. Blanton at http://www.nsaclas.org. We use here the version of the NSA updated for target selection of the MANGA Survey (Bundy et al. 2015), which extends to upper redshift limit to $z \approx 0.15$, which includes all galaxies in our group catalogues.

2Gyr in this migration, respectively.

2Mpc per side, evolving a density field resolved with 2048$^3$ particles, yielding a mass resolution of $5.91 \times 10^8 M_\odot$. The cosmology of the simulation is flat $\Lambda$CDM, with $\Omega_m = 0.286$, $\sigma_8 = 0.82$, $h = 0.7$, and $n_s = 0.96$. Haloes are found in the simulation using the ROCKSTAR code of Behroozi, Wechsler & Wu (2013c) and Consistent Trees (Behroozi et al. 2013d) is used to track halo growth. Halo masses are defined as spherical overdensity masses according to their virial overdensity. The second simulation is smaller but with higher mass resolution. This simulation was performed using the TNG code of White (2002), and first presented in Wetzel & White (2010). This simulation has a box size of 250 h$^{-1}$ Mpc per side with 2048$^3$ particles, yielding a mass resolution four times higher than Chinchilla. Halo finding uses the friends-of-friends algorithm with a linking length of 0.18. This simulation will be used to track merger histories of mock galaxies, as we will discuss in the next subsection. This simulation has slightly lower $\Omega_\Lambda$ and $\sigma_8$ values compared to the Chinchilla simulation (0.27, 0.8), but these differences are not expected to cause significant differences in the comparison.

2The purpose of this paper is to quantify any correlations between the properties of star-forming central galaxies and their large-scale environments. The scatter of star formation rates for galaxies on the SFMS is high, and thus weak correlations with $\delta_{\text{gal}}$ can be easily obscured by noise and limited statistics. To boost the signal to noise of the measurement, we measure the mean environment as a function of galaxy property, rather than the traditional method of binning galaxies by $\delta_{\text{gal}}$ and calculating the mean of the galaxy property within that bin. This method was used by Hogg et al. (2003) to quantify the relationship between environment and galaxy luminosities and colours.

limit to calculate galaxy density. We use this sample, rather than the stellar mass volume-limited sample, simply because the magnitude-limited sample has more galaxies and thus reduces shot noise in the measurement. The effect of peculiar velocities is small, and the 10 h$^{-1}$ Mpc scale is a clear distinction from the density on the scale of the halo virial radius. We use the marGle software of Swanson et al. (2008) to characterize the SDSS survey geometry and create random samples.

Rather than use the absolute number of galaxies around each object, we use the density relative to the mean density around each galaxy in a given sample,

$$\delta_{\text{gal}} = \rho_{\text{gal}} / \langle \rho_{\text{gal}} \rangle - 1,$$

where $\rho_{\text{gal}}$ is the density in galaxies around each object and $\langle \rho_{\text{gal}} \rangle$ is the mean density around all galaxies, as opposed the mean density of galaxies. Thus, positive and negative values of $\delta_{\text{gal}}$ indicate galaxies that live in higher or lower densities relative to the mean for that type of galaxy.

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### 2.3 Numerical simulations and theoretical models

As in Papers I and II, we will compare the results from the group catalogue to expectations from dark matter haloes. Here, we utilize two simulations. Most of our theoretical predictions use the ‘Chinchilla’ simulation, also used in the previous instalments. The box size is 400 h$^{-1}$ Mpc per side, evolving a density field resolved with 2048$^3$ particles, yielding a mass resolution of $5.91 \times 10^8 M_\odot$. The cosmology of the simulation is flat $\Lambda$CDM, with $\Omega_m = 0.286$, $\sigma_8 = 0.82$, $h = 0.7$, and $n_s = 0.96$. Haloes are found in the simulation using the ROCKSTAR code of Behroozi, Wechsler & Wu (2013c) and Consistent Trees (Behroozi et al. 2013d) is used to track halo growth. Halo masses are defined as spherical overdensity masses according to their virial overdensity. The second simulation is smaller but with higher mass resolution. This simulation was performed using the TNG code of White (2002), and first presented in Wetzel & White (2010). This simulation has a box size of 250 h$^{-1}$ Mpc per side with 2048$^3$ particles, yielding a mass resolution four times higher than Chinchilla. Halo finding uses the friends-of-friends algorithm with a linking length of 0.18. This simulation will be used to track merger histories of mock galaxies, as we will discuss in the next subsection. This simulation has slightly lower $\Omega_\Lambda$ and $\sigma_8$ values compared to the Chinchilla simulation (0.27, 0.8), but these differences are not expected to cause significant differences in the comparison.

The compare simulation results to galaxy results binned as a function of environment, we measure the density around each halo in the simulation in the same manner as for the galaxies. Using the halo occupation distribution (HOD) fitting results of Zehavi et al. (2011) from the SDSS main galaxy sample, we populate the simulation with galaxies that match the density and clustering of each of our volume-limited samples. Using the distant-observer
approximation and the $z$-axis of the box as the line of sight, the top-hat redshift-space galaxy densities are measured around each halo.

We use the relation between central-$M_*$ and $M_b$ shown in Paper I (fig. 3 in that paper) to select haloes to compare to measurements at fixed central $M_*$. This manner of selecting haloes does not include any scatter in the stellar mass-to-halo mass relation, but in tests we have found that including scatter does not change our results.

To test the hypothesis that halo assembly bias is imprinted onto the properties of the galaxies, it is necessary to make theoretical models that map halo properties onto galaxies properties at fixed $M_*$. For comparisons to our three observable galaxy properties – SFR, $R_{\text{exp}}$, and $n_s$ – we map these properties onto three different properties of dark matter haloes.

(i) Halo growth from $z = 0.1$ to $z = 0$, which we will refer to as $\dot{M}_b$. We use this halo property to assign SFR values to haloes at fixed halo mass.

(ii) Halo angular momentum, parameterized through the dimensionless spin parameter $\lambda$, as defined by Bullock et al. (2001). We use this halo property to assign values of $R_{\text{exp}}$ to haloes at fixed mass.

(iii) Galaxy merger history. We use the fractional amount of stellar mass in a mock galaxy accreted from galaxy mergers to map values of $n_s$ onto mock galaxies. We define this quantity as $f_{\text{merge}}$.

To a reasonable approximation, the baryonic accretion rate onto a dark matter halo is simply $f_b \times \dot{M}_b$, where $f_b$ is the universal baryon fraction and $\dot{M}_b$ is the dark matter accretion rate onto the halo (Behroozi et al. 2013a; Moster et al. 2013). For low-mass haloes, for which shock heating is not efficient, gas will be accreted ‘cold’ and sink to the centre of the halo in a dynamical time (Kereš et al. 2005, 2009; Dekel & Birnboim 2006). Once at the halo centre, the gas should accrete onto the central galaxy and supplement the gas reservoir from which stars are created. For higher mass haloes, where gas is no longer accreted cold, the situation is more complex but the overall baryonic accretion rate will still follow the dark matter accretion rate.

Using this relation between baryonic accretion rate and $\dot{M}_b$, we can use the abundance-matching ansatz to make theoretical models in which central galaxy sSFR is correlated with the growth of the dark matter halo. In the simplest of such models, we assume no scatter between sSFR and $\dot{M}_b$. In such a model, at fixed halo mass (and thus $M_*$), the halo with the highest growth rate contains the galaxy with the highest sSFR, and on down the rank-ordered list. This is analogous to the conditional abundance-matching model of Watson et al. (2015), who used halo age to match to galaxy SFR. Although, in our model, it may be more physical to connect present-day SFR to halo growth measured sometime in the past – thus accounting for the time it takes baryons to be accreted on the galaxy – in practice this has little impact on the results (Hahn et al. in preparation).

Although some fraction of galaxies at any $M_*$ are quiescent, in our model, all haloes are available to contain star-forming central galaxies. This means that star-forming haloes are not a ‘special subset’ of host haloes. Haloes with quiescent central galaxies represent a random subset of host haloes. This is backed up by the results of Papers I and II, in which the fraction of quiescent central galaxies in independent of environment.

Incorporating scatter in the $M_*$–sSFR relation is relatively straightforward given that we assume a lognormal distribution in SFR. See Appendix A.

The theoretical models for assigning values of $R_{\text{exp}}$ to haloes follow in analogous fashion. We assume a lognormal distribution of $R_{\text{exp}}$ values with a scatter of 0.2 dex independent of $M_*$. In a given bin of $\log M_b$, haloes are ranked according to their angular momentum, expressed through the dimensionless spin parameter $\lambda$ (Bullock et al. 2001), which expresses the ratio between the halo angular momentum and the angular momentum if the matter was all in circular orbits. The quantity is calculated during the halo finding process by the ROCKSTAR algorithm. For greater context, we present
the correlation between large-scale density and these halo properties in Appendix D.

Our procedure for constructing abundance-matching models for \( n_5 \) follows the same outline. We assume a lognormal distribution of \( n_5 \). The scatter in \( n_5 \) increases from low to high \( M_* \), however. Over the three bins in \( \log M_* \), the scatter in \( \log n_5 \) is 0.13, 0.155, and 0.18 dex. To calculate \( f_{\text{merge}} \), we first identify all \( z = 0 \) distinct haloes (i.e. haloes that house central galaxies). With this list, we follow the evolution of these haloes forward in time starting at \( z = 1 \), when the typical mass of a Milky Way sized galaxy is only \( \sim 20 \) per cent of its present-day value. Stellar masses are assigned to each halo at each redshift independently, using abundance matching and the stellar mass functions measured by at each redshift range (see Hahn et al. 2017 for details of this model).

As smaller haloes are accreted onto larger haloes, mergers take place when a satellite is no longer identifiable as its own halo. Wetzel & White (2010) determined that satellite disruption occurs when a subhalo is stripped of 97 to 99 per cent of its mass. This criterion, combined with abundance matching, gives results consistent with observations of spatial clustering and the fraction of galaxies that are satellites. For low-mass galaxies that live in \( 10^{11.2} M_\odot \) haloes, our procedure may overestimate the number of minor mergers that occur because we are unable to track all haloes below \( 10^{11} M_\odot \) down to 1 per cent of their mass at the time of accretion, but given the slope of the stellar-to-halo mass relation, the overall contribution of these galaxies to the \( z = 0 \) stellar mass of a galaxy is likely to be small.

As the evolution of each halo is followed, the total stellar mass of satellite galaxies that have merged with the parent galaxy is summed up. We define \( f_{\text{merge}} \), as the ratio between this mass and the \( z = 0 \) stellar mass within the halo, as defined by abundance matching once again.

3 RESULTS

3.1 Do the properties of star-forming central galaxies depend on large-scale environment?

According to Fig. 2, the answer depends on the property in question. As detailed in Section 2, all results in this section are restricted to pure central galaxies that lie on the SFMS. Each row shows results for a different galaxy property. The bottom row shows results when binning galaxies by \( R_{\text{exp}} \), the scale radius of the exponential fit to each galaxy’s light profile. The middle row shows results for \( n_S \), the best-fitting Sersic index to the galaxy light profile. The top row shows results when binning galaxies by sSFRs. The columns show bins in stellar mass. From left to right, the bins are \( \log M_* = [9.7, 10.0], [10.1, 10.5], [10.7, 10.9] \). Wide bins are necessary to increase the statistical power of the samples. In each panel, the \( x \)-axis is the galaxy property relative to the mean. Due to the width of the bin, the mean of a galaxy property can evolve significantly from the low-mass end of the bin to the high-mass end. To prevent biases from this evolution, the mean galaxy property is first calculated in 0.1-dex subbins of \( \log M_* \), and each galaxy’s properties are with respect to the mean in the subbin. Errors represent statistical errors in the mean.

The top row shows results when binning galaxies by sSFRs. In each panel, there is a clear correlation between sSFR\( (\text{sSFR}) \) and \( \delta_{\text{gal}} \) such that galaxies that are stronger than average star formers live in lower densities, while below-average star formers live in higher densities. The slope of this correlation is monotonically shallower with higher \( M_* \), but in each panel there is a statically significant correlation; using a \( \chi^2 \) statistic to test the consistency of each panel’s result with a straight line yields \( \chi^2 \) values of 23.6, 31.6, and 22.3 for each panel from left to right, respectively, for 10 data points in each panel.

The middle row shows results when binning galaxies by \( n_5 \). There is no clear correlation between \( n_5 \) and \( \delta_{\text{gal}} \) for \( M_* \lesssim 10^{10.5} M_\odot \), but at high masses a statistically significant correlation exists. In the far-right panel, galaxies with higher \( n_S \) – i.e. galaxies with more elliptical and less disky morphology – live in slightly higher than average density environments. Galaxies that are more disc dominated, however, live in significantly lower densities than average.

The \( \chi^2 \) test described above yields values of 16.8, 21.0, and 37.9 for the panels from left to right, respectively. The \( \chi^2 \) of 2.10 for the middle panel is mostly driven by the datum at \( n_S (n_5) = 0.6 \), without which the \( \chi^2 \) is 8.0. The large \( \chi^2 \) for the high-mass bin is distributed more evenly in the data. Removing the far left datum, which has \( \delta_{\text{gal}} = -0.22 \), reduces the \( \chi^2 \) to 32.

The bottom panel shows results for \( R_{\text{exp}} \). In all panels, there is no clear dependence of \( \delta_{\text{gal}} \) on \( R_{\text{exp}}/\langle R_{\text{exp}} \rangle \). The \( \chi^2 \) test yields values, from left to right, of 6.8, 11.7, and 10.7. There is a slight positive slope in the high-mass bin. A line with a slope of 0.05 yields a \( \Delta \chi^2 = 4.3 \) with respect to a straight line, but a straight line fit is statistically reasonable given 10 data points. We will discuss these results in the context of halo angular momentum in subsequent subsections.

3.2 Does halo growth rate correlate with galaxy growth rate?

Using the method described in Section 2.3, we match halo growth rate to galaxy sSFR. In this scenario, the fastest growing haloes have the highest star formation rates, while the slowest growing haloes (or negatively growing haloes) have the lowest sSFR values. The correlation between halo growth rate and halo environment will impart a strong correlation between sSFR and \( \delta_{\text{gal}} \) in the. It is important to note the result of Papers I and II, which imply that quenching is a stochastic process with respect to halo growth rate, especially for haloes with \( M_h \lesssim 10^{12.5} \). Thus, star-forming haloes are likely not a ‘special subset’ of dark matter haloes, and we can draw from the full population of haloes to make predictions.

Fig. 3 compares two theoretical models to the data presented in the top row of Fig. 2. The dotted curves show one model in which \( M_h \) is mapped onto log sSFR assuming no scatter between the two quantities. The solid curves are the results of a model in which the scatter between these two quantities is 0.25 dex. Both models yield results that are qualitatively in good agreement with the data: the models predict an inverse correlation between star formation rate and \( \delta_{\text{gal}} \), with a slope that monotonically decreases with increasing \( M_h \). The slope of the correlation predicted in the no-scatter model is too steep relative to the data, especially for the slowest growing haloes. The model that incorporates scatter, however, is in excellent agreement with the data. The value of 0.25 dex was obtained by finding the scatter that yielded the lowest \( \chi^2 \) when comparing the model to the data, with a value of 28 for 30 data points. This model yields a \( \Delta \chi^2 \) of 21 with respect to a model with no correlation (but has the same errors as the simulation). A scatter of 0.25 dex in log sSFR is approaching the overall scatter of in the SFMS of 0.28 dex, but even with this amount of scatter at fixed \( M_h \), the model still creates a significant correlation between sSFR and \( \delta_{\text{gal}} \). These
values imply a correlation coefficient of $r = 0.63$ between $M_h$ and log $sSFR$.

3.3 Does merger activity correlate with galaxy light profile?

Fig. 4 shows the $n_S$–$\delta_{gal}$ relation first presented in Fig. 2, but now with a comparison to the model in which $f_{\text{merge}}$ is abundance matched onto $n_S$ at fixed $M_h$. Error bars are calculated by jackknife sampling of the simulation volume into eight subvolumes. The slightly larger error bars in this comparison, relative to those seen in Fig. 3 and what we will see in Fig. 6 are due to the smaller box size of this simulation.

In all three panels, the model shows no evidence of a correlation between $f_{\text{merge}}$ and $\delta_{gal}$, and thus yields no correlation between $n_S$ and $\delta_{gal}$. In our fiducial model, we incorporate 0.2 dex of scatter in log $M_*$ at fixed log $M_h$. This value is consistent with recent measurements (e.g. Reddick et al. 2013; Zu & Mandelbaum 2015; Tinker et al. 2017). Physically, the amount of merging a galaxy has over its lifetime may contribute to this scatter, but this is not reflected in our fiducial implementation. Thus, we have run an additional model in which there is no scatter at $z = 0$. The results are unchanged, verifying that our fiducial model is not affected by uncorrelated scatter.

The parameter $n_S$ need not be correlated only to $f_{\text{merge}}$, but it is difficult to find another halo parameter that could match the signal measured in Fig. 4. This is due to the fact that assembly bias created by most halo parameters is maximal at low halo masses – $M_h \lesssim 10^{11} M_\odot$. These parameters include $c_{\text{vir}}$, $z_{1/2}$, or short-term halo growth, $\dot{M}_h$. However, halo spin parameter $\lambda$ yields a rather different assembly bias signal than these other parameters (see e.g Gao & White 2007). For $\lambda$, the assembly bias signal actually gets larger with higher halo mass, and goes away completely at $M_h \lesssim 10^{12} M_\odot$. Fig. 5 shows the comparison between measurements and an abundance-matching model which maps $\lambda$ onto $n_S$, with no scatter, at fixed $M_h$. This comparison is quite favourable, matching the slope of the observed correlation at $M_* \sim 10^{10.8}$ and showing a correlation coefficient of $r = 0.63$ between $M_h$ and log $sSFR$. The correlation between large-scale density, $\delta_{gal}$, and properties of star-forming galaxies. From bottom to top, the galaxy properties in each row are $R_{\text{exp}}$, the scale length of the exponential fit to the galaxy light profile, $n_S$, the best-fitting Sersic index of the galaxy light profile, and $sSFR$, the specific star formation rate. The columns represent different galaxy stellar masses, from low to high, as indicated in the panels.
Figure 3. Comparison between measurements and models for the correlation between sSFR and $\delta_{\text{gal}}$ for central galaxies. The points with error bars are the same as those presented in Fig. 2. The curves are the results from halo abundance-matching models. The dotted line is a model in which there is no scatter between $M_h$ and sSFR. This model yields results that agree with the general trends of the data, but the slope of the correlation between sSFR and $\delta_{\text{gal}}$ is notably steeper. The solid curve is a model which incorporates 0.25 dex of scatter in log sSFR at fixed $M_h$. This value of scatter yields the best $\chi^2$. The shaded region is the uncertainty in the model through jackknife sampling of the simulation volume.

Figure 4. Comparison between measurements and models for the correlation between $n_S$ and $\delta_{\text{gal}}$ for central galaxies. The points with error bars are the same as those presented in Fig. 2. The curves are the results from halo abundance-matching models. First, central galaxy stellar mass is mapped onto halo mass using the empirical relation from the group catalogue. In each bin in halo mass, halo merger activity is mapped onto $n_S$ using the same procedure in Fig. 3 for SFR (see the text for details on how ‘merger activity’ is defined and calculated). We assume a lognormal distribution of $n_S$ values with a dispersion that increases from 0.13 to 0.18 dex across the three galaxy mass bins. The solid curves represent the results from dark matter haloes assuming no scatter in the relation between $f_{\text{merge}}$ and $R_{\text{exp}}$. Because there is no clear correlation in the theoretical model, we do not include additional models that incorporate scatter in this relation.

3.4 Does halo angular momentum correlate with galaxy disc size?

As already shown in the previous subsection, the assembly bias signal created by halo spin has minimal amplitude at $M_h \lesssim 10^{12} M_\odot$, but becomes measurable for galaxies that live in higher mass haloes. For $n_S$, there is a clear correlation with environment at $M_h \sim 10^{10.8} M_\odot$, and this correlation is consistent with a model in which $n_S$ is strongly correlated with $\lambda$. For $R_{\text{exp}}$, the observational situation is less clear. In our high-mass galaxy bin, there is a measurable slope...
Figure 5. Same as Fig. 4, but now the curves show a theoretical model in which halo spin parameter $\lambda$ is mapped onto $n_S$. There is no scatter between the two in this comparison.

Figure 6. Comparison between measurements and models for the correlation between $R_{\text{exp}}$ and $\delta_{\text{gal}}$ for central galaxies. The points with error bars are the same as those presented in Fig. 2. The curves are the results from halo abundance-matching models. First, central galaxy stellar mass is mapped onto halo mass using the empirical relation from the group catalogue. In each bin in halo mass, halo angular momentum is mapped onto $R_{\text{exp}}$ using the same procedure in Fig. 3 for SFR. We assume a lognormal distribution of $R_{\text{exp}}$ values with a dispersion in log $R_{\text{exp}}$ of 0.2 dex. The dotted curves represent the results from dark matter haloes assuming no scatter in the relation between $\lambda$ and $R_{\text{exp}}$. The solid curve assumes a scatter in log $R_{\text{exp}}$ at fixed $\lambda$ of 0.17 dex. The assembly bias of halo angular momentum does not become significant in this relation until $M_h \gtrsim 10^{12} M_\odot$. The model with no scatter produces too steep a slope to be consistent with the data, but the model with 0.17 dex of scatter is a better fit than no relation at all, yielding a $\Delta \chi^2$ of 3.2 with respect to a straight line.

4 DISCUSSION

Papers I and II of this series demonstrated that large-scale environment – and, by extension, halo growth history – plays a limited impact on whether a central galaxy is quenched. In this paper, we have restricted our analysis to central galaxies that lie on the star-forming sequence, allowing us to examine properties that are unique to such galaxies; the star formation rates, disc sizes, and light profiles. As with Paper I and II, previous investigations have focused on how assembly bias might impact either galaxy bimodality (see
e.g. Lacerna, Padilla & Stasyszyn 2014; Lin et al. 2016) or the full galaxy population (e.g. Tinker et al. 2008; Zentner et al. 2016). This is the first study to look at secondary properties within the set of star-forming galaxies.

4.1 Assembly bias and star formation rates

Our results indicate that, at fixed stellar mass, central galaxies on the SFMS have higher star formation rates in lower density environments. These data are consistent with a model in which sSFR is correlated with near-term halo growth rate. This is a detection of assembly bias within this class of galaxies. It demonstrates consistency between the assumptions of the abundance-matching model – namely, that galaxy growth should be correlated with halo growth – and the properties of observed star-forming galaxies.

Extrapolated to high redshift, this result implies that the total stellar mass of the galaxy is related to the formation history of its host halo. Using redshift-dependent abundance matching, Behroozi et al. (2013a) calculated the efficiency of converting accreted baryons into stars as a function of both time and halo mass. For haloes less massive than $10^{12} \, M_{\odot}$ at $z = 0$, this efficiency is lower at higher redshift than it is today. Thus, haloes that form early accrete most of their baryons when this conversion efficiency is low, and will form galaxies that are less massive than late-forming haloes of the same mass that accrete most of their mass at when efficiencies are higher. Tinker (2017) demonstrated that this is a source of scatter in the stellar-to-halo mass relation.

This is, however, the opposite of the assembly bias described in Lim et al. (2016) and measured in the GAMA survey by Tojeiro et al. (2017). In Lim et al. (2016), the ratio of $M_{\star}/M_{\text{h}} \equiv f_{\text{c}}$ is a proxy for halo formation time, with haloes with higher $f_{\text{c}}$ forming earlier. This effect is also seen in hydrodynamic simulations (Matthee et al. 2017). In these models, haloes that form early accrete significant amounts of gas early, and this gas therefore has a longer time-scale over which to form stars. These two scenarios make mutually exclusive predictions for the haloes around these galaxies. At fixed halo mass, the abundance-matching model predicts that late-forming haloes have larger galaxies, while in the SAMs and hydro simulations, early-forming haloes have larger galaxies. Thus, at fixed central galaxy stellar mass, abundance matching predicts that halo mass will increase as you go from sSFR$/sSFR$ ~ $-1$ to $+1$. The other models will predict the opposite trend. Galaxy–galaxy lensing or satellite kinematics for galaxies within the star-forming environments. These data are consistent with a model in which sSFR and sSFR/halo. However, at higher stellar masses, there is indeed a small but non-zero slope in the correlation such that central galaxies in higher density regions are more often quenched. This is consistent with the assembly bias yielded from a correlation with halo spin, but the implication would be that higher spin haloes are more likely to be quenched. At first glance, this result would seem to challenge the traditional orthodoxy of galaxy formation within dark matter haloes – namely, that high-spin haloes would form rotationally supported galaxies. As noted by Vitvitska et al. (2002), however, if spin is indeed created in the process of galaxy formation within dark matter haloes, then there is no observational signature of such a correlation. The statistic probed in Rodriguez-Gomez et al. (2017) was the fraction of total kinetic energy in the galaxy contributed by rotational motion, which is not possible to measure directly in the full group catalogue. We also note that results for low-mass galaxies in Illustris may suffer from resolution effects.

We also note that the results of Paper I appear similar to those of $n_{S}$ and $R_{\text{exp}}$; at low galaxy masses, there is no correlation between the quenched fraction of central galaxies and $\delta_{\text{gal}}$. However, at higher stellar masses, there is indeed a small but non-zero slope in the correlation such that central galaxies in higher density regions are more often quenched. This is consistent with the assembly bias yielded from a correlation with halo spin, but the implication would be that higher spin haloes are more likely to be quenched. At first glance, this result would seem to challenge the traditional orthodoxy of galaxy formation within dark matter haloes – namely, that high-spin haloes would form rotationally supported galaxies. As noted by Vitvitska et al. (2002), however, if spin is indeed created by mergers, the merger activity may cause galaxy transformation. The merger scenario for galaxy quenching has come into question, as hydrodynamical simulations suggest that, without the presence of an active post-merger feedback mechanism, star formation is likely to be restarted after the merger is complete (e.g. Springel & Hernquist 2005; Pontzen et al. 2017). But mergers may still temporarily quench galaxies, or the induced quenching may be permanent for some small fraction of merger events.
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Of course, we cannot rule out the possibility that the agreement between the halo spin abundance-matching models and the data is simply coincidence. But the results here indicate that further investigation of the secondary properties of passive galaxies – their velocity dispersions, size, and light profiles – may elucidate the processes that caused their transformation to the red sequence.

4.3 Emission-line galaxy samples as cosmological probes

The detection of assembly bias in star-forming objects may have implications for the use of such objects as tracers of the dark matter density field. The emission line galaxy (ELG) has been situated as the cosmological workhorse for the next generation of galaxy redshift surveys. Data are already being taken on a cosmological sample in the eBOSS programme (Dawson et al. 2016; see Raichoor et al. 2017 for details of the ELG selection). Assembly bias in ELG samples would alter both their large-scale bias and the shape of their clustering, relative to a model that assumes that halo mass is the only property that determines their occupation (Sunayama et al. 2016). This is unlikely to bias measurements of baryon acoustic oscillations, but may have an impact on efforts to use clustering as a probe of the growth rate, neutrino masses, and non-Gaussianity. Given the high precision expected from the clustering measurements of ELG samples, further investigation of the possible impact of the type of assembly bias measured here is warranted.

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First, we assume that SFMS is a lognormal. Thus, the cumulative rank \( i_{\text{rank}} \) at any location in the distribution can be expressed as

\[
i_{\text{rank}} = \frac{1}{2} \left[ 1 - \text{erf}(x / \sqrt{2}) \right],
\]

where \( i_{\text{rank}} \) is a normalized rank in the range [0,1] and \( x \) is defined as

\[
x = \frac{\text{SFR} - \langle \text{SFR} \rangle}{\sigma_{\log \text{SFR}}} \tag{A2}
\]

and we assume \( \sigma_{\log \text{SFR}} = 0.3 \), independent of stellar mass. For the case of no intrinsic scatter between \( M_h \) and SFR, the rank-ordered list of haloes can be matched to SFR by inverting equation (A1). To include intrinsic scatter, \( \sigma_{\text{int}} \), we assume that the total scatter in SFMS is 0.3, and the value used in equation (A2) is

\[
\sigma_{\log \text{SFR}}^2 = 0.3^2 - \sigma_{\text{int}}^2.
\]

Thus, after determining the SFR of each halo based on abundance matching, each halo receives an additional log SFR drawn from a Gaussian distribution with zero mean and \( \sigma = \sigma_{\text{int}} \).

**APPENDIX B: TESTING DIFFERENT SAMPLES OF CENTRAL STAR-FORMING GALAXIES**

In Fig. B1, we show measurements of the correlation between SFR and \( \delta_{\text{gal}} \) for different samples of star-forming galaxies. Our fiducial sample contains only star-forming galaxies likely to be on the SFMS. Thus, we randomly remove galaxies with low star formation rates in order to...
preserve the lognormal distribution of SFR. Additionally, our fiducial sample contains only central galaxies indicated as ‘pure’ centrals by the group catalogue. These are centrals with $P_{\text{sat}} > 0.99$. Removing non-pure centrals only reduces the overall sample size by $\sim 10$ per cent.

In Fig. B1, we compare our fiducial measurements to those for samples in which we relax the restrictions on the sample. The blue curve is the fiducial measurement from Fig. 2. The green circles show measurements that include all central galaxies, not just pure centrals. The red circles show measurements for all star-forming galaxies down to a specific SFR of $10^{-11}$ yr$^{-1}$. In both of these tests, the results are fully consistent with the fiducial measurement.

**Figure D1.** The large-scale density as a function of halo properties. Both quantities are shown relative to the mean values for a specific halo mass. The red solid curves show results for $M_h = 10^{11.5} \, M_\odot$, while the dashed blue curves show results for $M_h = 10^{13.5} \, M_\odot$. The left-hand panel shows results for $\dot{M}_h$, the quantity used to construct the model of galaxy sSFRs. The right-hand panel shows results for $\lambda$, the quantity used to construct models of galaxy $R_{\text{exp}}$ and $n_S$. 
APPENDIX C: COMPARISON OF SFR RESULTS TO DIFFERENT HALO PROPERTIES

Fig. C1 compares the measurements of the SFR–$\delta_{gal}$ correlation to abundance-matching models that use halo properties other than $M_h$ as a proxy for star formation. Here, we replace $M_h$ with $z_{1/2}$, the redshift at which the halo reached half its present-day mass, the concentration parameter $c_{vir}$, and the halo spin parameter $\lambda$. For the first two halo properties, there is a correlation between $z_{1/2}$, $c_{vir}$, and $M_h$ (see e.g. Wechsler et al. 2002). Thus, all of these halo properties yield similar correlations. We note, however, that the sign of the correlation is opposite to that of $M_h$. In Fig. 3, haloes with the highest $M_h$ had the highest SFR. For $c_{vir}$ and $z_{1/2}$, haloes with the lowest values of these properties have the highest star formation rates. Note that there is no scatter introduced in these comparisons.

As expected from Figs 5 and 6, the assembly bias signature created by a model that matches $\lambda$ to SFR does not compare favourably to the data. Here, again, we assert an inverse relationship between spin and star formation rate, with no scatter.

For $M_h$, we do find some dependence on the time baseline over which $M_h$ is calculated. The maximal assembly bias signal is found for $M_h$ calculated over a redshift baseline of $\Delta z = 0.8$. Smaller values of $\Delta z$ correspond to smaller assembly bias signals. At baselines larger than 0.8, the assembly bias signal is largely unchanged. We have not shown these results to preserve clarity in the plot, but the results for $\Delta z = 0.8$ are comparable to those for $c_{vir}$.

APPENDIX D: HALO PROPERTIES AND HALO ENVIRONMENTS

Fig. D1 shows the correlation between halo properties and halo environments. The two panels show results for $M_h$ and $\lambda$ in two halo mass bins. The y-axis shows the density relative to the mean density for that halo mass bin, yielding curves that vary around unity regardless of halo mass. Results are shown for $M_h$ and $\lambda$. We do not show results for the galaxy merger model, as there is not a significant correlation between merger activity and large-scale density.

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