Exploring the links between star formation and minor companions around isolated galaxies

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ABSTRACT

Previous studies have shown that galaxies with minor companions exhibit an elevated star formation rate. We reverse this inquiry, constructing a volume-limited sample of $\sim L^\star (M_r \leq -19.5 + 5\log h)$ galaxies from the Sloan Digital Sky Survey Data Release 6 that are isolated with respect to other luminous galaxies. Cosmological simulations suggest that 99.8 per cent of these galaxies are alone in their dark matter haloes with respect to other luminous galaxies. We search the area around these galaxies for photometric companions. Matching strongly star forming \([\text{EW}(\text{H}\alpha) \geq 35 \, \text{Å}]\) and quiescent \([\text{EW}(\text{H}\alpha) < 35 \, \text{Å}]\) samples for stellar mass and redshift using a Monte Carlo resampling technique, we demonstrate that rapidly star forming galaxies are more likely to have photometric companions than other galaxies. The effect is relatively small; about 11$\pm$1 per cent of quiescent, isolated galaxies have minor photometric companions at radii $\leq 60 \, \text{kpc} \, h^{-1} \, \text{kpc}$, while about 16$\pm$1 per cent of strongly star forming ones do. Though small, the cumulative difference in satellite counts between strongly star forming and quiescent galaxies is highly statistically significant ($P_{\text{KS}} = 1.350 \times 10^{-3}$) out to radii of $\sim 100 \, h^{-1} \, \text{kpc}$. We discuss explanations for this excess, including the possibility that $\sim 5$ per cent of strongly star forming galaxies have star formation which is causally related to the presence of a minor companion.

Key words: galaxies: evolution -- galaxies: formation -- galaxies: haloes -- galaxies: interactions -- galaxies: statistics.

1 INTRODUCTION

Many studies have established that the environmental properties of galaxies are closely related to their star formation histories (e.g. Dressler 1980; Postman & Geller 1984). On large scales, stronger clustering effects are observed in red galaxies than in blue galaxies, because red galaxies also tend to be more massive and reside in more massive dark matter haloes (see Zehavi et al. 2011, and references therein). However, at scales less than $\sim 300 \, \text{kpc}$, where galaxies are likely to be part of the same halo, these clustering effects are poorly understood, and at scales less than 50 kpc, blue galaxies may cluster more strongly (Masjedi, Hogg & Blanton 2008).

Previous studies establish that galaxy interactions and the presence of a companion are both associated with an increased rate of star formation (e.g. Larson & Tinsley 1978; Mihos & Hernquist 1994; Barton, Geller & Kenyon 2000; Lambas et al. 2003). In particular, closer companions lead to an increased rate of star formation for both major and minor interactions (e.g. Barton, Geller & Kenyon 2000; Lambas et al. 2003; Nikolic, Cullen & Alexander 2004; Woods, Geller & Barton 2006). These results are qualitatively in line with expectations from numerical simulations that predict enhanced star formation in interacting pairs before the galaxies finally merge (e.g. Mihos & Hernquist 1994; Barnes & Hernquist 1996), though those results are sensitive to uncertain star formation physics (e.g. Cox et al. 2006). In principle, close passes in both major and minor pairs can initiate a burst of star formation.

The questions that surround minor mergers are closely related to the properties of the satellite galaxies and their hosts. The radial distribution of satellites around primary galaxies has been extensively explored. Chen (2008) finds that the radial distribution of blue satellites around isolated hosts is significantly shallower than that of red satellites. There were also hints in this study that red and blue hosts may have different satellite distributions (Chen 2008). Previous studies have also examined the effects of galaxy colour on the anisotropic distribution of satellite galaxies around their hosts (Agustsson & Brainerd 2007; Azzaro et al. 2007; Kang et al. 2007; Bailin et al. 2008). For red central galaxies, satellites tend to be more strongly aligned along the major axis, while the distribution of satellites for blue central galaxies is consistent with an isotropic distribution. These observations further demonstrate the expectation that relationships exist between galaxy colour and satellite distribution.

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Some studies reveal a deficiency of satellites at very small radii (less than 20 kpc) compared to the extrapolated outer density profile (Sales & Lambas 2005; van den Bosch et al. 2005). This deficiency may be due to a failure to resolve interacting pairs into single galaxies, or it could be a real deficiency due to galaxy destruction. Sales & Lambas (2005) find that this deficiency can be predictably found in poorly star forming galaxies which tend to have larger core radii, while strongly star forming galaxies often have more close neighbours than predicted (Sales & Lambas 2005). This finding lends support to the long-established hypothesis that interaction with a nearby galaxy often causes enhanced star formation.

Despite our knowledge that both major and minor interactions trigger star formation, the complete cosmological impact of these processes remains unknown. When galaxies do exhibit significantly enhanced star formation, it is not known how often that star formation is related to an interaction. Here, we reverse the standard approach to minor companions by identifying a volume-limited sample of \( \sim L^* \) galaxies from the Sloan Digital Sky Survey Data Release 6 (SDSS DR6; Adelman-McCarthy et al. 2008) that are isolated with respect to other luminous galaxies. We then compare the photometric companion counts around the star-forming galaxies to the counts around other galaxies. In Section 2, we describe the initial galaxy sample and search procedures. Section 3 describes the bias corrections we apply to ensure a fair comparison. We describe the results in Section 4, discuss them in Section 5, and conclude in Section 6.

### 2 SAMPLE

We begin by identifying a set of galaxies in the Value Added Galaxy Catalog of SDSS DR6 (VAGC; Blanton et al. 2005; Adelman-McCarthy et al. 2008). We restrict the sample to sources that are isolated with respect to other luminous galaxies. We compile all sources in SDSS DR6 that are more luminous than \( M_r \leq -20.5 \) at a redshift \( z < 0.0804 \), which is the upper limit at which a galaxy of this luminosity will appear in the spectroscopic sample. We then identify galaxies that have no neighbours within a projected distance of 400 kpc \( h^{-1} \) and 1000 km s\(^{-1}\) of the primary, and at most one neighbour within 700 kpc \( h^{-1} \) and 1000 km s\(^{-1}\). These conservative isolation criteria include neighbours with measured redshifts and potential neighbours which are in the photometric survey but do not have measured redshifts. For example, a galaxy with a potential luminous neighbour with unmeasured redshift at 300 kpc \( h^{-1} \) will be rejected. Additionally, we took steps to ensure the sample of neighbour galaxies was not polluted with duplicate objects or objects that are actually just substructure of the host galaxy. After carefully inspecting images of upwards of 20 such objects, we devised a method which removed the erroneously identified objects but preserved the actual neighbours. For the entire sample of neighbours, we removed objects that were less than 3 kpc \( h^{-1} \) away from the host and any repeated objects with similar physical locations.

These criteria result in a sample of 24 753 isolated central galaxies. Using the techniques of Barton et al. (2007), we employ cosmological simulations to demonstrate the expected purity of this sample. The method relies on assuming that halo circular velocities in simulations scale monotonically with \( M_r \). The space density of galaxies with \( M_r + 5 \log(h) = -19.5 \) in SDSS, computed by integrating the luminosity function of Blanton et al. (2003), corresponds to haloes that had circular velocities \( \geq 164 \) km s\(^{-1}\) at the present epoch, or at the time they became substructure if they are not central sources in the hybrid N-body and semi-analytic simulations of Zentner et al. (2005). Forming an artificial redshift survey with these galaxies and applying selection criteria that are identical to those applied to the data, we show that 99.8 per cent of the isolated sample consists of galaxies selected via our isolation criteria that are alone in their dark matter haloes (with respect to other galaxies with \( M_r \leq -19.5 + 5 \log(h) \)).

A subset of the SDSS central galaxies are near the edges of the survey, in less complete regions, or close to bright stars. As a result, we may not be completely probing their environments for potential companions. We thus identify a ‘complete environment’ subsample of galaxies using the tools available in VAGC. In particular, we remove the lowest and highest redshift sources so that we can probe the entire 1000 km s\(^{-1}\) in front of and behind the galaxies. Then, we use the random subsamples provided in VAGC, weighted by the completeness of each sector and weighted based on the magnitude limit of the survey in that sector. We add the ‘random counts’ in each galaxy’s relevant environment, in essence performing a Monte Carlo integration of its environment weighted by completeness. We then restrict the ‘complete environment’ subsample to 18 601 galaxies where the value of this integral is within 2\( \sigma \) of the mode for the entire distribution. We explore whether this restriction subsample affects any of our results. Because it does not have any qualitative effect, we confine our discussion to the original 24 853 isolated galaxy sample hereafter, which we subdivide based on \( g - r \) colour and EW (H\(\alpha \)) as shown in Table 2.

We use the SDSS DR7 online data base to tabulate potential minor companions to an angular radius that would correspond to 200 kpc \( h^{-1} \) kpc from each central galaxy, with an apparent magnitude limit of \( m_r = 21 \). In the remaining sections of this paper, we explore the dependence of the companion counts on galaxy properties.

### 3 BIAS CORRECTIONS

In this study, we focus on the counts of potential faint companion galaxies around otherwise isolated \( \sim L^* \) central galaxies. In particular, we separate pair samples into rapidly star forming galaxies and galaxies that are not rapidly star forming. Because we do not have redshifts for these potential companions, we must count them in an angular radius around the centrals. In addition, because we count them to a fixed flux limit, the study will include relatively less luminous companions around nearby galaxies. As a result, any differences in the redshift distributions of the two samples of galaxies that we compare will cause potential biases in the comparisons. Because galaxies are known to cluster, and because satellites should be more numerous around more massive galaxies, halo mass is
another key parameter that must be controlled when comparing two samples. No direct measure of halo mass is available, so we use stellar mass as a proxy. In this section, we describe our simple techniques to resample the data in order to compare galaxies with the same distributions of redshift and stellar mass.

We employ a Monte Carlo random selection method to compare the radial distributions of neighbours around blue and red central galaxies with similar redshifts and stellar masses. Our Monte Carlo simulation selects a random sample of five red galaxies with similar redshift and stellar mass to each of the blue galaxies in the sample. A red galaxy is considered similar to a blue galaxy if the $z$ is within $\pm0.005$ and the stellar mass is within $\pm10$ per cent.

Fig. 1 depicts the redshift distributions of strongly star forming and quiescent central galaxies, based on EW(H$\alpha$) cut-off of 35 Å, for the complete sample and one of the subsamples derived using our Monte Carlo selection method. Visually, the redshift distributions of the strongly star forming and quiescent galaxies in the complete sample are significantly different. There is an excess of strongly star forming galaxies at lower redshifts when compared to the quiescent galaxies. The corrected sample appears to match much more closely. This interpretation is supported by the Kolmogorov–Smirnov (KS) test results, which are reported in Table 2. $P_{KS}(z) = 5.417 \times 10^{-9}$ for the full sample indicates that the redshifts of star-forming and quiescent galaxies have a different distribution. For the corrected sample, $P_{KS}(z) = 0.5746$, so the two subsamples are drawn likely from the same distribution.

The stellar mass distributions for the complete sample, plotted in the top panel of Fig. 2, are even more disparate than the redshift distributions. As expected, there is an excess of centrals with EW(H$\alpha$) $< 35$ Å in the high-mass range, and an excess of centrals with EW(H$\alpha$) $> 35$ Å in the low-mass range. The extremely low $P_{KS}(z)$ and $P_{KS}$(stellar mass) values for the subsamples taken from the complete set of central galaxies demonstrate that they have extremely different redshift and stellar mass distributions. The Monte Carlo derived sample, plotted in the bottom panel of Fig. 2, provides a much better visual match between the stellar mass distributions of strongly and not strongly star forming central galaxies. Once again, this interpretation is supported by the KS test results, which are shown in Table 2. We show the KS statistics from 10 Monte Carlo simulations; $KS(z)$ ranges from 0.249 to 0.696 and the KS(stellar mass) ranges from 0.818 to 0.969.

Additionally, because we necessarily observe a two-dimensional view of astronomical objects, our sample of potential satellites is contaminated by interlopers, that is, objects that are not physically within our searched radius but nevertheless appear to be true companions when projected on the sky. Overall, interlopers tend to flatten the projected radial mass distribution, and the fraction of observed satellites that are actually interlopers increases with search radius. Chen et al. (2006) tested both volume-limited and flux-limited samples (which are biased towards brighter satellites) and found consistent radial distributions, showing that there is at best a limited dependence of interloper contamination on the magnitude of the satellites and the colour of the primaries. Sales & Lambas (2005) find a flat distribution of interlopers between 20 and 500 kpc by specifically sampling for companion galaxies with a large projected velocity difference ($2000 < |\Delta V| < 10000$ km s$^{-1}$) compared to the central, allowing them to assume a uniform contamination when calculating the radial density profiles of satellites.

For our study, interloper contamination will obscure the relationship between close satellites and blue hosts, because red galaxies tend to be more massive and reside in larger dark matter haloes than blue galaxies. This larger halo size means there is a stronger clustering effect on scales of $\sim$300 kpc and larger (Masjedi et al. 2008). When searching on small radial scales (e.g. less than 100 kpc), there should be minimal contamination, but potential satellites at larger radii in these larger dark matter haloes are more likely to be
interlopers because the environment is more crowded. Assuming an isotropic background, if interlopers are a significant factor in our study, we would expect the radial distribution of satellites to be roughly proportional to $r^2$. However, as we will demonstrate below, the radial distribution we observe scales closer to $\sim r$. At small radii, the true companions appear to dominate.

4 RESULTS

We compare the list of potential companions with their associated central galaxies and compute the projected radial distance to each companion, throwing out any companions at a distance that exceeds the specified search radius, or that have a Petrosian r magnitude greater than 21. For our primary analysis, we choose to set the red–blue cut-off for our central galaxies at $\mathrm{EW(H\alpha)} = 35$ Å. This cut-off allows us to examine only the most strongly star forming galaxies, giving us the best chance of detecting the effect of close neighbours on galaxy star formation activity.

4.1 Numbers of neighbours

In Figs 3(a) and (b), we demonstrate that strongly star forming central galaxies are more likely to have a close neighbour. Fig. 3(a) contains histograms of the frequency of a central galaxy having a given number of neighbours within 100 kpc for the complete (top) and corrected (bottom) samples. We choose to plot 100 kpc because closer neighbours are associated with more recent starbursts, and thus larger stellar populations in the blue spectral range (Barton et al. 2000). Again, the central galaxies are grouped into strongly star forming and quiescent subsamples, with the cut-off at $\mathrm{EW(H\alpha)} = 35$ Å. The quiescent central galaxies are represented by the solid red line and the strongly star forming centrals by the dashed blue line. The frequency is expressed as a fraction of the total neighbours in each category.

For both the complete and the corrected sample, there is an excess of strongly star forming central galaxies with one or two neighbours within 100 kpc. We find that the KS probability that the neighbour distributions are the same is zero, indicating an extremely high degree of significance. For greater numbers of neighbours, the red and blue lines are nearly identical. Fig. 3(b) is similar to Fig. 3(a) but for a radius of 200 kpc. At this radius, the distribution of the number of neighbours for both types of centrals is more similar, but $P_{\text{KS}} = 0$, which indicates again that the observed (small) difference has a high degree of significance.

We made similar plots for radii ranging from 20 to 200 kpc, and a few trends become obvious. As the search radius decreases, the difference between star-forming and quiescent centrals becomes magnified, indicating that there is a relationship between star formation and distance to the nearest companion (Chen et al. 2006). With increasing radius, the line representing the quiescent central galaxies becomes closer and closer to the blue line, until they become nearly indistinguishable around 150 kpc. This behaviour is expected, because at large radii, the effect a companion can have on triggering star formation is small. Additionally, the signal is increasingly dominated by interlopers as the searched radius increases. Finally, star-forming galaxies tend to have one close neighbour, while quiescent galaxies tend to have a large number of neighbours at larger distances away. This result indicates that some of the star-forming central galaxies may be part of an interacting pair of galaxies, possibly triggering a burst of star formation.

The behaviour of the quiescent centrals arises because red galaxies are more massive and thus can be expected to cluster more strongly. For all samples at all radii, KS tests indicate a very high degree of statistical significance ($>99.999$ per cent) for the difference between distributions of the number of neighbours, whether divided by $g-r$ colour or $\mathrm{EW(H\alpha)}$. Ultimately, these plots suggest that star-forming central galaxies tend to have more near neighbours than quiescent central galaxies, which lends support to the idea that many are because of a triggered star formation event.

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4.2 Radial distribution of neighbours

After showing that central galaxies above the EW(Hα) cut-off are somewhat more likely to have a near neighbour than centrals below the cut-off, we quantify the difference in the radial distribution of satellites between the strongly star forming and less star forming centrals. For this, we use the redshift and stellar mass corrected Monte Carlo samples. Each Monte Carlo sample chooses five red central galaxies similar to each blue central. In Fig. 4, we plot the radial distribution of neighbours for 10 of these Monte Carlo samples in two different ways.

Fig. 4 (top panel) shows the fraction of central galaxies with at least one neighbour in each annulus, with annulus bins in steps of 10 kpc. The blue dashed line represents centrals with EW(Hα) ≥ 35 Å and the red lines represent quiescent centrals with EW(Hα) < 35 Å. There is some variation among the quiescent subsamples because of the random selection, but it is well within the Poisson error bars shown. Inside 85 kpc, central galaxies above the EW(Hα) break are significantly more likely to have a neighbour. This result clearly indicates that the strongly star forming galaxies are more likely to have a neighbour nearby. Beyond 85 kpc, the plot gets noisier, and there is little significant difference between the red and blue lines. We expect this because at such large radii a neighbouring galaxy can have little direct effect on the star formation of the central galaxy, and interlopers begin to dominate (Tollerud et al. 2011).

Fig. 4 (bottom panel) is similar to Fig. 4 (top panel), but instead we plot the cumulative fraction of central galaxies with at least one neighbour inside a given radius. At the innermost bin, centred at 5 kpc, the gap narrows; objects separated by less than 3 kpc (including mergers that are often associated with bursts of star formation) are nearly impossible for the detector to resolve. We find that the cumulative difference between star-forming and quiescent centrals is significant out to 100 kpc, implying that star-forming galaxies are ~5 per cent more likely to have at least one neighbour within 100 kpc than quiescent galaxies of the same stellar mass. However, the overall fraction of star-forming galaxies with a neighbour within 100 kpc is still small.

The difference in nearest neighbour distribution between strongly star forming and quiescent galaxies is significant as demonstrated by the KS statistics, which are tabulated in Table 3. Here we present comparisons for several choices for how to divide the populations between quiescent or red galaxies and star-forming or blue galaxies, as specified by a ‘cut-off criterion in the middle column, either in g − r colour or EW(Hα). The corrected samples used in this analysis contain 20 quiescent or red central galaxies for each strongly star forming or blue central galaxy.

The complete sample statistics, presented in the top two rows, include the entire sample of 24,753 galaxies, uncorrected for redshift or stellar mass. We find the neighbour distributions within the complete sample to be marginally different for cut-offs at both g − r = 0.4 and EW(Hα) = 35 Å, with the PKS values of 0.01345 and 0.00264, respectively. The corrected samples demonstrate more significant differences. The highest degree of significance is found for the cut-off at EW(Hα) = 35 Å, which has PKS = 1.350 × 10^{-3}. However, when our resampling method is applied using g − r colour as the cut-off, the difference between the nearest neighbour

![Figure 4](https://example.com/figure4.png)

**Figure 4.** Top panel: the fraction of central galaxies with at least one neighbour in decadal bins ranging from 0 to 200 kpc for 10 Monte Carlo selected samples. The blue dashed line indicates strongly star forming galaxies with EW(Hα) ≥ 35 Å, while the red solid lines are centrals with EW(Hα) < 35 Å. Bottom panel: similar to the top panel, but here we plot the cumulative fraction of centrals with at least one neighbour within a given radius for 10 Monte Carlo samples.

| Sample type | Comparison cut-off | PKS (neighbour) |
|-------------|--------------------|-----------------|
| Complete    | EW(Hα) = 35 Å      | 0.02642         |
| Corrected   | g − r = 0.4        | 0.0145          |
| Corrected   | EW(Hα) = 20 Å      | 8.452 × 10^{-2} |
| Corrected   | EW(Hα) = 35 Å      | 1.350 × 10^{-3} |
| Corrected   | EW(Hα) = 40 Å      | 8.615 × 10^{-3} |
| Corrected   | g − r = 0.4        | 0.1390          |
| Corrected   | g − r = 0.5        | 0.1022          |
| Corrected   | g − r = 0.6        | 2.269 × 10^{-3} |

Table 3. Results of the KS test for nearest neighbour distributions of central galaxies.
distributions for blue and red central galaxies becomes less significant, possibly due to the differing time-scales of $g - r$ as an indicator of recent star formation or simply a consequence of the reduced sample size. Using $g - r$ colour as a proxy for star formation is also prone to errors due to dust reddening, which would tend to cancel out the effect we see when using EW(Hα).

Fig. 5 is a histogram of the differences in apparent r-band magnitude for each companion and its host. The blue dashed line represents companions of strongly star forming hosts, while the red solid line represents quiescent hosts. From this plot, we see that strongly star forming central galaxies tend to have relatively brighter companions than quiescent centrals.

5 DISCUSSION

In summary, we selected a sample of isolated galaxies from SDSS DR6, and by employing a Monte Carlo resampling technique, demonstrated that strongly star forming and quiescent galaxies exhibit different probabilities of having a close companion, even when samples are selected to have matching redshift and stellar mass distributions. When using EW(Hα) as a proxy for star formation, these differences are small (star formers are $\sim 5$ per cent more likely to have a close neighbour) but highly significant ($P_{KS} = \sim 10^{-3}$). Thus, we have shown that strongly star forming and quiescent galaxies exhibit different radial distributions of photometric companions.

We summarize our primary result in Fig. 6, which is similar to Fig. 4 (bottom panel), but here we plot the difference in the cumulative fraction of strongly star forming and quiescent central galaxies as a function of separation. We are again using EW(Hα) = 35 Å as the dividing criterion to separate star-forming and quiescent galaxies. The maximum difference is 5 ± 2 per cent in the 55-kpc-radius bin. We explored the effects of using different EW(Hα) cut-offs in our simulations, and the results are described in Table 3. We explored multiple cut-offs for EW(Hα), but found that EW(Hα) = 35 Å provided the best balance between maintaining adequate sample size and significant differences between the strongly star forming and quiescent samples. When the EW(Hα) cut-off is moved to 40 Å, the size of the sample of strongly star forming galaxies is reduced significantly. Thus, the differences between radial distributions are less statistically significant due to the increase in uncertainty in each radius bin. When the cut-off is lowered to 30 Å, the radial distributions of neighbours become more similar as shown by the increasing $P_{KS}$ values away from EW(Hα) = 35 Å in Table 3. This result is also shown in Fig. 7, where we plot the cumulative fraction of central galaxies with at least one neighbour within each radius for two alternative EW(Hα) cut-offs, 30 and 40 Å. In both cases, the differences in neighbour distributions between the strongly star forming and quiescent central galaxies are severely reduced at large radii ($>100\, h^{-1}\text{kpc}$) and somewhat more moderately reduced at smaller radii. For the EW(Hα) cut-off of 35 Å the maximum difference between strongly star forming and quiescent samples was at the 50 $h^{-1}\text{kpc}$ bin, with 16 ± 1.0 and 11 ± 0.8 per cent having a neighbour with that radius, respectively. In contrast, for EW(Hα) = 30 Å we see 15 ± 0.8 per cent (star-forming) and 11 ± 0.5 per cent (quiescent) with a neighbour within 50 $h^{-1}\text{kpc}$, and for EW(Hα) = 40 Å we see 14 ± 1.5 per cent (strongly star forming) and 10 ± 0.7 per cent (quiescent).

There are several possible explanations for the 5 per cent excess in companions seen for the strongly star forming central galaxies. One possibility is that galaxies are more likely to be star forming if they have a close companion – that is, some small fraction of these star forming galaxies ($\sim 5$ per cent) are star forming because they are experiencing an interaction with a close companion. This is a mechanism that has been well documented in previous studies (Larson & Tinsley 1978; Mihos & Hernquist 1994; Barton et al. 2000; Lambas et al. 2003; Woods et al. 2006). Alternatively, there is something else about having an elevated star formation rate that increases a galaxy’s likelihood to have a close companion. One possibility is that objects that are currently accreting gas via ‘cold-mode’ deposition are more likely to have companionship, as this source of fuel is usually associated with larger scale filamentary...
Figure 7. Top panel: the cumulative fraction of central galaxies with at least one neighbour in decadal bins ranging from 0 to 200 kpc for 10 Monte Carlo selected samples. The blue dashed line indicates strongly star forming galaxies with $\text{EW}(\text{H}\alpha) \geq 30$ Å, while the red solid lines are centrals with $\text{EW}(\text{H}\alpha) < 30$ Å. Bottom panel: similar to the top panel, but here we use an $\text{EW}(\text{H}\alpha)$ cut-off of 40 Å.

Finally, it is possible that there is some systematic error in the determination of $M_*$ which would obscure the fact that the strongly star forming central galaxies in our sample reside in more massive haloes than the less strongly star forming central galaxies. However, this is unlikely, because red galaxies (which generally have lower star formation rates) tend to be in higher mass haloes than blue galaxies.

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