On the origin of red spirals: does assembly bias play a role?

Suman Sarkar,\textsuperscript{a} Biswajit Pandey\textsuperscript{b} and Apashanka Das\textsuperscript{b}

\textsuperscript{a}Department of Physics, Indian Institute of Science Education and Research Tirupati, Tirupati 517507, Andhra Pradesh, India
\textsuperscript{b}Department of Physics, Visva-Bharati University, Santiniketan 731235, India

E-mail: suman2reach@gmail.com, biswap@visva-bharati.ac.in, a.das.cosmo@gmail.com

Received November 23, 2021
Revised January 30, 2022
Accepted February 19, 2022
Published March 10, 2022

Abstract. The formation of the red spirals is a puzzling issue in the standard picture of galaxy formation and evolution. Most studies attribute the colour of the red spirals to different environmental effects. We analyze a volume limited sample from the SDSS to study the roles of small-scale and large-scale environments on the colour of spiral galaxies. We compare the star formation rate, stellar age and stellar mass distributions of the red and blue spirals and find statistically significant differences between them at 99.9\% confidence level. The red spirals inhabit significantly denser regions than the blue spirals, explaining some of the observed differences in their physical properties. However, the differences persist in all types of environments, indicating that the local density alone is not sufficient to explain the origin of the red spirals. Using an information theoretic framework, we find a small but non-zero mutual information between the colour of spiral galaxies and their large-scale environment that are statistically significant (99.9\% confidence level) throughout the entire length scale probed. Such correlations between the colour and the large-scale environment of spiral galaxies may result from the assembly bias. Thus both the local environment and the assembly bias may play essential roles in forming the red spirals. The spiral galaxies may have different assembly history across all types of environments. We propose a picture where the differences in the assembly history may produce spiral galaxies with different cold gas content. Such a difference would make some spirals more susceptible to quenching. In all environments, the spirals with high cold gas content could delay the quenching and maintain a blue colour, whereas the spirals with low cold gas fractions would be easily quenched and become red.

Keywords: galaxy evolution, galaxy formation, galaxy morphology, redshift surveys

ArXiv ePrint: 2111.11252
1 Introduction

Understanding the formation and evolution of galaxies remains one of the most challenging goals in cosmology. The galaxies are the building blocks of the large-scale structures in the Universe. They are distributed along an interconnected filamentary network surrounded by nearly empty regions. They form and evolve in different environments of the cosmic web [1] and they can have various shapes, sizes, masses, colours, star formation rates (SFR) and metallicities. The galaxies can be primarily divided into two distinct morphological types based on their visual appearances, namely the spirals and the ellipticals. The morphological bimodality [2] in the galaxy population has been known for nearly a century. More recently, similar bimodalities have also been observed in galaxy colour [3–6], star formation rate, stellar age [7], bulge to disc ratio [7] and gas to stellar mass ratio [8]. The observed bimodality in optical colour [3–7, 9] indicates that the galaxies in the present Universe can also be segregated into two distinct populations, namely the “blue cloud” and the “red sequence”. The colour bimodality is strongly correlated with morphological bimodality. The spirals are predominantly found in the blue cloud, and the ellipticals are mostly found in the red sequence.

The colour represents the stellar population in a galaxy. The blue colour indicates active star formation, whereas the red colour is known to be associated with quenching of star formation and an older stellar population. The strong correlation between morphology and colour of galaxies indicates that quenching of star formation in galaxies are usually accompanied by a morphological transformation. However, this may not be necessarily true. The transformation to early-type morphologies is not required for quenching. Exception to this correlation is now quite evident from the observational fact that a significant number of ellipticals are part of the blue cloud [10] and a large number of spirals are the members of the
red sequence [11, 12]. Such exceptions may hold important clues about galaxy formation and evolution. These deviations have drawn considerable interest in recent years, and several works have addressed this issue and tried to accommodate these findings within the existing paradigm.

In the present work, we mainly focus on the red spirals and their origin. The presence of the red spirals is first noted by van den Bergh [13] in the Virgo cluster. The red spirals are also detected in distant clusters [14–16] and clusters at low redshift [17–20]. Although the existence of the red spirals is known for quite some time, the data available from these observations are not sufficient to address the issue statistically. The Galaxy Zoo project [87] provides the visual morphological classifications of nearly one million galaxies with the help of the citizen scientists. The studies with Galaxy Zoo data reveal that $\sim 20\%$ of the spiral galaxies are contained in the red sequence [21, 22].

Most of the spiral galaxies are known to be actively star forming. They preferentially reside in the less dense environments [51]. Contrary to this, the red spirals are passive, and they exhibit a preference for the higher density environment even at fixed stellar mass [21]. It suggests an environment dependent suppression of star formation in the red spirals. It has been suggested that mild environmental effects can change the colours of spiral galaxies without altering their morphology. A number of physical processes such as tidal interactions, minor mergers, thermal evaporation [23], ram pressure stripping [24], galaxy harassment [25, 26] and strangulation [27–29] may play a significant role in quenching the star formation in the red spirals. Further, the fact that the red spirals are massive implies that mass quenching [30–33] may have a role in curtailing star formation in these galaxies. A higher bar fraction in the red spirals suggests that bar quenching can also play a role in suppressing the star formation in the red spirals [11]. The morphological quenching may also prohibit star formation in the red spirals by stabilizing the gas disk due to the presence of big bulges in these galaxies [35]. Besides, the high angular momentum of the infalling gas may settle down the gas on the outer part, thereby quenching the star formation in the disk [36]. The red colour of spiral galaxies may also arise due to several other factors such as internal reddening by dust [37], high metallicity [38] and low star formation rate [39].

The existence of the red spirals is clearly at odds with the standard picture of galaxy formation and evolution. Our current understanding of galaxy formation and evolution may need some revision in order to explain the origin of these unconventional objects. A number of works is devoted to explore the origin of red spirals. Masters et al. [11] analyze a sample of visually selected face-on disky red spiral galaxies from the Galaxy Zoo project and propose multiple scenarios for the origin of the red spirals. They suggest that the red spirals could be simply old spirals that have exhausted their gas reservoir. A strong correlation between stellar age and environment in different studies [40–42] suggests that the galaxies start to assemble earlier at higher density environments and have a longer time to use up their gas. Alternatively, the red spirals could be the satellite galaxies in massive dark matter halos where they are stripped off their gas by strangulation [11]. The bar instabilities can also remove the gas from the disk by driving it inwards. Tojeiro et al. [43] analyze data from the Galaxy Zoo project and find that the red spirals and the blue spirals share similar star formation histories at earlier times but depart from each other only in the last 0.5 Gyr. Their chemical composition and dust content are similar, indicating that the red spirals are a recent descendant of the blue spirals. They suggest that the red spirals may represent an evolutionary link between blue spirals and ellipticals. Mahajan et al. [44] analyze the data from the Galaxy and Mass Assembly (GAMA) survey [45] and conclude that the red optical colours in the nearby spiral galaxies are a direct consequence of some environment driven
processes operating on long timescales. Hao et al. [46] analyze data from the SDSS DR15 (Sloan Digital Sky Survey Data Release Fifteen) MaNGA (Apping Nearby Galaxies at APO) observations to find that the central stellar populations in red spirals are more similar to ellipticals than to blue spirals of similar masses. They conclude that the red spirals can not be the evolutionary remnants of blue spirals and are likely a product of very gas-rich mergers above $z \sim 1$. Guo et al. [47] analyze the SDSS data to conclude that different quenching mechanisms and galaxy interactions may jointly cause a suppression of star formation in the red spirals.

Although some roles of environments are indicated in most of the studies, it is still not clear which environmental processes play the crucial role in quenching the red spirals. There is no clear consensus on the evolutionary pathways leading to the red spirals. [48] analyze a sample of red spiral galaxies from the 2-Micron All Sky Survey (2MASS) and conclude that no single mechanism is responsible for quenching in red spirals and only a mixture of different mechanisms may produce the observed red spiral population in the present Universe. [44] show that at fixed stellar mass, the red spirals inhabit denser environments. An increased fraction of red spirals in a higher density environment does not ensure that environment alone is sufficient to transform the optical colour of such galaxies. Masters et al. [11] show that red spirals have lower star formation rates than the blue spirals in all environments, and there are no obvious correlations between the environment and properties of these galaxies. They suggest that the environment alone can not quench the star formation in red spirals. More recently, [49] analyze the SDSS data and find that the fraction of star forming red galaxies is nearly independent of their environment.

Environment plays a vital role in the formation and evolution of galaxies. The observed morphology-density relation [50–52] and SFR-density relation [53–55] show that galaxy properties are strongly correlated with their local environment. The galaxies are part of the large-scale coherent structures such as filaments, sheets or clusters in the cosmic web. The influence of the environment on a galaxy may not be limited to its local density alone. For instance, the mass, shape and angular momentum of the dark matter halos in N-body simulations are known to be sensitive to their large-scale geometric environments [56]. Also, the clustering of dark matter halos is known to depend on halo formation time at fixed halo mass [57–62]. This dependence of halo clustering on the assembly history is popularly known as the ‘assembly bias’, which has been extensively studied in the literature [63–66]. The existence of halo assembly bias is now well established. Similarly, galaxies are also expected to have a wide variety of assembly history at fixed masses. The differences in the assembly history can influence the galaxy properties, which is known as the galaxy assembly bias. The evidence of galaxy assembly bias in observations is highly debated in the literature. Many observations do not find any evidence of assembly bias in the galaxy distribution [67–72]. On the other hand, several studies reported a clear evidence of assembly bias [73–75].

The assembly history of galaxies are correlated with their large-scale environment. The large-scale environmental dependence of galaxy properties may thus signal the existence of galaxy assembly bias. A large number of studies with different observational data sets indicate statistically significant correlations between the large-scale environment and different galaxy properties [76–86].

In this work, we intend to investigate if the galaxy assembly bias plays any role in the formation and evolution of red spirals. If the assembly history of spirals plays any role in determining their colour then the colour of these galaxies should depend on their large-scale environment at fixed mass and morphology. Recently, Pandey & Sarkar [84] analyze the
SDSS data and find that the fraction of red and blue galaxies depend on their geometric environment at fixed density. The correlation between any galaxy property and the large-scale environment can also be measured using the mutual information between them [83]. Sarkar & Pandey [85] propose an information theoretic framework to assess the statistical significance of any observed non-zero mutual information. We plan to use this method to probe if the optical colour of galaxies at fixed stellar mass and fixed morphology is sensitive to their large-scale environment. It would help us verify the role of galaxy assembly bias in deciding the colour of spiral galaxies.

The SDSS measure the photometric and spectroscopic information of millions of galaxies in the nearby Universe. The Galaxy Zoo [87, 88] provides the morphological classification of nearly one million galaxies from the SDSS. They together provide an unprecedented opportunity to study the origin of the red spirals. We use these datasets for the analysis presented in this paper.

The plan of the paper is as follows. We present the data in section 2, describe the method of analysis in section 3, discuss the results in section 4 and present our conclusions in section 5.

2 SDSS data

We use data from the 16th data release [89] of the Sloan Digital Sky Survey (SDSS) [90]. The SDSS is the largest and one of the most successful redshift surveys to date. The technical details of the SDSS photometric camera are described in Gunn et al. [91]. Gunn et al. [92] describe the construction, design and performance of the SDSS telescope. The detailed algorithm for selecting the SDSS main sample for spectroscopy is provided in Strauss et al. [93].

The SDSS, in its fourth phase, targets nearly three million galaxies covering a vast area of 14,555 square degrees of the sky. DR16, the final data release of phase IV, is a superset of all the prior data releases of SDSS to date. SDSS IV provides corrected data for previous bad plates and includes several new objects as targets. We download the data from the SDSS CASjobs1 using Structured Query Language (SQL). We consider all the objects of class galaxy with zwarning = 0 and the apparent r-band Petrosian magnitude $m_r < 17.77$ within redshift range $0 \leq z \leq 0.2$. We join six different tables of the DR16 database to obtain the required information of the galaxies. The photometric and spectroscopic information of the galaxies are taken from SpecPhotoAll and Photoz. The galSpecIndx table provides 4000Å break strength [94] derived from the MPA-JHU spectroscopic catalogue [95] of galaxies. The stellar mass and star formation rate of galaxies estimated using stellar population synthesis model [96] are provided in stellarMassFSPSGranWideDust. The internal dust extinction of the source using Gas AND Absorption Line Fitting (GANDALF) [97] is obtained from emissionLinesPort [98–100]. Finally, the morphologies are specified in the zooSpec table, which provides the visual classification of SDSS galaxies performed through the Galaxy Zoo project [87, 101]. We identify elliptical and spiral galaxies as those which have their elliptical and spiral flag set to 1 (debiased vote fraction > 0.8) respectively. We obtain this information for a total 619007 galaxies by combining the six tables mentioned here.

We then construct a volume limited sample using the downloaded data. We identify a contiguous region within $135^\circ \leq \alpha \leq 225^\circ$, $0^\circ \leq \delta \leq 60^\circ$ and apply a cut in the r-band absolute magnitude $M_r \leq -21$. These cuts provide us with a volume limited sample that

1https://skyserver.sdss.org/casjobs/.
contains 124911 galaxies within $z \leq 0.12$, out of which 46261 are spirals, 12772 are ellipticals and 65878 are galaxies with uncertain morphology.

According to the need of the present work, we only retain the 46261 spiral galaxies in our volume limited sample. We classify these galaxies into red, green and blue classes using the technique discussed in subsection 3.1. This classification scheme divides the galaxies according to their dust corrected $u - r$ colour. We find that the number of blue, green and red spirals in our volume limited samples are 29592, 8120 and 8549, respectively.

One of the important aims of this work is to test the correlation between the colour of spiral galaxies and their large-scale environment. We need to subdivide the region occupied by the red and blue spirals into regular cubic voxels and randomly shuffle them in order to assess the statistical significance of any observed correlations between colour and large-scale environment of the spirals. So we extract the largest cube with sides of $181 h^{-1}$ Mpc that can fit within our volume limited sample. It contains 12589 spiral galaxies, of which 8522, 2133 and 1934 are blue, green and red, respectively. This analysis aims to test the effects of the assembly bias on the colour of spiral galaxies. The assembly bias manifests as a dependence of clustering on the formation time or history at a fixed stellar mass. We choose a fixed stellar mass range $2 \times 10^{10} \leq M / M_\odot \leq 2 \times 10^{11}$ and apply this cut to the galaxies in the cubic region. After adopting the stellar mass cut, we are left with 11800 spiral galaxies of which 8068 are blue, 1963 are green and 1769 are red.

In this work, we use $\Lambda$CDM cosmological model with $\Omega_m = 0.315$, $\Omega_{\Lambda} = 0.685$ and $h = 0.674$ [102].

3 Method of analysis

3.1 Classifying the spirals according to their colours

We adopt a fuzzy set theory based classification scheme proposed in [103]. We briefly describe the primary steps involved in this classification.

Let us consider a fuzzy set $A$ defined as, [104],

$$ A = \{ (x, \mu_A(x)) \mid x \in X \} \quad (3.1) $$

where $A$ is a set of ordered pairs $x$ and the corresponding membership function $\mu_A(x)$. The membership function measures the degree of membership of $x$ by mapping it to a real number in the interval $[0, 1]$.

This method of classification is solely motivated by the observed bimodal distribution of galaxy colours. Our primary goal is to separate the red spirals, and blue spirals from the volume limited sample of spiral galaxies described in the previous section. Both a reduced star formation activity and the presence of dust can redden the colour of spirals. Besides correcting for the dust within our own galaxy, we also make corrections for the dust attenuation in the source galaxy. We use the internal reddening $E(B-V)$ for each galaxy to make this correction.

The fuzzy set $R$ for the redness of galaxies in the volume limited sample is define as,

$$ R = \{ (u - r, \mu_R(u - r)) \mid (u - r) \in X \}. \quad (3.2) $$

Here $X$ is the Universal set of dust corrected $(u - r)$ colour. The membership function for this fuzzy set is described as [103],

$$ \mu_R(u - r; a, c) = \frac{1}{1 + e^{-a[(u-r) - c]}}, \quad (3.3) $$
The above figure shows the membership function for the red, blue and green galaxies. The region in between the two solid black vertical lines represents the green galaxies. The left and the right side of this region corresponds to the blue and the red galaxies respectively.

\[
\text{where } c \text{ and } a \text{ are constants representing the crossover point of the fuzzy set and the slope at the crossover. The choice of the sigmoidal membership function is motivated by the bimodal nature of the } u-r \text{ colour distribution. The two peaks in the bimodal } u-r \text{ colour distribution represent the galaxies in the ‘blue cloud’ and ‘red sequence’, whereas the intermediate valley is believed to be populated by the transitional green galaxies. The observed } u-r \text{ colour distribution is known to dip at } (u-r) \sim 2.2 \text{ where the two distributions for the red and blue population meet each other. The classification according to colour becomes most uncertain at this point. The fuzzy set } R \text{ has the maximum uncertainty in its membership function at the crossover point. A value of } c = 2.2 \text{ is chosen based on this observation. We choose } a = 5.2 \text{ to ensure that the galaxy with the smallest and largest } (u-r) \text{ colour respectively has its membership function 0 and 1 in the fuzzy set } R. \text{ Next, we define the fuzzy set } B \text{ for the ‘blueness’ of galaxies by taking a fuzzy complement of the set } R. \text{ The membership function of the fuzzy set } B \text{ can be written as,}
\]

\[
\mu_B(u-r) = 1 - \mu_R(u-r), \forall (u-r) \in X
\]

(3.4)

Now the fuzzy set \( G \) for the ‘greenness’ of galaxies is defined by simply taking a fuzzy intersection of the sets \( R \) and \( B \). The corresponding membership function is thus defined as,

\[
\mu_G(u-r) = 2 \min \{ \mu_R(u-r), \mu_B(u-r) \}, \forall (u-r) \in X
\]

(3.5)

where \( \min \) in equation (3.5) represents minimum operator. The factor 2 in the right hand side of equation (3.5) is multiplied so as to ensure that galaxies with \( (u-r) = 2.2 \) are maximally green with \( \mu_G(u-r) \) value equal to 1 (figure 1).
Using the scheme described above, we classify red galaxies as those for which \( \mu_R(u-r) \) dominates \( \mu_B(u-r) \) and \( \mu_G(u-r) \). The blue and green galaxies are also classified similarly. For the present analysis, we find that galaxies having \( (u-r) \geq 2.333 \) are red, \( (u-r) \leq 2.067 \) are blue and \( 2.067 < (u-r) < 2.333 \) are green (figure 1). We classify the 46261 spiral galaxies in our volume limited sample as red, blue and green based on the above criteria. We find that our volume limited sample contains 29592 blue spirals, 8549 red spirals and 8120 green spirals.

### 3.2 Comparing the properties of red and blue spirals using KS-test

We consider all the blue and red spirals (29592 blue and 8549 red) in our volume limited sample and determine the probability distribution functions (PDFs) of their stellar mass, star formation rate, D4000 and local density. The stellar mass, star formation rate and D4000 for the blue and red spirals are obtained from the SDSS database as described in section 2. We calculate the local number density for each of the galaxies using \( k \)th nearest neighbour method \[105\]. We measure the distance between a galaxy and its \( k \)th closest galaxy, which we denote as \( r_k \). The local number density around a galaxy is given by

\[
\eta_k = \frac{k-1}{V(r_k)}
\]  

(3.6)

where, \( V(r_k) = \frac{4}{3} \pi r_k^3 \). We choose \( k = 5 \) for this analysis.

We want to test the differences in the properties of the blue and red spirals. The null hypothesis assumes that the red and blue spirals have identical probability distributions for these properties. We test the null hypothesis using a Kolmogorov-Smirnov test.

The Kolmogorov-Smirnov test is a non-parametric test that does not make any assumptions about the distributions. We calculate the maximum difference between cumulative distribution functions (CDFs) for the two samples. The supremum difference between the two CDFs \( D_{KS} \) is defined as

\[
D_{KS} = \sup_X \{ |f_{1,m}(X) - f_{2,m}(X)| \}
\]  

(3.7)

\( f_{1,m}(X) \) and \( f_{2,m}(X) \) are the cumulative distribution functions of a chosen property \( X \) in the \( m \)th bin for the red and blue spirals respectively. Here \( m \in \{1,2,3, \ldots, N' \} \) and sup operator represents the supremum of all the \( (N'_1 + N'_2) \) differences. Here \( N'_1 \) and \( N'_2 \) are the number of red and blue spirals in the sample.

One can test the null hypothesis at different significance level \( \alpha \) to find if the PDFs for the red and blue spirals are significantly different. One can obtain the critical value of the supremum difference corresponding to a given significance level \( \alpha \) as,

\[
D_{KS}(\alpha) = \sqrt{-\ln\left(\frac{\alpha}{2}\right) \frac{N'_1 + N'_2}{2N'_1N'_2}}
\]  

(3.8)

The null hypothesis may be rejected or accepted depending on whether the measured value \( D_{KS} \) is greater or smaller than its critical value at a given significance level \( \alpha \). If \( D_{KS} > D_{KS}(\alpha) \), then the null hypothesis is rejected at a significance level \( \alpha \).
3.3 Mutual information between color and environment of spirals

We extract the largest cubic region with side $L h^{-1} \text{Mpc}$ that fit within our volume limited sample and consider only the red and blue spirals within it. We subdivide the entire cube in $N_d$ number of $d h^{-1} \text{Mpc} \times d h^{-1} \text{Mpc} \times d h^{-1} \text{Mpc}$ voxels. A discrete random variable $X$ is defined with $N_d$ outcomes $\{x_i : i = 1, \ldots, N_d\}$ which corresponds to the environment at length scale $d$. The probability of finding a randomly selected galaxy in the $i^{th}$ cube is $p(x_i) = \frac{N_i}{N}$, where $N_i$ is the number of galaxies in the $i^{th}$ voxel and $N$ is the total number of galaxies in the cube. The Shannon entropy associated with the environment at scale $d$ is given by

$$H(X) = - \sum_{i=1}^{N_d} p(x_i) \log p(x_i)$$

$$= \log N - \frac{N_i \log N_i}{N} \quad (3.9)$$

We use another variable $Y$ to describe the colour of the galaxies. Our data consists of only spiral galaxies that are either blue or red. If the cube consists of $N_b$ blue spirals and $N_r$ red spirals then the information entropy for colour will be

$$H(Y) = - \left( \frac{N_b}{N} \log \frac{N_b}{N} + \frac{N_r}{N} \log \frac{N_r}{N} \right)$$

$$= \log N - \frac{N_b \log N_b + N_r \log N_r}{N} \quad (3.10)$$

One can determine the mutual information between the environment ($X$) of the galaxies and their colour ($Y$). The mutual information is defined as

$$I(X;Y) = H(X) + H(Y) - H(X,Y) \quad (3.11)$$

If $N_{ij}$ is the number of galaxies in the $i^{th}$ voxel that belongs to the $j^{th}$ colour, then $H(X,Y)$ is the joint entropy given by

$$H(X,Y) = - \sum_{i=1}^{N_d} \sum_{j=1}^{2} p(x_i, y_j) \log p(x_i, y_j)$$

$$= \log N - \frac{1}{N} \sum_{i=1}^{N_d} \sum_{j=1}^{2} N_{ij} \log N_{ij} \quad (3.12)$$

where

$$\sum_{i=1}^{N_d} \sum_{j=1}^{2} N_{ij} = N \quad (3.13)$$

and $p(x_i, y_j) = p(x_i|y_j) p(y_j) = \frac{N_{ij}}{N}$ following Bayes’ theorem.

The two random variables may share information about each other and $H(X,Y)$ is a measure of the information mutually shared by them. In other words, $H(X,Y)$ is the reduction in uncertainty in one random variable given the knowledge of the other.
3.4 Randomizing the colour tags of blue and red spirals

We take each of the spiral galaxies in the cube and randomly tag them as blue spirals or red spirals, obliterating their actual colour. We do it in such a way that both the number of red spirals and blue spirals in the new distribution remains the same as the original one. Here the position of galaxies being unchanged, the entropy $H(X)$ would be unaltered at a given length scale. Similarly, the value of $H(Y)$ would not change as the number of galaxies in each category (red and blue) remains the same. However, this would change the joint entropy $H(X,Y)$ by destroying any existing correlation between the colour of spiral galaxies and their environment. The joint probability distribution, in this case, would be simply a product of the individual probabilities, $p(X_i,Y_j) = p(X_i)p(Y_j)$. Ideally, the randomization of colour tags should completely erase any non-zero mutual information between the environment and the colour of the spiral galaxies. One can test if the observed mutual information is physical or not by comparing the mutual information $I(X;Y)$ in the randomized and the original distributions and assessing the statistical significance of the correlations at different length scales.

3.5 Shuffling of subdivided cubes

In subsection 3.4, we discuss how the randomization of the colour tags would destroy any existing correlations between the colour of spiral galaxies and their environment. One can also destroy any such existing correlations by randomizing the spatial distribution of the galaxies while keeping their colour tags intact. We divide the entire cube of size $L h^{-1} \text{Mpc}$ containing the spiral galaxies in smaller sub-cubes of size $l_s = \frac{L}{n_s}$. Here $n_s$ is the number of segments made along each side of the cube. We ensure that the side of the sub-cubes (shuffling length) corresponding to each $n_s$ is not equal or an integral multiple of the grid size employed for calculation of the mutual information. We randomly pick any of the $N_c = n_s^3$ subcubes and allow them to swap positions. A random rotation of the sub-cubes in multiples of $90^\circ$ is performed each time. This random shuffling process followed by random rotation is repeated $100 \times N_c$ times so that all the cubes are properly shuffled. We carry this whole exercise for three choices $n_s = 3$, $n_s = 7$ and $n_s = 15$ that corresponds to shuffling lengths of $\sim 60 h^{-1} \text{Mpc}$, $\sim 26 h^{-1} \text{Mpc}$ and $\sim 12 h^{-1} \text{Mpc}$ respectively.

The shuffling of the subcubes does not affect the spiral galaxies’ colour and only alters their spatial distribution within the cube. It destroys all the coherent patterns in the spatial distribution above the shuffling length $l_s$, resulting in a significant reduction in the mutual information $I(X;Y)$. The clustering of the galaxies on a length scale $< l_s$ would remain nearly intact. Most of the coherent features spanning up to $l_s$ would survive the shuffling procedure. However, the shuffling may also destroy such features if they lie across the subcubes. So we also expect a small reduction in $I(X;Y)$ below $l_s$. The shuffling may also introduce some spurious spatial patterns due to pure chance alignments. However, these random features are not expected to introduce a physical correlation between the environment and the colour of the spiral galaxies. A comparison of the mutual information in the shuffled and the original distributions can be used to test the statistical significance of the observed correlations between environment and colour.

3.6 Testing statistical significance of the mutual information with t-test

We test the statistical significance of the mutual information between colour and environment of the spiral galaxies using an equal variance $t$-test. The $t$-test is carried out to determine if the means of two sets of data are significantly different from each other. The $t$ score at each
length scale is determined as,

\[ t = \frac{|\bar{X}_1 - \bar{X}_2|}{\sigma_s \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \quad (3.14) \]

where \( \bar{X}_1 \) and \( \bar{X}_2 \) are the average values, \( \sigma_1 \) and \( \sigma_2 \) are the standard deviations and

\[ \sigma_s = \sqrt{\frac{(n_1-1)\sigma_1^2 + (n_2-1)\sigma_2^2}{n_1+n_2-2}}. \]

Here, \( n_1 \) and \( n_2 \) are the number of datapoints associated with the two distributions and \((n_1 + n_2 - 2)\) is the degree of freedom in this test. A large t-score indicates a significant difference between the means of the two datasets whereas a small t-score indicates that the means are similar. We use a significance level \( \alpha = 0.0005 \) that corresponds to 99.9% confidence.

The null hypothesis assumes that the average mutual information in the two distributions is statistically similar at any given length scale. The randomization of colour and shuffling the spatial distribution may reduce the mutual information statistically. A statistically significant reduction in the mutual information conveys a physical correlation between the two random variables.

4 Results

4.1 Physical properties and the local environments of red and blue spirals

We compare the PDFs of different galaxy properties and local environments for the red and blue spirals in the left panels of figure 2. The corresponding CDFs are shown in the respective right panels of the same figure. Different panels clearly show that the distributions are noticeably different for the red and the blue spirals in each case. It is clear that the distributions of the physical properties like stellar mass, star formation rate and \( D_{4000} \) are significantly different for the red and blue spirals. The red spirals tend to be more massive compared to the blue spirals. They host an older stellar population with a relatively lower star formation rate than the blue spirals. We assess the statistical significance of the differences in each case with a Kolmogorov-Smirnov test. The results of these tests are tabulated in table 1. We find that the null hypothesis can be rejected at 99.9% confidence level for each property. We note that the local density of the red and blue spirals are also different in a statistically significant way where the null hypothesis can also be rejected at 99.9% confidence level. Observations suggest that the red spirals tend to inhabit relatively denser regions compared to the blue spirals. So the local environment may play some role in the formation of the red spirals. The critical question is whether these differences in the physical properties of the red and blue spirals are solely due to their local environments alone. It is well known that the more massive galaxies are generally found in relatively denser regions. But the differences in the stellar mass distributions of the red and blue spirals may not purely arise due to the differences in their environmental density alone. [44] show that at fixed stellar mass, the red spirals prefer denser environments. They also find that the stellar mass of red spirals is anti-correlated with the density of their environment. A number of other studies indicate that there are no significant correlation between the environment and the colour of spiral galaxies [11, 49].

We also test if the differences in the physical properties of the red and blue spirals persist in different types of environments. We divide the combined sample of red and blue spirals into two subsamples based on the local density. The median density of the sample is used to separate the galaxies in the high-density and low-density regions. We define the
Figure 2. The four left panels in this figure respectively show the PDFs of $\log(M_{\text{stellar}}/M_{\odot})$, star formation rate (SFR), local density ($\eta_5$) and $D_{4000}$ for the red spirals and blue spirals in our volume limited sample. The corresponding CDFs are shown in the four right panels of this figure.
red and blue spirals with local density above the median as from high-density regions and those with a local density below the median from low-density regions. There are 13987 blue spirals and 5084 red spirals in the high-density regions and 15605 blue spirals and 3465 red spirals in the low-density regions. Our goal is to separately compare the PDFs of different physical properties of the red and blue spirals in the low-density and high-density regions. The comparisons are shown in figure 3. Only the PDFs of stellar mass, star formation rate and $D_{4000}$ for the red and blue spirals in the low-density and high-density regions are shown in this figure. The CDFs are not shown here. We test the differences in these PDFs using Kolmogorov-Smirnov test in each case. The tests show that the PDFs of different physical properties.
properties for the red and blue spirals are statistically different at 99.9% significance level both in the low-density and high-density regions. It indicates that the local environment alone can not explain the origin of the red spirals. The assembly history of the spiral galaxies may also have a role in their formation. We test this possibility using an information theoretic framework and discuss the results in the following subsection.

4.2 Effects of randomization on the mutual information

We measure the mutual information between the colour of spiral galaxies and their large-scale environment as a function of length scales. The solid red line in the top left panel of figure 4 show the mutual information between the colour and environment of the spiral galaxies in our volume limited sample. The results show that the correlation between the colour and the environment of spiral galaxies decreases with the increasing length scales. We observe a non-zero mutual information between the two variables throughout the entire length scales considered here. It is crucial to test the statistical significance of any such non-zero mutual information. A statistically significant non-zero mutual information on a given length scale would suggest that the environment on that length scale have a role in deciding the colours of spiral galaxies.

We construct ten mock Poisson random distributions within an identical cubic region, each with the same number of points (10456) as there are total number of red and blue spirals in the actual SDSS data cube. The original SDSS data cube contains 8522 blue spirals and 1934 red spirals. We randomly tag 1934 points as red spirals in each mock dataset, and the remaining data points are tagged as blue spirals. We carry out an analysis with these mock datasets in the same way. The mutual information between the colour and environment of spiral galaxies in these mock random datasets are shown in the top left panel of figure 4 with a dotted black line. The mutual information in the actual SDSS dataset is higher than the mock random dataset at most scales. It may be noted that the mutual information in the random dataset is higher than in the actual dataset at the smallest grid size. It indicates the dominance of the Poisson noise on such length scales. The shot noise decreases with the increasing voxel sizes, and the differences in the mutual information in the actual and random data sets are evident at larger length scales.

We further randomize the colour tags of spiral galaxies in the actual SDSS data without affecting their spatial distributions. The numbers of red and blue spirals in the randomized datasets are identical to the original SDSS data. We generate ten such new distributions and
Figure 4. The top left and bottom left panels of this figure show the mutual information between colour and environment of spirals as a function of length scales. The top left panel shows the effect of randomization, and the bottom left panel shows the effect of shuffling on the mutual information. The $1 - \sigma$ error bars for the SDSS data points are obtained by jackknife resampling. It is obtained for the randomized and shuffled data using ten different realizations in each case. The top right and the bottom right panels show the t-score for the differences in the mutual information caused by randomization and shuffling, respectively. The threshold value of the t-score corresponding to 99.9% confidence level are shown together with a horizontal line in these two panels.

We carry out an analysis in the same way. The results are shown in the top left panel of figure 4 where we find that mutual information in the randomized data sets is nearly identical to that with the mock Poisson random distribution. The randomization of the colour tags reduces the mutual information at nearly all length scales. We use a t-test to assess the difference between the mutual information in the original and the randomized data sets. The resulting t-score at each length scale is shown in the top right panel of figure 4. The t-scores and the corresponding p-values for different grid size are also listed in table 2. The threshold value of the t-score corresponding to 99.9% confidence level is shown together with a horizontal line in the same panel. We find that the differences between the mutual information in the original and randomized data are statistically significant at 99.9% confidence level at all length scales probed.
Table 2. This table shows the $t$ score and the associated $p$ value at each length scale when we compare the mutual information in the actual SDSS data and the SDSS data with randomized classification.

| Grid size ($h^{-1}$ Mpc) | $t$ score | $p$ value       |
|--------------------------|-----------|----------------|
| 15.08                    | 4.619     | $1.06 \times 10^{-4}$ |
| 16.45                    | 8.419     | $5.87 \times 10^{-8}$ |
| 18.10                    | 9.733     | $6.76 \times 10^{-9}$ |
| 20.11                    | 8.385     | $6.23 \times 10^{-8}$ |
| 22.62                    | 12.513    | $1.28 \times 10^{-10}$ |
| 25.86                    | 14.679    | $9.24 \times 10^{-12}$ |
| 30.17                    | 17.814    | $3.51 \times 10^{-13}$ |
| 36.20                    | 19.359    | $8.44 \times 10^{-14}$ |
| 45.25                    | 26.193    | $4.37 \times 10^{-16}$ |
| 60.33                    | 34.434    | $3.49 \times 10^{-18}$ |
| 90.50                    | 35.924    | $1.64 \times 10^{-18}$ |

4.3 Effects of shuffling on the mutual information

We divide the SDSS data cube into a number of subcubes and shuffle them around many times following the method described in subsection 3.5. The mutual information between colour and environments of the spiral galaxies before and after shuffling the spatial distributions are shown in the bottom left panel of figure 4. The results for the mock Poisson samples are also shown together in the same panel. We find that the mutual information between colour and environment reduces after shuffling at nearly all length scales. Shuffling the data is expected to destroy any spatial coherence in the galaxy distribution beyond the size of the subcubes. Decreasing the size of the subcubes causes a larger reduction in the mutual information as this destroys more coherent patterns at smaller length scales. Shuffling the data with subcubes of size $12 h^{-1}$ Mpc causes the mutual information in the shuffled data to nearly coincide with that from the mock Poisson distributions. It indicates that the mutual information between the colour and the large-scale environment would be completely erased when the data is shuffled with subcubes smaller than $12 h^{-1}$ Mpc.

We test the statistical significance of the differences in the mutual information in the original SDSS data and its shuffled realizations using a t-test. The resulting $t$-scores at different length scales are shown in the bottom right panel of figure 4 and also in table 3. The mutual information is dominated by the Poisson noise at smaller length scales. The mutual information in both the shuffled SDSS data and the original SDSS data are quite similar to unshuffled mock Poisson datasets at these length scales. It is clear that the differences are statistically significant at 99.9% confidence level throughout the entire length scale above $20 h^{-1}$ Mpc. Such statistically significant reduction in the mutual information due to shuffling indicates that the observed correlations between colour and environment of spirals on large-scales are physical.
We study the distributions of different physical properties like stellar mass, star formation rate, stellar age of the red and blue spiral galaxies in a volume limited sample from the SDSS. We compare the distributions of the red and blue spirals using a Kolmogorov-Smirnov test and find that the differences are statistically significant at 99.9% confidence level. We also compare the distributions of the local density of the red and blue spirals. Our results show that the red spirals inhabit relatively denser regions compared to the blue spirals and the local environments of the red and blue spirals differ statistically at 99.9% confidence level. The galaxy properties are known to be strongly correlated with their environments. So the local environments of the spirals must have some roles in transforming their colour and deciding their physical properties. However, it is essential to test if the differences in the colour and other physical properties of the spirals are entirely due to the differences in their local environments alone. We separately compare the physical properties of the red and blue spirals in the low-density and high-density regions of our sample and find that the differences are statistically significant at 99.9% confidence level in both types of environments. It implies that the local density of environment alone is not sufficient to explain the differences in the physical properties of the red and blue spirals. These results are in good agreement with a number of earlier works [11, 49].

Many earlier studies point out the role of higher density environments in the formation of red spirals. The environmental processes such as tidal interactions, minor mergers, thermal evaporation, ram pressure stripping, galaxy harassment and strangulation may initiate quenching of star formation in spiral galaxies in such environments. Other mechanism such as halo quenching, morphological quenching and bar quenching may also have some role in such transformation. These mechanisms are either driven by their local environment or triggered by

| Grid size $(h^{-1}\text{Mpc})$ | $n_s = 3$ | $n_s = 7$ | $n_s = 15$ |
|-------------------------------|-----------|-----------|-----------|
| $t$ score                     | $p$ value | $t$ score | $p$ value | $t$ score | $p$ value |
| 15.08                         | —         | 7.777     | $1.82 \times 10^{-7}$ | 8.649     | $3.96 \times 10^{-8}$ |
| 16.45                         | 0.676     | 2.53 $\times 10^{-1}$ | 1.566     | $6.73 \times 10^{-2}$ | 1.541     | $7.02 \times 10^{-2}$ |
| 18.10                         | 1.722     | 5.10 $\times 10^{-2}$ | 0.468     | $3.22 \times 10^{-1}$ | 1.617     | $6.16 \times 10^{-2}$ |
| 20.11                         | —         | 1.473     | $7.88 \times 10^{-2}$ | 2.161     | $2.22 \times 10^{-2}$ |
| 22.62                         | 3.962     | 4.56 $\times 10^{-4}$ | 3.558     | $1.12 \times 10^{-3}$ | 8.250     | $7.88 \times 10^{-8}$ |
| 25.86                         | 7.691     | 2.13 $\times 10^{-7}$ | —         | —         | 8.878     | $2.70 \times 10^{-8}$ |
| 30.17                         | —         | 8.954     | $2.37 \times 10^{-8}$ | 16.770    | $9.86 \times 10^{-13}$ |
| 36.20                         | 5.185     | 3.11 $\times 10^{-5}$ | 10.181    | $3.38 \times 10^{-9}$ | 12.897    | $7.83 \times 10^{-11}$ |
| 45.25                         | 9.884     | 5.33 $\times 10^{-9}$ | 13.659    | $3.05 \times 10^{-11}$ | 21.619    | $1.25 \times 10^{-14}$ |
| 60.33                         | —         | 21.800    | $1.08 \times 10^{-14}$ | 29.782    | $4.55 \times 10^{-17}$ |
| 90.50                         | 11.997    | 2.53 $\times 10^{-10}$ | 26.307    | $4.05 \times 10^{-16}$ | 32.021    | $1.26 \times 10^{-17}$ |

Table 3. This table shows the $t$ score and the associated $p$ value at each length scale when we compare the mutual information between actual SDSS data and its shuffled realizations for different shuffling lengths. The grid size for each $n_s$ is chosen so that the shuffling length is not equal or an integral multiple of the grid size.

5 Conclusions

We study the distributions of different physical properties like stellar mass, star formation rate, stellar age of the red and blue spiral galaxies in a volume limited sample from the SDSS. We compare the distributions of the red and blue spirals using a Kolmogorov-Smirnov test and find that the differences are statistically significant at 99.9% confidence level. We also compare the distributions of the local density of the red and blue spirals. Our results show that the red spirals inhabit relatively denser regions compared to the blue spirals and the local environments of the red and blue spirals differ statistically at 99.9% confidence level. The galaxy properties are known to be strongly correlated with their environments. So the local environments of the spirals must have some roles in transforming their colour and deciding their physical properties. However, it is essential to test if the differences in the colour and other physical properties of the spirals are entirely due to the differences in their local environments alone. We separately compare the physical properties of the red and blue spirals in the low-density and high-density regions of our sample and find that the differences are statistically significant at 99.9% confidence level in both types of environments. It implies that the local density of environment alone is not sufficient to explain the differences in the physical properties of the red and blue spirals. These results are in good agreement with a number of earlier works [11, 49].

Many earlier studies point out the role of higher density environments in the formation of red spirals. The environmental processes such as tidal interactions, minor mergers, thermal evaporation, ram pressure stripping, galaxy harassment and strangulation may initiate quenching of star formation in spiral galaxies in such environments. Other mechanism such as halo quenching, morphological quenching and bar quenching may also have some role in such transformation. These mechanisms are either driven by their local environment or triggered by
the internal processes within the galaxies. None of these environmental processes or quenching mechanisms can explain the origin of the red spirals alone. Rather, combinations of these mechanisms is required to produce the present day population of red spirals [48]. Even then there will be a large uncertainty in the evolutionary pathways leading to the red spirals.

In the present work, we test if the colour of the spiral galaxies is affected by their large-scale environment. We measure the mutual information between the colour and environment of the spiral galaxies on different length scales. We find a small but non-zero mutual information between colour and environment throughout the entire length scale probed. We randomize the colour tags without affecting the spatial distribution of the spiral galaxies and find that it decreases the mutual information at each length scale. The differences between the original and the randomized datasets are statistically significant at 99.9% confidence level at all length scales. We then shuffle the spatial distribution of the spiral galaxies retaining their original colour tags. The shuffling procedure also decreases the mutual information at each length scale. A larger drop in mutual information is observed when the data is shuffled at smaller length scales. We test the statistical significance of the observed differences between the original and shuffled datasets. The test shows that the differences are statistically significant at 99.9% confidence level for nearly the entire length scale.

Several observational studies [76–86] show that the physical association between galaxy properties and environment extend much beyond the size of their host halo. In this work, we test if the colour of galaxies at fixed stellar mass and fixed morphology is sensitive to the large-scale environment. Our analysis shows that the correlations between the colour of the spiral galaxies and their large-scale environments are statistically significant and hence physical. This implies that the colour of spiral galaxies at fixed stellar mass exhibit an additional dependence on their large-scale clustering. Such an additional dependence on the large-scale clustering may arise due to the assembly bias. The clustering of dark matter halos are known to depend on their mass [106]. But the clustering also depends on the assembly history of the dark matter halos [60]. The formation time of smaller halos can differ with their large-scale environment [107]. It has been also suggested that the mass accretion rates of the dark matter halos at fixed stellar mass may be correlated even at larger distances if they are hosted in the same large-scale tidal environment [108]. In the halo model, the galaxy properties are entirely determined by the mass of the host halo. But the halo occupation distribution is also sensitive to the large-scale environment of the halo [57, 59]. Zehavi et al. [109] analyze the semi-analytic models applied to the Millennium simulation and find that the central galaxies at lower halo mass are more likely to be hosted in the early-forming halos whereas the opposite is true for the satellite galaxies. A recent analysis [110] of the IllustrisTNG simulations [111] explores the signatures of the assembly bias on the physical properties of galaxies and their large-scale distributions.

The morphological transformations are very often associated with the quenching of star formation. However, the existence of the red spirals suggests that quenching can also occur without any morphological transformation. There may exist multiple evolutionary pathways from the blue cloud to the red sequence. We propose one such pathway based on the results of our analysis. The assembly history of the galaxies may play an important role beside their local environment. The mass assembly history of the spiral galaxies may differ significantly [112, 113]. Such differences can make some spirals more susceptible to mild environmental effects than others. A recent study based on hydrodynamic simulations indicates that the halo assembly bias may lead to a wide variation in the amount of cold gas within halos [114]. The early-formed halos accumulate large cold gas fractions which can
delay the onset of quenching. On the other hand, the late-formed halos have a poor cold gas supply. The galaxies in the late-formed halos thus remain more vulnerable to quenching. One can explain the origin of the red spirals by considering a combined role of the assembly bias and the local environment. The physical properties of the red and blue spirals differ both at the low-density and high-density regions. This may partly arise due to the difference in the assembly history of spiral galaxies across all types of environments. The quenching in spirals in the high-density regions is primarily driven by different environmental effects like minor mergers, stripping and strangulation. In contrast, internal physical processes like mass quenching, morphological quenching and bar quenching may play a more important role in quenching the spirals in the low-density regions. The spiral galaxies in the early formed halos retain large amount of cold gas that helps them to maintain a blue colour by delaying the quenching. The spirals in the late-formed halos may be easily quenched and turn red due to their poor cold gas supply. However, it is not possible to fully ascertain this from the current analysis. Further studies are required to understand better the roles of assembly bias on the formation of the red spirals.

Acknowledgments

We thank an anonymous reviewer for useful comments and suggestions that helped us to improve the draft. The authors thank the SDSS team and the Galaxy Zoo team for making the data publicly available. We also greatly acknowledge the efforts of the citizen scientists in the Galaxy Zoo and Galaxy Zoo 2 projects who made the detailed visual morphological classifications of the SDSS galaxies possible.

BP would like to acknowledge financial support from the SERB, DST, Government of India through the project CRG/2019/001110. BP would also like to acknowledge IUCAA, Pune, for providing support through the associateship programme. SS thanks IISER, Tirupati, for providing support through a postdoctoral fellowship.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, University of Cambridge, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.
References

[1] J.R. Bond, L. Kofman and D. Pogosyan, How filaments are woven into the cosmic web, Nature 380 (1996) 603 [astro-ph/9512141] [inSPIRE].

[2] E.P. Hubble, Extragalactic nebulae, Astrophys. J. 64 (1926) 321 [inSPIRE].

[3] SDSS collaboration, Color separation of galaxy types in the Sloan Digital Sky Survey imaging data, Astron. J. 122 (2001) 1861 [astro-ph/0107201] [inSPIRE].

[4] SDSS collaboration, The Overdensities of Galaxy Environments as a Function of Luminosity and Color, Astrophys. J. Lett. 585 (2003) L5 [astro-ph/0212085] [inSPIRE].

[5] M.L. Balogh, I.K. Baldry, R. Nichol, C. Miller, R. Bower and K. Glazebrook, The Bimodal galaxy color distribution: Dependence on luminosity and environment, Astrophys. J. Lett. 615 (2004) L101 [astro-ph/0406266] [inSPIRE].

[6] I.K. Baldry et al., Quantifying the bimodal color-magnitude distribution of galaxies, Astrophys. J. 600 (2004) 681 [astro-ph/0309710] [inSPIRE].

[7] SDSS collaboration, The Dependence of star formation history and internal structure on stellar mass for 10^5 low-redshift galaxies, Mon. Not. Roy. Astron. Soc. 341 (2003) 54 [astro-ph/0205070] [inSPIRE].

[8] S.J. Kannappan, Linking gas fractions to bimodalities in galaxy properties, Astrophys. J. Lett. 611 (2004) L89 [astro-ph/0405136] [inSPIRE].

[9] M.R. Blanton et al., Estimating fixed frame galaxy magnitudes in the SDSS, Astron. J. 125 (2003) 2348 [astro-ph/0205243] [inSPIRE].

[10] K. Schawinski et al., Galaxy Zoo: A sample of blue early-type galaxies at low redshift, Mon. Not. Roy. Astron. Soc. 396 (2009) 818 [arXiv:0903.3415] [inSPIRE].

[11] K.L. Masters et al., Galaxy Zoo: Passive Red Spirals, Mon. Not. Roy. Astron. Soc. 405 (2010) 783 [arXiv:0910.4113] [inSPIRE].

[12] A. Fraser-McKelvie, M.J.I. Brown, K.A. Pimbblet, T. Dolley, J.P. Crossett and N.J. Bonne, A photometrically and spectroscopically confirmed population of passive spiral galaxies, Mon. Not. Roy. Astron. Soc. 462 (2016) L11.

[13] S. van den Bergh, A new classification system for galaxies, Astrophys. J. 206 (1976) 883.

[14] W.J. Couch, A.J. Barger, I. Smail, R.S. Ellis and R.M. Sharples, Morphological studies of the galaxy populations in distant butcher-oemler clusters with HST. 2. AC 103, AC 118 and AC 114 at z = 0.31, Astrophys. J. 497 (1998) 188 [astro-ph/9711019] [inSPIRE].

[15] A. Dressler et al., A Spectroscopic catalog of 10 distant rich clusters of galaxies, Astrophys. J. Suppl. 122 (1999) 51 [astro-ph/9901263] [inSPIRE].

[16] B. Poggianti et al., The Star formation histories of galaxies in distant clusters, Astrophys. J. 518 (1999) 576 [astro-ph/9901264] [inSPIRE].

[17] T. Goto et al., The Morphology-density relation in the SDSS, Mon. Not. Roy. Astron. Soc. 346 (2003) 601 [astro-ph/0312043] [inSPIRE].

[18] S.M. Moran et al., Galex observations of passive spirals in the cluster cl 0024+17: clues to the formation of s0 galaxies, Astrophys. J. Lett. 641 (2006) L97 [astro-ph/0603182] [inSPIRE].

[19] C. Wolf et al., The STAGES view of red spirals and dusty red galaxies: Mass-dependent quenching of star-formation in cluster infall, Mon. Not. Roy. Astron. Soc. 393 (2009) 1302 [arXiv:0811.3873] [inSPIRE].

[20] A. Gallazzi et al., Obscured star formation in intermediate-density environments: A Spitzer study of the Abell 901/902 supercluster, Astrophys. J. 690 (2009) 1883 [arXiv:0809.2042] [inSPIRE].

– 19 –
[21] S.P. Bamford et al., Galaxy Zoo: the independence of morphology and colour, Mon. Not. Roy. Astron. Soc. 393 (2009) 1324 [arXiv:0805.2612] [inSPIRE].

[22] R.A. Skibba et al., Galaxy Zoo: Disentangling the Environmental Dependence of Morphology and Colour, Mon. Not. Roy. Astron. Soc. 399 (2009) 966 [arXiv:0811.3970] [inSPIRE].

[23] L.L. Cowie and A. Songaila, Thermal evaporation of gas within galaxies by a hot intergalactic medium, Nature 266 (1977) 501.

[24] J.E. Gunn and J.R. Gott, III, On the Infall of Matter into Clusters of Galaxies and Some Effects on Their Evolution, Astrophys. J. 176 (1972) 1 [inSPIRE].

[25] B. Moore, N. Katz, G. Lake, A. Dressler and A. Oemler Jr., Galaxy harassment and the evolution of clusters of galaxies, Nature 379 (1996) 613 [astro-ph/9510034] [inSPIRE].

[26] B. Moore, G. Lake and N. Katz, Morphological transformation from galaxy harassment, Astrophys. J. 495 (1998) 139 [astro-ph/9701211] [inSPIRE].

[27] R.B. Larson, B.M. Tinsley and C.N. Caldwell, The evolution of disk galaxies and the origin of S0 galaxies, Astrophys. J. 237 (1980) 692 [inSPIRE].

[28] M.L. Balogh, J.F. Navarro and S.L. Morris, The origin of star formation gradients in rich galaxy clusters, Astrophys. J. 540 (2000) 113 [astro-ph/0004078] [inSPIRE].

[29] D. Kawata and J.S. Mulchaey, Strangulation in Galaxy Groups, Astrophys. J. Lett. 672 (2008) L103 [arXiv:0707.3814] [inSPIRE].

[30] Y. Birnboim and A. Dekel, Virial shocks in galactic haloes?, Mon. Not. Roy. Astron. Soc. 345 (2003) 349 [astro-ph/0302161] [inSPIRE].

[31] A. Dekel and Y. Birnboim, On the origin of bimodality in galaxy properties: Cold flows vs. shock heating, clustering and feedback, Mon. Not. Roy. Astron. Soc. 368 (2006) 2 [astro-ph/0412300] [inSPIRE].

[32] D. Keres, N. Katz, D.H. Weinberg and R. Dave, How do galaxies get their gas?, Mon. Not. Roy. Astron. Soc. 363 (2005) 2 [astro-ph/0407095] [inSPIRE].

[33] J.M. Gabor, R. Dave, K. Finlator and B.D. Oppenheimer, How is Star Formation Quenched in Massive Galaxies?, Mon. Not. Roy. Astron. Soc. 407 (2010) 749 [arXiv:1001.1734] [inSPIRE].

[34] F. Combes and R.H. Sanders, Formation and properties of persisting stellar bars, Astron. Astrophys. 96 (1981) 164.

[35] M. Martig, F. Bournaud, R. Teyssier and A. Dekel, Morphological quenching of star formation: making early-type galaxies red, Astrophys. J. 707 (2009) 250 [arXiv:0905.4669] [inSPIRE].

[36] Y. jie Peng and A. Renzini, Disc growth and quenching, Mon. Not. Roy. Astron. Soc.: Letters 491 (2019) L51.

[37] S.P. Driver et al., The Millennium Galaxy Catalogue: the B-band attenuation of bulge and disc light and the implied cosmic dust and stellar mass densities, Mon. Not. Roy. Astron. Soc. 379 (2007) 1022 [arXiv:0704.2140] [inSPIRE].

[38] S. Mahajan and S. Raychaudhury, Red star-forming and blue passive galaxies in clusters, Mon. Not. Roy. Astron. Soc. 400 (2009) 687 [arXiv:0908.2434] [inSPIRE].

[39] L. Cortese, Are passive red spirals truly passive? — The current star formation activity of optically-red disc galaxies, Astron. Astrophys. 543 (2012) A132 [arXiv:1205.6819] [inSPIRE].

[40] K. Bundy et al., The mass assembly history of field galaxies: detection of an evolving mass limit for star forming galaxies, Astrophys. J. 651 (2006) 120 [astro-ph/0512465] [inSPIRE].

[41] M.C. Cooper et al., The deep2 galaxy redshift survey: the relationship between galaxy properties and environment at z ~ 1, Mon. Not. Roy. Astron. Soc. 370 (2006) 198 [astro-ph/0603177] [inSPIRE].
[42] M.C. Cooper, A. Gallazzi, J.A. Newman and R. Yan, Galaxy Assembly Bias on the Red Sequence, Mon. Not. Roy. Astron. Soc. 402 (2010) 1942 [arXiv:0910.0245] [inSPIRE].

[43] R. Tojeiro et al., The different star-formation histories of blue and red spiral and elliptical galaxies, Mon. Not. Roy. Astron. Soc. 432 (2013) 359 [arXiv:1303.3551] [inSPIRE].

[44] S. Mahajan et al., Galaxy and mass assembly (GAMA): properties and evolution of red spiral galaxies, Mon. Not. Roy. Astron. Soc. 491 (2019) 398.

[45] S.P. Driver et al., Galaxy and Mass Assembly (GAMA): survey diagnostics and core data release, Mon. Not. Roy. Astron. Soc. 413 (2011) 971 [arXiv:1009.0614] [inSPIRE].

[46] C.-N. Hao et al., Spatially resolved studies of local massive red spiral galaxies, Astrophys. J. Lett. 883 (2019) L36.

[47] R. Guo et al., Toward an understanding of the massive red spiral galaxy formation, Astrophys. J. 897 (2020) 162.

[48] A. Fraser-McKelvie, M.J.I. Brown, K. Pimbblet, T. Dolley and N.J. Bonne, Multiple mechanisms quench passive spiral galaxies, Mon. Not. Roy. Astron. Soc. 474 (2018) 1909.

[49] F.A. Evans, L.C. Parker and I.D. Roberts, Red misfits in the sloan digital sky survey: properties of star-forming red galaxies, Mon. Not. Roy. Astron. Soc. 476 (2018) 5284.

[50] E.P. Hubble, The Realm of the Nebulae, Oxford University Press, Oxford (1936).

[51] A. Dressler, Galaxy morphology in rich clusters: Implications for the formation and evolution of galaxies, Astrophys. J. 236 (1980) 351 [inSPIRE].

[52] M. Postman and M.J. Geller, The morphology-density relation — the group connection, Astrophys. J. 281 (1984) 95.

[53] I. Lewis et al., The 2dF Galaxy Redshift Survey: The Environmental dependence of galaxy star formation rates near clusters, Mon. Not. Roy. Astron. Soc. 334 (2002) 673 [astro-ph/0203336] [inSPIRE].

[54] SDSS collaboration, Galaxy star-formation as a function of environment in the early data release of the Sloan Digital Sky Survey, Astrophys. J. 584 (2003) 210 [astro-ph/0210193] [inSPIRE].

[55] G. Kauffmann et al., The Environmental dependence of the relations between stellar mass, structure, star formation and nuclear activity in galaxies, Mon. Not. Roy. Astron. Soc. 353 (2004) 713 [astro-ph/0402030] [inSPIRE].

[56] O. Hahn, C. Porciani, C.M. Carollo and A. Dekel, Properties of Dark Matter Haloes in Clusters, Filaments, Sheets and Voids, Mon. Not. Roy. Astron. Soc. 375 (2007) 489 [astro-ph/0610280] [inSPIRE].

[57] L. Gao, V. Springel and S.D.M. White, The Age dependence of halo clustering, Mon. Not. Roy. Astron. Soc. 363 (2005) L66 [astro-ph/0506510] [inSPIRE].

[58] R.H. Wechsler, A.R. Zentner, J.S. Bullock and A.V. Kravtsov, The dependence of halo clustering on halo formation history, concentration, and occupation, Astrophys. J. 652 (2006) 71 [astro-ph/0512416] [inSPIRE].

[59] L. Gao and S.D.M. White, Assembly bias in the clustering of dark matter haloes, Mon. Not. Roy. Astron. Soc. 377 (2007) L5 [astro-ph/0611921] [inSPIRE].

[60] D.J. Croton, L. Gao and S.D.M. White, Halo assembly bias and its effects on galaxy clustering, Mon. Not. Roy. Astron. Soc. 374 (2007) 1303 [astro-ph/0605636] [inSPIRE].

[61] M. Musso, C. Cadiou, C. Pichon, S. Codis, K. Kraljic and Y. Dubois, How does the cosmic web impact assembly bias?, Mon. Not. Roy. Astron. Soc. 476 (2018) 4 [arXiv:1709.00834] [inSPIRE].
M. Vakili and C.H. Hahn, *How are galaxies assigned to halos? Searching for assembly bias in the SDSS galaxy clustering*, Astrophys. J. **872** (2019) 115 [arXiv:1610.01991] [SPIRE].

N. Dalal, M. White, J.R. Bond and A. Shirokov, *Halo Assembly Bias in Hierarchical Structure Formation*, Astrophys. J. **687** (2008) 12 [arXiv:0803.3453] [SPIRE].

O. Hahn, C. Porciani, A. Dekel and C.M. Carollo, *The Tidal Origin of the Environment Dependence of Halo Assembly*, Mon. Not. Roy. Astron. Soc. **398** (2009) 1742 [arXiv:0803.4211] [SPIRE].

N. Dalal, M. White, J.R. Bond and A. Shirokov, *Halo Assembly Bias in Hierarchical Structure Formation*, Astrophys. J. **687** (2008) 12 [arXiv:0803.3453] [SPIRE].

O. Hahn, C. Porciani, A. Dekel and C.M. Carollo, *The Tidal Origin of the Environment Dependence of Halo Assembly*, Mon. Not. Roy. Astron. Soc. **398** (2009) 1742 [arXiv:0803.4211] [SPIRE].

A.R. Zentner, A.P. Hearin and F.C. van den Bosch, *Galaxy Assembly Bias: A Significant Source of Systematic Error in the Galaxy-Halo Relationship*, Mon. Not. Roy. Astron. Soc. **443** (2014) 3044 [arXiv:1311.1818] [SPIRE].

Y.-Y. Mao, A.R. Zentner and R.H. Wechsler, *Beyond Assembly Bias: Exploring Secondary Halo Biases for Cluster-size Haloes*, Mon. Not. Roy. Astron. Soc. **474** (2018) 5143 [Erratum ibid. **481** (2018) 3167] [arXiv:1705.03888] [SPIRE].

SDSS collaboration, *Galaxy Clustering in the Completed SDSS Redshift Survey: The Dependence on Color and Luminosity*, Astrophys. J. **736** (2011) 59 [arXiv:1005.2413] [SPIRE].

H. Yan, Z. Fan and S.D.M. White, *The dependence of galaxy properties on the large-scale tidal environment*, Mon. Not. Roy. Astron. Soc. **430** (2013) 3432.

A. Paranjape, K. Kovac, W.G. Hartley and I. Pahwa, *Correlating galaxy colour and halo concentration: A tunable Halo Model of galactic conformity*, Mon. Not. Roy. Astron. Soc. **454** (2015) 3030 [arXiv:1503.08212] [SPIRE].

Y.-T. Lin et al., *On Detecting Halo Assembly Bias with Galaxy Populations*, Astrophys. J. **819** (2016) 119 [arXiv:1504.07632] [SPIRE].

L.P.T. Sin, S.J. Lilly and B.M.B. Henriques, *On the evidence for large-scale galactic conformity in the local Universe*, Mon. Not. Roy. Astron. Soc. **471** (2017) 1192 [arXiv:1702.08460] [SPIRE].

S. Alam, Y. Zu, J.A. Peacock and R. Mandelbaum, *Cosmic web dependence of galaxy clustering and quenching in SDSS*, Mon. Not. Roy. Astron. Soc. **483** (2019) 4501 [arXiv:1801.04878] [SPIRE].

H. Miyatake et al., *Evidence of Halo Assembly Bias in Massive Clusters*, Phys. Rev. Lett. **116** (2016) 041301 [arXiv:1506.06135] [SPIRE].

A.D. Montero-Dorta et al., *The Dependence of Galaxy Clustering on Stellar-mass Assembly History for LRGs*, Astrophys. J. Lett. **848** (2017) L2 [arXiv:1705.00013] [SPIRE].

M. Kerscher, *Spatial range of conformity*, Astron. Astrophys. **615** (2018) A109 [arXiv:1705.07582] [SPIRE].

B. Pandey and S. Bharadwaj, *The luminosity, colour and morphology dependence of galaxy filaments in the sloan digital sky survey data release four*, Mon. Not. Roy. Astron. Soc. **372** (2006) 827 [astro-ph/0601179] [SPIRE].

B. Pandey and S. Bharadwaj, *Exploring star formation using the filaments in the Sloan Digital Sky Survey Data Release Five (SDSS DR5)*, Mon. Not. Roy. Astron. Soc. **387** (2008) 767 [arXiv:0804.0072] [SPIRE].

J.M. Scudder, S.L. Ellison and J.T. Mendel, *The dependence of galaxy group star formation rates and metallicities on large scale environment*, Mon. Not. Roy. Astron. Soc. **423** (2012) 2690 [arXiv:1204.2828] [SPIRE].

H. Lietzen, E. Tempel, P. Heinamaki, P. Nurmi, M. Einasto and E. Saar, *Environments of galaxies in groups within the supercluster-void network*, Astron. Astrophys. **545** (2012) A104 [arXiv:1207.7070] [SPIRE].
B. Darvish et al., *Cosmic web and star formation activity in galaxies at $z \sim 1$*, Astrophys. J. **796** (2014) 51.

M.E. Filho, J.S. Almeida, C. Muñoz-Tuñón, S.E. Nuza, F. Kitaura and S. Heß, *Extremely metal-poor galaxies: the environment*, Astrophys. J. **802** (2015) 82.

H.E. Luparello, M. Lares, D. Paz, C.Y. Yaryura, D.G. Lambas and N. Padilla, *Brightest group galaxies and the large-scale environment*, Mon. Not. Roy. Astron. Soc. **448** (2015) 1483 [arXiv:1502.01221] [inSPIRE].

B. Pandey and S. Sarkar, *How much a galaxy knows about its large-scale environment?: An information theoretic perspective*, Mon. Not. Roy. Astron. Soc. **467** (2017) L6 [arXiv:1611.00283] [inSPIRE].

B. Pandey and S. Sarkar, *Exploring galaxy colour in different environments of the cosmic web with SDSS*, Mon. Not. Roy. Astron. Soc. **498** (2020) 6069 [arXiv:2002.08400] [inSPIRE].

H.E. Luparello, M. Lares, D. Paz, C.Y. Yaryura, D.G. Lambas and N. Padilla, *Brightest group galaxies and the large-scale environment*, Mon. Not. Roy. Astron. Soc. **448** (2015) 1483 [arXiv:1502.01221] [IN SPIRE].

B. Pandey and S. Sarkar, *Can a conditioning on stellar mass explain the mutual information between morphology and environment?*, JCAP **09** (2020) 039 [arXiv:2004.05016] [inSPIRE].

C.J. Lintott et al., *Galaxy Zoo: Morphologies derived from visual inspection of galaxies from the Sloan Digital Sky Survey*, Mon. Not. Roy. Astron. Soc. **389** (2008) 1179 [arXiv:0804.4483] [inSPIRE].

K.W. Willett et al., *Galaxy Zoo 2: detailed morphological classifications for 304,122 galaxies from the Sloan Digital Sky Survey*, Mon. Not. Roy. Astron. Soc. **435** (2013) 2835 [arXiv:1308.3496] [inSPIRE].

SDSS-IV collaboration, *The 16th Data Release of the Sloan Digital Sky Surveys: First Release from the APOGEE-2 Southern Survey and Full Release of eBOSS Spectra*, Astrophys. J. Suppl. **249** (2020) 3 [arXiv:1912.02905] [inSPIRE].

SDSS collaboration, *The Sloan Digital Sky Survey: Technical Summary*, Astron. J. **120** (2000) 1579 [astro-ph/0006396] [inSPIRE].

SDSS collaboration, *The Sloan digital sky survey photometric camera*, Astron. J. **116** (1998) 3040 [astro-ph/9809085] [inSPIRE].

SDSS collaboration, *The 2.5 m Telescope of the Sloan Digital Sky Survey*, Astron. J. **131** (2006) 2332 [astro-ph/0602326] [inSPIRE].

SDSS collaboration, *Spectroscopic Target Selection in the Sloan Digital Sky Survey: The Main Galaxy Sample*, Astron. J. **124** (2002) 1810 [astro-ph/0206225] [inSPIRE].

G. Bruzual A. and S. Charlot, *Spectral evolution of stellar populations using isochrone synthesis*, Astrophys. J. **405** (1993) 538 [inSPIRE].

J. Brinchmann et al., *The Physical properties of star forming galaxies in the low redshift universe*, Mon. Not. Roy. Astron. Soc. **351** (2004) 1151 [astro-ph/0311060] [inSPIRE].

C. Conroy, J.E. Gunn and M. White, *The propagation of uncertainties in stellar population synthesis modeling I: The relevance of uncertain aspects of stellar evolution and the IMF to the derived physical properties of galaxies*, Astrophys. J. **699** (2009) 486 [arXiv:0809.4261] [inSPIRE].

M. Sarzi et al., *The sauron project. 5. integral-field emission-line kinematics of 48 elliptical and lenticular galaxies*, Mon. Not. Roy. Astron. Soc. **366** (2006) 1151 [astro-ph/0511307] [inSPIRE].
[98] M. Cappellari and E. Emsellem, *Parametric recovery of line-of-sight velocity distributions from absorption-line spectra of galaxies via penalized likelihood*, *Publ. Astron. Soc. Pac.* 116 (2004) 138 [astro-ph/0312201] [inSPIRE].

[99] C. Maraston and G. Stromback, *Stellar population models at high spectral resolution*, *Mon. Not. Roy. Astron. Soc.* 418 (2011) 2785 [arXiv:1109.0543] [inSPIRE].

[100] D. Thomas, C. Maraston and J. Johansson, *Flux-calibrated stellar population models of Lick absorption-line indices with variable element abundance ratios*, *Mon. Not. Roy. Astron. Soc.* 412 (2011) 2183 [arXiv:1010.4569] [inSPIRE].

[101] C. Maraston and G. Stromback, *Stellar population models at high spectral resolution*, *Mon. Not. Roy. Astron. Soc.* 418 (2011) 2785 [arXiv:1109.0543] [inSPIRE].

[102] D. Thomas, C. Maraston and J. Johansson, *Flux-calibrated stellar population models of Lick absorption-line indices with variable element abundance ratios*, *Mon. Not. Roy. Astron. Soc.* 412 (2011) 2183 [arXiv:1010.4569] [inSPIRE].

[103] B. Pandey, *A method for classification of red, blue and green galaxies using fuzzy set theory*, *Mon. Not. Roy. Astron. Soc.* 499 (2020) L31 [arXiv:2005.11678] [inSPIRE].

[104] L.A. Zadeh, *Fuzzy sets*, *Info. Control* 8 (1965) 338.

[105] S. Casertano and P. Hut, *Core radius and density measurements in n-body experiments connections with theoretical and observational definitions*, *Astrophys. J.* 298 (1985) 80.

[106] H.J. Mo and S.D.M. White, *An Analytic model for the spatial clustering of dark matter halos*, *Mon. Not. Roy. Astron. Soc.* 282 (1996) 347 [astro-ph/9512127] [inSPIRE].

[107] I. Jung, J. Lee and S.K. Yi, *Effects of large-scale environment on the assembly history of central galaxies*, *Astrophys. J.* 794 (2014) 74 [arXiv:1409.0860] [inSPIRE].

[108] A.P. Hearin, P.S. Behroozi and F.C. van den Bosch, *On the Physical Origin of Galactic Conformity*, *Mon. Not. Roy. Astron. Soc.* 461 (2016) 2135 [arXiv:1504.05578] [inSPIRE].

[109] I. Zehavi, S. Contreras, N. Padilla, N.J. Smith, C.M. Baugh and P. Norberg, *The Impact of Assembly Bias on the Galaxy Content of Dark Matter Halos*, *Astrophys. J.* 853 (2018) 84 [arXiv:1706.07871] [inSPIRE].

[110] B. Hadzhiyska et al., *Galaxy assembly bias and large-scale distribution: a comparison between IllustrisTNG and a semi-analytic model*, *Mon. Not. Roy. Astron. Soc.* 508 (2021) 698 [arXiv:2108.00006] [inSPIRE].

[111] D. Nelson et al., *The IllustrisTNG simulations: public data release*, *Comput. Astrophys. Cosmol.* 6 (2019) 2.

[112] P.G. van Dokkum et al., *The Assembly of Milky Way-like Galaxies Since z ~ 2.5*, *Astrophys. J. Lett.* 771 (2013) L35 [arXiv:1304.2391] [inSPIRE].

[113] V. Rodríguez-Gomez et al., *The stellar mass assembly of galaxies in the Illustris simulation: growth by mergers and the spatial distribution of accreted stars*, *Mon. Not. Roy. Astron. Soc.* 458 (2016) 2371 [arXiv:1511.08804] [inSPIRE].

[114] W. Cui, R. Davé, J.A. Peacock, D. Anglés-Alcázar and X. Yang, *The origin of galaxy colour bimodality in the scatter of the stellar-to-halo mass relation*, *Nature Astron.* 5 (2021) 1069.