New constraints on red-spiral galaxies from their kinematics in clusters of galaxies

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ABSTRACT

The distributions of the pairwise line-of-sight velocity between galaxies and their host clusters are segregated according to the galaxy's colour and morphology. We investigate the velocity distribution of red-spiral galaxies, which represents a rare population within galaxy clusters. We find that the probability distribution function of the pairwise line-of-sight velocity $v_{\text{los}}$ between red-spiral galaxies and galaxy clusters has a dip at $v_{\text{los}} = 0$, which is a very odd feature, at 93% confidence level. To understand its origin, we construct a model of the phase space distribution of galaxies surrounding galaxy clusters in three-dimensional space by using cosmological N-body simulations. We adopt a two component model that consists of the infall component, which corresponds to galaxies that are now falling into galaxy clusters, and the splash-back component, which corresponds to galaxies that are on their first (or more) orbit after falling into galaxy clusters. We find that we can reproduce the distribution of the line-of-sight velocity of red-spiral galaxies with the dip with a very simple assumption that red-spiral galaxies reside predominantly in the infall component, regardless of the choice of the functional form of their spatial distribution. Our results constrain the quenching timescale of red-spiral galaxies to a few Gyrs, and the time when the morphological transformation finishes to $\sim 1.4$ Gyr after the quenching completes.

Key words: galaxies: clusters: general – galaxies: kinematics and dynamics – galaxies: spiral – galaxies: evolution

1 INTRODUCTION

The galaxy evolution is one of the most important topics in modern astrophysics. Although galaxies have been observed in various ways and are known to have many features such as colours, stellar masses, star formation rate densities, and morphologies, the unified theory to describe the relation between all these features and its evolution has not yet been established. The environment in which galaxies reside is one of the key factors that determines the features of galaxies. For instance, it has been known that in the denser region (i.e., cluster-like environments), red, passive, and early-type galaxies are dominant, whereas in the less dense region (i.e., field-like environments), blue, star-forming, and late-type galaxies are dominant (e.g., Dressler 1980; Peng et al. 2010).

There are several mechanisms that drive such environmental dependence, including the effects of the interactions with other galaxies (e.g., Toomre & Toomre 1972, Oelamoto & Nagashima 2001), ram pressure stripping due to the pressure exerted by the intra-cluster medium (Gunn & Gott 1972), and the strangulation effect, which is the lack of the gas in galaxies due to the cutoff of the gas stock (Larson et al. 1980; Balogh et al. 2000). These mechanisms can quench star formation of galaxies and turn them into red, passive, and early-type galaxies. These mechanisms are implemented to cosmological simulations, and the relation between the quenching mechanism and the resulting distribution of galaxies is also investigated (e.g., Gabor & Davé 2012; Lotz et al. 2018).

It has been known that the majority of galaxies fol-
low the tight colour-morphology relationship. Lintott et al. (2008) showed that red galaxies are dominated by early-type galaxies, and the majority of blue galaxies are late-type galaxies at \( z < 0.12 \). This tight relationship can be explained as follows. The red galaxies tend to have old stellar populations, and the early-type galaxies are the end point of the dynamical history of galaxies. In addition, timescales of mechanisms that drive the morphological transformation and quench star formation are strongly related in most cases.

Red-spiral galaxies are the rare subpopulation of galaxies, whose colours are red, and the morphology is late-type, i.e., old stellar-population and young dynamical state. The red-spiral galaxies are investigated in some previous papers. For example, Masters et al. (2010) studied spectroscopic properties and environments of passive red-spiral galaxies found in the Galaxy Zoo project (Lintott et al. 2008). One of the possible scenarios which explains the red-spiral galaxies is that red-spiral galaxies are accreted on to massive haloes as blue-spirals, after which their outer halo gas reservoirs are stripped by environmental effects without transforming their morphology, and quench the star formation (e.g., Bekki et al. 2002). Red-spiral galaxies then turn into another morphological type of galaxies by merging with other galaxies and/or their spontaneous dynamical evolution. This scenario is consistent with the observational results shown in Masters et al. (2010), although other reasonable scenarios that explain the red-spiral galaxies has also been proposed (e.g., Masters et al. 2010; Schawinski et al. 2014). The identification of the detailed scenario for the formation of red-spiral galaxies provides an important clue for understanding the origin of the colour-morphology relationship of galaxies, and therefore crucial for obtaining the whole picture of galaxy evolution. This is why new observational clues to constrain the scenario are anticipated.

The distribution of the pairwise line-of-sight velocity (\( v_{\text{los}} \)) between galaxies and their host clusters has been used to estimate the depths of the gravitational potential and to infer the masses of their host clusters (e.g., Smith 1936; Busha et al. 2005). Furthermore, the segregations of the distribution of \( v_{\text{los}} \) by galaxy types have also been studied. Some studies have found that the dispersion of the probability distribution function (PDF) of \( v_{\text{los}} \) for blue, late-type, and star-forming galaxies tends to be larger than that for red, early-type, and passive galaxies (e.g., Sodre et al. 1989; Biviano et al. 2002; Bayliss et al. 2017). It has also been found that the PDF of \( v_{\text{los}} \) for fainter galaxies has the larger dispersion than that for luminous galaxies (e.g., Chincarini & Rood 1977; Goto 2005). Since the segregations of the distribution of \( v_{\text{los}} \) between galaxies and their host clusters contain a lot of information about the properties of galaxy populations in the most dense environments, it is important to use the full distribution of line-of-sight velocities, not just the dispersion of the PDF as often studied in the literature. Indeed, in some studies (e.g., Oman & Hudson 2016, Rhee et al. 2017, Adhikari et al. 2018 Arthur et al. 2019), the segregation of the full distribution of \( v_{\text{los}} \) has been studied using galaxies obtained from cosmological simulations. However, a proper interpretation of the observed phase-space data is not been straightforward because it requires the knowledge of the full phase space distribution and taking a proper account of projection along the line-of-sight.

Red-spiral galaxies are a very rare class of galaxies. In addition, it is difficult to obtain the morphological information of galaxies from observations. Hence, the PDF of \( v_{\text{los}} \) between red-spiral galaxies and their host clusters has not been measured because of the large statistical error originating from a small number of red-spiral galaxies. With the help of the morphological information for a large number of galaxies from Galaxy Zoo project (Lintott et al. 2008) and galaxy cluster catalogues that contain a large number of galaxy clusters (e.g., Rykoff et al. 2014; Oguri 2014), in this paper we investigate the PDF of \( v_{\text{los}} \) between red-spiral galaxies and galaxy clusters by stacking different clusters to reduce the statistical error.

Hamabata et al. (2018) studied the relationship between the PDF of \( v_{\text{los}} \) between galaxies and galaxy clusters, the phase space distribution around clusters in three-dimensional space, and the radial distribution of galaxies by using cosmological \( N \)-body simulations. In this paper, we adopt the model of Hamabata et al. (2018) to interpret the observed PDF of \( v_{\text{los}} \) for red-spiral galaxies, by taking proper account of the observed radial distribution of red-spiral galaxies. Our approach allows us to make full use of the phase space distribution information obtained from the observation, not just the dispersion of the PDF, and extract the information that the observed PDF contains properly.

This paper is organised as follows. In Section 2, we show the observational data and our analysis method. In Section 3, we present our model of the phase space distribution of galaxies in three-dimensional space from cosmological \( N \)-body simulations. In Section 4, we compare the results obtained from the observation and our simulations. In Section 5, we provide a detailed discussion of the results. Finally, we conclude in Section 6. We adopt cosmological parameters \( h = 0.7, \Omega_{M,0} = 0.279, \Omega_{\Lambda} = 0.721, n_s = 0.972, \) and \( \sigma_8 = 0.821 \) following the WMAP nine year result (Hinshaw et al. 2013) throughout this paper.

## 2 RESULT FROM OBSERVATIONAL DATA

### 2.1 Data of Clusters and Galaxies

To determine the kinematics of cluster galaxies, we require precise spectroscopic redshifts. For this purpose, we employ the spectroscopic galaxy sample from SDSS DR10 data (Ahn et al. 2014). We use galaxies observed by Legacy spectroscopic observation (York et al. 2000) only, because we have to use galaxies selected by uniform criteria. Following Masters et al. (2010), we select red galaxies based on their cModelMag, as \( (g - r) > 0.63 - 0.02(M_g + 20) \), where \( M_g \) is the absolute magnitude in \( g \) band. We also limit the galaxy sample for our analysis to \( M_r < -20.17 \). For each galaxy, the absolute magnitude is computed from its apparent cModelMag with the k-correction using the technique defined in Chilingarian & Zotolikhin (2012), and also with the correction of Galactic extinction (Schlegel et al. 1998).

Galaxy Zoo is an online citizen science project to obtain morphological information for a large number of galaxies from visual inspections. We use the Galaxy Zoo 1 data release (Lintott et al. 2008), which is the largest morphologically classified sample of galaxies. We select spiral galaxies as \( p_{\text{CS debiased}} > 0.8 \), where \( p_{\text{CS debiased}} \) is the debiased fraction of votes for combined spiral galaxies with the correction of
the selection bias and the classification bias of the Galaxy Zoo sample in Bamford et al. (2009).

In this paper, we use a cluster sample constructed by a red-sequence cluster method, in which clusters are selected by overdensities of red galaxies (e.g., Rykoff et al. 2014; Oguri 2014). Here we adopt the SDSS DR8 redMaPPer cluster catalogue (Rozo et al. 2015), because the redMaPPer cluster catalogue contains clusters down to the sufficiently low redshift of \( z = 0.05 \) and hence has a large overlap of the redshift range with the Galaxy Zoo galaxy sample.

In Fig. 1, we show the colour-magnitude diagram of red-spiral galaxies that we use in this paper. For comparison, we also show the distribution of the Galaxy Zoo 1 sample. Our sample consists of 968 red galaxies and 101 red-spiral galaxies at \( |z_{c} - z_{g}| < 0.01 \) within the transverse distance of \( 0.5 \, h^{-1}\text{Mpc} \) from the centre of galaxy clusters at \( 0.05 < z < 0.1 \) that we use in this analysis, where \( z_{g} \) and \( z_{c} \) are redshifts of the galaxy and the cluster, respectively.

2.2 The Observed PDF of the line-of-sight velocity \( v_{\text{los}} \)

The line-of-sight velocity \( v_{\text{los}} \) between a galaxy and a cluster is given by

\[
v_{\text{los}} = c \left( \frac{z_{c} - z_{g}}{1 + z_{c}} \right). \tag{1}\]

Throughout the paper we adopt the spectroscopic redshift of the central galaxy as the redshift of each cluster. Because we are interested in average features of the kinematics of galaxies, we stack galaxies around clusters to obtain statistically better sample. We apply a richness cut \( 20 < \lambda < 40 \), where \( \lambda \) is the richness of each cluster estimated in the redMaPPer. We also adopt a redshift cut \( 0.05 < z_{c} < 0.1 \), and only stack clusters whose central galaxies have spectroscopic redshifts. Finally, we stack 90 clusters in this work.

Figure 1. Colour-magnitude diagram of our galaxy sample. Red points indicate red-spiral galaxies at \( |z_{g} - z_{c}| < 0.01 \) within the transverse distance of \( 0.5 \, h^{-1}\text{Mpc} \) from the centre of galaxy clusters at \( 0.05 < z < 0.1 \) that we use in this analysis. The contours show the number distribution of the Galaxy Zoo 1 sample in the redshift range \( 0.05 < z < 0.1 \). The solid lines indicate the colour cut and the absolute magnitude cut adopted in this paper.

Figure 2. The PDF of \( |v_{\text{los}}| \) of red-spiral galaxies (blue triangle down) and red galaxies (red triangle up). Galaxies within projected \( 0.5 h^{-1}\text{Mpc} \) from the centre of the clusters are used.

In Fig. 2, we show the PDF of the line-of-sight velocity, \( p(|v_{\text{los}}|) \), for red-spiral galaxies. For comparison, we also show \( p(|v_{\text{los}}|) \) for all red galaxies, which are galaxies with \( (g - r) > 0.63 - 0.02(M_{r} + 20) \), \( M_{r} < -20.17 \), and \( p_{\text{debiased}} \leq 1.0 \). We stack galaxies within projected \( 0.5 h^{-1}\text{Mpc} \) from the centres of the clusters. The error bars are Poisson errors from the number of galaxies in each \( |v_{\text{los}}| \) bin. We can see that the PDF of \( v_{\text{los}} \) for red-spiral galaxies has a dip at \( v_{\text{los}} = 0 \), which is not seen in the PDF for all red galaxies. The statistical significance of the dip as measured by the difference of the first two bins is 1.4 \( \sigma \) (93% C.L.). By using the Kolmogorov-Smirnov test, we find that \( p(|v_{\text{los}}|) \) for red-spiral galaxies and that for all red galaxies are different from each other at the significance higher than 99.99%.

3 PHASE SPACE DISTRIBUTION IN THREE-DIMENSIONAL SPACE FROM SIMULATIONS

To interpret the observational data, we construct a model of the distributions of \( v_{\text{los}} \) between the galaxy and the cluster. The PDF of \( v_{\text{los}} \) can be described as

\[
p_{\text{obs}}(v_{\text{los}}, r_{\perp}) = \frac{1}{N(r_{\perp})} \iiint d\vec{v} \int dr_{\parallel} \rho(\vec{r}) p_{r}(\vec{v}, \vec{r}) \delta D(v_{\text{los}} - v'_{\text{los}}), \tag{2}\]

where \( \vec{v} \) is the three-dimensional peculiar pairwise velocity between the galaxy and the cluster, \( \vec{r} \) is the physical spatial coordinates of the galaxy relative to the cluster, \( r_{\perp} \) is the transverse distance from the cluster centre, \( r_{\parallel} \) is the line-of-sight distance from the cluster centre, \( \rho(\vec{r}) \) is the spatial distribution of galaxies, \( \delta D(x) \) is the Dirac’s delta function, \( p_{r}(\vec{v}, \vec{r}) \) is phase space distribution in three-dimensional space, and \( N(r_{\perp}) \) is the normalisation factor. Here, \( v'_{\text{los}} \) is defined as

\[
v'_{\text{los}} = v_{\parallel} + \frac{H(z) r_{\parallel}}{1 + z}. \tag{3}\]
where $v_{\parallel}$ is the parallel component to the line-of-sight of the peculiar pairwise velocity between the galaxy and the cluster, and $H(z)$ is the Hubble parameter. As shown in equation (2), to construct a model of the distributions of $v_{\text{los}}$, we have to construct a model of the phase space distribution in three-dimensional space. In this Section, we present our model of the phase space distribution in three-dimensional space, based on the model presented in Section 2 of Hamabata et al. (2018).

### 3.1 Simulations

We use four random realisations of cosmological $N$-body simulations with a TreePM code Gadget-2 (Springel 2005). These simulations run from $z = 99$ to 0, the box size is comoving $360 \, h^{-1}\text{Mpc}$ on a side, and the gravitational softening length is comoving $20 \, h^{-1}\text{kpc}$. They are performed with the periodic boundary condition. The number of dark matter particles is $1024^3$ with $m_p = 3.4 \times 10^9 h^{-1}M_\odot$. In setting up the initial conditions, we first compute the linear matter power spectrum at $z = 0$ using a Boltzmann solver CAMB (Lewis et al. 2000). We then scale it to $z = 99$ by the linear growth factor computed for the $\Lambda$CDM cosmology ignoring radiation or relativistic corrections. Subsequently, a Gaussian random field for the linear overdensity $\delta_\text{lin}(z_0)$ is generated following this power spectrum. We finally compute the displacement field for the fluid elements located at a regular lattice up to the second order in $\delta_\text{lin}(z_0)$ using a code developed in Nishimichi et al. (2009) and parallelised in Valageas & Nishimichi (2011). We use six-dimensional friend of friend (FoF) algorithm implemented in Rockstar (Behroozi et al. 2013). While the Rockstar identifies both haloes and subhaloes from $N$-body simulations, we do not distinguish them and call both of them haloes.

### 3.2 Stacked Phase Space Distribution

We use haloes with masses $M_{200m} > 1 \times 10^{11} h^{-1}M_\odot$ to represent galaxy haloes in this work, where $M_{200m}$ is the mass within $r_{200m}$, which is the radius within which the average density is 200 times the background matter density at the redshift of interest. We use haloes with masses $9.5 \times 10^{11} h^{-1}M_\odot < M_{200m} < 2.3 \times 10^{14} h^{-1}M_\odot$ to represent cluster haloes, which corresponds to galaxy clusters with $20 < \lambda < 40$ given the mass-richness relation shown in (Simet et al. 2018, see also Murata et al. 2018), where $\lambda$ is the richness of galaxy clusters calculated in the redMaPPer. To mimic the observed cluster catalogue, we remove cluster haloes from our analysis if there are any other cluster haloes with larger masses within physical $1 \, h^{-1}\text{Mpc}$ from those cluster haloes. We use only snapshots at $z = 0.1$ in this work.

To obtain accurate phase space distributions in three-dimensional space, we stack a large number of pairs of galaxy haloes and cluster haloes from these simulations without aligning their orientations. The peculiar pairwise velocity between cluster haloes and galaxy haloes can be divided into three orthogonal components, the radial velocity ($v_r$) and two tangential velocities ($v_{\perp1}, v_{\perp2}$). Since we can choose the coordinates such that one tangential velocity component is always orthogonal to the line-of-sight, we can ignore $v_{\perp2}$ and denote $v_{\perp1}$ as $v_{\perp}$. The asphericity of cluster haloes tends to disappear after stacking, and the resultant averaged phase space should be fully specified by the subspace of $(r, v_r, v_{\perp})$. Indeed, we are not interested in the asphericity of the observed clusters, and a model in this subspace is sufficient to obtain the projected phase space $(r, v_r, v_{\perp})$.

We adopt a two component model of the phase space distribution presented in Hamabata et al. (2018). This model assumes that the PDF of the phase space distribution can be divided into two components, the infall component (IF) and the splashback component (SB). The PDF of the phase space distribution can be derived as

$$p_r(v_r, v_{\perp}, r) = \left(1 - \alpha\right) p_{\text{infall}}(v_r, v_{\perp}, r) + \alpha p_{\text{SB}}(v_r, v_{\perp}, r),$$

(4)

where $p_{\text{infall}}$ and $p_{\text{SB}}$ are properly normalised, and $\alpha$ denotes the fraction of the splashback component at given $r$. The first term of the right hand side of equation (4) represents the infall component, whose average value of the radial velocity is negative. Thus, the infall component corresponds to galaxy haloes that are now falling into cluster haloes. On the other hand, the send term of the right hand side of equation (4) represents the splashback component, whose average value of the radial velocity is positive. The splashback component which corresponds to galaxy haloes that are on their first (or more) orbit after falling into cluster haloes. Following Hamabata et al. (2018), we ignore the correlation between $v_r$ and $v_{\perp}$ for both the two components, and rewrite equation (4) as

$$p_r(v_r, v_{\perp}, r) = \left(1 - \alpha\right) p_{\text{infall}}(v_r, v_{\perp}, r) p_{\text{infall}}(v_r, r) + \alpha p_{\text{SB}}(v_r, v_{\perp}, r) p_{\text{SB}}(v_r, r).$$

(5)

Again, $p_{\text{infall}}, p_{\text{infall}}, p_{\text{SB}}$, and $p_{\text{SB}}$ are properly normalised. While there is a room to improve the two component model, for example by adding more components, we adopt this two component model for simplicity. We leave the construction of more complex models for future work. We discuss each component in equation (5) in what follows.

#### 3.2.1 Radial Velocity Distribution

We start with the distribution of radial velocities. Hamabata et al. (2018) found that the radial velocity distribution of the infall component have non-negligible skewness and kurtosis, and adopt the Johnson’s SU-distribution (Johnson 1949) as the model function for the radial velocity distribution of the infall component. Following Hamabata et al. (2018), we adopt the Johnson’s SU-distribution as

$$p_{v_r, \text{infall}}(v_r, r) = SU(v_r; \delta_r, \lambda_r, \gamma_r, \xi_r)$$

$$= \frac{\delta_r}{\lambda_r \sqrt{2 \pi \sqrt{\chi^2}}} \exp \left[ -\frac{1}{2} \left( \frac{v_r + \delta_r \sinh^{-1} z(v_r)}{\lambda_r} \right)^2 \right],$$

(6)

where

$$z(v_r) = \frac{v_r - \xi_r}{\lambda_r}.$$  

(7)

Note that $\delta_r, \lambda_r, \gamma_r$, and $\xi_r$ are free parameters, and they are functions of the radius $r$.

For the splashback component, we adopt the Gaussian
distribution, \( p_{v_r,SB}(v_r,r) = G(v_r; \mu_r, \sigma_r^2) \)
\[
= \frac{1}{\sqrt{2\pi\sigma_r^2}} \exp \left\{ - \frac{(v_r - \mu_r)^2}{2\sigma_r^2} \right\},
\]
where \( \mu_r \) and \( \sigma_r \) are free parameters, and they are also functions of \( r \).

We constrain these free parameters as follows. By integrating over the tangential velocity, we can derive the model function of the PDF of the radial velocity distribution from equation (6) as
\[
p_{v_r}(v_r,r) = \int dv_r \{(1 - \alpha)p_{v_r,\text{infall}}(v_r,r)p_{v_t,\text{infall}}(v_r,r) \]
\[
+ \alpha p_{v_r,SB}(v_r,r)p_{v_t,SB}(v_r,r) \}
\]
\[
= (1 - \alpha)p_{v_r,\text{infall}} + \alpha p_{v_r,SB}.
\]
For a given radial bin, there are seven free parameters in equation (9). We fit the histogram of the radial velocity obtained from our N-body simulations with equation (9) for each radial bins. We adopt 0.1 \( h^{-1}\text{Mpc} \) as the width of each radial bin.

Fig. 3 shows examples of radial velocity distributions and fitting results of equation (9). Here the error bars are Poisson errors from the number of haloes in each \( v_r \) bin. Our model function of the radial velocity distribution is in good agreement with the histogram from our N-body simulations even at \( r \) smaller than 2.0 \( h^{-1}\text{Mpc} \), where Hamabata et al. (2018) did not investigate. Since the splashback component is negligibly small at large \( r \), in fitting we always fix \( \alpha = 0 \) at \( r \) larger than 5 \( h^{-1}\text{Mpc} \). This Figure indicates that the absolute value of the average radial velocity of the infall component is larger than that of the splashback component. By using the fitting results, we interpolate the parameters linearly and use them as smooth functions of \( r \).

3.2.2 Tangential Velocity Distribution

Next we model the tangential velocities. We adopt the John- son’s SU-distribution again as a model function for the tangential velocity distribution of both the infall and splashback components. We adopt the model function of the distributions of tangential velocity as
\[
p_{v_t}(v_t,r) = SU(v_t; \delta_{X,t}, \lambda_{X,t})
\]
\[
= \frac{\delta_{X,t}}{\lambda_{X,t} \sqrt{2\pi} \sqrt{\left(\frac{1}{2}\right)} \left(\frac{1}{2}\right) \sinh^{-1} \frac{1}{2} \left[\frac{v_t}{\lambda_{X,t}} \right]}.
\]
where \( \lambda_{X,t} \) and \( \delta_{X,t} \) are free parameters as functions of \( r \). The odd-order moments of the PDF of the tangential velocity distribution must be zero, because we assume the spherical symmetry. Hence, we set the \( \gamma_{X,t} \), and \( \xi_{X,t} \) in the Johnson’s SU-distribution to zero.

The model function for the tangential distribution is
\[
p_{v_t}(v_t,r) = \int dv_r \{(1 - \alpha)p_{v_r,\text{infall}}(v_r,r)p_{v_t,\text{infall}}(v_r,r) \]
\[
+ \alpha p_{v_r,SB}(v_r,r)p_{v_t,SB}(v_r,r) \}
\]
\[
= (1 - \alpha)p_{v_r,\text{infall}} + \alpha p_{v_t,SB}.
\]
There are four free parameters in equation (12) for the single radial bin, because we fix \( \alpha \) to the value that is obtained from the fitting of the radial velocity distribution at the same radial bin.

Fig. 4 shows examples of tangential velocity distributions. Again, our model function for the tangential velocity distribution is in good agreement with the histogram from our N-body simulations. We interpolate the parameters linearly and use them as smooth functions of \( r \).

4 COMPARISON BETWEEN OBSERVATIONAL DATA AND THE MODEL

4.1 The Radial Distribution of Red-Spiral Galaxies

To complete the model of PDF of \( v_{\text{obs}} \) shown in equation (2), we need the radial distribution of red-spiral galaxies. Assuming the spherical symmetry, we can derive the two-dimensional projected radial distribution of galaxies from
Finally, we fit the observed function of $\rho$ and then calculate the model contributions. We adopt three models for $\rho$ as follows. First, we assume a model function of $r$ as follows.\footnote{Note that $A_0, A_1, P_0, P_1, P_2, Q_0, Q_1, Q_2, R_0, R_1, R_2,$ and $R_3$ are free parameters. Since we calibrate $A_0$ and $A_1$ by using only $\Sigma(r_\perp > 2 \ h^{-1} \text{Mpc})$, $A_0$ and $A_1$ share the same values for all the models. We adopt these functional forms just to describe $\Sigma(r_\perp)$ of red-spiral galaxies with a small number of free parameters.

The top panel of Fig. 5 shows the observed $\Sigma(r_\perp)$ of red-spiral galaxies. Again, the error bars are Poisson errors from the number of galaxies in each $r_\perp$ bin. We also show the best fit result of the model $\Sigma(r_\perp)$ for each model. The degree of freedom for the fitting of the inner part ($0 \ h^{-1} \text{Mpc} < r < 2.0 \ h^{-1} \text{Mpc}$) is 17 (16) (16) for the shell (cusp) (core) model, and the $\chi^2$ for the inner part is 12.3 (16.7) (14.9) for the shell (cusp) (core) model. By performing F-test, we find that $\Sigma(r_\perp)$ fitted with the shell model better fits the observed one than the cusp (core) model at the significance of 77.0% (69.3%). This indicates that the shell model is the best model to represent the observed $\Sigma(r_\perp)$ at small $r_\perp$, whereas the core and cusp models are also in good agreement with the observed distribution. The bottom panel of Fig. 5 shows the model $\rho(r)$ of red-spiral galaxies with best fitting parameters obtained in the top panel of Fig. 5. In the shell model, the radial distribution peaks at $r \sim 0.4 \ h^{-1} \text{Mpc}$, and the majority of red-spiral galaxies in the sample are located around the peak.}

\begin{align}
\rho(r) &= \int_0^\infty \rho(r) \frac{r}{\sqrt{r^2 - r_\perp^2}} \, dr, \\
\Sigma(r_\perp) &= 2 \int_0^\infty \rho(r) \frac{r}{\sqrt{r^2 - r_\perp^2}} \, dr,
\end{align}

where $\Sigma(r_\perp)$ is the projected surface density of galaxies and $\rho(r)$ is the three-dimensional radial distribution. We obtain $\rho(r)$ as follows. First, we assume a model function of $\rho(r)$ of red-spiral galaxies that contains some free parameters. We then calculate the model $\Sigma(r_\perp)$ by substituting the model function of $\rho(r)$ with free parameters in equation (13). Finally, we fit the observed $\Sigma(r_\perp)$ of the red-spiral galaxies with the model $\Sigma(r_\perp)$ to obtain the best fit parameters used in our model $\rho(r)$. Even though we can reconstruct $\rho(r)$ from the observed $\Sigma(r_\perp)$ in an analytic way by using the Abel integral transform (Binney & Tremaine 2008), we do not adopt this method because our observed $\Sigma(r_\perp)$ of red-spiral galaxies is noisy due to the small number of red spiral galaxies.

We adopt three models for $\rho(r)$ of red-spiral galaxies. The first model is the shell model, whose model function is described as

\begin{align}
\rho_{\text{shell}}(r) &= \begin{cases} 
C_{\text{shell}} r^2 & (r < 2 \ h^{-1} \text{Mpc}) \\
2A_0/(r + A_1) & (r \geq 2 \ h^{-1} \text{Mpc})
\end{cases}, \\
C_{\text{shell}} &= \frac{1 + \{(2 - P_1)/P_2\}^2}{2P_0} \{A_0/(2 + A_1)\}.
\end{align}

The second one is the cusp model. We adopt the double power-law density distribution as the distribution of the inner part,

\begin{align}
\rho_{\text{cusp}}(r) &= \begin{cases} 
\frac{C_{\text{cusp}}}{[r^2/(r + r(Q_1))^{Q_2}]} & (r < 2 \ h^{-1} \text{Mpc}) \\
2A_0/(r + A_1) & (r \geq 2 \ h^{-1} \text{Mpc})
\end{cases},
\end{align}

where

\begin{align}
C_{\text{cusp}} &= \frac{2}{1 + (2/Q_1)Q_2} \{A_0/(2 + A_1)\}.
\end{align}

The last one is the core model, whose model function is described as

\begin{align}
\rho_{\text{core}}(r) &= \begin{cases} 
C_{\text{core}} (r_0 \tanh(r - R_3) - R_3) & (r < 2 \ h^{-1} \text{Mpc}) \\
A_0/\{(r + A_1)\} & (r \geq 2 \ h^{-1} \text{Mpc})
\end{cases},
\end{align}

where

\begin{align}
C_{\text{core}} &= \frac{1}{\{(r_0 \tanh(r - R_3) - R_3)\}} \{A_0/(2 + A_1)\}.
\end{align}

In Section 3, we derive the phase space distribution in three-dimensional space ($\rho_\text{los}$) by using cosmological $N$-body simulations. In Section 4.1, we also derive the radial distributions of red-spiral galaxies ($\rho(r)$) from the observed surface density distribution. We can calculate the PDFs of $\rho_\text{los}$ using equation (2) with $\rho_\text{los}$ and $\rho(r)$ derived above.

Fig. 6 shows the PDFs of $\rho_\text{los}$. The black solid line is the PDF calculated from equation (2) with $\rho_\text{los}$ and $\rho(r)$ derived above. We also show the PDF of $\rho_\text{los}$ calculated from equation (2) with $\rho(r) = 0$, i.e., the PDF with only the infall component with red dashed line. This figure indicates that, when we adopt
the shell model, the kinematics of infalling galaxies can
represent that of red-spiral galaxies, as it nicely reproduces
the dip at $v_{\text{los}} = 0$. The $\chi^2$ for the PDF by
using both the infall and splashback components is 8.8,
and that for the PDF by using both the core and splashback
components is 8.9. For the PDF by using the infall component
only $i.e.$, PDF calculated from equation (2) with $\alpha(r) = 0$. We adopt the
shell model as the radial distributions of red-spiral galaxies here. The
projected aperture adopted here is $0.5h^{-1}\text{Mpc}$.

We also check how the choice of $\rho(r)$ affects the PDF
of $|v_{\text{los}}|$. In Fig. 7, we compare the PDFs of $|v_{\text{los}}|$ with each
model of $\rho(r)$. We use $p_\alpha$ with both the infall and splashback
components here. This Figure indicates that we cannot
reproduce the observed PDF of $|v_{\text{los}}|$ of red-spiral galaxies
regardless of the choice of $\rho(r)$. The $\chi^2$ for the PDF by
using $\rho_{\text{cusp}}(r)$ is 9.8, and that with $\rho_{\text{core}}(r)$ is 8.9.

Fig. 8 shows the comparison of the PDFs of $|v_{\text{los}}|$ for
each model of $\rho(r)$ and only the infall component, $i.e.$, $\alpha = 0$.
We find that only the shell model can reproduce the dip,
although the other model can also fit the observed PDF of
red-spiral galaxies reasonably well. The $\chi^2$ for the PDF by
using $\rho_{\text{cusp}}(r)$ is 5.8, and that with $\rho_{\text{core}}(r)$ is 4.2. Again, by
performing F-test, we find that the PDF of $|v_{\text{los}}|$ calculated
with the shell model is preferred over the cusp (core) model
at 76% (61%) significance, when we assume that red-spiral
galaxies reside only in the infall component.
blue-spiral galaxies do not turn into red immediately after the strangulation effect occurs. We regard the quenching time as the time from the strangulation effect occurs to turn blue-spiral galaxies into red (see Fig. 9). We can estimate the quenching timescale as 0.7 Gyr (2.0 Gyr) if the strangulation effect occurs at $r = 1 h^{-1} \text{Mpc}$ ($r = 1.5 h^{-1} \text{Mpc}$) from the centre of the galaxy cluster. Bekki et al. (2002) also show that when the mass accretion to the galaxy decreases, the spiral arms of the galaxy disappear. We regard the time of the strangulation effect as the time that the mass accretion to the galaxy stops. We also assume that the morphological transformation happens from the radii where the strangulation effect occurs to the radii where red-spiral galaxies disappear. We regard the radius where red-spiral galaxies disappear as the smaller one of the two half maximum points of the radial distribution of red-spiral galaxies ($r < 0.5 h^{-1} \text{Mpc}$). From these radii, we calculate the time when the morphological transformation finishes to $\sim 1.4$ Gyr after the quenching completes.

We also discuss other mechanisms of quenching and morphological transformation. Assuming that ram pressure stripping is the dominant mechanism of quenching, which is also suggested as the main mechanism to quench star formation of cluster galaxies in Lotz et al. (2018), we can constrain radii where ram pressure stripping is effective. Since ram pressure stripping affects not only the interstellar medium in galaxies but hot surrounding gas, it quenches star formation of galaxies and turns them into red immediately. Assuming that blue-spiral galaxies turn into red-spiral galaxies typically at the radius where red-spiral galaxies appear, i.e., the larger one of the two half maximum points of the radial distribution of red-spiral galaxies (see Fig. 9), we estimate that the radius where ram pressure stripping is effective is $r \sim 0.7 h^{-1} \text{Mpc}$. In this case, the radius where the morphological transformation is effective corresponds to the radius where red-spiral galaxies disappear, i.e., the smaller one of the two half maximum points of the radial distribution of red-spiral galaxies ($r \sim 0.1 h^{-1} \text{Mpc}$).

It is worth noting that since we define spiral galaxies as $p_{\text{galaxy, red}} > 0.8$ based on the Galaxy Zoo, we may miss some spiral galaxies whose spiral arms are hard to detect from images. This means that the time estimate of the timescale of the morphological transformation might be overestimated.

6 SUMMARY AND CONCLUSION

We have performed the stacking analysis of red-spiral galaxies around galaxy clusters by using the Galaxy Zoo and the redMaPPer cluster catalogue. We have found that the PDF of $v_{\text{los}}$ of red-spiral galaxies is significantly different from that of all red galaxies, and has a dip at $v_{\text{los}} = 0$ at $1.4r$ significance. To interpret this observation, we have constructed a model of the phase space distribution of galaxies surrounding galaxy clusters in three-dimensional space based on the stacked phase space distribution from cosmological $N$-body simulations. Following Hamabata et al. (2018), we have adopted a two component model, which consists of the infall component and the splashback component. We have investigated the radial distribution of red-spiral galaxies from observed surface density distribution of red-spiral galaxies. We have considered three model, the shell model, the cusp model, and the core model. We have found that the PDF of
$v_{\text{los}}$ of red-spiral galaxies can be reproduced by assuming that red-spiral galaxies reside predominantly in the infall component, particularly for the case of the shell model as it nicely reproduces the central dip of the PDF.

Our results and analysis suggest that the shell model is the most plausible model of the radial distribution of red-spiral galaxies among the models investigated in this paper, although the core and the cusp models also show reasonably good agreements. We have found that we can constrain the quenching timescale by the environmental effect to a few Gyrs, and the time when the morphological transformation finishes to ~ 1.4 Gyr after the quenching completes.

We have demonstrated that the detailed analysis of the PDF of $v_{\text{los}}$ such as the one we have presented in this paper provides much more information on the motion of cluster galaxies than the analysis of just the dispersion of the PDF as often performed in the literature, which provides an important clue to understand the galaxy evolution. Our results and analysis indicate that the kinematics of galaxies is not fully virialized, but a significant fraction of galaxies are infalling even at $r$ smaller than $0.5h^{-1}\text{Mpc}$ at $0.05 < z < 0.1$. Our results also highlight the fact that we can extract kinematically coherent sample of galaxies by using the features of galaxies such as colours, morphologies, and luminosities, which may help the analysis of the redshift-space distortion effect. By comparing the observed PDF of $v_{\text{los}}$ of red-spiral galaxies to that obtained from hydrodynamical cosmological simulations (e.g., Schaye et al. 2015, Dubois et al. 2016) and cosmological semi-analytic simulations (e.g., Henriques et al. 2015, Lacey et al. 2016, Makiya et al. 2016), we can test the validity of the mechanism of the environmental effect implemented in these simulations. Finally, by increasing the sample of red spiral galaxies, we can obtain the PDF of $v_{\text{los}}$ of red-spiral galaxies with smaller statistical errors, which will constrain the kinematics and radial distribution of red-spiral galaxies more accurately.

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