Toward an Understanding of the Massive Red Spiral Galaxy Formation

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Abstract

To understand the formation and quenching processes of local massive red spiral galaxies with \(M_\ast > 10^{10.5} M_\odot\), we perform a statistical analysis of their spectroscopic and structural properties and compare them with elliptical and blue spiral galaxies of similar mass. The sample was selected from the stellar mass catalog of galaxies in SDSS DR7, according to their locations on the \(u - r\) color–stellar mass diagram. We find that red spirals harbor compact cores with high stellar mass surface densities measured by \(\Sigma_1\) and are bulge dominated. Particularly, the red spirals, especially their bulges, follow the \(\Sigma_1 - M_\ast\) ridgeline for quenched galaxies. Furthermore, the red spirals show similarly large central \(D_{\text{c}}(4000)\), high [Mg/Fe], and dark matter halo mass to ellipticals. These results suggest that the bulges of red spirals formed within a short timescale before redshift \(\sim 1 - 2\) and were quenched via a fast mode, similar to ellipticals. Careful examinations of the optical morphologies reveal that \(\sim 70\%\) of red spirals show strong bars, rings/shells, and even merging features, which suggests that interactions or mergers might have played an important role in the formation of red spirals. In contrast, most of the massive blue spirals have completely different spectral and structural properties from red spirals. However, the blue spirals with high \(\Sigma_1\) (\(\Sigma_1 > 10^{9.5} M_\odot \text{kpc}^{-2}\)) show similar structural and morphological properties, as well as similar halo mass and \(\text{H}1\) mass to red spirals. We discuss rejuvenation from red to blue as a possible explanation for these high-\(\Sigma_1\) blue spirals.

Unified Astronomy Thesaurus concepts: Galaxy bulges (578); Galaxy evolution (594); Galaxy formation (595); Spiral galaxies (1560); Star formation (1569); Galaxy structure (622)

1. Introduction

Since the discovery of the galaxy color bimodality in the color–magnitude or color–stellar mass diagrams both locally and at high redshifts (e.g., Kauffmann et al. 2003b; Baldry et al. 2004, 2006; Bell et al. 2004; Faber et al. 2007; Ilbert et al. 2010), there have been mounting works investigating the evolutionary pathways from the blue cloud of star-forming galaxies to the red sequence of quiescent galaxies (e.g., Bell et al. 2004; Faber et al. 2007; Marchesini et al. 2014; Schawinski et al. 2014). However, when the morphologies of galaxies are taken into account, the bimodality almost disappears (Schawinski et al. 2014). This is a result of the close relation between galaxy colors and morphological types: early-type galaxies are mainly located in the red sequence, while disk galaxies mostly populate the blue cloud. Therefore, the popular picture proposed for galaxy evolution is that quenching processes are accompanied with structure transformation, i.e., quenched massive spheroids were transformed from blue star-forming disk galaxies. On the other hand, there is a striking feature in the color–stellar mass diagram for spiral galaxies: while the less massive spirals (\(M_\ast < 3 \times 10^{10} M_\odot\)) occupy the blue cloud region, a population of massive spiral galaxies (\(M_\ast > 3 \times 10^{10} M_\odot\)) are in the red sequence (Schawinski et al. 2014). The existence of such massive red spiral galaxies challenges the scenario that galaxy quenching must be in company with the morphological transformation (e.g., Skibba et al. 2009; Bundy et al. 2010; Masters et al. 2010; Fraser-McKelvie et al. 2018).

It has been over 40 yr since the first studies for passive spiral galaxies (e.g., van den Bergh 1976; Dressler et al. 1999; Poggianti et al. 1999; Goto et al. 2003; Skibba et al. 2009). At earlier times, the focus was mainly on the environmental effects on the formation of red spirals. For galaxies in clusters, ram pressure could strip off the gas in and around galaxies and hence shut down the star formation. In the past decade, with the advent of several wide or deep photometric and spectroscopic surveys, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000), Cosmic Evolution Survey (COSMOS, Scoville et al. 2007), Galaxy Evolution Explorer (Martin et al. 2005), and Wide-field Infrared Survey Explorer (Wright et al. 2010), passive spirals have attracted more attention. Many efforts have been invested in understanding the origin of red spirals by studying their stellar populations, structures, and environments (e.g., Bundy et al. 2010; Masters et al. 2010; Robaina et al. 2012; Tojeiro et al. 2013; Fraser-McKelvie et al. 2018). Based on the Galaxy Zoo project (GZ), Masters et al. (2010) found that at high stellar masses (\(M_\ast > 10^{10} M_\odot\)), a significant fraction of spirals are red and the environment is not sufficient to quench these massive spirals. In consideration of the old stellar populations hosted by red spirals (see also Robaina et al. 2012; Tojeiro et al. 2013) and the intact disk morphology, Masters et al. (2010) proposed that red spirals might be old spirals that have exhausted all of their gas. Meanwhile, Bundy et al. (2010) investigated the evolution of passive spirals since \(z \sim 1 - 2\) based on the COSMOS survey and made extensive discussions about possible origins of red spirals. They found that red spirals have more concentrated light distribution than blue spirals, and hence red spirals are unlikely to originate from...
blue spirals. It is still unclear how red spirals formed and the star formation was quenched.

Galaxy bulges are prominent components of massive spiral galaxies. Robaina et al. (2012) compared the central stellar population properties of massive ($M_*>10^{10.4}M_\odot$) red spirals with elliptical galaxies based on SDSS Data Release 7 (DR7) and GZ. They found that the formation epoch and the star formation duration are related to the bulge mass. Interestingly, bulge building is also a key process in galaxy quenching (Martig et al. 2009; Bluck & Mendel 2014). Based on the half-million local SDSS galaxy sample, Bluck & Mendel (2014) systematically investigated the connection of quenching mechanisms to galaxy properties and found that the bulge mass is the dominator of the passive galaxy fraction, indicating the importance of morphological quenching. Therefore, the bulge is an important component in our understanding of galaxy formation and evolution. Several parameters have been used to characterize bulge properties, such as bulge mass, bulge-to-total light/mass ratio, bulge surface mass density, Sérsic index, etc. More recently, the stellar mass surface density within a radius of 1 kpc ($\Sigma_1$), a measure of the innermost structure of galaxies, has been considered as a more powerful probe of galaxy quenching (Cheung et al. 2012; Fang et al. 2013; Barro et al. 2017a). The scale of 1 kpc is coincident with those of the young bulges forming at $z \sim 2$, as revealed by the ALMA and Hubble Space Telescope observations (Barro et al. 2016, 2017b; Tadaki et al. 2017a, 2017b; Newman et al. 2018). Taken together, $\Sigma_1$ is linked with both bulge formation and galaxy quenching. A visit of this parameter will help to understand these two processes.

Many quenching mechanisms have been explored in the literature. Apart from the aforementioned morphological quenching, halo quenching (Dekel & Birnboim 2006) is also among the most popular ones for central galaxies. It is expected that galaxies hosted by dark matter halos above some critical halo mass are unable to form new stars owing to the shock heating of circumgalactic gas. This critical halo mass is about $10^{12}M_\odot$ (Dekel & Birnboim 2006). Fraser-McKelvie et al. (2018) examined a sample of 35 nearby passive spiral galaxies that consists of 30 massive ones with $M_*>10^{10}M_\odot$. After investigating the bar fractions and environments, they concluded that the quenching mechanisms for massive passive spiral galaxies are still a puzzle.

In this work, we concentrate on a relatively large sample of massive ($M_*>10^{10.5}M_\odot$) red spiral galaxies and compare them to blue spiral and red elliptical galaxies above the same mass limit. By investigating their central stellar population properties, detailed morphological features, $\Sigma_1$, bulge properties, gas contents, dark matter halo masses, etc., we expect to shed light on the formation and quenching mechanisms of red massive spiral galaxies. This is the first paper in this series. In a follow-up study by Hao et al. (2019), based on Mapping Nearby Galaxies at the Apache Point Observatory (MaNGA; Bundy et al. 2015) two-dimensional spectra, we explored the spatially resolved stellar population and kinematical properties using subsamples of galaxies in this work. In Section 2, we describe the sample selection and parameter derivation for our sample galaxies. We present the results in Section 3. In Sections 4 and 5, we discuss and summarize our findings, respectively. Throughout this paper, we adopt the Chabrier (2003) initial mass function (IMF) and a cosmology with $H_0=70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m=0.3$, and $\Omega_\Lambda=0.7$.

2. Sample and Parameters

2.1. Sample Selection

Our samples were drawn from the catalog of Mendel et al. (2014) by constraining the redshift range to $0.02<z<0.05$ and further requiring the luminosity of the galaxies in the range of $M_{C,\text{Petro}}<-19.5$ mag (Schawinski et al. 2014) in order to derive the distribution of a parent sample covering a wider range of stellar mass in the color–stellar mass diagram. For our working samples, we only selected galaxies with the total stellar mass $M_*>10^{10.5}M_\odot$. This yielded a sample of 11,172 massive galaxies. We will use spirals and ellipticals to denote our massive spiral and elliptical galaxies hereafter.

We then used the visual morphological classifications from the GZ 1 project (Lintott et al. 2008, 2011) to obtain the morphological types of the galaxies. This resulted in 3908 spirals and 3261 elliptical galaxies. To ensure the reliability of the photometric bulge–disk decomposition and minimize the dust reddening effect on the color measurements for spiral galaxies, the spiral galaxies with minor-to-major axis ratio $b/a<0.5$ were excluded. In addition, we examined each image of these spiral galaxies to further remove false face-on galaxies. This step reduced the number of face-on spiral galaxies to 1914.

Finally, we utilized the dust-corrected $u-r$ color–stellar mass diagram to single out blue cloud galaxies and red sequence galaxies (see Figure 1), using similar criteria to Guo et al. (2016). This selection produced 279 red, 961 blue spiral, and 2889 red elliptical galaxies as our working samples. This shows that more than 10% of massive spiral galaxies (279/1914) are red, and 50% of them are blue. We note that our samples are not complete but should be representative samples for galaxies in each category. Especially, when some parameters are not available for a subset of our sample galaxies (see Section 2.2), only the subsamples with available measurements will be used.

Figure 2 shows the redshift and stellar mass distributions for the three subsamples. It is clear from the left panel of Figure 2 that the three samples have similar redshift distributions. However, from the right panel of Figure 2, although the distributions of stellar mass for the red spirals and ellipticals are similar, quite a large fraction of blue spirals show relatively lower stellar mass, compared with red spiral and elliptical galaxies.

Given that the color measurements of our sample galaxies may be influenced by the presence of AGNs, we evaluate this effect by examining the optical spectral types. The sample of Mendel et al. (2014) does not include Seyfert 1 galaxies. We identified Seyfert 2 galaxies by widely used BPT diagrams proposed by Baldwin et al. (1981) and developed by Kauffmann et al. (2003a) and Kewley et al. (2001, 2006). It turned out that only 4.3% (12/279) of red spirals, 4.1% (39/961) of blue spirals, and 0.4% (11/2889) of ellipticals are Seyfert 2 galaxies. Since the fractions of Seyfert 2 galaxies are small and would not affect our statistical results, we did not remove them from our samples.

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As pointed out by Gadotti (2009), axial ratios derived from SDSS are not correct in some cases.
2.2. Parameter Derivation

The parameters used in this work were mainly obtained from the public database, except for $\Sigma_1$. We will briefly describe the derivation of the parameters below and refer the reader to the original papers for more details.

The bulge masses ($M_{\text{bulge}}$), disk masses ($M_{\text{disk}}$) and total stellar masses were retrieved from Mendel et al. (2014). The $u$- and $r$-band magnitudes of the bulge components were from Mendel et al. (2014) (J. T. Mendel 2020, private communication) and Simard et al. (2011), respectively. Simard et al. (2011) performed photometric measurements on the $g$- and $r$-band images of galaxies from the SDSS DR7 (York et al. 2000; Abazajian et al. 2009) using three sets of models: a single Sérsic profile, a de Vaucouleurs bulge plus exponential disk, and a Sérsic bulge plus exponential disk. A probability parameter $P_{g5}$ was derived to judge the necessity of a bulge+disk model compared to a pure Sérsic model, and $P_{g5} \leq 0.32$ was proposed as a criterion of real bulge+disk systems. Mendel et al. (2014) extended their work to the $u$, $i$, and $z$ bands and focused on either a single Sérsic profile or a de Vaucouleurs bulge plus exponential disk fitting to derive the bulge, disk, and total stellar masses via SED fitting. They classified the galaxies into different types according to their best-fit two-dimensional profiles. We used the combination of the $P_{g5}$ value provided by Simard et al. (2011) and the best-fit profile types in Mendel et al. (2014) to distinguish a genuine bulge+disk system from a single-profile system and adopted the corresponding stellar mass derived from the best-fitting profile. The stellar masses with dust corrections were used. For galaxies with extremely red colors, the bulge masses are sometimes severely overestimated with dusty models, so we used the dust-free results for galaxies with $M_{\text{bulge}} + M_{\text{disk}}$ higher than their total masses by $1\sigma$ or above, as recommended by Mendel et al. (2014). There are 92.5% ($258/279$) of red spirals and 87.4% ($840/961$) of blue spirals being best fitted with a bulge+disk model, and only these galaxies will be used in the analysis of the effective radius ($R_e$) and $u - r$ color for the bulge components, the bulge mass, and the bulge-to-total stellar mass ratio ($B/T$). The $u$- and $r$-band magnitudes of the bulge components were corrected for internal extinctions using the $E(B - V)$ provided by the Oh–Sarzi–Schawinski–Yi (OSSY) catalog (Oh et al. 2011). The $B/T$ was defined as $M_{\text{bulge}}/(M_{\text{bulge}} + M_{\text{disk}})$.

The dust-corrected $u - r$ colors for the entire galaxies were calculated from the $u$- and $r$-band model magnitudes that were retrieved from the SDSS DR7. We first applied k-corrections to the $u$- and $r$-band model magnitudes based on the New York University Value-Added Galaxy Catalog (NYU-VAGC; Blanton & Roweis 2007). Then, we corrected the k-corrected $u$- and $r$-band model magnitudes for the foreground Galactic extinctions using the dust maps from Schlegel et al. (1998), and for the internal dust extinctions using the $E(B - V)$ from stellar continuum fitting provided by the OSSY catalog, based on the Calzetti et al. (2000) extinction law.

The spectral indices $D_{\alpha}(4000)$ and $[\text{Mg}/\text{Fe}]$ measured from the central 3″-diameter fiber spectrum were taken from the catalog of the Max Planck Institute for Astrophysics–Johns Hopkins University (MPA-JHU) and the OSSY catalog, respectively. Specifically, we corrected the internal dust extinctions for $D_{\alpha}(4000)$ according to Calzetti’s law. The $[\text{Mg}/\text{Fe}]$, defined as log (Mgb/0.5(Fe5270 + Fe5335)) normalized to the solar abundances, were calculated based on the Lick indices Mgb, Fe5270, and Fe5335 obtained from the OSSY catalog, which improved on the MPA-JHU in the absorption-line measurements, especially in accounting for the impact of [N I] $\lambda\lambda$5198, 5200 lines on Mgb measurements. Since the $D_{\alpha}(4000)$ and $[\text{Mg}/\text{Fe}]$ were measured from the central 3″-diameter fiber spectrum, they roughly represent the properties of the central regions of galaxy bulges, as demonstrated by the bulge $R_e$ distribution for our red and blue galaxies.

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5. [http://gem.yonsei.ac.kr/~ksoh/wordpress](http://gem.yonsei.ac.kr/~ksoh/wordpress)
6. [http://www.mpa-garching.mpg.de/SDSS](http://www.mpa-garching.mpg.de/SDSS)
spiral galaxies in Figure 3. We note that the spectral indices measured from the central fiber spectrum may suffer from contamination from the disk component, although we have attempted to minimize this effect by excluding galaxies with \( b/a < 0.5 \). However, this effect should act on the blue and red spirals in the same way and hence does not produce biased results in the comparisons.

The dark matter halo masses were extracted from the halo mass catalog of Yang et al. (2007), which were derived using statistical estimation for galaxies in a group. Yang et al. (2007) provide two sets of masses for each group based on the characteristic stellar mass and the characteristic luminosity, respectively. The dark matter halo mass based on the characteristic stellar mass was adopted. There are 94.6% (264/279) of red spirals, 94.8% (911/961) of blue spirals, and 95.9% (2770/2889) of ellipticals in the group catalog, among which 65.6% (173/264) of red spirals, 77.8% (709/911) of blue spirals, and 68.1% (1886/2770) of ellipticals are central.

Figure 2. Redshift (left) and stellar mass (right) distributions for our sample galaxies. The red and blue open histograms represent spirals belonging to the red sequence and blue cloud, respectively. The gray filled histogram is for ellipticals in the red sequence. The median values for the respective categories are labeled in each panel.

Figure 3. Distributions of effective radius of bulges for our sample spiral galaxies. The red and blue open histograms represent spirals belonging to the red sequence and blue cloud, respectively. The light-blue filled histogram represents blue spirals with \( \Sigma_1 > 10^{9.5} \ M_\odot \cdot \text{kpc}^{-2}. \) The median values for the respective categories are labeled in the upper right corner.
galaxies. Only the dark matter halo masses of central galaxies will be explored.

The Arecibo Legacy Fast ALFA (ALFALFA) Survey provides a database of an extragalactic H\textsc{i} 21 cm line survey covering $\sim$7000 deg² (Giovanelli et al. 2005; Haynes et al. 2018). We cross-matched our samples with the ALFALFA ($\alpha$.100) database using a 4″ searching radius to derive the masses of the atomic H\textsc{i} gas. There are 59.5% (166/279) of red spirals, 58.3% (560/961) of blue spirals, and 56.3% (1627/2889) of elliptical galaxies in the ALFALFA survey area, and 74 red spirals, 327 blue spirals, and 39 ellipticals have H\textsc{i} detections.

We measured the stellar mass surface density $\Sigma_1$ for our sample galaxies using the five broadband ($u$, $g$, $r$, $i$, $z$) SDSS Atlas images. We first retrieved point-spread function (PSF) FWHM for the five bands from the “photoObjall” catalog via the SDSS CasJobs service. For each galaxy, we then performed PSF matching between images in different bands by smoothing the four band images with better PSFs to the worst PSF using Gaussian kernels. Then, circular aperture photometry with a radius of 1 kpc was carried out on the PSF-matched images. The observed spectral energy distribution (SED) consisting of five broadband photometry was thus obtained and corrected for Galactic reddening. By comparing this SED to the SEDs in the model library using Bayesian likelihood estimates (Kauffmann et al. 2003b), we derived the probability distribution of the corresponding stellar mass within the central 1 kpc. We used the median of the probability distribution as our best fit of the stellar mass and the 16%–84% values as the ±1σ errors. The details about how to generate the model library can be found in Chen et al. (2012).

3. Results

In this work, we focus on investigating the formation and assembly processes, as well as the possible quenching mechanisms, for massive red spiral galaxies, by comparing the red spirals with blue spirals and ellipticals on their bulge colors, $\alpha$-enhancement traced by [Mg/Fe] excess, age of stellar populations indicated by $D_n$(4000), and structures. We also analyze the similarities and differences among the red spirals, blue spirals, and elliptical galaxies, which might be able to provide some clues to understanding the whole picture of massive galaxy formation and evolution.

3.1. The Spectroscopic Properties

Galaxy color is a direct probe of stellar populations. Figure 4 shows the $u - r$ color distributions for the bulges of red and blue spirals, as well as the ellipticals. It is clear from Figure 4 that the bulges of red spirals are even redder than ellipticals. The median values of $u - r$ colors for the bulges of red spirals and ellipticals are 2.75 and 2.57, respectively. Considering the negative color gradient of early-type galaxies, we expect that the central regions of ellipticals are redder than the entire galaxies and hence have similar $u - r$ colors to the bulges of red spirals. Furthermore, both the bulges of red spirals and ellipticals cover a relatively narrow range in $u - r$ color with the rms scatters of 0.14 and 0.09, respectively. In contrast, the color range for the bulges of blue spirals is much larger with an rms scatter of 0.69, and the median value of $u - r$ color is 1.85, which is lower than those of red spirals and ellipticals by ~33% and ~28%, respectively. The Kolmogorov–Smirnov (K-S) test shows that the distributions of $u - r$ color for red and blue spirals are completely different with a significance of 99.99%. It implies that star formation is still taking place in a large fraction of bulges of blue spirals, which is consistent with their spectral features, such as strong H\textsc{ii} emission lines.

It is well known that $\alpha$-elements are mainly delivered by Type II supernova (SN II) explosions of massive stars, while a substantial fraction of SN II-peak elements come from the delayed SN I explosions. Therefore, the $\alpha$/Fe ratio, indicated by [Mg/Fe], can reflect the relative importance of SN II and SN I in galaxies, and it carries the information of star formation timescale in galaxies (Thomas et al. 2005). On the other hand, $D_n$(4000), defined as the ratio of the average flux density in the bands 4000–4100 Å and 3850–3950 Å, is a proxy for the galaxy age. Especially, it is an excellent age indicator for old galaxies (e.g., Kauffmann et al. 2003b; Tacchella et al. 2017).

Figure 5 shows the relation between [Mg/Fe] and $D_n$(4000) for the red and blue spirals, as well as ellipticals. We can see from Figure 5 that the red spirals and ellipticals occupy almost the same region in the [Mg/Fe] versus $D_n$(4000) diagram. Moreover, both of them follow a trend that as $D_n$(4000) increases, the [Mg/Fe] also increases, although the correlations between [Mg/Fe] and $D_n$(4000) are not strong, with the Spearman’s rank order correlation coefficients of 0.32 and 0.35, respectively. Since both $D_n$(4000) and [Mg/Fe] were measured based on the SDSS fiber spectra within a 3″ diameter aperture, they probe the stellar population properties of the central regions of our sample spirals and ellipticals. Therefore, Figure 5 indicates that the formation epoch and formation duration for the main stellar populations in the central regions of red spirals are similar to those of ellipticals. Furthermore, the correlations between [Mg/Fe] and $D_n$(4000) for red spirals and ellipticals illustrate that the earlier the main stellar population formed, the shorter the star formation timescale was. On the other hand, it is obvious from Figure 5...
that the blue spirals are located in a completely different region in the $[\text{Mg/Fe}]$ versus $D_n(4000)$ diagram, and there is almost no correlation between $[\text{Mg/Fe}]$ and $D_n(4000)$, with the Spearman’s rank correlation coefficient of 0.21.

We also investigate the histograms of $[\text{Mg/Fe}]$ and $D_n(4000)$ for the bulges of red and blue spirals, as well as ellipticals, as shown in Figure 6. The median values of $[\text{Mg/Fe}]$ and $D_n(4000)$ are labeled in the figure, and the rms scatters of the distributions for ellipticals in $[\text{Mg/Fe}]$ and $D_n(4000)$ are $\sim 0.05$ dex and $\sim 0.07$ Å, respectively. From the left panel of Figure 6, the median values of $[\text{Mg/Fe}]$ for the central regions of red spirals and ellipticals are 0.16 and 0.19, respectively. They are in good agreement with each other within the scatter. In contrast, the median value of $[\text{Mg/Fe}]$ for the central regions of blue spirals is just 0.06, which is systematically smaller than that of red spirals and ellipticals at $>2\sigma$ levels. As Thomas et al. (2005) claimed, the longer the star formation timescale, the lower is the $[\text{Mg/Fe}]$ ratio. They also pointed out that $[\text{Mg/Fe}]$ is...
Fe] = 0.2 corresponds to a star formation timescale within 1 Gyr for composite stellar populations. Therefore, the star formation timescales for the central regions of red spirals and ellipticals are similarly short, whereas the star formation timescale for the bulges of blue spirals is longer.

Furthermore, from the right panel of Figure 6, the median values of $D_{n}(4000)$ for the main stellar populations of the central regions of red spirals and ellipticals are 1.89 and 1.92, respectively, which are almost the same within the rms scatter of $D_{n}(4000)$. This implies a similar formation epoch of these two populations. In contrast, the median value of $D_{n}(4000)$ for the main stellar populations in the central regions of blue spirals is just 1.36, which is obviously smaller than that of red spirals and ellipticals at $>3\sigma$ levels. To avoid suffering from model dependence, we adopted spectral indices to probe the properties of stellar populations in this paper. From our experiment, the ages, especially the luminosity-weighted ages derived from FIREFLY (Comparat et al. 2017), produced consistent results with $D_{n}(4000)$.

Given that the local massive ellipticals formed their main stellar populations by redshift $\sim$2 and the star formation timescale is $\sim$1 Gyr (e.g., Worthey et al. 1992; Thomas et al. 2005), the similar distributions of [Mg/Fe] and $D_{n}(4000)$ for the central regions of red spirals and ellipticals strongly suggest that the central regions of red spirals had also formed by redshift $\sim$2 and within $\sim$1 Gyr. These results support the conclusions for bulge formation by Robaina et al. (2012), Belli et al. (2015), and Onodera et al. (2015), also consistent with the recent analysis based on the MaNGA database (Hao et al. 2019).

However, the central regions of blue spirals formed later, and the formation timescale is longer than those of ellipticals as shown in Figures 5 and 6. Therefore, we need to explore possible reasons that are responsible for the differences in stellar populations of these different types of massive galaxies. It seems to be widely accepted that galaxy quenching is often associated with the construction of central concentration, especially for massive galaxies (Bell et al. 2012; Cheung et al. 2012; Fang et al. 2013; Woo et al. 2015; Pan et al. 2016). Investigations for the central structures and morphologies of massive spiral galaxies might help to gain insights into the physical processes for galaxy formation.

### 3.2. The Structure Properties of Massive Spiral Galaxies

#### 3.2.1. The Central Stellar Mass Density

It has been established that galaxy formation and quenching are closely related to their central structures, represented by $\Sigma_{1}$, which is a key parameter connecting the galaxy formation history (e.g., Fang et al. 2013; Barro et al. 2017a; Tacchella et al. 2017; Tadaki et al. 2017a; Whitaker et al. 2017; Chen et al. 2019). The relation between $\Sigma_{1}$ and stellar mass has been widely investigated for both local and high-redshift galaxies (e.g., Cheung et al. 2012; Fang et al. 2013; Barro et al. 2017a; Whitaker et al. 2017). It was found that there is a tight correlation between $\Sigma_{1}$ and stellar mass for quenched galaxies. The best-fitting line for quiescent galaxies is called the $\Sigma_{1}-M_{*}$ ridgeline. In addition, star-forming galaxies tend to be located below the $\Sigma_{1}-M_{*}$ ridgeline.

The left panel of Figure 7 shows the $\Sigma_{1}$ versus $M_{*}$ relation for our sample massive red spirals and ellipticals. It is clear that the red spirals are located similarly to the ellipticals. Both of them show relatively strong correlations between $\Sigma_{1}$ and $M_{*}$, with Spearman’s rank correlation coefficients of 0.44 and 0.51, respectively. For a direct comparison with Fang et al. (2013), we adopt the ordinary least-squares fitting method to derive the best-fit $\Sigma_{1}-M_{*}$ relations and quote the associated vertical scatter in this work. It turns out that the best ordinary least-squares fitting lines for our red spirals and ellipticals are similar, with consistent slopes within 1σ uncertainties and a slightly different normalization in the sense that the normalization of the relation for red spirals is 0.12 dex lower than the one for red ellipticals. We speculate that the lower normalization for red spirals is caused by the presence of a disk component in addition to the bulge component, and this will be tested below. The best-fitted relation for ellipticals is in good agreement with that of Fang et al. (2013) after being shifted by 0.15 and 0.04 dex on the vertical and horizontal axes, respectively. Such offsets in the $\Sigma_{1}-M_{*}$ relation are caused by the different methods adopted in the stellar mass measurements. In addition, the 1σ vertical scatter about the relation for our ellipticals is exactly the same as that of Fang et al. (2013), with a value of 0.16 dex, although the sample selection criteria of these two studies are different. Interestingly, the red spirals show a very similar vertical scatter of 0.17 dex. In contrast, the blue spirals are located systematically lower than the $\Sigma_{1}-M_{*}$ ridgeline and show a larger scatter, as shown in the right panel of Figure 7.

It is very interesting that if we just focus on the bulge mass of red spirals, we can see from the left panel of Figure 8 that the bulges of red spirals and ellipticals follow the same $\Sigma_{1}-M_{*}$ relation in terms of both the slope and the intercept. Their Spearman’s rank correlation coefficients are also very similar, i.e., 0.54 and 0.51, respectively, with 1σ vertical scatter of 0.16 dex. This indicates that the bulges of red spirals share the $\Sigma_{1}-M_{*}$ relation with quenched galaxies. Note that all the above correlation analyses show significance levels larger than 99.99%. Altogether, it illustrates that the central structure of red spirals is more closely connected with the bulge mass, instead of the mass of the whole galaxy. This confirms our above speculation that the disk component is responsible for the relatively lower normalization of the $\Sigma_{1}-M_{*}$ relation for red spirals compared to that of the ellipticals. This can be easily understood in consideration of the results in Section 3.1. The central parts of bulges of red spirals formed rapidly by $z \sim 2$, and then the disks of the galaxies started to also grow fast by gas falling from larger radii during very gas-rich mergers (Hao et al. 2019).

Moreover, we examine the $\Sigma_{1}-M_{*}$ relation for the bulges of blue spirals, as shown in the right panel of Figure 8. It can be seen that there is also a correlation between $\Sigma_{1}$ and $M_{*}$ for the bulges of blue spirals, with the Spearman’s rank correlation coefficient of 0.53 at a significance level >99.99%. The 1σ vertical scatter for blue spirals is 0.21 dex, which is larger than that of red spirals by ~30%. Taken together, the bulges of both massive red and blue spirals follow the $\Sigma_{1}-M_{*}$ ridgeline for quenched galaxies. The behavior of the bulges of blue spirals is distinct from that of the entire blue spiral galaxies, which are mainly located below the $\Sigma_{1}-M_{*}$ ridgeline for quenched galaxies, as shown in the right panel of Figure 7. The close correlation between $\Sigma_{1}$ and the bulge mass for both red and blue spirals may support the statement of Bluck & Mendel (2014) that bulge mass is the king for galaxy quenching.
star formation in high-$\Sigma_1$ blue spirals is very likely due to rejuvenation. We will discuss this possibility in Section 3.2.3.

As another popular probe of galaxy bulges, $B/T$ is also expected to be correlated with $\Sigma_1$. Figure 9 shows the $\Sigma_1$-$B/T$ relation for the red and blue spirals. There is a weak correlation between $\Sigma_1$ and $B/T$ for red spirals and a relatively strong correlation for blue spirals, with the Spearman’s rank correlation coefficients of 0.26 and 0.45, respectively. Therefore, the central structure represented by $\Sigma_1$ is more closely coupled with the bulge mass than the bulge-to-total mass ratio $B/T$, which reinforces the importance of bulge mass once more.

### 3.2.2. The Morphologies of Massive Red Spiral Galaxies

More and more pieces of evidence suggest that massive elliptical galaxies formed mainly via two phases (e.g., Oser et al. 2010; van Dokkum et al. 2010; Huang et al. 2018; Tanaka et al. 2019; Zibetti et al. 2020). During the first phase, the central compact region formed rapidly by cold gas falling triggered by violent disk instabilities or gas-rich mergers (Dekel & Burkert 2014; Zolotov et al. 2015) by redshift $\sim$2. In the second phase, the outer extended part emerged gradually by accreting surrounding gas-poor satellites or minor dry mergers (e.g., Naab et al. 2009). On the other hand, the formation process of massive spiral galaxies, especially massive red spiral galaxies, is still under debate (e.g., Bundy et al. 2010; Masters et al. 2010; Hao et al. 2019). The disk formation models have been proposed since the 1980s (Fall & Efstathiou 1980; Mo et al. 1998; Dutton et al. 2007). It was claimed that galactic disks formed from the dissipational collapse of gas in dark matter halos and then evolved secularly with quiet merging histories. More recently, numerical simulations showed another possibility, in which very gas-rich major mergers can also produce spiral galaxies (Springel & Hernquist 2005; Robertson et al. 2006; Hopkins et al. 2009; Athanassoula et al. 2016; Sparre & Springel 2017). In this scenario, the bulge formed first by cold gas falling into the center with a starburst mode, and then the gas at sufficiently large radii cool quickly and reform a rotating disk. Such merging events should have imprinted on the morphologies of galaxies. Therefore, we study the morphologies and detailed structures of red spirals to understand the possible mass assembly processes for their disks and outer parts.

We visually inspect the SDSS images of our 279 sample red spirals very carefully, also consulting the classification results by GZ 2 (Willett et al. 2013; Hart et al. 2016). The morphologies of red spirals can be roughly classified into three categories: (1) galaxies with strong bars and inner and outer rings (or shells); (2) interacting galaxies/mergers; and (3) normal spiral galaxies with bulge, disk, and clear spiral arms. For the reliability of the classification of galaxies in the second category, we checked the redshifts of their neighbors. When the velocity difference between the target galaxy and its neighbor is less than 500 km s$^{-1}$, the target galaxy is classified as an interacting galaxy/merger. For galaxies with a target-neighbor velocity difference larger than 500 km s$^{-1}$ or without redshift information available for their neighbors, only those with clear merging features, such as tidal tails, are classified as mergers.

The fractions of these three categories are about 50%, 20%, and 30%, respectively. The top row of Figure 10 shows the first class of our sample red spirals, i.e., the galaxies with strong bars and inner and outer rings (or shells), while the bottom row gives examples for the interacting or merging galaxies. It is obvious from the top row of Figure 10 that the rings, especially the outer rings (or shells), are symmetric. In contrast, the galaxies in the bottom row show asymmetric or incomplete outer rings, which are the tidal streams. It seems that these tidal streams are in the process of forming rings/shells. By comparing the morphologies of red spirals in the first and second categories, we speculate that rings or shells might be produced in mergers.

Recent deep observations have revealed that tidal streams and shells around massive early-type galaxies are popular (e.g., Tal et al. 2009; Atkinson et al. 2013; Hood et al. 2018). On the other hand, numerical simulations, especially the recent
cosmological hydrodynamical zoom-in simulations, such as EAGLE, Illustris, and Horizon-AGN, revealed the role of galaxy interaction and merger on shaping galaxy morphologies. Their results showed that the vast majority of ring galaxies formed via interactions of galaxies (Elagali et al. 2018), most of the strong bars in the local universe are triggered by galaxy mergers or external perturbations (Peschken & Lokas 2019), and the gas-rich major mergers can form rotationally supported structure by regrowing a disk (e.g., Athanassoula et al. 2016; Rodriguez-Gomez et al. 2017; Sparre & Springel 2017; Martin et al. 2018). Therefore, our morphological results are consistent with the simulations, i.e., interactions and mergers probably play an important role in the formation of the disk and outer parts of red spirals.

Furthermore, we can also see from Figure 10 that the massive red spiral galaxies of all kinds of morphologies have typical spectra of old stellar populations with very weak or no emission lines, consistent with the bulge $u - r$ color distributions. Both indicate that the bulges of massive red spiral galaxies have been quenched.

### 3.2.3. The High-$\Sigma_1$ Massive Blue Spiral Galaxies

As shown in the right panel of Figure 7, most blue spirals are located below the $\Sigma_1-M_*$ ridgeline. However, there do exist some high-$\Sigma_1$ blue spirals lying on the $\Sigma_1-M_*$ ridgeline. It means that these blue spirals have already acquired dense cores but have not been quenched. Fang et al. (2013) already noted this and speculated that high-$\Sigma_1$ blue spirals may be rejuvenated galaxies from red to blue at fixed stellar mass but without central mass growth. However, more pieces of evidence are needed. We investigate the high-$\Sigma_1$ (defined as galaxies with $\Sigma_1$ larger than $10^{9.5} M_\odot \text{ kpc}^{-2}$) blue spirals by comparing their morphology, structures traced by bulge mass and bulge-to-total mass ratio $(B/T)$, and the dark matter halo mass to those of red spirals and ellipticals.

The high-$\Sigma_1$ blue spirals compose $\sim 10\%$ of our sample of blue spirals. We classified their morphologies into three categories as for the red spirals in the above subsection. Figure 11 shows the examples of the first and second categories, i.e., the galaxies with strong bars and inner and outer rings (top row) and those with interacting or merging features (bottom row). The fractions of the three categories are almost the same as those of red spirals, i.e., $\sim 2/3$ of high-$\Sigma_1$ blue spirals are with strong bars and inner and outer rings or in the interacting/merger stage. However, when we perform the same classification for our sample blue spirals with $\Sigma_1$ less than $10^{9.5} M_\odot \text{ kpc}^{-2}$ (denoted as low $\Sigma_1$ hereafter), the fractions belonging to the three categories are about 20%, 15%, and 65%, respectively. The fact that most low-$\Sigma_1$ blue spirals are normal spiral galaxies is significantly different from that of the high-$\Sigma_1$ blue spirals.

Figure 12 shows the distributions of the bulge mass (left panel) and the bulge-to-total stellar mass ratio $B/T$ (right panel) for red and blue spirals, as well as for the red and blue spirals with high $\Sigma_1$. From the left panel of Figure 12, the $\Sigma_1$-red and blue spirals are similar, i.e., $\sim 0.2$ dex, but the $\Sigma_1$-blue spirals is obviously larger, with a value of $0.33$ dex. The median values of the distributions, as shown in the left panel of Figure 12, tell that the bulge mass of the red spirals $(10^{10.60} M_\odot)$ is larger than that of the blue spirals $(10^{10.35} M_\odot)$ by $0.25$ dex, slightly larger than 1σ. In comparison, the median value of the bulge mass for high-$\Sigma_1$ blue spirals $(10^{10.62} M_\odot)$ is almost the same as that of the red spirals, although it is smaller than that of the high-$\Sigma_1$ red spirals by $0.13$ dex. From the right panel of Figure 12, it is interesting to note that the median values of the $B/T$ ratios for high-$\Sigma_1$ red and blue spirals are the same (0.65), and even a little higher than that of the whole population of red spirals (0.57). Furthermore, the fractions of high-$\Sigma_1$ red and blue spirals with $B/T > 0.6$ are larger than those of the whole population of red and blue spirals. In contrast, blue spirals show a smaller median value of the $B/T$ ratio than all of the other three subsamples and have the smallest fraction of galaxies with $B/T > 0.6$. Therefore, there is no doubt that bulges are the dominant component and contribute $\sim 2/3$ of the total stellar mass for both high-$\Sigma_1$ red and blue spirals. Although blue spirals also harbor massive bulges, their bulges are less prominent and less massive than those of high-$\Sigma_1$ red and blue spirals.

Figure 13 shows the cumulative fractions of the halo mass of the central galaxies for our sample of red and blue spirals, as well as the elliptical galaxies. We can see that the halo masses of the red spirals and ellipticals are in a similar range but are...
for red and blue spirals, respectively, with significan
tics, and halo mass range, which strongly suggest that there
are physical connections between these two populations. The only difference between them is in the star formation properties. Compared to the red spirals, whose star formation has been quenched, the high-$\Sigma_1$ blue spirals host on-going star formation throughout the galaxy, even within their bulges, as exhibited by their optical spectra and $u-r$ colors.

On the other hand, the central velocity dispersion was found to be tightly correlated with $\Sigma_1$ for red sequence galaxies, with an rms scatter of 0.18 dex in $\Sigma_1$ (Fang et al. 2013). In fact, the central velocity dispersion $\sigma_0$ has long been used to study its correlations with stellar population properties (e.g., Burstein et al. 1988; Bender et al. 1993). For example, Thomas et al. (2005) pointed out that at a given $\sigma_0$ the stellar populations of the bulges of spirals are indistinguishable from those of the ellipticals. Wake et al. (2012) claimed that $\sigma_0$ is the best indicator of galaxy color and is correlated with halo and central black hole mass. Most recently, Bluck et al. (2020) emphasized that $\sigma_0$ is used more widely as a quenching indicator nowadays. The large $\Sigma_1$ values of the high-$\Sigma_1$ blue spirals possibly suggest that they were ever quenched before the reignition of the star formation. The similarities of the high-$\Sigma_1$ blue and red spirals in morphology, structure, and halo mass range provide a further suggestion that the ever quenched high-$\Sigma_1$ blue spirals were red spirals indeed. Therefore, one of the reasonable interpretations for the similarities between the high-$\Sigma_1$ blue and red spirals is that high-$\Sigma_1$ blue spirals are rejuvenated red spirals, as induced by bar instabilities or
interactions, which lead cold gas to fall into the galaxies and trigger star formation again in the bulges and disks of red spirals, driving them toward blue. However, further careful investigations on the star formation histories of high-$\Sigma_1$ blue spirals are needed to validate this scenario, as those did in Mancini et al. (2019) or in Hao et al. (2019).

4. Discussion

Our results showed that red spirals and ellipticals have similar integrated $u - r$ colors, central stellar population properties, and a dark matter halo mass range and harbor similarly compact cores with high stellar mass surface densities measured by $\Sigma_1$, but their outer structures are completely different, the rotational disks hosted by red spirals in particular. This may hint that there are both similarities and differences in the formation and quenching processes for massive ellipticals and spirals. An investigation into their gas properties may help us shed light on this issue.

We investigate the atomic gas content in our sample galaxies based on the ALFALFA ($\alpha$ .100) data, which have a beam size of $3\arcsec \times 3\arcsec$. As expected, the H I detection rate for ellipticals is very low (2%). However, it is surprising that the H I detection rate for our red spirals is not too different from that of the blue spirals, i.e., 45% and 58%, respectively, considering that red spirals have been quenched. A further examination on the distribution of gas-to-stellar mass ratio $M_{\text{H I}}/M_*$ for all types of H I-detected sample galaxies was shown in Figure 14. The median H I mass fraction for the 2% H I-detected ellipticals is only about 10%, while the median H I mass fractions for all types of H I-detected spiral galaxies are about 20%, which is
consistent with earlier works (e.g., Gerêb et al. 2018; Parkash et al. 2019; Zhang et al. 2019). The similar H I detection rate and ratio of H I mass to stellar mass of red and blue spirals seem to conflict with the halo quenching scenario, considering that red spirals are mostly hosted by dark matter halos more massive than the critical mass ($\sim 10^{12} M_\odot$) for quenching, as shown in Figure 13. Therefore, where the cold atomic gas is located is the key to understanding the formation and quenching for red spirals.

Actually, there have been studies on the locations of neutral atomic gas of red spirals. Lemonias et al. (2014) provided resolved H I images observed by the Jansky Very Large Array (VLA) for 20 H I-rich massive galaxies with low specific star formation rates, in which there are four of our sample red spirals. They found that the H I gas is distributed in the very extended rotational disks with low H I surface densities, whose sizes are twice those of the optical disks. Therefore, Lemonias et al. (2014) speculated that the low specific star formation rates may be caused by the low H I gas surface densities on the large H I disks. More recently, Zhang et al. (2019) also found that most of the massive quenched central disk galaxies possess a large amount of H I gas content and show symmetric double-horn H I spectra, suggesting regularly rotating H I disks, and the radii of H I disks are estimated to be $\sim 30$ kpc according to the H I size–mass relation. From these studies, it is clear that the cold atomic gas is already in the extended rotating gas disks of galaxies, instead of a part of the intergalactic medium in halos. This solves the puzzle of our suspicion of the halo quenching scenario. Halo quenching is essential to preventing fresh cold gas from flowing into galaxies. To explain why the quenched
central disk galaxies have plenty of H I gas but ceased star formation, Peng & Renzini (2020) proposed a new quenching mechanism for disk galaxies—angular momentum quenching: once the accreted material, mainly in the form of H I, flows in with too high angular momentum to maintain the radial inflow, the star formation in the disk will be quenched and the incoming gas will settle down on the outer part of the disk. In addition, morphological quenching may also contribute to the quenching of red spirals given the presence of the big bulges in red spirals (Figure 12), which will stabilize the gas disks, and hence star formation is prohibited (Martig et al. 2009). To summarize, halo quenching, angular momentum quenching, and morphological quenching may have been working together to cease the star formation in red spirals.

Belli et al. (2019) claimed that quenching processes are closely linked with the formation processes, i.e., the physical mechanisms responsible for quenching are tightly related to the properties of progenitors. The different quenching processes of ellipticals and red spirals may imply that their formation processes are also different. As stated in Section 3.2.2, massive ellipticals formed mainly via two phases (e.g., Oser et al. 2010; van Dokkum et al. 2010), i.e., the formation of compact cores via violent gas-rich processes, including violent disk instabilities or gas-rich mergers, followed by the buildup of extended outer regions through minor dry mergers. As for red spirals, by comparing the MaNGA data analysis for red spirals with simulations (Springel & Hernquist 2005; Robertson et al. 2006; Hopkins et al. 2009; Athanassoula et al. 2016; Sparre & Springel 2017), Hao et al. (2019) speculated that red spirals are the result of very gas-rich major mergers at high redshift, instead of violent disk instabilities. During such a gas-rich major merger, gas within some characteristic radius loses angular momentum and then falls into the center rapidly and forms a compact bulge in a starburst mode. Meanwhile, the gas and stars, without losing a significant amount of angular momentum, will form a rotational disk surrounding the bulge in the merger remnant. Our results on the stellar population properties of the central regions and the morphologies of red spirals in this work are also coincident with this formation scenario. Although the specific formation processes are different, both the central regions of ellipticals and red spirals formed via very gas-rich processes that induce starbursts in galaxy centers. The rapid gas-rich processes and the associated starbursts could result in the close properties of the central regions of ellipticals and red spirals in stellar populations and structures.

Furthermore, Dekel & Burkert (2014) pointed out that only half of the z ~ 2 star-forming galaxies can form compact cores and the remaining half became extended stellar disks owing to the lognormal distribution of spin parameters. Accordingly, we suggest a scenario: the instabilities of very gas-rich disks with low angular momentum can form compact cores of ellipticals, while red spirals were formed by major mergers between the extended disk galaxies with high angular momentum before most of the gas turned into stars. Our conjecture can be tested using modern high-resolution cosmological hydrodynamical simulations, such as IllustrisTNG (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018, 2019; Pillepich et al. 2018, 2019; Springel et al. 2018), by tracing back the formation histories of red spirals. Before such a sophisticated work, a consistency check on the number density of z ~ 2 gas-rich major mergers with that of our red spirals and high-SΣ1 blue spirals would be helpful. There are several obstacles to an accurate comparison between these number densities. For one thing, our galaxy samples are representative but not complete. For the other, the merger rate of high-z galaxies suffers from large uncertainties and the redshift interval for the integration is also uncertain. Despite these difficulties, a rough estimate can be made. Considering the number density of z ~ 2 massive star-forming galaxies of 10^{-3} Mpc^{-3} (e.g., Muzzin et al. 2013) and the major merger fraction of main-sequence galaxies at the corresponding redshift of 5%–10% (Cibinel et al. 2019), the number density of gas-rich major mergers at z = 2 would be 5 × 10^{-5} to 10^{-4} Mpc^{-3}. This agrees with the estimate of Barro et al. (2013) based on earlier studies. For our red spirals, their number density was estimated using two methods. One is based on the combination of the number density of massive star-forming galaxies at z ~ 0.1 (Moustakas et al. 2013) over the mass range of our samples (~7 × 10^{-4} Mpc^{-3}) and the fraction of red spirals (279/1914). The other is based on the

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Figure 12. Bulge mass (left) and stellar mass B/T (right) distributions for red (red open histogram) and blue (blue open histogram) spirals, as well as for the red (pink open histogram) and blue (light-blue filled histogram) spirals with Σ > 10^{−3} M⊙ kpc^{-2}. The median values are labeled in the upper left corner of each panel. The rms scatters of the bulge mass distributions for red and blue spirals and high-SΣ1 red and blue spirals are 0.21, 0.33, 0.18, and 0.24 dex, respectively. The rms scatters of the stellar mass B/T distributions for the galaxies belonging to these four categories are 0.17, 0.22, 0.18, and 0.20 dex, respectively.
The combination of the number density of \( z \sim 0.1 \) massive quiescent galaxies (\( 10^{-3} \) Mpc\(^{-3} \)) and the number ratio of red spirals to red ellipticals (279/2889). Inspiringly, these two methods produced consistent results, with the number density of red spirals about \( 10^{-4} \) Mpc\(^{-3} \). Similarly, the number density of high-\( \Sigma_1 \) blue spirals is estimated to be \( \sim 5 \times 10^{-5} \) Mpc\(^{-3} \). Therefore, the combined number density of red spirals and high-\( \Sigma_1 \) blue spirals is roughly consistent with the number density of \( z \sim 2 \) gas-rich major mergers, which lends further support to our proposed scenarios for the formation mechanisms of red spirals and high-\( \Sigma_1 \) blue spirals.

5. Summary

For the purpose of unveiling the formation and quenching processes for massive red spiral galaxies, we select a sample of massive red spiral galaxies, as well as samples of blue spiral and red elliptical galaxies, with \( M_\odot > 10^{10.5} M_\odot \) from the stellar mass catalog of Mendel et al. (2014) that is based on the SDSS DR7 (York et al. 2000; Abazajian et al. 2009). Under the constraint of redshift range of \( 0.02 < z < 0.05 \) and the luminosity with \( M_\odot^{\text{petro}} < -19.5 \) mag, our massive galaxy sample consists of 279 red spirals, 961 blue spirals, and 2889 red ellipticals, respectively. The main results are summarized as follows.

1. We find that the red spirals and ellipticals are located in the same region in the central spectral indices [Mg/Fe] versus \( D_n(4000) \) diagram, and the relation between [Mg/Fe] and \( D_n(4000) \) followed by them is similar. In contrast, the blue spirals are located in a completely different region in this diagram, being younger and less \( \alpha \)-element enhanced. Given that \( D_n(4000) \) and [Mg/Fe] are age and star formation timescale indicators for galaxies, respectively, the similar ranges and relations of \( D_n(4000) \) and [Mg/Fe] followed by the central regions of red spirals and ellipticals suggest their similar formation epoch and star formation timescale, i.e., by redshift \( \sim 1-2 \) and within \( \sim 1 \) Gyr.

2. We also find that most red spirals harbor compact cores with high stellar mass surface densities measured by \( \Sigma_1 \), and quite a large fraction of red spirals are bulge dominated. In particular, the red spirals, especially the bulges of red spirals, follow the same \( \Sigma_1-M_\odot \) relation for quenched galaxies, in terms of the slope, \( 1\sigma \) vertical scatters, and the intercept. It supports the statement based on the spectroscopic analysis that the bulges of red spirals and ellipticals formed in the same epoch and quenched rapidly. Moreover, the cumulative halo mass distribution of central red spirals is also similar to that of ellipticals, and most of them have halo masses larger than \( 10^{12} M_\odot \). Therefore, halo quenching, morphological quenching, and the most recently proposed angular momentum quenching mechanisms may jointly play a role in quenching red spirals. Furthermore, by careful morphological examinations, we find that quite a large fraction (\( \sim 70\% \)) of red spirals show abnormal morphologies with strong bars, inner and outer rings (shells), and even tidal streams and other merger remnants. These results are consistent with the simulations in which very gas-rich major mergers can form disk galaxies.

3. The investigations for high-\( \Sigma_1 \) blue spirals reveal their similarities to red spirals in morphology, bulge mass, \( B/T \) distribution, halo mass range, H I detection rate, and mass fraction. This strongly suggests that the high-\( \Sigma_1 \) blue spirals have experienced similar formation histories to red spirals. Considering the fact that there is ongoing star formation in high-\( \Sigma_1 \) blue spirals, one of the reasonable explanations for the similarities and dissimilarities between high-\( \Sigma_1 \) blue spirals and red spirals would be rejuvenation from red spirals to blue spirals. The
rejuvenation is likely induced by interactions or bar instabilities, which make cold gas flow into the galaxies and reignite star formation in the bulges and disks of red spirals, driving them toward blue.

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Figure 14. Ratio of H I gas mass to stellar mass for H I-detected sample galaxies. The colors of the histograms are the same as in Figure 2. The median values for the respective categories are labeled in the upper right corner.
