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Full Text

Preamble

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Small-scale Clustering of Star-forming Galaxies Relative to Early-type and Late-type Galaxies: IllustrisTNG versus the Sloan Digital Sky Survey

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Abstract

We investigate the small-scale clustering of star-forming galaxies (SFGs) in the local universe, using both observational samples from the final data release of the Sloan Digital Sky Survey and IllustrisTNG300, one of the state-of-the-art hydrodynamic simulations of galaxy formation. We measure the projected two-point cross-correlation function, $w_p(r_p)$, for subsamples of SFGs with different specific star formation rates (sSFRs) and stellar masses (M_*), with respect to reference samples of galaxies with early-type or late-type morphology. On scales smaller than $\sim$ 100 kpc and at fixed M_*, SFGs with higher sSFR are more strongly clustered, reflecting the interaction-induced central star formation found in previous studies. More importantly, the small-scale clustering-sSFR correlation is stronger when the reference sample is limited to late-type galaxies only. This confirms the previous finding that the enhancement of star formation in close pairs depends on the morphology of companion galaxies. These observational trends are broadly reproduced by IllustrisTNG300, indicating that current hydrodynamic simulations are capable of capturing the main recipes governing star formation in interacting/merging galaxies, although further work is needed to identify the exact physical processes involved.

Key words: galaxies: evolution -galaxies: star formation -galaxies: interactions

1. Introduction

It is widely accepted that intergalactic interactions can enhance the star formation activity of galaxies, particularly in their central regions. This idea dates back to pioneering works of half a century ago, when Toomre & Toomre (1972) first used numerical simulations to study galaxy interactions, proposing that strong tidal forces could drive cold gas inflow from the disk to the galactic center, enhancing their central star formation activity. Since then, numerous studies—spanning observational analyses, theoretical research, and numerical simulations—have explored the connection between galaxy-galaxy interactions and the central star formation of galaxies.

Early observational studies mostly utilized broad-band colors (e.g., Larson & Tinsley 1978), equivalent width of Hα emission line (e.g., Keel et al. 1985; Bushouse 1986; Kennicutt et al. 1987), far-infrared luminosities (e.g., Bushouse et al. 1988), or molecular emission lines such as CO (e.g., Sanders et al. 1986; Young et al. 1986, 1996; Solomon & Sage 1988; Tinney et al. 1990) as indicators of star formation. These studies generally found a statistically significant correlation between galactic interactions and increased rates of star formation (see Keel 1991 and Struck 1999 for reviews). Thanks to the many imaging and spectroscopic surveys, as well as space telescopes operating in UV, optical, and IR bands that have become available over the past two decades, an increasing number of studies have investigated the connection between galaxy-galaxy interactions/mergers and their star formation activity in varying depths (e.g., Barton et al. 2000; Lambas et al. 2003; Alonso et al. 2004; Nikolic et al. 2004; Ellison et al. 2008; Li et al. 2008; Scudder et al. 2012, 2015; Yuan et al. 2012; Sabater et al. 2013; Barrera-Ballesteros et al. 2015; Davies et al. 2015; Knapen et al. 2015; Pan et al. 2018; Yoon & Im 2020; Steffen et al. 2021; Shah et al. 2022; Thorp et al. 2022; Sureshkumar et al. 2024; Zee et al. 2024). In recent years, integral field spectroscopy surveys of nearby galaxies, such as the Mapping Nearby Galaxies at Apache Point Observatory survey (MaNGA; Bundy et al. 2015), have enabled the investigation of star formation on kpc scales across interacting/merging galaxies at different merger stages (e.g., Pan et al. 2019; Thorp et al. 2019; Moreno et al. 2021). These studies have well established that the interaction-induced star formation depends on a variety of factors, including the mass and gas content of the star-forming galaxies being studied, the separation, mass ratio, and spin difference relative to the companion, and the local environment.

Theoretically, numerical simulations of galaxy formation have also confirmed the original finding of Toomre & Toomre (1972), showing that galaxy-galaxy interactions and mergers play a crucial role in driving the evolution of galaxies, particularly by significantly promoting star-forming activity (e.g., Di Matteo et al. 2008; Renaud et al. 2014; Moreno et al. 2019). Simulations have also successfully reproduced several observational features related to galaxy interactions, such as enhanced gas inflow (e.g., Torrey et al. 2012; Hopkins et al. 2013; Sparre et al. 2022), the duration of star formation rate (SFR) enhancement (e.g., Di Matteo et al. 2008; Hani et al. 2020), intergalactic distance dependence (Torrey et al. 2012), stellar mass evolution (Moreno et al. 2015), gas content changes (Fensch et al. 2017), spin direction differences between interacting galaxies (Moreno et al. 2015), and even the evolution of the Hubble sequence (Brown et al. 2023).

The enhancement of central star formation in interacting/merging galaxies is believed to be a result of cold gas inflow caused by tidal torques induced by the companion galaxy (Hernquist & Barnes 1991; Barnes & Hernquist 1996), which mainly depends on the mass of the nearest neighboring galaxy and its proximity to the star-forming galaxy. In fact, the strong dependence on pair separation has been clearly observed in previous studies. For instance, using $\sim 10^5$ star-forming galaxies from an early sample of the Sloan Digital Sky Survey (SDSS; York et al. 2000), Li et al. (2008) measured the enhancement of central star formation as functions of galaxy pair separation using three different statistical quantities: two-point cross-correlation function (2PCCF), star formation enhancement function, and background-subtracted neighbor counts (N_c). Within a projected separation of $r_p \sim 100$ kpc, both the 2PCCF and N_c were found to increase rapidly as the specific star formation rate (sSFR) in galactic centers increases, while the central star formation enhancement consistently increases as the projected separation decreases from $r_p \sim 100$ kpc down to the size of individual galaxies.

Additionally, the impact of interactions appears to be linked to the Hubble type of companion galaxies (e.g., Park & Choi 2009; Xu et al. 2010; Cao et al. 2016; He et al. 2022). For instance, by analyzing Spitzer observations of 27 close pairs of nearby galaxies, Xu et al. (2010) found that, compared to single spiral galaxies in a control sample, spiral galaxies in pairs exhibit a significant enhancement in sSFR only when their companion galaxy is also a spiral. This phenomenon cannot be fully explained by gravitational tidal forces alone.

As pointed out by Xu et al. (2010), in addition to pure gravitational effects, other factors related to the companion galaxy must play an important role in enhancing star formation in interacting galaxies. Several mechanisms have been proposed in previous studies, but no consensus has been reached so far. Some authors suggest that in close galaxy pairs, ram pressure stripping and the hot gas "wall" of the companion galaxy' s halo may prevent the star-forming galaxy from acquiring the cold gas necessary for star formation, thereby suppressing its star-forming activity (Park & Choi 2009; Gabor & Davé 2015; Moon et al. 2019). Alternatively, He et al. (2022) proposed that, due to their lower local densities and lower relative velocities compared to elliptical–elliptical pairs, spiral–spiral pairs are more likely found in field environments, which favor coplanar interactions (Dubois et al. 2014). Such interactions can trigger strong nuclear starbursts through tidal torques (Barnes & Hernquist 1996). Differently, Hwang et al. (2011) suggested that the dependence of star formation enhancement on the companion' s morphology may simply be attributed to the well-known morphology–density relation (Dressler 1980), as early-type galaxies are more likely found in high-density environments where the average star formation rates of galaxies are suppressed.

In this paper, we extend the work of Li et al. (2008) using both observational samples from the final data release of SDSS (Abazajian et al. 2009) and IllustrisTNG (Nelson et al. 2018), one of the state-of-the-art hydrodynamical simulations of galaxy formation. We measure the projected 2PCCF for subsamples of star-forming galaxies selected by sSFR and stellar mass, with respect to a reference galaxy sample. As shown in Li et al. (2008), the amplitude of 2PCCFs on scales smaller than ~ 100 kpc as a function of sSFR provides a measure of star formation induced by galaxy–galaxy interactions. Unlike Li et al. (2008), we divide the reference galaxies into two subsets according to their morphology, enabling the examination of the dependence on companion morphology.

Previous studies of this phenomenon were mostly limited to small samples, whereas the large SDSS-based sample and the 2PCCF technique should provide more robust and detailed results. The comparison between SDSS and IllustrisTNG offers a valuable test of current hydrodynamical simulations, particularly regarding their physical recipes for regulating star formation in interacting and merging galaxies.

The paper is organized as follows. Section 2 describes the observational and simulation samples, along with the clustering analysis method. In Section 3, we present the results of the projected 2PCCFs measured from the SDSS/DR7 sample. Section 4 provides the results from the IllustrisTNG galaxy sample. Finally, Section 5 summarizes the study and offers concluding remarks and outlook. Throughout this paper, we assume a cosmological model with a density parameter of $\Omega_0 = 0.3$ and a cosmological constant of $\Lambda_0 = 0.7$.

2. Data and Methodology

We quantify the clustering of star-forming galaxies selected by different SFRs and morphological types using the 2PCCF relative to a reference galaxy sample. Both the star-forming galaxy samples and the reference sample, along with measurements of galaxy properties, are drawn from the final data release (DR7; Abazajian et al. 2009) of the SDSS (York et al. 2000). To compare our clustering measurements with theoretical expectations, we use simulation samples from the TNG300 data set of the Illustris-TNG project (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018). In this section, we briefly describe these samples and our methodology for measuring galaxy clustering, with further details available in the referenced studies.

2.1. SDSS Reference Galaxy Sample

As our reference sample, we use sample dr72 from the New York University Value Added Galaxy Catalog (NYU-VAGC), described in detail by Blanton et al. (2005). This sample includes approximately half a million galaxies with spectroscopically measured redshifts in the range $0.01 < z < 0.2$, r-band Petrosian apparent magnitudes brighter than $r = 17.6$, and r-band Petrosian absolute magnitudes in the range $-23 < M_{r,0.1} < -16$. Here, $M_{r,0.1}$ represents the absolute magnitude at $z = 0.1$, obtained by applying both evolution correction and K-correction to its value at $z = 0$. The NYU-VAGC also provides stellar mass (M_*) estimates for each galaxy, derived by Blanton & Roweis (2007) using spectroscopic redshifts and SDSS *ugriz* photometry, assuming a stellar initial mass function from Chabrier (2003). Morphological classifications for the reference galaxies are adopted from Domínguez Sánchez et al. (2018), who employed deep learning algorithms with Convolutional Neural Networks (CNNs) trained on two visual classification catalogs: Galaxy Zoo 2 (Willett et al. 2013) and Nair & Abraham (2010). In this study, we use the T-type parameter, which corresponds to the Hubble sequence. A negative T-type value indicates early-type morphology, encompassing 265,007 galaxies, while a positive T-type value corresponds to late-type morphology, totaling 255,906 galaxies.

2.2. SDSS Star-forming Galaxies

The sample of star-forming galaxies is drawn from the MPA/JHU SDSS/DR7 catalog, which contains 927,552 galaxies from SDSS/DR7. The spectral fitting technique of Brinchmann et al. (2004) was applied to the SDSS single-fiber spectrum of each galaxy, providing measurements of emission line properties, spectral indices and SFRs. Following common practice, we use the BPT diagram (Baldwin et al. 1981), defined by the emission lines [O III] $\lambda5007$, Hβ $\lambda4861$, Hα $\lambda6563$, and [N II] $\lambda6584$, to select star-forming galaxies from the MPA/JHU catalog. A galaxy is classified as a high S/N star-forming galaxy if the signal-to-noise ratio (S/N) of all four emission lines exceeds 3 and the [O III]/Hβ and [N II]/Hα flux ratios place it within the star-forming region of the BPT diagram. Based on these criteria, we identify 125,220 high S/N star-forming galaxies. Additionally, we include a supplementary sample of low S/N star-forming galaxies, following the definition of Brinchmann et al. (2004). These galaxies, which remain after excluding AGN and high S/N star-forming galaxies, are required to have only S/N > 2 in Hα. While their emission line intensities still allow SFR estimation, the associated uncertainties are significantly larger than in the high S/N sample. The total number of low S/N star-forming galaxies is 77,881.

For each galaxy in the MPA/JHU catalog, SFR and sSFR (defined as SFR/M_*) are estimated both within the central 3 fiber and for the entire galaxy. Since our study focuses on star formation activity in central regions, we adopt the fiber sSFR throughout this paper. Although the MPA/JHU catalog also provides a stellar mass estimate for each galaxy, we adopt the stellar mass from the NYU-VAGC, which has been more commonly adopted in recent years. Throughout this paper, M_*, SFR and sSFR are in units of $M_\odot$, $M_\odot$ yr^{-1}, and yr^{-1}, unless otherwise stated.

2.3. The IllustrisTNG Simulations

The IllustrisTNG project is a suite of state-of-the-art cosmological galaxy formation simulations (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018). Each simulation in the IllustrisTNG series tracks the evolution of matter distribution from redshift 127 to the present day, while incorporating a wide range of physical processes that govern galaxy formation. These processes include gas dynamics, star formation, black hole growth, and feedback mechanisms, among others, providing a detailed and comprehensive view of the formation and evolution of galaxies. The highest resolution simulations employ more than 20, 10, and 30 billion resolution elements for the TNG50, TNG100, and TNG300 boxes. In this work we use TNG300, which has a baryon mass of $1.1 \times 10^7 M_\odot$, and a minimum gas resolution of 370 pc.

For comparison with our observational samples, we construct a reference galaxy sample from the $z = 0.1$ snapshot of TNG300. Galaxy properties such as spatial location, stellar mass (M_*), and SFR are obtained from the simulation catalog (Donnari et al. 2019; Pillepich et al. 2019). The sample contains 492,000 galaxies with stellar mass $M_* > 10^8 M_\odot$. Following the method of Zhou et al. (2020), we classify galaxies with $M_* \geq 10^{10} M_\odot$ into disk and non-disk subsets. For galaxies with $M_* < 10^{10} M_\odot$—where the classification method of Zhou et al. (2020) is not applicable—we assign them to the disk sample if their sSFR exceeds 10^{-10} yr^{-1}, and to the non-disk sample otherwise, based on the typical stronger star formation activity of disk galaxies. Additionally, we remove any non-disk galaxy from the sample if it either lacks an SFR measurement from the simulation or has $\mathrm{SFR}/M_* \leq 10^{-10}$ yr^{-1}, to maintain the distinction between disk and non-disk populations. The final sample consists of 238,554 disk galaxies and 177,655 non-disk galaxies.

From the reference sample, we select star-forming galaxies based on their sSFR, resulting in a sample of 375,022 star-forming galaxies with $\mathrm{SFR}/M_* \geq 10^{-10.5}$ yr^{-1}. We will cross-correlate this sample with the reference sample to estimate the clustering of star-forming galaxies and compare the results with those obtained from the observational samples.

To further test whether the morphology classification method adopted for TNG300 impacts our results, we also include galaxy data from the $z = 0$ snapshot of TNG100 (Donnari et al. 2019; Pillepich et al. 2019). From this snapshot, we select a reference galaxy sample consisting of 9787 simulated galaxies with $M_* \geq 10^8 M_\odot$, each assigned a probability of being late-type, p_{late}, ranging from 0 to 1, based on deep learning classifications (Huertas-Company et al. 2019; Varma et al. 2022). Using $p_{\mathrm{late}} = 0.5$ as the threshold, we identify 6860 late-type and 2927 early-type galaxies in the reference sample. Additionally, we select 29,701 star-forming galaxies (SFGs) with $\mathrm{SFR}/M_\odot \geq 10^{-10.5}$ and $M_* \geq 10^8 M_\odot$, without imposing any morphological classification. Note that only a subset of TNG100 galaxies is assigned a p_{late} due to limitations of the classification method; see Huertas-Company et al. (2019) and Varma et al. (2022) for details. For this reason, we use the TNG100 samples solely for cross-checking purposes, while the TNG300 samples are used for the main analysis.

2.4. Clustering Measure

Following Li et al. (2008), we estimate the 2PCCF for a given galaxy sample (Sample Q; e.g., star-forming galaxies from SDSS or TNG simulations, as described above, limited to a range of sSFR and/or other properties) with respect to the reference galaxy sample (Sample D). The 2PCCF is measured over a wide range of spatial scales, from a few ×10 kpc to a few ×10 Mpc. As demonstrated in Li et al. (2008), the amplitude of the 2PCCF on small scales as a function of sSFR provides an estimate of the impact of galaxy-galaxy interactions on star formation activity. Additionally, we divide the reference sample into early-type and late-type galaxies based on their morphological type and measure the 2PCCFs between the SF galaxy sample and each morphological subset separately. By comparing the 2PCCF measurements, we can assess whether and how interaction-induced star formation activity depends on the morphology of neighboring galaxies.

To compute 2PCCFs for the observational samples, we construct a random sample (Sample R) that replicates the selection effects of the reference galaxy sample. For this, we follow the method of Li et al. (2006), which generates the random sample directly from the reference sample. Briefly, for each galaxy in the reference sample, we randomly generate ten sky positions within the survey mask and assign them the same properties as the original galaxy, including redshift, stellar mass, and other relevant parameters. This results in a random sample ten times larger than the reference sample, ensuring identical position- and redshift-dependent selection effects. Extensive tests by Li et al. (2006) have demonstrated that such random samples are statistically unclustered, making them suitable for measuring galaxy clustering, provided the survey area is sufficiently large and depth variations across the field are minimal. The SDSS satisfies both conditions. For TNG samples, there is no need to construct a random sample, as the pair counts expected from a random distribution can be analytically computed, given that the volume of the sampled galaxies forms a regular cubic box.

For a given set of samples (Sample Q, Sample D and Sample R), we first estimate the two-dimensional 2PCCF in redshift space, $\xi^{(s)}(r_p, \pi)$, using the following estimator:

$$\xi^{(s)}(r_p, \pi) = \frac{Q_D}{Q_R}\frac{N_R}{N_D} - 1$$

where N_D and N_R are the numbers of galaxies in the reference sample (Sample D) and the random sample (Sample R); r_p and π are the pair separation perpendicular and parallel to the line of sight; Q_D and Q_R are the counts of cross pairs with separations r_p and π, between Sample Q and Sample D and between Sample Q and Sample R, respectively. Next, the projected 2PCCF, $w_p(r_p)$ is then obtained by integrating $\xi^{(s)}(r_p, \pi)$ over the line-of-sight separation π:

$$w_p(r_p) = 2\sum_{i=1}^{80} \xi^{(s)}(r_p, \pi_i)\Delta\pi$$

where the summation runs from $\pi_1 = -39.5h^{-1}$ Mpc to $\pi_{80} = 39.5h^{-1}$ Mpc with $\Delta\pi = 1h^{-1}$ Mpc. We have corrected the effect of fiber collisions in the SDSS samples following Li et al. (2006). The errors on the clustering measurements are estimated using the bootstrap resampling technique (Barrow et al. 1984).

3. Results from SDSS

3.1. Dependence on sSFR, M_* and Reference Galaxy Morphology

We first estimate $w_p(r_p)$ for the high S/N star-forming galaxy sample from SDSS. To explore the connection between $w_p(r_p)$ and star formation activity, we rank all high S/N star-forming galaxies by SFR/M_* and define two sub-samples: "high sSFR" and "low sSFR" galaxies, corresponding to the top and bottom 25% of the distribution, respectively. We then measure $w_p(r_p)$ for each sub-sample relative to the reference sample using the estimator described above. The results are shown in Figure 1 [Figure 1: see original paper]. As expected, galaxies with higher SFR/M_* exhibit a stronger clustering amplitude on smaller scales ($r_p \lesssim 0.1h^{-1}$ Mpc), indicating a correlation between galaxy–galaxy interactions and enhanced central star formation. This is consistent with the earlier findings of Li et al. (2008), who applied the same sample definition and clustering measurement method to an earlier SDSS sample.

To investigate the dependence of the clustering-sSFR relation on stellar mass, we divide all high S/N star-forming galaxies into six subsamples based on the logarithm of their stellar mass, $\log_{10}(M_*/M_\odot)$. Within each mass bin, we further define two subsets: "high sSFR" and "low sSFR" galaxies, following the same percentile-based selection as above. The $w_p(r_p)$ measurements for the high- and low-sSFR subsamples, along with the full sample in each mass bin, are shown in the top panels of Figure 2 [Figure 2: see original paper]. As seen, the difference in small-scale clustering amplitude between the high- and low-sSFR subsamples, previously observed for the full sample, persists when limiting the stellar mass to narrower ranges, with the effect being stronger at lower masses. Once again, this result is consistent with the earlier findings of Li et al. (2008). On scales larger than ~ 100 kpc, the clustering amplitude shows no dependence on sSFR. At fixed r_p, the clustering amplitude increases with M_*, reflecting the well-known mass dependence of galaxy clustering (e.g., Li et al. 2006).

Figure 1 and the top panels of Figure 2 reproduce the earlier results from Li et al. (2008), which were interpreted as observational evidence for interaction-induced central star formation enhancement. To further examine the dependence on the morphology of companion galaxies, we divide the reference sample into early-type (E) and late-type (S) galaxies based on their T-type values. We then estimate the projected 2PCCF for each of the star-forming galaxy subsamples shown in the top panels of Figure 2 with respect to the two reference samples separately. The $w_p(r_p)$ measurements are displayed in the middle and bottom panels of Figure 2. We find that, at fixed stellar mass, the difference in small-scale clustering amplitude between the high- and low-sSFR subsamples is more pronounced when using the reference sample of late-type galaxies compared to that of early-type galaxies. This result is broadly consistent with previous studies which found that the interaction-induced star formation depends on the morphological type of companion galaxies (e.g., Park & Choi 2009; Xu et al. 2010; Yuan et al. 2012; Cao et al. 2016), as mentioned in Section 1.

On scales larger than ~ 100 kpc, where the dependence of clustering on sSFR is weak, we observe that for any given mass bin, the $w_p(r_p)$ estimated using the early-type reference sample is systematically higher than that obtained with the late-type reference sample, particularly at relatively low masses and on smaller scales. This echoes the finding from Li et al. (2006) that, at fixed stellar mass and scale, galaxies exhibit stronger clustering when they have higher values of concentration index C and surface mass density μ_*, both of which are indicative of early-type morphology. This result also reflects the well-known relationship between galaxy morphology and the density of the local environment (e.g., Dressler 1980; Goto et al. 2003). To minimize the influence of the morphology-density relation, we normalize the $w_p(r_p)$ of the high- and low-sSFR subsamples in each mass bin by the $w_p(r_p)$ of the full SF sample within the same mass bin. This normalization allows us to more clearly isolate the dependence of interaction-induced SF enhancement on the morphology of companion galaxies. The results are shown in Figure 3 [Figure 3: see original paper], with dashed and solid lines representing the measurements obtained using the early-type and late-type reference samples, respectively.

Figure 3 provides a clearer view compared to Figure 2. For SFGs with higher sSFR, the clustering amplitude is greater for both reference samples, and the effect becomes more significant as r_p decreases. More importantly, on scales smaller than a few ×10 kpc, which corresponds to the regime of galaxy–galaxy interactions, the SF enhancement—as indicated by the difference between the high- and low-sSFR subsamples—is notably stronger when the reference sample is restricted to late-type galaxies. The $w_p(r_p)$ for high-sSFR galaxies rises more steeply, whereas the low-sSFR galaxies exhibit a more pronounced decline. This indicates that the morphology of companion galaxies influences the star-forming activity of star-forming galaxies, with late-type companions having a more significant effect than early-type ones.

This result appears to be in conflict with previous findings, considering that the clustering amplitude on scales larger than a few Mpc is a well-known indicator of the mass of dark matter halos hosting the galaxies. Specifically, More et al. (2011) reported that the dark matter halo mass of galaxy groups from SDSS shows no dependence on the color of central galaxies less massive than $\sim 10^{10.5} M_{\odot}$, whereas for more massive central galaxies, the halo mass is significantly larger if the central galaxy is redder (More et al. 2011; Mandelbaum et al. 2016). Since red galaxies typically have relatively low sSFR, these previous findings imply no difference in large-scale clustering between high- and low-sSFR subsamples, but weaker large-scale clustering for high-sSFR galaxies once the stellar mass is fixed. Our result is opposite to this expectation. However, we emphasize that this discrepancy should not be overstated and may be understood through the following considerations. First, the galaxies studied here are already restricted to be star-forming and would therefore all be classified as blue galaxies in previous studies. Second, the SF galaxy samples analyzed here include both central and satellite galaxies. It is well established that satellite galaxies reside in more massive halos than central galaxies of similar stellar mass or luminosity (e.g., see Figure 12 [Figure 12: see original paper] of Li et al. 2007). Therefore, it is likely that the stronger large-scale clustering observed for the high-sSFR subsamples is primarily driven by the contribution of satellite galaxies. To fully understand this result, it would be necessary to further divide the SFGs in each subsample into centrals and satellites, and measure their clustering properties separately. However, this is beyond the scope of the present work, which focuses on small-scale clustering. Finally, as we will see shortly, the sSFR dependence of the large-scale clustering will change significantly if low-S/N SF galaxies are further included. This again suggests that more work would be needed if one were to have a full understanding of this result.

3.2. $w_p(r_p)$ as a Function of SFR/M_*

To study the above phenomena in more detail, we divide all galaxies from the high S/N star-forming sample into non-overlapping subsamples, each with narrow but overlapping intervals of $\log_{10}(\mathrm{SFR}/M_*)$, varying interval widths and containing a sufficiently large number of galaxies. We then estimate the $w_p(r_p)$ for each subsample following the same method described above. For clarity, we normalize each $w_p(r_p)$ measurement using a real-space three-dimensional 2PCCF, assumed to follow a simple power-law: $\xi(r) = (r/r_0)^{-1.8}$. In practice, we derive the corresponding projected 2PCCF, $w_p(r_p)$, by applying the Abel transform to $\xi(r)$, and then use it to normalize the $w_p(r_p)$ of our sSFR subsamples. In addition, to isolate the effect of the aforementioned density-morphology relation, we further normalize the $w_p(r_p)$ of subsamples with varying SFR/M_* intervals by the $w_p(r_p)$ of the subsample at $\log_{10}(\mathrm{SFR}/M_*) = -10.5$.

In Figure 4 [Figure 4: see original paper], we show the amplitude of the normalized $w_p(r_p)$ as a function of $\log_{10}(\mathrm{SFR}/M_*)$, obtained for different projected separations r_p, using the full reference sample (black lines), as well as early-type (yellow lines) and late-type (blue lines) reference samples, respectively. Additionally, given that the high-S/N SF sample is limited to relatively high sSFRs ($\log_{10}(\mathrm{SFR}/M_*) > -10.5$), we attempt to supplement the sample by including low-S/N SFGs following the definition from Brinchmann et al. (2004), as described in Section 2.2. We combine the high- and low-S/N SF samples, repeat the analysis, and display the measurements of the normalized $w_p(r_p)$ as dashed lines in Figure 4.

The results obtained using the full reference sample, plotted as gray lines, are consistent with those reported in Li et al. (2008), as expected. First, at $\log_{10}(\mathrm{SFR}/M_*) > -10.5$, $w_p(r_p)$ is an increasing function of sSFR on smaller scales ($r_p \lesssim 0.1h^{-1}$ Mpc), with the effect strengthening as the scale decreases. This result essentially reflects the interaction-induced central star formation. We notice that, when the sSFR exceeds $\log_{10}(\mathrm{SFR}/M_*) \sim -9.5$, the increasing trend of clustering amplitude is reversed. This result was also observed in Li et al. (2008, see their Figure 4). This might be related to the known fact that galaxy mergers are most efficient in galaxy groups, rather than in either galaxy clusters or isolated systems. Second, still at $\log_{10}(\mathrm{SFR}/M_*) > -10.5$, but on larger scales ($r_p \gtrsim 0.1h^{-1}$ Mpc), $w_p(r_p)$ shows a weak dependence on sSFR. Third, at $\log_{10}(\mathrm{SFR}/M_*) < -10.5$, the clustering amplitude increases as sSFR decreases, and this anti-correlation appears to hold over a wide range of spatial scales—from the smallest scales up to ~ 1 Mpc for the high-S/N sample, and extending to almost 10 Mpc when the low-S/N sample is also included. This anti-correlation was interpreted by Li et al. (2008) as a consequence of environmental effects occurring in dark matter halos, which effectively remove cold gas from galaxies and suppress or even quench their star formation activities (e.g., Kauffmann et al. 2004; Zhang et al. 2013).

For subsamples with $\log_{10}(\mathrm{SFR}/M_*) > -10.5$, the dependence on companion galaxy morphology is clearly seen at the smallest scales (the left two panels in the top row of Figure 4), where the normalized clustering amplitude at a given sSFR is higher when the reference sample consists only of late-type galaxies. This morphology dependence is stronger at smaller scales and at higher sSFRs, consistent with the results seen from the previous figure.

It is noticeable that subsamples with sSFR below $\log_{10}(\mathrm{SFR}/M_*) \sim -10.5$ tend to be more weakly clustered than those with higher sSFR, except for the lowest-sSFR subsamples, which are quite noisy due to small sample sizes. This echoes the anti-correlation between the clustering amplitude on large scales and the sSFR of the SF galaxies, as observed above in Figure 3. We notice that, however, although both the high-S/N SF samples and the combined high- and low-S/N samples consistently show an anti-correlation at low sSFRs between $w_p(r_p)$ and sSFR in most cases, they differ significantly in terms of the $w_p(r_p)$ amplitude at a given sSFR. As a result, for the sample additionally including low-S/N SF galaxies, the average clustering amplitude at low sSFRs is significantly higher than that at high sSFRs, and this is true at all scales except the smallest scales. This implies that, if this sample was used instead of the high-S/N sample for the analyses in Figures 2 and 3, one would find the dependence of clustering on sSFR on large scales to be reversed. On the other hand, as pointed out by Li et al. (2008), the discrepancy between high-S/N and low-S/N samples could be due to the large uncertainties in the SFRs of the low-S/N galaxies. Apparently, more work would be needed in future in order to fully understand the SFR-dependence of galaxy clustering on large scales.

4. Results from IllustrisTNG

4.1. Dependence on sSFR, M_* and Reference Galaxy Morphology

Following the approach used for the observational sample, we divide all SF galaxies from TNG300 into "high sSFR" and "low sSFR" subsamples, defined as the top and bottom 25% in terms of sSFR. We then compute $w_p(r_p)$ for the two subsamples, as well as for the full sample. The results are shown in Figure 5 [Figure 5: see original paper]. On scales smaller than $\sim$ 100 kpc, the $w_p(r_p)$ estimates behave similarly to the observational measurements shown in Figure 1, in the sense that high-sSFR galaxies are more strongly clustered than low-sSFR galaxies. This demonstrates that the interaction-induced star formation observed in real galaxies is well reproduced by current hydrodynamic simulations. On larger scales, however, $w_p(r_p)$ of the low-sSFR subsample is slightly higher than that of the high-sSFR subsample, which is opposite to the observational trends. We note that the same analysis of the TNG100 galaxies yields the same result, indicating that this behavior is a common property of the TNG series, robust to both simulation box size and resolution. We will return to this point and discuss it shortly.

We further divide the simulated SF galaxies into six subsamples based on $\log_{10}(M_*/M_\odot)$. Note that the stellar mass intervals of these subsamples differ from those in the previous section, since the stellar mass distribution in the simulation is somewhat different from that in the observational sample. For this reason, we will not make direct comparisons of $w_p(r_p)$ between the simulation and SDSS. For each M_* subsample, the galaxies are categorized as high-sSFR and low-sSFR galaxies following the same methodology described previously. We then compute $w_p(r_p)$ for each subsample, using the full reference sample as well as the disk and non-disk reference samples, respectively. The results are presented in Figure 6 [Figure 6: see original paper], in the same format as Figure 2. Furthermore, following the approach of Figure 3, in Figure 7 [Figure 7: see original paper] we present the ratio of $w_p(r_p)$ obtained for the high-sSFR (red lines) and low-sSFR (green lines) subsamples relative to that of the full SF sample, in order to normalize out the morphology–density relation. The solid and dashed lines represent the results obtained using the disk and non-disk reference samples, as indicated.

It is encouraging that, on scales smaller than $\sim 0.1h^{-1}$ Mpc, the results obtained from TNG300 closely resemble those of the observational data: $w_p(r_p)$ differs between subsamples with different sSFR, and this difference gradually decreases with increasing stellar mass. More importantly, the dependence of the clustering-sSFR relation on the morphology of reference galaxies seen from the SDSS sample is also clearly seen from TNG300. This similarity is particularly interesting, as it demonstrates that the TNG300 simulation correctly captures the physical processes responsible for the different star formation enhancements induced by different companion morphologies. To investigate whether the TNG300 results are affected by the oversimplified morphology classification method, we have repeated the analysis using the $z = 0$ snapshot of TNG100, for which morphology classification is derived using deep learning. Although the TNG100 results are noisier due to the smaller sample size, they are broadly consistent with the TNG300 results presented above. This demonstrates that our conclusions are robust to the morphology classification method, as well as to the simulation box size and resolution.

We notice that the simulation exhibits a more significant transition between the small-scale and large-scale terms, with a more rapid increase/decrease in the $w_p(r_p)$ ratio at $r_p < 0.1h^{-1}$ Mpc than observed in the SDSS sample. In addition, the scale at which this transition occurs appears to depend on the morphology of the reference galaxies, with smaller transition scales in the case of non-disk morphologies. This trend is not obviously seen in Figure 3, however. Furthermore, the simulation differs from the observations on larger scales—in all mass bins except the most massive one, and for both disk and non-disk reference samples, the $w_p(r_p)$ of the low-sSFR sample is higher than that of the high-sSFR sample, which is opposite to the observational result (see Figure 3). As discussed earlier, the different $w_p(r_p)$ on large scales between subsamples with different sSFR is likely attributed to satellite galaxies, which are usually hosted by more massive halos than central galaxies of similar stellar mass. Thus, the opposite behavior in the simulation suggests that the recipes regulating the star formation of satellite galaxies in simulations may need to be revised.

4.2. $w_p(r_p)$ as a Function of SFR/M_*

Similar to Figure 4, we compute the normalized $w_p(r_p)$ for subsamples divided by SFR/M_*, by normalizing the $w_p(r_p)$ of each subsample using the $w_p(r_p)$ corresponding to the real-space 2PCCF of $\xi(r) = (r/r_0)^{-1.8}$. Similarly, to normalize out the morphology-density relation, the results of all sSFR subsamples are normalized by the subsample at $\log_{10}(\mathrm{SFR}/M_*) = -10.5$. In this analysis, we extend the selection criterion of SF galaxies to include subsamples with lower sSFRs, enabling a more complete comparison with observational results. The results are presented in Figure 8 [Figure 8: see original paper].

Overall, the results from the simulation broadly align with the trends observed in the observational data. Particularly, the simulation well reproduces both the positive correlation of the small-scale clustering amplitude with sSFR for SF galaxies at $\log_{10}(\mathrm{SFR}/M_*) > -10.5$, a signature of the interaction-induced star formation enhancement, and the morphology dependence of the clustering-sSFR relation which strengthens as one moves to smaller scales. For low-sSFR galaxies with $\log_{10}(\mathrm{SFR}/M_*) < -10.5$, the simulation can also reproduce the anti-correlation between $w_p(r_p)$ amplitude and sSFR, similarly to the SDSS sample, particularly the one including both high-S/N and low-S/N SF galaxies. These results reinforce the conclusion from Section 4.1 that the TNG simulations capture the physical recipes that regulate the star formation in interacting/merging galaxy systems.

The primary difference between TNG and SDSS is that, for $\log_{10}(\mathrm{SFR}/M_*) > -10.5$, $w_p(r_p)$ in the simulation samples continues to increase with SFR/M_*, whereas in the observational samples, the increasing trend is reversed, although the effect becomes weaker at larger scales (see Figure 4). As pointed out above, the observed reversion at the highest sSFRs could reflect the fact that galaxy interactions/mergers are most abundant and efficient in galaxy groups, which are at intermediate halo mass scales between the most massive systems (galaxy clusters) and those located in underdense regions (isolated systems). In this regard, the discrepancy between the simulation and the observation may suggest that simulations need to be improved in terms of the environmental influence on the galaxy merging process and the related star formation enhancement effect.

The SDSS galaxy samples, including both the star-forming galaxy subsamples and the reference sample, are flux-limited, while the galaxy samples from the TNG300 simulation are complete, although with a limited volume. One may wonder that the discrepancies between SDSS and the simulation, as mentioned above, may be somewhat caused by the selection effects of the SDSS samples. To test this out, we have generated a mock catalog that includes the same selection effects as the SDSS sample, finding that the results obtained from the mock catalog agree well with those from the simulation itself. This test demonstrates that our results are robust to the sample selection effects.

5. Summary

In this work, we have revisited the interaction-induced star formation enhancement in galaxies in the local Universe, which was studied in depth by Li et al. (2008) using an earlier SDSS galaxy sample. We have extended the work of Li et al. (2008) in the following aspects. First, we make use of the final data release of the SDSS main galaxy sample, as well as simulation data from IllustrisTNG300, thus enabling a comparison between state-of-the-art simulations and real galaxies in the nearby Universe. Second, in addition to stellar mass and SFR, we further consider the morphology of companion galaxies, motivated by the previous finding that star formation enhancement occurs only when the companion galaxy has a late-type morphology (e.g., Park & Choi 2009; Xu et al. 2010). For this purpose, we divide the reference samples in both SDSS and TNG300 into subsamples according to morphology, and measure the projected 2PCCF, $w_p(r_p)$, for star-forming galaxies of different stellar mass (M_*) and sSFR with respect to the reference samples consisting of galaxies of different morphological types.

As demonstrated in Li et al. (2008), the amplitude of $w_p(r_p)$ at scales smaller than ~ 100 kpc probes the effect of galaxy-galaxy interactions/mergers. Therefore, by comparing the $w_p(r_p)$ obtained at different M_* and sSFR, and using reference samples of different morphologies, we are able to quantify the dependence of interaction-induced star formation on M_* and sSFR, as in Li et al. (2008), and additionally on companion morphology. The comparison with TNG300 should provide new tests and useful constraints on current hydrodynamical simulations, particularly in terms of the recipes regulating star formation in interacting/merging systems.

Our results from the observational sample are presented in Section 3. At fixed stellar mass, SF galaxies with higher sSFR are more strongly clustered, and this difference increases at smaller scales. The effect becomes particularly strong at ~ 100 kpc or smaller, reflecting the interaction-induced star formation found in Li et al. (2008) and other previous studies. More importantly, the small-scale clustering-sSFR correlation is stronger when the reference samples are limited to late-type galaxies only. This result confirms the morphology dependence of star formation enhancement in interacting/merging galaxies as found in previous studies. We note that, however, previous studies found that the star formation enhancement occurs only when the companions are spirals/disk galaxies (e.g., Park & Choi 2009; Xu et al. 2010; Cao et al. 2016). In contrast, the star formation enhancement, as indicated by the enhanced small-scale clustering, is detected in our star-forming galaxies regardless of the reference galaxy morphology, although the enhancement is weaker in case that the reference sample includes only early-type galaxies. According to a parallel work (Guo Y. H. et al. 2025, in preparation), this discrepancy should be attributed to the fact the SFR measurements from the SDSS fiber spectroscopy are limited to the central region of the SDSS galaxies, while the SFRs in previous studies are usually measured for the whole galaxies.

Our results from the IllustrisTNG simulation are presented in Section 4. Although a variety of discrepancies between the simulation and the observational data are identified, it is encouraging that the simulation successfully reproduces the most important observational trends, including both the sSFR dependence of the small-scale clustering and its dependence on the morphology of reference galaxies. This result indicates that current hydrodynamical simulations are capable of capturing the main recipes governing star formation in interacting/merging galaxies, although further work is needed to identify the exact physical processes involved.

There is still room to improve our work. From the observational side, the newly released bright galaxy sample (BGS) from the Dark Energy Spectroscopic Instrument survey (DESI/DR1; DESI Collaboration et al. 2025) provides spectroscopy for 5.9 million galaxies covering a sky area of ~ 9700 square degrees, down to an r-band limiting magnitude of $r = 19.5$ (about two magnitudes deeper than the SDSS main sample). It would be interesting to extend the work presented in this paper to much lower stellar masses and lower sSFRs using the DESI/BGS data. In addition, ongoing and upcoming large surveys, including DESI and Subaru/PFS, will provide significantly larger samples at higher redshifts, enabling us to extend the current work to redshifts of $z \sim 1$ or even $z \sim 2$.

From the simulation side, in this work we have considered only the IllustrisTNG, and it would be valuable to include other simulations such as EAGLE and SIMBA in the analysis. This would allow us to determine whether the main observational trends identified here can also be reproduced by other simulations. Third, and more importantly, examining different simulations should, in principle, help reveal the exact physical processes driving the observational trends, which remain unclear so far.

In the analyses presented in Sections 3 and 4, when we compare the projected 2PCCFs for subsamples of different sSFR or those obtained using reference samples of different morphology, we always limit the subsamples in comparison to a narrow range of stellar mass in order to normalize out the mass dependence of galaxy clustering. In fact, previous studies have well established that, even at fixed stellar mass, galaxy clustering shows significant dependence on other properties, particularly galaxy color and structural parameters (e.g., Li et al. 2006). Therefore, it is necessary to limit the subsamples in comparison to be matched in all such properties if we aim to isolate the dependence on sSFR and companion morphology from the dependence on other properties. To this end, one possible approach is to trim the comparison subsamples so that they have the same distributions in all these properties. However, this comes at the cost of significantly reducing the sample sizes. We have performed tests in which we attempt to control the subsamples in comparison by matching redshift, optical color ($g-r$), D4000 (the spectral break around 4000 Å), concentration index ($C \equiv R_{90}/R_{50}$, where R_{90} and R_{50} are the radii enclosing 90% and 50% of the total light in the r-band) and surface mass density (μ_*). We found that our results remain unchanged statistically, but they became rather noisy due to the limited sample sizes of both SDSS and TNG300. The newly available sample from DESI/BGS should enable more rigorous and accurate analyses along this line.

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References

Abazajian, K. N., Adelman-McCarthy, J. K., Agüeros, M. A., et al. 2009, ApJS, 182, 543

Alonso, M. S., Tissera, P. B., Coldwell, G., & Lambas, D. G. 2004, MNRAS, 352, 1081

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5

Barnes, J. E., & Hernquist, L. 1996, ApJ, 471, 115

Barrera-Ballesteros, J. K., Sánchez, S. F., García-Lorenzo, B., et al. 2015, A&A, 579, A45

Barrow, J. D., Bhavsar, S. P., & Sonoda, D. H. 1984, MNRAS, 210, 19

Barton, E. J., Geller, M. J., & Kenyon, S. J. 2000, ApJ, 530, 660

Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734

Blanton, M. R., Schlegel, D. J., Strauss, M. A., et al. 2005, AJ, 129, 2562

Brinchmann, J., Charlot, S., White, S. D. M., et al. 2004, MNRAS, 351, 1151

Brown, W., Patton, D. R., Ellison, S. L., & Faria, L. 2023, MNRAS, 522, 5107

Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7

Bushouse, H. A. 1986, AJ, 91, 255

Bushouse, H. A., Lamb, S. A., & Werner, M. W. 1988, ApJ, 335, 74

Cao, C., Xu, C. K., Domingue, D., et al. 2016, ApJS, 222, 16

Chabrier, G. 2003, PASP, 115, 763

Davies, L. J. M., Robotham, A. S. G., Driver, S. P., et al. 2015, MNRAS, 452, 616

DESI Collaboration, Karim, M. A., Adame, A. G., et al. 2025, arXiv:2503.14745

Di Matteo, P., Bournaud, F., Martig, M., et al. 2008, A&A, 492, 31

Domínguez Sánchez, H., Huertas-Company, M., Bernardi, M., Tuccillo, D., & Fischer, J. L. 2018, MNRAS, 476, 3661

Donnari, M., Pillepich, A., Nelson, D., et al. 2019, MNRAS, 485, 4817

Dressler, A. 1980, ApJ, 236, 351

Dubois, Y., Pichon, C., Welker, C., et al. 2014, MNRAS, 444, 1453

Ellison, S. L., Patton, D. R., Simard, L., & McConnachie, A. W. 2008, AJ, 135, 1877

Fensch, J., Renaud, F., Bournaud, F., et al. 2017, MNRAS, 465, 1934

Gabor, J. M., & Davé, R. 2015, MNRAS, 447, 374

Goto, T., Yamauchi, C., Fujita, Y., et al. 2003, MNRAS, 346, 601

Hani, M. H., Gosain, H., Ellison, S. L., Patton, D. R., & Torrey, P. 2020, MNRAS, 493, 3716

He, C., Xu, C. K., Domingue, D., Cao, C., & Huang, J.-s. 2022, ApJS, 261, 34

Hernquist, L., & Barnes, J. E. 1991, Natur, 354, 210

Hopkins, P. F., Cox, T. J., Hernquist, L., et al. 2013, MNRAS, 430, 1901

Huertas-Company, M., Rodriguez-Gomez, V., Nelson, D., et al. 2019, MNRAS, 489, 1859

Hwang, H. S., Elbaz, D., Dickinson, M., et al. 2011, A&A, 535, A60

Kauffmann, G., White, S. D. M., Heckman, T. M., et al. 2004, MNRAS, 353, 713

Keel, W. C. 1991, in IAU Symp. 146, Dynamics of Galaxies and Their Molecular Cloud Distributions, ed. F. Combes & F. Casoli (Dordrecht: Springer), 243

Keel, W. C., Kennicutt, R. C. J., Hummel, E., & van der Hulst, J. M. 1985, AJ, 90, 708

Kennicutt, R. C. J., Keel, W. C., van der Hulst, J. M., Hummel, E., & Roettiger, K. A. 1987, AJ, 93, 1011

Knapen, J. H., Cisternas, M., & Querejeta, M. 2015, MNRAS, 454, 1742

Lambas, D. G., Tissera, P. B., Alonso, M. S., & Coldwell, G. 2003, MNRAS, 346, 1189

Larson, R. B., & Tinsley, B. M. 1978, ApJ, 219, 46

Li, C., Jing, Y. P., Kauffmann, G., et al. 2007, MNRAS, 376, 984

Li, C., Kauffmann, G., Heckman, T. M., Jing, Y. P., & White, S. D. M. 2008, MNRAS, 385, 1903

Li, C., Kauffmann, G., Jing, Y. P., et al. 2006, MNRAS, 368, 21

Mandelbaum, R., Wang, W., Zu, Y., et al. 2016, MNRAS, 457, 3200

Marinacci, F., Vogelsberger, M., Pakmor, R., et al. 2018, MNRAS, 480, 5113

Moon, J.-S., An, S.-H., & Yoon, S.-J. 2019, ApJ, 882, 14

More, S., van den Bosch, F. C., Cacciato, M., et al. 2011, MNRAS, 410, 210

Moreno, J., Torrey, P., Ellison, S. L., et al. 2015, MNRAS, 448, 1107

Moreno, J., Torrey, P., Ellison, S. L., et al. 2019, MNRAS, 485, 1320

Moreno, J., Torrey, P., Ellison, S. L., et al. 2021, MNRAS, 503, 3113

Naiman, J. P., Pillepich, A., Springel, V., et al. 2018, MNRAS, 477, 1206

Nair, P. B., & Abraham, R. G. 2010, ApJS, 186, 427

Nelson, D., Pillepich, A., Springel, V., et al. 2018, MNRAS, 475, 624

Nikolic, B., Cullen, H., & Alexander, P. 2004, MNRAS, 355, 874

Pan, H.-A., Lin, L., Hsieh, B.-C., et al. 2018, ApJ, 868, 132

Pan, H.-A., Lin, L., Hsieh, B.-C., et al. 2019, ApJ, 881, 119

Park, C., & Choi, Y.-Y. 2009, ApJ, 691, 1828

Pillepich, A., Nelson, D., Hernquist, L., et al. 2018, MNRAS, 475, 648

Pillepich, A., Nelson, D., Springel, V., et al. 2019, MNRAS, 490, 3196

Renaud, F., Bournaud, F., Kraljic, K., & Duc, P. A. 2014, MNRAS, 442, L33

Sabater, J., Best, P. N., & Argudo-Fernández, M. 2013, MNRAS, 430, 638

Sanders, D. B., Scoville, N. Z., Young, J. S., et al. 1986, ApJL, 305, L45

Scudder, J. M., Ellison, S. L., Momjian, E., et al. 2015, MNRAS, 449, 3719

Scudder, J. M., Ellison, S. L., Torrey, P., Patton, D. R., & Mendel, J. T. 2012, MNRAS, 426, 549

Shah, E. A., Kartaltepe, J. S., Magagnoli, C. T., et al. 2022, ApJ, 940, 4

Solomon, P. M., & Sage, L. J. 1988, ApJ, 334, 613

Sparre, M., Whittingham, J., Damle, M., et al. 2022, MNRAS, 509, 2720

Springel, V., Pakmor, R., Pillepich, A., et al. 2018, MNRAS, 475, 676

Steffen, J. L., Fu, H., Comerford, J. M., et al. 2021, ApJ, 909, 120

Struck, C. 1999, PhR, 321, 1

Sureshkumar, U., Durkalec, A., Pollo, A., et al. 2024, A&A, 686, A40

Thorp, M. D., Ellison, S. L., Pan, H.-A., et al. 2022, MNRAS, 516, 1462

Thorp, M. D., Ellison, S. L., Simard, L., Sánchez, S. F., & Antonio, B. 2019, MNRAS, 482, L55

Tinney, C. G., Scoville, N. Z., Sanders, D. B., & Soifer, B. T. 1990, ApJ, 362, 473

Toomre, A., & Toomre, J. 1972, ApJ, 178, 623

Torrey, P., Cox, T. J., Kewley, L., & Hernquist, L. 2012, ApJ, 746, 108

Varma, S., Huertas-Company, M., Pillepich, A., et al. 2022, MNRAS, 509, 2654

Willett, K. W., Lintott, C. J., Bamford, S. P., et al. 2013, MNRAS, 435, 2835

Xu, C. K., Domingue, D., Cheng, Y.-W., et al. 2010, ApJ, 713, 330

Yoon, Y., & Im, M. 2020, ApJ, 893, 117

York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, AJ, 120, 1579

Young, J. S., Allen, L., Kenney, J. D. P., Lesser, A., & Rownd, B. 1996, AJ, 112, 1903

Young, J. S., Kenney, J. D., Tacconi, L., et al. 1986, ApJL, 311, L17

Yuan, F. T., Takeuchi, T. T., Matsuoka, Y., et al. 2012, A&A, 548, A117

Zee, W.-B. G., Moon, J.-S., Paudel, S., & Yoon, S.-J. 2024, ApJ, 963, 141

Zhang, W., Li, C., Kauffmann, G., & Xiao, T. 2013, MNRAS, 429, 2191

Zhou, Z.-B., Zhu, W., Wang, Y., & Feng, L.-L. 2020, ApJ, 895, 92

Note: Figure translations are in progress. See original paper for figures.