Galaxy Interactions in Filaments and Sheets: Insights from EAGLE Simulations (Postprint)

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Abstract

We investigate the colors and star formation rates of galaxy pairs in filaments and sheets using the EAGLE simulations. We find that major pairs with separations less than 50 kpc are bluer and exhibit higher star formation rates in filamentary environments compared to those in sheet-like environments. This trend reverses beyond a pair separation of approximately 50 kpc. For interacting pairs with larger separations (>50 kpc), those in filaments are on average redder and less star-forming compared to those embedded in sheets. The galaxies in filaments and sheets may have different stellar mass and cold gas mass distributions. Using a Kolmogorov-Smirnov (KS) test, we find that for paired galaxies with separations less than 50 kpc, there are no significant differences in these properties between sheets and filaments. Filaments transport gas toward galaxy clusters. Some earlier studies find preferential alignment of galaxy pairs with the filament axis. Such alignment may lead to different gas accretion efficiencies for galaxies residing in filaments versus sheets. We propose that the enhanced star formation rates at smaller pair separations in filaments are caused by the alignment of galaxy pairs. A recent study using SDSS data reports the same findings. Confirmation of these results by the EAGLE simulations suggests that hydrodynamical simulations are powerful theoretical tools for studying galaxy formation and evolution in the cosmic web.

Full Text

Preamble

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Galaxy Interactions in Filaments and Sheets: Insights from EAGLE Simulations

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Abstract

We study the color and star formation rates of paired galaxies in filaments and sheets using the EAGLE simulations. We find that major pairs with pair separation <50 kpc are bluer and more star-forming in filamentary environments compared to those hosted in sheet-like environments. This trend reverses beyond a pair separation of 50 kpc. The interacting pairs with larger separations (>50 kpc) in filaments are on average redder and low-star-forming compared to those embedded in sheets. The galaxies in filaments and sheets may have different stellar mass and cold gas mass distributions. Using a KS test, we find that for paired galaxies with pair separation <50 kpc, there are no significant differences in these properties between sheets and filaments. The filaments transport gas toward the cluster of galaxies. Some earlier studies find preferential alignment of galaxy pairs with the filament axis. Such alignment of galaxy pairs may lead to different gas accretion efficiency in galaxies residing in filaments and sheets. We propose that the enhancement of star formation rate at smaller pair separation in filaments is caused by the alignment of galaxy pairs. A recent study with SDSS data reports the same findings. The confirmation of these results by the EAGLE simulations suggests that hydrodynamical simulations are powerful theoretical tools for studying galaxy formation and evolution in the cosmic web.

Key words: methods: data analysis – methods: statistical – galaxies: evolution – galaxies: interactions – (cosmology:) large-scale structure of universe

1. Introduction

Galaxies are the fundamental units of the observed large-scale structures in the Universe. Understanding their formation and evolution is one of the primary goals of modern cosmology. The growth of primordial density perturbations via gravitational instability eventually leads to the formation of dark matter halos. Dark matter halos represent peaks in the density field. The halos are surrounded by a diffuse neutral hydrogen distribution after recombination. They accrete gas, a process which radiates away kinetic energy and causes gas to settle at their centers. The cooling and condensation of gas at the centers of these halos are believed to be the primary mechanism for galaxy formation (Silk 1977; White & Rees 1978).

The formation and evolution of galaxies are expected to be influenced by both the initial conditions at their formation sites and their interactions with the surrounding environment. Galaxies interact with other galaxies in their neighborhood. Galaxy-galaxy interactions are known to amplify the star formation rate (SFR) in galaxies (Barton et al. 2000; Nikolic et al. 2004; Woods & Geller 2007; Ellison et al. 2010; Patton et al. 2011). The environments of galaxies play crucial roles in their evolution. The colors and SFRs of galaxies are strongly affected by the local density of their environment (Gómez et al. 2003; Lewis et al. 2002). Galaxies become redder and low-star-forming in higher density environments (Kauffmann et al. 2004). The suppression of star formation can be driven by different physical mechanisms. Ram pressure stripping is a common phenomenon in galaxy clusters (Gunn & Gott 1972). Galaxies in high density regions are more likely to encounter harassment (Moore et al. 1996, 1998), starvation (Larson et al. 1980; Somerville & Primack 1999), strangulation (Gunn & Gott 1972; Balogh et al. 2000), and gas expulsion by supernovae, AGN, or stellar winds (Cox et al. 2004; Murray et al. 2005; Springel et al. 2005). Star formation in a galaxy may also be quenched through several other routes. The mass (Birnboim & Dekel 2003; Dekel & Birnboim 2006), morphology (Martig et al. 2009), presence of a bar (Masters et al. 2010), and high angular momentum (Peng 2020) can cause star formation activity in galaxies to cease.

Many other galaxy properties depend on the environment. Elliptical galaxies are more commonly observed in dense groups and clusters (Oemler 1974; Dressler 1980; Davis & Geller 1976; Guzzo et al. 1997; Goto et al. 2003). Spiral galaxies mostly occupy intermediate and low density regions of the Universe. These environmental dependencies of clustering are reflected in different statistical measures such as the correlation function (Zehavi et al. 2005), genus (Park et al. 2005), filamentarity (Pandey & Bharadwaj 2005, 2006), local dimension (Pandey & Sarkar 2020), and mutual information (Pandey & Sarkar 2017; Bhattacharjee et al. 2020; Sarkar & Pandey 2020). The environment of a galaxy is generally characterized by the local density. The local density undoubtedly plays a decisive role in galaxy evolution. However, it cannot completely characterize the environment of a galaxy.

Early generation redshift surveys revealed that galaxies are part of an all-inclusive network comprising clusters, filaments, and sheets (Joeveer & Einasto 1978; Gregory & Thompson 1978; Einasto et al. 1980; Zeldovich & Shandarin 1982). Galaxies and their host halos are embedded in different environments of the cosmic web (Bond et al. 1996). Pandey & Bharadwaj (2008) find that star-forming blue galaxies trace a more filamentary distribution compared to red galaxies. More than 80% of the baryonic budget in the Universe is accounted for by low density gas (warm-hot intergalactic medium, WHIM) in filaments (Tuominen et al. 2021; Galarraga-Espinosa et al. 2021). Consequently, the gas accretion efficiency of dark matter halos in different environments may differ in a significant manner. Thus, the cosmic web can have a significant impact on galaxy properties and their evolution. Galaxies located in different parts of the cosmic web can experience different physical conditions, such as different densities of gas, different levels of tidal forces, and different frequencies of interactions and mergers.

Interactions between galaxies with comparable masses are known as major interactions. Such interactions trigger new star formation in galaxies. Interacting pairs can be hosted in different morphological environments of the cosmic web. Galaxy pairs are more frequently observed in denser regions. The filaments and sheets, being the denser parts of the cosmic web, can host a significant number of major galaxy pairs. In a recent work, Das et al. (2023) analyze Sloan Digital Sky Survey (SDSS) data to compare the SFR and color of major pairs hosted in filaments and sheets. They find that major galaxy pairs with separation <50 kpc are relatively high star-forming and bluer when hosted in filaments. Contrarily, major pairs at separations greater than 50 kpc show significantly higher SFR and bluer color in sheet-like environments. This behavior may be related to the preferential alignment of galaxy pairs with the filament axis reported in a number of recent works (Tempel & Tamm 2015; Mesa et al. 2018). Star formation in a galaxy is primarily regulated by its available gas mass. Inflows and outflows (Dekel et al. 2009; Davé et al. 2012) can significantly modulate the gas mass in a galaxy. Transient events like interactions and mergers can drive galaxies out of equilibrium. The alignment of galaxy pairs with filament spines may lead to anisotropic accretion and higher gas accretion efficiency in these galaxies. In this work, we intend to verify these findings using hydrodynamical simulations.

The Evolution and Assembly of GaLaxies and their Environments (EAGLE) simulation (McAlpine et al. 2016) is a hydrodynamical simulation that studies galaxy formation and evolution in a cosmological volume. It describes the formation of galaxies by gas falling into dark matter halos and their subsequent cooling and condensation. It would be interesting to study the color and SFR in major pairs in filaments and sheets using EAGLE simulations. In observations, galaxy pairs are usually identified by applying simultaneous cuts on the projected separation and the velocity difference of the galaxies in the rest frame. However, all these pairs may not be undergoing interactions. Some pairs identified in observations may not be close in three dimensions due to chance superpositions in high-density regions like groups and clusters (Alonso et al. 2004). Also, we cannot construct a mock catalog for the observational sample of galaxy pairs used in Das et al. (2023) due to the smaller volume of the EAGLE simulations. So, we decided to use the real-space positions of galaxies available in the simulation to identify major pairs. This avoids any errors in identification due to projection effects. We identify the geometric environments of galaxy pairs using the local dimension (Sarkar & Bharadwaj 2009). Our primary aim is to study interaction-induced star formation in filaments and sheets using EAGLE simulations. This will help us assess the roles of filaments and sheets in galaxy evolution.

We organize the structure of the paper as follows: we describe the data and method of analysis in Section 2 and present the results and conclusions in Section 3.

2.1. EAGLE Simulation Data

The EAGLE simulation (McAlpine et al. 2016) is a set of cosmological hydrodynamical simulations in periodic, cubic comoving volumes ranging in side length from 25 to 100 Mpc. Such simulations track the evolution of both baryons and dark matter in the Universe from a redshift of 127 to 0. The simulation adopts a flat ΛCDM cosmology with $\Omega\Lambda = 0.693$, $\Omega m = 0.307$, $\Omega b = 0.04825$, and $H0 = 67.77$ km s^{-1} Mpc^{-1} (Planck Collaboration et al. 2014).

We download various properties of galaxies from the publicly available EAGLE simulation data. We extract information on the three-dimensional position of the center of mass of galaxies within a comoving cubic volume of size 100 Mpc^3 from the Ref-L0100N1504_{Subhalo} table. We consider the last snapshot of the simulation having Snapnum = 28, which corresponds to redshift z = 0. We select only those galaxies flagged as Spurious = 0. This ensures that we select only genuine simulated galaxies by discarding all unusual objects with anomalous stellar mass, metallicity, or black hole mass. We also download the SFR, stellar mass, and cold gas mass of simulated galaxies using the Aperture table. These are estimated within a spherical three-dimensional (3D) aperture with radius 30 kpc centered at the location of the minimum gravitational potential of a galaxy. Use of this criterion gives stellar mass and star formation estimates well-suited for comparison with observational results and is also recommended by the EAGLE simulation team (McAlpine et al. 2016). We also consider only those galaxies with stellar mass > 0.

Combining the two tables with GalaxyID, we obtain all the above-mentioned information for 325,358 galaxies. We also extract broadband magnitudes of galaxies estimated in u and r band filters (Doi et al. 2010) from the Ref-L0100N1504_{Magnitude} table, where u and r respectively denote the ultraviolet and red filter bands of SDSS. We combine this table with the Ref-L0100N1504_{Subhalo} table using GalaxyID to get all required information. The magnitudes of galaxies in different SDSS filters are also computed in 30 kpc spherical apertures (Trayford et al. 2015). Finally, we have this information for 29,754 galaxies. For the rest of the analysis, we refer to u–r color of galaxies as the difference in their rest-frame non-dust-attenuated absolute magnitudes in u and r bands.

Only the magnitudes of galaxies with stellar mass above $10^{8\cdot5}$ M are provided in the Ref-L0100N1504_{Subhalo} table. However, we use stellar mass estimates from the Aperture table where the minimum stellar mass of a galaxy is lower. Observations show that galaxies with $Mstellar < 3 \times 10^{10}$ M are actively star-forming and galaxies with stellar masses above this critical value are generally quiescent systems (Kauffmann et al. 2003). For the present analysis, we consider only those galaxies with stellar mass between these limits. Our mass-limited sample contains a total of 21,305 galaxies.

We identify the nearest neighbor in three dimensions for each galaxy in our mass-limited sample. We denote the distance to the nearest neighbor for each galaxy by r, which refers to the 3D physical separation between the centers of mass of the galaxies. Initially, we label each galaxy and its nearest neighbor as a possible pair. We then select only those pairs for which $r \leq 200$ kpc. We also apply a cut on their stellar mass ratio to include only major pairs in our analysis. This provides us with a total of 2,264 major pairs. The smallest pair separation in our sample is 6 kpc.

We determine the morphological environment of galaxies in the EAGLE simulation by estimating their local dimension (Section 2.2). We use GalaxyID to cross-match these galaxies with our pair sample. The cross-matching yields a total of 2,537 galaxies in major pairs. We find that 373 and 276 of these galaxies reside in filaments and sheets, respectively. It may be noted that we cannot determine the local dimension for all galaxies in the simulation.

2.2. Geometry of the Local Environment

We characterize different geometric environments of the cosmic web using the local dimension (Sarkar & Bharadwaj 2009). The local dimension is a simple measure based on galaxy counts within spheres of different radii centered on a galaxy. The galaxy counts within a sphere of radius R centered on a galaxy can be written as N(<R) R , where D is the local dimension and the proportionality constant is arbitrary. The number counts N(<R) scale differently with radius R depending on the local geometry of the embedding environment. The radius of the sphere around each galaxy is varied between $R_1 = 2$ Mpc $\leq R \leq R_2 = 10$ Mpc and galaxy counts are measured for each radius. Only galaxies that have at least 10 neighboring galaxies within this range are considered. We fit the observed number counts N(<R) to the power-law relation using least-squares fitting. The goodness of each fit is determined by estimating the ^{2} per degree of freedom. We retain only fits having $^{2}/\mathrm{dof} \leq 0.5$ (Sarkar & Pandey 2019) and discard the rest.

The local dimension D describes the morphology of the embedding environment. Ideally, a filamentary environment should have $D = 1$ and a sheet-like environment should have $D = 2$. A homogeneous distribution in three dimensions is represented by $D = 3$. However, filaments, sheets, clusters, and voids are not idealized structures and can have a wide variety of shapes and sizes. Each geometric environment is assigned a range of local dimension as listed in Table 1. A nearly straight filament is represented by a D1 type environment. Similarly, a D2 type environment represents a two-dimensional sheet-like structure. A D3 type environment is embedded in a 3D distribution with homogeneous nature. Galaxies can also reside near the junction of different morphological environments. D1.5 and D2.5 can be treated as intermediate environments.

3. Results and Conclusions

The cumulative mean u–r color for major galaxy pairs as a function of pair separation is plotted in the left panel of Figure 1. We compare results for major pairs in filaments and sheets in the same panel. This affirms that major pairs with pair separation r $<$ 50 kpc are on average bluer in filamentary environments compared to those residing in sheet-like environments. However, this trend only persists up to a pair separation of 50 kpc. A crossover of the two curves corresponding to D1 and D2 type environments is observed at r 50 kpc. Major pairs with pair separation r $>$ 50 kpc are significantly redder in filaments compared to those located in sheets. We also analyze the SFR in major pairs residing in filaments and sheets and show the results in the right panel of Figure 1. We find that major pairs at closer separation ($<$50 kpc) in filaments are comparatively more star-forming than those located in sheets. We see exactly the opposite trend for major pairs with larger separation ($>$50 kpc). The colors of galaxies are strongly correlated with their SFR (Baldry et al. 2009) and the results depicted in the two panels of Figure 1 are consistent with each other. It is also interesting that the crossover is observed at nearly the same pair separation (50 kpc) for both color and SFR. We estimate 1σ error bars at each pair separation using 10 Jackknife samples drawn from the original data sets.

Stellar mass (Birnboim & Dekel 2003; Dekel & Birnboim 2006; Bamford et al. 2009) and available cold gas mass content (Saintonge et al. 2012; Violino et al. 2018; Thorp et al. 2022) also play very important roles in determining SFR in galaxies. We test whether differences in u–r color and SFR of galaxies in major pairs residing in D1 and D2 type environments arise due to differences in their stellar mass and cold gas content. We apply a Kolmogorov-Smirnov (KS) test to compare the distributions of stellar mass and cold gas mass of major paired galaxies in D1 and D2 type environments. The probability distribution functions of these properties in D1 and D2 type environments are visualized in the two panels of Figure 2. We first carry out the test for major pairs with all possible pair separations. We then conduct separate tests for major pairs with pair separation $>$50 kpc and $<$50 kpc. The results are tabulated in Table 2. We note that the null hypothesis cannot be rejected at the 90% confidence level for stellar mass, but can be rejected at the 99% confidence level for cold gas mass. This implies that the stellar mass distribution of galaxies in major pairs residing in D1 and D2 type environments is likely drawn from the same parent population. However, galaxies in major pairs from filaments and sheets have significantly different cold gas mass distributions. We arrive at the same conclusions for major pairs with r $>$ 50 kpc. Interestingly, results for major pairs with r $<$ 50 kpc suggest that the null hypothesis for stellar mass can be rejected only at a very low confidence level ($<$60%), whereas for cold gas mass it can be rejected at the $>$90% confidence level. Thus, the stellar mass of major pair galaxies with r $<$ 50 kpc in D1 and D2 type environments is highly likely to be drawn from the same underlying population. This clearly shows that stellar mass and available cold gas mass of paired galaxies are not responsible for the differences observed in their u–r color and SFR in D1 and D2 type environments at smaller pair separations (r < 50 kpc).

[Figure 2: see original paper]

Each galaxy is believed to have formed within a dark matter halo. The properties of a galaxy are expected to be intimately connected to the mass of its dark matter halo. In fact, the mass of the dark matter halo is believed to be the most important parameter that determines galaxy properties (Corray & Sheth 2002). The amount of substructure in dark matter halos increases with increasing halo mass (Gao et al. 2004; Pandey et al. 2013). There is observational evidence for correlations between substructure and star formation fraction in galaxy clusters (Bravo-Alfaro et al. 2009; Cohen et al. 2014). Substructure can also influence the stellar population in galaxies (Helmi 2020). We depict the distributions of halo masses for paired galaxies in filaments and sheets in Figure 3. Halo masses are obtained within the same aperture as the galaxies. We perform a KS test and find that the halo mass distributions of paired galaxies in sheets and filaments are significantly different (Table 3). We ascertain that the halo masses of paired galaxies in sheets are relatively more massive than those residing in filaments.

[Figure 3: see original paper]

The effects of halo mass may also arise from virial shock heating of the halo gas that becomes important at masses greater than 10^{12} M (Birnboim & Dekel 2003). Such heating can suppress the supply of cold gas by preventing cold streams from the intergalactic medium. However, we find that none of the paired galaxies in filaments and sheets in our sample reside in such massive dark matter halos. At low masses, supernova feedback may expel or heat the gas reservoir and quench star formation (Kaviraj et al. 2007). Halo mass may have a role in shaping the physical properties of galaxy pairs in filaments and sheets, but it is difficult to explain the crossovers observed in Figure 1 using these differences in halo mass distributions.

Filaments appear at the intersections of sheets and are generally denser than sheets. Studies with N-body simulations suggest a successive flow of matter from voids to sheets, sheets to filaments, and filaments to clusters (Ramachandra & Shandarin 2015; Galárraga-Espinosa et al. 2023). A number of earlier studies find that galaxy pairs are preferentially aligned with the filament axis (Tempel & Tamm 2015; Mesa et al. 2018). The alignment signal is reported to be stronger for closer pairs residing near the filament spine. Anisotropic accretion along filaments may significantly influence gas accretion efficiency in these aligned galaxy pairs and trigger interaction-induced star formation in them. Contrarily, major pairs with r > 50 kpc show less star formation in filaments than in sheets.

Filaments are generally denser than sheets. D1 type galaxies are embedded in a higher density environment compared to D2 type galaxies (Pandey & Sarkar 2020). Galaxies in denser environments are known to be redder and less star-forming (Lewis et al. 2002; Gómez et al. 2003; Kauffmann et al. 2004). So, naively one would expect galaxies in filamentary environments to be less star-forming and redder compared to galaxies in sheet-like environments. We find that this is true for galaxies in major pairs with separation larger than 50 kpc. However, galaxies in major pairs at closer separation exhibit strikingly opposite behavior.

We do not analyze the alignment of galaxy pairs in this study. Individual sheets and filaments cannot be identified using the local dimension. We plan to carry out a detailed study of galaxy pair alignment using different cosmic web identification techniques in future work.

The EAGLE simulation provides two definitions for galaxy positions: one based on the center of mass and another based on the location of the minimum gravitational potential. The two positions do not coincide for some galaxies. In this work, we use the center of mass to define galaxy positions. We also repeat our analysis using the minimum of the gravitational potential as the position definition. The results of this analysis are shown in Figure 4. The main findings remain unchanged with this alternative definition.

[Figure 4: see original paper]

It is important to ensure that the major pairs considered in our analysis do not belong to galaxy groups. We measure distances to the 5th nearest neighbors for paired galaxies in sheets and filaments and find that 20% have their 5th nearest neighbor within 500 kpc–1 Mpc. We discard these galaxy pairs and repeat our analysis. The results are displayed in Figure 5. Discarding such galaxy pairs does not alter our results.

[Figure 5: see original paper]

The results reported in this work are very similar to those obtained in a recent study (Das et al. 2023) of the color and SFR of major pairs in filaments and sheets using SDSS data. Das et al. (2023) rely on a volume-limited sample of galaxies ($Mr \leq -19$) and find a crossover in these properties at nearly the same length scale (50 kpc). It is interesting that we observe exactly the same trend in the EAGLE simulation data. This provides strong theoretical support to the observational findings that large-scale structures like sheets and filaments affect galaxy interactions. This also indicates that galaxy properties are modulated by the geometry of their large-scale environment.

Finally, we conclude that filaments play a significant role in determining the color and SFR of galaxies. The observed differences in color and SFR of major pairs in filaments and sheets cannot be interpreted in terms of differences in local density and stellar mass distributions. Interacting galaxy pairs with smaller separations can trigger star formation. Filaments provide a favorable environment for such interactions, making interacting galaxies bluer in filaments compared to those found in sheets.

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References

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

Baldry, I. K., Glazebrook, K., Brinkmann, J., et al. 2009, ApJ, 600, 681

Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, ApJ, 540, 113

Bamford, S. P., Nichol, R. C., Baldry, I. K., et al. 2009, MNRAS, 393, 1324

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

Bhattacharjee, S., Pandey, B., & Sarkar, S. 2020, JCAP, 09, 039

Birnboim, Y., & Dekel, A. 2003, MNRAS, 345, 349

Bond, J. R., Kofman, L., & Pogosyan, D. 1996, Natur, 380, 603

Bravo-Alfaro, H., Caretta, C. A., Lobo, C., Durret, F., & Scott, T. 2009, A&A, 495, 379

Cohen, S. A., Hickox, R. C., Wegner, G. A., Einasto, M., & Vennik, J. 2014, ApJ, 783, 136

Corray, A., & Sheth, R. K. 2002, PhR, 371, 1

Cox, T. J., Primack, J., Jonsson, P., & Somerville, R. S. 2004, ApJL, 607, L87

Das, A., Pandey, B., & Sarkar, S. 2023, RAA, arXiv:2303.16826

Davé, R., Finlator, K., & Oppenheimer, B. D. 2012, MNRAS, 421, 98

Davis, M., & Geller, M. J. 1976, ApJ, 208, 13

Dekel, A., & Birnboim, Y. 2006, MNRAS, 368, 2

Dekel, A., Sari, R., & Coverino, D. 2009, ApJ, 703, 785

Doi, M., Tanaka, M., Fukugita, M., et al. 2010, AJ, 139, 1628

Dressler, A. 1980, ApJ, 236, 351

Einasto, J., Joeveer, M., & Saar, E. 1980, MNRAS, 193, 353

Ellison, S. L., Patton, D. R., Simard, L., et al. 2010, MNRAS, 407, 1514

Galarraga-Espinosa, D., Aghanim, N., Langer, M., & Tanimura, H. 2021, A&A, 649, A117

Galárraga-Espinosa, D., Garaldi, E., & Kauffmann, G. 2023, A&A, 671, A160

Gao, L., White, S. D. M., Jenkins, A., Stoehr, F., & Springel, V. 2004, MNRAS, 355, 819

Gómez, P. L., Nichol, R. C., Miller, C. J., et al. 2003, ApJ, 584, 210

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

Gregory, S. A., & Thompson, L. A. 1978, ApJ, 222, 784

Gunn, J. E., & Gott, J. R. 1972, ApJ, 176, 1

Guzzo, L., Strauss, M. A., Fisher, K. B., Giovanelli, R., & Haynes, M. P. 1997, ApJ, 489, 37

Helmi, A. 2020, ARA&A, 58, 205

Joeveer, M., & Einasto, J. 1978, IAUS, 79, 241

Kauffmann, G., Heckmann, T., White, S. D. M., et al. 2003, MNRAS, 341, 54

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

Kaviraj, S., Kirkby, L. A., Silk, J., & Sarzi, M. 2007, MNRAS, 382, 960

Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, ApJ, 237, 692

Lewis, I., Balogh, M., Propris, R., et al. 2002, MNRAS, 334, 673

Martig, M., Bournaud, F., Teyssier, R., & Dekel, A. 2009, ApJ, 707, 250

Masters, K. L., Mosleh, M., Romer, A. K., et al. 2010, MNRAS, 405, 783

McAlpine, S., Helly, J., Schaller, C., & Trayford, M. 2016, A&C, 15, 72

Mesa, V., Duplancic, F., Alonso, S., et al. 2018, A&A, 619, A24

Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A. 1996, Nature, 379, 613

Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139

Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569

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

Oemler, A. 1974, ApJ, 194, 1

Pandey, B., & Bharadwaj, S. 2005, MNRAS, 357, 1068

Pandey, B., & Bharadwaj, S. 2006, MNRAS, 372, 827

Pandey, B., & Bharadwaj, S. 2008, MNRAS, 387, 767

Pandey, B., & Sarkar, S. 2017, MNRAS, 467, L6

Pandey, B., & Sarkar, S. 2020, MNRAS, 498, 6069

Pandey, B., White, S. D. M., Springel, V., & Angulo, R. E. 2013, MNRAS, 435, 2968

Park, C., Choi, Y.-Y., Vogeley, M. S., et al. 2005, ApJ, 633, 11

Patton, D. R., Ellison, S. L., Simard, L., McConnachie, A. W., & Mendel, J. T. 2011, MNRAS, 412, 591

Peng, Y. J., & Renzini, A. 2020, MNRAS, 491, L51

Planck Collaboration et al. 2014, A&A, 571, A1

Ramachandra, N. S., & Shandarin, S. F. 2015, MNRAS, 452, 1643

Saintonge, A., Tacconi, L. J., Fabello, S., et al. 2012, ApJ, 758, 73

Sarkar, P., & Bharadwaj, S. 2009, MNRAS, 394, L66

Sarkar, S., & Pandey, B. 2019, MNRAS, 485, 4743

Sarkar, S., & Pandey, B. 2020, MNRAS, 497, 4077

Silk, J. 1977, ApJ, 211, 638

Somerville, R. S., & Primack, J. R. 1999, MNRAS, 310, 1087

Springel, V., Di Matteo, T., & Hernquist, L. 2005, MNRAS, 361, 776

Tempel, E., & Tamm, A. 2015, A&A, 576, L5

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

Trayford, J., Theuns, T., Bower, R. G., et al. 2015, MNRAS, 452, 2879

Tuominen, T., Nevalainen, J., Tempel, E., et al. 2021, A&A, 646, A156

Violino, G., Ellison, S. L., Sargent, M., et al. 2018, MNRAS, 476, 2591

White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341

Woods, D. F., & Geller, M. J. 2007, AJ, 134, 527

Zehavi, I., Zheng, Z., Weinberg, D. H., et al. 2005, ApJ, 630, 1

Zeldovich, I. B., & Shandarin, S. F. 1982, PAZh, 8, 131

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