



A Gradual Decline of Star Formation since Cluster Infall: New Kinematic Insights into Environmental Quenching at $0.3 < z < 1.1$

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Abstract

The environments where galaxies reside crucially shape their star formation histories. We investigate a large sample of 1626 cluster galaxies located within 105 galaxy clusters spanning a large range in redshift ($0.26 < z < 1.13$). The galaxy clusters are massive ($M \sim 2 \times 10^{14} M_\odot$) and uniformly selected from the SPT and ACT Sunyaev–Zel’dovich surveys. With spectra in hand for thousands of cluster members, we use the galaxies’ position in projected phase space as a proxy for their infall times, which provides a more robust measurement of environment than quantities such as projected clustercentric radius. We find clear evidence for a gradual age increase of the galaxy’s mean stellar populations ($\sim 0.71 \pm 0.4$ Gyr based on a 4000 Å break) with the time spent in the cluster environment. This environmental quenching effect is found regardless of galaxy luminosity (faint or bright) and redshift (low or high- z), although the exact stellar age of galaxies depends on both parameters at fixed environmental effects. Such a systematic increase of age with infall proxy would suggest that galaxies that were accreted into hosts earlier were quenched earlier due to longer exposure to environmental effects such as ram pressure stripping and starvation. Compared to the typical dynamical timescales of 1–3 Gyr of cluster galaxies, the relatively small age increase ($\sim 0.71 \pm 0.4$ Gyr) found in our sample galaxies seems to suggest that a slow environmental process such as starvation is the dominant quenching pathway. Our results provide new insights into environmental quenching effects spanning a large range in cosmic time (~ 5.2 Gyr, $z = 0.26$ – 1.13) and demonstrate the power of using a kinematically derived infall time proxy.

Unified Astronomy Thesaurus concepts: [Galaxy clusters \(584\)](#); [High-redshift galaxy clusters \(2007\)](#); [Galaxy quenching \(2040\)](#); [Galaxy evolution \(594\)](#); [Galaxy environments \(2029\)](#); [Galaxies \(573\)](#)

1. Introduction: A Kinematic Method for Investigating Environmental Quenching at High- z

The environment where galaxies reside is closely linked to the galaxies’ characteristic folding key information for their evolutionary histories. In particular, cluster environments have shown remarkably tight relationships with the fundamental properties of galaxies, such as morphology (Dressler 1980; Oh et al. 2018), star formation rate (SFR; Park & Hwang 2009;

Noble et al. 2013; Muzzin et al. 2014), and gas components (e.g., Kenney et al. 2004; Chung et al. 2009).

Such close relationships between cluster environments and galaxy properties suggest that the extremely dense environments of clusters have indeed affected the residing galaxies through various effects, such as hot intracluster medium (ICM) ram pressure stripping (Gunn & Gott 1972; Abadi et al. 1999; Ebeling et al. 2014; Boselli et al. 2022), strangulation (starvation; Larson et al. 1980), harassment (Moore et al. 1996), and tidal interactions (Byrd & Valtonen 1990).

In particular, these environmental effects are known to efficiently suppress (aka quench) the star formation activity of cluster galaxies. Indeed, the higher fraction of quiescent



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galaxies in clusters compared to field environments (Pintos-Castro et al. 2019; Strazzullo et al. 2019; Paulino-Afonso et al. 2020) and systematically truncated gas disks found in Local cluster galaxies (e.g., the Virgo cluster; Yoon et al. 2017) suggest the cluster environmental “quenching” effects at play.

However, no clear consensus about the environmental effects has been established yet at high redshifts, contrary to the local Universe ($z < 0.2$), where a wealth of clusters have been observed and analyzed in detail (e.g., Oh et al. 2018; Pasquali et al. 2019; Smith et al. 2019; Boselli et al. 2022; Cortese et al. 2021; Morokuma-Matsui et al. 2021; Upadhyay et al. 2021, for a review). The decreasing number of clusters and the reduced brightness with increasing redshift make it challenging to study high-redshift cluster populations. While several studies have indeed investigated the environmental effects outside the local Universe (e.g., Strazzullo et al. 2013; Pintos-Castro et al. 2019; Kelkar et al. 2019; Khullar et al. 2021; Webb et al. 2020; Balogh et al. 2021; Noordeh et al. 2021; Reeves et al. 2021), only a relatively small number of clusters at high redshift ($z \gtrsim 0.4$) have been studied in detail for environmental quenching effects with spectroscopically confirmed member galaxies (e.g. Muzzin et al. 2012; Tiley et al. 2020; Vaughan et al. 2020; Balogh et al. 2021; Matharu et al. 2021). Furthermore, most studies at high redshift use the galaxies’ projected distance from the cluster center as a primary environmental measure for quenching effects in clusters. While the projected clustercentric distance is a useful environmental parameter, it inevitably suffers from contamination from interlopers that happen to lie within the cluster’s projected radius but in turn are unrelated to the host cluster.

Notably, by adopting an advanced environmental metric based on the cluster galaxies’ kinematic information, our study attempts to minimize the contamination from projected interlopers. Thus, our study enables us to investigate in detail how the star formation of galaxies changes over time since infall into the host cluster. Specifically, we estimate the galaxies’ infall stages (ranging from recently accreted populations to early ancient infallers) by putting together their clustercentric distance and peculiar velocity relative to the cluster center.

This “phase space” (i.e., the diagram of the clustercentric distance versus the peculiar velocity normalized by the velocity dispersion of the cluster) is a powerful tool to study the detailed infall histories of cluster galaxies since it considers not only the distance from the cluster center but also the “kinematic” velocity of infalling galaxies. Numerous cluster simulations, where the galaxies’ time steps can be traced, have indeed demonstrated the clear separation of galaxies by different infall stages in phase space (Mahajan et al. 2011; Oman et al. 2013; Muzzin et al. 2014; Haines et al. 2015; Jaffé et al. 2015; Oman & Hudson 2016; Rhee et al. 2017, 2020).

Motivated by the simulation results, several studies utilized the projected phase space (i.e., the projected clustercentric radius and the line-of-sight peculiar velocity used instead) for actual cluster galaxies to estimate the galaxies’ orbital stages over a wide range of redshifts both local (e.g., Vollmer et al. 2001; Mahajan et al. 2011; Boselli et al. 2014b; Hernández-Fernández et al. 2014; Haines et al. 2015; Gavazzi et al. 2018; Jaffé et al. 2018; Shen et al. 2020; Loni et al. 2021; Reeves et al. 2023) and high-redshift clusters (e.g., Noble et al. 2013; Muzzin et al. 2014; Liu et al. 2021). In particular, Noble et al. (2013) estimated the infall time of galaxies in a $z \sim 0.9$ cluster.

They found a systematic decrease of the specific star formation rates (sSFRs) of galaxies as a function of the infall time proxy derived from the galaxies’ location in the projected phase space, suggesting the projected phase space as a robust observational environmental measure for infall time. Later studies in the local Universe ($z < 0.2$; e.g., Pasquali et al. 2019; Smith et al. 2019; Sampaio et al. 2021) support this by showing a similar trend of reduced sSFR of cluster galaxies based on a similar method using projected phase space.

The goal of our study is to provide a clear view of the environmental quenching effects than the projected distance alone at high redshifts by crucially utilizing the advanced kinematic approach over a huge range in cosmic time (~ 5.2 Gyr, $z = 0.26$ – 1.13). For that, we employ a large number of clusters uniformly selected by the Sunyaev–Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972) from the South Pole Telescope (SPT; Bleem et al. 2015) and Atacama Cosmology Telescope (ACT; Marriage et al. 2011) cluster surveys. We obtain the photometric and spectroscopic information of cluster galaxies from the optical follow-up observations of the SZ clusters (Ruelet et al. 2014; Bleem et al. 2015; Bayliss et al. 2016, and references therein).

Section 2 describes the observational data sets. The sample selection procedure and data analysis are described in Section 3. We present and discuss our results in Section 4. We summarize our conclusions with final remarks in Section 5. We adopt the Λ CDM cosmology of $(H_0, \Omega_m, \Omega_\Lambda) = (70 \text{ km s}^{-1} \text{ Mpc}^{-1}, 0.3, 0.7)$ throughout the paper.

2. The Observational Data Sets

We use observational data sets drawn from the 2500 deg² SPT-SZ (Vanderlinde et al. 2010; Reichardt et al. 2013; Ruel et al. 2014; Bleem et al. 2015; Bayliss et al. 2016, 2017) and ACT-SZ (Marriage et al. 2011; Hasselfield et al. 2013; Sifón et al. 2013) cluster surveys and the associated optical/near-IR follow-up observations. Due to the redshift independence of the SZ effect, the clusters identified by these surveys are nearly mass-limited with a mass threshold of $\gtrsim 3 \times 10^{14} M_\odot$ at all redshifts (see, e.g., Figure 6 of Bleem et al. 2015). This uniform cluster selection function through the SZ effect, combined with the uniform selection of the galaxy samples, allows us to study environmental effects on galaxy properties in a uniform way over a wide range of redshifts ($0.26 < z < 1.13$). In this section, we describe the details of the cluster surveys (Section 2.1), the galaxy photometric i-band luminosity (Section 2.2) and the spectral 4000 Å break measurements (Section 2.3).

2.1. Clusters Uniformly Selected by the SZ Effect from SPT and ACT at $0.26 < z < 1.13$

Our sample of clusters is a subsample of the clusters identified in the 2500 deg² SPT-SZ (Reichardt et al. 2013; Bleem et al. 2015) and ACT-SZ surveys (Marriage et al. 2011; Hasselfield et al. 2013). We refer the reader to the aforementioned publications for full descriptions of these surveys. In short, these cluster candidates were first detected through their SZ signal (i.e., the SZ signal-to-noise threshold $\xi \gtrsim 4.5$) and subsequently followed up with optical/near-IR imaging to confirm the clusters associated with the SZ signal. About 500 clusters (415 and 68 from the SPT and ACT, respectively, with some overlapping clusters between the surveys) have been discovered in the surveys at redshifts $z = 0.1$ – 1.5 . The cluster

masses— M_{500} , the mass measured within the radius r_{500} at which the mean density of the cluster is 500 times the critical density at the cluster redshift—are $\approx 3 \times 10^{14} M_\odot$, nearly independent of redshift due to the selection function based on the SZ effect.

From the surveys, we adopt information about the cluster center, redshift (z_{cl}), and mass (M_{500}) of our 105 sample clusters at $0.26 < z_{cl} < 1.13$ (see Section 3.1 for details about sample selection). Specifically, 99 clusters from SPT and nine from ACT satisfy these criteria, with three clusters appearing in both catalogs. The result is a total sample of 105 SZ-selected galaxy clusters. For the three clusters in both catalogs, we use the SZ information from SPT alone (there are no published scaling relations for a combination of SPT and ACT SZ data, but see Hilton et al. 2018 for a discussion of ACT and SPT mass consistency). In particular, the cluster mass (M_{500}) is derived from the SZ signal–cluster mass scaling relation (for 99 SPT clusters measured from Reichardt et al. 2013 and Bleem et al. 2015 and six ACT clusters measured from Hasselfield et al. 2013). For the SPT clusters, the following scaling relation is used:

$$z = A_{SZ} \left(\frac{M_{500}}{3 \times 10^{14} M_\odot} \right)^{B_{SZ}} \left(\frac{H(z)}{H(0.6)} \right)^{C_{SZ}}, \quad (1)$$

where A_{SZ} is the normalization factor, B_{SZ} is the slope, and C_{SZ} is the redshift evolution term associated with the Hubble parameter $H(z)$. Here ζ is the unbiased SZ significance²⁰ associated with the SZ signal-to-noise threshold ξ as follows:

$$z = \sqrt{\xi^2 - 3}. \quad (2)$$

The values of A_{SZ} , B_{SZ} , and C_{SZ} are 4.14, 1.44, and 0.59, respectively, as determined in Reichardt et al. (2013). For the six ACT clusters, we adopt the SZ signal-based–cluster mass that is calibrated with the cluster physics model of Bode et al. (2012) in Hasselfield et al. (2013; see Section 3.4 and Table 10 of Hasselfield et al. 2013 for more details).

Further details on the cluster surveys, such as cluster identification and mass estimates, can be found in Bleem et al. (2015) and Hasselfield et al. (2013) for the SPT and ACT clusters, respectively.

2.2. Galaxy i-band Luminosity Relative to the Characteristic Luminosity (L_i/L^*) for Photometric Brightness

We obtain the i-band luminosity (L_i) of our sample galaxies from the optical follow-up observations of the SPT cluster surveys (Bleem et al. 2015, 2020, and references therein) that are conducted to confirm the clusters associated with the SZ signal. Several different telescopes are used for the follow-up observations (see Table 2 of Bleem et al. 2015; for more recent observations with the PISCO instrument, Stalder et al. 2014, see Section 4 of Bleem et al. 2020), including the Blanco/MOSAIC-II; Magellan/Baade IMACS f-2; Magellan/Clay LDSS3, Megacam, and PISCO; Swope/SITe3; MPG/ESO WFI; and New Technology Telescope/EFOSC2.

While the aperture size of the telescopes is not the same (1–6.5 m), we note that the follow-up campaign is optimally designed to observe clusters with uniformly sufficient depth at both low ($z \lesssim 0.3$) and high ($z \gtrsim 0.75$) redshifts. Typically, the

observations are required to detect $0.4 L^*$ galaxies with 5 σ depth, where L^* is the characteristic luminosity of galaxies at a given redshift. The majority of the photometry uses the Sloan Digital Sky Survey (SDSS) i-band filter. For clusters observed with the older Johnson–Cousins photometric BVRI system, the filter transformation of the I band into the SDSS i band is applied in Bayliss et al. (2016; see their Section 5.2). As a result, all of our sample galaxies is measured with respect to the SDSS i-band filter.

We use the i-band luminosity (L_i), scaled by L_i/L^* , as our sample galaxies' photometric brightness. We adopt the i-band L^* values computed in the SPT–SZ surveys (High et al. 2010; Bleem et al. 2015). Specifically, L^* is derived using the stellar population synthesis model of Bruzual & Charlot (2003), and the stellar population modeling assumes a k-corrected, passively evolving instantaneous-burst stellar population with formation redshift of $z = 3$. The Salpeter initial mass function (Salpeter 1955) and the Padova 1994 stellar evolutionary tracks (Fagotto et al. 1994) are used. Metallicities are selected based on analytic fits to the Red-sequence Cluster Survey 2 data (Gilbank et al. 2011). Interpolation using cubic splines is applied to generate L^* values at redshifts where the stellar synthesis model did not directly compute L^* . The models are further calibrated to the actual SPT spectroscopic subsample. A comparison shows that the computed L^* for our sample cluster galaxies is in good agreement with that of the maxBCG cluster sample of Rykoff et al. (2012). Specifically, the L^* values between the two studies are consistently better than $\approx 5\%$ over the overlapping redshift range at $z = 0.05$ – 0.35 . As we will describe in Section 3.1, we use galaxies brighter than $0.35 L_i/L^*$ as our sample galaxies across all redshifts of interest ($0.26 < z < 1.13$).

2.3. The Age-sensitive 4000 Å Break (D_n4000) for the Mean Stellar Age of Galaxies

We use the 4000 Å break strength (D_n4000) as a proxy for the luminosity-weighted mean stellar age of galaxies. The D_n4000 is a spectral feature that arises from the accumulation of the metal absorption lines of stars making a “break” between the blue- and red-side continua around 4000 Å in rest-frame wavelength (Bruzual 1983; Hamilton 1985; Balogh et al. 1999). Because the metal absorption line strength is sensitive to stellar type (i.e., age given surface gravity and temperature), D_n4000 is sensitive to the luminosity-weighted mean stellar age of galaxies. Thus, D_n4000 has been widely adopted as a useful stellar age indicator of galaxies (Kauffmann et al. 2003, 2004; Hernán-Caballero et al. 2013; Geller et al. 2014; Haines et al. 2017; Kim et al. 2018, and reference therein).

The D_n4000 is defined as the average flux density ($\langle F \rangle$) ratio between the blue-side ($\langle F_B \rangle$) and the red-side ($\langle F_R \rangle$) continua centered at 4000 Å such that

$$\langle F \rangle = \frac{\int_{\lambda_1}^{\lambda_2} F_n d\lambda}{\int_{\lambda_1}^{\lambda_2} d\lambda}; \quad (3)$$

thus, D_n4000 is expressed as

$$D_n4000 = \frac{\langle F_R \rangle}{\langle F_B \rangle} = \frac{(\int_{\lambda_2}^{\lambda_1} F_n d\lambda)^R}{(\int_{\lambda_2}^{\lambda_1} F_n d\lambda)^B}, \quad (4)$$

²⁰ See Appendix B in Vanderlinde et al. (2010) for details.

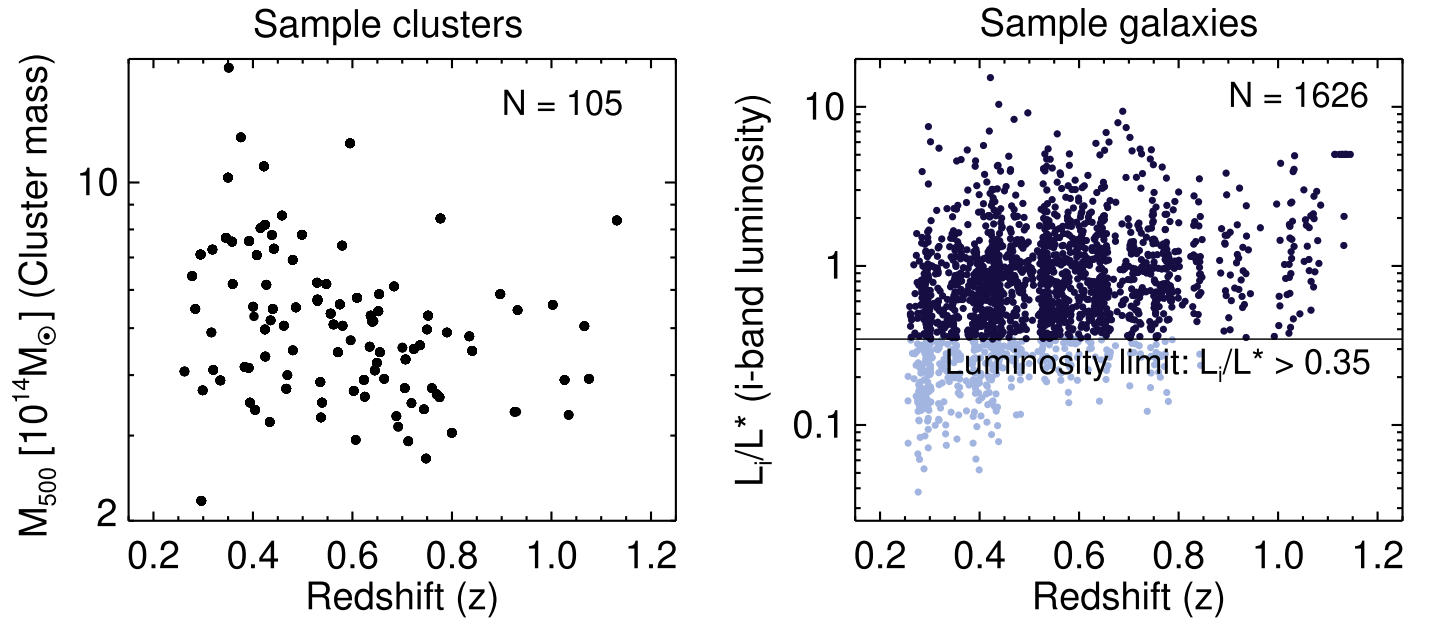


Figure 1. Left: sample cluster mass distribution with redshift. Due to the uniform selection function based on the redshift-independent SZ effect, our sample clusters are nearly mass-limited at all redshifts, forming a relatively narrow mass range with a median (standard deviation) mass of $4.9 \times (12.2) M_{\odot}$ (Section 2.1). Right: i-band luminosity (L_i/L^* , relative to the characteristic luminosity) distribution of sample cluster galaxies with redshift. Dark blue points are the sample galaxies used after applying the luminosity cut, $L_i/L^* > 0.35$, while the light blue points are the ones excluded. The numbers of sample clusters and cluster galaxies considered in this study are marked in the top right corner in the left and right panels, respectively. See also Table 1 and Section 3.1 for details on the sample selection.

where $(\ell_1^B, \ell_2^B, \ell_1^R, \ell_2^R) = (3850, 3950, 4000, 4100) \text{ \AA}$. The D_n4000 increases with galaxy age such that galaxies with young stellar populations ($\lesssim 1 \text{ Gyr}$) show $D_n4000 \lesssim 1.5$, while galaxies with old stars ($\gtrsim 1 \text{ Gyr}$) show $D_n4000 \gtrsim 1.5$ based on simple stellar population modelings (see, e.g., Figure 2 of Kauffmann et al. 2003).

We obtain the D_n4000 of our sample galaxies measured from the optical follow-up spectroscopic observations of SPT-SZ (Ruel et al. 2014; Bayliss et al. 2016, 2017, and references therein) and ACT-SZ (Sifón et al. 2013) clusters. Most clusters are observed with the Gemini Multi-Object Spectrograph on Gemini South, IMACS on Magellan/Baade, or FORS2 on the Very Large Telescope. The observations are primarily designed to measure spectroscopic redshifts of galaxies for accurate cluster membership through the cluster velocity dispersion (σ_{cl}).

The specific observing strategy (e.g., target selection, multislit mask design, and the choice of grating and filter) is set up to uniformly observe a large number (~ 100) of clusters. The spectroscopic integration times for individual masks were computed to ensure that the signal-to-noise ratio is $\gtrsim 3$ spectral pixel $^{-1}$ in the continuum around D_n4000 based on a model passive galaxy spectrum with a brightness equal to 0.4 at the cluster redshift. Note that we quite consistently sample this luminosity range (see the right panel of Figure 1).

The target selection is based on the color-magnitude diagram of galaxies observed in the field of view of a given cluster. The highest priority is given to cluster galaxies identified by the red sequence, regardless of luminosity down to $0.4 L_i/L^*$. We first identified the red sequence as an overdensity in color and then fit a tilted red sequence to the data in color-magnitude. Likely red-sequence galaxies were those galaxies within $\pm 0.15 \text{ mag}$ (in color) of the best-fit red sequence. The choice of $\pm 0.15 \text{ mag}$ corresponds to $\pm 2.5-3 \sigma_{RS}$, where σ_{RS} is the intrinsic width of the observed

red sequence, which has been measured to be $\sim 0.05 \text{ mag}$ for massive galaxy clusters (Hennig et al. 2017). The next highest priority is given to candidate “blue cloud” galaxies, which are identified as those galaxies that are bluer than the red sequence (i.e., star-forming). We also only include galaxies that are fainter than the brightest red-sequence member to filter out foreground galaxies.

Obtaining spectroscopic follow-up of a complete sample of cluster galaxies in hundreds of distant galaxy clusters is not practical given the observational resource costs, so it is not a realistic possibility to measure D_n4000 for every cluster member galaxy in our cluster sample. This limitation prevents us from interpreting our results as an absolute measurement of the D_n4000 of the complete sample of SPT cluster member galaxies. That said, we note that the slit placement strategy that produced our spectroscopic member sample was uniformly applied to all spectroscopic observations with no systematic evolution in the radial density of the spectroscopic slits or the rest-frame magnitude limits. Because the slit placement strategy was applied uniformly, any systematic D_n4000 difference within our sample that scales with other parameters (e.g., galaxy luminosity, redshift, and environment) should be robust.

Understanding our spectroscopic galaxy sample selection is essential to interpreting our results, so we also perform a direct comparison of our spectroscopic cluster member sample against a published photometric analysis that uses complete cluster galaxy populations. Specifically, we measure the fractions of passive (red sequence) and star-forming (blue cloud) cluster member galaxies in our final spectroscopic catalog in our two redshift bins. We measure passive (star-forming) fractions of $\sim 70\%$ (30%) and $\sim 66\%$ (34%) for low-redshift ($\langle z \rangle$ of 0.41) and high-redshift ($\langle z \rangle$ of 0.66) clusters, respectively. These fractions are consistent with the observed red/passive galaxy fraction measured for all SPT clusters using photometric data (Hennig et al. 2017; see their Figure 15). The

Table 1
Summary of Sample Selection (Section 3.1)

Criterion	Explanation/(Number of Galaxies)
Cross-matching the cluster catalog and optical photometric and spectroscopic follow-up catalogs	To obtain cluster mass (M_{500}), redshift, velocity dispersion (σ), galaxy i-band luminosity (L_i/L^*), spectroscopic redshift, and $D_{n4000}/(4089)$
$0.7 < D_{n4000} < 2.3$ and $\sigma(D_{n4000})/D_{n4000} < 0.3$	To remove the poor or missing measurements of D_{n4000} due to wavelength coverage of observed spectra/(2709)
$0.26 < z < 1.13$	Redshift range divided into low- z ($0.26 < z < 0.53$) and high- z ($0.53 < z < 1.13$) bins with 46 and 59 clusters, respectively
$L_i/L^* > 0.35^b$	Galaxy luminosity cut to ensure a uniform lower limit of galaxy luminosity at all redshifts/(2125)
Cluster member galaxies $ \Delta v /\sigma_{cl} < 3.5$ and $r_{proj}/r_{500} < 3$	Membership based on the normalized line-of-sight peculiar velocity ($ \Delta v /\sigma$) and projected clustercentric radius (r_{proj}/r_{500}) (1626: 802 and 824 in low- and high- z bins, respectively)
Total number in sample	105 clusters and 1626 member galaxies

Notes.

^a The catalogs for SPT-SZ (Reichardt et al. 2013; Bleem et al. 2015) and ACT-SZ (Hasselfield et al. 2013) clusters and the optical photometric (High et al. 2010; Bleem et al. 2015) and spectroscopic (Sifón et al. 2013; Ruel et al. 2014; Bayliss et al. 2016, 2017) follow-ups (Section 2).

^b Luminosity cut of $L_i/L^* > 0.35$ estimated from the 90th percentile of the high- z subsamples (Section 3.1 and the right panel of Figure 1).

consistency between the passive and star-forming fractions in $\sigma(D_{n4000})/D_{n4000}$ (relative error) < 0.3 , leaving 2709 galaxies. The D_{n4000} range selected reasonably covers the observed D_{n4000} strengths across all types of galaxies, from young (~ 10 Myr) to old (~ 15 Gyr) stellar ages based on simple stellar population modeling (e.g., Kauffmann et al. 2003; Hernán-Caballero et al. 2013).

Typically, $N \approx 40$ galaxies per cluster are observed. The observed spectra cover a galaxy rest-frame wavelength of $3500\text{--}5150$ Å across redshifts z ; $0.25\text{--}1.1$. The observations have a similar spectral resolution, $dR \approx 5\text{--}10$ Å, corresponding to $R (= \lambda/d\lambda)$; $500\text{--}1200$. The observed spectroscopy is used to measure D_{n4000} by Bayliss et al. (2016) using the same definition given in Equations (3) and (4).

We refer the reader to the spectroscopic follow-ups of SPT-SZ clusters (Ruelet et al. 2014; Bayliss et al. 2016, 2017) for more details about the observing strategy and the D_{n4000} measurements.

3. Sample Selection and Data Analysis

3.1. Sample Selection: A Uniform Set of 105 Clusters and 1626 Galaxies at $0.26 < z < 1.13$

We select our sample clusters by cross-matching the SZ cluster catalog and the optical photometric and spectroscopic follow-up catalogs described in Section 2. From the cross-match, we obtain the cluster mass (M_{500}), galaxy luminosity (L_i/L^*), D_{n4000} , and cluster velocity dispersion, σ . There are 105 clusters and 4089 galaxies in our initial sample with a redshift ranging from 0.26 to 1.13. Of the 105 clusters, 99 of them are SPT clusters, and the remaining six are ACT clusters. The cluster mass range is $3 \times 10^{14} M_\odot \leq M_{500} \leq 3 \times 10^{15} M_\odot$ with a median mass of $4.97 \times 10^{14} M_\odot$ and an associated 1σ population spread of $\pm 2.24 \times 10^{14} M_\odot$. The mass distribution of our sample clusters is shown in the left panel of Figure 1.

Sampling galaxies with reliable D_{n4000} measurements is crucial in our analysis. We apply additional sample selection criteria based on physically reasonable D_{n4000} values from reliable measurements, so these cuts remove galaxies whose spectra suffer from data reduction artifacts (e.g., bright sky line residuals), as well as high noise. Specifically, we select galaxies whose D_{n4000} satisfies $0.7 < D_{n4000} < 2.3$,

We also apply a luminosity cut of $L_i/L^* > 0.35$ to the remaining sample galaxies to ensure a uniform lower limit of galaxy luminosity at all redshifts. Specifically, we derive the luminosity cut by considering the 10th percentile (i.e., above which 90% of the population lies) of the L_i/L^* distribution of our high-redshift ($0.53 < z < 1.13$) subsamples. This corresponds to 0.35 of L_i/L^* , which is very similar to the typical depth (5σ for $0.4L^*$) of the photometric follow-ups of SPT-SZ clusters (Bleem et al. 2015). We thus remove galaxies with $L_i/L^* < 0.35$, leaving 2125 galaxies. The L_i/L^* distribution of our sample galaxies with the luminosity cut ($L_i/L^* > 0.35$) applied is shown in the right panel of Figure 1. The range of the sample galaxies roughly corresponds to $10.3 \leq \log(M_{\text{star}}/M_\odot) \leq 11.6$, given the typical characteristic stellar mass of $0.8 \leq \log(M_{\text{star}}/M_\odot)$ (e.g., Adams et al. 2021) at similar redshifts and an i-band mass-to-light ratio of 0.8–2.5 (e.g., McGaugh & Schombert 2014).

Lastly, of 2125 galaxies, 499 galaxies are further removed based on their projected clustercentric radius (r_{proj}/r_{500}) and the normalized line-of-sight peculiar velocity ($|\Delta v|/\sigma_{cl}$; Equation (5)). This criterion is applied to select cluster member galaxies with reasonable orbital stages (i.e., $|\Delta v|/\sigma_{cl} < 3.5$ and $r_{proj}/r_{500} < 3$), as we will describe in detail in Section 3.2.

In total, our final sample throughout the paper is 105 clusters and 1626 galaxies at $0.26 < z < 1.13$. On average, 15 galaxies cluster⁻¹ are sampled. The typical uncertainty in cluster mass in our cluster sample is $0.9 \times 10^{14} M_\odot$, and the typical uncertainty in the i-band photometry of cluster member galaxies is 0.06 mag. The sample selection procedure is summarized in Table 1.

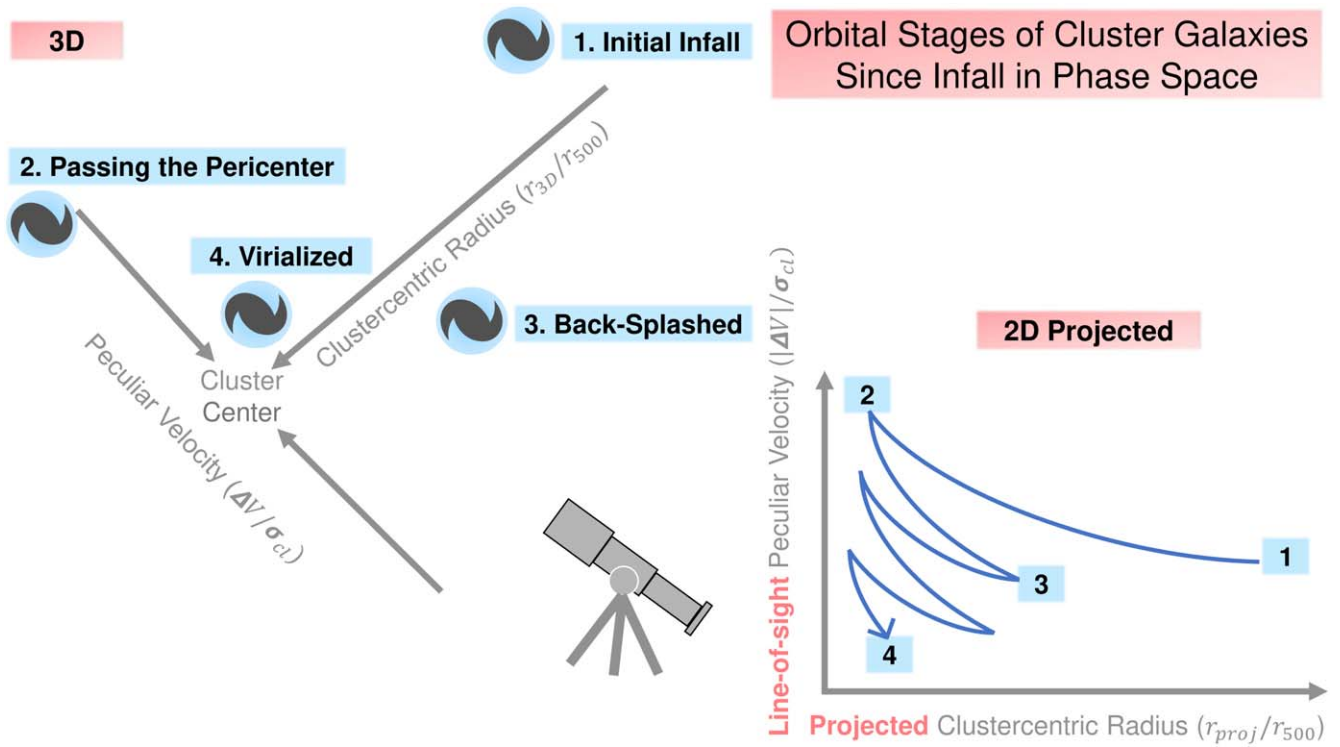


Figure 2. Schematic diagram showing the orbit of an infalling galaxy into a cluster. This is illustrated in 3D (left) and 2D projected (right) phase space (i.e., peculiar velocity vs. clustercentric radius). Moving from stages 1 to 4, (1) an infalling galaxy plunges into the gravitational potential of the cluster, (2) passes the pericenter, backsplashes, and eventually becomes (4) virialized. The simplified orbit of an infalling galaxy is qualitatively consistent with that of an infalling galaxy traced in cluster simulations (e.g., see Figure 4 of Jaffe et al. 2015). This figure illustrates how a galaxy orbit is statistically traced in a phase space diagram during infall (see also Figure 3 for the projected phase space of our sample galaxies).

3.2. Kinematically Estimating the Infall Time of Galaxies from Projected Phase Space

We estimate the infall time of galaxies based on their location in the phase space, similar to other studies (Noble et al. 2013, 2016; Pasquali et al. 2019). The phase space is a diagram where the infall stage of cluster galaxies can be kinematically estimated (Figure 2). It uses the clustercentric distance and peculiar velocity normalized by cluster velocity dispersion on its axes. For the projected phase space, the projected clustercentric distance (r_{proj}/r_{500}) and the line-of-sight peculiar velocity normalized by the cluster velocity dispersion ($|\Delta v|/\sigma_{\text{cl}}$) are employed.

Indeed, cluster simulations where the infall stages of galaxies can be traced have demonstrated that galaxies distinctively occupy different locations of phase space depending on their infall time (Mamon et al. 2004; Gill et al. 2005; Mahajan et al. 2011; Haines et al. 2012; Oman et al. 2013; Rhee et al. 2017). Typically, galaxies that were accreted early show a wide range of peculiar velocities ($|\Delta v|/\sigma_{\text{cl}}$) at small clustercentric distances (r/r_{500}) but only populate small peculiar velocities over larger clustercentric distances. In contrast, galaxies that were accreted recently are distributed over ranges of clustercentric distance and peculiar velocity but preferentially distributed following trumpet-like profiles that can be described by lines of constant ($r/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}})$ (see, e.g., Figure 3 of Haines et al. 2012).

Motivated by these phase space trends with infall time in simulations, Noble et al. (2013) observationally utilized the caustic lines—the trumpet-shaped lines satisfying $(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) = \text{constant}$ (see also Figure 3)—of the projected phase space to divide galaxies into different infall time stages for a $z \sim 0.9$ cluster. Their analysis and later studies

(Noble et al. 2016; Pasquali et al. 2019) demonstrated the utility of the caustic lines as a useful infall time proxy for cluster galaxies. In particular, a comparison with cluster simulations in Pasquali et al. (2019) shows that galaxies separated by the caustic lines in the projected phase space indeed show systematically different mean infall times, as described below.

We adopt the same definition of infall time zones based on the location of phase space as in Noble et al. (2013), which is as follows:²¹

1. early infall, $(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) < 0.1$;
2. intermediate infall, $0.1 < (r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) < 0.4$;
- and
3. recent infall, $(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) > 0.4$.

As the names of each infall zone indicate, the early infall zone primarily consists of virialized galaxies that were accreted early. The intermediate infall zone contains a mix of galaxy populations with intermediate infallers, as well as a backsplash population that has passed the first cluster pericenter and is currently outbound. The recent infall zone is mainly populated by galaxies that were recently accreted. The mean infall time of the galaxies is typically $2.7^{+1.4}_{-1.7}$, $4.5^{+1.9}_{-2.2}$, and $5.1^{+1.8}_{-2.1}$ Gyr for the recent, intermediate, and early infall zones, respectively. This is based on the comparison with the cluster simulation at $z = 0$ in Pasquali et al. (2019). (However, we also note that there is

²¹ While the original definition of Noble et al. (2013) is based on r_{500} for a cluster radius, we note that using r_{200} instead makes only a 0.15 dex shift in our infall time proxy (i.e., $\log[(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}})]$) and thus does not qualitatively change our results given $r_{500}/0.7r_{200}$ (e.g., Ettori & Salestra 2009).

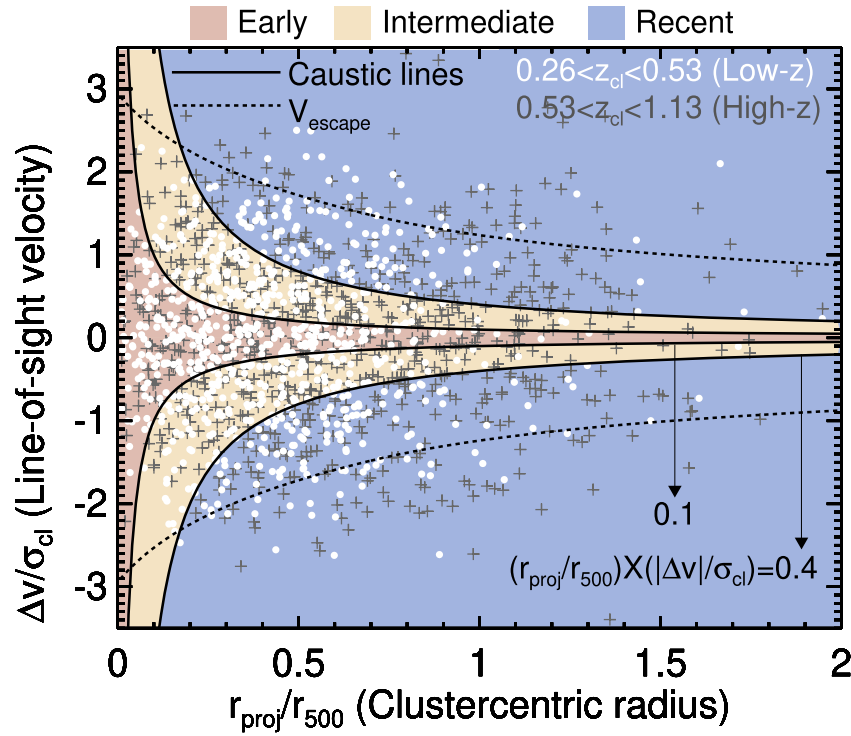


Figure 3. Projected phase space diagram of galaxies stacked from 105 clusters at $0.26 < z < 1.13$. The color-coded regions represent different infall time zones based on the caustic lines (i.e., solid lines; Section 3.2): early infall (red), $(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) < 0.1$; intermediate infall (orange), $0.1 < (r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) < 0.4$; and recent infall (blue), $(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}}) > 0.4$. The dashed line is the escape velocity curve of a cluster assuming an NFW potential (Navarro et al. 1996) with the typical cluster mass ($M_0 = 4.97 \times 10^{14} M_{\odot}$) and velocity dispersion ($\sigma = 1052 \text{ km s}^{-1}$) of our sample clusters. Comparison of the galaxies' distribution with the escape velocity curve suggests that galaxies within the early and intermediate infall zones are likely gravitationally bound to the cluster, while galaxies within the recent infall zone are becoming gravitationally bound. This figure shows the overall accretion stages of cluster galaxies over a wide range of redshifts and illustrates how our analysis adopts the galaxies' location in the projected phase space to statistically infer the mean infall time of galaxies based on cluster simulations (Section 3.2).

scatter in the mean infall time space due to projection effects.

For the projected phase space, σ_{cl} are based on the spectroscopic velocity dispersion (Section 2.3). In particular, the line-of-sight peculiar velocity (Δv) is expressed as follows:

$$\Delta v = c \left(\frac{z_{\text{gl}} - z_{\text{cl}}}{1 + z_{\text{cl}}} \right), \quad (5)$$

where z_{gl} , z_{cl} , and c are the redshifts of a galaxy and a cluster and the speed of light, respectively. The r_{proj} is derived by measuring the angular separation between the cluster center and a galaxy's projected location in units of R.A. and decl. To obtain the clustercentric radius (r_{proj}/r_{500}), we derive the r_{500} of our sample clusters using the cluster mass (Section 2.1) and assuming a spherical mass density profile,

$$M_{500} = \frac{4\pi}{3} r_{500}^3 \rho_{\text{crit}}, \quad (6)$$

where ρ_{crit} is the critical density of the Universe at the cluster redshift.

We select galaxies with $|\Delta v|/\sigma_{\text{cl}} < 3.5$ and $r_{\text{proj}}/r_{500} < 3$ as infalling cluster galaxies as stated in Section 3.1. Figure 3 shows the projected phase space of the sample galaxies. Galaxies mostly populate regions within $|\Delta v|/\sigma_{\text{cl}} \leq 2$ and

$r_{\text{proj}}/r_{500} \leq 1.5$. These regions are closely matched with the inner region of the escape velocity radial profile (dashed lines) for the median mass ($4.97 \times 10^{14} M_{\odot}$) of our sample clusters. This suggests that the bulk of infalling galaxies are gravitationally bound by cluster potential wells. To derive the escape velocity profile, we assume a Navarro–Frenk–White (NFW) dark matter halo density profile (Navarro et al. 1996) and a cluster concentration parameter of 4.

The early and intermediate infall zones are all located within the inner region of the escape velocity profile, while the recent infall zone spans the escape velocity profile. The comparison of infall zones with the escape velocity profile makes intuitive sense in that galaxies that have infallen at earlier times are expected to have virialized earlier than those that have infallen more recently. Our low- z ($0.26 < z < 0.53$) and high- z ($0.53 < z < 1.13$) subsamples (i.e., gray and white points, respectively, in Figure 3) show similar phase space distributions.

4. Results and Discussion

In this section, we look at how the mean age of the galaxies (using D_{4000}) statistically varies with their infall time proxy to investigate the environmental quenching effects since the galaxies entered into clusters. In Section 4.1, we show the trends of D_{4000} with infall time proxy across redshifts $z = 0.26$ – 1.13 . In Section 4.2, we investigate the galaxy

luminosity dependence (using L_i/L^*) of the environmental quenching by dividing galaxies into “faint” ($\text{sub-}L_i/L^* < 1$) and “bright” ($\text{super-}L_i/L^* > 1$) galaxies. In Section 4.3, we simultaneously control for the galaxy luminosity and redshift dependence of the environmental quenching by dividing galaxies into redshift and luminosity bins. We discuss the potential projection effects in our projected phase space analysis in Section 4.4.

4.1. Quenching since Infall: A Continuous Increase of Galaxies from Recent to Early Infall

We now investigate how the D_{n4000} (mean stellar age) of galaxies varies with time since infall to study the environmental impacts on the star formation of galaxies. Figure 4 shows D_{n4000} versus $(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})$ (a proxy for infall time; see Section 3.2 for details). The top panel shows the distribution of galaxies at all redshifts ($0.26 < z < 1.13$). The colored diamonds indicate the mean D_{n4000} of galaxies in the corresponding colored infall time zone, which is derived from 1000 bootstrap realizations accounting for the D_{n4000} uncertainties.

Notably, there is a continuous increase in the mean D_{n4000} of galaxies with the infall time proxy moving from recent to early infall populations. The increase in the mean D_{n4000} is from 1.51 ± 0.01 to 1.62 ± 0.01 . The net increase (ΔD_{n4000}) corresponds to an age increase of $\sim 0.71 \pm 0.4$ Gyr based on a simple stellar population modeling assuming an instantaneous burst of star formation with solar metallicity from Kauffmann et al. (2003).²² The quantitative age increase estimated above only describes the relative difference in mean stellar age between recent and early infall populations. This average age difference is estimated from galaxies that span a wide range of redshifts ($0.26 < z < 1.13$); therefore, the reported age difference does not capture any redshift-dependent age differences between infall zones. We examine in detail the redshift dependence of the age difference between infall zones in Section 4.3.

The continuous increase in the mean D_{n4000} of galaxies with infall proxy is also shown by the gradual shift of the D_{n4000} histograms of each infall zone in the right panels of Figure 4. That is, early infall galaxies (red solid line) tend to have a larger fraction of high- D_{n4000} ($D_{n4000} \gtrsim 1.5$) galaxies compared to the recent infall counterparts (blue dashed line), and the intermediate infall galaxies show the intermediate distribution between recent and early infall zones. This steady shift of the distributions toward larger D_{n4000} strength from recent (blue) to early (red) infall populations suggests that the mean age of cluster galaxies increases with time since infall, although there is a broad distribution of D_{n4000} values in each infall zone, which is reflected in the overlapping D_{n4000} histograms of different infall populations.

The different D_{n4000} distributions between different infall time zones are further supported by the two-sample Kolmogorov–Smirnov (K-S) test (Table 2). Table 2 presents the results of the K-S tests for the null (i.e., false-positive)

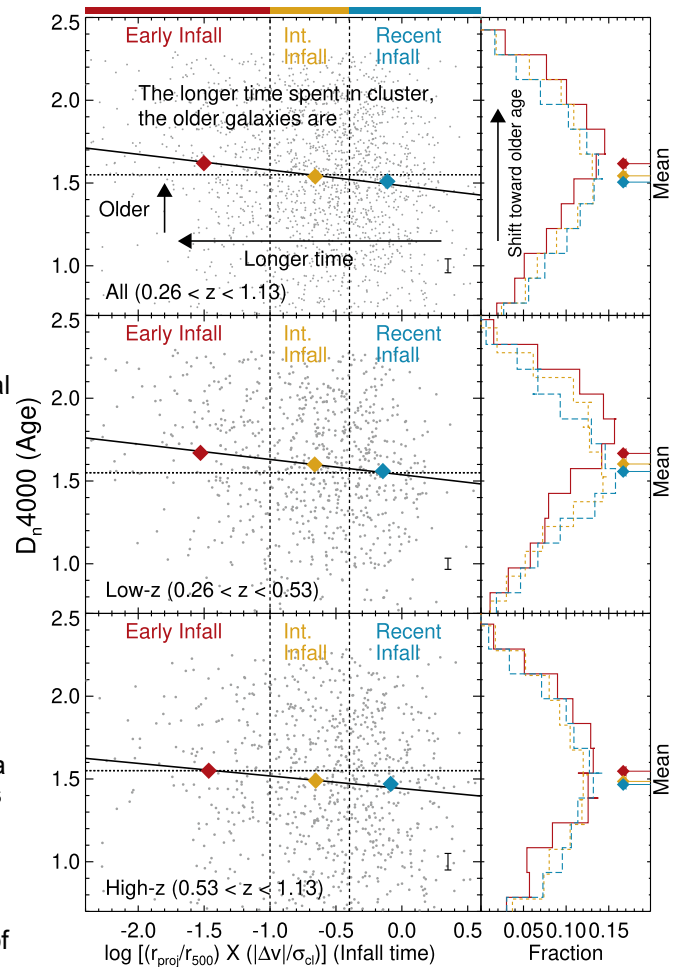


Figure 4. Diagram showing that galaxies that have infallen at earlier times are quenched earlier across all of our sample redshifts ($z = 0.26\text{--}1.13$). The 4000 Å break (D_{n4000}) and the position in the projected phase space, $(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})$; Figure 3) are used as proxies for mean stellar age and cluster infall time, respectively. In each panel, different colors indicate different infall time zones separated by vertical dashed lines and the color bars on top (Section 3.2): early (red), intermediate (orange), and recent (blue) infall. Top: distribution of galaxies at all redshifts ($0.26 < z < 1.13$). Colored diamonds indicate the bootstrapped mean D_{n4000} of galaxies in the corresponding infall time zones. The error of the mean is smaller than the symbol size. The black solid line is a linear fit to individual galaxies derived from bootstrapping with the D_{n4000} uncertainties accounted for (Table 3). The dotted horizontal line indicates $D_{n4000} = 1.55$ as the guideline used in the literature to separate star-forming ($D_{n4000} < 1.55$) and quiescent ($D_{n4000} > 1.55$) galaxies. The typical uncertainty of D_{n4000} is marked in the bottom right of each panel. Middle: distribution of low-redshift ($0.26 < z < 0.53$) subsamples. Bottom: distribution of high-redshift ($0.53 < z < 1.13$) subsamples. Note that there is a continuous increase in the mean D_{n4000} of galaxies with the infall time proxy at all redshifts (from top to bottom), as also shown in the histograms on the right. The continuous D_{n4000} increase with the infall time proxy (from recent to early infall) shown in all panels suggests that galaxies become quenched as they spend a longer time in the cluster environment at all redshifts $z = 0.26\text{--}1.13$ (Section 4.1).

probability that the two selected distributions are statistically different. The left column of the table shows that the D_{n4000} distributions between early infallers and the other two categories of infallers are statistically different, with null probabilities of < 0.05 .

We also perform a linear fit to the D_{n4000} versus infall time proxy relation for galaxies with the following form:

$$D_{n4000} = a \log[(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})] + b, \quad (7)$$

²² The “exact” net age increase depends on the details of the assumed stellar population modeling parameters, such as the shape of the star formation history and metallicity (see, e.g., Figure 2 of Kauffmann et al. 2003 and Figure 1 of Hernán-Caballero et al. 2013). For instance, the variations in the assumed metallicity ($0.4\text{--}2.5 Z_{\odot}$) result in the corresponding age increase to the D_{n4000} increase to vary from ~ 0.31 to ~ 1.12 Gyr. However, more importantly, we note that there is no qualitative change in our interpretation of the D_{n4000} increase as the age increase of galaxies with infall time proxy.

Table 2
The Two-sample K-S Test Shows whether the D_{n4000} Distributions of Different Infall Time Zones Are Statistically Different (Section 4.1 and the Right Panel of Figure 4)^{a,b,c}

	Total-z ($0.26 < z < 1.13$)	Low-z ($0.26 < z < 0.53$)	High-z ($0.53 < z < 1.13$)
Early–intermediate	0.002	0.03	0.3
Early–recent	0.00004	0.0007	0.07
Intermediate–recent	0.3	0.4	0.8

Notes.

^a Galaxies are classified as early, intermediate and recent infall galaxies based on their location in the phase space as a proxy for their infall stage into the cluster (Figure 3 and Section 3.2).

^b Numbers indicate the null (i.e., false-positive) probability that a given pair of infall time zones' (early, intermediate, and recent) D_{n4000} distributions are drawn from the same parent distribution.

^c Bold null probabilities indicate that the D_{n4000} distributions of a given pair of infall time zones are statistically different at a level less than 0.05.

where α and β are the slope and intercept of the relation, respectively. We perform 1000 iterations for the fits by accounting for the D_{n4000} uncertainties. We find a negative slope (α) of -0.096 ± 0.016 of the relation that is constrained to be negative at high statistical significance. This suggests that the D_{n4000} of galaxies increases with lower $(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})$, meaning older age with longer time spent in clusters since infall. We note, however, that the quantitative slope that we measure could be subject to small selection biases due to our observational selection effects, specifically that we preferentially target red-sequence (passive) galaxies (see Section 3.1 for details).

The middle panel of Figure 4 shows the distribution of low-redshift ($0.26 < z < 0.53$) subsamples. The low-z galaxies show similar trends as those of the entire sample (top panel). That is, they also show a constant increase of D_{n4000} with infall proxy, with a fitting slope (α) of -0.093 ± 0.020 (Table 3) and statistically different D_{n4000} distributions between early infallers and other infallers by the K-S test (middle panel of Table 2). A noticeable difference from the entire sample is that the D_{n4000} of low-z galaxies is on average larger by ~ 0.05 , regardless of infall time proxy. This is further shown by the larger intercept value of the fitted D_{n4000} versus infall proxy relation in low-z subsamples compared to the entire sample in Table 3 (i.e., 1.54 ± 0.02 versus 1.48 ± 0.01 for low-z subsamples and the entire sample, respectively). The ΔD_{n4000} of the mean D_{n4000} from recent to early infall is a 0.11 increase from ~ 1.56 , which corresponds to an $\sim 0.84 \pm 0.6$ Gyr age increase.

The bottom panel of Figure 4 shows the distribution of high-redshift ($0.53 < z < 1.13$) subsamples. Like the other two redshift bins (top and middle panels), the high-z subsamples also show the increasing D_{n4000} trends with infall proxy, as shown by the increasing mean D_{n4000} and the gradual shift of the D_{n4000} histogram toward larger D_{n4000} strength when moving from recent to early infallers. We also found a negative slope (α of -0.078 ± 0.025) of the relation for high-z galaxies, which is slightly shallower but still consistent with the other redshift bins within 1σ uncertainties (Table 3).

The K-S test for the D_{n4000} distributions of different infall zones of the high-z subsamples does not show statistical significance, as the related null probability that the tested distributions are drawn from the same distribution is larger than 0.05 (right column of Table 2). Nonetheless, like the other redshift bins, the null probabilities systematically vary with infall time zones, such that we see the same qualitative trends in D_{n4000} with infall time proxy. These systematic K-S test

Table 3
The Fit Relation of D_{n4000} vs. Infall Time Proxy Shows the Consistent Negative Slope α across All Redshift and Luminosity Bins (Sections 4.1–4.3)

Redshift/Luminosity ^c	Slope α^d	Intercept β
Total-z /faint+bright	-0.096 ± 0.016	1.48 ± 0.01
Low-z/faint+bright	-0.093 ± 0.020	1.54 ± 0.02
High-z/faint+bright	-0.078 ± 0.025	1.44 ± 0.02
Total-z /faint	-0.082 ± 0.022	1.45 ± 0.02
Low-z/faint	-0.080 ± 0.027	1.52 ± 0.02
High-z/faint	-0.052 ± 0.035	1.39 ± 0.03
Total-z /bright	-0.108 ± 0.024	1.53 ± 0.02
Low-z/bright	-0.096 ± 0.033	1.60 ± 0.04
High-z/bright	-0.095 ± 0.033	1.50 ± 0.03

Notes.

^a The relation is described by, $D_{n4000} = \alpha \log [(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})] + \beta$, same as Equation (7).

^b Total-z, $0.26 < z < 1.13$; low-z, $0.26 < z < 0.53$; high-z, $0.53 < z < 1.13$.

^c Galaxy i-band luminosity (L/L^*) is used (Section 2.2). Galaxies are divided into faint (sub- L^* , $L_i/L^* < 1$) and bright (super- L^* , $L_i/L^* > 1$) subsamples relative to the characteristic luminosity L^* .

^d The values and uncertainties are derived from 1000 bootstrappings of the fit with the D_{n4000} uncertainties accounted for.

results with infall zones at least suggest that the D_{n4000} distribution of our high-z subsamples is related to the galaxies' infall time proxy. The ΔD_{n4000} of the mean D_{n4000} from recent to early infall for high-z galaxies is an ~ 0.08 increase from ~ 1.47 , which corresponds to an $\sim 0.63 \pm 0.4$ Gyr age increase.

Contrary to the low-z galaxies, the high-z subsamples show, on average, smaller D_{n4000} values by ~ 0.05 compared to the entire sample at all infall proxies. The smaller D_{n4000} value of the high-z subsamples is also seen by their smaller intercept of the D_{n4000} versus infall proxy relation compared to the entire sample and low-z subsamples in Table 3.

This redshift dependence of the D_{n4000} strengths across infall proxies is likely attributed to the redshift evolution of the star-forming main sequences such that the average D_{n4000} strength of galaxies at fixed stellar mass decreases with increasing redshift (e.g., Whitaker et al. 2012; Haines et al. 2017; Pandya et al. 2017). We will further discuss the redshift dependence of the D_{n4000} distributions of our sample galaxies associated with infall time in Section 4.3.

The continuous galaxy age (D_{n4000}) increase with infall time proxy (Figure 4) is also consistent with the increasing

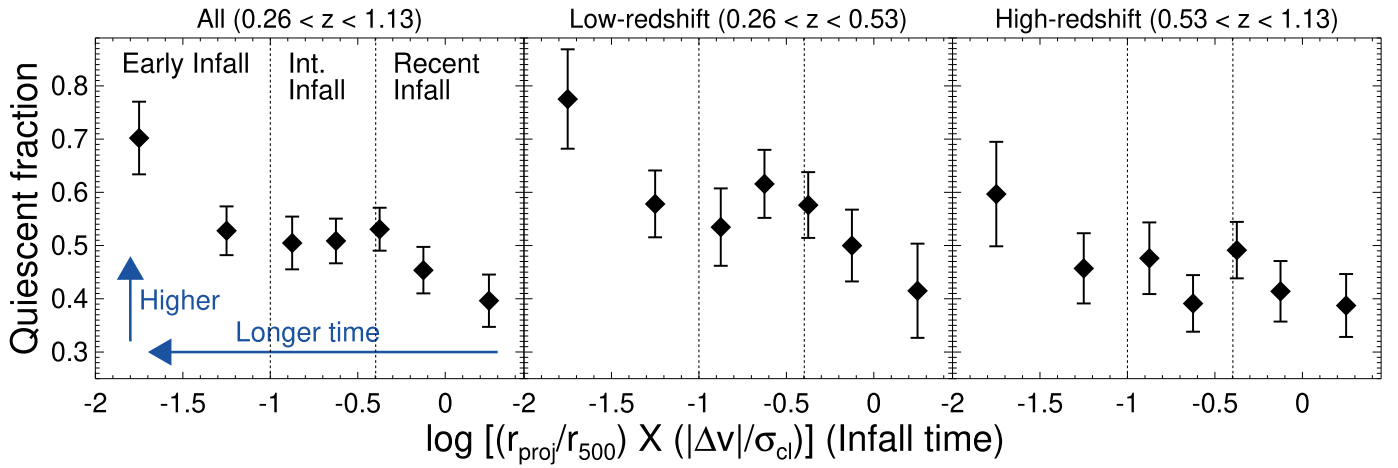


Figure 5. Diagram showing that the fraction of quiescent galaxies (f_Q) increases with infall time proxy. Each panel shows the same relationship for different redshift ranges, as indicated on the tops of the panels. Quiescent galaxies are defined as $D_{4000} > 1.55$. The f_Q are calculated in bins of 0.25 or 0.5 dex (smaller bin size adopted for crowded infall bins) of infall proxy $\log[(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}})]$. The error bars indicate 1σ uncertainties based on Poisson statistics. There is an increasing f_Q with infall proxy in all panels (i.e., regardless of redshift), although the low- z galaxies (middle panel) show a systematically higher f_Q compared to the high- z galaxies (right panel) for any given infall bin (see Section 4.3 for the redshift dependence of environmental quenching trends). The increasing quiescent fraction of galaxies with infall time proxy suggests that galaxies become quiescent due to longer exposure to environmental effects.

fraction of quiescent galaxies (f_Q) with infall proxy shown in Figure 5. In the figure, f_Q is calculated as the fraction of galaxies whose D_{4000} is > 1.55 in bins of infall proxy. Indeed, the f_Q increases from 0.4 ± 0.05 to 0.7 ± 0.07 while moving from recent to early infall zones across all redshifts ($z = 0.26$ – 1.13).

These steady increases in D_{4000} and f_Q with infall time proxy would suggest that galaxies that have fallen into clusters earlier are quenched earlier due to longer exposure to environmental effects. Our findings are qualitatively consistent with previous studies for several high- z ($z \sim 1$; Noble et al. 2013, 2016; Werner et al. 2022) and local ($z < 0.2$) clusters (Pasquali et al. 2019; Smith et al. 2019; Upadhyay et al. 2021) as well as recent cluster simulations showing systematic suppression of star formation of galaxies since infall (Wetzel et al. 2013; Oman & Hudson 2016; Rhee et al. 2020; Coenda et al. 2022; Oman et al. 2021). Our time-averaged kinematic analysis spans a wide range of redshift, $z = 0.26$ – 1.13 , with a sample of clusters that are uniformly selected above an approximately constant mass threshold²³ and reveals a remarkably consistent picture of environmental quenching extending out to $z \sim 1$.

For instance, environmental mechanisms such as ram pressure stripping (Gunn & Gott 1972; Abadi et al. 1999; Ebeling et al. 2014), starvation (Larson et al. 1980), harassment (Moore et al. 1996), and tidal interactions (Byrd & Valtonen 1990) have been suggested as the ones enabling suppression of star formation of galaxies in clusters. Indeed, a systematic gas stripping process has been observed in the Virgo and A963 clusters based on the projected phase space analysis (Vollmer et al. 2001; Boselli et al. 2014b; Jaffé et al. 2015; Yoon et al. 2017; Morokuma-Matsui et al. 2021), where the level of HI gas stripping is closely related to the infalling stages identified in the phase space (see, e.g., Figure 5 of Yoon et al. 2017). Furthermore, the stripping of other components of

galaxies, such as warm dust (Noble et al. 2016), molecular gas (CO; Fumagalli et al. 2009; Boselli et al. 2014a; Lee & Chung 2018) and dust (Cortese et al. 2016; Longobardi et al. 2020), is also reported in cluster environments. These results clearly show that gas stripping is actively occurring in cluster galaxies (likely) through the ram pressure by the hot ICM in the deep gravitational potential well of clusters. This is further supported by the recent cosmological cluster simulation that shows the systematic gas depletion of galaxies by ram pressure stripping since infall (Jung et al. 2018).

It is not unreasonable to expect that such ram pressure stripping has occurred in our sample cluster galaxies as well, considering the similar mass range (and thus gravitational potential well) of our sample clusters with those reported for gas stripping (i.e., 1 – $8 \times 10^{14} M_\odot$). Indeed, the significant X-ray detection (X-ray luminosity $> 10^{44} \text{ erg s}^{-1}$) and the associated hot ICM temperature ($> 2 \times 10^8 \text{ K}$) are found in our cluster subsamples across all redshifts (McDonald et al. 2014; Bulbul et al. 2019). However, ram pressure stripping should be most effective on low-mass systems (e.g., Janz et al. 2021), and the luminosity cut of our analysis (i.e., $L_i/L^* > 0.35$; Section 3) restricts our sample to moderately massive galaxies, suggesting that we should not be highly sensitive to the effects of the ram pressure mechanism.

A slow quenching process, such as the gradual shutoff of gas supply (“starvation”; see, for example, Larson et al. 1980), seems to be a plausible quenching process driving the gradual age (D_{4000}) trend with infall proxy in our sample galaxies (Figure 4). Physically, this process is one that acts via the truncation of the galaxy’s circumgalactic medium, rather than a faster mechanism that achieves the rapid removal of interstellar medium gas. A slow starvation quenching process would take effect over the course of several dynamical crossing times after a galaxy has fallen into the galaxy cluster environment, which is in good agreement with our measurement of a small average net age increase from recent to early infall populations (i.e., $0.71 \pm 0.4 \text{ Gyr}$) compared to the typical dynamical timescales of 1 – 3 Gyr of cluster galaxies (e.g., Rhee et al. 2020).

A slow quenching trend is also consistent with the approximately constant slope (α) that we measure for the

²³ We note that our results of increasing D_{4000} with infall time proxy virtually do not change even when the sample clusters are divided into specific cluster mass criteria (e.g., the expected mass-growth curve with redshift; Fakhouri et al. 2010) within the sample clusters’ mass range, $3 \times 10^{14} M_\odot \square M_{500} \square 3 \times 10^{15} M_\odot$ (Section 2.1).

mean stellar population age versus infall proxy relation (i.e., the Dependence of environmental quenching on galaxy luminosity D_{n4000} versus $\alpha \log [(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})] + \beta$ relation; Equation (7)). Specifically, the slope α does not significantly depend on the galaxies' L_i/L^* (stellar mass), as both bright ($L_i/L^* > 1$) and faint ($L_i/L^* < 1$) subsamples have statistically similar α (~ -0.09) at all redshifts (Table 3). The similar α we measure across galaxy luminosity suggests that the environmental quenching mechanism acting on these galaxies is not strongly dependent on either galaxy stellar mass or orbital velocity, which matches the expectation for the starvation effect in cluster environments. Qualitatively, our results are in broad agreement with the known “delayed-then-rapid” quenching processes (e.g. Wetzel et al. 2013; Haines et al. 2015; Gallazzi et al. 2021).

We also note that while the average net age increase (0.7 ± 0.4 Gyr) seen in our sample galaxies appears to be broadly consistent with the quenching age (0.1–1.3 Gyr) by the ram pressure gas stripping in local galaxy clusters (Crowl & Kenney 2008; Boselli et al. 2016), one should be cautious in directly comparing the age increase we measure with the quenching ages from the literature. This is due to the difference in how the quenching-related ages are measured between the studies such that our measurement is based on the average net age increase of stellar populations since infall, whereas the SFH quenching age often measured in the literature is considered to be the time taken for a galaxy to transform from gas-rich and star-forming to a totally quenched passive system.

We also note that there are other environmental mechanisms that are likely at play in our sample galaxies. Of them, preprocessing—i.e. pre-exposure of group-scale environmental effects before infalling to the main cluster (Balogh et al. 2000; Fujita 2004; Han et al. 2018; Lee et al. 2022)—is known to be able to quench the star formation of infalling galaxies even in the cluster outskirts ($\square R_r$; Balogh et al. 2000), the region where cluster environmental effects are expected to be insignificant. Indeed, recent observations for high-redshift clusters ($z \sim 1$) suggest that the majority of massive galaxies are quenched during infall in the cluster outskirts ($1 < R/R_{200} < 3$), which might imply preprocessing effects prior to infall (Werner et al. 2022).

While our analysis alone cannot pin down the most likely environmental mechanisms responsible for the quenching of cluster galaxies, we emphasize that the steady D_{n4000} increase with infall proxy in Figure 4 strongly indicates the environmental quenching at play over a wide span of redshift ($0.26 < z < 1.13$). Also, our results are qualitatively consistent with recent work at similar redshifts ($0.3 < z < 1.5$; Webb et al. 2020; Khullar et al. 2021), where the authors used a stellar population fitting analysis to measure the star formation histories and ages of quiescent cluster galaxies.

4.2. Luminosity Dependence of Environmental Quenching: Trends with Faint ($L_i/L^* < 1$) and Bright ($L_i/L^* > 1$) Galaxies

In the previous section, we have shown that there is a continuous increase of D_{n4000} with infall time proxy, which suggests that galaxies that have fallen earlier are quenched earlier due to environmental effects. In this section, we investigate a galaxy luminosity dependence of the environmental quenching trend. We divide our sample galaxies into faint (sub- L^* ; $L_i/L^* < 1$) and bright (super- L^* ; $L_i/L^* > 1$) subsamples based on their i-band luminosity (Section 2.2).

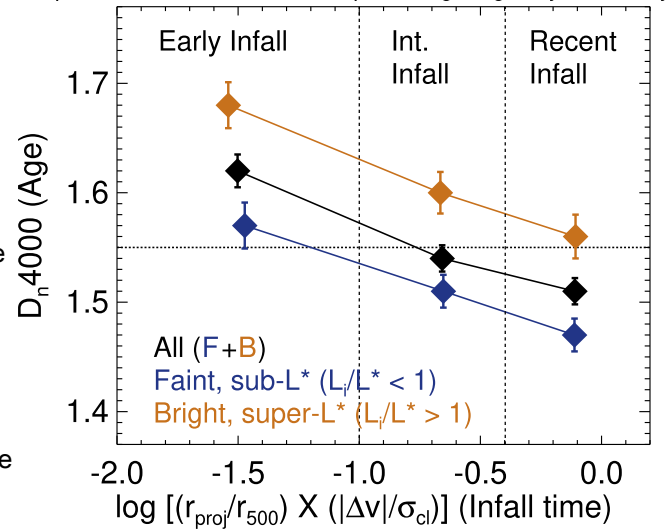


Figure 6. Similar to the top panel of Figure 4 but focusing on the galaxy luminosity dependence of the environmental quenching effect (i.e., the continuous D_{n4000} increase of galaxies since infall). The diamonds and associated error bars are the bootstrapped mean D_{n4000} strength and the 1σ standard deviation of galaxies in each infall zone. Different colors indicate the different i-band luminosity bins: all (black), faint (sub- L^* ; orange), and bright (super- L^* ; blue). Note that both the faint and bright subsamples show a continuous D_{n4000} increase with infall proxy. However, at all fixed infall zones, bright galaxies have larger mean D_{n4000} compared to their faint counterparts. This suggests that environmental quenching impacts galaxies regardless of the galaxies' luminosity, yet the exact age (D_{n4000}) depends on the galaxies' luminosity due to an internal mass quenching (i.e. downsizing) effect at a fixed environment (Section 4.2).

Figure 6 shows the same D_{n4000} versus infall time proxy diagram as the top panel of Figure 4 but focusing on the galaxy luminosity dependence by splitting it into faint and bright subsamples. The black diamonds and associated error bars are the bootstrapped mean D_{n4000} strength and the 1σ spread of the full sample, same as in the top panel of Figure 4. Orange and blue indicate the same symbols as black but for faint and bright subsamples, respectively.

Notably, both the faint and bright subsamples qualitatively show the same environmental quenching trend with infall time, as both subpopulations show the continuous increase of D_{n4000} with the infall time proxy. The faint and bright subsamples also have slopes (α) of D_{n4000} versus infall proxy relation consistent within 1σ , with $\alpha = -0.082 \pm 0.022$ and -0.108 ± 0.024 for faint and bright galaxies, respectively, as in Table 3. This means that the environmental quenching affects galaxies regardless of galaxy luminosity (stellar mass).

However, there is a noticeable difference between the faint and bright subsamples, such that the bright subsamples always have a larger mean D_{n4000} strength than their faint counterparts across infall zones. This trend does not arise from any potential dependence of luminosity on infall proxy in the sense that bright galaxies might be preferentially located toward earlier infall zones and thus have a larger mean D_{n4000} than

²⁴ Note that while the i-band luminosity (L_i/L^*) is a useful quantity for the optical light of stellar populations, it is only a rough proxy for stellar mass and subject to significant mass-to-light (M/L) ratio variations. This caveat especially applies for galaxies at high redshift ($z > 0.8$), where the i-band samples rest-frame light blueward of the 4000 Å break. Only a small fraction (8%) of our galaxies are at $z > 0.8$, so that the large majority of our analysis is based on galaxies where the i-band samples rest-frame light redward of the 4000 Å break.

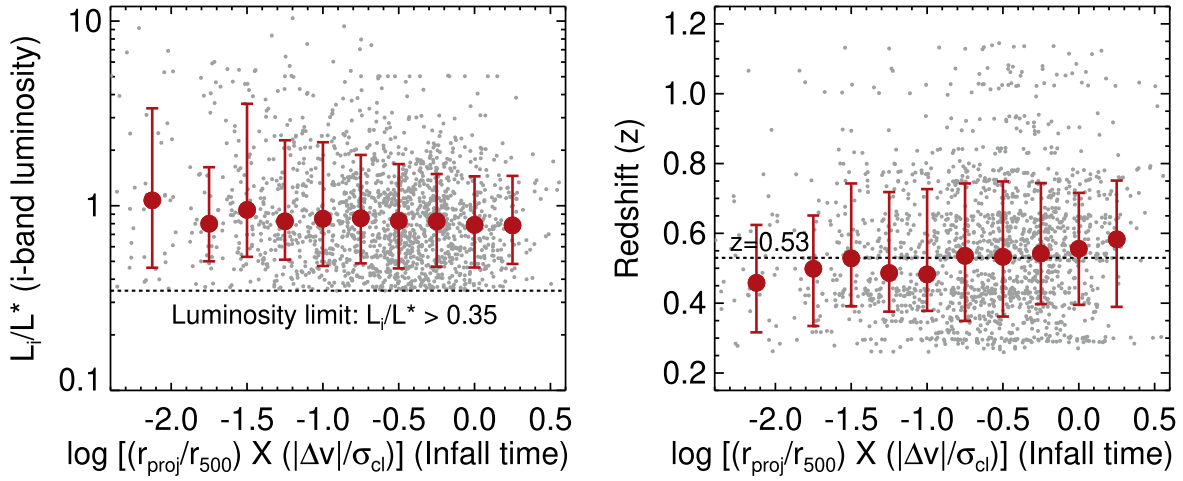


Figure 7. The figure shows that galaxy luminosity (left) and redshift (right) do not show an obvious dependence on infall proxy. The red points with error bars indicate the median values and associated 1σ spread per infall proxy bin. In the left panel, the galaxy luminosity distribution is similar regardless of infall proxy, with median values consistent within 1σ . In the right panel, the redshift distribution is also consistent across all infall proxies, although the median redshift seems to slightly decrease with infall proxy within 1σ population spread. Little (or no) dependence of luminosity and redshift on infall proxy suggests that the infall time proxy with infall time proxy (e.g., Figure 4 and Section 4.1) is not driven by either luminosity or redshift. Rather, it is most likely due to environmental quenching such that galaxies that have infallen earlier stopped star formation earlier. It is also regardless of specific galaxy luminosity (Figures 6 and 8 and Section 4.2) and redshift bin (Figure 9 and Section 4.3).

the faint counterparts. We show that the luminosity distribution of sample galaxies is similar across all infall proxies in the left panel of Figure 7.

Thus, at a fixed infall zone (environmental effect), this quantitative D_n4000 difference between faint and bright subsamples is likely attributed to the mass-dependent “internal” quenching of galaxies (e.g., Gavazzi & Scodeggio 1996; Boselli et al. 2001; Peng et al. 2010; Kim et al. 2016, 2018, and references therein). That is, more massive (bright) galaxies become quenched earlier than their less massive (faint) counterparts. This mass quenching may be attributed to mechanisms such as virial shock heating of infalling gas in massive galaxy halos (e.g. Dekel & Birnboim 2006) and/or secular AGN feedback from the supermassive black holes in the galaxy center (e.g. Choi et al. 2015; Bluck et al. 2022).

The individual effects of environment-related infall time proxy and galaxy luminosity (L_i/L^*) on quenching as traced by mean galaxy age are demonstrated in Figure 8. Figure 8 is generated by creating a density map of the spatially averaged D_n4000 value within a grid of infall proxy and luminosity. Each pixelated grid position is 0.025 in L_i/L^* by 0.05 in $\log[(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}})]$, and within each grid pixel, we measure the mean D_n4000 strength of the nearest 100 sample galaxies. Due to some regions of the grid space being very sparsely sampled we then apply a 2D Gaussian smoothing kernel with a width of 3 grid pixels to improve the visualization of the resulting density map. Clearly, the mean D_n4000 (age) of the galaxies is a function of both environment and luminosity, as the colored D_n4000 strength continuously increases with infall proxy (y-axis) and luminosity (x-axis). However, when fixing one parameter (i.e., x- or y-axis), the mean D_n4000 strength increases along with the other parameter. This means that a continuous D_n4000 increase along with the y-axis (infall proxy) is due to the environmental quenching effect at any given luminosity. This trend is also consistent with the “knee”-shaped white dashed lines that are the contours of constant D_n4000 strength tracing the mean D_n4000 distributions of sample galaxies.

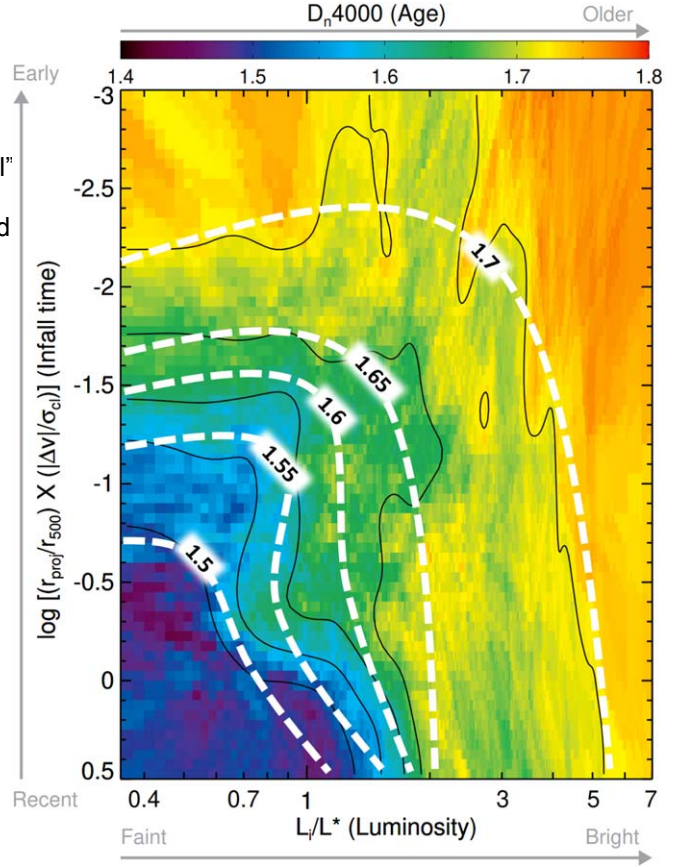


Figure 8. Diagram showing that environment and luminosity are the two main drivers of galaxy quenching where the environmental effect is kinematically measured from the phase space of cluster galaxies (Figure 3 and Section 3.2). The color indicates the mean D_n4000 strength of the nearest 100 sample galaxies at a given luminosity and infall proxy location with a grid spacing of $0.025 L_i/L^*$ and $0.05 \log[(r_{\text{proj}}/r_{500}) \times (|\Delta v|/\sigma_{\text{cl}})]$. The white dashed lines are the contours of several D_n4000 values tracing the mean D_n4000 distributions of sample galaxies. It is clear that the mean D_n4000 typically increases with infall proxy for any luminosity, which suggests that environmental quenching affects galaxies regardless of luminosity (Section 4.2).

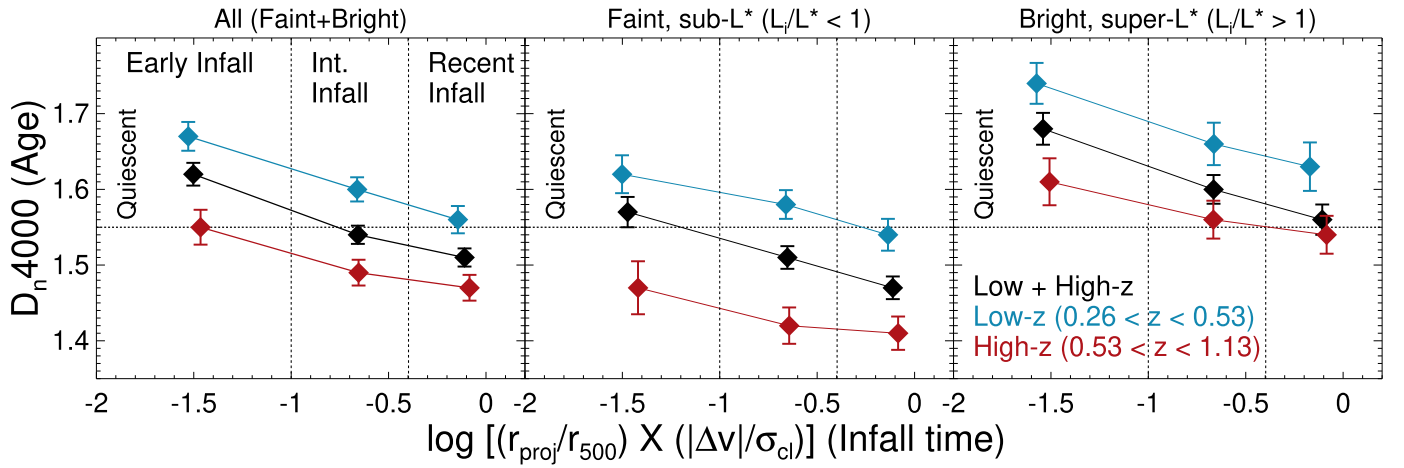


Figure 9. Diagram showing the trends of quenching since infall (i.e., a continuous increase of D_{n4000} with infall time proxy) across redshift and luminosity bins. In all panels, different colors indicate different redshift bins: black, all z ($0.26 < z < 1.13$); blue, low- z ($0.26 < z < 0.53$); and red, high- z ($0.53 < z < 1.13$). Different panels show different luminosity bins: left, all (faint+bright); middle, faint (sub- L^* ; $L/L^* < 1$); and right, bright (super- L^* ; $L/L^* > 1$). The diamonds with error bars indicate the bootstrapped mean D_{n4000} and associated standard deviation of sample galaxies in each infall zone, which also accounts for D_{n4000} measurement uncertainties. The formats are the same as in Figure 4. By comparing the blue and red points in each panel, it is clearly shown that low- z galaxies have a larger mean D_{n4000} than their high- z counterparts at a fixed infall zone (fixed environmental effect), regardless of luminosity. This is due to the redshift dependence of the star-forming main sequence (Section 4.3). Also, by comparing the middle and right panels for the same colored points, it is shown that bright galaxies have a larger mean D_{n4000} than their faint counterparts at a fixed infall zone across redshift, which is due to the mass-dependent quenching effect (Section 4.2). Thus, by dividing sample galaxies into specific redshift and luminosity bins, this figure clearly shows that environmental quenching does exist and impact galaxies since their infall into clusters at all redshifts and luminosities, yet the exact age (D_{n4000}) depends on both redshift and luminosity at a fixed environment (infall zone; Section 4.3).

Therefore, Figures 6 and 8 suggest that environmental quenching impacts galaxies independent of galaxy luminosity, although the exact age (D_{n4000}) depends on the galaxies' luminosity due to the internal mass quenching mechanism. Our decreasing redshift through infall time proxy show a consistent picture, where stellar mass and environment are the two main drivers of galaxy quenching (e.g., Peng et al. 2010; Smith et al. 2012; Kawinwanichakij et al. 2017; Sobral et al. 2022).

4.3. Environmental Quenching Observed across Wide Ranges of Redshift ($0.26 < z < 1.13$) and Luminosity ($0.35 < L/L^* < 10$)

So far, we have demonstrated that environmental quenching occurs since infall such that the galaxies' D_{n4000} continuously increases when moving from recent to early infallers (Figure 4). Also, environmental quenching seems to impact galaxies regardless of their luminosity (Figures 6 and 8). We now control for redshift and luminosity simultaneously to further isolate environmental quenching effects, as both parameters can independently alter the D_{n4000} strengths (similarly sSFR) of the galaxies regardless of environment (e.g., Kauffmann et al. 2003; Haines et al. 2017; Kim et al. 2018).

Figure 9 shows the same D_{n4000} trends with infall time proxy as in other figures but further divided by specific redshift and luminosity bins.

First, in all panels showing different luminosity bins, low- z galaxies (blue points) clearly show larger mean D_{n4000} values than their high- z counterparts (red points) across infall zones. At the same time, both redshift bins show a continuous increase of mean D_{n4000} with infall time proxy due to the environmental quenching at play at all redshift bins. This systematic redshift dependence of D_{n4000} at a fixed infall proxy (environmental effect) and luminosity is likely attributed to the redshift-dependent star-forming main sequence of galaxies (e.g., Whitaker et al. 2012; Sobral et al. 2014; Pandya et al.

2017). As the sSFRs of galaxies for a given stellar mass decrease with decreasing redshift, the D_{n4000} strength of galaxies given luminosity is also expected to increase with decreasing redshift. Note that this trend does not arise from any potential dependence of galaxy redshift on infall proxy in the sense that low- z galaxies might be preferentially located toward earlier infall zones and thus have a larger mean D_{n4000} than their high- z counterparts. This is shown in the right panel of Figure 7, where the redshift distribution of sample galaxies is mostly similar across all infall proxies, although the median redshift appears to slightly increase with infall proxy within a 1σ population spread (i.e., $\Delta z \sim 0.1$ across infall proxies).

Also, by fixing the redshift bins (i.e., focusing on the same colored points across panels), it is clear that bright (super- L^*) galaxies have larger mean D_{n4000} values than the faint (sub- L^*) galaxies at all infall zones, while both luminosity subsamples show an environmental quenching effect (a continuous increase of D_{n4000} with infall time proxy). As noted in Section 4.2, this luminosity dependence of D_{n4000} is likely explained by the mass quenching effect in that more massive (bright) galaxies tend to stop star formation earlier than those with less mass (faint; e.g., Peng et al. 2010; Kim et al. 2016, 2018; Haines et al. 2017). By splitting into low- and high-redshift bins, we further show that this luminosity dependence of D_{n4000} at a fixed infall proxy exists independent of specific redshift bins.

The trends shown in Figure 9 further suggest that environmental quenching indeed affects galaxies since infall regardless of redshift and luminosity, as clearly shown by the systematic increase of the mean D_{n4000} with infall time proxy across all redshift and luminosity bins. This is also supported by the similar gradient (slope α) of D_{n4000} versus infall proxy relation for all subsamples (Table 3) that are consistent within the uncertainties. However, it is also evident that the exact D_{n4000} strength (age) at a fixed environmental effect shows the systematic dependency on redshift and luminosity due to their individual effects on D_{n4000} as discussed above.

4.4. Caveats on Projected Phase Space

Despite the exceptional usefulness of the projected phase space for investigating environmental effects, it is also worth noting that there is a spread in our infall time proxy due to sources of uncertainty, such as projection effects and variations in the orbital parameters (e.g., velocity dispersion anisotropy profiles; see Capasso et al. 2019). These include a difference between the projected 2D clustercentric distance and the actual 3D distance and a mix of infalling and outfalling (e.g., backsplash and mere interlopers) populations in the projected phase space.

Cluster simulations (Gill et al. 2005; Rhee et al. 2017) have demonstrated that the line-of-sight velocity distribution of backsplash galaxies, which have passed the first pericenter and are currently outbound, overlap with the infalling galaxies at a low-velocity regime ($\lesssim 400 \text{ km s}^{-1}$) in the cluster outskirts ($1-2 R_{200}$; see, i.e., Figure 8 of Gill et al. 2005). These backsplash populations are thus likely mixed with the infalling galaxies in the projected phase space.

As a result, such sources of uncertainty in the projected phase space possibly cause a moderate spread ($\sim 1.5 \text{ Gyr}$) in the mean infall time of each infall zone based on the comparison with the cluster simulation at $z = 0$ (see, i.e., Table 1 and Figure A1 of Pasquali et al. 2019; Smith et al. 2019; Rhee et al. 2017, 2020). Nevertheless, such a comparison clearly shows that the mean infall time of each infall zone continuously increases from recent ($\sim 2.7 \text{ Gyr}$) to early ($\sim 5 \text{ Gyr}$) infallers. This suggests that (1) the projected phase space is indeed a powerful tool to study the average properties of cluster galaxies as a function of infall time, and (2) projected radial studies can only be more affected by these projection effects than phase space studies. More importantly, we note that these sources of uncertainty only make the trends in Figures 4, 6, 8, and 9 shallower, which means that the trends would be more significant if there were no such sources of uncertainty.

5. Summary and Conclusions

We have investigated environmental quenching effects using a large sample of clusters over a wide span of redshift. A uniform set of clusters and spectroscopically confirmed member galaxies enables us to study the quenching effects kinematically by measuring the average time spent in cluster environments spanning a huge range in cosmic time of $\sim 5.2 \text{ Gyr}$, up to $z \sim 1$ ($0.26 < z < 1.13$). For that, we have mapped the location of galaxies in the cluster phase space diagram to their mean infall time.

We found that the age-sensitive 4000 Å break (D_{n4000}) of galaxies continuously increases with infall time proxy. This means that galaxies that spent a longer time in the cluster environment are quenched earlier, likely due to longer exposure to environmental effects such as ram pressure stripping and strangulation. The most notable findings are summarized as follows.

1. We utilize the projected phase space (i.e., clustercentric radius, r_{proj}/r_{500} , versus normalized line-of-sight velocity, $\Delta v/\sigma_{\text{cl}}$) of cluster galaxies over a large redshift baseline ($z = 0.26-1.13$) to estimate the galaxies' kinematic infall stages (Figures 2 and 3). For that, we sample 105 clusters (median mass of $4.97 \times 10^{14} M_{\odot}$) and 1626 cluster galaxies from the SPT-SZ and ACT-SZ cluster

surveys and the optical follow-ups (Figure 1 and Table 1).

2. We classify galaxies by their infall time proxy. Specifically, we use the caustic profiles of the phase space (i.e., the lines of constant $(r_{\text{proj}}/r_{500}) \times (\Delta v/\sigma_{\text{cl}})$) as the infall time proxy to split the galaxies into early, intermediate, and recent infallers (Section 3.2). The early and intermediate infallers are found to be gravitationally bound by the potential well of clusters, while recent infallers are either gravitationally bound or approaching the boundary based on the comparison with the escape velocity radial profile of typical clusters (Figure 3).
3. Notably, a continuous D_{n4000} (proxy for stellar age) increase with infall proxy (from recent to early infall) is found in galaxies at all redshifts, $z = 0.26-1.13$ (Figure 4). The increase in the mean D_{n4000} is statistically significant, showing an increase from 1.51 ± 0.01 to 1.62 ± 0.01 . This indicates that early infall populations are, on average, $\sim 0.71 \pm 0.4 \text{ Gyr}$ older than their recent infall counterparts based on the net D_{n4000} increase (ΔD_{n4000}) of the mean D_{n4000} strengths of recent to early infall populations and simple stellar population modeling (Section 4.1). This trend is consistent with a higher fraction of quiescent galaxies having smaller infall time proxy values, i.e., having spent more time in the cluster environments (Figure 5). This suggests that galaxies that spent a longer time in hosts are quenched earlier, likely due to longer exposure to environmental effects (e.g., ram pressure stripping and strangulation). Compared to the typical dynamical time-scales of 1–3 Gyr of cluster galaxies (e.g., Rhee et al. 2020), the quenching age in our sample galaxies is small (i.e., $0.71 \pm 0.4 \text{ Gyr}$), which is qualitatively consistent with a slow quenching starvation process (e.g., Larson et al. 1980) and/or the known “delayed-then-rapid” quenching process (e.g., Wetzel et al. 2013; Haines et al. 2015; Gallazzi et al. 2021).
4. The quenching trend with infall proxy is found regardless of specific galaxy luminosity and redshift bins. Specifically, both the faint (sub- L^*) and bright (super- L^*) subsamples show the continuous increase of mean D_{n4000} strengths with infall proxy (Figure 6). This still holds when the subsamples are further divided into low- and high- z bins (Figure 9) and is also supported by the similar gradient (slope α) of D_{n4000} versus infall proxy relation across all redshift and luminosity bins (Table 3). However, the exact D_{n4000} strengths at a fixed infall proxy (fixed environmental effect) depend on galaxy luminosity and redshift. That is, bright galaxies show larger D_{n4000} than faint galaxies for any redshift bins, and low- z galaxies show larger D_{n4000} than the high- z counterparts for any luminosity bins. This indicates that while galaxies experience environmental quenching since infall, their absolute mean age at a fixed environmental effect depends on internal mass (luminosity) quenching (Figure 8 and Section 4.2) and the redshift evolution of the star-forming main sequence (Section 4.3).

This work substantially extends previous findings and provides crucial evidence for the environmental quenching effects at play outside the local Universe. Our findings were uniquely achieved by using both a wide range of redshift and the time-averaged kinematic approach in a uniformly selected

sample of clusters with nearly flat mass sensitivity. Additionally, our results demonstrate a continuous increase of galaxies with infall time proxy, in good agreement with cluster simulations that show the systematic gas stripping and quenching of galaxies since infall. Future studies of the gas properties of these high- z cluster galaxies combined with the phase space analysis will provide additional insights on environmental effects at high redshifts.

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References

- Abadi, M. G., Moore, B., & Bower, R. G. 1999, *MNRAS*, **308**, 947
 Adams, N. J., Bowler, R. A. A., Jarvis, M. J., et al. 2021, *MNRAS*, **506**, 4933
 Balogh, M. L., Morris, S. L., Yee, H. K. C., et al. 1999, *ApJ*, **527**, 54
 Balogh, M. L., Navarro, J. F., & Morris, S. L. 2000, *ApJ*, **540**, 113
 Balogh, M. L., van der Burg, R. F. J., Muzzin, A., et al. 2021, *MNRAS*, **500**, 358
 Bayliss, M. B., Ruel, J., Stubbs, C. W., et al. 2016, *ApJS*, **227**, 3
 Bayliss, M. B., Zengo, K., Ruel, J., et al. 2017, *ApJ*, **837**, 88
 Bleem, L. E., Bocquet, S., Stalder, B., et al. 2020, *ApJS*, **247**, 25
 Bleem, L. E., Stalder, B., de Haan, T., et al. 2015, *ApJS*, **216**, 27
 Bluck, A. F. L., Maiolino, R., Brownson, S., et al. 2022, *A&A*, **659**, A160
 Bode, P., Ostriker, J. P., Cen, R., et al. 2012, arXiv:1204.1762
 Boselli, A., Cortese, L., Boquien, M., et al. 2014a, *A&A*, **564**, A67
 Boselli, A., Fossati, M., & Sun, M. 2022, *A&ARv*, **30**, 3
 Boselli, A., Gavazzi, G., Donas, J., et al. 2001, *AJ*, **121**, 753
 Boselli, A., Roehly, Y., Fossati, M., et al. 2016, *A&A*, **596**, A11
 Boselli, A., Voyer, E., Boissier, S., et al. 2014b, *A&A*, **570**, A69
 Bruzual, A. G. 1983, *ApJ*, **273**, 105
 Bruzual, G., & Charlot, S. 2003, *MNRAS*, **344**, 1000
 Bulbul, E., Chiu, I.-N., Mohr, J. J., et al. 2019, *ApJ*, **871**, 50
 Byrd, G., & Valtonen, M. 1990, *ApJ*, **350**, 89
 Capasso, R., Saro, A., Mohr, J. J., et al. 2019, *MNRAS*, **482**, 1043
 Choi, E., Ostriker, J. P., Naab, T., et al. 2015, *MNRAS*, **449**, 4105
 Chung, A., van Gorkom, J. H., Kenney, J. D. P., et al. 2009, *AJ*, **138**, 1741
 Coenda, V., de los Rios, M., Muriel, H., et al. 2022, *MNRAS*, **510**, 1934
 Cortese, L., Bekki, K., Boselli, A., et al. 2016, *MNRAS*, **459**, 3574
 Cortese, L., Catinella, B., & Smith, R. 2021, *PASA*, **38**, e035
 Crowl, H. H., & Kenney, J. D. P. 2008, *AJ*, **136**, 1623
 Dekel, A., & Birnboim, Y. 2006, *MNRAS*, **368**, 2
 Dressler, A. 1980, *ApJ*, **236**, 351
 Ebeling, H., Stephenson, L. N., & Edge, A. C. 2014, *ApJL*, **781**, L40
 Ettori, S., & Balestra, I. 2009, *A&A*, **496**, 343
 Fagotto, F., Bressan, A., Bertelli, G., et al. 1994, *A&AS*, **104**, 365
 Fakhouri, G., Ma, C.-P., & Boylan-Kolchin, M. 2010, *MNRAS*, **406**, 2267
 Fujita, Y. 2004, *PASJ*, **56**, 29
 Fumagalli, M., Krumholz, M. R., Prochaska, J. X., et al. 2009, *ApJ*, **697**, 1811
 Gallazzi, A. R., Pasquali, A., Zibetti, S., et al. 2021, *MNRAS*, **502**, 4457
 Gavazzi, G., Consolandi, G., Gutierrez, M. L., et al. 2018, *A&A*, **618**, A130
 Gavazzi, G., & Scodreggio, M. 1996, *A&A*, **312**, L29
 Geller, M. J., Hwang, H. S., Fabricant, D. G., et al. 2014, *ApJS*, **213**, 35
 Gilbank, D. G., Gladders, M. D., Yee, H. K. C., et al. 2011, *AJ*, **141**, 94
 Gill, S. P. D., Knebe, A., & Gibson, B. K. 2005, *MNRAS*, **356**, 1327
 Gunn, J. E., & Gott, J. R. 1972, *ApJ*, **176**, 1
 Haines, C. P., Iovino, A., Krywult, J., et al. 2017, *A&A*, **605**, A4
 Haines, C. P., Pereira, M. J., Sanderson, A. J. R., et al. 2012, *ApJ*, **754**, 97
 Haines, C. P., Pereira, M. J., Smith, G. P., et al. 2015, *ApJ*, **806**, 101
 Hamilton, D. 1985, *ApJ*, **297**, 371
 Han, S., Smith, R., Choi, H., et al. 2018, *ApJ*, **866**, 78
 Hasselfield, M., Hilton, M., Marriage, T. A., et al. 2013, *JCAP*, **2013**, 008
 Hennig, C., Mohr, J. J., Zenteno, A., et al. 2017, *MNRAS*, **467**, 4015
 Hernán-Caballero, A., Alonso-Herrero, A., Pérez-González, P. G., et al. 2013, *MNRAS*, **434**, 2136
 Hernández-Fernández, J. D., Haines, C. P., Diaferio, A., et al. 2014, *MNRAS*, **438**, 2186
 High, F. W., Stalder, B., Song, J., et al. 2010, *ApJ*, **723**, 1736
 Hilton, M., Hasselfield, M., Sifón, C., et al. 2018, *ApJS*, **235**, 20
 Jaffé, Y. L., Poggianti, B. M., Moretti, A., et al. 2018, *MNRAS*, **476**, 4753
 Jaffé, Y. L., Smith, R., Candlish, G. N., et al. 2015, *MNRAS*, **448**, 1715
 Janz, J., Salo, H., Su, A. H., et al. 2021, *A&A*, **647**, A80
 Jung, S. L., Choi, H., Wong, O. I., et al. 2018, *ApJ*, **865**, 156
 Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, *MNRAS*, **341**, 33
 Kauffmann, G., White, S. D. M., Heckman, T. M., et al. 2004, *MNRAS*, **353**, 713
 Kawinwanichakij, L., Papovich, C., Quadri, R. F., et al. 2017, *ApJ*, **847**, 134
 Kelkar, K., Gray, M. E., Aragón-Salamanca, A., et al. 2019, *MNRAS*, **486**, 868
 Kenney, J. D. P., van Gorkom, J. H., & Vollmer, B. 2004, *AJ*, **127**, 3361
 Khullar, G., Bayliss, M. B., Gladders, M. D., et al. 2021, *ApJ*, **934**, 177
 Kim, K., Malhotra, S., Rhoads, G. N., et al. 2018, *ApJ*, **867**, 118
 Kim, K., Oh, S., Jeong, H., et al. 2016, *ApJS*, **225**, 6
 Larson, R. B., Tinsley, B. M., & Caldwell, C. N. 1980, *ApJ*, **237**, 692
 Lee, B., & Chung, A. 2018, *ApJL*, **866**, L10
 Lee, B., Wang, J., Chung, A., et al. 2022, *ApJS*, **262**, 31
 Liu, Q., Yee, H. K. C., Drissen, L., et al. 2021, *ApJ*, **908**, 228
 Longobardi, A., Boselli, A., Fossati, M., et al. 2020, *A&A*, **644**, A161
 Loni, A., Serra, P., Kleiner, D., et al. 2021, *A&A*, **648**, A31
 Mahajan, S., Mamon, G. A., & Raychaudhury, S. 2011, *MNRAS*, **416**, 2882
 Mamon, G. A., Sanchis, T., Salvador-Solé, E., et al. 2004, *A&A*, **414**, 445
 Marriage, T. A., Acquaviva, V., Ade, P. A. R., et al. 2011, *ApJ*, **737**, 61
 Matharu, J., Muzzin, A., Brammer, G. B., et al. 2021, *ApJ*, **923**, 222
 McDonald, M., Benson, B. A., Vikhlinin, A., et al. 2014, *ApJ*, **794**, 67
 McGaugh, S. S., & Schombert, J. M. 2014, *AJ*, **148**, 77
 Moore, B., Katz, N., Lake, G., et al. 1996, *Natur*, **379**, 613
 Morokuma-Matsui, K., Kodama, T., Morokuma, T., et al. 2021, *ApJ*, **914**, 145
 Muzzin, A., van der Burg, R. F. J., McGee, S. L., et al. 2014, *ApJ*, **796**, 65
 Muzzin, A., Wilson, G., Yee, H. K. C., et al. 2012, *ApJ*, **746**, 188
 Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, *ApJ*, **462**, 563
 Noble, A. G., Webb, T. M. A., Muzzin, A., et al. 2013, *ApJ*, **768**, 118
 Noble, A. G., Webb, T. M. A., Yee, H. K. C., et al. 2016, *ApJ*, **816**, 48

- Noordeh, E., Canning, R. E. A., Willis, J. P., et al. 2021, *MNRAS*, **507**, 5272
- Oh, S., Kim, K., Lee, J. H., et al. 2018, *ApJS*, **237**, 14
- Oman, K. A., Bahé, Y. M., Healy, J., et al. 2021, *MNRAS*, **501**, 5073
- Oman, K. A., & Hudson, M. J. 2016, *MNRAS*, **463**, 3083
- Oman, K. A., Hudson, M. J., & Behroozi, P. S. 2013, *MNRAS*, **431**, 2307
- Pandya, V., Brennan, R., Somerville, R. S., et al. 2017, *MNRAS*, **472**, 2054
- Park, C., & Hwang, H. S. 2009, *ApJ*, **699**, 1595
- Pasquali, A., Smith, R., Gallazzi, A., et al. 2019, *MNRAS*, **484**, 1702
- Paulino-Afonso, A., Sobral, D., Darvish, B., et al. 2020, *A&A*, **633**, A70
- Peng, Y.-J., Lilly, S. J., Kovač, K., et al. 2010, *ApJ*, **721**, 193
- Pintos-Castro, J., Yee, H. K. C., Muzzin, A., et al. 2019, *ApJ*, **876**, 40
- Reeves, A. M. M., Balogh, M. L., van der Burg, R. F. J., et al. 2021, *MNRAS*, **506**, 3364
- Reeves, A. M. M., Hudson, M. J., & Oman, K. A. 2023, *MNRAS*, **522**, 1779
- Reichardt, C. L., Stalder, B., Bleem, L. E., et al. 2013, *ApJ*, **763**, 127
- Rhee, J., Smith, R., Choi, H., et al. 2017, *ApJ*, **843**, 128
- Rhee, J., Smith, R., Choi, H., et al. 2020, *ApJS*, **247**, 45
- Ruel, J., Bazin, G., Bayliss, M., et al. 2014, *ApJ*, **792**, 45
- Rykoff, E. S., Koester, B. P., Rozo, E., et al. 2012, *ApJ*, **746**, 178
- Salpeter, E. E. 1955, *ApJ*, **121**, 161
- Sampaio, V. M., de Carvalho, R. R., Ferreras, I., et al. 2021, *MNRAS*, **503**, 3065
- Shen, L., Lemaux, B. C., Lubin, L. M., et al. 2020, *MNRAS*, **494**, 5374
- Sifón, C., Menanteau, F., Hasselfield, M., et al. 2013, *ApJ*, **772**, 25
- Smith, R., Pacifici, C., Pasquali, A., et al. 2019, *ApJ*, **876**, 145
- Smith, R. J., Lucey, J. R., Price, J., et al. 2012, *MNRAS*, **419**, 3167
- Sobral, D., Best, P. N., Smail, I., et al. 2014, *MNRAS*, **437**, 3516
- Sobral, D., van der Wel, A., Bezanson, R., et al. 2022, *ApJ*, **926**, 117
- Stalder, B., Stark, A. A., Amato, S. M., et al. 2014, *Proc. SPIE*, **9147**, 91473Y
- Strazzullo, V., Gobat, R., Daddi, E., et al. 2013, *ApJ*, **772**, 118
- Strazzullo, V., Pannella, M., Mohr, J. J., et al. 2019, *A&A*, **622**, A117
- Sunyaev, R. A., & Zeldovich, Y. B. 1972, *CoASP*, **4**, 173
- Tiley, A. L., Vaughan, S. P., Stott, J. P., et al. 2020, *MNRAS*, **496**, 649
- Upadhyay, A. K., Oman, K. A., & Trager, S. C. 2021, *A&A*, **652**, A16
- Vanderlinde, K., Crawford, T. M., de Haan, T., et al. 2010, *ApJ*, **722**, 1180
- Vaughan, S. P., Tiley, A. L., Davies, R. L., et al. 2020, *MNRAS*, **496**, 3841
- Vollmer, B., Cayatte, V., Balkowski, C., et al. 2001, *ApJ*, **561**, 708
- Webb, K., Balogh, M. L., Leja, J., et al. 2020, *MNRAS*, **498**, 5317
- Werner, S. V., Hatch, N. A., Muzzin, A., et al. 2022, *MNRAS*, **510**, 674
- Wetzel, A. R., Tinker, J. L., Conroy, C., et al. 2013, *MNRAS*, **432**, 336
- Whitaker, K. E., van Dokkum, P. G., Brammer, G., et al. 2012, *ApJL*, **754**, L29
- Yoon, H., Chung, A., Smith, R., et al. 2017, *ApJ*, **838**, 81