

Stellar mass-metallicity relation throughout the large-scale of the Universe: CAVITY mother sample

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ABSTRACT

Context. Void galaxies are essential to understand the physical processes that drive galaxy evolution as they are less affected by external factors than galaxies in denser environments, i.e. filaments, walls, and clusters. The stellar metallicity of a galaxy traces the accumulated fossil record of star formation through its entire life. Comparing the stellar metallicity of galaxies in various environments, including voids, filaments, walls, and clusters, can provide valuable insights into how the large-scale environment impacts galaxy chemical evolution.

Aims. We present the first comparison of the total stellar mass vs. central stellar metallicity relation between galaxies in voids, filaments, walls, and clusters with different star formation history (SFH) types, morphologies, and colours, for stellar masses between $10^{8.0}$ to $10^{11.5}$ solar masses and redshift $0.01 < z < 0.05$. We aim to better understand how the large-scale structure affects galaxy evolution by studying the stellar mass-metallicity relation of thousands of galaxies, which allows us to make a statistically sound comparison between galaxies in voids, filaments, walls, and clusters.

Methods. We apply non-parametric full spectral fitting techniques (pPXF and STECKMAP) to 10807 spectra from the SDSS-DR7 (987 in voids, 6463 in filaments and walls, and 3357 in clusters) and derive their central mass-weighted average stellar metallicity ($[M/H]_M$).

Results. We find that galaxies in voids have on average slightly lower stellar metallicities than galaxies in filaments and walls (by ~ 0.1 dex), and much lower than galaxies in clusters (by ~ 0.4 dex). These differences are more significant for low-mass ($\sim 10^{9.25} M_\odot$) than for high-mass galaxies, for long-timescale SFH (LT-SFH, extended along time) galaxies than for short-timescale SFHs (ST-SFH, concentrated at early times) galaxies, for spiral than for elliptical galaxies, and for blue than for red galaxies.

Key words. Galaxy: evolution, (Cosmology:) large-scale structure of Universe

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1. Introduction

The distribution of galaxies in the Universe forms a web-like structure with over-dense clusters, elongated filaments, sheetlike walls, and under-dense voids. This structure is shown by large redshift galaxy surveys such as the Sloan Digital Sky Survey (SDSS, York et al. 2000), the 2dF Galaxy Redshift Survey (2dFGRS, Colless et al. 2001), or the 2MASS Redshift Survey (2MRS, Huchra et al. 2012). Voids occupy large volumes (from 10 to 30 h^{-1} Mpc in diameter) with a low number density of galaxies (density contrast $\delta = \delta\rho/\rho \lesssim -0.8$, where ρ is the average density of the Universe, Peebles 2001; Kreckel

et al. 2011, 2012; Pan et al. 2012; Varela et al. 2012; van de Weygaert 2016). Galaxies in voids are less affected by an intense gravitational potential and local processes than galaxies in filaments, walls and clusters. These local processes include mergers or tidal interactions with other galaxies, as well as hydro-dynamical interactions between the intracluster medium (ICM) and the interstellar medium (ISM), such as ram pressure stripping (Boselli & Gavazzi 2006). This makes voids a good probe to study the importance of internal processes in galaxy evolution.

Previous studies have shown that galaxies in voids are on average bluer, less massive, have later morphological types, and higher specific star formation rates (SFR) than galaxies in denser environments (Rojas et al. 2004; Park et al. 2007; Hoyle et al. 2012; Kreckel et al. 2012; Florez et al. 2021). However, there is no consensus about SFR differences for a given stellar mass, luminosity, or morphology. Some studies have found that void galaxies have an enhanced SFR for a given stellar mass (Rojas et al. 2005; Beygu et al. 2016; Florez et al. 2021) but others did not find any significant difference (Patiri et al. 2006; Kreckel et al. 2012; Ricciardelli et al. 2014; Domínguez-Gómez et al. 2022). Additionally, Porter et al. (2023) have recently found that at low redshift ($z < 0.075$) the fraction of late-type galaxies is higher in voids than in the field but these differences are not conclusive at higher redshifts ($0.075 < z < 0.150$).

In our recent work (Domínguez-Gómez et al. 2023) we have compared the star formation histories (SFHs, as derived from a full-spectral fitting of the central parts) between galaxies located in different large-scale environments, and we have found that galaxies in voids assemble their stellar mass slower than galaxies in filaments, walls, and clusters. Several physical processes might be responsible for these differences: the different gas accretion modes that dominate in each large-scale environment (Kereš et al. 2005), the lack of atomic hydrogen that might be present in void galaxies (Kreckel et al. 2012; Domínguez-Gómez et al. 2022; Rosas-Guevara et al. 2022), their higher halo-to-stellar mass ratio (Artale et al. 2018; Alfaro et al. 2020; Habouzit et al. 2020; Rosas-Guevara et al. 2022), their higher fraction of active galactic nuclei (AGNs, Mishra et al. 2021; Ceccarelli et al. 2022), their higher fraction of massive black holes (BHs, Constantin et al. 2008), and their lower local density (Kuutma et al. 2020).

There are numerous studies about the gas-phase mass-metallicity relation ($MZ_g R$), which only consider star forming galaxies, but only a few studies focus on the stellar mass-metallicity relation ($MZ_\star R$), which also consider quenched galaxies. The gas metallicity is largely affected by the current star formation (Salim et al. 2014; Duarte Puertas et al. 2022) but the stellar metallicity traces the accumulated fossil record of the galaxy's star formation through its entire life. The comparison of the $MZ_\star R$ between galaxies in voids, filaments, walls and clusters will help us to better understand how the large-scale environment affects the galaxy evolution.

Some studies have compared the $MZ_\star R$ between different large-scale environments, but there is no consensus about the metallicity properties in void galaxies. Pustilnik et al. (2011) found that dwarf void galaxies (absolute B-band magnitude, $-18.4 < M_B < -11.9$) have around 30% lower gas metallicity than galaxies in denser large-scale environments, but Kreckel et al. (2015) did not find any significant difference between dwarf galaxies in different large-scale environments. Wegner & Grogin (2008) found tentatively lower gas-phase metallicities in early-type void galaxies, but Wegner et al. (2019) did not find any significant gas-phase metallicity difference between star-forming galaxies in voids and galaxies in denser large-scale environments. However, the robustness of these results is hampered by the low number of galaxies (20, 8, 26, and 33, respectively) not allowing strong conclusions. Additionally, Panter et al. (2008) have shown that the gas-phase metallicity of cluster galaxies increases with their environmental density.

Other studies have analysed the effect of the local environment in the gas-phase chemical abundance of galaxies. Pasquali et al. (2012) found that satellite galaxies have higher gas-phase metallicities than central galaxies with the same stellar

mass, more significantly at low than at high stellar masses, with maximum differences (by ~ 0.06 dex) at $M_\star \sim 10^{8.25} M_\odot$. Additionally, at a fixed stellar mass, the gas-phase metallicity of satellite galaxies increase with the halo mass (M_h) of the group, also more significantly for low-mass galaxies, with maximum differences (by ~ 0.15 dex) at $M_\star \sim 10^9 M_\odot$ inside the range $10^{11} < M_h/M_\odot < 10^{14}$. Deng (2011) found that star-forming galaxies with high ($-22.5 \leq M_r \leq -20.5$) and low luminosities ($-20.5 \leq M_r \leq -18.5$) have higher oxygen abundances in regions with higher local densities. Pilyugin et al. (2017) found that late-type galaxies with higher local densities have higher oxygen (by ~ 0.05 dex) and nitrogen (by ~ 0.1 dex) abundances. This effect is more significant for low-mass than for high-mass galaxies. They derived the local density as the number of neighbours inside five different projected distances: $R_0 = 1, 2, 3, 4$, and 5 Mpc but they did not compare galaxies in different large-scale structures such as voids, filaments, walls and clusters. They also found that regions with the highest local ($R_0 = 1$ Mpc) densities are not necessarily associated with the highest large-scale ($R_0 = 5$ Mpc) densities, which supports that high local densities are also found in voids. This confirms that local and large-scale environments are not the same, and further comparisons are needed between galaxies in voids, filaments, walls and clusters.

A few studies have analysed how the stellar metallicity of galaxies is affected by their local environment but little is known about the effect of the large-scale environment. Gallazzi et al. (2021) found that the stellar metallicity of cluster galaxies increases with the halo mass but they did not compare with void galaxies. Pasquali et al. (2010) found that satellite galaxies have higher stellar metallicities than central galaxies with the same stellar mass. Additionally, the $MZ_\star R$ is shallower in systems with more massive halos because the stellar metallicity of low-mass satellite galaxies increase with the halo mass of the system. These findings prove that the local environment of the galaxies affects the chemical evolution of their stars but the effect of their large-scale environment remains unknown.

In this paper we compare for the first time the $MZ_\star R$ between thousands of galaxies in voids, filaments, walls, and clusters. This study is linked to the Calar Alto Void Integral-field Treasury survey (CAVITY¹) project, which is an integral-field unit (IFU) legacy survey for void galaxies. It aims to observe around 300 galaxies with the PMAS-PPAK IFU of the Centro Astronómico Hispano en Andalucía (CAHA) together with ancillary deep imaging, HI, and CO data (Pérez et al. in prep.) to study the spatially resolved stellar populations, gas properties, and kinematics of void galaxies. As a complementary and preparatory study of this project, we derive here the average stellar metallicity of the void galaxy mother sample of CAVITY, and compare with galaxies in filaments, walls, and clusters. We apply non-parametric full spectral fitting techniques to the integrated optical spectra in the centre of the galaxies, which are already available in the SDSS, to obtain the stellar populations and metallicities.

This paper is organised in six sections and five appendices. In Section 2 we present the void galaxies and control samples of the study. In Section 3 we describe analysis to obtain the stellar metallicities. In Section 4 we compare the $MZ_\star R$ between galaxies in different large-scale environments for different SFH types, morphology and colours. In Section 5 we discuss our results and compare with previous studies. In Section 6 we summarise our conclusions. In Appendix A we

¹ <https://cavity.caha.es/>

extend our study to galaxy samples with the same stellar mass distribution. In Appendix B we check if our results remain for volume-limited sub-samples with redshifts between 0.01 and 0.03. In Appendix C we analyse if there is any sample selection effect due to our signal-to-noise cut. In Appendix D we show similar results for the luminosity-weighted metallicities. In Appendix E we present the tables with our $MZ_{\star}R$ results.

2. Sample

We use the samples of galaxies defined in our previous work (Domínguez-Gómez et al. 2023), which have been extracted from the spectroscopic catalogue of the SDSS-DR7 with redshifts $0.01 < z < 0.05$. We select as mother sample of void galaxies in our study the mother sample of the CAVITY project, with 2529 galaxies (see Section 2.1). Our mother control sample is made of 6189 galaxies in clusters from Tempel et al. (2017), and 15000 galaxies in filaments and walls as they belong neither to voids nor to clusters (see Section 2.2). We consider that filaments and walls belong to the same large-scale environment (filaments & walls here after) as the number density of galaxies is very similar. After applying the spectral analysis (see Section 3) to these galaxies we carry out a quality control (see Section 3.1) and remove from the mother samples those galaxies with low quality spectra (signal-to-noise $S/N < 20$), leaving us with 987 galaxies in voids, 6463 in filaments & walls, and 3357 in clusters for our study. Additionally, in Appendix A we define three sub-samples with the same total stellar mass distribution as our sample of void galaxies by applying the Kolmogorov-Smirnov test. The total stellar masses of the galaxies are obtained from the Max-Planck-Institut für Astrophysik and Johns Hopkins University database (MPA-JHU, Kauffmann et al. 2003; Salim et al. 2007). All these samples are magnitude-limited due to the SDSS completeness limit at r -Petrosian < 17.77 mag (Strauss et al. 2002; Argudo-Fernández et al. 2015).

2.1. Calar Alto Void Integral-field Treasury survey

The mother sample of the CAVITY comprises 2529 galaxies, which form a sub-sample of the Pan et al. (2012) catalogue of SDSS void galaxies. Pan et al. (2012) applied the VoidFinder algorithm (El-Ad & Piran 1997; Hoyle & Vogeley 2002) to the distribution of SDSS galaxies with redshifts $z < 0.107$, and found 79947 void galaxies inside 1055 cosmic voids with typical density contrast $\delta = -0.94 \pm 0.03$ and radii larger than $10 \text{ h}^{-1} \text{ Mpc}$. The CAVITY collaboration (Pérez et al. in prep.) reduced the redshift range ($0.01 < z < 0.05$) to concentrate on nearby galaxies that are observable with PMAS-PPAK; chose 15 voids with more than 20 galaxies each to observe around 300 galaxies distributed along the entire right ascension range of the SDSS; and selected galaxies in the inner region of the voids (i.e., inside the 80% of the void's effective radius) to avoid the possible inclusion of galaxies that are inhabiting or affected by denser environments. Additionally, the CAVITY collaboration carried out a visual inspection of the galaxies, and removed from the sample the duplicated objects, and the spectra integrated in HII regions, not in the centre of the galaxy.

2.2. Control samples

The aim of this study is to compare the stellar metallicities between galaxies in voids and galaxies in denser environments.

Therefore, we define two control samples: one of galaxies in clusters, and the other one of galaxies in filaments & walls. The mother sample of galaxies in clusters is extracted from the Tempel et al. (2017) catalogue of groups of SDSS galaxies within the same redshift range as the CAVITY mother sample. Galaxies in groups with ≥ 30 members are selected as cluster galaxies (Abell et al. 1989, see Appendix B for some discussions on how this criterium might affect our results). With these selection criteria, our mother sample of cluster galaxies contains 6189 galaxies.

The mother sample of galaxies in filaments & walls in this study is extracted from all the SDSS galaxies within the same redshift range as the mother sample of CAVITY that are neither in the complete catalogue of void galaxies of Pan et al. (2012) nor in the mother sample of cluster galaxies defined above. To save computational time, we select a sub-sample of 15000 galaxies in filaments & walls preserving similar stellar mass, $g - r$ colour, and redshift distributions (two sample Kolmogorov-Smirnov test with p-values > 0.95) than the original sample of galaxies in filaments & walls directly extracted from SDSS.

3. Data analysis

In Domínguez-Gómez et al. (2023) we carried out a non-parametric full spectral fitting analysis to derive the stellar populations and compare the star formation histories of galaxies in voids, filaments & walls, and clusters. Now, in this study we compare the stellar metallicities of these three galaxy samples (see Section 2) using the same stellar populations. This spectral analysis recovers the stellar line-of-sight velocity distribution (LOSVD), gas emission lines, and generates a combination of stellar population models that best fit the observed spectra of the galaxies in a wavelength range from 3750 to 5450 Å, in which the most relevant absorption lines of the stars are located. From this combination of models we can estimate the mass, age, and metallicity of the stars within the galaxies.

For the analysed data we use optical spectra from the SDSS-DR7 (Abazajian et al. 2009) integrated (fibre aperture with 3 arcsec diameter) in the very centre of the galaxies (from 0.3 to 1.6 kpc in the redshift range of $0.01 < z < 0.05$) observed at the Apache Point Observatory (APO) 2.5 m telescope. We use the stellar models of the Extended Medium resolution INT Library of Empirical Spectra (E-MILES, Sánchez-Blázquez et al. 2006; Falcón-Barroso et al. 2011; Vazdekis et al. 2015, 2016), which are single-age and single-metallicity stellar population (SSP) spectral templates generated assuming the BaSTI isochrones (Pietrinferni et al. 2004) and Kroupa universal initial mass function (IMF, Kroupa 2001). With the Penalized Pixel-Fitting (pPXF, Cappellari & Emsellem 2004; Cappellari 2017, 2022) algorithm we generate a combination of stellar population models (E-MILES SSPs) and pure Gaussian emission line templates that best fit the observed spectra of the galaxies, recovering the stellar LOSVD and gas emission. The gas emission obtained by pPXF is subtracted from the observed spectrum of the galaxy to obtain a clean spectrum with only the emission from the stars. Afterwards we apply the STELLar Content and Kinematics from high resolution galactic spectra via Maximum A Posteriori algorithm (STECKMAP, Ocvirk et al. 2006b,a) to recover the stellar populations (stellar mass, age, and metallicity) of a galaxy by fitting a combination of E-MILES SSPs (as for pPXF) to the clean spectrum of the galaxy (only emission from the stars), assuming a fixed stellar LOSVD (previously derived with pPXF). We estimate the errors

of the stellar populations (stellar mass, age and metallicity) as the standard deviation of five Monte Carlo iterations from STECKMAP. For each Monte Carlo solution, we use as input the observed spectrum plus a spectrum of noise with the same standard deviation in the continuum. With this method, we analyse different spectra with the same signal and the same level of noise, but different distribution the noise.

The recovered stellar populations are affected by the age-metallicity degeneracy of the stars (Worley 1994), and young metal-poor galaxies might have been classified as old metal-rich. This effect is due to the fact that old stars with low metallicities have similar spectra as young stars with high metallicities. Sánchez-Blázquez et al. (2011) analysed the effect of the age-metallicity degeneracy for STECKMAP using synthetic spectra of ages 1 and 10 Gyr and solar metallicity (0 dex), and compared with other spectral index techniques. It can be seen in their Figure 7 that the age-metallicity degeneracy effect is much more reduced in the case of STECKMAP (ages of $\sim 1.00 \pm 0.04$ Gyr and $\sim 11 \pm 1$ Gyr, respectively, and metallicities of $\sim 0.02 \pm 0.04$ dex) than in the case of spectral indices (ages of $\sim 1.0 \pm 0.1$ Gyr and $\sim 10 \pm 5$ Gyr, respectively, and metallicities of $\sim -0.1 \pm 0.2$ dex).

The stellar and gas migration may influence the central metallicities, especially if and when there is a bar in a galaxy. Previous studies found that the gas-phase metallicity (Ellison et al. 2011) and stellar metallicities (Pérez & Sánchez-Blázquez 2011) in the centre of barred galaxies are higher than those of unbarred galaxies, but Cacho et al. (2014) did not find significant difference on metallicity (neither gaseous nor stellar) between barred and unbarred galaxies. Nevertheless, there is no evidence whether the fraction of barred galaxies is different in voids compared to denser environments.

3.1. Quality control

The quality of the outcome of spectral fitting techniques is affected by the signal-to-noise ratio (S/N) in the continuum (6000 – 6100 Å, rest frame) and the intensity of the emission lines, among others. A good indicator of the quality of the spectral fit is the residual spectrum, which is the difference between the observed and fitted spectrum. If the residuals are high, it means that the observed spectrum is noisy, or the fitted spectrum is not a perfect match to the observed one. We remove from our sample a fraction of galaxies (61% in voids, 57% in filaments & walls, and 46% in clusters) with $S/N < 20^2$, for which the residuals are higher than 2% of the continuum level around H β . This selection by S/N removes from our samples mainly low-mass galaxies but we do not expect that it will introduce any bias in our sample as the mean stellar mass of the removed galaxies is similar in the three environments ($10^{9.2 \pm 0.1} M_\odot$ in voids, $10^{9.3 \pm 0.1} M_\odot$ in filaments & walls, and $10^{9.5 \pm 0.1} M_\odot$ in clusters). However, even after this cut, the stellar mass distribution of the three samples are different. To avoid any effect of the difference stellar mass distributions in our results, we compare in Section 4 the stellar metallicities for stellar mass bins of 0.5 dex width. However, the distributions may be still slightly different within each stellar mass bin. Therefore, in order to check that this does not introduce any effect in our analysis for a given stellar mass, we define in Appendix A three sub-samples with the same stellar mass distribution within each stellar mass bin by applying the Kolmogorov-Smirnov test, and analyse the

stellar metallicities of these sub-samples. In addition, we also compare in Appendix A the stellar metallicities for narrower stellar mass bins of 0.25 dex width. We find similar results to the ones derived from the entire sample and bins of 0.5 dex width.

Some galaxies have a high S/N (> 20) spectrum, and residuals lower than 2% of the continuum level but larger than the level of noise. This is due to a bad fit of the gas emission lines. The pPXF algorithm is not efficient in fitting wide or asymmetric emission lines and may leave wavy features in the clean spectrum that consequently affect the STECKMAP fit and lead to recover wrong stellar populations. We remove from our samples small fractions of galaxies (5% in voids, 8% in filaments & walls, and 7% in clusters) with a high S/N (> 20) spectrum and residuals twice higher than the level of noise over H β after subtracting the emission lines. After a careful visual inspection, we confirm that these galaxies have intense, wide, and asymmetric emission lines that pPXF is not able to fit properly. These small percentages of removed galaxies does not introduce any bias in our analysis.

The optical spectra from SDSS are integrated over the central region of the galaxies. This might introduce a bias for large redshift range galaxy samples where this aperture would cover a large fraction of remote galaxies but only the inner part of nearby ones. However, the redshift range of our samples is rather narrow (0.01 – 0.05), and their apparent size (r -Petrosian radius, R_{90r} , from SDSS) distributions are very similar for the three environments a(see Domínguez-Gómez et al. 2023, and Extended Data Figure 6 therein). In order to minimise a possible size effect in our study, we remove from our samples a small fraction (1% in voids, 4% in filaments & walls, and 5% in clusters) of galaxies with $R_{90r} > 20$ arcsec, for which the spectrum would be relatively more influenced by the fibre aperture. After this quality control we are left with 987 galaxies in voids, 6463 in filaments & walls, and 3357 in clusters, which are the samples of study in this work.

3.2. Averaged stellar metallicity

The stellar populations recovered by STECKMAP are characterised by their stellar mass, stellar age, and the metallicity of the gas from which the stars were formed, providing an estimation of the type of stars that currently form a galaxy. In the E-MILES models, the metallicity is defined as the fraction of metals (Z) normalised to the solar value ($Z_\odot = 0.0198$) as $[M/H] = \log_{10}(Z/Z_\odot)$. We can then derive the mass-weighted average stellar metallicity of the galaxy as:

$$[M/H]_M = \frac{\sum M_\star [M/H]_\star}{\sum M_\star} \quad (1)$$

where M_\star and $[M/H]_\star$ are the mass and metallicity of the stellar populations that form the galaxy, respectively, which are obtained through spectral fit. The BaSTI theoretical isochrones that are used by the E-MILES models cover the metallicity range $-2.27 \leq [M/H]_\star \leq 0.4$. We find that the stellar metallicity values of some galaxies saturate at the upper boundary of the stellar models. The central parts of the galaxies can be metal-rich, $0.30 < [M/H]_M < 0.47$ (González Delgado et al. 2015, see Section B therein), with values higher than the stellar models, leading to a saturation effect. In this work we derive the stellar metallicities of the centre (3 arcsec diameter) of nearby galaxies ($0.01 < z < 0.05$) using the integrated spectrum in the innermost regions of the galaxies (aperture from 0.3 to 1.6 kpc). For some galaxies, the stars in these inner regions are very metal

² We have tested that the results presented in this work are not contingent upon this S/N cut choice, see Appendix C for more details.

rich and the average stellar metallicity of the galaxy reach the limit of the stellar models.

This effect is also found by [Gallazzi et al. \(2005\)](#) (see Figure 8 therein). However, they obtain average metallicities that are lower than ours because they analyse a sample of galaxies with a wider redshift range ($0.005 < z < 0.22$) and the SDSS spectra that they use are integrated over more external regions of the galaxies, where the stars are metal-poorer than in the centre. In our results, the fraction of galaxies with this saturation issue in each stellar mass bin, SFH type, and environment is lower than 10%, except for filament & wall and cluster galaxies with short-timescale SFHs (see Sectio 3.3) at high stellar masses ($M_\star > 10^{10.5} M_\odot$), for which the fraction of saturated galaxies is around 20%. There is no saturation for void galaxies. The saturation effect is conservative as it reduces the average stellar metallicity of filament & wall and cluster massive galaxies but does not affect void galaxies, diluting the stellar metallicity differences that we find at high stellar masses (see Section 4).

3.3. Star formation histories

The metallicity of a galaxy is strongly influenced by its SFH ([Tantalo & Chiosi 2002](#)). A high star formation rate quickly enriches the ISM and the stars that will form from it. Therefore, the effect of the SFH has to be considered in our analysis of the stellar metallicities. We derived and discussed the SFHs in our previous work ([Domínguez-Gómez et al. 2023](#)) as the fraction of stellar mass that was formed at a given look-back time, which is based on the same spectral analysis. We found that the SFHs at early times describe a bimodal distribution in the three large-scale environments (see [Domínguez-Gómez et al. 2023](#), and Figure 2 therein for more details) that allowed us to classify the SFHs in two types: short-timescale SFH (ST-SFH) galaxies formed a large fraction of their stellar mass (on average 27%) ~ 12.5 Gyr ago and progressively reduced their star formation since then, while long-timescale SFH (LT-SFH) galaxies formed a lower fraction of their stellar mass (< 21.4%) than the ST-SFH galaxies 12.5 Gyr ago but formed stars more uniformly over time, see examples in Figure 1. By definition, ST-SFH galaxies formed their stellar mass earlier than LT-SFH galaxies, therefore this classification needs to be taken into account when comparing the SFHs between galaxies in different environments.

It is more likely for galaxies in voids to have a LT-SFH ($51.7 \pm 0.9\%$) than for galaxies in filaments & walls ($44.5 \pm 0.3\%$) and cluster ($36.1 \pm 0.5\%$). For a given SFH type, galaxies in voids, on average, formed their stars slower than in filaments & walls at intermediate stellar masses, and much slower than in clusters at any given stellar mass. The SFH differences between galaxies in the three large-scale environments might have affected the stellar metallicities diversely in voids, filaments & walls, and clusters. Therefore, in this work we analyse the effect of the large-scale environment on the stellar metallicities of the galaxies for different SFH types.

3.4. Morphology and colour

It might be intuitive to associate the ST-SFH type with red elliptical galaxies, and the LT-SFH type with blue spiral galaxies. However, the SFH type of a galaxy clearly correlates neither with its colour nor its morphology (see [Domínguez-Gómez et al. 2023](#), and Extended Data Figure 7 therein for more details). We then also analyse the $MZ_\star R$ for different morphologies and colours. We use the g and r dereddened magnitudes from SDSS

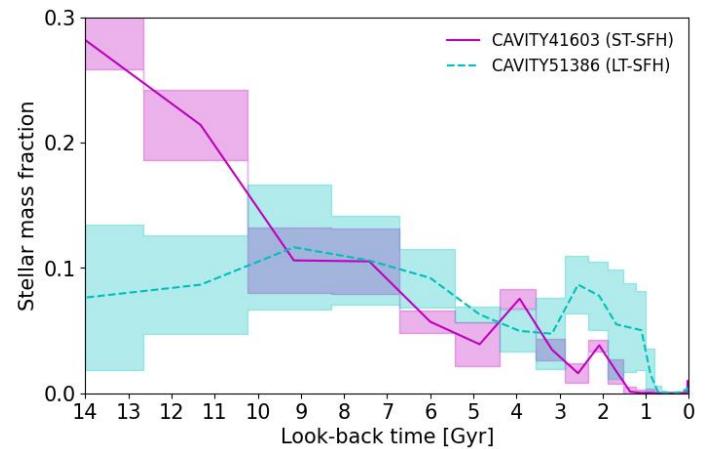


Fig. 1: Star formation history examples as the stellar mass fraction vs. the look-back time of galaxies CAVITY41603 (magenta solid line) and CAVITY51386 (cyan dashed line), which are examples of ST-SFH and LT-SFH, respectively. The shaded boxes represent the uncertainties of the stellar mass fraction of the galaxy associate to each SSP that is representative for ach look-back time bin. The lines represent the interpolation between the nominal values of the SSP mass fractions.

to define the colour of the galaxies as $g - r$, and the T-type parameter from [Domínguez Sánchez et al. \(2018\)](#) to characterise the morphology of the SDSS galaxies. We consider that galaxies with $T\text{-type} < 0$ are elliptical and galaxies with $T\text{-type} > 0$ are spiral ([Domínguez Sánchez et al. 2018](#)), and here we define galaxies with $g - r \leq 0.7$ mag as blue, and $g - r > 0.7$ mag as red. Note that the SDSS g and r magnitudes are integrated over the entire galaxy, but the stellar populations are recovered from the very centre of the galaxy, where the stars are redder than the average colour $g - r$ of the entire galaxy.

4. Results

4.1. Average stellar metallicity distribution

We show in Figure 2 the normalised distribution of $[M/H]_M$ for galaxies in voids (blue dashed line), filaments & walls (green dot-dashed line), and clusters (red solid line) at three total stellar mass bins. There are some small peaks at $[M/H]_M \sim 0.4$, which are produced by the saturation of our results at the metallicity upper limit of the E-MILES SSPs. The distributions exhibit a sharp cut-off at higher values (around 0.5) due to the broadening effect caused by the errors. We find that the stellar metallicity distribution is similar for galaxies in voids and galaxies in filaments & walls. However, cluster galaxies are distributed at much higher metallicities. These differences might be affected by their different stellar mass distributions and star formation history types. Void galaxies are on average less massive and form their stars slower than galaxies in denser environments ([Domínguez-Gómez et al. 2023](#)). We then carry out comparisons for different stellar mass bins, SFH types, morphologies, and colours.

4.2. Stellar mass effect

We show in Figure 3 (left column) the $MZ_\star R$ for all the galaxies regardless of their SFH type, in voids (first row), filaments & walls (second row), and clusters (third row). We define total

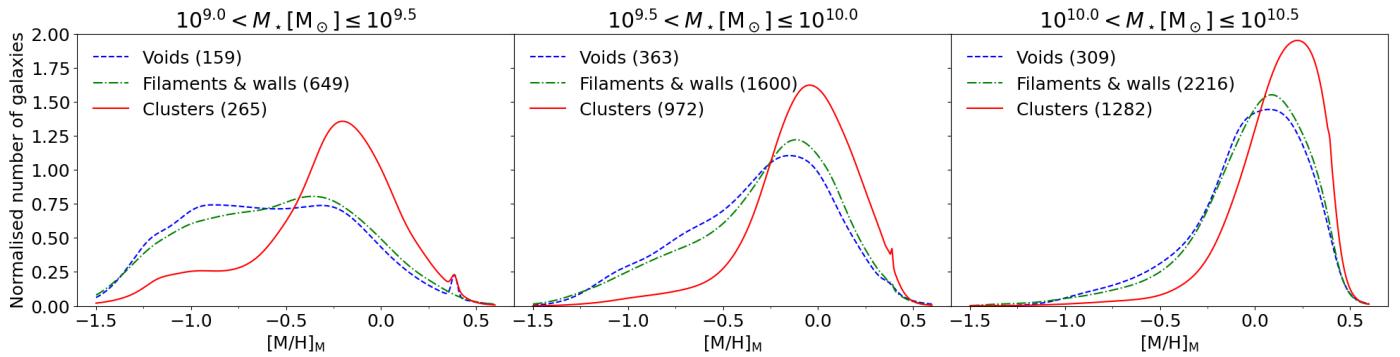


Fig. 2: Mass-weighted average stellar metallicity ($[M/H]_M$) distribution of our samples of galaxies in voids (blue dashed line), filaments & walls (green dot-dashed line), and clusters (red solid line) for three stellar mass bins as labelled. The number of galaxies in each sample is showed in the legend. The peaks at ~ 0.4 is due to the metallicity limit of the E-MILES stellar models. The distribution sharply ends at higher values (~ 0.5) than the limit due to the widening by the errors.

stellar mass bins of 0.5 dex from $10^{8.0}$ to $10^{11.5} M_\odot$, and obtain the $MZ_{\star}R$ (thick lines) as the 50th percentile of the distribution of galaxies inside each stellar mass bin. We estimate the error of the $MZ_{\star}R$ (shaded areas) as the standard error of the mean (s.e.m.) inside each stellar mass bin. Additionally, we calculate the 16th and the 84th percentiles (thin lines) to visualise the dispersion of values. We compare the $MZ_{\star}R$ between the three environments in the fourth row, together with the $MZ_{\star}R$ from Gallazzi et al. (2005) as a reference. In the fifth row we show the $MZ_{\star}R$ differences between galaxies in voids and filaments & walls, and also between galaxies in voids and clusters. In Table E.1 we report the 50th (together with the s.e.m.), 16th and the 84th percentiles of the $MZ_{\star}R$ for the different large-scale environments and SFH types. We report in Table E.2 the differences of the 50th percentile between voids and filaments & walls, and also between voids and clusters.

In the left column panels of Figure 3 we find that galaxies in voids have on average slightly lower stellar metallicities than galaxies in filaments & walls, and much lower than galaxies in clusters for any given stellar mass regardless of their star formation history type. These differences are more significant at low stellar masses than at high stellar masses, at which the difference might have been diluted by the effect of the metallicity saturation (see Section 3.2). The stellar metallicity in void galaxies is slightly lower than in filaments & walls by 0.108 ± 0.019 (5.7σ) at low stellar masses ($\sim 10^{9.25} M_\odot$) to 0.031 ± 0.009 (3.4σ) at intermediate stellar masses ($\sim 10^{10.25} M_\odot$). Void galaxies have lower stellar metallicities than cluster galaxies by 0.40 ± 0.02 (20.0σ) at low stellar masses ($\sim 10^{9.25} M_\odot$) to 0.084 ± 0.013 (6.5σ) at high stellar masses ($\sim 10^{10.75} M_\odot$). Our results at very low ($\sim 10^{8.25} M_\odot$) or very high ($\sim 10^{11.25} M_\odot$) stellar masses are not statistically significant due to the low number of galaxies in voids (4) and clusters (2). In our conclusions we only consider stellar mass bins with more than 10 galaxies.

The $MZ_{\star}R$ derived by Gallazzi et al. (2005) is in general below what we obtain. They derived the stellar metallicity from the SDSS-DR2 spectra in the centre (3 arcsec aperture) of 175128 galaxies. They use the same type of spectral data as we do in this paper. However, the redshift range of their galaxy sample ($0.005 < z < 0.22$) is much wider than ours ($0.01 < z < 0.05$). On average, the apparent size of their galaxies is smaller than ours. Therefore, the spectrum of their galaxies is integrated over more external regions, where the stellar populations are younger and metal-poorer. The spectra of our

galaxies are integrated in smaller regions from the centre, where the stars are older and metal-richer. At low stellar masses ($< 10^{9.5} M_\odot$) our $MZ_{\star}R$ is similar to theirs. This might be due to the completeness limit of the sample as the number of low-mass galaxies decreases with redshift. Therefore, the low-mass galaxies in their sample might be at similar redshifts as low-mass galaxies in our samples, and the aperture effect explained above is negligible.

4.3. Star formation history effect

In Figure 3 (centre and right columns panels) we show how the SFH type (ST-SFH and LT-SFH, respectively) of the galaxies affects the $MZ_{\star}R$ and compare galaxies in voids, filaments & walls, and clusters. We find that ST-SFH galaxies have higher stellar metallicities than LT-SFH galaxies for a given stellar mass in the three environments. This, together with the fact that it is more likely for galaxies in voids to have a LT-SFH ($51.7 \pm 0.9\%$) than for galaxies in filaments & walls ($44.5 \pm 0.3\%$) and cluster ($36.1 \pm 0.5\%$), can explain that void galaxies have on average slightly lower metallicities than galaxies in filaments & walls, and much lower than galaxies in clusters when we compare all the galaxies regardless of their SFH type in Figure 3 (left column panels).

We now analyse the stellar metallicity differences for two different SFH types. Galaxies with ST-SFHs have similar stellar metallicities (within the errors) in voids and filaments & walls, except for intermediate stellar masses ($\sim 10^{10.25} M_\odot$) where void galaxies have slightly lower stellar metallicities, by 0.035 ± 0.011 (3.2σ). Galaxies with ST-SFHs in voids have lower stellar metallicities than galaxies in clusters by 0.152 ± 0.011 (13.8σ) at $M_\star \sim 10^{10.25} M_\odot$ or by 0.063 ± 0.017 (3.7σ) at $M_\star \sim 10^{9.75} M_\odot$. Galaxies with LT-SFHs have similar stellar metallicities (within the errors) in voids and filaments & walls, except for low stellar masses ($\sim 10^{9.25} M_\odot$) where void galaxies have slightly lower stellar metallicities, by 0.104 ± 0.021 (5.0σ). Galaxies with LT-SFHs in voids have lower stellar metallicities than in clusters. These differences are more significant at low stellar masses ($\sim 10^{9.25} M_\odot$), by 0.419 ± 0.024 (17.5σ), than at high stellar masses ($\sim 10^{10.75} M_\odot$), by 0.11 ± 0.03 (3.7σ). The differences that we find for galaxies with LT-SFHs are similar to what we find for all the galaxies regardless of their SFH type in Figure 3 (left column panels). However, the differences that we find for galaxies with ST-SFHs are less significant. This means that the

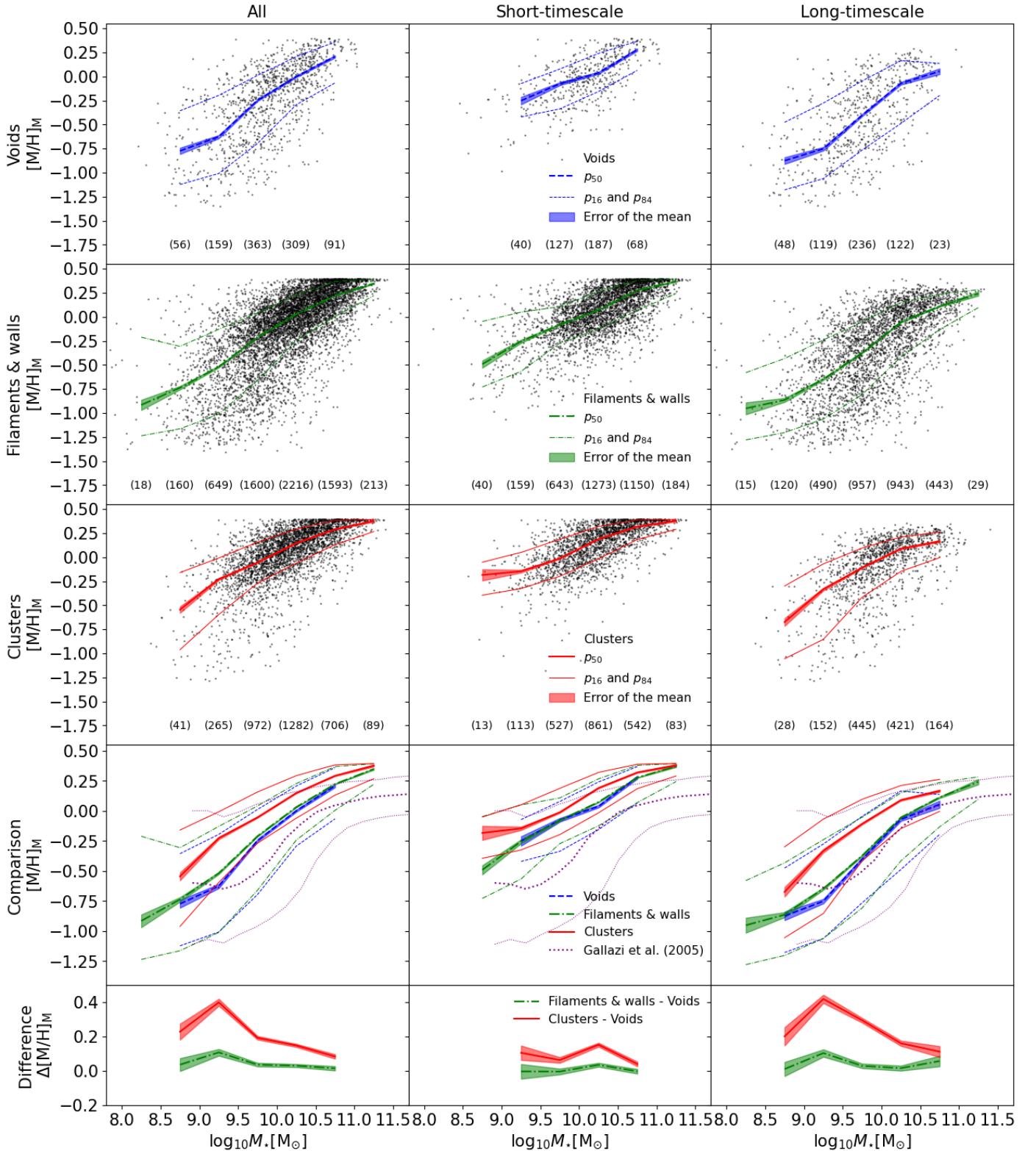


Fig. 3: Stellar mass-metallicity relation (MZR). Mass-weighted average stellar metallicity ($[M/H]_M$) as a function of the total stellar mass for the galaxies regardless of their SFH type (left column), galaxies with short-timescale star formation histories (ST-SFH, centre column), and galaxies with long-timescale star formation histories (LT-SFH, right column); in voids (first row), filaments & walls (second row), and clusters (third row). The MZR (blue dashed lines for voids, green dot-dashed lines for filaments & walls, and red solid lines for clusters) is derived as the 50th percentile (thick lines) inside each stellar mass bin of 0.5 dex. The number of galaxies inside each stellar mass bin is shown in brackets at the bottom of the panels. The shade areas represent the standard error of the mean (s.e.m.), and the 16th and 84th percentiles (thin lines) the dispersion of the MZR. The fourth row shows a comparison of the MZR between galaxies voids, filaments & walls, and clusters, together with the MZR from Gallazzi et al. (2005) as a reference. In the fifth row we show the differences of the MZR (lines), together with the error of the difference (shaded areas). See values reported in tables E.1 and E.2.

stellar metallicity differences that we find between galaxies in different environments, regardless of their SFH type, are mainly due to the galaxies with LT-SFHs, while the contribution of galaxies with ST-SFH is not significant.

4.4. Morphology effect

In Figure 4 (left and right columns panels) we analyse the $MZ_{\star}R$ for different morphological types (elliptical and spiral, respectively) and compare between galaxies in voids, filaments & walls, and clusters. Additionally, we report in tables E.3 and E.4 the percentiles (50th with the standard error of the mean (s.e.m.), 16th, and 84th) of the $MZ_{\star}R$, and the 50th percentile differences between galaxies located in the three large-scale environments. We find that elliptical galaxies have higher stellar metallicities than spiral galaxies in all environments and at all stellar masses. However, galaxies have similar stellar metallicities (within the errors) in voids and filaments & walls for the two morphological types and for any given stellar mass, except for intermediate stellar masses ($\sim 10^{9.75} M_{\odot}$) where void galaxies have slightly lower stellar metallicities, by 0.057 ± 0.017 (3.4σ) for elliptical galaxies and 0.071 ± 0.016 (4.4σ) for spiral galaxies. Void galaxies have lower stellar metallicities than cluster galaxies in the two morphological types. These differences are more significant at low stellar masses ($\sim 10^{9.25} M_{\odot}$), by 0.26 ± 0.04 (6.5σ) for elliptical galaxies and 0.27 ± 0.03 (9.0σ) for spiral galaxies, than at high stellar masses ($\sim 10^{10.25} M_{\odot}$), by 0.075 ± 0.012 (6.2σ) for elliptical galaxies and 0.077 ± 0.017 (4.5σ) for spiral galaxies.

The differences that we find for elliptical galaxies, and also for spiral galaxies, are similar to what we find for galaxies with LT-SFHs in Figure 3 (right column panels). This occurs more clearly for spiral than for elliptical galaxies. The stellar metallicity differences that we find between the three environments for spiral galaxies are similar to what we find for LT-SFHs due to the fraction of spiral galaxies with LT-SFHs (62.7% in voids, 56.5% in filaments & walls, 52.6% in clusters, see Domínguez-Gómez et al. (2023) and Extended Data Figure 7 therein). A similar effect happens for elliptical galaxies, which also have similar stellar metallicity differences between environments as LT-SFH galaxies, but much more diluted by the higher fraction of elliptical galaxies with ST-SFHs (56.8% in voids, 65.8% in filaments & walls, 70.9% in clusters).

4.5. Colour effect

In Figure 5 we analyse the relation between colour and the $MZ_{\star}R$, and compare galaxies in voids, filaments & walls, and clusters. The $MZ_{\star}R$ and their differences between environments are reported in table E.5 and E.6. We find that red galaxies (left column panels) have higher stellar metallicities than blue galaxies (right column panels) for a given stellar mass. However, galaxies have similar stellar metallicities (within the errors) in voids and filaments & walls for the two colours and for any given stellar mass, except for low stellar masses ($\sim 10^{9.25} M_{\odot}$) where blue galaxies in voids have slightly lower stellar metallicities than in filaments & walls by 0.091 ± 0.020 (4.5σ). Red galaxies in voids have slightly lower stellar metallicities than in clusters by 0.103 ± 0.016 (6.4σ) at intermediate stellar masses ($\sim 10^{9.75} M_{\odot}$) to 0.066 ± 0.013 (5.1σ) at high stellar masses ($\sim 10^{10.75} M_{\odot}$). Blue galaxies in voids have lower stellar metallicities than in clusters by 0.315 ± 0.023 (13.7σ)

at low stellar masses ($\sim 10^{9.25} M_{\odot}$) to 0.150 ± 0.015 (10.0σ) at intermediate stellar masses ($\sim 10^{9.75} M_{\odot}$).

The stellar metallicity differences of blue galaxies (see right column panels in Figure 5) look very similar to what we find for galaxies with LT-SFH (right column panels in Figure 3) but in a narrower stellar mass range. Blue galaxies in voids have lower stellar metallicities than in clusters for stellar masses between $10^{8.75} M_{\odot}$ and $10^{9.75} M_{\odot}$, for LT-SFHs galaxies these differences between voids and clusters remain up to $10^{10.25} M_{\odot}$. On the contrary, the stellar metallicity differences that we find for red galaxies are less significant, similar to what we find for ST-SFH. This happens because a high fraction of red galaxies have a ST-SFH and a high fraction of blue galaxies have a LT-SFH ($\sim 65 - 70\%$, see Domínguez-Gómez et al. 2023, and Extended Data Figure 7 therein).

The comparison of blue galaxies between different large-scale environments is not straightforward as the colour distribution is not the same. This also holds for the comparison of red galaxies. This means that a different criterion of classification between blue and red galaxies may change our results. However, in Figure A.6 we show the same as in Figure 5 but with the colour classification criterion at 0.6 instead of 0.7, for which the metallicity differences that we find are very similar.

5. Discussion

5.1. Stellar mass-metallicity relation

We see that the $MZ_{\star}R$ correlates with the large-scale environment, SFH type, morphology, and colour of the galaxies. The stellar metallicity of galaxies in voids is slightly lower than in filaments & walls at specific stellar mass bins, and much lower than in clusters at any given stellar mass. There are many works that study the $MZ_g R$ of galaxies and some of them even compare between different local (Deng 2011; Pasquali et al. 2012; Pilyugin et al. 2017), and large-scale environments (Wegner & Grogin 2008; Pustilnik et al. 2011; Kreckel et al. 2015; Wegner et al. 2019) but there is no consensus about the gas metallicity properties in void galaxies. However, only a few works study how the local environment affects the $MZ_{\star}R$, and none of them study how it is affected by the large-scale structures of the Universe.

Pasquali et al. (2010) and Gallazzi et al. (2021) studied the stellar populations of galaxies in groups and found that the stellar age and metallicity of central galaxies increases with the halo mass when they average for all stellar masses. However, Scholz-Díaz et al. (2022) found that this correlation is produced by the stellar-to-halo mass relation. The stellar age and metallicity of central galaxies actually decreases with the halo mass for a fixed stellar mass in low-mass halos ($< 10^{13.5} M_{\odot}$). This means that the lower stellar metallicities that we find for void galaxies might be due to their higher halo-to-stellar mass ratios compared to denser environments (Artale et al. 2018; Alfaro et al. 2020; Habouzit et al. 2020; Rosas-Guevara et al. 2022). However, they did not compare with void galaxies.

Kuutma et al. (2020) studied the effect of the local and the large-scale environment on the properties of galaxies in groups (i.e. from two to six galaxies); such as colour, stellar mass, morphology and the 4000 Å break. They compared galaxies inside (within a 1 Mpc radius from the filament axes) and outside the filament (within a 1 Mpc to 4 Mpc radius), and concluded that the effect of filaments on the properties of galaxies in groups is marginal, and the local environment is the main factor in determining their properties. However, the delimitation of

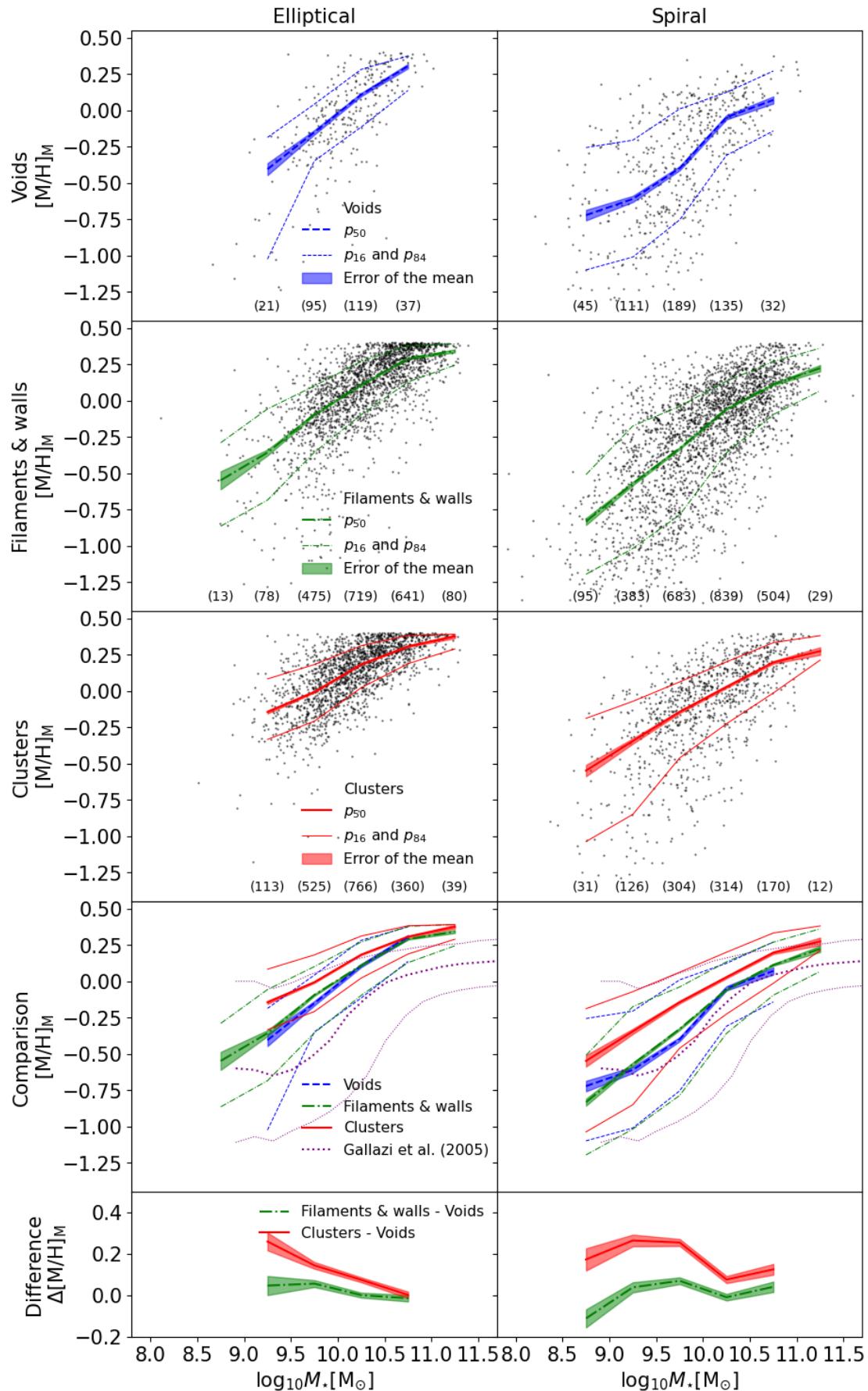


Fig. 4: Same as Figure 3 but for elliptical (left column) and spiral galaxies (right column). See values reported in tables E.3 and E.4.

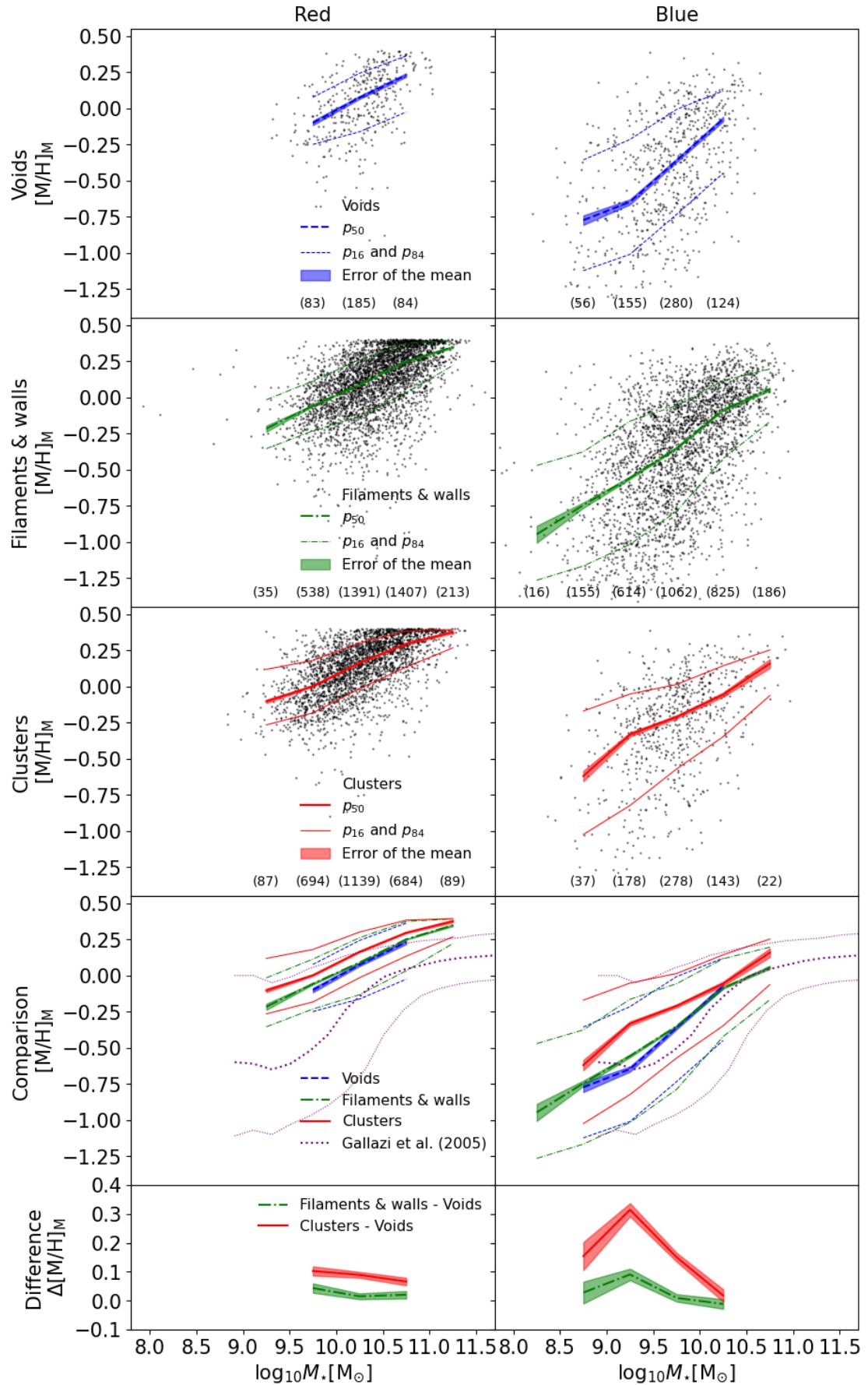


Fig. 5: Same as Figure 3 but for red (left column) and blue galaxies (right column). See values reported in tables E.5 and E.6.

voids within the large-scale structure of the Universe and the classification of void galaxies are not as easy as measuring their distance to the closest filament, and many of the galaxies outside the filament might be inside a wall, whose galaxies have similar properties as galaxies inside the filaments. Furthermore, they did not study the galaxies in the deepest regions of the voids, which may be located up to 15 Mpc from the closest filament. Clearly, the local density is, on average, lower in voids than in filaments, but both the local and large-scale environments, whether directly or indirectly, influence the properties of galaxies.

[Gallazzi et al. \(2021\)](#) found that the stellar metallicity of recent clusters/groups infallers (i.e., those galaxies that passed the virial radius of the host halo < 2.5 Gyr ago) is lower than that of those that have been exposed to the environment of clusters/groups for a longer time (> 2.5 Gyr). Recent infallers keep forming stars (although with lower rates) for ~ 2 Gyr after their infall ([Rhee et al. 2020](#), Figure 7 therein). The typical timescale of ram pressure stripping in clusters as massive as Virgo is < 1 Gyr, and ~ 2 Gyr for gas stripping due to tidal interactions ([Boselli & Gavazzi 2006](#)). This means that, for about 2 Gyr after falling into the cluster, the galaxies (recent infaller) still act as if they are in the previous host environment (i.e. voids or filaments & walls) with little changes in the SFR. [Gallazzi et al. \(2021\)](#) results would be in agreement with ours as they found that recent infallers (i.e. with void and filament & wall galaxy properties) have lower stellar metallicities compared to ancient infallers (with cluster galaxy properties).

It is well known that the metallicity of a galaxy is significantly determined by its SFH ([Tantalo & Chiosi 2002](#)), and this is reflected in our results. The stellar metallicity differences that we find for galaxies in different large-scale environments are much more significant for LT-SFH than for ST-SFH. ST-SFH galaxies formed a high fraction (~ 27%) of their stellar mass very early (more than 12.5 Gyr ago [Domínguez-Gómez et al. 2023](#)) enriching their ISM very quickly for the next generation of stars to be formed. Furthermore, they assembled 50% of their stellar mass at a similar time (~ 11 Gyr ago) in voids, filaments & walls, and clusters. This suggests that in the early Universe there was less contrast between the large-scale environments, which did not affect the evolution of the ST-SFH galaxies in the beginning but later, i.e. when they formed 70% of their stellar mass. Void galaxies assembled 70% of their stellar mass later than in filaments & walls (by ~ 1 Gyr) and much later than in clusters (by ~ 2 Gyr), more significantly at low ($10^{9.0} - 10^{9.5} M_{\odot}$) than at high stellar masses ($10^{10.0} - 10^{10.5} M_{\odot}$).

LT-SFH galaxies have had a more steady SFHs, enriching their ISM slower, and possibly diluting their metallicity by metal-poor gas accretion. Moreover, LT-SFH galaxies have been affected by their large-scale environments since very early, assembling their stellar mass later in voids than in filaments & walls (at intermediate stellar masses, $10^{9.5} - 10^{10.0} M_{\odot}$, by ~ 1 Gyr), and much later than in clusters (at any given stellar mass by ~ 2 Gyr). This indicates that galaxies that had similar SFHs in the beginning (i.e. ST-SFH galaxies that assembled 50% of their stellar mass at similar times in the three environments) would have similar stellar metallicities now, even if their SFH differ later (assembling 70% of their stellar mass at different times). On the contrary, galaxies with different SFHs in the beginning (i.e. LT-SFH galaxies that assembled 50% of their stellar mass at different times in the three environments) would have different stellar metallicities now. Therefore, the mass-weighted stellar metallicity of a galaxy is mostly determined by its initial SFH period (old stars). We confirm this

in Figure 6a, where we show a direct correlation (blue arrow) in the mass-weighted stellar age-metallicity distribution. We derive the mass-weighted stellar age following the same recipe as for metallicity given in Equation 1.

[Gallazzi et al. \(2005\)](#) found an effect of the age-metallicity degeneracy as an anti-correlation for the oldest galaxies in the stellar age-metallicity distribution for luminosity-weighted ages and metallicities (see their figures 11 and 12). We do not find this anti-correlation for the mass-weighted average in Figure 6a. However, the comparison between luminosity-weighted and mass-weighted averages is not straightforward. We derive in Appendix D the $MZ_{\star}R$ applying the luminosity-weighted average, where we find similar results to what we find in Section 4 for the mass-weighted average. We show in Figure 6b the luminosity-weighted stellar age-metallicity distribution for our sample of galaxies and we recover a similar anti-correlation (red arrow) for the oldest galaxies. However, we keep having a direct correlation (blue arrow) for young galaxies. Void galaxies have assembled their mass on average slower than galaxies in denser environments (see [Domínguez-Gómez et al. 2023](#)), and their stellar populations are consequently younger than in filaments & walls, and clusters. This is in agreement with the lower stellar metallicities that we find for void galaxies.

We also show that the stellar metallicity differences that we find between different large-scale environments are more significant for blue spiral galaxies than for red elliptical galaxies. [Gallazzi et al. \(2005\)](#) found that, for a given stellar mass, early-type galaxies have on average older and more metal rich stellar populations than late-type galaxies. Red elliptical galaxies are more likely to be gas-poor quenched massive galaxies that have suffered high star formation bursts after galaxy-galaxy interactions or mergers, quickly enriching their ISM. They also suffer from internal feedback processes such as AGNs, supernovae, and stellar winds. Blue spiral galaxies are more likely to be gas-rich star-forming galaxies with less chances to have suffered mergers in the past, preserving their metal-poor surrounding gas, and enriching their ISM slower than red elliptical galaxies. Void galaxies are on average bluer and have later morphological types than in denser environments, fulfilling the expectations of finding lower stellar metallicities in void galaxies.

5.2. Scatter around the gas-phase mass-metallicity relation

As very little is known about the correlation between the $MZ_{\star}R$ and the large-scale environment we compare our results with previous studies about the gas-phase metallicity. It is not obvious to directly compare the $MZ_{\star}R$ with studies focusing on the MZ_gR as this procedure only takes into account star-forming galaxies (with gas emission lines) but we also consider quenched galaxies (without gas emission lines). We can only refer to blue and spiral (i.e. star-forming) galaxies of our sample (right columns panels in figures 4 and 5, respectively) when comparing our $MZ_{\star}R$ results with the MZ_gR . Additionally, previous studies ([Gallazzi et al. 2005](#); [Panter et al. 2008](#); [Zahid et al. 2017](#)) have shown that the stellar metallicity correlates with the gas-phase metallicity when considering young stellar populations or the luminosity-weighted average stellar metallicity. We show in Appendix D the $MZ_{\star}R$ applying the luminosity-weighted average, where we find similar results to what we find in Section 4 for the mass-weighted average of blue and spiral galaxies. Blue and spiral galaxies in voids have lower stellar metallicities than in filaments & walls and much lower than in clusters, and the differences are more significant at low than at

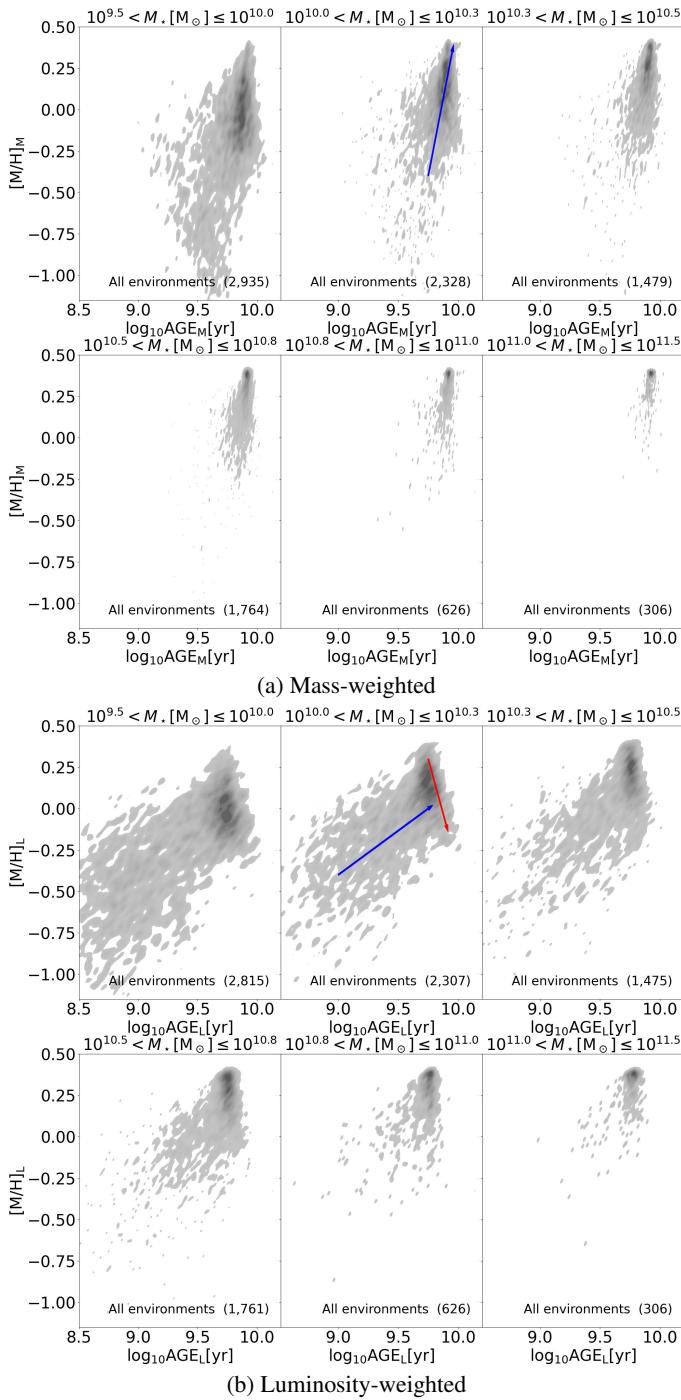


Fig. 6: Stellar age-metallicity distribution for several stellar mass ranges. The stellar metallicities and ages of the galaxies are derived as the mass-weighted (a) and luminosity-weighted (b) averages. The arrows visually illustrate the age-metallicity correlation (blue arrows) and anti-correlation (red arrow).

high stellar mass. Thus, we assume that it is fair to compare our mass-weighted $MZ_{\star}R$ for blue spiral galaxies with the MZ_gR results in the literature, and interpret our differences in the $MZ_{\star}R$ for different large-scale environments as a scatter around the main MZ_gR , associated with the halo mass of the galaxies, gas accretion, and gas feedback.

IllustrisTNG simulation (Torrey et al. 2019) shows that the scatter in the MZ_gR correlates with the ISM-to-stellar mass ratio

(M_{ISM}/M_{\star}) and the SFR. High SFRs or low M_{ISM}/M_{\star} ratios increase the gas metallicity of star forming galaxies. That would imply that the higher stellar metallicity that we find for the blue and spiral galaxies in clusters is driven by a lower M_{ISM}/M_{\star} or higher SFR than in less dense environments.

Observations (Yang et al. 2022) show that the gas mass and the gas metallicity are anti-correlated at a given stellar mass up to $M_{\star} < 10^{10.5} M_{\odot}$. Simulations (van de Voort et al. 2011) predict a correlation between the gas accretion rates and the host halo mass of the galaxy up to $M_h < 10^{12.0} M_{\odot}$. So, the more massive the halo, the higher the gas accretion and the gas fraction. This implies a decreased gas-phase metallicity, since the inflowing gas is assumed to be more metal-poor than the ISM. This would imply that the lower stellar metallicity that we find for our void galaxies is due to a higher gas mass or higher gas accretion rates driven by their more massive host halos. This scenario is supported by simulations that find that the halo-to-stellar mass ratio is higher in void galaxies compared to galaxies in denser large-scale environments (Artale et al. 2018; Alfaro et al. 2020; Habouzit et al. 2020; Rosas-Guevara et al. 2022). Another possibility is that there are two different modes of gas accretion (Kereš et al. 2005): the cold gas accretion mode dominates in void galaxies, while the hot gas accretion mode prevails in denser environments. Additionally, a previous observational study (Florez et al. 2021) found that void galaxies have higher gas mass than galaxies in denser environments, more significantly for low-mass ($M_{\star} < 10^{10.0} M_{\odot}$) and early-type galaxies than for high-mass or late-type galaxies. However, other observational studies (Szomoru et al. 1996; Kreckel et al. 2012; Domínguez-Gómez et al. 2022) and simulations (Rosas-Guevara et al. 2022) did not find significant gas mass differences between galaxies in different large-scale environments for this stellar mass regime. Very little observational evidences have been provided for gas accretion rates onto galaxies, given the considerable challenge of directly measuring it.

At higher stellar masses ($M_{\star} > 10^{10.5} M_{\odot}$), Yang et al. (2022) find that the scatter of the MZ_gR correlates only very weakly with the gas mass but a stronger trend is found with AGN activity. Both EAGLE and IllustrisTNG simulations find that the scatter of the MZ_gR is no longer driven by systematic variations in gas inflow rate, but instead dominated by the impact of AGN feedback (De Rossi et al. 2017; Torrey et al. 2019; van Loon et al. 2021). Galaxies with the higher nuclear activity have the lowest metallicities. Previous observational studies (Constantin et al. 2008; Ceccarelli et al. 2022) found a larger fraction of AGNs or massive black holes (BH) in voids than in denser large-scale environments. However, there is no consensus on the effect of the large-scale structure over the nuclear activity in galaxies yet, as Argudo-Fernández et al. (2018) found the opposite result for quenched isolated galaxies, and other studies did not find significant differences in the fraction of AGNs (Amiri et al. 2019, observation) or in the BH-to-galaxy mass ratio (Habouzit et al. 2020, simulation) between different large-scale environments. This would not be in disagreement with our results as we do not find significant stellar metallicity differences between galaxies in different large-scale environments at high stellar masses ($M_{\star} > 10^{10.5} M_{\odot}$). However, in this stellar mass range, the stellar metallicity differences that we find between galaxies in voids and denser large-scale environments might have been diluted by the effect of the metallicity saturation.

6. Conclusions

We apply a non-parametric full spectral fitting analysis to the SDSS spectra in the centre of statistically sound samples of galaxies in voids, filaments & walls, and clusters. We recover their stellar populations and study how the large-scale structures of the Universe affect the stellar mass-metallicity relation of galaxies for different SFH types, morphologies, and colours. The main conclusions are listed below:

1. Void galaxies have slightly lower stellar metallicities than galaxies in filaments & walls, more significantly at low stellar masses ($10^{9.25} M_{\odot}$ by 0.108 ± 0.019) than at high stellar masses ($10^{10.25} M_{\odot}$ by 0.031 ± 0.009), and much lower than galaxies in clusters, also more significantly at low stellar masses ($10^{9.25} M_{\odot}$ by 0.40 ± 0.02) than at high stellar masses ($10^{10.75} M_{\odot}$ by 0.084 ± 0.013). At high stellar masses ($10^{10.75} M_{\odot}$), the differences between galaxies in voids and denser environments might have been diluted by the effect of the metallicity saturation.
2. The stellar metallicity differences between galaxies in voids and galaxies in denser environments are more significant for LT-SFH than for ST-SFH galaxies, more significant for spiral than for elliptical galaxies, and more significant for blue than for red galaxies.
3. ST-SFH galaxies in voids have slightly lower stellar metallicities than galaxies in filaments & walls at intermediate stellar masses ($10^{10.25} M_{\odot}$, by 0.035 ± 0.011), and much lower than galaxies in clusters, more significantly at intermediate stellar masses ($10^{10.25} M_{\odot}$, by 0.152 ± 0.011) than at low stellar masses ($10^{9.25} M_{\odot}$, by 0.063 ± 0.017). LT-SFH galaxies in voids and filaments & walls have similar stellar metallicities, except for low stellar masses ($10^{9.25} M_{\odot}$), where void galaxies have slightly lower stellar metallicities (by 0.104 ± 0.021). LT-SFH galaxies in voids have much lower stellar metallicities than in clusters, more significantly at low stellar masses ($10^{9.25} M_{\odot}$, by 0.419 ± 0.024), than at high stellar masses ($10^{10.75} M_{\odot}$, by 0.11 ± 0.03).
4. Both elliptical and spiral galaxies in voids have slightly lower stellar metallicities than in filaments & walls at intermediate stellar masses ($10^{9.75} M_{\odot}$, by 0.057 ± 0.017 and 0.071 ± 0.016 , respectively), and much lower than in clusters, more significantly at low stellar masses ($10^{9.25} M_{\odot}$, by 0.26 ± 0.04 and 0.27 ± 0.03 , respectively) than at high stellar masses ($10^{10.25} M_{\odot}$, by 0.075 ± 0.012 and 0.077 ± 0.017 , respectively).
5. Blue galaxies in voids have slightly lower stellar metallicities than in filaments & walls at low stellar masses ($10^{9.25} M_{\odot}$, by 0.091 ± 0.020) but not significant differences are found between red galaxies in voids and filaments & walls. Red galaxies in voids have slightly lower stellar metallicities than in clusters, more significantly at lower stellar masses ($10^{9.75} M_{\odot}$ by 0.103 ± 0.016) than at higher stellar masses ($10^{10.75} M_{\odot}$ by 0.066 ± 0.013). Blue galaxies in voids have lower stellar metallicities than in clusters, more significantly at lower stellar masses ($10^{9.25} M_{\odot}$ by 0.315 ± 0.023) than at higher stellar masses ($10^{9.75} M_{\odot}$ by 0.150 ± 0.015).

In summary, galaxies in voids and filaments & walls have similar stellar metallicities, except for intermediate stellar masses, where void galaxies have slightly lower stellar metallicities. Void galaxies have lower stellar metallicities than galaxies in clusters (more significantly at low than at high stellar masses). These differences can be explained by the slower

SFHs of voids galaxies, specially at the initial star formation period in LT-SFH galaxies. Additionally, if we assume a good correlation between the stellar and gas-phase metallicities of star forming galaxies (i.e. blue and spiral galaxies, for which we find the highest stellar metallicity differences between galaxies in different large-scale environments, compared to red and elliptical galaxies, where the differences are less significant), we can explain the lower stellar metallicity of void galaxies at intermediate stellar masses ($M_{\star} < 10^{10.5} M_{\odot}$) based on their higher halo-to-stellar mass ratio, and higher gas accretion. However, further research is needed in terms of gas mass content, gas-phase metallicity, and nuclear activity of void galaxies, together with the correlation between these physical processes and the SFH. The CAVITY project aims to fulfil these needs by analysing the resolved emission lines, stellar populations, and kinematics from PPAK IFU data, together with ancillary data, such as atomic and molecular gas, of galaxies in voids.

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Appendices

A. Sub-samples with the same stellar mass distribution

We show in Figure A.1 the colour vs. stellar mass diagram distribution of our galaxy samples. Void galaxies are on average bluer and less massive than galaxies in denser environments. Our analysis might be affected by the different stellar mass distribution of the three samples. We define five stellar mass bins of 0.5 dex between $10^{8.5}$ and $10^{11.0} M_{\odot}$ and select random sub-samples with the same stellar mass distribution as our void galaxy sample inside each stellar mass bin. The number of galaxies beyond these limits was not enough to define sub-samples with a similar stellar mass distribution applying KS-test. We are left with 978 galaxies in voids, 4800 galaxies in filaments & walls, and 2570 galaxies in clusters for our study.

In figures A.2-A.4 we show the same as figures 3-5, respectively, but for the sub-samples with the same stellar mass distribution inside each stellar mass bin. The values represented in the figures are reported in tables E.7-E.12. The stellar metallicity differences that we find between galaxies in voids, filaments & walls, and cluster for the sub-samples with the same stellar mass distribution are similar to what we find in Section 4 for the main sample. We also show in Figure A.5 the same as in Figure 3 but for narrower stellar mass bins of 0.25 dex width. Additionally, in Figure A.6 we show the same as in Figure 5 for red and blue galaxies but with the classification criterion at 0.6 instead of 0.7 mag. The results change but the general tendency is similar.

B. On the effect of using flux-limited samples from the SDSS

By definition, SDSS is a flux-limited sample, i.e. only galaxies with $r < 17.77$ mag are observed. Such a magnitude limit prevents the observation of faint galaxies at large distances (see Fig. 2 of Tempel et al. 2014), and this, together with the cluster definition adopted in this paper, might induce the misclassification of galaxies belonging to clusters as filaments.

In the redshift range analysed in this work, $0.01 < z < 0.05$, the magnitude limit affects galaxies with absolute magnitude $M_r > -18.25$, which roughly corresponds to stellar masses of $M_{\star} < 10^{9.5} M_{\odot}$, overlapping with the stellar mass range of this study, $M_{\star} > 10^{8.5} M_{\odot}$. In order to test for possible biases introduced by this effect, we analyse in this appendix a volume-limited sub-sample. For that, we restrict the analysis to redshifts between 0.01 and 0.03, in which case the flux limit of the SDSS produces an incompleteness of faint galaxies with $M_r > -17.0$. This magnitude limit corresponds roughly to a limit in stellar mass of $10^{8.5} M_{\odot}$, which is the lower end of the masses considered in our analysis and is therefore not expected to be of any relevance for our analysis. The results of our analysis based on this volume-limited sub-sample is shown in Fig. B.1. As we can see, not only the results remain, but the differences are slightly higher, reinforcing the main conclusions of this work. In addition, we show as error bars the differences between the results for the flux-limited sub-samples of Figure 3 and the results for the volume-limited sub-samples of this figure in order to present an estimate of the uncertainty of our analysis due to possible biases inherit in the sample. The differences reported in this work cannot be accounted for by only considering the systematic errors in the analysis.

This shows that, although the use of a flux-limited sample can in principle affect the classification of galaxies as clusters or filaments, in our sample selected from a relatively small redshift range ($0.01 < z < 0.05$), the effect is small and does not alter the conclusions of our analysis.

C. Sample selection effect of the signal-to-noise cut

In this section we test if the S/N cut of our sample selection might introduce a bias on our results. We show in Figure C.1 the stellar metallicity vs. stellar mass relation for two ranges of the signal-to-noise ratio of the spectra of the galaxies. In Figure C.2, we compare the stellar mass-stellar metallicity relation between galaxies in voids, filaments & walls, and clusters for the same two ranges of the signal-to-noise. We see that the slope of the stellar mass-metallicity relation changes little with the signal-to-noise ratio for galaxies in voids and filaments & walls, but the change is more significant for galaxies in clusters. However, we see in Figure C.2 that this change does not affect our main result, i.e. we find a significant difference in stellar metallicity between galaxies in different large-scale environments for both ranges of the signal-to-noise ratio.

D. Luminosity-weighted stellar mass-metallicity relation

In this section we present the $MZ_{\star}R$ for different SFH types (Figure D.1), morphologies (Figure D.2), and colours (Figure D.3) when the stellar metallicity of a galaxy is calculated as the luminosity-weighted average:

$$[M/H]_L = \frac{\sum L_{\star} [M/H]_{\star}}{\sum L_{\star}}$$

where L_{\star} and $[M/H]_{\star}$ are the luminosity and metallicity of the stars within the galaxy.

The luminosity-weighted stellar metallicities differences that we find between galaxies in different large-scale environments are similar to what we find in Section 4 for the mass-weighted average.

E. Tables

In this section we report the $MZ_{\star}R$ in tables. In tables E.1 and E.2 we present values represented in Figure 3 for all the galaxies, galaxies with ST-SFH and galaxies with LT-SFH. In table E.3 and E.4 we present values represented in Figure 4 for elliptical and spiral galaxies. In tables E.5 and E.6 we present values represented in Figure 5 for red and blue galaxies with the classification criterion at 0.7 mag. In tables E.7-E.12 we present values represented in figures A.2-A.4 for the sub-samples with the same stellar mass distribution. In tables E.13 and E.14 we present values represented in Figure A.5 for narrower stellar mass bins of 0.25 dex width. In tables E.15 and E.16 we present values represented in Figure A.6 for red and blue galaxies with the classification criterion at 0.6 mag. In tables E.20-E.24 we present values represented in figures D.1-D.3 applying the luminosity-weighted average.

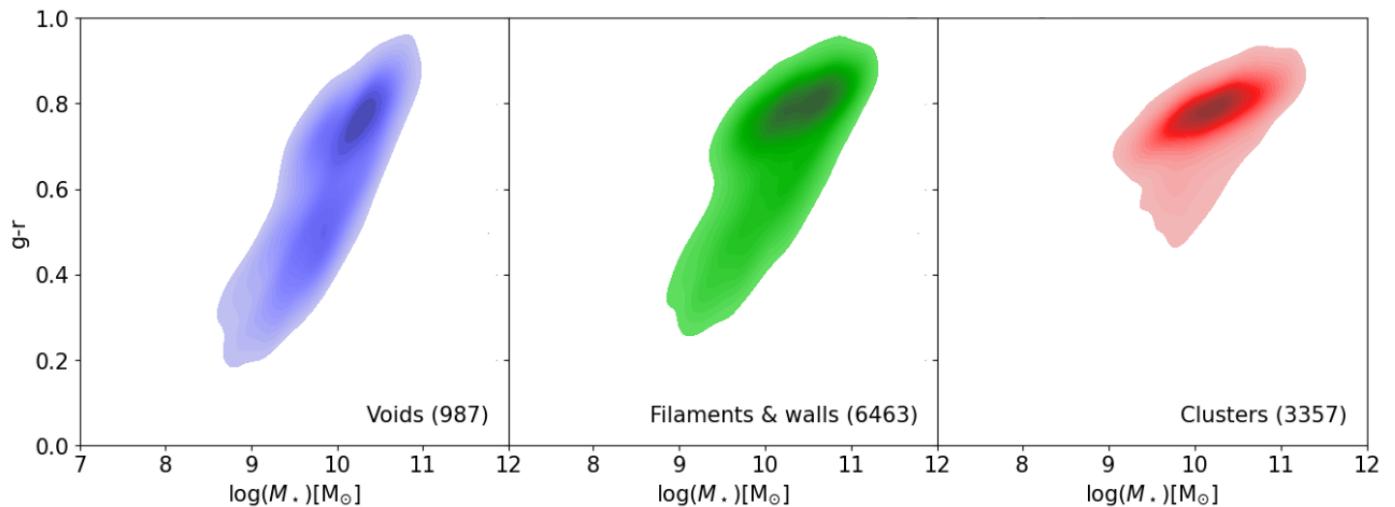


Fig. A.1: Colour vs. stellar diagram distribution of our samples of galaxies in voids (left), filaments & walls (centre), and clusters (right). The number of galaxies in each sample is shown between brackets in the legend.

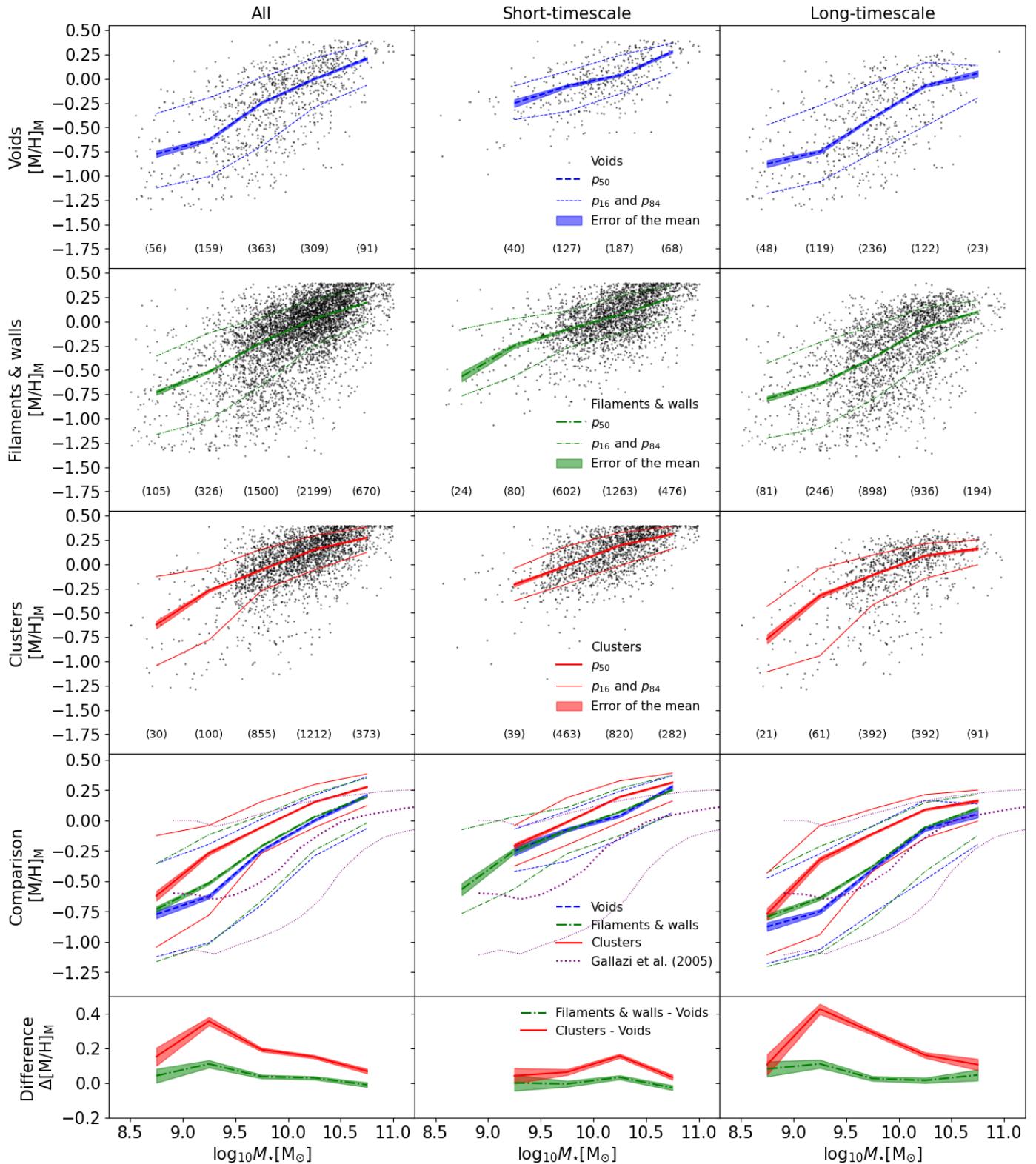


Fig. A.2: Same as Figure 3 but for the sub-samples of galaxies with the same stellar mass distribution. See values reported in tables E.7 and E.10.

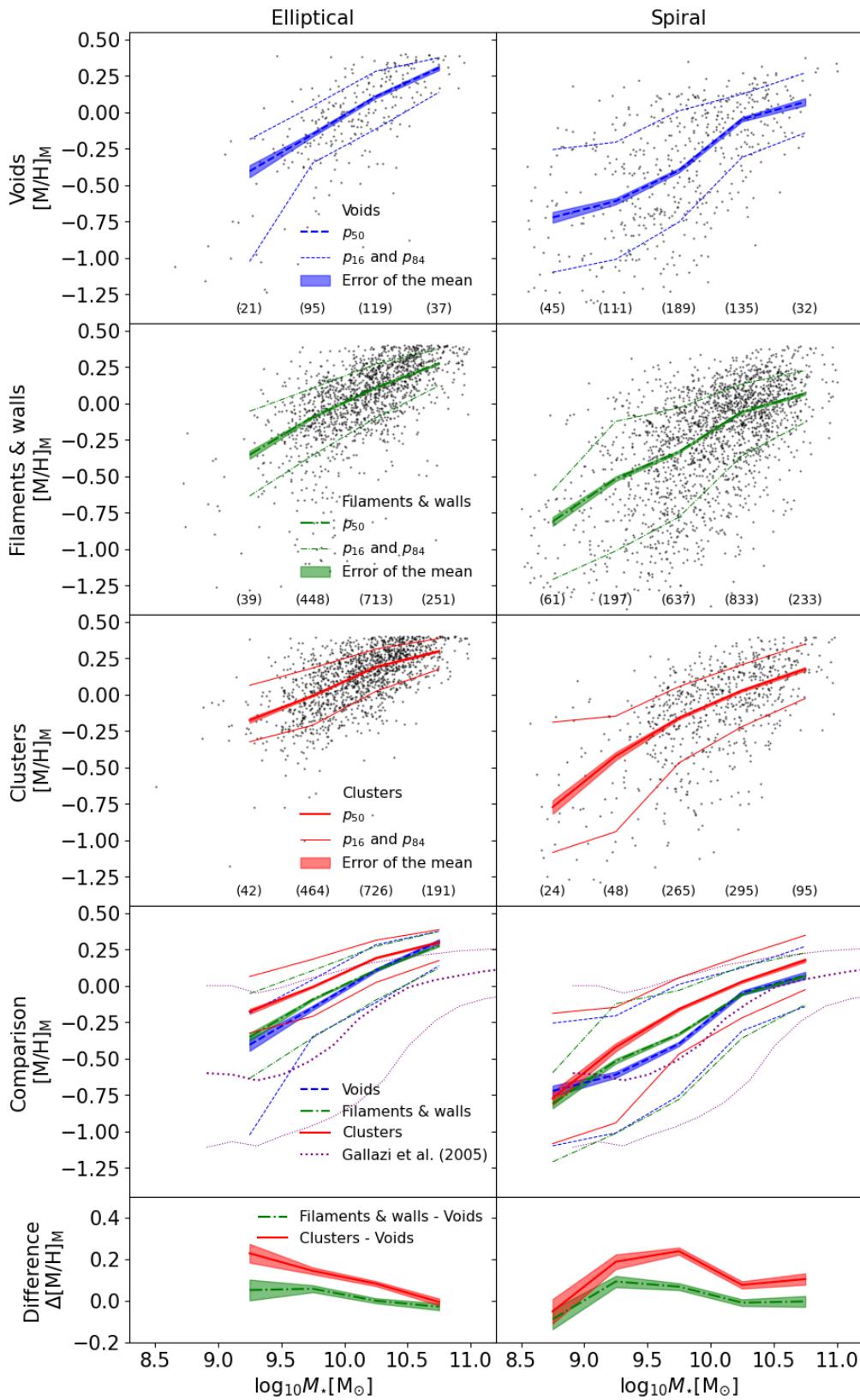


Fig. A.3: Same as Figure 4 but for the sub-samples of galaxies with the same stellar mass distribution. See values reported in tables E.9 and ??.

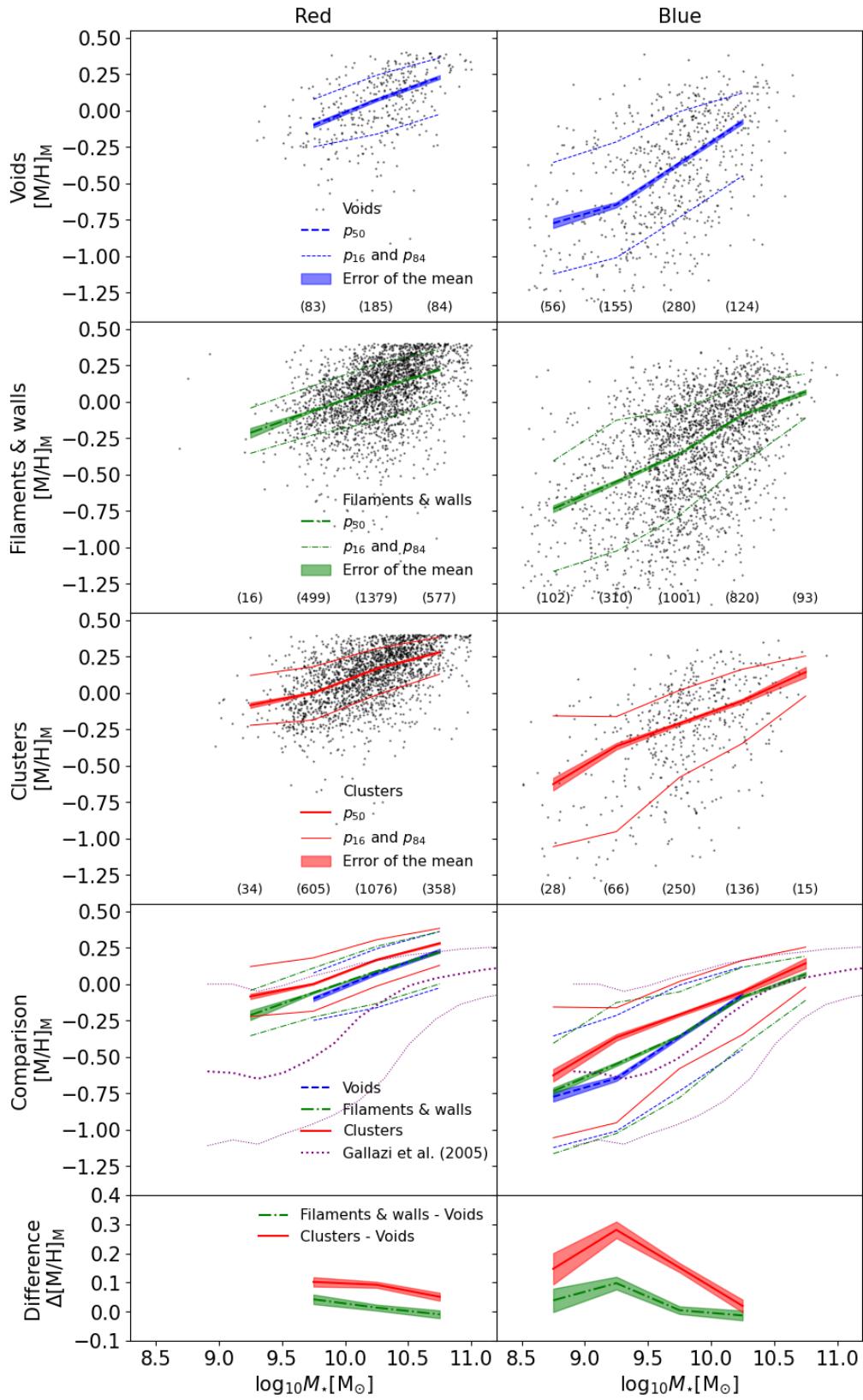


Fig. A.4: Same as Figure 5 but for the sub-samples of galaxies with the same stellar mass distribution. See values reported in tables E.11 and E.12.

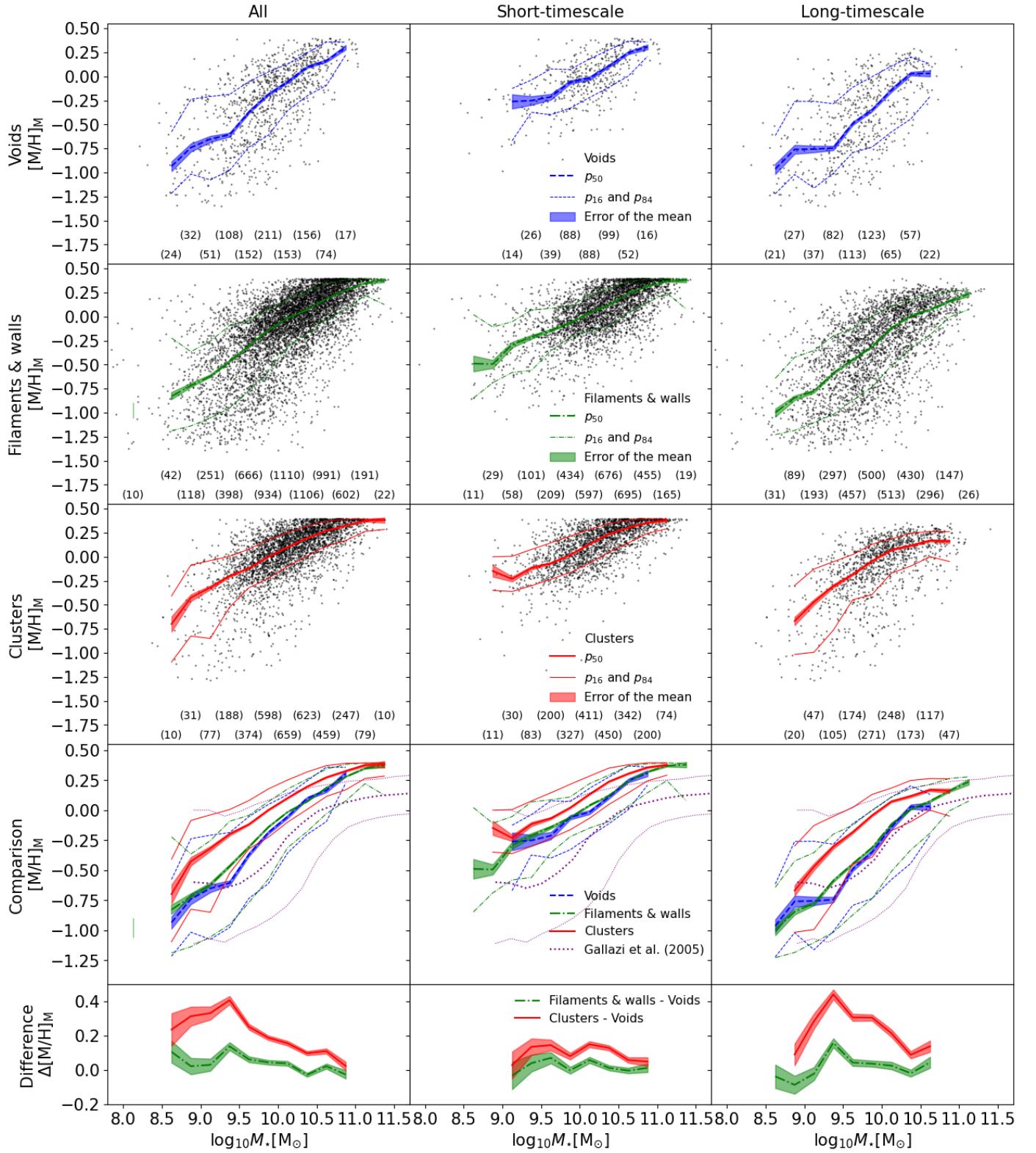


Fig. A.5: Same as Figure 3 but for stellar mass bins of 0.25 dex width. See values reported in tables E.13 and E.14.

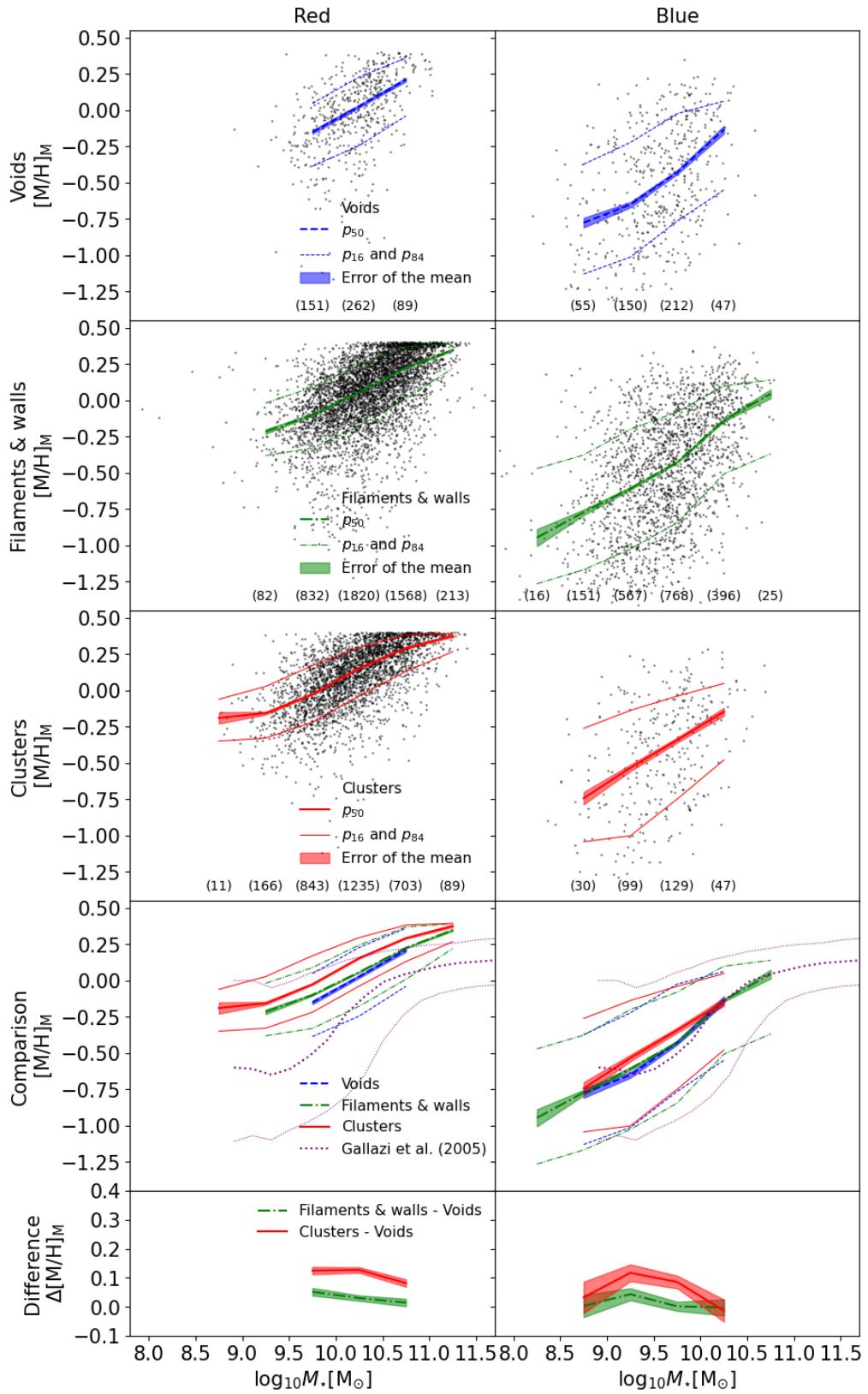


Fig. A.6: Same as Figure 5 but with the colour classification criterion at 0.6 instead of 0.7. See values reported in tables E.15 and E.16.

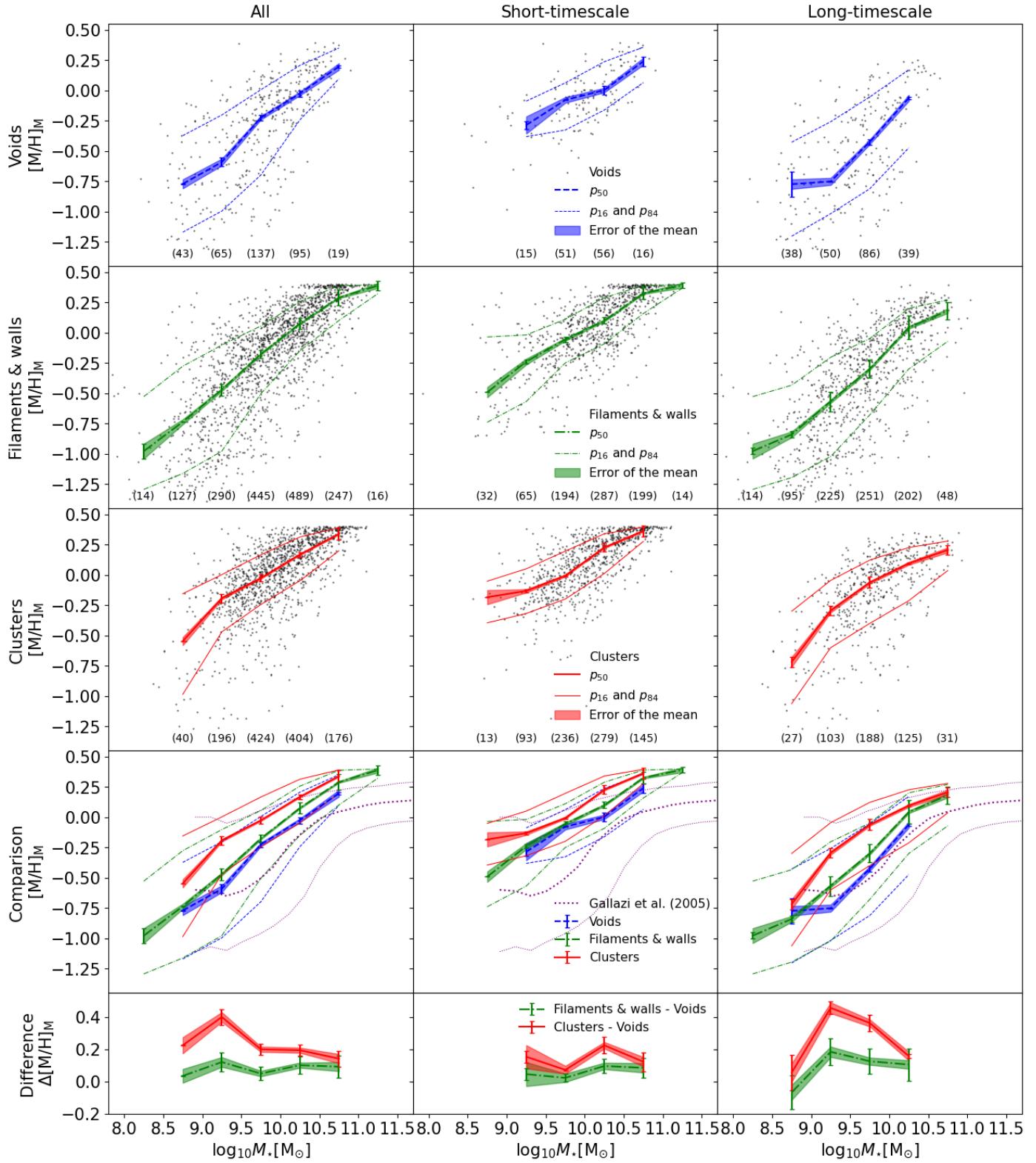


Fig. B.1: Same as Figure 3 but for volume-limited sub-samples of galaxies with redshifts between 0.01 and 0.03. The error bars represent the differences between the results for the flux-limited sub-sample of Figure 3 and the results for the volume-limited sub-samples of this figure. See values reported in tables E.17 and E.18.

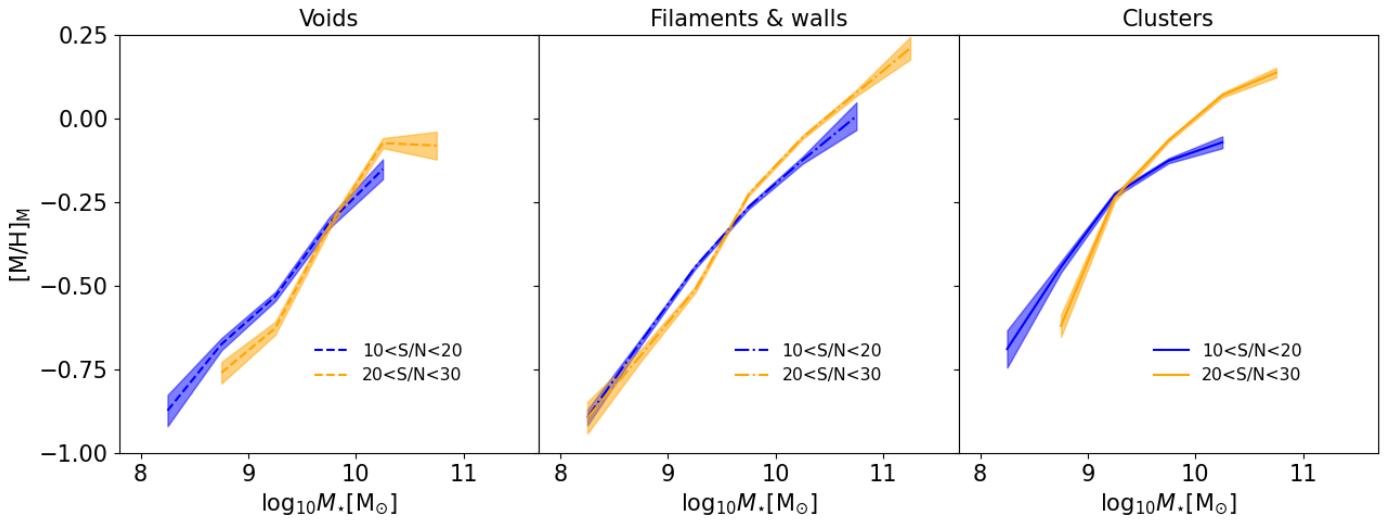


Fig. C.1: Stellar metallicity vs. stellar mass relation for two ranges of the signal-to-noise ratio of the spectra of the galaxies.

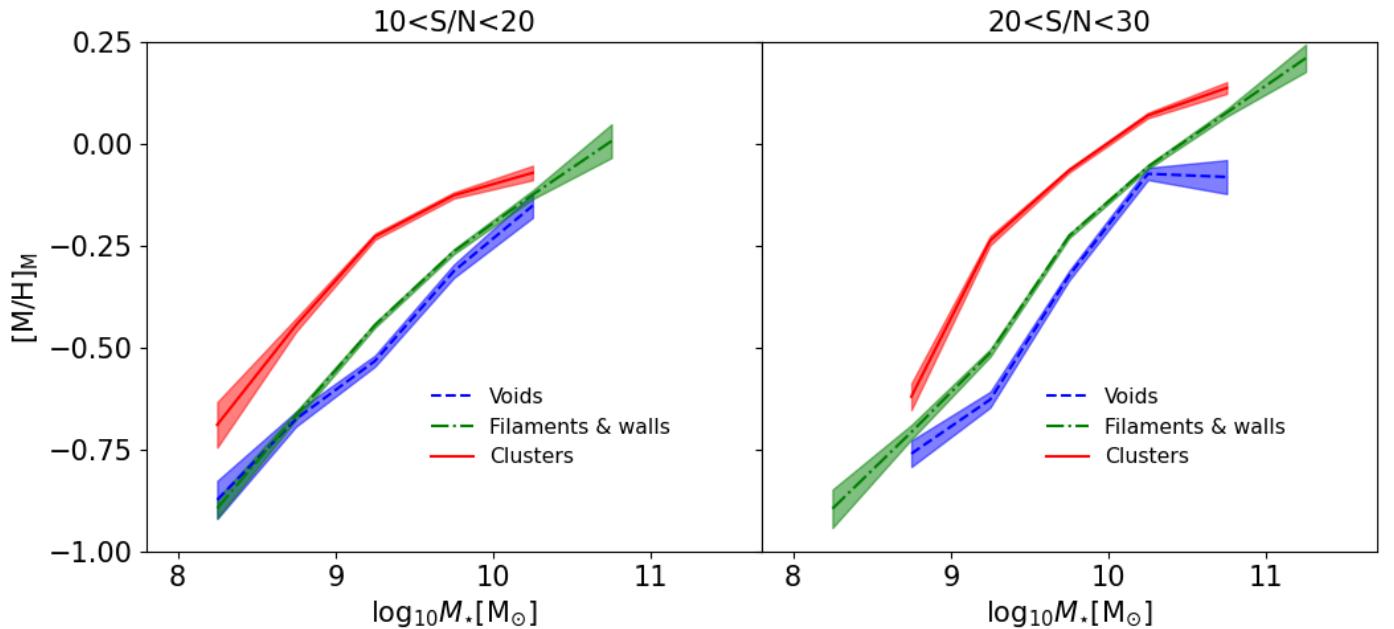


Fig. C.2: Comparison of the stellar metallicity vs. stellar mass relation between galaxies in voids, filaments & walls, and clusters for two ranges of the signal-to-noise of the spectra of the galaxies.

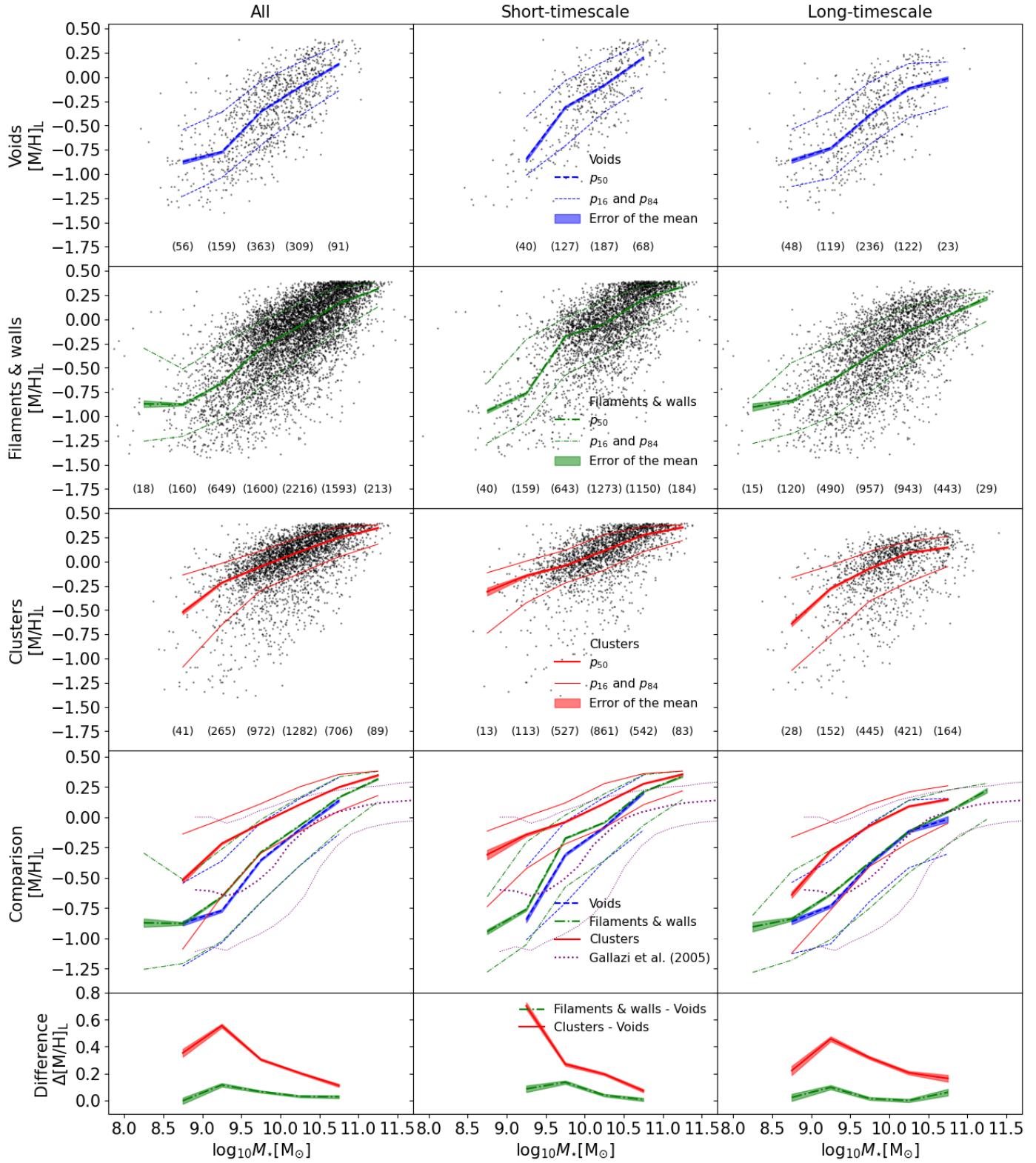


Fig. D.1: Same as Figure 3 but for the stellar metallicity calculated as the luminosity-weighted average. See values reported in tables E.20 and ??.

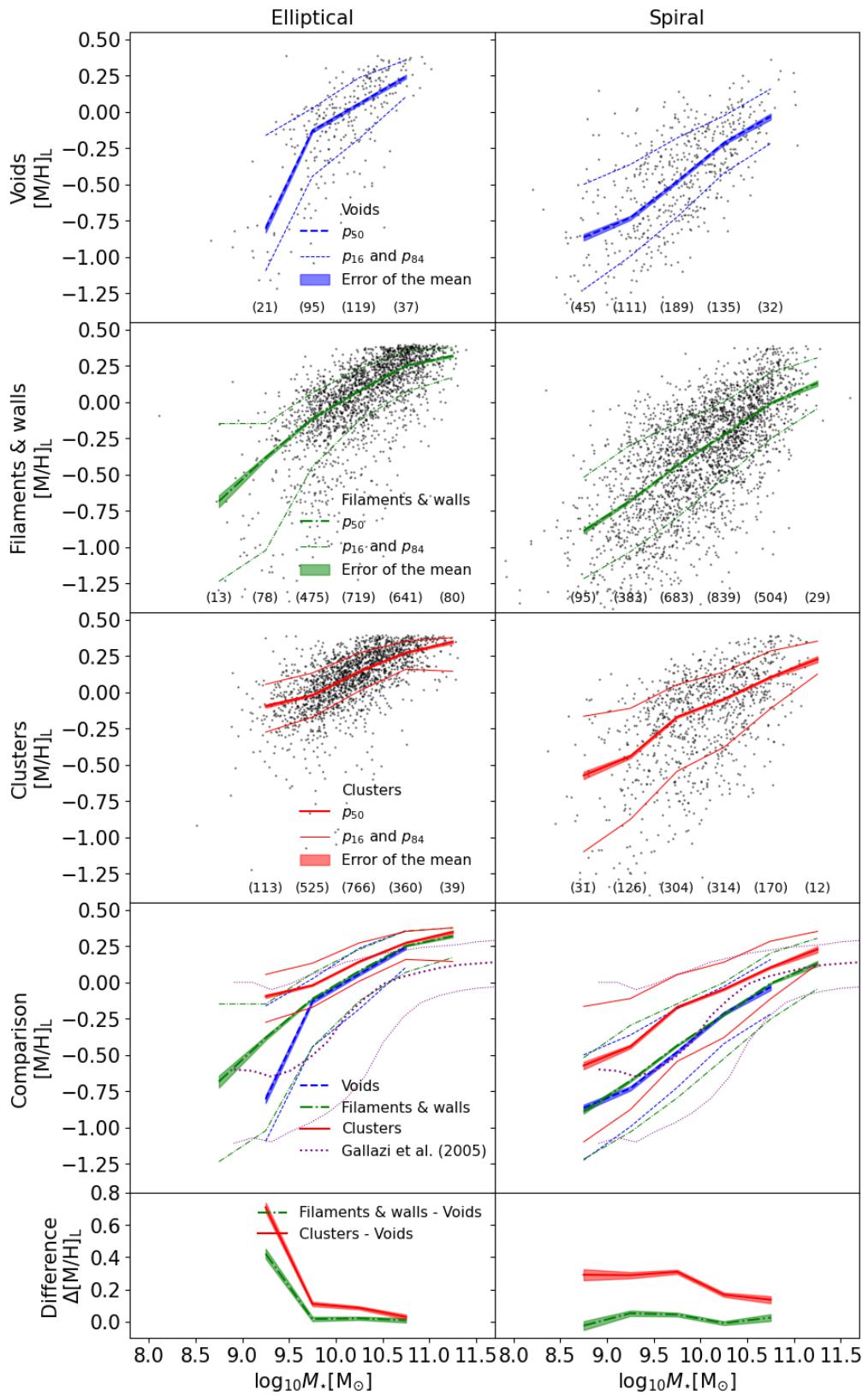


Fig. D.2: Same as Figure 4 but for the stellar metallicity calculated as the luminosity-weighted average. See values reported in tables E.21 and E.22.

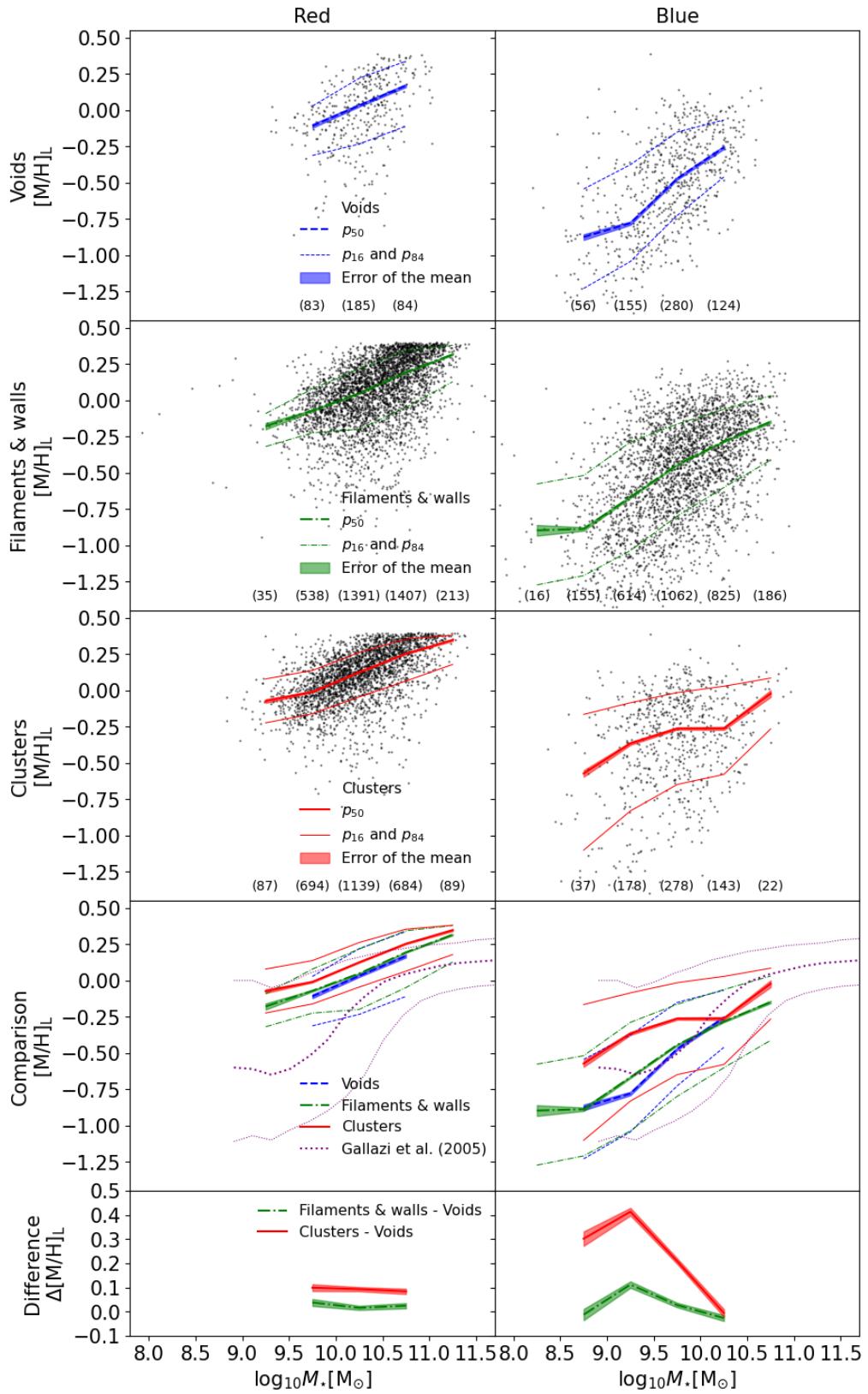


Fig. D.3: Same as Figure 5 but for the stellar metallicity calculated as the luminosity-weighted average. See values reported in tables E.23 and E.24.

Table E.1: Stellar mass-metallicity relation for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_M$											
	All				ST-SFH				LT-SFH			
	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids												
8.25	4	-	-	-	1	-	-	-	3	-	-	-
8.75	56	-0.77±0.03	-1.12	-0.36	8	-	-	-	48	-0.88±0.04	-1.18	-0.48
9.25	159	-0.627±0.017	-1.01	-0.20	40	-0.25±0.04	-0.42	-0.07	119	-0.752±0.019	-1.06	-0.28
9.75	363	-0.247±0.009	-0.70	0.01	127	-0.076±0.016	-0.34	0.08	236	-0.403±0.012	-0.77	-0.05
10.25	309	-0.000±0.009	-0.29	0.21	187	0.038±0.011	-0.16	0.24	122	-0.072±0.014	-0.49	0.16
10.75	91	0.208±0.012	-0.07	0.36	68	0.279±0.013	0.06	0.37	23	0.05±0.03	-0.20	0.14
11.25	4	-	-	-	3	-	-	-	1	-	-	-
(b) Filaments & walls												
8.25	18	-0.92±0.05	-1.24	-0.21	3	-	-	-	15	-0.95±0.06	-1.28	-0.58
8.75	160	-0.737±0.018	-1.16	-0.31	40	-0.49±0.04	-0.73	-0.05	120	-0.865±0.021	-1.20	-0.43
9.25	649	-0.519±0.009	-1.01	-0.13	159	-0.255±0.017	-0.57	0.05	490	-0.648±0.01	-1.06	-0.24
9.75	1600	-0.211±0.004	-0.66	0.04	643	-0.080±0.006	-0.27	0.11	957	-0.374±0.006	-0.81	-0.05
10.25	2216	0.031±0.003	-0.24	0.23	1273	0.073±0.004	-0.12	0.27	943	-0.056±0.005	-0.42	0.15
10.75	1593	0.223±0.003	0.00	0.37	1150	0.277±0.003	0.07	0.38	443	0.111±0.006	-0.13	0.24
11.25	213	0.347±0.007	0.22	0.39	184	0.370±0.007	0.24	0.39	29	0.241±0.022	0.10	0.28
(c) Clusters												
8.25	2	-	-	-	0	-	-	-	2	-	-	-
8.75	41	-0.55±0.03	-0.96	-0.16	13	-0.18±0.06	-0.40	-0.05	28	-0.67±0.04	-1.06	-0.30
9.25	265	-0.23±0.01	-0.60	-0.01	113	-0.146±0.014	-0.33	0.05	152	-0.333±0.015	-0.85	-0.07
9.75	972	-0.054±0.004	-0.27	0.16	527	-0.012±0.005	-0.20	0.19	445	-0.108±0.007	-0.42	0.10
10.25	1282	0.148±0.003	-0.06	0.29	861	0.190±0.004	-0.02	0.32	421	0.089±0.006	-0.15	0.21
10.75	706	0.292±0.004	0.13	0.38	542	0.319±0.004	0.18	0.39	164	0.166±0.009	-0.00	0.26
11.25	89	0.376±0.008	0.27	0.39	83	0.379±0.008	0.29	0.39	6	-	-	-

Notes. Stellar mass-metallicity relation for all the galaxies regardless of their SFH type (left multi-column), galaxies with ST-SFH (centre multi-column), and galaxies with LT-SFH (right multi-column) in voids (a), filaments & walls (b), and clusters (c). The stellar mas-metallicity relation is derived as the 50th percentile (p_{50}) of the distribution, together with the error of the mean, inside each stellar mass bin. The 16th (p_{16}) and 84th (p_{84}) percentiles represent the dispersion of the stellar mass-metallicity relation. The number of galaxies (n) inside each stellar mas bin is also reported.

Table E.2: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$					
	All		ST-SFH		LT-SFH	
	Δp_{50}	σ	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids						
8.25	-	-	-	-	-	-
8.75	0.04±0.04	1.0	-	-	0.01±0.04	0.2
9.25	0.108±0.019	5.7	-0.00±0.04	-0.0	0.104±0.021	5.0
9.75	0.04±0.01	4.0	-0.004±0.017	-0.2	0.029±0.013	2.2
10.25	0.031±0.009	3.4	0.035±0.011	3.2	0.016±0.015	1.1
10.75	0.015±0.013	1.2	-0.003±0.014	-0.2	0.06±0.03	2.0
11.25	-	-	-	-	-	-
(b) Clusters - Voids						
8.25	-	-	-	-	-	-
8.75	0.23±0.05	4.6	-	-	0.20±0.05	4.0
9.25	0.40±0.02	20.0	0.11±0.04	2.8	0.419±0.024	17.5
9.75	0.19±0.01	19.0	0.063±0.017	3.7	0.295±0.014	21.1
10.25	0.148±0.009	16.4	0.152±0.011	13.8	0.161±0.015	10.7
10.75	0.084±0.013	6.5	0.040±0.014	2.9	0.11±0.03	3.7
11.25	-	-	-	-	-	-

Notes. Differences of stellar mass-metallicity relation between galaxies in filaments & walls and voids (a), and between galaxies in clusters and voids (b) for all the galaxies regardless of their SFH type (left multi-column), galaxies with ST-SFH (centre multi-column), and galaxies with LT-SFH (right multi-column). Δp_{50} represents the difference (together with its error) of the 50th percentile of the stellar mass-metallicity distribution between different large-scale environments, and σ is the ratio between the nominal value and the error or the difference.

Table E.3: Stellar mass-metallicity relation for different morphologies.

$\log_{10} M_\star [\text{M}_\odot]$	[M/H] _M							
	n	Elliptical			Spiral			
		p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids								
8.25	0	-	-	-	3	-	-	-
8.75	3	-	-	-	45	-0.72±0.04	-1.10	-0.26
9.25	21	-0.41±0.04	-1.02	-0.19	111	-0.610±0.022	-1.01	-0.21
9.75	95	-0.151±0.015	-0.35	0.04	189	-0.399±0.014	-0.75	0.01
10.25	119	0.108±0.011	-0.12	0.28	135	-0.048±0.015	-0.31	0.12
10.75	37	0.305±0.015	0.14	0.37	32	0.071±0.024	-0.14	0.27
11.25	1	-	-	-	2	-	-	-
(b) Filaments & walls								
8.25	1	-	-	-	9	-	-	-
8.75	13	-0.55±0.06	-0.87	-0.29	95	-0.833±0.024	-1.20	-0.51
9.25	78	-0.357±0.02	-0.68	-0.06	383	-0.571±0.012	-1.02	-0.17
9.75	475	-0.094±0.006	-0.36	0.10	683	-0.328±0.008	-0.79	-0.04
10.25	719	0.110±0.004	-0.10	0.27	839	-0.057±0.006	-0.36	0.13
10.75	641	0.291±0.004	0.13	0.38	504	0.113±0.006	-0.10	0.27
11.25	80	0.34±0.01	0.24	0.39	29	0.224±0.022	0.07	0.36
(c) Clusters								
8.25	0	-	-	-	2	-	-	-
8.75	8	-	-	-	31	-0.55±0.04	-1.04	-0.19
9.25	113	-0.145±0.011	-0.33	0.08	126	-0.345±0.018	-0.85	-0.07
9.75	525	-0.006±0.005	-0.21	0.18	304	-0.144±0.009	-0.46	0.06
10.25	766	0.184±0.004	0.02	0.31	314	0.028±0.008	-0.23	0.20
10.75	360	0.307±0.004	0.19	0.38	170	0.197±0.009	-0.01	0.33
11.25	39	0.376±0.013	0.29	0.39	12	0.27±0.03	0.21	0.38

Notes. Same as Table E.1 but for elliptical (left multi-column) and spiral galaxies (right multi-column).

Table E.4: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for different morphologies.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$			
	Elliptical	Spiral		
		Δp_{50}	σ	Δp_{50}
(a) Filaments & walls - Voids				
8.25	-	-	-	-
8.75	-	-	-0.11±0.04	-2.8
9.25	0.05±0.05	1.0	0.039±0.024	1.6
9.75	0.057±0.017	3.4	0.071±0.016	4.4
10.25	0.002±0.012	0.2	-0.009±0.016	-0.6
10.75	-0.014±0.016	-0.9	0.04±0.03	1.3
11.25	-	-	-	-
(b) Clusters - Voids				
8.25	-	-	-	-
8.75	-	-	0.17±0.05	3.4
9.25	0.26±0.04	6.5	0.27±0.03	9.0
9.75	0.145±0.016	9.1	0.255±0.017	15.0
10.25	0.075±0.012	6.2	0.077±0.017	4.5
10.75	0.003±0.016	0.2	0.13±0.03	4.3
11.25	-	-	-	-

Notes. Same as Table E.2 but for elliptical (left multi-column) and spiral galaxies (right multi-column).

Table E.5: Stellar mass-metallicity relation for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_M$					
	n	Red ($g - r > 0.7$)			Blue ($g - r \leq 0.7$)	
		p_{50}	p_{16}	p_{84}	n	p_{50}
(a) Voids						
8.25	0	-	-	-	4	-
8.75	0	-	-	-	56	-0.77 ± 0.03
9.25	4	-	-	-	155	-0.648 ± 0.018
9.75	83	-0.101 ± 0.015	-0.25	0.08	280	-0.361 ± 0.011
10.25	185	0.075 ± 0.01	-0.16	0.24	124	-0.074 ± 0.016
10.75	84	0.230 ± 0.013	-0.03	0.36	7	-
11.25	4	-	-	-	0	-
(b) Filaments & walls						
8.25	2	-	-	-	16	-0.95 ± 0.06
8.75	5	-	-	-	155	-0.746 ± 0.019
9.25	35	-0.216 ± 0.021	-0.36	-0.02	614	-0.557 ± 0.009
9.75	538	-0.057 ± 0.005	-0.23	0.11	1062	-0.351 ± 0.006
10.25	1391	0.090 ± 0.003	-0.13	0.26	825	-0.086 ± 0.006
10.75	1407	0.250 ± 0.003	0.03	0.37	186	0.057 ± 0.011
11.25	213	0.347 ± 0.007	0.22	0.39	0	-
(c) Clusters						
8.25	0	-	-	-	2	-
8.75	4	-	-	-	37	-0.62 ± 0.04
9.25	87	-0.103 ± 0.012	-0.27	0.12	178	-0.333 ± 0.014
9.75	694	0.002 ± 0.004	-0.18	0.18	278	-0.21 ± 0.01
10.25	1139	0.164 ± 0.003	-0.02	0.30	143	-0.056 ± 0.014
10.75	684	0.296 ± 0.004	0.13	0.38	22	0.16 ± 0.03
11.25	89	0.376 ± 0.008	0.27	0.39	0	-

Notes. Same as Table E.1 but for red (left multi-column) and blue galaxies (right multi-column).

Table E.6: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$			
	Red ($g - r > 0.7$)	Blue ($g - r \leq 0.7$)		
		Δp_{50}	σ	Δp_{50}
(a) Filaments & walls - Voids				
8.25	-	-	-	-
8.75	-	-	0.03 ± 0.04	0.8
9.25	-	-	0.091 ± 0.020	4.5
9.75	0.044 ± 0.016	2.8	0.010 ± 0.013	0.8
10.25	0.02 ± 0.01	2.0	-0.012 ± 0.017	-0.7
10.75	0.021 ± 0.013	1.6	-	-
11.25	-	-	-	-
(b) Clusters - Voids				
8.25	-	-	-	-
8.75	-	-	0.15 ± 0.05	3.0
9.25	-	-	0.315 ± 0.023	13.7
9.75	0.103 ± 0.016	6.4	0.150 ± 0.015	10.0
10.25	0.09 ± 0.01	9.0	0.018 ± 0.021	0.9
10.75	0.066 ± 0.013	5.1	-	-
11.25	-	-	-	-

Notes. Same as Table E.2 but for red (left multi-column) and blue galaxies (right multi-column).

Table E.7: Stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	n	All				[M/H] _M				LT-SFH			
		p_{50}	p_{16}	p_{84}		n	ST-SFH			p_{50}	p_{16}	p_{84}	n
							p_{50}	p_{16}	p_{84}				
(a) Voids													
8.75	56	-0.77±0.03	-1.12	-0.36	8	-	-	-	-	48	-0.88±0.04	-1.18	-0.48
9.25	159	-0.627±0.017	-1.01	-0.20	40	-0.25±0.04	-0.42	-0.07	119	-0.752±0.019	-1.06	-0.28	
9.75	363	-0.247±0.009	-0.70	0.01	127	-0.076±0.016	-0.34	0.08	236	-0.403±0.012	-0.77	-0.05	
10.25	309	-0.000±0.009	-0.29	0.21	187	0.038±0.011	-0.16	0.24	122	-0.072±0.014	-0.49	0.16	
10.75	91	0.208±0.012	-0.07	0.36	68	0.279±0.013	0.06	0.37	23	0.05±0.03	-0.20	0.14	
(b) Filaments & walls													
8.75	105	-0.732±0.023	-1.16	-0.36	24	-0.57±0.05	-0.77	-0.08	81	-0.79±0.03	-1.20	-0.43	
9.25	326	-0.516±0.012	-1.02	-0.12	80	-0.250±0.023	-0.56	0.03	246	-0.641±0.014	-1.10	-0.21	
9.75	1500	-0.210±0.005	-0.66	0.04	602	-0.080±0.007	-0.27	0.11	898	-0.376±0.006	-0.81	-0.05	
10.25	2199	0.030±0.003	-0.25	0.22	1263	0.071±0.004	-0.13	0.26	936	-0.056±0.005	-0.42	0.15	
10.75	670	0.198±0.005	-0.02	0.35	476	0.253±0.005	0.05	0.37	194	0.100±0.01	-0.12	0.22	
(c) Clusters													
8.75	30	-0.62±0.04	-1.04	-0.13	9	-	-	-	-	21	-0.77±0.05	-1.11	-0.43
9.25	100	-0.270±0.016	-0.78	-0.04	39	-0.210±0.02	-0.38	-0.04	61	-0.324±0.022	-0.94	-0.04	
9.75	855	-0.055±0.004	-0.27	0.16	463	-0.012±0.006	-0.20	0.19	392	-0.110±0.007	-0.42	0.09	
10.25	1212	0.151±0.003	-0.06	0.29	820	0.195±0.004	-0.02	0.33	392	0.090±0.006	-0.15	0.21	
10.75	373	0.277±0.005	0.12	0.38	282	0.313±0.005	0.16	0.39	91	0.161±0.012	-0.01	0.25	

Notes. Same as Table E.1 but for sub-samples with the same stellar mass distribution.

Table E.8: Differences of the stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$					
	All		ST-SFH		LT-SFH	
	Δp_{50}	σ	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids						
8.75	0.04±0.04	1.0	-	-	0.08±0.04	2.0
9.25	0.111±0.021	5.3	0.00±0.05	0.0	0.111±0.024	4.6
9.75	0.038±0.011	3.5	-0.004±0.017	-0.2	0.027±0.013	2.1
10.25	0.030±0.009	3.3	0.033±0.011	3.0	0.016±0.015	1.1
10.75	-0.009±0.013	-0.7	-0.026±0.014	-1.9	0.05±0.03	1.7
(b) Clusters - Voids						
8.75	0.15±0.05	3.0	-	-	0.11±0.06	1.8
9.25	0.357±0.023	15.5	0.04±0.04	1.0	0.43±0.03	14.3
9.75	0.19±0.01	19.0	0.063±0.017	3.7	0.293±0.014	20.9
10.25	0.152±0.009	16.9	0.157±0.011	14.3	0.161±0.015	10.7
10.75	0.069±0.013	5.3	0.034±0.014	2.4	0.11±0.03	3.7

Notes. Same as Table E.2 but for sub-samples with the same stellar mass distribution.

Table E.9: Stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different morphologies.

$\log_{10} M_\star [\text{M}_\odot]$	n	[M/H] _M			Spiral			
		Elliptical			Spiral			
		p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids								
8.75	3	-	-	-	45	-0.72±0.04	-1.10	-0.26
9.25	21	-0.41±0.04	-1.02	-0.19	111	-0.610±0.022	-1.01	-0.21
9.75	95	-0.151±0.015	-0.35	0.04	189	-0.399±0.014	-0.75	0.01
10.25	119	0.108±0.011	-0.12	0.28	135	-0.048±0.015	-0.31	0.12
10.75	37	0.305±0.015	0.14	0.37	32	0.071±0.024	-0.14	0.27
(b) Filaments & walls								
8.75	9	-	-	-	61	-0.81±0.03	-1.21	-0.60
9.25	39	-0.35±0.03	-0.64	-0.05	197	-0.517±0.016	-1.01	-0.12
9.75	448	-0.093±0.007	-0.36	0.10	637	-0.331±0.008	-0.78	-0.03
10.25	713	0.109±0.004	-0.10	0.27	833	-0.057±0.006	-0.36	0.13
10.75	251	0.276±0.006	0.12	0.37	233	0.069±0.009	-0.13	0.23
(c) Clusters								
8.75	5	-	-	-	24	-0.77±0.05	-1.08	-0.19
9.25	42	-0.176±0.017	-0.32	0.06	48	-0.42±0.03	-0.94	-0.15
9.75	464	-0.007±0.005	-0.21	0.18	265	-0.160±0.01	-0.47	0.05
10.25	726	0.191±0.004	0.02	0.31	295	0.029±0.008	-0.22	0.21
10.75	191	0.299±0.006	0.17	0.39	95	0.176±0.012	-0.03	0.35

Notes. Same as Table E.3 but for sub-samples with the same stellar mass distribution.

Table E.10: Differences of the stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$					
	All		ST-SFH		LT-SFH	
	Δp_{50}	σ	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids						
8.75	0.04±0.04	1.0	-	-	0.08±0.04	2.0
9.25	0.111±0.021	5.3	0.00±0.05	0.0	0.111±0.024	4.6
9.75	0.038±0.011	3.5	-0.004±0.017	-0.2	0.027±0.013	2.1
10.25	0.030±0.009	3.3	0.033±0.011	3.0	0.016±0.015	1.1
10.75	-0.009±0.013	-0.7	-0.026±0.014	-1.9	0.05±0.03	1.7
(b) Clusters - Voids						
8.75	0.15±0.05	3.0	-	-	0.11±0.06	1.8
9.25	0.357±0.023	15.5	0.04±0.04	1.0	0.43±0.03	14.3
9.75	0.19±0.01	19.0	0.063±0.017	3.7	0.293±0.014	20.9
10.25	0.152±0.009	16.9	0.157±0.011	14.3	0.161±0.015	10.7
10.75	0.069±0.013	5.3	0.034±0.014	2.4	0.11±0.03	3.7

Notes. Same as Table E.2 but for sub-samples with the same stellar mass distribution.

Table E.11: Stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_M$						
	n	Red ($g - r > 0.7$)			Blue ($g - r \leq 0.7$)		
		p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}
(a) Voids							
8.75	0	-	-	-	56	-0.77 ± 0.03	-1.12
9.25	4	-	-	-	155	-0.648 ± 0.018	-1.01
9.75	83	-0.101 ± 0.015	-0.25	0.08	280	-0.361 ± 0.011	-0.73
10.25	185	0.075 ± 0.01	-0.16	0.24	124	-0.074 ± 0.016	-0.45
10.75	84	0.230 ± 0.013	-0.03	0.36	7	-	-
(b) Filaments & walls							
8.75	3	-	-	-	102	-0.735 ± 0.023	-1.17
9.25	16	-0.21 ± 0.03	-0.36	-0.04	310	-0.550 ± 0.013	-1.03
9.75	499	-0.058 ± 0.006	-0.23	0.11	1001	-0.356 ± 0.006	-0.78
10.25	1379	0.089 ± 0.003	-0.13	0.26	820	-0.087 ± 0.006	-0.43
10.75	577	0.221 ± 0.005	0.00	0.36	93	0.068 ± 0.015	-0.11
(c) Clusters							
8.75	2	-	-	-	28	-0.63 ± 0.04	-1.06
9.25	34	-0.085 ± 0.018	-0.22	0.12	66	-0.367 ± 0.022	-0.95
9.75	605	0.001 ± 0.005	-0.19	0.18	250	-0.209 ± 0.011	-0.58
10.25	1076	0.167 ± 0.003	-0.01	0.30	136	-0.054 ± 0.015	-0.35
10.75	358	0.281 ± 0.005	0.13	0.38	15	0.14 ± 0.04	-0.02

Notes. Same as Table E.5 but for sub-samples with the same stellar mass distribution.

Table E.12: Differences of the stellar mass-metallicity relation of sub-samples with the same stellar mass distribution for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$			
	Red ($g - r > 0.7$)		Blue ($g - r \leq 0.7$)	
	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids				
8.75	-	-	0.04 ± -0.04	1.0
9.25	-	-	0.098 ± -0.022	4.5
9.75	0.042 ± -0.016	2.6	0.005 ± -0.013	0.4
10.25	0.01 ± -0.01	1.0	-0.013 ± -0.017	-0.8
10.75	-0.009 ± -0.013	-0.7	-	-
(b) Clusters - Voids				
8.75	-	-	0.15 ± -0.05	3.0
9.25	-	-	0.28 ± -0.03	9.3
9.75	0.102 ± -0.016	6.4	0.151 ± -0.016	9.4
10.25	0.09 ± -0.01	9.0	0.020 ± -0.021	1.0
10.75	0.051 ± -0.014	3.6	-	-

Notes. Same as Table E.6 but for sub-samples with the same stellar mass distribution.

Table E.13: Stellar mass-metallicity relation with stellar mass bins of 0.25 dex width for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	[M/H] _M											
	All				ST-SFH				LT-SFH			
	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids												
8.12	1	-	-	-	0	-	-	-	1	-	-	-
8.38	3	-	-	-	1	-	-	-	2	-	-	-
8.62	24	-0.94+/-0.05	-1.22	-0.58	3	-	-	-	21	-0.96+/-0.05	-1.22	-0.62
8.88	32	-0.74+/-0.04	-1.02	-0.24	5	-	-	-	27	-0.76+/-0.05	-1.02	-0.26
9.12	51	-0.65+/-0.03	-1.08	-0.21	14	-0.26+/-0.07	-0.67	-0.13	37	-0.76+/-0.03	-1.16	-0.26
9.38	108	-0.607+/-0.021	-0.98	-0.19	26	-0.25+/-0.05	-0.37	-0.04	82	-0.745+/-0.023	-1.01	-0.28
9.62	152	-0.369+/-0.015	-0.73	-0.05	39	-0.21+/-0.03	-0.40	0.08	113	-0.490+/-0.018	-0.79	-0.11
9.88	211	-0.187+/-0.012	-0.61	0.05	88	-0.060+/-0.018	-0.33	0.07	123	-0.349+/-0.016	-0.74	-0.00
10.12	153	-0.054+/-0.013	-0.36	0.13	88	-0.017+/-0.017	-0.22	0.18	65	-0.142+/-0.021	-0.58	0.11
10.38	156	0.098+/-0.011	-0.20	0.24	99	0.109+/-0.014	-0.11	0.28	57	0.028+/-0.019	-0.44	0.20
10.62	74	0.163+/-0.014	-0.10	0.36	52	0.246+/-0.015	0.00	0.37	22	0.03+/-0.03	-0.21	0.13
10.88	17	0.303+/-0.024	0.22	0.36	16	0.31+/-0.02	0.21	0.36	1	-	-	-
11.12	4	-	-	-	3	-	-	-	1	-	-	-
11.38	0	-	-	-	0	-	-	-	0	-	-	-
(b) Filaments & walls												
8.12	10	-0.98+/-0.08	-1.31	-0.47	1	-	-	-	9	-	-	-
8.38	8	-	-	-	2	-	-	-	6	-	-	-
8.62	42	-0.83+/-0.04	-1.19	-0.22	11	-0.49+/-0.08	-0.85	0.02	31	-1.00+/-0.04	-1.23	-0.64
8.88	118	-0.718+/-0.021	-1.14	-0.37	29	-0.49+/-0.04	-0.69	-0.11	89	-0.846+/-0.024	-1.19	-0.42
9.12	251	-0.621+/-0.014	-1.06	-0.25	58	-0.29+/-0.03	-0.58	-0.05	193	-0.777+/-0.016	-1.10	-0.35
9.38	398	-0.468+/-0.011	-0.95	-0.09	101	-0.212+/-0.02	-0.56	0.07	297	-0.587+/-0.013	-1.02	-0.20
9.62	666	-0.307+/-0.007	-0.77	-0.04	209	-0.142+/-0.012	-0.36	0.09	457	-0.447+/-0.009	-0.87	-0.13
9.88	934	-0.142+/-0.005	-0.57	0.07	434	-0.062+/-0.007	-0.22	0.11	500	-0.312+/-0.008	-0.74	-0.00
10.12	1110	-0.016+/-0.004	-0.31	0.18	597	0.041+/-0.006	-0.15	0.22	513	-0.116+/-0.007	-0.51	0.11
10.38	1106	0.070+/-0.004	-0.18	0.26	676	0.121+/-0.005	-0.09	0.29	430	0.010+/-0.007	-0.33	0.18
10.62	991	0.186+/-0.004	-0.03	0.34	695	0.243+/-0.004	0.03	0.37	296	0.075+/-0.008	-0.19	0.21
10.88	602	0.277+/-0.004	0.08	0.38	455	0.320+/-0.004	0.15	0.39	147	0.16+/-0.01	-0.01	0.26
11.12	191	0.347+/-0.007	0.22	0.39	165	0.369+/-0.007	0.25	0.39	26	0.236+/-0.024	0.08	0.28
11.38	22	0.373+/-0.02	0.13	0.39	19	0.378+/-0.022	0.08	0.39	3	-	-	-
(c) Clusters												
8.12	0	-	-	-	0	-	-	-	0	-	-	-
8.38	2	-	-	-	0	-	-	-	2	-	-	-
8.62	10	-0.70+/-0.08	-1.10	-0.41	2	-	-	-	8	-	-	-
8.88	31	-0.43+/-0.04	-0.83	-0.09	11	-0.15+/-0.06	-0.35	-0.00	20	-0.67+/-0.04	-1.02	-0.30
9.12	77	-0.320+/-0.02	-0.85	-0.04	30	-0.23+/-0.03	-0.36	0.00	47	-0.47+/-0.03	-0.99	-0.13
9.38	188	-0.200+/-0.012	-0.53	0.00	83	-0.116+/-0.017	-0.30	0.08	105	-0.304+/-0.017	-0.76	-0.05
9.62	374	-0.117+/-0.007	-0.32	0.08	200	-0.068+/-0.009	-0.23	0.14	174	-0.183+/-0.011	-0.45	0.02
9.88	598	0.001+/-0.005	-0.23	0.18	327	0.021+/-0.006	-0.16	0.22	271	-0.043+/-0.009	-0.39	0.13
10.12	659	0.101+/-0.005	-0.10	0.25	411	0.133+/-0.006	-0.07	0.28	248	0.073+/-0.008	-0.17	0.18
10.38	623	0.196+/-0.004	0.01	0.32	450	0.238+/-0.005	0.05	0.35	173	0.117+/-0.009	-0.10	0.25
10.62	459	0.273+/-0.005	0.11	0.37	342	0.304+/-0.005	0.14	0.38	117	0.169+/-0.011	0.00	0.26
10.88	247	0.326+/-0.006	0.17	0.39	200	0.356+/-0.006	0.24	0.39	47	0.161+/-0.018	-0.05	0.26
11.12	79	0.376+/-0.009	0.26	0.39	74	0.377+/-0.009	0.29	0.39	5	-	-	-
11.38	10	0.38+/-0.03	0.28	0.39	9	-	-	-	1	-	-	-

Notes. Same as Table E.1 but for narrower stellar mass bins of 0.25 dex width.

Table E.14: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters with stellar mass bins of 0.25 dex width for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_M$					
	All		ST-SFH		LT-SFH	
	Δp_{50}	σ	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids						
8.12	-	-	-	-	-	-
8.38	-	-	-	-	-	-
8.62	0.11+/-0.06	1.8	-	-	-0.04+/-0.07	-0.6
8.88	0.02+/-0.05	0.4	-	-	-0.09+/-0.05	-1.8
9.12	0.03+/-0.04	0.8	-0.03+/-0.08	-0.4	-0.02+/-0.04	-0.5
9.38	0.138+/-0.023	6.0	0.04+/-0.05	0.8	0.16+/-0.03	5.3
9.62	0.062+/-0.017	3.6	0.07+/-0.03	2.3	0.044+/-0.02	2.2
9.88	0.045+/-0.013	3.5	-0.002+/-0.02	-0.1	0.037+/-0.018	2.1
10.12	0.038+/-0.014	2.7	0.058+/-0.018	3.2	0.026+/-0.022	1.2
10.38	-0.028+/-0.012	-2.3	0.013+/-0.015	0.9	-0.019+/-0.02	-0.9
10.62	0.023+/-0.015	1.5	-0.003+/-0.016	-0.2	0.04+/-0.03	1.3
10.88	-0.026+/-0.024	-1.1	0.01+/-0.03	0.3	-	-
11.12	-	-	-	-	-	-
11.38	-	-	-	-	-	-
(b) Clusters - Voids						
8.12	-	-	-	-	-	-
8.38	-	-	-	-	-	-
8.62	0.24+/-0.09	2.7	-	-	-	-
8.88	0.31+/-0.06	5.2	-	-	0.09+/-0.06	1.5
9.12	0.33+/-0.04	8.2	0.03+/-0.08	0.4	0.29+/-0.04	7.2
9.38	0.407+/-0.024	17.0	0.14+/-0.05	2.8	0.44+/-0.03	14.7
9.62	0.252+/-0.017	14.8	0.15+/-0.03	5.0	0.307+/-0.021	14.6
9.88	0.188+/-0.013	14.5	0.081+/-0.02	4.0	0.306+/-0.018	17.0
10.12	0.156+/-0.014	11.1	0.150+/-0.018	8.3	0.215+/-0.022	9.8
10.38	0.098+/-0.012	8.2	0.129+/-0.015	8.6	0.089+/-0.021	4.2
10.62	0.110+/-0.015	7.3	0.058+/-0.016	3.6	0.14+/-0.03	4.7
10.88	0.023+/-0.024	1.0	0.05+/-0.03	1.7	-	-
11.12	-	-	-	-	-	-
11.38	-	-	-	-	-	-

Notes. Same as Table E.2 but for narrower stellar mass bins of 0.25 dex width.

Table E.15: Stellar mass-metallicity relation for a different classification of the colour of the galaxies.

$\log_{10} M_\star [M_\odot]$	n	[M/H] _M			Blue ($g - r \leq 0.6$)			
		Red ($g - r > 0.6$)			n	p_{50}	p_{16}	p_{84}
		p_{50}	p_{16}	p_{84}				
(a) Voids								
8.25	0	-	-	-	4	-	-	-
8.75	1	-	-	-	55	-0.78 ± 0.03	-1.13	-0.37
9.25	9	-	-	-	150	-0.652 ± 0.018	-1.01	-0.22
9.75	151	-0.151 ± 0.012	-0.39	0.05	212	-0.429 ± 0.014	-0.77	-0.02
10.25	262	0.027 ± 0.009	-0.25	0.23	47	-0.13 ± 0.03	-0.55	0.06
10.75	89	0.210 ± 0.012	-0.04	0.36	2	-	-	-
11.25	4	-	-	-	0	-	-	-
(b) Filaments & walls								
8.25	2	-	-	-	16	-0.95 ± 0.06	-1.27	-0.47
8.75	9	-	-	-	151	-0.773 ± 0.019	-1.17	-0.38
9.25	82	-0.216 ± 0.016	-0.38	-0.02	567	-0.608 ± 0.009	-1.03	-0.20
9.75	832	-0.100 ± 0.005	-0.33	0.09	768	-0.427 ± 0.008	-0.85	-0.08
10.25	1820	0.057 ± 0.003	-0.18	0.24	396	-0.137 ± 0.009	-0.51	0.10
10.75	1568	0.225 ± 0.003	0.01	0.37	25	0.04 ± 0.03	-0.37	0.14
11.25	213	0.347 ± 0.007	0.22	0.39	0	-	-	-
(c) Clusters								
8.25	0	-	-	-	2	-	-	-
8.75	11	-0.19 ± 0.04	-0.35	-0.06	30	-0.74 ± 0.04	-1.04	-0.26
9.25	166	-0.157 ± 0.01	-0.33	0.03	99	-0.534 ± 0.023	-1.00	-0.14
9.75	843	-0.026 ± 0.004	-0.22	0.17	129	-0.343 ± 0.017	-0.75	-0.04
10.25	1235	0.154 ± 0.003	-0.04	0.30	47	-0.15 ± 0.03	-0.48	0.05
10.75	703	0.292 ± 0.004	0.13	0.38	3	-	-	-
11.25	89	0.376 ± 0.008	0.27	0.39	0	-	-	-

Notes. Same as Table E.5 but for the colour classification criterion at 0.6 instead of 0.7.

Table E.16: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments& walls, and clusters for a different classification of the colour of the galaxies.

$\log_{10} M_\star [M_\odot]$	$\Delta[M/H]_M$			
	Red (> 0.6)		Blue (≤ 0.6)	
	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids				
8.25	-	-	-	-
8.75	-	-	0.03 ± 0.05	0.6
9.25	-	-	0.12 ± 0.03	4.0
9.75	0.125 ± 0.013	9.6	0.086 ± 0.022	3.9
10.25	0.127 ± 0.009	14.1	-0.01 ± 0.04	-0.2
10.75	0.082 ± 0.013	6.3	-	-
11.25	-	-	-	-
(b) Clusters - Voids				
8.25	-	-	-	-
8.75	-	-	0.15 ± 0.05	3.0
9.25	-	-	0.315 ± 0.023	13.7
9.75	0.103 ± 0.016	6.4	0.150 ± 0.015	10.0
10.25	0.09 ± 0.01	9.0	0.018 ± 0.021	0.9
10.75	0.066 ± 0.013	5.1	-	-
11.25	-	-	-	-

Notes. Same as Table E.6 but for the colour classification criterion at 0.6 instead of 0.7.

Table E.17: Stellar mass-metallicity relation for volume-limited sub-samples.

$\log_{10} M_\star [\text{M}_\odot]$	n	All				[M/H] _M				LT-SFH			
		p_{50}	p_{16}	p_{84}		n	ST-SFH			p_{50}	p_{16}	p_{84}	
							p_{50}	p_{16}	p_{84}				
(a) Voids													
8.25	3	-	-	-	1	-	-	-	-	2	-	-	-
8.75	43	-0.77±0.04	-1.17	-0.37	5	-	-	-	-	38	-0.77±0.04	-1.20	-0.43
9.25	65	-0.59±0.03	-1.00	-0.20	15	-0.29±0.07	-0.38	-0.09	50	-0.75±0.03	-1.02	-0.26	
9.75	137	-0.226±0.015	-0.70	0.01	51	-0.079±0.023	-0.33	0.06	86	-0.425±0.019	-0.81	-0.05	
10.25	95	-0.026±0.015	-0.24	0.21	56	0.002±0.019	-0.16	0.24	39	-0.063±0.024	-0.47	0.17	
10.75	19	0.20±0.03	0.10	0.35	16	0.24±0.03	0.06	0.36	3	-	-	-	
11.25	0	-	-	-	0	-	-	-	0	-	-	-	
(b) Filaments & walls													
8.25	14	-0.98±0.06	-1.29	-0.53	0	-	-	-	-	14	-0.98±0.06	-1.29	-0.53
8.75	127	-0.736±0.021	-1.16	-0.28	32	-0.49±0.04	-0.74	-0.04	95	-0.840±0.024	-1.20	-0.43	
9.25	290	-0.471±0.012	-0.98	-0.10	65	-0.239±0.024	-0.57	-0.02	225	-0.567±0.014	-1.02	-0.20	
9.75	445	-0.176±0.008	-0.50	0.06	194	-0.056±0.011	-0.25	0.11	251	-0.299±0.011	-0.68	-0.05	
10.25	489	0.076±0.006	-0.15	0.26	287	0.099±0.008	-0.09	0.29	202	0.04±0.01	-0.30	0.20	
10.75	247	0.290±0.006	0.10	0.39	199	0.325±0.007	0.16	0.39	48	0.180±0.018	-0.07	0.27	
11.25	16	0.388±0.02	0.32	0.40	14	0.390±0.02	0.37	0.40	2	-	-	-	
(c) Clusters													
8.25	2	-	-	-	0	-	-	-	-	2	-	-	-
8.75	40	-0.55±0.03	-0.99	-0.16	13	-0.18±0.06	-0.40	-0.05	27	-0.72±0.04	-1.06	-0.30	
9.25	196	-0.19±0.01	-0.47	0.00	93	-0.132±0.014	-0.32	0.05	103	-0.295±0.016	-0.60	-0.05	
9.75	424	-0.026±0.006	-0.24	0.17	236	-0.006±0.008	-0.20	0.20	188	-0.06±0.01	-0.40	0.12	
10.25	404	0.168±0.006	-0.05	0.31	279	0.227±0.007	0.01	0.34	125	0.095±0.012	-0.21	0.23	
10.75	176	0.339±0.006	0.20	0.39	145	0.363±0.007	0.28	0.40	31	0.206±0.02	0.04	0.28	
11.25	6	-	-	-	6	-	-	-	0	-	-	-	

Notes. Same as Table E.1 but for volume-limited sub-samples with redshifts between 0.01 and 0.03.

Table E.18: Differences of the stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for volume-limited sub-samples.

$\log_{10} M_\star [\text{M}_\odot]$	All				$\Delta[\text{M}/\text{H}]_M$							
	Δp_{50}	σ	ST-SFH		Δp_{50}	σ	LT-SFH		Δp_{50}	σ		
			Δp_{50}	σ			Δp_{50}	σ				
(a) Filaments & walls - Voids												
8.25	-	-	-	-	-	-	-	-	-	-	-	-
8.75	0.04±0.04	1.0	-	-	-	-	-0.07±0.05	-1.4	-	-	-	-
9.25	0.12±0.03	4.0	0.05±0.07	0.7	0.18±0.03	6.0	-	-	-	-	-	-
9.75	0.050±0.017	2.9	0.02±0.03	0.7	0.126±0.022	5.7	-	-	-	-	-	-
10.25	0.102±0.016	6.4	0.097±0.02	4.8	0.11±0.03	3.7	-	-	-	-	-	-
10.75	0.09±0.03	3.0	0.09±0.03	3.0	-	-	-	-	-	-	-	-
11.25	-	-	-	-	-	-	-	-	-	-	-	-
(b) Clusters - Voids												
8.25	-	-	-	-	-	-	-	-	-	-	-	-
8.75	0.22±0.05	4.4	-	-	0.06±0.06	1.0	-	-	-	-	-	-
9.25	0.40±0.03	13.3	0.15±0.07	2.1	0.46±0.03	15.3	-	-	-	-	-	-
9.75	0.200±0.016	12.5	0.07±0.02	3.5	0.363±0.022	16.5	-	-	-	-	-	-
10.25	0.195±0.016	12.2	0.225±0.02	11.2	0.16±0.03	5.3	-	-	-	-	-	-
10.75	0.14±0.03	4.7	0.12±0.03	4.0	-	-	-	-	-	-	-	-
11.25	-	-	-	-	-	-	-	-	-	-	-	-

Notes. Same as Table E.2 but for volume-limited sub-samples with redshifts between 0.01 and 0.03.

Table E.19: Luminosity-weighted stellar mass-metallicity relation for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_L$											
	All				ST-SFH				LT-SFH			
	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids												
8.25	4	-	-	-	1	-	-	-	3	-	-	-
8.75	56	-0.875±0.02	-1.23	-0.54	8	-	-	-	48	-0.863±0.022	-1.13	-0.54
9.25	159	-0.772±0.012	-1.04	-0.36	40	-0.847±0.022	-1.01	-0.41	119	-0.733±0.014	-1.05	-0.36
9.75	363	-0.354±0.007	-0.70	-0.05	127	-0.309±0.011	-0.71	-0.04	236	-0.387±0.009	-0.69	-0.05
10.25	309	-0.099±0.007	-0.40	0.15	187	-0.082±0.008	-0.36	0.16	122	-0.116±0.011	-0.42	0.14
10.75	91	0.14±0.01	-0.14	0.33	68	0.204±0.011	-0.11	0.35	23	-0.017±0.024	-0.30	0.16
11.25	4	-	-	-	3	-	-	-	1	-	-	-
(b) Filaments & walls												
8.25	18	-0.87±0.03	-1.26	-0.30	3	-	-	-	15	-0.91±0.04	-1.28	-0.81
8.75	160	-0.878±0.012	-1.21	-0.51	40	-0.946±0.02	-1.28	-0.66	120	-0.841±0.014	-1.18	-0.45
9.25	649	-0.656±0.006	-1.03	-0.26	159	-0.761±0.011	-1.05	-0.21	490	-0.635±0.007	-1.01	-0.27
9.75	1600	-0.289±0.003	-0.70	-0.02	643	-0.174±0.005	-0.58	0.02	957	-0.373±0.005	-0.75	-0.07
10.25	2216	-0.068±0.002	-0.40	0.16	1273	-0.043±0.003	-0.36	0.19	943	-0.116±0.004	-0.46	0.14
10.75	1593	0.1644±0.0024	-0.11	0.33	1150	0.210±0.003	-0.07	0.35	443	0.044±0.005	-0.22	0.22
11.25	213	0.316±0.005	0.13	0.38	184	0.337±0.005	0.14	0.38	29	0.221±0.019	-0.02	0.28
(c) Clusters												
8.25	2	-	-	-	0	-	-	-	2	-	-	-
8.75	41	-0.522±0.022	-1.09	-0.14	13	-0.31±0.04	-0.74	-0.12	28	-0.64±0.03	-1.12	-0.17
9.25	265	-0.216±0.008	-0.65	-0.02	113	-0.144±0.012	-0.43	0.00	152	-0.275±0.011	-0.77	-0.04
9.75	972	-0.050±0.004	-0.30	0.11	527	-0.039±0.005	-0.22	0.12	445	-0.070±0.006	-0.41	0.10
10.25	1282	0.105±0.003	-0.12	0.25	861	0.114±0.003	-0.09	0.28	421	0.090±0.005	-0.21	0.21
10.75	706	0.248±0.003	0.05	0.35	542	0.276±0.003	0.10	0.36	164	0.148±0.008	-0.05	0.26
11.25	89	0.347±0.007	0.18	0.38	83	0.354±0.007	0.22	0.38	6	-	-	-

Notes. Same as Table E.1 but for the stellar metallicity calculated as the luminosity-weighted average.

Table E.20: Luminosity-weighted stellar mass-metallicity relation for different star formation history types.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_L$											
	All				ST-SFH				LT-SFH			
	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids												
8.25	4	-	-	-	1	-	-	-	3	-	-	-
8.75	56	-0.875±0.02	-1.23	-0.54	8	-	-	-	48	-0.863±0.022	-1.13	-0.54
9.25	159	-0.772±0.012	-1.04	-0.36	40	-0.847±0.022	-1.01	-0.41	119	-0.733±0.014	-1.05	-0.36
9.75	363	-0.354±0.007	-0.70	-0.05	127	-0.309±0.011	-0.71	-0.04	236	-0.387±0.009	-0.69	-0.05
10.25	309	-0.099±0.007	-0.40	0.15	187	-0.082±0.008	-0.36	0.16	122	-0.116±0.011	-0.42	0.14
10.75	91	0.14±0.01	-0.14	0.33	68	0.204±0.011	-0.11	0.35	23	-0.017±0.024	-0.30	0.16
11.25	4	-	-	-	3	-	-	-	1	-	-	-
(b) Filaments & walls												
8.25	18	-0.87±0.03	-1.26	-0.30	3	-	-	-	15	-0.91±0.04	-1.28	-0.81
8.75	160	-0.878±0.012	-1.21	-0.51	40	-0.946±0.02	-1.28	-0.66	120	-0.841±0.014	-1.18	-0.45
9.25	649	-0.656±0.006	-1.03	-0.26	159	-0.761±0.011	-1.05	-0.21	490	-0.635±0.007	-1.01	-0.27
9.75	1600	-0.289±0.003	-0.70	-0.02	643	-0.174±0.005	-0.58	0.02	957	-0.373±0.005	-0.75	-0.07
10.25	2216	-0.068±0.002	-0.40	0.16	1273	-0.043±0.003	-0.36	0.19	943	-0.116±0.004	-0.46	0.14
10.75	1593	0.1644±0.0024	-0.11	0.33	1150	0.210±0.003	-0.07	0.35	443	0.044±0.005	-0.22	0.22
11.25	213	0.316±0.005	0.13	0.38	184	0.337±0.005	0.14	0.38	29	0.221±0.019	-0.02	0.28
(c) Clusters												
8.25	2	-	-	-	0	-	-	-	2	-	-	-
8.75	41	-0.522±0.022	-1.09	-0.14	13	-0.31±0.04	-0.74	-0.12	28	-0.64±0.03	-1.12	-0.17
9.25	265	-0.216±0.008	-0.65	-0.02	113	-0.144±0.012	-0.43	0.00	152	-0.275±0.011	-0.77	-0.04
9.75	972	-0.050±0.004	-0.30	0.11	527	-0.039±0.005	-0.22	0.12	445	-0.070±0.006	-0.41	0.10
10.25	1282	0.105±0.003	-0.12	0.25	861	0.114±0.003	-0.09	0.28	421	0.090±0.005	-0.21	0.21
10.75	706	0.248±0.003	0.05	0.35	542	0.276±0.003	0.10	0.36	164	0.148±0.008	-0.05	0.26
11.25	89	0.347±0.007	0.18	0.38	83	0.354±0.007	0.22	0.38	6	-	-	-

Notes. Same as Table E.1 but for the stellar metallicity calculated as the luminosity-weighted average.

Table E.21: Luminosity-weighted stellar mass-metallicity relation for different morphologies.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_L$							
	Elliptical				Spiral			
	n	p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}	p_{84}
(a) Voids								
8.25	0	-	-	-	3	-	-	-
8.75	3	-	-	-	45	-0.865 ± 0.022	-1.23	-0.50
9.25	21	-0.81 ± 0.03	-1.10	-0.16	111	-0.731 ± 0.015	-0.99	-0.36
9.75	95	-0.130 ± 0.012	-0.44	0.02	189	-0.48 ± 0.01	-0.72	-0.18
10.25	119	0.057 ± 0.009	-0.18	0.24	135	-0.215 ± 0.011	-0.42	-0.03
10.75	37	0.243 ± 0.013	0.10	0.36	32	-0.032 ± 0.021	-0.22	0.16
11.25	1	-	-	-	2	-	-	-
(b) Filaments & walls								
8.25	1	-	-	-	9	-	-	-
8.75	13	-0.68 ± 0.04	-1.24	-0.15	95	-0.889 ± 0.016	-1.22	-0.52
9.25	78	-0.383 ± 0.015	-1.02	-0.15	383	-0.678 ± 0.008	-1.03	-0.30
9.75	475	-0.113 ± 0.006	-0.45	0.06	683	-0.435 ± 0.006	-0.80	-0.15
10.25	719	0.078 ± 0.004	-0.13	0.23	839	-0.223 ± 0.004	-0.53	-0.00
10.75	641	0.252 ± 0.003	0.07	0.35	504	-0.007 ± 0.005	-0.25	0.20
11.25	80	0.319 ± 0.008	0.17	0.38	29	0.130 ± 0.018	-0.04	0.30
(c) Clusters								
8.25	0	-	-	-	2	-	-	-
8.75	8	-	-	-	31	-0.57 ± 0.03	-1.10	-0.17
9.25	113	-0.096 ± 0.012	-0.27	0.05	126	-0.442 ± 0.013	-0.88	-0.11
9.75	525	-0.020 ± 0.005	-0.17	0.13	304	-0.170 ± 0.007	-0.54	0.05
10.25	766	0.143 ± 0.003	0.01	0.27	314	-0.047 ± 0.007	-0.38	0.14
10.75	360	0.273 ± 0.004	0.16	0.35	170	0.104 ± 0.007	-0.11	0.28
11.25	39	0.347 ± 0.011	0.14	0.38	12	0.227 ± 0.021	0.12	0.35

Notes. Same as Table E.3 but for the stellar metallicity calculated as the luminosity-weighted average.

Table E.22: Differences of the luminosity-weighted stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for different morphologies.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_L$			
	Elliptical		Spiral	
	Δp_{50}	σ	Δp_{50}	σ
(a) Filaments & walls - Voids				
8.25	-	-	-	-
8.75	-	-	-0.02 ± 0.03	-0.7
9.25	0.42 ± 0.03	14.0	0.052 ± 0.017	3.1
9.75	0.017 ± 0.014	1.2	0.045 ± 0.012	3.8
10.25	0.02 ± 0.01	2.0	-0.009 ± 0.012	-0.7
10.75	0.009 ± 0.014	0.6	0.026 ± 0.021	1.2
11.25	-	-	-	-
(b) Clusters - Voids				
8.25	-	-	-	-
8.75	-	-	0.29 ± 0.03	9.7
9.25	0.71 ± 0.03	23.7	0.289 ± 0.019	15.2
9.75	0.110 ± 0.013	8.5	0.309 ± 0.013	23.8
10.25	0.086 ± 0.01	8.6	0.168 ± 0.013	12.9
10.75	0.030 ± 0.014	2.1	0.136 ± 0.022	6.2
11.25	-	-	-	-

Notes. Same as Table E.4 but for the stellar metallicity calculated as the luminosity-weighted average.

Table E.23: Luminosity-weighted stellar mass-metallicity relation for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$[\text{M}/\text{H}]_L$						
	n	Red ($g - r > 0.7$)			Blue ($g - r \leq 0.7$)		
		p_{50}	p_{16}	p_{84}	n	p_{50}	p_{16}
(a) Voids							
8.25	0	-	-	-	4	-	-
8.75	0	-	-	-	56	-0.875±0.02	-1.23
9.25	4	-	-	-	155	-0.779±0.012	-1.04
9.75	83	-0.109±0.013	-0.31	0.03	280	-0.472±0.008	-0.73
10.25	185	0.032±0.008	-0.23	0.22	124	-0.257±0.011	-0.46
10.75	84	0.169±0.011	-0.11	0.34	7	-	-
11.25	4	-	-	-	0	-	-
(b) Filaments & walls							
8.25	2	-	-	-	16	-0.90±0.04	-1.27
8.75	5	-	-	-	155	-0.888±0.012	-1.21
9.25	35	-0.179±0.022	-0.32	-0.09	614	-0.667±0.006	-1.04
9.75	538	-0.071±0.005	-0.22	0.08	1062	-0.445±0.004	-0.80
10.25	1391	0.048±0.003	-0.20	0.22	825	-0.283±0.005	-0.60
10.75	1407	0.1938±0.0024	-0.05	0.34	186	-0.148±0.009	-0.41
11.25	213	0.316±0.005	0.13	0.38	0	-	-
(c) Clusters							
8.25	0	-	-	-	2	-	-
8.75	4	-	-	-	37	-0.573±0.022	-1.10
9.25	87	-0.074±0.013	-0.22	0.08	178	-0.366±0.011	-0.83
9.75	694	-0.010±0.004	-0.16	0.14	278	-0.263±0.008	-0.65
10.25	1139	0.125±0.003	-0.05	0.26	143	-0.262±0.011	-0.58
10.75	684	0.253±0.003	0.06	0.35	22	-0.022±0.023	-0.27
11.25	89	0.347±0.007	0.18	0.38	0	-	-

Notes. Same as Table E.5 but for the stellar metallicity calculated as the luminosity-weighted average.

Table E.24: Differences of the luminosity-weighted stellar mass-metallicity relation between galaxies in voids, filaments & walls, and clusters for different colours.

$\log_{10} M_\star [\text{M}_\odot]$	$\Delta[\text{M}/\text{H}]_L$			
	Red ($g - r > 0.7$)	Blue ($g - r \leq 0.7$)		
		Δp_{50}	σ	Δp_{50}
(a) Filaments & walls - Voids				
8.25	-	-	-	-
8.75	-	-	-0.012±0.023	-0.5
9.25	-	-	0.112±0.013	8.6
9.75	0.038±0.014	2.7	0.028±0.009	3.1
10.25	0.016±0.009	1.8	-0.026±0.012	-2.2
10.75	0.025±0.011	2.3	-	-
11.25	-	-	-	-
(b) Clusters - Voids				
8.25	-	-	-	-
8.75	-	-	0.30±0.03	10.0
9.25	-	-	0.414±0.016	25.9
9.75	0.099±0.014	7.1	0.209±0.012	17.4
10.25	0.093±0.009	10.3	-0.006±0.016	-0.4
10.75	0.084±0.011	7.6	-	-
11.25	-	-	-	-

Notes. Same as Table E.6 but for the stellar metallicity calculated as the luminosity-weighted average.