Galaxy properties in the cosmic web of EAGLE simulation

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ABSTRACT
We investigate the dependence of the galaxy properties on cosmic web environments using the most up-to-date hydrodynamic simulation: Evolution and Assembly of Galaxies and their Environments (EAGLE). The baryon fractions in haloes and the amplitudes of the galaxy luminosity function decrease going from knots to filaments to sheets to voids. Interestingly, the value of $L^*$ varies dramatically in different cosmic web environments. At $z = 0$, we find a characteristic halo mass of $10^{12} h^{-1} M_\odot$, below which the stellar-to-halo mass ratio is higher in knots while above which it reverses. This particular halo mass corresponds to a characteristic stellar mass of $8 \times 10^{10} h^{-1} M_\odot$. Below the characteristic stellar mass central galaxies have redder colors, lower sSFRs and higher metallicities in knots than those in filaments, sheets and voids, while above this characteristic stellar mass, the cosmic web environmental dependences either reverse or vanish. Such dependences can be attributed to the fact that the active galaxy fraction decreases along voids, sheets, filaments and knots. The cosmic web dependences get weaker towards higher redshifts for most of the explored galaxy properties and scaling relations, except for the gas metallicity vs. stellar mass relation.

Key words: Cosmology: Large-scale Structure of the Universe – galaxies: general – galaxies: evolution

1 INTRODUCTION
The large scale structure (LSS) of the Universe exhibits a web-like structure, which is usually categorized into four components: voids, sheets, filaments and knots. It originates from small perturbations in the very early Universe and is shaped gradually by the large scale gravitational fields. Different components correspond to different stages of gravitational collapse. Large sheets of matter form via gravitational collapse along one principal direction, filaments form via gravitational collapse along two principal axes and knots form via gravitational collapse along three principal axes. The relatively empty regions of the Universe between knots, filaments and sheets are referred to as cosmic voids, whose density is well below the cosmic mean value. Most mass is contained in knots and filaments, while most volume is filled by voids. The relative mass fractions and filling factors of each component could evolve significantly from high to low redshifts (Cui et al. 2019; Zhu & Feng 2017a).

The cosmic web environments have influences on the halo formation history and the halo properties. Haloes in knots tend to be older than those in other web environments, and massive haloes in knots have higher spin than those in filaments, sheets and voids (e.g. Hahn et al. 2007). The halo mass function strongly depends on the web environment such that it has a much higher amplitude in filaments than in voids (e.g. Ganeshaiah Veena et al. 2018). Recently, the large-scale cosmic web environment was also found to correlate with the orientation of haloes (e.g. Zhang et al. 2009; Codis et al. 2012; Ganeshaiah Veena et al. 2018). However, the role the cosmic web plays in galaxy formation is not clear. Recent work found that the blue galaxy fraction and the star formation rate of blue galaxies decline from the field to knots at low redshift, but the dependence disappears at higher redshifts (Darvish et al. 2017a; Kraljic et al. 2018). Similar trends are also found in the state-of-the-art hydrodynamical simulation HORIZON-AGN (Dubois et al. 2014). Using the Sloan Digital Survey (SDSS), Chen et al. (2017) demonstrated that red, massive galaxies tend to reside in filaments more than blue, less-massive galaxies.

It has been suggested that the cosmic web shapes the
galaxy properties primarily through the strong dependence of the galaxy properties on the mass of their host halo (e.g. Gay et al. 2010; Goh et al. 2019; Yan et al. 2013). This is also supported by Eardley et al. (2015) who found in Galaxy And Mass Assembly survey (GAMA) that the strong variation of galaxy properties in different cosmic web structures vanishes when comparing at the same local density. However, by using SDSS data, Poudel et al. (2017) found that at a fixed halo mass, central galaxies in filaments have redder colors, higher stellar mass, lower specific star formation rates and higher abundances of elliptical galaxies compared to those outside the filaments. Observationally it is hard to measure the halo mass for an individual galaxy while stacking methods could smear out the cosmic web dependence if it is not strong enough. Theoretical work using cosmological hydro-dynamical simulations can provide more clues to such studies. Using IllustrisTNG, Martizzi et al. (2020) found at a given halo mass, galaxies with stellar masses lower than the median value are more likely to be found in voids and sheets, whereas galaxies with stellar masses higher than the median are more likely to be found in filaments and knots. Liao & Gao (2019) found that haloes in filament have higher baryon fractions and stellar mass fractions compared to those in the field.

In recent years, cosmological hydro-dynamical simulations have gained great success in reproducing many observed galaxy properties (e.g. Vogelsberger et al. 2014; Schaye et al. 2015). In such simulations the cosmic web effect is taken into account automatically. Here we use the state-of-art cosmological hydrodynamical simulation, Evolution and Assembly of Galaxies and their Environments (EAGLE) to disentangle the connections between galaxies, dark matter haloes and the cosmic web and revisit the relation between galaxy properties and geometric cosmic web structures.

This paper is organized as follows. We introduce the EAGLE simulation and describe the environmental classification method in Section 2. The cosmic-web dependence of the various baryonic components and the scaling relations are presented in Section 3 and Section 4, respectively. In Section 5, we summarize our results.

# 2 SIMULATION AND METHODS

## 2.1 EAGLE simulation

The EAGLE simulation consists of a series of cosmological simulations performed with a modified version of the N-body Tree-PM smoothed particle hydrodynamics (SPH) code GADGET-3 (Springel 2005). In this paper we use the largest volume EAGLE simulation, labelled as L100N1504, which was carried out in a box of 100\,Mpc each side, tracing the largest volume EAGLE simulation, labelled as L100N1504, code GADGET-3 (Springel 2005). In this paper we use the N-body Tree-PM smoothed particle hydrodynamics (SPH) method (Davis et al. 1985) to simulate the particle data to generate FOF groups by linking particles separated by 0.2 times the average particle separation. In each FOF group, the SUBFIND (Springel et al. 2001; Dolag et al. 2009) algorithm was applied to identify the self-bound particles as subhalos/substructures. M200 is adopted to refer to the virial mass, which is the total mass within R200 within which the average density is 200 times the critical density. Galaxies reside in the center of each substructure. The stellar mass is defined as the total mass of stellar particles within 30\,pkpc radii of the centre of each subhalo. The luminosity and color are calculated using a stellar population synthesis model taking into account the SFR history and metallicity of each star particle (Trayford et al. 2015). In the public EAGLE simulation catalog, it provides magnitudes in the five rest-frame SDSS bands and 3 UKIRT bands. This sample contains absolute rest-frame magnitudes for all galaxies with M_*>10^{8.5}M_{\odot}. No dust attenuation has been included.

## 2.2 Environmental classification

The cosmic web present itself in large-scale surveys, as well as in cosmological simulations. Many different approaches to classify the cosmic web elements have been developed in the literature. The tidal tensor and the velocity shear tensor are two of the most popular quantities to identify the cosmic web (see Libeskind et al. (2018) for a comparison of different classifications of the cosmic web). Here we follow Hahn et al. (2007) to use the tidal tensor to classify the four cosmic web elements.

A region is identified as void, sheet, filament or knot according to the number of dimensions that this particular patch collapses along. The tidal tensor T_ij is given by the Hessian matrix of the gravitational potential φ:

$$T_{ij} = \frac{\partial^2 \phi}{\partial r_i \partial r_j}.$$  \hspace{1cm} (1)

The gravitational potential φ from the matter density field is obtained using the Poisson’s equation:

$$\nabla^2 \phi = \delta,$$  \hspace{1cm} (2)

where \(\delta\) denotes the mean mass density of the universe and \(\delta = \rho / \bar{\rho} - 1\) denotes the density contrast. In practice, we split the simulation box into 256^3 cartesian cells and estimate the density and density contrast by assigning the particles to each cell using the cloud-in-cell method (Sefusatti et al. 2016). We further smooth the discrete density field with a Gaussian filter of width Rʃ = 1.25\,Mpc/h.

There are three eigenvalues of the tidal tensor T_{ij}, \(\lambda_1 \geq \lambda_2 \geq \lambda_3\). Hahn et al. (2007) used the number of positive eigenvalues of \(T_{ij}\) (\(\lambda_{ij} > 0\)) to classify the four possible environments. However, in reality, such criteria lead to an under-estimate of the filling factor of the voids. We follow Forero-Romero et al. (2009) to introduce an eigenvalue...
threshold \( \lambda_h \), as a free parameter and define the cosmic web elements as following:

(i) Void: all eigenvalues \( \lambda_i \) below the threshold \( \lambda_{th} \) (\( \lambda_{th} \geq \lambda_{1} \geq \lambda_{2} \geq \lambda_{3} \)).

(ii) Sheets: two eigenvalues \( \lambda_i \) below the threshold \( \lambda_{th} \) (\( \lambda_{1} \geq \lambda_{th} \geq \lambda_{2} \geq \lambda_{3} \)).

(iii) Filaments: one eigenvalues \( \lambda_i \) below the threshold \( \lambda_{th} \) (\( \lambda_{1} \geq \lambda_{2} \geq \lambda_{th} \geq \lambda_{3} \)).

(iv) Knots: all eigenvalues \( \lambda_i \) above the threshold (\( \lambda_{1} \geq \lambda_{2} \geq \lambda_{3} \geq \lambda_{th} \)).

Here we adopt a fixed \( \lambda_{th} = 0.25 \) at \( z = 0, 1, 3.01, 5.97 \). We test our results using different \( \lambda_{th} \) at different redshifts and find the results are in qualitative agreement with those with the fixed \( \lambda_{th} \). This is consistent with the conclusions reached by Zhu & Feng (2017b). In Fig. 1, we show the map of the overdensity and the corresponding cosmic web in a slice 0.265Mpc/h thick at \( z = 0 \). The cosmic structures are well captured by the tidal tensor method.

### 3 BARYONIC PROPERTIES IN THE COSMIC WEB

#### 3.1 Total baryons

Table 1 summarizes the volume fractions and mass fractions in different cosmic web environments. At \( z = 0 \) the volume fractions are 0.407, 0.416, 0.168, 0.010 among the void, sheets, filaments and knots, while the total mass fractions located in each structure element are 0.089, 0.239, 0.392, 0.279. This is consistent with the results using Illustris simulation that most matter resides either in haloes or in filaments but very little in voids, though the voids contribute a significant fraction of the total volume (Haider et al. 2016). Both the volume fraction and mass fraction of voids increase with redshift, whilst they decrease in knots and filaments.

For the baryon component, as expected, it is a good tracer of the total matter at large scales across cosmic time (Cen & Ostriker 1999; Davé et al. 2001; Eckert et al. 2015). We find that the baryon fraction in knots and filaments decreases dramatically with redshifts. Cui et al. (2019) reached similar conclusions as ours, though their classification of the cosmic web adopted a different cell size and eigenvalue threshold, indicating our results are qualitatively robust against the method of classification of the cosmic web. In addition, Cui et al. (2019) demonstrated that the baryon fraction in different components of the web and its evolution depend only very weakly on the different physics implemented in the simulations.

We further investigate the normalized baryon fraction (\( f_{\text{bar}} / \bar{f} = (M_{\text{bar}} / M_{200\text{crit}}) / (\Omega_b / \Omega_0) \)) as a function of halo mass in different cosmic web environments (Fig. 2), where \( \bar{f} \) is the universal baryonic fraction 15.7%, \( f_{\text{bar}} \) is the baryon fraction measured within \( R_{200} \). It shows that the baryonic fraction is an increasing function of the halo mass in all web environments. The strong halo mass dependence of the baryonic fraction presents itself over all the redshifts from 0 to 6. At \( z = 0 \), only in massive clusters (\( \sim 10^{14} h^{-1} M_\odot \)), the baryonic fraction does reach the universal value, while this fraction...
drops dramatically towards lower masses. At low masses, the overall baryonic fraction increases significantly with redshifts. For example, for haloes of $M_{200\text{crit}} \sim 10^{10} h^{-1} M_{\odot}$ the baryon fraction increases from 0.1 at $z \sim 0$ to 0.4 at $z \sim 5.97$. In the MassiveBlack-II simulation, Khandai et al. (2015) found an even stronger redshift evolution of the baryon fraction. Peirani et al. (2012) found a similar trend of the mean baryonic fraction in groups over cosmic time using hydrodynamical zoom-in simulations. They claimed that it is due to the lower accretion rate of dissipative gas onto the haloes compared to that of dark matter at low redshifts. Another reason for the high baryon fraction at high redshifts is that the potential well is deeper and it is thus harder to expel baryons out even for haloes of relatively low masses. On the other hand, for the massive systems (more massive than $10^{13} h^{-1} M_{\odot}$) their baryonic fractions hardly change with redshifts. Haloes of such masses have potential wells deep enough to keep most of their baryons both at low and at high redshifts.

The baryonic fraction increases from voids, sheets, filaments towards knots. For haloes of $10^{12} h^{-1} M_{\odot}$, the baryonic fraction in voids is lower than that in knots by 0.8 dex at $z=0$. It is much stronger dependence than that found by Metuki et al. (2015) who used simulations with different subgrid physics. This cosmic web dependence gets weaker towards lower masses and almost vanishes at $10^{10} h^{-1} M_{\odot}$. Fig. 2 also shows that in general the cosmic web dependence gets stronger with redshifts up to $z =3$, especially at low masses. At the highest redshift, $z=6$, the cosmic web dependence gets weaker again.

### 3.2 Stellar mass-to-halo mass ratios

In this section, we focus on the stellar mass and its relation to the cosmic web. The cosmic web dependences of the galaxy properties vs. stellar masses relations are presented in Sec. 4.

We show the stellar mass-to-halo mass ratio for central galaxies ($M_{\star, \text{central}}/M_{200\text{crit}}$) at various redshifts in Fig. 3. As presented by Schaye et al. (2015), the trend of the full sample is consistent with that inferred by the subhalo abundance matching methods (e.g. Guo et al. 2011; Moster et al. 2013) at $z = 0$. A similar analysis is applied to the total stellar mass fraction ($M_{\star, \text{group}}/M_{200\text{crit}}$, dotted curves), where the total stellar mass referred to is the total stellar masses within $R_{200}$. It peaks at $\sim 10^{12} h^{-1} M_{\odot}$ and drops fast both towards the low mass and high mass ends. Different from the stellar-to-halo mass ratio for central galaxies, the slope at high masses is much flatter for the total stellar masses. At low masses, the central and total stellar mass to halo mass ratios are almost identical, indicating that satellite galaxies and intra-cluster lights contribute more to massive systems than to low mass systems. These trends are found at redshifts up to $z \sim 3$. At $z = 6$ no high mass systems are formed due to the limited box size. The amplitudes of the central and total stellar-to-halo mass ratios decrease towards higher redshifts, consistent with the finding from the subhalo abundance matching methods.

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**Figure 2.** Baryon fraction as a function of halo mass in different cosmic web environments. The shaded regions indicate the 16th-84th percentile scatter in each corresponding halo mass bin. Red, cyan, blue and green curves donate the median values of the baryonic fractions in knots, filaments, sheets and voids, respectively. Error bars present errors on the median values estimated based on 1000 bootstrap samples. Redshifts are indicated on the top right corner of each panel.
In the top left panel, it shows that at $z = 0$ most of the corresponding web environment by the total number of galaxies. The evolution is stronger at low masses than that at high masses. At higher redshifts, more galaxies are found in voids and sheets than at lower redshifts, while less is found in knots and filaments, especially at low masses.

At $z = 0$ the central and total stellar mass-to-halo mass ratios decrease from knots to filaments to sheets and to voids for haloes below $\sim 10^{12} h^{-1} M_\odot$. In haloes of $10^{11} h^{-1} M_\odot$, where most of the dwarf galaxies reside, the ratios drop by a factor of $\sim 2$. At high masses, it is at the opposite. In knots the ratios are the lowest while in voids the ratios are the highest. At the peak location ($\sim 10^{12} h^{-1} M_\odot$), about the mass of the Milky Way’s halo, the central and total stellar mass-to-halo mass ratios do not vary between different cosmic web environments. Such environmental dependencies are also found at $z=1$, though somehow weaker than that at $z=0$. At even higher redshifts ($z > 3$), the cosmic web dependence vanishes at low masses, and no statistical results can be obtained at high masses due to the limited number of high mass systems.

### 3.3 Stellar mass functions

Most stars are locked in galaxies. The fraction of galaxies as a function of stellar mass in different cosmic web environments are shown in Fig. 4. In a given stellar mass bin, the fraction of galaxies in any cosmic web environment is calculated by dividing the number of galaxies in the corresponding web environment by the total number of galaxies. In the top left panel, it shows that at $z = 0$ most of the massive galaxies reside in knots, consistent with previous results (Metuki et al. 2015; Eardley et al. 2015). For galaxies of the Milky Way mass and dwarf galaxies, most reside in filaments, though a comparable, yet slightly lower fraction reside in knots. This is also found by Eardley et al. (2015) using GAMA data and Metuki et al. (2015) using simulations. Only a very small fraction of galaxies reside in voids at all masses considered here. The fractions in different cosmic web environments are similar at $z = 1$. At higher redshifts, more galaxies are found in voids and sheets than at lower redshifts, while less is found in knots and filaments, especially at low masses.

The dependence on the cosmic web is more significant when converting the total number of galaxies to the volume number density (the stellar mass functions) as shown in Fig. 5. At $z = 0$, the number density drops by two orders of magnitude from knots to voids. Such strong dependences are also found by theoretical work (Metuki et al. 2015) and observational work (Alpaslan et al. 2015). Interestingly, we find the mass at the knee (corresponding to $L^*$) decreases by a factor of $\sim 8$, with the value of $10^{10.8} h^{-1} M_\odot$ in the knots and $10^{10.0} h^{-1} M_\odot$ in voids. This change is dramatic given that a factor of $\sim 1$ (e.g. Beare et al. 2019). As for the number fractions, the cosmic web environmental dependence of the stellar mass functions gets weaker at high redshifts. The evolution is stronger at low masses than that at high masses.
Figure 4. Fractions of galaxies in different web environments as a function of stellar mass at \( z \sim 0, 1, 3.01, 5.97 \). Red, cyan, blue and green regions represent the fractions in knots, filaments, sheets and voids, respectively. Redshifts are indicated at the top right corner of each panel.

Figure 5. The stellar mass functions in different cosmic web environments at different redshifts. Solid black curves are the overall stellar mass functions, while dashed ones are those for different environments with the same color coding as those in Fig. 4.
For each $M_{200\text{cmt}}$ at a given redshift, we calculate the average value of $X$, $\langle X | M_{200\text{cmt}} \rangle$, in advance. $R_X$ quantifies the off-set of the property $X$ that deviates from the expected values for given halo masses.

For any quantity $X$ that depends directly only on halo mass, the mean of $R_X$ will equal 0 for any subsample, including one defined by stellar mass and environment, as below. By using $R_X$, we can test whether an apparent dependence of $X$ on environment at a given stellar mass is entirely driven by the dependence of halo mass on environment at given stellar mass, or whether there is some remaining dependence on environment at fixed halo mass.

### 4.1 Color vs. stellar mass

Color is one of the most important observables for it is key to understand galaxies’ star formation history. Previous studies found that galaxies on the color vs. stellar mass diagram can be grouped into three categories, blue cloud (active), red sequence (passive) and green valley (those in between). Galaxies in low density environments (e.g. filaments, sheets and voids) tend to be bluer, while those in high density environments (knots) tend to be redder (Poudel et al. 2017). However, this could be caused by the fact that in low density regions galaxies and their host haloes are smaller, while smaller galaxies are in general bluer (Cucciati et al. 2011; Baldry et al. 2006).

Fig. 7 shows the $g - r$ color vs. stellar mass relation as a function of the environments and stellar mass. Observed colors can be influenced by dust extinction and we thus use the intrinsic color. For the color is a dimensionless quantity and can be 0 in many cases, instead of using Eq. (3) we adopt a slightly different quantity to remove the halo dependence. For each galaxy, we calculate $R_C = (g - r) - (g - r)|_{M_{200\text{cmt}}}$.

At $z=0$, for galaxies less massive than $1.8\times10^{10} h^{-1} M_{\odot}$, it shows a clear dependence on environments, especially for those in knots. Galaxies in knots are redder than those in voids by $0.08 \text{mag}$ ($1.8 \sigma$). This is related to the fraction of active galaxies in different environments which we will discuss in more detail in the next subsection. At stellar masses above $1.8\times10^{10} h^{-1} M_{\odot}$, there is no clear cosmic web environmental dependence. The difference between voids and sheets is weak across all the stellar mass ranges.

The dependence on environments vanishes for galaxies at high redshifts: $z = 1.3$, and 6 at all masses. This is consistent with Darvish et al. (2017b) who found no cosmic web dependence of galaxy color in the COSMOS fields at $z = 1$.

### 4.2 Specific star formation rate vs. stellar mass

Colors are influenced by the star formation history, especially the current star formation rate. Fig. 8 shows the specific star formation rate (sSFR) as a function of stellar mass and cosmic environments. Similar to the color vs. stellar mass relation, at $z=0$, the cosmic environmental dependence is the strongest for galaxies with stellar mass less than $1.8\times10^{10} h^{-1} M_{\odot}$. The sSFR is lower by 50% in knots than that in voids. At higher masses, given the large scatter, we can not find clear environmental dependence. This is consistent with the observational results by Poudel et al. (2017) who found central galaxies in low-density environments with higher sSFR compared to those in high-density environments at a fixed group mass using group catalogs.
Figure 7. The deviation of $g - r$ color from the expected values as a function of stellar mass for central galaxies in different environments. Red, cyan, blue and green curves donate the median value of the deviation in knots, filaments, sheets and voids, respectively. Scatters are for each galaxy with the same color coding as the curves. Error bars are generated using the bootstrap method. Redshifts are indicated at the top right corner of each panel.

Figure 8. The deviation of specific star formation rate from the expected values as a function of stellar mass for central galaxies in different environments. Red, cyan, blue and green curves donate the median value of the deviation in knots, filaments, sheets and voids, respectively. Scatters are for each galaxy with the same color coding as the curves. Error bars are generated using the bootstrap method. Redshifts are indicated at the top right corner of each panel.
The deviation of the sSFR from the expected values as a function of stellar mass in different environments for active (sSFR$>10^{-11}$/yr, left panel) and passive (sSFR$<10^{-11}$/yr, right panel) galaxies at $z=0$. Red, cyan, blue and green curves donate the median value of the deviation in knots, filaments, sheets and voids, respectively. Error bars are generated using the bootstrap method.

The left panel in Fig. 9 shows the environmental dependence of the sSFR for active galaxies at $z=0$. For active galaxies, no environmental dependences present themselves except for those with masses $\sim 2.8 \times 10^9 h^{-1} M_\odot$ where the sSFR of central galaxies is lower in voids than in other cosmic web environments. At higher masses, such dependence vanishes. For passive galaxies, as shown in the right panel, there is no environmental dependence over all the stellar mass ranges considered.

The rather low sSFR in knots in the first panel of Fig. 8 might be explained by their low fraction of active galaxies. The average active galaxy fraction increases from knots, filaments to sheets and voids, ranging from 0.58, 0.81, 0.87, 0.88, respectively. When taking into account the expected active galaxy fraction for any given halo mass and the number of haloes of the given mass in each cosmic web environment, the derived expected active galaxy fractions are 0.66, 0.78, 0.87, 0.91 in knots, filaments, sheets, voids, respectively. To make it more clear, we redo this analysis in each stellar mass bin and subtract the direct measurement of the active galaxy fraction from the correspondingly expected active galaxy fraction. The results are presented in Fig. 10. It shows that at masses below $1.8 \times 10^{10} h^{-1} M_\odot$, there are less active galaxies in knots than in filaments, sheets and voids. It is the low fraction of active galaxies in knots that leads to the low sSFR in knots. It also explains the redder color in knots as shown in Fig. 7. Sobral et al. (2011) have also argued that the environment is responsible for star-formation quenching in dense environments. In other words, denser environments increase the possibility of galaxies to become quenched. At high masses, on the other hand, there is instead not much difference in the active fraction in different environments. As a consequence, the cosmic web dependences of the color and sSFR also vanish.

At high redshifts, most galaxies are star-forming and there is almost no environmental dependence of the active...
fraction: at $z > 1$, the active fraction approaches 1 in all cosmic web environments. The environmental dependence of the sSFR thus vanishes.

4.3 Metallicity vs. Stellar mass

Metal enrichment is one of the most important processes in galaxy evolution which involves the gas cooling, star formation, supernova feedback, etc. Schaye et al. (2015) found the gas and stellar metallicity vs. stellar mass relations in EAGLE are in broad agreement with observations for galaxies more massive than $10^9 M_\odot$, though at the low mass end the relations are not as steep as the observed ones.

Fig. 11 shows the stellar metallicity vs. stellar mass relation in the different cosmic web environment. At low masses ($M_\star \sim 1.8 \times 10^{10} h^{-1} M_\odot$) the metallicity is higher in knots than in other environments. This is related to the relation between stellar mass, metallicity and star formation rate, as discovered in previous works (e.g. Ellison et al. 2008; Manucci et al. 2010; Yates et al. 2012; De Rossi et al. 2015). Specifically, De Rossi et al. (2017) found that in EAGLE simulations the metallicity of low-mass systems decreases with SFR for a given stellar mass. The high metallicity in knots is thus consistent with their low star formation rates as shown in Fig. 8. Such environmental dependence is much weaker at high redshifts.

Different from the relation with sSFR and color, the stellar metallicity vs. stellar mass relation shows a strong dependence on cosmic environments at high masses. The metallicity increases from knots, filaments, sheets towards voids. This is consistent with the increasing central stellar mass-to-halo mass ratios along knots, filaments, sheets and voids, i.e. more metals are generated if more stars are formed. Such dependence persists up to $z=3$. At even higher redshifts, there are not enough samples to make solid conclusions.

As for the sSFR, we split the galaxies into active and passive subsamples at $z = 0$. The transition mass at $M_\star \sim 1.8 \times 10^{10} h^{-1} M_\odot$ presents itself both for the active and passive galaxies, below which the metallicity is higher in knots while above which the metallicity is lower in knots. The environmental dependence is stronger for passive galaxies than for active galaxies.

The cosmic web dependences of the gas metallicity as a function of stellar mass and redshift are presented in Fig. 13. Since there is very little gas in passive galaxies, here we focus on active galaxies. At $z=0$, at stellar masses below $1.8 \times 10^{10} h^{-1} M_\odot$ the gas metallicity is higher in knots, while at high masses the difference between different web environments disappears. Different from other scaling relations, this cosmic web dependence of gas metallicity gets stronger at higher redshifts for massive galaxies. The gas metallicity is the lowest in knots and gets higher along filaments, sheets and voids.
Figure 12. The deviation of the stellar metallicity from the expected values as a function of stellar mass in different environments for active (left panel) and passive (right panel) galaxies. Red, cyan, blue and green curves donate the median values of the deviation in knots, filaments, sheets and voids, respectively. Errors are generated using the bootstrap method.

Figure 13. Similar to Fig. 11 but for gas metallicity of active galaxies.

4.4 Combined effects of cosmic web and dark matter haloes

We remove the halo effect from the cosmic web dependence in previous sections. However, it is difficult to obtain halo mass observationally. Here we present the apparent cosmic web dependence (including halo effects, hereafter we refer to it as combined dependence) on the scaling relations. Since the cosmic environmental effect is weak at high redshifts for most of the scaling relations, we focus on results at z=0.

The top left panel of Fig. 14 shows the g-r color vs. stellar mass relations for galaxies in different environments. Galaxies are redder in knots compared to other environments at all masses. This is different from the results shown in Fig. 7 that when removing halo effects at stellar mass above $1.8 \times 10^{10} h^{-1} M_\odot$ galaxies in knots have similar colors as those in filaments, sheets and voids. Such dependences are also found in the sSFR vs. stellar mass relations (middle left panel). These can be explained by the fact that there are more massive haloes in high density regions and galaxies in
massive haloes are usually redder/with lower sSFR. The active fraction increases with stellar mass up to $\sim 3\times 10^9 h^{-1}M_\odot$ and decreases towards higher masses. This variations with stellar mass are similar to each other between voids, sheets and filaments. For those in knots, the amplitude is lower, the turn-over mass is higher, and at low masses the slope is steeper.

For a given stellar mass, the halo mass is lower in knots for those with stellar mass below $1.8 \times 10^{10} h^{-1}M_\odot$ (Fig. 6). In low mass haloes the feedback is usually more effective and it is thus easier for new formed heavy elements to escape. This compensate with the cosmic web dependence of stellar metallicity as shown in Fig. 11, resulting in the absence of variance between different environments as shown in the right top panel of Fig. 14. At high masses, the stellar metallicity decreases with environmental densities, similar to those without halo effects (Fig. 11). For the gas metallicity vs. stellar mass relation (right bottom panel of Fig. 14), there is almost no difference between voids, sheets and filaments. On the other hand, the scaling relation in knots is very different. It increases rapidly with stellar masses below $1.8 \times 10^{10} h^{-1}M_\odot$ and also decreases towards high masses. The absolute values are lower in knots both at low and high masses compared to other environments, but is higher at the turn over mass.

In summary, for the color vs. stellar mass relation and sSFR vs. stellar mass relation, the combined dependence follows the pure cosmic web dependence at low masses quanti-
tatively, while at high masses, the combined dependence is stronger. For the stellar metallicity vs. stellar mass, the combined dependence mimic the pure cosmic web dependence at high masses, but vanish at low masses. The gas metallicity vs. stellar mass relation behaves significantly different in knots compared to other environments, and the combined dependence deviate from the pure cosmic web dependence at all masses.

5 CONCLUSIONS

In this paper, we investigate the dependence of galaxy properties on different cosmic web environments and their evolution, using the EAGLE cosmological hydrodynamical simulations. We split the simulation box into $256^3$ cells and generate the web elements adopting the web classification method of Hahn et al. (2007). Here we summarize our results as follows.

We find the baryon fraction increases with halo mass in all environments, and the fraction is higher in denser regions, i.e. increasing along the sequence voids, sheets, filaments and knots. This environmental dependence persists up to redshift 6. The cosmic web dependence becomes slightly stronger at higher redshifts up to $z = 3$ and then becomes weaker towards even higher redshifts. The central and total stellar mass-to-halo mass ratios both peak at halo masses $\sim 10^{12} h^{-1} M_{\odot}$. At low masses, more stars are formed in knots than in other web environments, while at high masses, less stars are formed in knots. The cosmic web dependence of the galaxy stellar mass functions is very strong at all redshifts, with the amplitude decreasing along the sequence knots, filaments, sheets and voids. Interestingly, though the average characteristic stellar mass corresponding to $L^*$ does not evolve much since $z=1$, it changes by an order of magnitude going from knots to voids at $z=0$.

We remove the halo mass dependence and investigate the relation between the cosmic web and various scaling relations for central galaxies. We find a characteristic stellar mass of $1.8 \times 10^{10} h^{-1} M_{\odot}$, below and above which the cosmic web dependence behaves oppositely. Galaxies with stellar mass below the characteristic mass are redder, with lower active fraction, lower sSFR, and higher stellar metallicity in knots than in voids, while at stellar masses above the characteristic mass the dependences on the cosmic web either reverse or vanish. At low masses, the relatively strong web dependences of the color vs. stellar mass relation and of the sSFR vs. stellar mass relation can be attributed to the cosmic web dependence of the active galaxy fraction, i.e. the active fraction is higher in voids than in knots. For active galaxies, the stellar metallicity is higher in knots compared to other web environments for those with stellar mass below the characteristic mass.

The cosmic web dependences are weaker at higher redshifts for almost all the galaxy properties and scaling relations we explored, including the central (total) stellar-to-halo mass ratio, color vs. stellar mass relation, sSFR vs. stellar mass relation and stellar metallicity vs. stellar mass relation. But this is not the case for the gas metallicity vs. stellar mass relation. For galaxies above the characteristic stellar mass, this cosmic web dependence gets even stronger at high redshifts, decreasing along the sequence voids, sheets, filaments and knots.

The combined halo + cosmic web dependence follow the cosmic web dependence at low masses for the color/sSFR vs. stellar mass relations, but is stronger at high masses. It reverses for the stellar metallicity at high masses, the combined dependence mimic the cosmic web dependence, while at low masses, the combined dependence almost vanish. One can not use the combined dependence of gas metallicity relation vs. stellar mass relation to explore the pure cosmic web dependence at all for they behave different at all masses.

DATA AVAILABILITY

The data presented in this article are available at the EAGLE simulations public database (http://icc.dur.ac.uk/Eagle/database.php).

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