Profiles of Cosmic Filaments Since $z = 4.0$ in Cosmological Hydrodynamical Simulation

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Abstract

A large portion of the baryons at low redshifts are still missing from detection. Most of the missing baryons are believed to reside in large-scale cosmic filaments. Understanding the distribution of baryons in filaments is crucial to the search for missing baryons. We investigate the properties of cosmic filaments since $z = 4.0$ in a cosmological hydrodynamical simulation, focusing on the density and temperature profiles perpendicular to the filament spines. Our quantitative evaluation confirms the rapid growth of thick and prominent filaments after $z = 2$. We find that the local linear density of filaments shows a correlation with the local diameter since $z = 4.0$. The averaged density profiles of both dark matter and baryonic gas in filaments of different widths show self-similarity, and can be described by an isothermal single-beta model. The typical gas temperature increases as the filament width increases, and is hotter than $10^{8}$ K for filaments with width $D_{hi} \geq 4.0$ Mpc, which would be the optimal targets for the search of missing baryons via the thermal Sunyaev–Zel’dovich effect. The temperature rises significantly from the boundary to the inner core regime in filaments with $D_{hi} \geq 4.0$ Mpc, probably due to heating by accretion shock, while the temperature rises modestly in filaments with $D_{hi} < 4.0$ Mpc.

Unified Astronomy Thesaurus concepts: Large-scale structure of the universe (902); Cosmic web (330); Hydrodynamical simulations (767); Intergalactic medium (813)

1. Introduction

Baryons are expected to comprise $\sim 5\%$ of the energy density in the universe according to the concordance $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology along with observations such as the cosmic microwave background (e.g., Planck Collaboration et al. 2014). The abundance of baryonic matter at high redshifts, revealed by the Lyman-$\alpha$ (Ly$\alpha$) forest, agrees with the prediction of $\Lambda$CDM cosmology (Rauch et al. 1997; Weinberg et al. 1997). However, the baryons that have been detected at redshift $z < 2$ fall short of the expectation from the standard $\Lambda$CDM model by a substantial portion. At low redshifts, around 10% of the baryons reside in galaxies as stars and interstellar medium, and another 10% are found to be circumgalactic medium and diffuse medium in galaxy groups and clusters (Fukugita et al. 1998; Shull et al. 2012). The remaining baryons are expected to reside outside of collapsed halos. About 25%-42% of the baryons in a relatively cool state ($T \sim 10^{4}$ K) have been detected by the Ly$\alpha$ forest and broad Ly$\alpha$ absorbers, and $\sim 11\%$ have been observed by extragalactic O VI absorbers (Shull et al. 2012; Danforth et al. 2016; Tejos et al. 2016). Note that, these fractions associated with H I and O VI absorbers may have considerable uncertainties (e.g., Tuominen et al. 2021).

Overall, 30%-50% of the baryonic matter are missing from detection at low redshifts. On the other hand, cosmological simulations suggest that a significant fraction of the baryonic matter is residing in filamentary and sheet-like structures of the cosmic web (Cen & Ostriker 1999; Davé et al. 2001; Dolag et al. 2006; Haider et al. 2016; Zhu & Feng 2017a; Cui et al. 2018; Martizzi et al. 2019). Those baryons residing in filaments and sheets are predicted to be warm-hot with temperatures ranging from $10^{5}$–$10^{7}$ K, and overdensities of $\delta_{c} \sim 0 – 100$. This diffuse medium is referred to as warm-hot intergalactic medium (WHIM). In the past two decades, much effort has been made to detect this WHIM via different observational tools. Actually, those baryons detected via extragalactic O VI absorbers (e.g., Danforth et al. 2016) should be WHIM with temperature ranging from $10^{5} – 10^{5.5}$ K. However, it is very challenging to observe WHIM in hotter phases with $T > 10^{5.5} – 10^{7}$ K. Once most of the WHIM are located, it would largely solves the missing baryon problem.

Much effort has been made observing the WHIM via X-ray emission. However, as the emissions are quite faint, currently there are only a limited number of observations, which mainly focus on a few individual filaments linking or around massive clusters (Bregman 2007; Bregman et al. 2009; Eckert et al. 2015; Akamatsu et al. 2017). Very recently, Tanimura et al. 2020 reported a 4.2σ detection of stacked X-ray emission from the WHIM in filaments. Meanwhile, possible X-ray absorption by ions in the WHIM toward background quasars has also been reported in the literature (e.g., Fang et al. 2002; Nicastro et al. 2005; Bonamente et al. 2016; Nicastro et al. 2018; Nevalainen et al. 2019). However, those studies are not statistically significant, and some of them lack further confirmation.

Given the current challenge to locate the WHIM with X-ray emission and absorption, alternative tools, including the Sunyaev–Zel’dovich (SZ) effect, have been proposed. Several recent works have claimed the detection of a thermal SZ (tSZ) signal due to the WHIM in filaments between galaxy pairs, or galaxy clusters (Bonjean et al. 2018; de Graaff et al. 2019; Tanimura et al. 2019, 2020a). These works demonstrate that the SZ effect could be a powerful tool to use to locate the WHIM. Meanwhile, interpretation of these signals requires knowledge of the gas density and temperature in filaments. The assumed or estimated density and temperature profiles have notable differences between these works. A good understanding of the properties of baryonic matter in filaments is desired to justify the recent observational results and to help locate the WHIM with current and future detection via the SZ effect and X-ray emissions and absorption.
Recently, Gheller & Vazza (2019); Galárraga-Espinosa et al. (2021), and Tuominen et al. (2021) investigated the distribution of gas in filaments based on three different cosmological simulations. The filaments in different simulation samples are all found to have isothermal cores, despite the numerical methods used to identify filaments being different. However, there are notable differences in the central temperature, core radius, and mass density profiles. Moreover, the density, and temperature profiles measured in simulation samples also show notable differences with the estimations in those observational works that reported the detection of tSZ signals from filaments. It is worthwhile to probe the profiles of filaments in more simulation samples generated with different codes, and with different filament methods, as well as with different stacking/averaging methods for the measurement of the profile.

For instance, filaments with similar length or overdensity are stacked to obtain the average profiles in the literature. Few works have tried to measure the density and temperature profiles of gas in filaments with similar width/thickness. Cautun et al. (2014) demonstrate that the width is a better indicator than length to describe the evolution of prominent filaments, which may contain more hot intergalactic medium (IGM), i.e., more likely detected via the SZ effect and X-ray than tenuous filaments. In addition, the evolution of filament profiles with redshift is barely known.

In this work, we make use of samples from a cosmological hydrodynamic simulation with adaptive mesh refinement (AMR) to study the evolution of cosmic filaments, focusing on the density and thermal profiles. We measure the profiles of filaments with similar width. This paper is organized as follows: Section 2 introduces the cosmological simulation used here and the numerical methods employed for classifying filaments and measuring their diameter, density, and thermal profiles. Section 3 presents the number frequency, linear density, measured density, and temperature profiles of filaments and their evolution since redshift \( z = 4 \). In Section 4, we assess the impact of threshold values used in cosmic web classification, and compare our results with previous simulations and observational studies. Finally, our findings are summarized in Section 5.

2. Methodology

2.1. Simulation Samples

We use samples from a cosmological hydrodynamic simulation with AMR, which is run by the cosmological code RAMSES (Teyssier 2002). The simulation has a volume of \((100 \, h^{-1}\text{Mpc})^3\), assuming a ΛCDM cosmology with parameters \( \Omega_m = 0.317, \Omega_{\Lambda} = 0.683, h = 0.671, \sigma_8 = 0.834, \Omega_b = 0.049, \) and \( n_s = 0.962 \) (Planck Collaboration et al. 2014). The simulation is evolved with 1024\(^3\) dark matter particles and a 1024\(^3\) root grid cell. An AMR grid up to level \( l_{\text{max}} = 17 \) is adopted, namely, the spatial resolution is \( 97.6 \, h^{-1} \text{kpc} \) for the root grid, and reaches \( 0.763 \, h^{-1} \text{kpc} \) at the finest level. Radiative cooling and heating of gas, star formation, and stellar feedback are implemented, while feedback from active galactic nuclei is not included. A uniform UV background assuming the model in Haardt & Madau (1996) is switched on at redshift \( z = 8.5 \). More details about the simulation can be found in Zhu & Feng (2021). This simulation starts at \( z = 99 \) and ends at \( z = 0 \). In this work, we use samples from \( z = 4.0 \) to \( z = 0.0 \).

2.2. Filament Classification, Compression, and Measurement

From the simulation sample, we build the density of baryonic and dark matter on a \( 512^3 \) grid. The resampled density fields on the \( 512^3 \) grids are smoothed with a Gaussian kernel of radius \( 0.39 \, h^{-1} \text{Mpc} \). Then we assign the grid cells into four categories of cosmic large-scale structures, i.e., clusters/nodes, filaments, sheets/walls, and voids for baryonic and dark matter, respectively. We apply the tidal tensor, i.e., the Hessian matrix, of the rescaled peculiar gravitational potential, to complete the classification. For each grid cell, its type of cosmic web is determined by counting the number of eigenvalues larger than a given threshold \( \lambda_{\text{th}} \). We refer the readers to Hahn et al. (2007), Forero-Romero et al. (2009), and Zhu & Feng (2017a) for more details of this web classification scheme and the choice of \( \lambda_{\text{th}} \). In this work, we adopt \( \lambda_{\text{th}} = 0.2 \), and find that filaments occupy around 14% of the volume, and contain \( \sim 45\% \) of the mass at \( z = 0 \). The volume filled by filaments changes slightly between \( z = 0 \) and \( z = 3 \), while the mass fraction declines moderately to 34% at \( z = 3 \).

We follow the procedures in Cautun et al. (2014) (see their Section 4 and Appendix) to compress the grids in filaments, find the spines of filaments, and then estimate the contribution to filament length, the local linear density, \( \zeta_{\text{fil}} \), and the local width/diameter of filaments, \( D_{\text{fil}} \), for each grid in the filaments. We further set \( R_{\text{fil}} = D_{\text{fil}}^2 \) to denote the local radius of the filaments. We use the same spherical filter of radius \( R = 1 \, h^{-1} \text{Mpc} \) as in Cautun et al. (2014) to search for neighbors of grids during the compression of filaments, and take a segment of length \( \Delta L = 3 \, h^{-1} \text{Mpc} \) for estimating its contribution to filament length and the local width/thickness. Figure 1 illustrates the effect of the compression procedures. The top-left plot in Figure 1 shows the density field of baryonic matter residing in filaments and clusters/nodes in a sub-box of volume \((33.3 \, h^{-1}\text{Mpc})^3\), while the top-right plot shows filaments only. The position of grid cells in filaments after compression are presented in the bottom-left panel. Based on the compressed filaments, we measure the distance of each grid cell in filaments to the spine along the direction perpendicular to the orientation of the filament. We denote this distance as \( r \), and introduce a rescaled/normalized radial distance to spine for each filament grid defined by \( r_{\text{nnl}} = r/R_{\text{fil}} \). The bottom-right panel in Figure 1 shows the density field of grid cells in filament with \( r_{\text{nnl}} < 0.5 \), i.e., the relatively inner region of filaments.

3. Properties of Filaments

We first probe the evolution of filament width, the relation between local width and local linear density, and then investigate the density and temperature profiles of filaments.

3.1. Width and Linear Density

Visual impressions in previous studies have shown that most of the filaments at high redshifts are tenuous ones, and prominent filaments mostly emerge after \( z \sim 2 \) (Aragón-Calvo 2007; Hahn et al. 2007; Cautun et al. 2014; Zhu & Feng 2017a). To estimate this picture quantitatively, we probe the evolution of filament width following the method in Cautun et al. (2014). The top-left and top-right panels in Figure 2 show the distribution of the local diameter of baryonic and dark matter filament between \( z = 4 \) and \( z = 0 \) in our samples, respectively. The results of dark matter are very similar to those of baryonic gas. For relatively thinner
filaments with local diameter smaller than $\sim 4.0 \ Mpc h^{-1}$, the distribution and evolution of filament width is generally consistent with the findings in Cautun et al. (2014) (see their Figure 38), which is based on samples from the Millennium simulations. However, the number frequency of thicker filaments, with local diameter larger than 4.0 Mpc $h^{-1}$, grows significantly since $z \sim 2$ in our samples, which is in contrast to the trend reported in Cautun et al. (2014). This discrepancy may result from the differences on the methods applied to classify cosmic web. The results in Cautun et al. (2014) are based on filaments classified by the NEXUS+ method, which also uses the Hessian matrix of the density field, but smooths the input density field with a log-Gaussian filter of multi-radii, ranging from from 0.4–8.0 $h^{-1}$ Mpc. In comparison, we smooth the density with a Gaussian filter of fixed radius 0.39 $h^{-1}$ Mpc. In addition, Cautun et al. (2014) adopt a threshold value of $\lambda_{th} = 0.0$, which is smaller than the value $\lambda_{th} = 0.2$ used here.

In our work, the local radius of filaments can be as large as $\sim 4$ Mpc. However, few observational studies have revealed the width of cosmic filaments. Very recently, Wang et al. (2021) presented possible observational evidence for cosmic filament spin based on observed galaxy samples, and claims that the spin signal decreases to zero at a distance to the filament spine of $\sim 2$ Mpc. Their work seems to suggest that a galaxy at a distance $> 2$ Mpc to the filament spine has been barely impacted by filaments. This may result due to the following: The number of filaments with $R_{fil} > 2 h^{-1}$ Mpc is much less than those with $R_{fil} < 2 h^{-1}$ Mpc in our sample. Hence, the signal induced by filaments with $R_{fil} > 2 h^{-1}$ Mpc will be relatively weak in stacked filament samples.

As demonstrated in the middle panel of Figure 2, along with the emergence of prominent filaments, the mass fraction of gas and dark matter residing in thick filaments grows with time. The bottom panel of Figure 2 shows the cumulative distribution function of gas and dark matter mass as a function of the filament’s local diameter. Filaments with $D_{fil} > 4.0 \ Mpc h^{-1}$ contain about 7.5% of the IGM residing in filaments at $z = 4$. This fraction goes up moderately to about 10.0% at $z = 2$, and further increase to about 28% at $z = 0$, equivalent to $\sim 13\%$ of all the IGM in the universe. The corresponding mass fraction of dark matter residing in thick filaments is slightly higher than gas at $z \leq 1.0$. Thin filaments with $D_{fil} < 2.0 \ Mpc h^{-1}$ comprise 35% of the gas in filaments at $z = 0$, and decline to 25% at $z = 0$.

Cautun et al. (2014) show that there is a correlation between the local diameter and the local linear mass density of filaments, $\zeta_{fil}$, although bears considerable scatter. Figure 3 presents the scatter diagram between the local linear mass density $\zeta_{fil}$ and local
diameter of filaments, identified with the baryon density field from $z = 4.0$ to $z = 0.0$ in our samples. Note that the linear mass density measured here is the sum over baryonic and dark matter. Despite there being notable scatter, the local diameter shows a clear trend in correlating with the local linear mass density, in good agreement with Cautun et al. (2014).

The green solid line in Figure 3 indicates the median linear mass density as a function of the local diameter. We find that this correlation could be approximately fitted by the following function as

$$\zeta_{\text{fil}} \approx 2.7 \times 10^{11} M_\odot \left(\frac{R_{\text{fil}}}{\text{Mpc} h^{-1}}\right)^n \left(\frac{\text{Mpc} h^{-1}}{\text{Mpc} h^{-1}}\right),$$

where the power index grows gradually from $n \approx 2$ at $z = 4.0$ to $n \approx 2.5$ at $z = 0.0$. The increase in the power index probably results from the evolution of the density profiles in the filaments.
3.2. Density and Thermal Profiles

A thorough understanding of the density and temperature profiles of filaments is crucial to the efforts to locate the missing baryon, and for the interpretation of recent observational reports of the tSZ effect due to filaments. We investigate the density profiles perpendicular to the filament spine in our samples for both baryonic and dark matter, as well as the temperature profiles for baryonic matter. Previous studies have shown that the profiles of individual filaments can vary greatly from one to another (e.g., Aragón-Calvo et al. 2010; Gheller et al. 2015), and hence profiles are usually calculated by averaging a group of filaments with a similar property, such as length (Galárraga-Espinosa et al. 2021), luminosity density (Tuominen et al. 2021), or width (Cautun et al. 2014).

Here, we measure the average profiles of filament segments with similar local width/diameter. More specifically, all the grid cells in the filaments are first separated into subgroups according to their local diameters. We use an interval of 0.66 Mpc $h^{-1}$ on the local diameter as the bin size of the subgroup. This is equivalent to a bin size of 0.33 Mpc $h^{-1}$ on the local radius as $R_{fil} = D_{fil}/2$. Then we calculate the average density and temperature of cells as a function of the radial distance to the spine $r$ in each subgroup. Both volume-weighted and mass-weighted temperatures have been calculated. The former and latter are defined as $(\sum_{i=1}^{n} T_i)/n$, and $(\sum_{i=1}^{n} T_i \rho_i)/(\sum_{i=1}^{n} \rho_i)$, where $T_i$ and $\rho_i$ are the temperature and density of $i$th gas cells, respectively, and $n$ is the number of gas cells in a particular subgroup. Since there is a small number of filaments with $R_{fil} > 4.0$ Mpc $h^{-1}$ in our sample, our study focuses on filaments with local radius $R_{fil} < 4.0$ Mpc $h^{-1}$. Since we only include grid cells belonging to filaments in the calculation, the profiles are truncated at a radius $r \approx R_{fil}$.

The top-left panel in Figure 4 shows the density profiles of dark matter in filaments at $z = 0$. The overall shapes and overdensities of the profiles in our samples are similar to filaments with a width of $D_{fil} < 4.0$ Mpc $h^{-1}$ in Cautun et al. (2014), which are shown as the black-dashed and dotted-dashed lines in the top-left panel of Figure 4. The density profiles can be roughly divided into an inner core regime at $r < 0.5 R_{fil}$ and an outer envelope regime for $R_{fil} < 4.0$ Mpc $h^{-1}$. Since we only include grid cells belonging to filaments in the calculation, the profiles are truncated at a radius $r \approx R_{fil}$.

The correlation between the local diameter and the linear density of filaments from $z = 0.0$ to $z = 0.0$. Gray points in each panel are randomly selected, i.e., 100,000 or about 5% of the total grid cells in the filaments. The solid green line indicates the median linear density as a function of $D_{fil}$. The red and blue dashed lines show two power-law relations.

![Figure 3](image_url)

Figure 3. The correlation between the local diameter and the linear density of filaments from $z = 4.0$ to $z = 0.0$. Gray points in each panel are randomly selected, i.e., 100,000 or about 5% of the total grid cells in the filaments. The solid green line indicates the median linear density as a function of $D_{fil}$. The red and blue dashed lines show two power-law relations.
The density profiles of filaments with $R_{\text{fil}}$ between 1.0 and 4.0 Mpc $h^{-1}$ present the feature of self-similarity, and can be approximately fitted by an isothermal single-$\beta$ model as:

$$\rho_{\text{dm}}(r/R_{\text{fil}}) = \rho_{\text{dm,0}} \times \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-\frac{2}{3}}$$

with $\rho_{\text{dm,0}} = 6.8*(\Omega_m - \Omega_b)\rho_{\text{crit,0}}$, $r_c = 0.80R_{\text{fil}}$, and $\beta_{\text{dm}} = 2/3$.

The profiles within $r < 0.8R_{\text{fil}}$ can also be fitted with the same $\rho_{\text{dm,0}}$ and $r_c$, but with a larger $\beta = 1.0$, displayed as the pink-dotted–dashed line. Yet, the profiles of filaments thinner than $R_{\text{fil}} = 1.0$ Mpc $h^{-1}$ or thicker than $R_{\text{fil}} = 3.33$ Mpc $h^{-1}$ deviate evidently from the single-beta model in the inner core regime. The former and latter have profiles that are more shallow and steeper than in Equation (2), respectively.

Note that collapsed halos could make considerable contributions to the matter density in the inner region of filaments. To exclude the influence of halos, we discard those grid cells located within spheres centered on the mass center of halos more massive than $6.2 \times 10^8$ $M_\odot$ and with a radius 1.2 times the halo’s virial radius. As a result, the measured overdensity in the filament drops moderately in the inner core regime and slightly in the outer envelope regime. This is not surprising. The density profiles of filaments excluding contributions from halos are illustrated in the bottom row of Figure 4. Once the contributions from halos are excluded, the density profiles can be better fitted by the isothermal single-$\beta$ model as Equation (2) with parameters $\rho_{\text{dm,0}} = 4.3*(\Omega_m - \Omega_b)\rho_{\text{crit,0}}$, $r_c = 0.8R_{\text{fil}}$, and $\beta_{\text{dm}} = 2/3$.

Figure 5 shows the density profiles of baryonic gas in filaments at $z = 0$, which are generally similar to those of dark matter and can also be approximately fitted by an isothermal single-$\beta$ model as:

$$\rho_{\text{gas}}(r/R_{\text{fil}}) = \rho_{\text{gas,0}} \times \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-\frac{2}{3}}$$

with $\rho_{\text{gas,0}}$ equal to 6.5 and 4.1 times the cosmic mean baryon density if the contributions from halos are included and excluded, respectively, being slightly lower than the corresponding overdensity of dark matter. Meanwhile $r_c = 0.8R_{\text{fil}}$ and $\beta_{\text{gas}} = 2/3$, which are the same for dark matter.
Figure 6 illustrates the volume-weighted temperature profiles of baryonic gas in filaments at $z = 0$. Baryonic gases residing in thick filament are generally hotter than those in thin ones. Filaments with $R_{\text{fil}} < 2.0 \, \text{Mpc} \, h^{-1}$ are cooler than $10^6$ K, and vice versa. When moving from the boundary region inward to the central region along the direction perpendicular to the spine, the gas temperature shows different behavior in filaments with different widths. In filaments thinner than $1.33 \, \text{Mpc} \, h^{-1}$, the gas temperature drops slightly from the boundary to around half of the radius, and then increases gradually toward the central region. For filaments with a radius of $1.33 - 3.0 \, \text{Mpc} \, h^{-1}$, the temperature rises gently from outer region inward within the whole radial range and the temperature at the center is higher than that at the boundary by a factor $<1$. For thick filaments with $R_{\text{fil}} > 3.0 \, \text{Mpc} \, h^{-1}$, the increase in average temperature in the outer regime of $r > 0.8R_{\text{fil}}$ and the inner regime of $r < 0.5R_{\text{fil}}$ is also quite slow. In the middle regime $0.5 < r/R_{\text{fil}} < 0.8$; however, the temperature grows more rapidly, leading to the temperature at the center being 2–3 times that at the boundary. This rapid rise may have been caused by accretion shocks driven by gravitational collapse. Prominent filaments are more massive and likely to drive shocks.

We find that the halos have minor influences on the volume-weighted gas temperature profiles in filaments. The reason is that halos only occupy around 0.7% of the volume in filaments at $z = 0$. On the other hand, halos contribute $\sim$15% of the mass in filaments. Comparing the left and right panels in the bottom row of Figure 6, we can see that the mass-weighted temperature of filaments with $R_{\text{fil}} > 2.0 \, \text{Mpc} \, h^{-1}$ would drop by a factor up to 2 if the contribution from halo gas is not taken into account. However, excluding halos or not has a modest impact on the mass-weighted temperature in filaments with $R_{\text{fil}} < 2.0 \, \text{Mpc} \, h^{-1}$. It is reasonable because thicker filaments host more halos, especially those massive halos containing hot gases.

3.3. Evolution of Filament Profiles

In Section 3.1, we showed that the number frequency of tenuous filaments decreases slightly as redshift decreases, which is in agreement with Cautun et al. (2014). However, our work finds that the frequency of prominent filaments is increasing rapidly at $z < 2$. Along with the number frequency, the profiles of filaments may also evolve with time. Figure 7 shows the evolution of the density and temperature profiles of baryonic gas in filaments since $z = 2.0$. For the results presented in Figure 7, the contributions from halos are excluded.

The density profiles at high redshifts can also be approximately described by the isothermal single-beta model. Table 1 lists the parameters that are used to fit the density profiles of gas and dark matter at different redshifts, with or
without counting the contribution from halos. The density peaks in the inner regime change slightly between $z = 0.0$ and $z = 1.0$, and decline moderately at $z > 1.0$. Meanwhile, the density at radius $R_{fil}$ increases modestly with redshift increasing, which may result from a higher mean density in the overlapping regions of filaments and walls at high redshifts. Consequently, the density slope in filaments becomes more shallow at higher redshifts, leading to an extended core radius, i.e., larger $r_c$, in the single-beta formula. There are notable fluctuations in the profiles of thick filaments at high redshifts, due to the rapid decline of their number frequency as redshift increases.
The temperature profiles of baryonic gas in filaments at high redshifts are similar to those at $z=0$. There are, however, two slight differences. First, for filament with a given width, the overall gas temperature increases gradually with redshift decreasing. This feature arises from the rise in mean temperature over time for gases in overdense regions due to UV background and gravitational collapse heating (e.g., Zhu & Feng 2017b; Martizzi et al. 2019). Second, as redshift increases, baryonic gas hotter than $T=10^6$ K becomes more and more scarce in the cosmic filamentary structures because there are fewer and fewer prominent filaments.

Figure 7. Left: the density profile of baryon gas as a function of distance to the spine of the filament, without the contribution from halos at redshift 2.0 (top), 1.0 (middle), and 0.5 (bottom). Right: same as the left column, but for the volume-weighted temperature profile.
4. Discussion

4.1. Impact of Web Classification

In the procedure of web type classification, the threshold eigenvalue $\lambda_{th}$ is an important parameter. The results presented in the previous sections are based on a threshold eigenvalue of $\lambda_{th} = 0.2$. It is worthwhile to examine whether these results are sensitive to the adopted value of $\lambda_{th}$. So far, a precise value of $\lambda_{th}$ derived from the anisotropic collapse of structures is not available. In practice, $\lambda_{th}$ is taken currently as ranging from 0.2–0.6 in relevant works involving the classification of large-scale cosmic webs (e.g., Forero-Romero et al. 2009; Zhu & Feng 2017a; Martizzi et al. 2019). We perform a similar analysis as in the previous sections for the simulation sample at $z = 0$ but with $\lambda_{th} = 0.4$, and show the results at $z = 0$ in Figure 8.

A larger $\lambda_{th}$ leads to less grid cells residing in filaments of almost all widths, which is consistent with our expectation. On the other hand, the correlation between the linear density and the local diameter persists, although the linear density coefficient on the right-hand side of Equation (1) increases $\sim 20\%$. The density profiles in filaments with different widths are still similar, and can be approximately described by a single-beta model with the same value of $r_c$ and $\beta$ as in the case of $\lambda_{th} = 0.2$. Yet, the overall densities have been increased by $\sim 20\%$ from the inner region to the boundary region with respect to $\lambda_{th} = 0.2$.

The shape of the temperature profiles shows minor changes when $\lambda_{th}$ goes from 0.2–0.4, but the typical temperature for filaments with a particular width rise modestly. The reason is that the outer boundary of filaments moves inward to the spine of the filaments or to the center of nodes/clusters as $\lambda_{th}$ increases. Consequently, for filaments with the same width but

| Component       | $z$ | $\bar{\rho}/\bar{\rho}$ | $r_c/R_{fil}$ |
|-----------------|-----|--------------------------|---------------|
| Gas (halo incl.)| 0.0 | 6.5                      | 0.8           |
|                 | 0.5 | 6.0                      | 0.8           |
|                 | 1.0 | 5.7                      | 0.8           |
|                 | 2.0 | 4.4                      | 0.9           |
|                 | 3.0 | 3.6                      | 0.9           |
| Gas (halo excl.)| 0.0 | 4.1                      | 0.8           |
|                 | 0.5 | 4.1                      | 0.8           |
|                 | 1.0 | 4.2                      | 0.8           |
|                 | 2.0 | 3.8                      | 0.9           |
|                 | 3.0 | 3.6                      | 0.9           |
| CDM (halo incl.)| 0.0 | 6.8                      | 0.8           |
|                 | 0.5 | 6.8                      | 0.8           |
|                 | 1.0 | 6.8                      | 0.8           |
|                 | 2.0 | 4.8                      | 0.9           |
|                 | 3.0 | 3.8                      | 1.0           |
| CDM (halo excl.)| 0.0 | 4.3                      | 0.8           |
|                 | 0.5 | 4.8                      | 0.8           |
|                 | 1.0 | 4.8                      | 0.8           |
|                 | 2.0 | 4.4                      | 0.9           |
|                 | 3.0 | 3.9                      | 0.9           |

Figure 8. Properties of filaments identified with $\lambda_{th} = 0.4$. From top to bottom: the frequency as a function of local diameter; the scatter diagram of local diameter vs. local linear density; the density and volume-weighted temperature profile of baryonic gas as a function of the normalized distance to the spine of the filament, excluding the contribution from collapsed halos.
classified with different thresholds $\lambda_{\text{th}}$, the typical density and temperature would be systematically higher for larger $\lambda_{\text{th}}$.

### 4.2. Comparison to Previous Simulation Works

The density and temperature profiles of baryonic gas in filaments have been studied in recent works such as Gheller & Vazza (2019), Galárraga-Espinosa et al. (2021), and Tuominen et al. (2021). In Gheller & Vazza (2019), the properties of filaments (e.g., density, temperature, velocity, and magnetic field) across a few orders of magnitude in mass have been investigated. In Galárraga-Espinosa et al. (2021), filaments in three different ranges of length are averaged, respectively, to calculate the corresponding profiles. Tuominen et al. (2021) takes an average of all the filaments found and a subsample of the filaments, respectively, to obtain the profiles. A comparison with these works could provide a more comprehensive view of the properties of filaments. We first examine the temperature profiles, and then the density profiles.

The temperature profiles show an isothermal core and then drop either sharply or gradually at outer regions in all three works mentioned above. We also find an isothermal core region in the profiles of our samples, continuing to decline outward to the outer region, despite the differences in simulation samples, web classification, and profile averaging methods. However, the radius of the isothermal central part in our samples increases with the local filament width, which is different from what is reported in the literature. For thick filament segments with radius $R_{\text{fil}} > 2 \text{ Mpc} \ h^{-1}$, the isothermal core radius can extend to 1–2 Mpc in our work. This is comparable to the radius of the isothermal core in Gheller & Vazza (2019) and Galárraga-Espinosa et al. (2021). Nevertheless, for filament segments with $R_{\text{fil}} < 2 \text{ Mpc} \ h^{-1}$, the isothermal radius is smaller, and more close to the core radius in Tuominen et al. (2021).

The temperature peaks in the central core region of filaments varies from $10^5$ to $3 \times 10^6 \text{ K}$ in the previous studies, which agree with the overall temperature range in our samples. Our analysis shows that the typical temperature of gas is hotter in thicker and more prominent filaments, which usually locate in more dense regions. This feature is generally consistent with Galárraga-Espinosa et al. (2021) and Tuominen et al. (2021). Galárraga-Espinosa et al. (2021) shows that the temperature of short filaments in dense regions is about $1.3 \times 10^6 \text{ K}$, i.e., 3 times that of long filaments that trace less-dense regions. Moreover, the shorter filaments in Galárraga-Espinosa et al. (2021) tend to be thicker. Tuominen et al. (2021) find that the filaments with high luminosity density (tending to have high overdensity) have a peak temperature $\approx 1.2 \times 10^6 \text{ K}$, which is 12 times that of the total filaments sample. All these works are consistent with the picture that prominent and thick filaments, which usually form in more dense regions and closer to nodes/clusters, are much hotter than than thin filaments.

In our work, only grid cells in the environment of filaments are included to calculate the profiles of filaments. Therefore, the temperature profiles are truncated at a radius moderately larger than $R_{\text{fil}}$. In contrast, the average temperature at radius far from the outer boundary is available in Galárraga-Espinosa et al. (2021) and Tuominen et al. (2021), and is about $10^5–10^6 \text{ K}$, which is close to the average background temperature of the IGM.

The density profiles of filaments in Gheller & Vazza (2019) and Tuominen et al. (2021) have been presented explicitly, while it is not shown directly in Galárraga-Espinosa et al. (2021), and so it is somewhat difficult to make a detailed comparison with Galárraga-Espinosa et al. (2021). The density profile presented in Gheller & Vazza (2019) for a given filament is similar to our results as verified by a visual check. Tuominen et al. (2021) used an isothermal single-beta model with $\beta = 2.0$ to fit the density profiles of filaments with high luminosity density, which results in a gas density peak around 20 times the cosmic mean and a core radius $r_{c, p} \approx 1.2 \text{ Mpc}$, i.e., a profile steeper than our samples.

The overall values of densities in our samples are close to those in Gheller & Vazza (2019), which shows a peak about 5–10 times the cosmic mean, $\langle \rho_b \rangle$, at $r = 0$ and drops to $\sim 3$ at $r > 2 \text{ Mpc}$. For the total samples of filaments in Tuominen et al. (2021), the baryon overdensity at the filament spine is about $\rho_b/ \rho_{b, \text{med}} > 5$, in agreement with our results. Nevertheless, for their filaments with high luminosity density, the baryon overdensity at the center is much higher, up to $\rho_b/ \rho_{b, \text{med}} \approx 40$. This discrepancy may be partly because we only sum over grids in the environment of filaments to calculate the average density, and discard those grids in the environment of nodes/clusters. Therefore, some grid cells outside of the halos in high overdensity regions are removed. In Tuominen et al. (2021), only gas cells within Friends-of-Friends halos are excluded. Moreover, the EAGLE simulation used in Tuominen et al. (2021) has a higher resolution with respect to our simulation, which may enhance the density in the central regime of filaments.

We conclude that the range of the densities and temperatures in the filaments in our simulation are generally consistent with the literature. Nevertheless, there are notable discrepancies in the shape of profiles and core radius in comparison with many works, and even in the gas overdensity in the central core regions compared with some works. These differences should partly result from the web classification procedures, and the averaging methods used in calculating the profiles as well as different sample sizes. In addition, the differences in the simulation schemes, resolution, and sub-grid physics may also have contributed to the diversity.

### 4.3. Comparison to the Detection of WHIM in Filaments via tSZ Signals

Detection of the tSZ signal due to the warm and hot gas in filaments has been reported recently by several groups (de Graaff et al. 2019; Tanimura et al. 2019; Tanimura et al. 2020a). The former two works searched for signals caused by filaments between galaxy pairs taken from the Sloan Digital Sky Survey (SDSS), while the latter probes signals due to gas in filaments with lengths of 30–100 Mpc identified in the SDSS survey. Tanimura et al. (2019) found a Compton y parameter $y \approx 1 \times 10^{-8}$ for filaments between pairs of Luminous Red Galaxies at redshifts $z < 0.4$. Assuming the matter in filament follows an isothermal single-beta model with $\beta = 2/3$, they obtain an estimation on the product of overdensity and temperature to be $\delta_{\text{T}} \times (T_e - 10^{-7} \text{ K}) \times (r_{c, p} 0.5h^{-1} \text{ Mpc}) = 2.7 \pm 0.5$. This is in good agreement with our results for filaments with $R_{\text{fil}} > 2.0 \text{ Mpc}$, which have an overdensity of $\sim 4–5$ (halos excluded), temperature around $1.5–4 \times 10^{-6} \text{ K}$, and a core radius of $0.8 \times R_{\text{fil}}$ de Graaff et al. (2019) reported a mean Compton parameter, $y \approx 0.6 \pm 10^{-8}$, due to WHIM by stacking $1 \times 10^5$ pairs of CMASS galaxies in the redshift range $0.4 < z < 0.75$ (mean 0.55) from the SDSS survey. Assuming the gases in filaments follow a Gaussian profile with an FWHM of $1.5 h^{-1} \text{ Mpc}$ along the axis perpendicular to the spine of filaments, they estimated that a central gas density about $5.5 \pm 2.9$ times the cosmic mean and a
gas temperature of \( \sim 2.7 \times 10^8 \) K can explain the tSZ signal they detected. These values are also consistent with the profiles of thick filaments at \( z = 0.5 \) in our sample, although the shape of profile is different.

Tanimura et al. (2020a) detected the tSZ signal of filamentary structures at a significance of 4.4\( \sigma \). The central overdensities in filaments are estimated to be around 19.0\( ^{+12.1}_{-12.1} \) and 6.3\( ^{+0.8}_{-0.8} \) for the isothermal \( \beta \) model (\( \beta = 2/3 \)) and the constant density model, respectively. The former value is higher than our result. The electron temperatures are found to be \( \sim 1.3 - 1.4 \times 10^6 \) K for two models, which is consistent with the values in our samples.

In short, the gas overdensities and temperatures of thick filaments in our sample agree with most of the corresponding estimations in the recent observational works that have reported the detection of a tSZ signal attributed to filaments. Yet, we should remind the readers that the filament classification and averaging method we used are different from those used in observational works.

5. Summary

A theoretical knowledge of the distribution of baryonic matter in filaments is desired for the search for missing baryon. In this work, we have studied the properties of cosmic filaments since \( z = 4.0 \) in a cosmological hydrodynamic simulation with AMR. We have quantitatively evaluated the evolution of filaments with different widths after \( z = 4 \), and measured the density and temperature profiles perpendicular to the filament spine. Our findings are summarized as follows:

1. Quantitative evaluation shows that the number frequency of thick filaments grows rapidly after \( z = 2 \), in good agreement with the visual impressions presented in the literature. Filaments with width \( D \gtrsim 4.0 \) Mpc h\(^{-1}\) comprise \( \sim 10\% \) of the baryons contained in filaments at \( z = 2 \), i.e., \( \sim 4\% \) of the baryons in the universe. These fractions grow up to \( \sim 28\% \) and \( \sim 13\% \), respectively, at \( z = 0 \).
2. The linear density of filaments, i.e., the mass contained in a unit length along the filament spine, is correlated with the local diameter, and approximates a power-law function \( \propto (D_{\text{fil}})^{\beta} \), since redshift as high as \( z = 4 \). The power index increases gradually from \( n \approx 2 \) at \( z = 4 \) to \( n \approx 2.5 \) at \( z = 0 \).
3. The averaged density profiles of both dark matter and baryonic gas in filaments of different widths show self-similarity, and can be described by an isothermal single-beta model at redshift \( z < 4 \), as in Equations (2) and (3). The profiles for the baryonic gas and dark matter are quite similar. The density profiles become more shallow with increasing redshifts.
4. The gas temperature profiles in thin filaments are relatively flat in the whole radial region, while the temperature rises significantly in the middle radial regime for filaments with local width \( D_{\text{fil}} \gtrsim 4.0 \) Mpc. The typical gas temperature increases with the filament width increasing, and is hotter than \( 10^8 \) K for filaments with width \( D_{\text{fil}} \gtrsim 4.0 \) Mpc, and vice versa. Filament segments with \( D_{\text{fil}} > 4.0 \) Mpc dominate the tSZ signal caused by baryons in filaments.

Further investigation with other simulations samples is urged to verify the results revealed by our work. On the other hand, to make our results more conducive to an indirect search for the missing baryon, it would be necessary to optimize the strategy of constructing filament samples based on observational data. These studies will be carried out in the future.

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Software: RAMSES (Teyssier 2002)

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References

Akamatsu, H., Fujita, Y., Akahori, T., et al. 2017, A&A, 606, A1
Aragón Calvo, M. A. 2007, PhD thesis, Univ. Groningen
Aragón-Calvo, M. A., van de Weygaert, R., & Jones, B. J. T. 2010, MNRAS, 408, 2163
Bonamente, M., Nevalainen, J., Tilton, E., et al. 2016, MNRAS, 457, 4236
Bonjean, V., Aghanim, N., Salomé, P., Douspis, M., & Beelen, A. 2018, A&A, 609, A49
Bregman, J. N. 2007, ARA&A, 45, 221
Bregman, J. N., Otte, B., Irwin, J. A., et al. 2009, ApJ, 699, 1765
Cautun, M., van de Weygaert, R., Jones, B. J. T., & Frenk, C. S. 2014, MNRAS, 441, 2923
Cen, R., & Ostriker, J. P. 1999, ApJ, 514, 1
Cui, W., Knebe, A., Yepes, G., et al. 2018, MNRAS, 473, 68
Danforth, C. W., Keeny, B. A., Tilton, E. M., et al. 2016, ApJ, 817, 111
Davé, R., Cen, R., Ostriker, J. P., et al. 2001, ApJ, 552, 473
de Graaff, A., Cai, Y.-C., Heymans, C., & Peacock, J. A. 2019, A&A, 624, A48
Dolag, K., Meneghetti, M., Moscardini, L., Rasia, E., & Bonaldi, A. 2006, MNRAS, 370, 656
Eckert, D., Jauzac, M., Shan, H., et al. 2015, Natur, 528, 105
Fang, T., Marshall, H. L., Lee, J. C., Davis, D. S., & Canizares, C. R. 2002, ApJL, 572, L127
Forero-Romero, J. E., Hoffman, Y., Gottlöber, S., Klypin, A., & Yepes, G. 2009, MNRAS, 396, 1815
Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518
Galárraga-Espinoza, D., Aghanim, N., Langer, M., & Tanimura, H. 2021, A&A, 649, A117
Gheller, C., & Vazza, F. 2019, MNRAS, 486, 981
Gheller, C., Vazza, F., Favre, J., & Brüggen, M. 2015, MNRAS, 453, 1164
Haahtela, T., & Madau, P. 1996, ApJ, 461, 20
Hahn, O., Porciani, C., Carollo, C. M., & Dekel, A. 2007, MNRAS, 375, 489
Haider, M., Steinhauser, D., Vogelsberger, M., et al. 2016, MNRAS, 457, 3024
Martizzi, D., Vogelsberger, M., Artale, M. C., et al. 2019, MNRAS, 486, 3766
Nevalainen, J., Tempel, E., Ahoranta, J., et al. 2019, A&A, 621, A88
Nicastro, F., Mathur, S., Elvis, M., et al. 2005, ApJ, 629, 700
Nicastro, F., Kaastra, J., Krongold, Y., et al. 2018, Natur, 558, 406
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2014, A&A, 571, A16
Rauch, M., Miralda-Escudé, J., Sargent, W. L. W., et al. 1997, ApJ, 489, 71
Shull, J. M., Smith, B. D., & Danforth, C. W. 2012, ApJ, 759, 23
Tanimura, H., Aghanim, N., Bonjean, V., Malavasi, N., & Douspis, M. 2020a, A&A, 637, A41
Tanimura, H., Aghanim, N., Kolodzig, A., Douspis, M., & Malavasi, N. 2020b, A&A, 643, L2
Tanimura, H., Hinshaw, G., McCarthy, I. G., et al. 2019, MNRAS, 483, 223
Tejos, N., Prochaska, J. X., Crighton, N. H. M., et al. 2016, MNRAS, 455, 2662
Teyssier, R. 2002, A&A, 385, 337
Tuominen, T., Nevalainen, J., Tempel, E., et al. 2021, A&A, 646, A156
Wang, P., Libeskind, N. I., Tempel, E., Kang, X., & Guo, Q. 2021, NatAs, 5, 839

Weinberg, D. H., Miralda-Escudé, J., Hernquist, L., & Katz, N. 1997, ApJ, 490, 564
Zhu, W., & Feng, L.-L. 2017a, ApJ, 838, 21
Zhu, W., & Feng, L.-L. 2017b, ApJ, 847, 17
Zhu, W., & Feng, L.-L. 2021, ApJ, 906, 95