Detecting Galaxy-Filament Alignments in the Sloan Digital Sky Survey III

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ABSTRACT
Previous studies have shown the filamentary structures in the cosmic web influence the alignments of nearby galaxies. We study this effect in the LOWZ sample of the Sloan Digital Sky Survey using the “Cosmic Web Reconstruction” filament catalogue of Chen et al. (2016). We find that LOWZ galaxies exhibit a small but statistically significant alignment in the direction parallel to the orientation of nearby filaments. This effect is detectable even in the absence of nearby galaxy clusters, which suggests it is an effect from the matter distribution in the filament. A nonparametric regression model suggests that the alignment effect with filaments extends over separations of $30 - 40$ Mpc. We find that galaxies that are bright and early-forming align more strongly with the directions of nearby filaments than those that are faint and late-forming; however, trends with stellar mass are less statistically significant, within the narrow range of stellar mass of this sample.

Key words: (cosmology:) large-scale structure of Universe

1 INTRODUCTION
Cosmological simulations of large-scale structure reveal a consistent picture for the alignments of dark matter halo shapes and spins with filaments (for a review of galaxy and halo alignments, see Joachimi et al. 2015). The fact that filaments are associated with the large-scale tidal field (Hahn et al. 2007a,b; Sousbie et al. 2008; Forero-Romero et al. 2009; Aragón-Calvo et al. 2010; Cautun et al. 2013), which directly sources the dark matter halo spins through tidal torquing and imprint coherent patterns in their shapes, makes this connection quite natural and unsurprising. For details of how dark matter halo spins and shapes align with filamentary structures, and the dependence on other properties such as halo mass, see for example Altay et al. (2006); Hahn et al. (2007c); Zhang et al. (2009); Libeskind et al. (2013); Aragon-Calvo & Yang (2014).

However, the expectations for galaxy (not halo) shape and spin alignments are less obvious, and the observational results are somewhat in conflict with each other. For example, Tempel & Libeskind (2013) and Zhang et al. (2015) reported contradictory results for the alignments of spiral galaxy spins with filaments. The differing results may arise due to differences in sample selection, spin measurement, or mass ranges.

In this work, rather than investigate galaxy spin alignments with filaments, we focus on galaxy shape alignments with filaments. The primary motivation behind considering shape alignments is that coherent galaxy shape alignments with the cosmic web are a contaminant to weak gravitational lensing measurements (for recent reviews, see Kilbinger 2015; Mandelbaum 2017) that serve as one of the most promising probes of dark energy. Weak gravitational lensing involves statistical measurements of low-level coherent galaxy shape distortions induced by the gravitational potential of large-scale structure, and hence “intrinsic alignments” (coherent alignments due to large-scale tidal fields) must be modeled and removed. There are several approaches to modeling these alignments: to date, most cosmological weak lensing analyses (e.g., DES Collaboration et al. 2017;
Hildebrandt et al. (2017) have used numerical models for intrinsic alignments that should be valid only to mildly non-linear scales. More sophisticated analytic modeling schemes have been developed, some with additional nonlinear terms (e.g., Blazek et al. 2017), which can include the impact of spin alignments, and others based on the inclusion of a halo model for the effects that arise inside of dark matter halos (Schneider & Bridle 2010). It is important to understand whether galaxy shapes are aligned with filaments in a way that requires inclusion of additional terms in these models in order to properly remove intrinsic alignments contamination from future weak lensing measurements.

In this paper, we study the effect from filaments on galaxy shape alignments using the LOWZ sample in the Sloan Digital Sky Survey (SDSS). We acquire filaments from the cosmic web reconstruction catalogue (Chen et al. 2016) and use a catalogue of galaxy shapes measured using the re-Gaussianization method (Hirata & Seljak 2003). Our results can be compared with a similar analysis using the same filament-finding method in cosmological hydrodynamic simulations (Chen et al. 2015c). In addition to following previous works in quantifying how galaxy-filament alignments scale with galaxy properties, we also attempt to separate out the impact of filaments on galaxy alignments from the impact of clusters on galaxy alignments.

The outline of the paper is as follows. After describing the data used for this work in Section 2, we show the impact of filaments on galaxy-cluster alignments in Section 3.1. In Section 3.2, we measure galaxy-filament alignments after accounting for the alignment of galaxies towards clusters. We study how galaxy-filament alignments scale with separation as well as the impact of different galaxy properties. Finally, we conclude in Section 4.

Throughout the paper, we assume a WMAP7 ΛCDM cosmology with $H_0 = 70$ km/s/Mpc, $Ω_m = 0.274$, and $Ω_Λ = 0.726$ (Komatsu et al. 2011) and use angular diameter distances for calculation of physical distances.

2 DATA

2.1 The Sloan Digital Sky Survey

The SDSS (York et al. 2000) imaged roughly $π$ steradians of the sky, with the imaging carried out by drift-scanning the sky in photometric conditions (Hogg et al. 2001; Ivezić et al. 2004), in five bands (ugriz) (Fukugita et al. 1996; Smith et al. 2002) using a specially-designed wide-field camera (Gunn et al. 1998) on the SDSS Telescope (Gunn et al. 2006). These imaging data were used to create the catalogues of galaxy shapes that we use in this paper. The SDSS-I/II imaging surveys were completed with a seventh data release (Abazajian et al. 2009), though this work will rely as well on an improved data reduction pipeline that was part of the eighth data release, from SDSS-III (Aihara et al. 2011); and an improved photometric calibration (‘ubercalibration’, Padmanabhan et al. 2008).

2.2 Baryon Oscillation Spectroscopic Survey (BOSS)

Based on the photometric catalog from SDSS, galaxies are selected for spectroscopic observation (Dawson et al. 2013), and the BOSS spectroscopic survey was performed (Ahn et al. 2012) using the BOSS spectrographs (Smeeta al. 2013). Targets are assigned to tiles of diameter $3\degree$ using an adaptive tiling algorithm (Blanton et al. 2003), and the data were processed by an automated spectral classification, redshift determination, and parameter measurement pipeline (Bolton et al. 2012).

We use SDSS-III BOSS data release 12 (DR12; Alam et al. 2015) LOWZ galaxies. This sample consists of 361,762 galaxies over an area of 8377 deg$^2$ (Reid et al. 2016). We use these galaxies to construct an overdensity map from which we construct the filament map.

To get the shapes of BOSS galaxies, we use the same shape catalogue as was used in Singh et al. (2015). The galaxy shapes were measured by Reyes et al. (2012) using the re-Gaussianization method (Hirata & Seljak 2003) of correcting for the effects of the point-spread function (PSF) on the observed galaxy shapes. We refer the reader to Singh et al. (2015) and Reyes et al. (2012) for further details of the shape measurements.

We also use galaxy clusters from the redMaPPer catalogue version 10 (Rozo & Rykoff 2014; Rykoff et al. 2014; Rozo et al. 2015) to test the effects of clusters on the galaxy alignments. In addition we also use publicly-available estimates of galaxy stellar mass and age based on the Flexible Stellar Population Synthesis code of Conroy et al. (2009), in order to test the impact of these properties on galaxy alignments.

2.3 Filament Catalogue

We obtain filaments from the Cosmic Web Reconstruction catalogue (Chen et al. 2016), a publicly-available filament catalogue consisting of filaments in SDSS from redshift $z = 0.05$ to $z = 0.70$. Note that in this paper, we only use the LOWZ sample, so we restrict ourselves to $0.20 < z < 0.43$.

The catalogue is constructed by first slicing the spectroscopic galaxy sample from redshift $z = 0.05$ to $z = 0.70$ into 130 thin slices along line of sight with width $Δz = 0.005$ and then projecting galaxies within each slice onto two-dimensional plane of RA, DEC (denoted as $x$ in following discussion). The galaxies in the same slice are then smoothed into a two dimensional probability density field, $\rho(x)$ using a Gaussian kernel $K(x)$

$$p(x) = \frac{1}{nh^2} \sum_{i=1}^{n} K\left(\frac{x-x^i}{h}\right)$$

with the smoothing bandwidth $h > 0$ chosen by the reference rule described in Chen et al. (2015b). Finally, we detect the filaments as the ridges of the density field (Chen et al. 2015a) using the subspace constrained mean shift algorithm (Ozertem & Erdogmus 2011).

The ridges are identified using the hessian of the density

1 http://www.sdss.org/dr12/spectro/galaxy_granada/
2 https://sites.google.com/site/yenchicr/
field (tidal tensor) \( H_{ij}(x) = \frac{\partial^2}{\partial x_i \partial x_j} p(x) \) with \( v_1(x), v_2(x) \) as its eigenvectors corresponding to the eigenvalues \( \lambda_1(x) \geq \lambda_2(x) \). The ridges are defined as

\[
R = \left\{ x : v_2(x)^T \nabla p(x) = 0, \lambda_2 < 0 \right\},
\]

where \( \nabla p(x) \) is the gradient of the density field. \( R \) is the collection of points where the gradient projected onto the subspace spanned by the second eigenvector \( v_2(x) \) is zero and the second eigenvalue is negative. This implies that every point on \( R \) is a local maximum in the subspace spanned by \( v_2(x) \), so \( R \) can be viewed as a curve consisting of many local maxima in some subspaces, which is the feature of a ridgeline.

Note that ridges (hereafter filaments) are 1-dimensional objects (curves), so we can easily define the orientation of every point on a filament. In reality, a filament is represented by a collection of points and every point contains a vector \( \eta_{\text{filament}} \) indicating the orientation of the filament passing through the point.

For each galaxy, we denote \( d_F \) as its distance to the nearest point on the nearest filament; more specifically, \( d_F \) is the projected distance from a galaxy to the nearest filament in terms of angular diameter distance. More specifically, filaments in the Cosmic Web Reconstruction catalogue are constructed in each redshift slice. For a given galaxy, we first identify which redshift slice that it belongs to. Then we compute its distance to the nearest filament in the same slice, disregarding the fact that galaxies near the borders between slices may be physically closer to filaments in an adjacent slice. This simplification may slightly reduce the significance of the observed alignment effects. Given a galaxy located at position \( x \), we denote \( \eta_F(x) \) as its projected point onto the filament. Then the vector

\[
\eta_F(x) = \eta_{\text{filament}}( \Pi_F(x) )
\]

is defined as the orientation of the filament (unit vector tangential to the filament) nearest to the galaxy located at \( x \). Similarly, for each galaxy, we define \( d_C \) and \( \eta_C \) as the distance and unit vector to the nearest redMaPPer cluster.

3 RESULTS

3.1 Filament effect on galaxy-cluster alignment

Several studies have been performed to understand the galaxy alignments with surrounding density field using both observations and simulations (see e.g. Kirk et al. 2015, for review). In this section, we investigate the effects of filaments on the galaxy-density alignment using clusters as the tracers of density field. We quantify the galaxy-cluster alignment with the statistic (Zhang et al. 2009; Tempel et al. 2013, p

Figure 1. For a galaxy located at position \( x \), this figure illustrates the quantities \( \eta_F \) (orientation of the nearby filament at the point nearest to the galaxy) and \( \eta_C \) (orientation of the unit vector connecting the galaxy and a cluster). The distance to the filament \( d_F \) is the length of the brown dashed line and the distance to the cluster \( d_C \) is the length of the green dashed line. Finally, \( \eta_{\text{major}} \) shows the major axis direction of the projected galaxy shape.

Figure 2. An illustration of galaxies (black dots), clusters (red dots), and filaments (curves, represented by dark blue dots) in a narrow redshift slice in the LOWZ sample. The gray lines on the galaxies indicate the direction of their major axes. The light-blue line segments indicate the orientation of the filament at the location of the dark blue dots. One degree on this figure corresponds to \( \sim 20 \) Mpc given the redshift indicated on the legend.

Figure 1 provides an illustration of the quantities \( \eta_F, \eta_C, d_F, \) and \( d_C \) for a given galaxy, filament, and cluster. For each galaxy, the primary shape-related quantity we are interested in is \( \eta_{\text{major}} \), the direction of the major principal axis of the galaxy projected onto the plane of the sky.

In Figure 2 we show the distribution of galaxies, filaments and their shape orientations in a small region within the LOWZ sample \( (0.295 < z < 0.300) \). Our focus will be on understanding the alignments of the galaxies (gray lines) and the influence of filaments (blue lines) and clusters (red points) on these alignments. A notable feature in the figure is that the galaxies are primarily distributed close to the filaments and clusters, with clusters themselves being close to the filaments. This becomes important as we later split the galaxies into subsamples based on distances to filaments and clusters, where the samples with larger distance from clusters and filaments will have fewer galaxies, which increases the noise in the measurements.
3.2 Galaxy-filament alignment

In this section we investigate whether galaxies are aligned in parallel to nearby filaments. We define the filament orientation as the direction of the tangent at minimum separation from the galaxy (see Figure 1), which gives the alignment statistic

\[ \langle \rho_F \cdot \eta_{\text{major}} \rangle = \langle |\cos(\phi_F - \phi_{\text{major}})| \rangle \]  

(5)

where the inner product \( \langle \rho_F \cdot \eta_{\text{major}} \rangle \) measures the alignment between the direction of the major axis of the galaxy, \( \eta_{\text{major}} \), and the direction towards the cluster \( \rho_F \). Since for galaxy alignments the positive and negative value of inner product implies the same degree of alignment (rotating an ellipse by 180 degrees leads to the same ellipse), we measure the absolute values. For the case of random alignments, this inner product averages to 2/π. We note that for the galaxies with low ellipticity the estimates of the direction of the major axis become noisier (for a round galaxy, the major axis direction is ill-defined). However, we do not apply any preferential treatment to low ellipticity galaxies in our analysis as this effect mainly adds to noise to our measurement.

We study the alignment \( \langle |\rho_F \cdot \eta_{\text{major}}| \rangle \) in two cases. (i): we fix \( d_F \) and study how \( \langle |\rho_C \cdot \eta_{\text{major}}| \rangle \) changes as \( d_C \) changes; (ii): we fix \( d_C \) and study how \( \langle |\rho_C \cdot \eta_{\text{major}}| \rangle \) changes as \( d_F \) changes. Figure 3 shows the results for both cases; the error bars are based on the standard error of the average within each bin. In all cases, a statistically significant alignment of galaxies towards clusters is seen, but with different scale dependence. In the top row, we display the result of case (i). In the two leftmost panels (0 Mpc < \( d_F \) < 10 Mpc), we observe a significant dependence of the alignments on \( d_C \), with the strength of the galaxy alignment toward the cluster decreasing as the distance to the nearest cluster increases. This decreasing pattern is qualitatively consistent with the galaxy alignments literature where the alignments between galaxies and the density field follows a power law relation (see e.g. Kirk et al. 2015, for a review of galaxy alignment measurements). The significance of the galaxy-cluster alignment measurements decreases as the distance to the filaments increases (two rightmost panels in top row of Figure 3). This trend is primarily driven by the increased noise as the number of galaxies decreases with the increased distance to filament and does not imply a significant filament effect on the galaxy-cluster alignment.

In the bottom row, we show the result of case (ii) to study the galaxy-cluster alignment as function of the distance of the galaxies to the filaments. We do not observe any significant dependence of galaxy alignments towards galaxy clusters on the distance to the filaments. These results suggest that filaments do not have a significant impact on the tendency of galaxies to align towards galaxy clusters.
Figure 3. The galaxy alignment signal toward clusters $\langle \eta C - \eta \text{Major} \rangle = \langle \cos(\phi C - \phi \text{Major}) \rangle$ as a function of distance to the clusters, $d_C$, and filaments, $d_F$. The numbers on the bins denotes the number of galaxies in each bin. The brown horizontal line indicates the average value from a random alignment. Top panel: the alignment towards clusters as a function of projected distance to the clusters at various (fixed) distances to the clusters. The slope is from fitting a linear regression to the scale- (distance-) dependence of the signal. In the first two panels, there is significant scale dependence of the signal toward clusters. In the next two panels, measurements are noisier as the number of galaxies in bins decreases, making it harder to infer the scale dependence of the signal. Bottom panel: the alignment toward clusters as a function of distance to filament at various (fixed) distances to the clusters. In this case we do not observe a significant scale dependence. Results from both panels suggest that the filaments do not have a significant impact on the alignment of galaxies toward clusters, within the uncertainty in the measurements.

3.2.2 Range of galaxy-filament alignment effect

To determine the range of the filament alignment effect $\rho_0$, we use the cutoff distance where the alignment signal drops below the value of random alignment $\frac{2}{\pi} \approx 0.637$. Note that $\frac{2}{\pi}$ is a heuristic choice that does not have a physical meaning because we do not have a model for the phenomenon. Also note that the value of $\rho_0$ could be due to uncertainty in filaments and does not necessarily imply some physical scale.

We use the local polynomial regression (Wasserman 2006) as a non-parametric method to estimate the regression function. Given a value of covariate $x$ (here the covariate is the distance to filament $d_F$), the local polynomial regression weights all the data points based on the distance from their covariate values to $x$. Close data points are given higher weights and far away data points are given less weights. In the local polynomial regression, there is a smoothing bandwidth $b$ that determines how the weight as a distance to $x$ decays. Roughly speaking, points within $[x - b, x + b]$ will have a much higher weight compared to those outside this window. One can view this approach as a modified method of fitting a regression based on taking the average over a sliding window of width $2b$. The reasons of using a local polynomial regression are that (i) it has a smaller statistical error compared to the conventional binning approach, and (ii) it does not require any prior knowledge about the shape of the regression function.
We present the results in Figure 5 with a bandwidth $b = 5$ Mpc; an analysis with different bandwidths yields comparable results. The top panel displays the fit results for 100 bootstrap samples; the bottom panel shows the distribution of $\rho_0$ based on those bootstrap samples. In agreement with Figure 4, we find the range $\rho_0 \approx 35$ Mpc with a standard error of about 5 Mpc.

Using the range of the filament alignment effect, we calculate the excess probability density function of the difference angle $|\phi_{\text{F}} - \phi_{\text{Major}}|$ normalized to a pair of random axes. We only use galaxies within 40 Mpc, i.e. those that are within the range of the effect, with cluster-centric distances $d_C > 50$ Mpc. The results are shown in Figure 6, demonstrating that there are more galaxies aligned along their nearby filaments than one would expect from uniform random orientations. A similar result has been observed in Tempel et al. (2015) and Zhang et al. (2013). The excess probability rises to about 1.05, which is similar to the findings of Zhang et al. (2013) but somewhat smaller than the result of Tempel et al. (2015). In Section 3.2.3, we will make a more detailed comparison to these two works.

### 3.2.3 Galaxy properties and galaxy-filament alignment

To investigate whether the galaxy-filament alignment depends on galaxy properties, we perform the same analysis after separating galaxies by their absolute magnitude, stellar mass, and age. The stellar mass and age are obtained from the Granada group catalog (Ahn et al. 2014).³

When binning on each of these three properties in turn, we compare the two most extreme groups for a given property. For the brightness ($r$-band absolute magnitude), we compare the 25%/15%/10% brightest galaxies versus the 25%/15%/10% faintest galaxies, and likewise for stellar masses.

³ More details can be found at [http://www.sdss.org/dr13/spectro/galaxy_granada/](http://www.sdss.org/dr13/spectro/galaxy_granada/)
This figure shows the effect of galaxy properties on filament alignment. We compare the two most extreme groups of galaxies according to a particular galaxy property. From left to right, the extreme groups are selected with 25%, 15%, and 10% criteria. In all panels, we only consider galaxies with $d_C > 50$ Mpc to reduce the impact of cluster alignments. The p-value for the difference between the two extreme groups is given in Table 1. **Top row:** We separate galaxies by their brightness ($r$-band absolute magnitude). The upper and lower brightness thresholds are $(-22.16, -21.69)$, $(-22.31, -21.58)$, and $(-22.42, -21.50)$. **Middle row:** We separate galaxies by their stellar mass. The upper and lower mass thresholds are $\log_{10}(M_*/M_\odot) = (11.76, 11.55), (11.83, 11.50)$, and $(11.87, 11.47)$. **Bottom row:** We separate galaxies by their age. The upper and lower age thresholds are $(8.38, 7.06), (8.73, 6.59)$, and $(9.13, 6.41)$ Gyr.

To quantify the significance of the different alignment behavior between the two extreme groups of galaxies, we perform a simple $\chi^2$ test by binning galaxies according to their distance to filaments ($d_F$). Let $B_1, \ldots, B_8$ be the first 8 bins of $d_F$ in Figure 7. Namely, $B_\ell$ contains galaxies with $5(\ell-1) \leq d_F < 5\ell$ Mpc, where $\ell$ is the bin index, ranging from 1–8. These bins correspond to the galaxies with $d_F < 40$ Mpc. The upper bound 40 Mpc which is roughly the range of filament’s effect $\rho_0$; see Section 3.2.2. We use the following $\chi^2$ statistic to test if the two extreme groups have consistent alignment behavior:

$$\chi^2 = \sum_{\ell=1}^8 \frac{\left( \langle |\eta_{F \cdot \mu_{\text{Major}}}| \rangle_{\ell}^{\text{high}} - \langle |\eta_{F \cdot \mu_{\text{Major}}}| \rangle_{\ell}^{\text{low}} \right)^2}{\sigma_{\text{high},\ell}^2 + \sigma_{\text{low},\ell}^2},$$

where $\langle |\mu_{F \cdot \mu_{\text{Major}}}| \rangle_{\ell}^{\text{high}}$ is the average alignment of the highest group galaxies in bin $\ell$ and $\langle |\mu_{F \cdot \mu_{\text{Major}}}| \rangle_{\ell}^{\text{low}}$ is that of the lowest group in bin $\ell$. If there is no effect from the specified galaxy property, we expect no statistically significant difference between the two extreme groups, and the $\chi^2$ statistic will follow a $\chi^2_8$ distribution ($\chi^2$ distribution with degree of freedom 8). The results of this test for different galaxy properties and split criteria are displayed in Table 1.
In Figure 7, we show the impact of galaxy properties on alignment with filaments. In the top row, we split galaxies on absolute magnitude and observe a separation between the two groups of galaxies, with bright galaxies more aligned along nearby filaments compared to faint galaxies. The χ² test shown in Table 1 confirms this pattern—the two samples have a difference with p-values ranging from $1.1 \times 10^{-3}$ to $2.9 \times 10^{-2}$.

To further analyze how the brightness affects the alignment, we consider galaxies within 10 or 20 Mpc of a filament and at least 50 Mpc away from a cluster. We show the excess probability in terms of the angular difference between $\eta_{\text{Major}}$ and $\eta_F$ in Figure 8. Note that the alignment signal is just the cosine of the angular difference. If the alignment is random, then the angular difference will be uniformly distributed over $0^\circ - 90^\circ$. For both filament distance thresholds shown in Figure 8, we observe a clear increase in excess probability at small angular difference, implying that the major axes of both dim and bright galaxies tend to align along the orientation of nearby filaments. Moreover, the bright galaxies have a higher excess probability at the small angular difference, indicating that the galaxy-filament alignment is stronger for bright galaxies. This result is consistent with Figure B1 of Tempel et al. (2015) and Figure 4 of Zhang et al. (2013).

Despite this qualitative agreement, we observe a stronger alignment than Zhang et al. (2013) and Tempel et al. (2015). When we use the threshold $d_F < 10$ Mpc, we find an alignment effect that is roughly 20-30% larger. While $d_F < 20$ Mpc, we observe a similar effect (magnitude is about 1.1 - 1.15). Note that in Figure 6, where a larger threshold of $d_F < 40$ Mpc is used we only observe an increase at the order of 5%. There are many possible reasons why our results agree qualitatively but not quantitatively with these previous works. First, the galaxy populations being compared are different. In this work, we use the LOWZ sample, which consists predominantly of massive early-type galaxies. On the other hand, Zhang et al. (2013) and Tempel et al. (2015) use the MGS, which contains both red and blue galaxies with a lower average mass. Also, as seen in our
results, the amplitude of the alignment effect is impacted by the distance to the filament. We consider galaxies that are within 10/20 Mpc of a filament, which is a significantly further than Tempel et al. (2015), who consider galaxies within 0.71 Mpc of a filament. Finally, our definition of filaments differs from previous works. We define filaments as ridges of the galaxy distribution, while Tempel et al. (2015) defines filaments using the Bisous model (Stoica et al. 2007; Tempel et al. 2014a), and Zhang et al. (2013) finds filaments using the tidal tensor field from Wang et al. (2012).

The effect from stellar mass is more involved. The middle row of Figure 7 shows some small separations between the low mass and high mass galaxies in the sense that massive galaxies seem to have a stronger alignment effect. But the \( \chi^2 \) analysis in Table 1 leads to a result that is close to the boundary of significance. The \( \chi^2 \) statistics give p-values ranging from \( 1.6 \times 10^{-3} \) to \( 2.9 \times 10^{-2} \). However, this effect may just be due to the effect of brightness and the correlation between age and brightness. Because we have a limited sample size, we do not adjust for the effect from brightness. When we separate galaxies by their age, the resulting galaxies have an age-brightness correlation ranging from 0.24 to 0.37. Thus, when partitioning on age of galaxies, the early-forming galaxies tend to be brighter than the late-forming galaxies and this brightness difference may cause the age effect.

4 CONCLUSION

In this work, we have studied how filamentary structure impacts the orientation of galaxies in the SDSS LOWZ sample. We quantified two different types of galaxy alignments: galaxy-cluster alignments and galaxy-filament alignments. Our primary results are as follows:

- **We find a statistically significant galaxy-filament alignment.** In the analysis of Section 3.2, we observed a significant tendency for galaxies to be oriented in a direction parallel to the nearest filament. Such an effect exists when we consider galaxies at least 50 Mpc away from clusters, to remove the impact of galaxy alignments towards clusters. Moreover, the analysis in Section 3.2.2 further indicates that the range of filament influence on the alignment is \( \sim 30 - 45 \) Mpc, though some of this effect appears to be determined by uncertainty in filament positions rather than a real alignment over tens of Mpc.

- **Galaxy brightness (absolute magnitude) and age impact the amount of alignment with filaments.** Our analysis in Section 3.2.3 shows that the brightness and age of a galaxy impact the effect of filaments on alignment, with brighter galaxies and/or those that are early-forming tending to be more aligned, especially when the distance to the filament is \( < 10 \) Mpc. Overall, our results are qualitatively consistent with previous work (Tempel et al. 2015 and Zhang et al. 2013). In some scenarios, we observe a stronger effect than reported in those studies, although this may be due to differences in the galaxy samples and filament detection methodology.

- **We do not observe a significant impact of filaments on galaxy-cluster alignments.** In the analysis of Section 3.1, we find that the alignment of galaxies around clusters can be well explained by the distance to the cluster itself, and there is no statistically significant contribution from filaments. However, we note that such an effect may exist at a level too weak to be detected in our data.

- **We find weak evidence for the galaxy-filament alignment strength to depend on stellar mass.** When we separate galaxies according to their stellar mass, we only observe a difference in the galaxy-filament alignment that is on the boundary of significance. We do not observe a very significant effect as the findings of Zhang et al. (2009) and Chen et al. (2015c). However, as before, differences in galaxy samples and methodology may account for this difference. Our results indicate that galaxy alignments are impacted by the complexity of large-scale structure beyond the positions of the most massive objects (clusters). We leave for future work an assessment of whether existing models for galaxy alignment, which typically treat correlations with the total density field or within the halo environment, are sufficient to account for the impact of filaments. Models that explicitly treat density-filament correlations may improve the overall description of galaxy alignments. Potential inconsistencies with previous results highlight the value of performing similar analyses on future data sets with greater statistical power.
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APPENDIX A: EFFECT FROM FILAMENT UNCERTAINTY

To investigate the effect from filament uncertainty, we consider a very simple model where the alignment effect is

\[ \begin{align*}
1, & \quad \text{if } d_F \leq 3.5 \text{ Mpc}, \\
0, & \quad \text{if } d_F > 3.5 \text{ Mpc}.
\end{align*} \]

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The threshold 3.5 Mpc is from the study in simulations in Chen et al. (2015c). To model the impact of uncertainty in the filament position, we assume that our observed distance to filament

$$d_{F,\text{obs}} = d_F + |\epsilon|,$$

where $d_F$ is the true distance to filament and $\epsilon$ is a random number follows from a Normal distribution with variance $\sigma^2$. We consider $\sigma = 5$, 10, and 20 Mpc and we display the result on the alignment signal in Figure A1. The uncertainty of filaments in the LOWZ sample is about 10 – 20 Mpc according to Chen et al. (2016), model predictions with $\sigma = 10$ and 20 Mpc provide a rough idea for how the Gaussian uncertainty distance to the filament affects the range of effect. According to Figure A1 the uncertainty of filaments may lead to an alignment effect with a range up to 50 Mpc, which is close to what we observed in Figure 4.