Measuring Alignments between Galaxies and the Cosmic Web at \( z \sim 2–3 \) Using IGM Tomography

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Abstract

Many galaxy formation models predict alignments between galaxy spin and the cosmic web (i.e., directions of filaments and sheets), leading to an intrinsic alignment between galaxies that creates a systematic error in weak-lensing measurements. These effects are often predicted to be stronger at high redshifts (\( z \gtrsim 1 \)) that are inaccessible to massive galaxy surveys on foreseeable instrumentation, but IGM tomography of the Ly\( \alpha \) forest from closely spaced quasars and galaxies is starting to measure the \( z \sim 2–3 \) cosmic web with requisite fidelity. Using mock surveys from hydrodynamical simulations, we examine the utility of this technique, in conjunction with coeval galaxy samples, to measure alignment between galaxies and the cosmic web at \( z \sim 2.5 \). We show that IGM tomography surveys with \( \lesssim 5 \) \( h^{-1} \) Mpc sightline spacing can accurately recover the eigenvectors of the tidal tensor, which we use to define the directions of the cosmic web. For galaxy spins and shapes, we use a model parameterized by the alignment strength, \( \Delta (\cos \theta) \), with respect to the tidal tensor eigenvectors from the underlying density field, and also consider observational effects such as errors in the galaxy position angle, inclination, and redshift. Measurements using the upcoming \( \sim 1 \) \( \text{deg}^2 \) CLAMATO tomographic survey and 600 coeval zCOSMOS-Deep galaxies should place \( 3\sigma \) limits on extreme alignment models with \( \Delta (\cos \theta) \sim 0.1 \), but much larger surveys encompassing \( \gtrsim 10,000 \) galaxies, such as Subaru PFS, will be required to constrain models with \( \Delta (\cos \theta) \sim 0.03 \). These measurements will constrain models of galaxy–cosmic web alignment and test tidal torque theory at \( z \sim 2 \), improving our understanding of the physics of intrinsic alignments.

Key words: cosmology: observations – galaxies: high-redshift – intergalactic medium – large-scale structure of universe – quasars: absorption lines

1. Introduction

Gravitational collapse of the Gaussian random-phase initial conditions produced by inflation creates a network of dense nodes connected by filaments and sheets and separated by voids, the “cosmic web” (Zeldovich et al. 1982; Klypin & Shandarin 1983; Einasto et al. 1984; Davis et al. 1985; Geller & Huchra 1989; Bond et al. 1996). As a result of nonlinear structure formation, the cosmic web is distinctly non-Gaussian. In the Zel’dovich approximation, collapse occurs sequentially along the principal axes of the deformation tensor as matter flows out of voids onto sheets, collapses into filaments, and finally streams into high-density nodes (Zel’dovich 1970). The accretion of matter determines the shapes and angular momenta of galaxies and their dark matter halos, naturally suggesting a connection between the cosmic web and galaxy shapes and spins.

In the linear regime, the evolution of the angular momentum of a protohalo is described by tidal torque theory (TTT, Peebles 1969; Doroshkevich 1970; White 1984). TTT predicts that the protohalo’s angular momentum will be aligned with the intermediate eigenvector of the tidal tensor. However, nonlinear evolution can significantly weaken this alignment (Porciani et al. 2002), driving alignments with other preferred directions (e.g., the direction of filaments along which matter is accreting; Codis et al. 2012).

Alignments between the cosmic web and halo shapes and spins have been extensively studied in N-body simulations (Kiessling et al. 2015; see Tables 1 and 2 in Forero-Romero et al. (2014) for a recent compilation of results). Many authors suggest that halo spins transition from parallel to filaments at low halo mass to perpendicular to filaments at high mass (Ballin & Steinmetz 2005; Aragón-Calvo et al. 2007; Hahn et al. 2007a; Codis et al. 2012; Trowland et al. 2013; Aragon-Calvo & Yang 2014). In addition, Dubois et al. (2014) and Codis et al. (2015), using the cosmological hydrodynamical simulation HorizonAGN, argue that galaxy spin alignments exhibit a similar transition mass. However, these results are dependent on the measurement algorithm, simulation, and environmental classification (Kiessling et al. 2015) and it is unclear if spin-filament alignments are the dominant spin–cosmic web alignment. For instance, Libeskind et al. (2013) found a similar transition from aligned to anti-aligned in voids and sheets as well as filaments, although with a different transition mass in each web type, and Forero-Romero et al. (2014) found no alignment at low mass and argue that sheet alignments are as significant as filament alignments at high mass. In direct contradiction to the picture described above, the cosmological zoom simulations of Hahn et al. (2010) suggest that the spins of massive disk galaxies are aligned parallel to their host galaxies while the spins of low mass galaxies are aligned along the intermediate axis of the tidal tensor.

In contrast, halo shape–cosmic web alignments are both stronger and more robust to measure than spin–cosmic web alignments (Kiessling et al. 2015), although they have been less extensively studied. The major axis of the halo inertia tensor is preferentially aligned along filaments, in the plane of sheets (Altay et al. 2006; Aragón-Calvo et al. 2007; Hahn et al. 2007a;...
Zhang et al. 2009; Libeskind et al. 2013; Forero-Romero et al. 2014) and parallel to the surface of voids (i.e., the plane of sheets; Patiri et al. 2006; Brunino et al. 2007; Cuesta et al. 2008). Shape–cosmic web alignments monotonically increase from weak to strong as a function of mass, with no transition mass (Aragón-Calvo et al. 2007; Hahn et al. 2007a; Zhang et al. 2009; Libeskind et al. 2013; Forero-Romero et al. 2014). Using the MassiveBlack-II cosmological hydrodynamical simulation, Chen et al. (2015) reported similar results for alignments between galaxy shapes and filaments. Galaxy shape–cosmic web alignments are closely related to ellipticity–tide shear correlations (Codis et al. 2015), the “GI” term of intrinsic alignments, a potential major systematic for upcoming missions such as LSST, WFIRST, and EUCLID that aim to measure the dark energy equation of state using weak-lensing tomography (Hirata & Seljak 2004; Bridle & King 2007; Kirk et al. 2012).

Observational studies of galaxy–cosmic web alignment require large numbers of galaxy redshifts to trace the cosmic web in 3D and are therefore primarily feasible only at low redshift. Observations of alignments between spiral galaxy spin and void surfaces/sheets have produced conflicting results ranging from parallel to random to perpendicular alignment (Trujillo et al. 2006; Slosar & White 2009; Varela et al. 2012). Locally, Navarro et al. (2004) found that spiral galaxy spins preferentially lie in the supergalactic plane (see also Aryan & Saurer 2004). Early observations reported that spiral galaxy spins are aligned with the intermediate axis of the tidal shear tensor in concordance with TTT predictions (Lee & Pen 2002; Lee & Erdogdu 2007) and are therefore aligned perpendicular to filaments (Jones et al. 2010; Zhang et al. 2015). However, more recently Tempel et al. (2013) and Tempel & Libeskind (2013) found that spiral galaxy spins are parallel to filaments and lenticular/elliptical galaxy spins are perpendicular to filaments, in concordance with the transition mass picture from simulations. Similarly, Pawa et al. (2016) found that elliptical galaxy spins lie perpendicular to filaments and normal to sheets, while spiral galaxy spins exhibit much weaker alignments along filaments. In accordance with shape–cosmic web alignments from simulations, Zhang et al. (2013) found that galaxy major axes preferentially align with filaments and along sheets, a relationship that is weak for blue galaxies and highly significant for bright red galaxies.

Similar measurements at higher redshift ($z > 0.5$) are challenging due to the difficulty of measuring the cosmic web from the galaxy distribution, requiring large samples of faint galaxies to achieve sufficient spatial resolution of a few Mpc, although surveys such as VIPERS (Guzzo et al. 2014; Malavasi et al. 2017) are pushing this to $z ∼ 0.7$. Even with future 30m-class telescopes, it would be extremely time consuming to obtain the requisite galaxy samples at $z > 1$ due to the high number densities required. Studies of Lyα nebulae have discovered filaments around quasars at $z ∼ 2.5$ (Cantalupo et al. 2012, 2014; Cai et al. 2016), but they probe very small, non-representative volumes around the rarest density peaks, which are unsuitable for statistical studies of galaxy alignments.

At higher redshifts, Lyman-α forest tomography (Pichon et al. 2001; Caucci et al. 2008) offers an alternative method for characterizing the cosmic web at $z ∼ 2$, the epoch of peak star formation, by using observations of Lyα forest absorption in closely spaced quasars and Lyman-break galaxies to reconstruct the IGM absorption field. Using this technique, current instrumentation can probe a spatial resolution of a few Mpc (Lee et al. 2016), similar to the resolution of cosmic web studies at $z < 0.5$ (e.g., the GAMA Survey; Eardley et al. 2015). By simulating IGM tomographic observations with realistic signal-to-noise, resolution, and sightline separation, we have shown that the reconstructed flux fields visually match the underlying dark matter density (Lee et al. 2014b) and can be used to find high-redshift protoclusters and voids (Stark et al. 2015a, 2015b). Moreover, sufficiently large surveys (with $\geq 1$ deg of contiguous sky coverage) can recover kinematically defined cosmic web classifications with a fidelity comparable to low-redshift surveys using the galaxy density field (Lee & White 2016). These results suggest that IGM tomography could allow measurement of galaxy shape–cosmic web alignments at $z ∼ 2.5$ in the near future.

In this paper, we will discuss the prospects for measuring galaxy–cosmic web alignments using IGM tomography surveys with mean sightline separations of $(d_\ell) = [1.4, 2.5, 4, 6.5] h^{-1}$ Mpc. These reflect both existing and possible future surveys. First, $(d_\ell) = 2.5 h^{-1}$ Mpc reflects the ongoing COSMOS Lyα Mapping And Tomography Observations (CLAMATO) survey\(^5\) (for which the pilot phase is being completed; see Lee et al. 2014a, 2016), which aims to cover $\sim 1$ deg\(^2\) in the COSMOS field using the LRIS spectrograph on the 10.3 m Keck I telescope. CLAMATO will cover a redshift range $2.2 < z < 2.5$, mapping $\sim 10^6 h^{-3}$ Mpc\(^3\) comoving volume with a spatial resolution of $2.5 h^{-1}$ Mpc. By $\sim 2020$, the Subaru Prime-Focus Spectrograph (PFS) will begin operation (Takada et al. 2014), and an IGM tomographic survey building on the PFS galaxy evolution survey, but obtaining additional sightline spectra and higher S/N could cover $\sim 20$ deg\(^2\) with $(d_\ell) = 4 h^{-1}$ Mpc. On the other hand, an IGM tomography map could be constructed “for free” using the $i < 24$ LBGs targeted for the PFS Galaxy Evolution Survey (Takada et al. 2014) without additional IGM tomography targets, yielding $(d_\ell) = 6.5 h^{-1}$ Mpc. Finally, the proposed FOBOS instrument on Keck will offer much greater ($\sim 10\times$) multiplexing and field of view than LRIS on the same telescope, allowing for deeper integrations and hence denser sightline sampling of $(d_\ell) \sim 1.4 h^{-1}$ Mpc while surveying $\sim 1$ deg\(^2\), similar to CLAMATO.

In this paper, we will estimate the quality of cosmic web direction measurements (e.g., direction of filaments, normal vector to sheets, etc.) using mock observations based on the Nyx hydrodynamic IGM simulations. We will discuss the feasibility for measuring galaxy–cosmic web alignments using these surveys in tandem with coeval galaxy samples at $z ∼ 2.5$.

2. Methods

2.1. Nyx Simulations and Mock Observations

We use a cosmological hydrodynamical simulation generated with the N-body plus Eulerian hydrodynamics NYX code (Almgren et al. 2013). It has a $100 h^{-1}$ Mpc box size with 4096\(^3\) cells and particles, resulting in a dark matter particle mass of $1.02 \times 10^9 h^{-1} M_{\odot}$ and spatial resolution of $24 h^{-1}$ kpc. As discussed in Lukić et al. (2015), this resolution is sufficient to resolve the filtering scale, below which the IGM is pressure supported, and to reproduce the flux statistics at

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\(^5\) http://clamato.lbl.gov/
percent accuracy at redshift \(z = 2.4\). The box covers a similar size to the proposed CLAMATO and FOBOS survey volumes. We use a flat LCDM cosmology with \(\Omega_m = 0.3\), \(\Omega_b = 0.047\), \(h = 0.685\), \(n_s = 0.965\), and \(\sigma_8 = 0.8\), consistent with latest Planck measurements (Planck Collaboration et al. 2016). We define halos as contiguous regions of the density field with a value above a given threshold; in this work we assumed \(\rho_{\text{halo}} = 138(\rho)\).

In NYX, the baryons are modeled as an ideal gas on a uniform grid. The baryons have a primordial composition with hydrogen and helium mass abundances of 75% and 25%, respectively. We account for photoionization, recombination, and collisional excitation of all neutral and ionized species of hydrogen and helium, which evolve in ionization equilibrium with the uniform UV background given by Haardt & Madau (2012), with the mean flux normalized to match observational values. The reaction and cooling rates used in the code are given in Lukić et al. (2015). This simulation does not model star formation and hence has no feedback from stars, galaxies, or AGNs, but these are expected to have a negligible effect on the Ly\(\alpha\) forest statistics (Viel et al. 2013). Future NYX IGM simulations will include galaxy formation physics in order to self-consistently simulate a galaxy population, allowing better interpretation of the relationship between galaxies and the Ly\(\alpha\) forest.

We generated 512\(^3\) absorption skewers with a spacing of 0.2\(h^{-1}\)Mpc and sampled from these skewers to create mock data. We computed the Ly\(\alpha\) forest flux fluctuation along each skewer

\[
\delta_F = F / \langle F \rangle - 1,
\]

where \(F = \exp(-\tau)\) and \(\tau\) is the Ly\(\alpha\) optical depth, computed in redshift space and Doppler broadened using the gas temperature. Hereafter we refer to \(\delta_F\) as the flux.

We then create mock spectra that reflect the data quality expected from current and upcoming surveys. First, we randomly select absorption skewers with the appropriate mean sightline spacing \((d_s)\) and rebin them along the line of sight to a resolution of 0.78\(h^{-1}\)Mpc, similar to the line-of-sight spectral resolution from the CLAMATO spectra.

We simulate noise by assuming the S/N per pixel is a unique constant for each skewer. To determine the S/N for each skewer, we draw from a power-law S/N distribution \(dn_{\text{obs}}/dS/N \propto S/N^{-\alpha}\) (Stark et al. 2015b, hereafter S15b), where the S/N ranges between 1.5 (the minimum S/N in CLAMATO; Lee et al. 2014a, 2016) and infinity. Lee et al. (2014b) found that \(\alpha \sim 2.5\) for the LBGs and QSOs that we target; however, as the sightline separation increases, the sources targeted become brighter and we move further along the exponential tail of the luminosity function, so \(\alpha\) becomes larger. S15b found \(\alpha = 2.9\) (3.6) for \((d_s) = 2.5\) (4)\(h^{-1}\)Mpc, respectively. They did not determine \(\alpha\) for \((d_s) < 2h^{-1}\)Mpc or \(>4h^{-1}\)Mpc; therefore we use \(\alpha = 2.7\) (3.6) for our \((d_s) = 1.4\) (6.5)\(h^{-1}\)Mpc map, identical to the S15b values for \((d_s) = 2.5\) (4)\(h^{-1}\)Mpc. We confirm the power-law distribution is appropriate by comparing it to the S/N distribution of observed pixels from the CLAMATO pilot observations. Using the simulated S/N distribution, we add noise to each pixel assuming a Gaussian distribution. We also model the effect of continuum-fitting error with an rms of 10%: \(F_{\text{obs}} = F_{\text{sim}} / (1 + \delta_{\text{cont}})\) where \(\delta_{\text{cont}}\) is a random Gaussian deviate, identical for all pixels within a skewer, with a mean of 0 and a standard deviation of 0.1. This reflects the continuum-fitting uncertainties expected from data with comparable S/Ns (Lee et al. 2012).

For the tomographic reconstruction, we use the publicly available Wiener filter reconstruction code of Stark et al. (2015b)\(^6\) to create a 3D map of the flux field. The Wiener filter is ideal for reconstruction as it provides a minimum variance estimate of the 3D field, assuming the field is normally distributed (Caucci et al. 2008; Lee et al. 2014b; Stark et al. 2015b). The reconstructed signal is

\[
\hat{\delta} = S_{\text{md}} (S_{\text{dd}} + N)^{-1} d,
\]

where \(d\) is the data, \(N\) is the noise covariance, \(S_{\text{md}}\) is the map–data covariance, and \(S_{\text{dd}}\) is the data–data covariance. We assume that the noise covariance is diagonal, so that \(N_{ij} = n_i^2 \delta_{ij}\), where \(n_i\) is the simulated noise for each pixel. We further assume that \(S_{\text{md}} = S_{\text{dd}} = S\):

\[
S = \sigma_F^2 \exp \left[ -\frac{\Delta x_1^2}{2\ell_1^2} - \frac{\Delta x_2^2}{2\ell_2^2} \right].
\]

We use \(\sigma_F^2 = 0.05\) and isotropic smoothing with \(l_1 = l_2 = \langle d_s \rangle\). Hereafter we refer to the reconstructed flux as \(\delta_F\) and the simulated flux as \(\delta_F\). The mock Ly\(\alpha\) skewers and IGM tomography maps are publicly released on the web.\(^7\)

2.2. Defining the Cosmic Web

We measure the cosmic web directions using the eigenvectors of the deformation tensor, an approach inspired by the cosmic web classifications of Hahn et al. (2007b). While there are many alternative cosmic web classifiers (see enumeration in Cautun et al. 2014), we prefer the deformation tensor approach for a variety of reasons: it allows direct comparison with Lee & White (2016), it is physically motivated by the Zel’’dovich approximation, and it is directly related to the gravitational shear field relevant for weak-lensing intrinsic alignments (Codis et al. 2015).

The deformation tensor is defined as the Hessian of the gravitational potential \(\Phi\):

\[
D_{ij} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j}.
\]

The Hessian is most efficiently calculated in Fourier space, using the Poisson equation in suitable units where \(4\pi G = 1\), \(\nabla^2 \Phi = k^2 \Phi = \delta_k\). Therefore we can directly compute the Fourier transform of \(D_{ij}\) from the density:

\[
\tilde{D}_{ij}(k) = \frac{k_i k_j}{k^2} \delta_k
\]

and inverse-Fourier transform to obtain \(D_{ij}\). To compute \(D_{ij}\), we define \(\delta\) as the sum of the matter and baryonic overdensity measured in redshift space, binned on a 128\(^3\) grid and smoothed with a Gaussian kernel with standard deviation \(R_G = 2 h^{-1}\) Mpc (see below for details of smoothing). We then diagonalize the deformation tensor at every point in space to obtain its eigenvectors, \(\hat{e}_1\), \(\hat{e}_2\), and \(\hat{e}_3\), where the eigenvectors correspond to eigenvalues \(\lambda_1 < \lambda_2 < \lambda_3\). In the Zel’’dovich

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\(^6\) https://github.com/caseywstark/dachshund

\(^7\) http://tinyurl.com/hg7u4dg
approximation, collapse proceeds first along $\hat{e}_3$ and last along $\hat{e}_1$.

Note that the traceless tidal shear tensor

$$T_{ij} = \frac{\partial^2 \Phi}{\partial x_i \partial x_j} - \frac{1}{3} \nabla^2 \Phi \delta_{ij},$$

(6)

which is more relevant than $D_{ij}$ for intrinsic alignment (Codis et al. 2015), shares its eigenvectors with the deformation tensor. As a result, we will use the phrases “eigenvectors of the tidal tensor” and “eigenvectors of the deformation tensor” interchangeably.

We define the cosmic web directions of the IGM tomography map, which reconstructs the Ly\(\alpha\) forest flux, as the eigenvectors of the pseudo-deformation tensor (Lee & White 2016), where we simply substitute the Fourier transform of the flux field, $\delta_F$, for $\delta_k$ in Equation (5). Since $\delta_F$ has the opposite sign as $\delta_k$, we order the eigenvalues of the pseudo-deformation tensor from largest to smallest.

We classify each point as a node, filament, sheet, or void using the number of eigenvalues greater than a nonzero threshold value $\lambda_{th}$ similar to Lee & White (2016) and Forero-Romero et al. (2009). A nonzero threshold leads to a better agreement with visually prominent sheets and filaments (Forero-Romero et al. 2009) and is physically justified because directions with a small positive $\lambda$ are contracting so slowly they may not collapse in a Hubble time. Similar to Lee & White (2016), we choose $\lambda_{th, m}$ by matching the volumetric void fraction in the matter density to the $\sim19\%$ void fraction of Stark et al. (2015a). We choose the threshold for the flux, $\lambda_{th,F}$, using the same condition on the void fraction for the $\langle d_i \rangle = 1.4$, 2.5, 4, and 6.5 $h^{-1}$ Mpc reconstructions.

The eigenvectors of the deformation tensor are related to the underlying geometry and kinematics of the cosmic web (Figure 1). In the Zel’dovich approximation, matter collapses along an eigenvector if its eigenvalue is positive and expands along an eigenvector if its eigenvalue is negative (Hahn et al. 2007b). In a filament, there is only one negative eigenvalue, thus $\hat{e}_1$ is the only direction of expansion, making it the long axis of the filament. Similarly, in a sheet, there is only one positive eigenvalue, making $\hat{e}_2$ the normal vector to the sheet. Therefore, we define the directions of the cosmic web using the eigenvectors of the tidal tensor.

Following Lee & White (2016), we smooth the deformation tensor to minimize the effects of reconstruction noise and remove small-scale fluctuations. They found that a Gaussian kernel with $R_G \sim 1.5 \langle d_i \rangle$ was appropriate for this purpose (see also Caucci et al. 2008). Therefore, we use smoothing kernels with $R_G = [2, 4, 6, 10]$ for $\langle d_i \rangle = [1.4, 2, 4, 6.5]$ reconstructions. A larger smoothing scale leads to a more homogeneous map with less variation in $\delta_F$, so maps with a larger $\langle d_i \rangle$ have a smaller spread in $\delta_F$ (Figure 2).

We also smooth the underlying matter density which we use for comparison. Since our cosmic web classification scheme is based on the Zel’dovich approximation, it is only valid up to the mildly nonlinear scales where the Zel’dovich approximation fails (Eardley et al. 2015). Therefore, smoothing on scales of a few $h^{-1}$ Mpc is appropriate to eliminate highly nonlinear scales. We choose a matter smoothing scale of $2 h^{-1}$ Mpc, comparable to the smoothing scales used in shape–cosmic web and spin–cosmic web alignment studies from simulations (see the compilation in Forero-Romero et al. 2014).

The choice of smoothing scale is ultimately arbitrary; for instance, we could follow Lee & White (2016) and choose a different matter density smoothing scale for each reconstruction, matching the smoothing scales of the flux map and the matter. However, we prefer to use a single “true” matter map to generate galaxy spins (see Section 2.4). The results in this paper are qualitatively similar if we instead match the matter smoothing scale to the reconstruction smoothing scale, in that the recovery of the eigenvectors declines from $\langle d_i \rangle = 1.4 h^{-1}$ Mpc to $6.5 h^{-1}$ Mpc. However, the decline is much less steep if we match smoothing scales; thus, much of the misalignment between the matter field and IGM tomography maps with $\langle d_i \rangle > 2 h^{-1}$ Mpc is due to the mismatch in smoothing scales.

Figure 2 compares the matter density field to the reconstructed flux field for $\langle d_i \rangle = 1.4$, 2.5, 4, and 6.5 $h^{-1}$ Mpc for an $0.8 h^{-1}$ Mpc slice through the simulation box. We also show the simulated redshift-space $\delta_F$ field, equivalent to a “perfect resolution” IGM tomography survey. We overplot headless vectors corresponding to the projection of $\hat{e}_1$ onto the $xy$ plane; arrowheads are not displayed because the sign of $\hat{e}_1$ is arbitrary. The IGM tomography surveys are smoothed using the smoothing scales defined above, while the matter density and simulated flux field, $\delta_F$, are smoothed with $R_G = 2 h^{-1}$ Mpc. The simulated flux and $\langle d_i \rangle = 1.4 h^{-1}$ Mpc fields reproduce the matter density well, although with a very different dynamical range owing to the nonlinear transformation from $\delta$ to $\delta_F$. The simulated flux and $\langle d_i \rangle = 1.4 h^{-1}$ Mpc maps reproduce the small-scale structure in the matter density $\hat{e}_1$ quite well, while larger $\langle d_i \rangle$ yield a smoother distribution of $\delta_F$ and $\hat{e}_1$ that captures the large-scale features but misses much of the smaller scale structure.

2.3. Galaxy Spin Observations

Measuring galaxy–cosmic web alignments at $z \sim 2.5$ requires a large galaxy sample with accurate redshifts and structural parameters. The typical half-light radius of a $z \sim 2.4$ galaxy is $\sim 0.05$ (Giavalisco et al. 1996; van der Wel et al. 2014). Space-based or adaptive-optics observations are therefore preferred for measuring structural parameters at $z \sim 2.4$, although the shapes of faint galaxies can be measured well from the ground with deep exposures and $\sim 0.5$ seeing
Additionally, LSST plans to measure cosmic shear out to $z \sim 3$ using ground-based observations with $0\farcs7$ mean seeing (LSST Science Collaboration et al. 2009).

Galaxy spins can be determined from galaxy images using the galaxy’s position angle and axis ratio assuming the galaxy is an oblate spheroid spinning about its short axis (Haynes & Giovanelli 1984). The position angle defines the direction of the projected major axis, while the inclination is calculated from the axis ratio, assuming the galaxy is circular if viewed face-on and the intrinsic thickness is known. As a result, this method is only applicable to spiral or spheroidal galaxies, which can be approximated as oblate spheroids (e.g., Lee & Erdogdu 2007; Tempel et al. 2013). For elliptical galaxies with minimal rotation, alignments between the galaxy’s major axis and the projected eigenvectors of the tidal tensor are most relevant.

The spin axis is then assumed to be the minor axis of the galaxy ellipsoid. In principle, the spin and minor axis may be misaligned, though both observations and simulations find small misalignments (Franz et al. 1991; Codis et al. 2015), ~15° at $z \sim 2$ (Wisnioski et al. 2015). High-resolution or adaptive-optics IFU observations can measure the kinematic major axes of galaxies at $z \sim 2$ (e.g., Wisnioski et al. 2015), but even large surveys with KMOS or NIRSpec (Giardino et al. 2016) may only accumulate 1000 galaxies over the next several years, far smaller than the sample sizes expected from wide-field imaging surveys.

Galaxies at $z \sim 2$ have a clumpier and more irregular morphology than galaxies at low redshift (Elmegreen et al. 2005; Lotz et al. 2006). This may present an additional challenge for measuring the major axis and ellipticity of the light profile. In addition, the intrinsic thickness is a major source of systematic error in determining the inclination: it varies by morphology (Haynes & Giovanelli 1984) and potentially also with redshift, as galaxies at $z \sim 2$ are thicker than galaxies at low redshift (Law et al. 2012). Furthermore, only the absolute value of the inclination is measurable, so there will always be a degeneracy between spins pointing toward the observer and spins pointing away from the observer, except for face-on or edge-on galaxies. Alignment studies have attempted to mitigate this degeneracy in several ways (Trujillo et al. 2006; Lee & Erdogdu 2007; Slosar & White 2009; Varela et al. 2012; Pahwa et al. 2016) but ultimately the degeneracy will degrade the measured alignment signal.

To understand the impact of these systematics on alignment measurements at $z \sim 2$, we include realistic errors in the galaxies’ position angles and inclinations. Since the inclination measurements may be particularly impacted by systematic errors from the unknown intrinsic thickness and anisotropies in the PSF, we consider both 3D and 2D alignment measurements, where the 2D alignment measurements ignore the $z$-direction of the eigenvectors altogether. To model the spin...
for the galaxy–cosmic web alignment signal. Hence, we assign galaxy spins to the simulation halos using a stochastic relationship between the eigenvectors of the tidal tensor of the matter density field and galaxy spin. This prescription allows us greater flexibility to adjust the strengths of galaxy alignments compared to adhering to the results of a single simulation. The galaxy formation physics governing the shape–cosmic web relationship are not well understood (e.g., see the disagreement between MassiveBlack-II and HorizonAGN alignment results at low redshift; Tenneti et al. 2016; Chisari et al. 2016), so flexibility in modeling this relationship is valuable. Moreover, it is not clear which eigenvector the spin is most strongly aligned with, so our model allows us to adjust the alignment strength with any of the three eigenvectors (although for simplicity we do not consider alignments with more than one eigenvector at a time).

Our model takes as input \( \langle \cos \theta \rangle \), the mean of the cosine of the angle between the galaxy spins and the local eigenvector of the matter field tidal tensor. We parameterize the PDF of \( \mu \equiv \cos \theta \) as

\[
P(\mu) = a\mu^2 + c, \tag{7}
\]

where \( c = 1 - a/3 \) such that \( P(\mu) \) is normalized.

To compare to various observational and simulation results, we parameterize \( P(\mu) \) using \( \langle \cos \theta \rangle \) rather than \( a \):

\[
a = 12\langle \cos \theta \rangle - 6. \tag{8}
\]

Equation (7) roughly reproduces \( P(\mu) \) as measured from simulations (e.g., Aragón-Calvo et al. 2007; Zhang et al. 2009; Codis et al. 2012; Libeskind et al. 2013; Trowland et al. 2013; Aragon-Calvo & Yang 2014; Dubois et al. 2014; Codis et al. 2015). A representative value of \( \langle \cos \theta \rangle \) from simulations is given by Codis et al. (2015), \( \langle \cos \theta \rangle = 0.509 \), similar to \( \langle \cos \theta \rangle \) for \( \hat{e}_1 \)-spin alignments measured at low redshift (Tempel & Libeskind 2013; Zhang et al. 2013; Pahwa et al. 2016) and spin-filament alignments in simulations (Dubois et al. 2014) and observations (Tempel et al. 2013). Moreover, for small deviations from random alignments, Equation (7) agrees well with Equation (5) in Lee & Erdogdu (2007), who derived an analytic expression for the misalignment angle between galaxy spin and \( \hat{e}_2 \) in TTT.

To assign each galaxy a spin axis, we start by finding the eigenvectors of the tidal tensor of the matter density field at the nearest grid point to the galaxy’s redshift-space position. The misalignment angle \( \theta \) is randomly drawn from Equation (7) and the azimuthal angle \( \phi \) from the uniform distribution between 0 and \( 2\pi \). Since both the eigenvectors and the galaxy spin axis are headless vectors, we randomly generate a direction for the galaxy spin as well. Last, we add a random Gaussian deviate with standard deviation \( \sigma_{PA} \) (\( \sigma_e \)) to the position angle (inclination) and randomly choose whether the galaxy spin will be oriented toward or away from the observer.

2.5. IGM and Galaxy Survey Parameters

We estimate the significance of a galaxy–cosmic web alignment measurement with fiducial parameters \( \langle d_i \rangle = 2.5 h^{-1}\text{Mpc} \), 10,000 coeval galaxies, redshift errors of 100 km s\(^{-1}\), \( \sigma_{PA} = 10^\circ \) and \( \sigma_e = 10^\circ \). Subsequently, we consider how the significance of the alignment signal varies with different sightline spacings, galaxy sample sizes and redshift and structural parameter errors.

Sightline spacings of 6.5, 4.0, 2.5, and 1.4 h\(^{-1}\) Mpc are considered, as well as the full noiseless \( \delta \) simulation grid (with 0.8 h\(^{-1}\) Mpc voxels) as the limiting case of “perfect” IGM tomography. The 4.0, 2.5, and 1.4 h\(^{-1}\) Mpc spacings correspond to the sightline spacings expected for the PFS, CLAMATO, and FOBOS IGM tomography surveys, respectively, while 6.5 h\(^{-1}\) Mpc is the sightline spacing of an IGM reconstructions using only the baseline PFS galaxy evolution survey (Takada et al. 2014) without incorporating additional targets for tomography.

We use coeval galaxy samples of 600, 3000, 10,000, and 30,000 galaxies. The density of target galaxies for tomography differs by an order of magnitude between the \( \langle d_i \rangle = 1.4 \) and 4.0 h\(^{-1}\) Mpc cases, so the galaxy samples were chosen to span an order of magnitude as well, allowing us to directly compare the importance of coeval galaxy sample size versus number of sightlines. The fiducial 10,000 galaxy sample does not require 10,000 galaxies in 1 deg\(^2\) (the angular size of our simulation box at \( z \sim 2.4 \)); rather, the galaxies may be spread over a wider area if the tomographic map also has the same coverage. The cosmic web recovery does not depend on halo mass of the galaxies (Figure 5), so we emulate a survey with larger area by simply including lower mass galaxies in our sample.

The 10,000 galaxy sample is similar to the number of 2.15 < \( z < 2.55 \) redshifts that the PFS galaxy evolution survey could obtain. Structural parameters for such a sample could be measured either from the deep HyperSuprimeCam imaging used for PFS targeting or from wide-field space-based imaging from Euclid or WFIRST. More ambitious future surveys could perform IGM tomography with even larger samples of coeval galaxies, such as the proposed “Billion-Object Apparatus” (Dodelson et al. 2016), which could execute a CLAMATO-like survey over 10\(^5\) deg\(^2\) with a few hundred coeval galaxies per square degree. As a conservative choice, we therefore include a 30,000 galaxy sample to represent these futuristic surveys. At the other extreme, we also consider a 600 galaxy sample, roughly matching the number of coeval galaxies in the CLAMATO volume, primarily from the zCOSMOS-deep survey ( Lilly et al. 2007; Scoville et al. 2007).

The fiducial redshift errors are 100 km s\(^{-1}\), appropriate for redshifts from nebular emission lines in rest-frame optical spectra (Steidel et al. 2010). We consider redshift errors of 300 km s\(^{-1}\), appropriate for redshifts from UV absorption lines or Ly\(\alpha\) emission lines (Steidel et al. 2010; Kriek et al. 2015), and 500 km s\(^{-1}\), appropriate for emission-line redshifts from grism spectra (Kriek et al. 2015; Momcheva et al. 2016). We also consider the maximal redshift errors allowed by our box size, in which the \( z \) position of each galaxy in the box is drawn from a uniform distribution. This produces a distribution with \( \sigma_v \sim 2000 \text{ km s}^{-1} \), somewhat better than typical photometric redshifts (\( \sigma_v \gtrsim 9000 \text{ km s}^{-1} \)) or Ly\(\alpha\) tomographic redshifts (\( \sigma_v \gtrsim 3000 \text{ km s}^{-1} \); Schmittfull & White 2016).

The fiducial error on the galaxy position angle is 10\(^\circ\), consistent with position angle errors as estimated from both
cosmic shear measurements from Hubble Space Telescope imaging (Leauthaud et al. 2007; Joachimi et al. 2013) and from structural parameter measurements using CANDELS imaging (van der Wel et al. 2012)8 for galaxies with magnitudes, sizes, and Sérsic indices typical of z ~ 2 galaxies. We also consider position angle errors of 5° and 20° in order to determine the importance of imaging quality. These position angle errors may not be appropriate for ground-based imaging, which generally suffers from increased uncertainty in shape modeling (e.g., Chang et al. 2013). We therefore also consider position angle errors of 40°, which may be more realistic for structural parameters derived from ground-based imaging.

We use a fiducial inclination error of 10°. The error on the inclination can be related to the error on the ellipticity using Taylor series error propagation. Using the ellipticity errors from the CANDELS catalog for z ~ 2 galaxies assuming intrinsic thickness 0.25 (van der Wel et al. 2012), we find a median σi = 6°. To conservatively account for systematic errors from the intrinsic thickness and possible departures from axisymmetry, the fiducial value of σi is 10°. We also consider σi = 5° and σi = 20° to determine the impact of inclination error on our measurement.

For each measurement, we simulate galaxy selection by randomly selecting Ngal halos with Mh > 10^{10.5} M_{\odot}. While this is does not reflect a realistic selection function, the cosmic web recovery does not depend on mass (Figure 5), so we expect similar results for realistic selection functions. This also allows us to mock up larger area surveys without using a larger simulation box, as we can simply select more galaxies within the same 100 h^{-1} Mpc volume.

To simulate the cosmic-web galaxy spin alignment measurement, we measure (cos θ_mg), the dot product of the reconstructed eigenvector and the galaxy spin, as a function of (cos θ_mg), where θ_mg is the angle between the matter field eigenvector and the galaxy spin. We turn this into a significance above random by subtracting 0.5, the mean of cos θ for a random distribution, and dividing by the standard deviation of 1000 simulations of the measurement. For 2D measurements, the significance is defined as (θ_mg − π/4 divided by the standard deviation, since a random vector in 2D follows a uniform distribution in θ. Computing the significance using (cos θ_mg) gives similar results to other reasonable choices, such as the difference between the number of aligned and anti-aligned galaxies.

3. Results

3.1. Recovery of Cosmic Web Directions

We first compare our cosmic web classification to Lee & White (2016), who used an N-body simulation rather than a hydrodynamic IGM simulation and match the DM and IGM tomography smoothing scales. We confirm their finding that IGM tomography can recover cosmic web classifications with similar fidelity to low-redshift surveys, suggesting this finding is insensitive to the details of the simulation and the choice of smoothing scale.

The fraction of the volume with ΔN = 0 is somewhat lower in our ⟨d⟩ = 2.5 h^{-1} Mpc reconstruction than in Lee & White (2016), as they found [15, 69, 15]% of the volume was classified within [−1, 0, +1] eigenvalues. However, we do not match the matter smoothing scale to the IGM tomography smoothing scale and we include continuum errors in our mock absorption skewers, both of which degrade the reconstructions. Compared to Lee & White (2016), we recover sheets, voids, and filaments with slightly lower fidelity, and nodes with significantly lower fidelity.

Figure 3 displays the PDF of cos θ, where θ is the misalignment angle between the matter field tidal tensor eigenvectors and the pseudo-deformation tensor eigenvectors from the reconstructed IGM maps. We also compute the misalignment angle PDF between the matter field tidal tensor eigenvectors and the pseudo-deformation tensor eigenvectors from the simulated δ_F smoothed on 2 h^{-1} Mpc scales,
equivalent to an idealized reconstruction with no instrumental noise and infinite sightline density.

The mock surveys with \( \langle d_i \rangle < 5 \ h^{-1} \) Mpc recover the eigenvectors of the tidal tensor at high significance. The recovery of the eigenvectors degrades quickly for \( \langle d_i \rangle > 5 \ h^{-1} \) Mpc, due in part to the mismatch between \( \langle d_i \rangle \) and the 2 \( h^{-1} \) Mpc smoothing scale of the matter field. The mean of the cosine of the misalignment angle for \( \hat{e}_1, \hat{e}_2, \hat{e}_3 \) is [0.874, 0.809, 0.901] for \( \langle d_i \rangle = 1.4 \ h^{-1} \) Mpc, [0.813, 0.716, 0.833] for \( \langle d_i \rangle = 2.5 \ h^{-1} \) Mpc, [0.736, 0.629, 0.757] for \( \langle d_i \rangle = 4.0 \ h^{-1} \) Mpc, and [0.573, 0.508, 0.600] for \( \langle d_i \rangle = 6.5 \ h^{-1} \) Mpc. Errors on these quantities are <0.1%. The mean of the cosine of the misalignment angle between is [0.945, 0.921, 0.967] using the simulated \( \delta_p \) field. This is the upper limit of how well Lyα absorption measurements can measure the eigenvectors of the tidal tensor.

We also compute the mean of the misalignment angle at halo positions only. For \( \hat{e}_1, \hat{e}_2, \hat{e}_3 \), we find means of [0.891, 0.837, 0.919] for \( \langle d_i \rangle = 1.4 \ h^{-1} \) Mpc, [0.815, 0.722, 0.838] for \( \langle d_i \rangle = 2.5 \ h^{-1} \) Mpc, [0.734, 0.628, 0.761] for \( \langle d_i \rangle = 4.0 \ h^{-1} \) Mpc, [0.571, 0.516, 0.607] for \( \langle d_i \rangle = 6.5 \ h^{-1} \) Mpc, and [0.950, 0.929, 0.970] for simulated \( \delta_p \). The differences between these values and the means of \( \cos \theta \) using the entire grid are quite modest, although statistically significant.

Figure 4 shows the quality of cosmic web recovery as a function of cosmological type as classified in the matter map, using the \( \langle d_i \rangle = 2.5 \ h^{-1} \) Mpc reconstruction. Mirroring the results in Table 1, \( \hat{e}_1, \hat{e}_2, \) and \( \hat{e}_3 \) are recovered worst in nodes. Despite the relatively high volume overlap for the void recovery, the tidal tensor eigenvectors are recovered slightly worse in voids than in anisotropic structures such as filaments and sheets. All three eigenvalues are similar in voids, possibly causing confusion between perpendicular eigenvalues and leading to the poorer recovery of the cosmic web in voids. The recovery of eigenvectors in sheets and filaments are similar, although \( \hat{e}_1 \) is recovered better in filaments while \( \hat{e}_3 \) is recovered better in sheets. This is unsurprising given the connection between the eigenvectors and the geometry of the cosmic web, as \( \hat{e}_1 \) in filaments and \( \hat{e}_3 \) in sheets correspond to inherently anisotropic directions that should be easier to recover.

We additionally test the quality of the reconstruction as a function of halo mass. We divide the halo catalog into four bins and measure the angle between the eigenvectors in the matter field and the eigenvectors in the \( \langle d_i \rangle = 2.5 \ h^{-1} \) Mpc reconstruction using the nearest grid point in redshift space. The recovery of the eigenvectors is nearly independent of the halo mass (Figure 5). None of the distributions are significantly different at the \( p = 0.05 \) level (2\( \sigma \)) according to Kolmogorov–Smirnov.
Table 2
Summary of Alignment Models

| $\Delta \langle \cos \theta \rangle$ | Description | References |
|---------------------------------|-------------|------------|
| 0.009                           | $z \sim 1.2$ alignments between $\hat{e}_1$ and galaxy spin from HorizonAGN | Codis et al. (2015) |
| 0.020                           | $z \sim 2.3$ alignments between filaments and galaxy spins from HorizonAGN | Dubois et al. (2014) |
| 0.054                           | $z \sim 1.05$ alignment between $\hat{e}_1$ and halo shape (N-body), plus misalignment between halo shape and galaxy shape, alignments extrapolated to $z \sim 2.4$ and $M_h \sim 10^{12} M_\odot$, assuming alignments constant as a function of $M_h$ | Hahn et al. (2007a); Okumura et al. (2009) |
| 0.092                           | $z \sim 1.05$ alignment between $\hat{e}_1$ and halo shape (N-body), plus misalignment between galaxy shape and galaxy shape, alignments extrapolated to $z \sim 2.4$ and $M_h \sim 10^{12} M_\odot$, assuming alignments constant as a function of $M_h/M_\odot$ | Hahn et al. (2007a); Okumura et al. (2009) |

Note. Alignment models considered in Figure 6. See the text for details. Each alignment model is parameterized using Equation (7) with $\langle \cos \theta \rangle = 0.5 + \Delta \langle \cos \theta \rangle$.

tests, implying that the eigenvectors can be recovered accurately at galaxy positions independent of halo mass.

We provide the first assessment of the accuracy of tidal tensor reconstruction by comparing the tidal tensor eigenvectors from the matter field to the tidal tensor eigenvectors from realistic mock observations. We expect that IGM tomography will be better at recovering the tidal tensor eigenvectors than existing or upcoming galaxy surveys at the same redshift, such as zCOSMOS or PFS; these will provide much coarser cosmic web maps with galaxy separations of $9 (13) h^{-1}$ Mpc for PFS (zCOSMOS) (Diener et al. 2013; Takada et al. 2014). For instance, since protocluster identification with zCOSMOS required additional follow-up spectroscopy (Diener et al. 2015), the zCOSMOS redshift survey alone is likely insufficient to measure the cosmic web at $z > 2$. In addition, cosmic web maps from IGM tomography are free from many of the biases that make measuring the cosmic web from spectroscopic $z \sim 2$ galaxy surveys difficult; these surveys have complex selection functions (e.g., Diener et al. 2013), inaccurate and/or biased redshift estimates (e.g., Adelberger et al. 2005; Steidel et al. 2010; Rakic et al. 2012), cannot detect close pairs due to slit collisions (Wilson et al. 2015), and preferentially select star-forming galaxies, which may be biased toward particular regions of the cosmic web (Alpaslan et al. 2015). In contrast, IGM tomography sightlines provide an unbiased sampling of the foreground cosmic web, and errors from pixel noise and continuum errors are well understood, making a subdominant contribution to errors in the reconstruction.

3.2. Predictions for Galaxy–Cosmic Web Alignment Measurements

Several authors have considered the alignment of galaxies and the cosmic web in simulations, but thus far observational studies of the galaxy–cosmic web alignment have been restricted to low redshift ($z \lesssim 0.5$) where sufficiently large galaxy catalogs exist to measure the cosmic web (Lee & Pen 2002; Lee & Erdogdu 2007; Tempel & Libeskind 2013; Tempel et al. 2013; Zhang et al. 2013, 2015; Pahwa et al. 2016, although see Malavasi et al. 2017 for recent results at $\langle z \rangle \sim 0.7$). We now consider the prospects for a galaxy–cosmic web alignment study at $z \sim 2$ using the cosmic web from IGM tomography maps and coeval galaxy samples from space-based or large ground-based telescopes.

First, we estimate the significance of the measured galaxy-eigenvector alignment signal as a function of the true strength of the galaxy-eigenvector alignment. We describe the PDF of the true galaxy-eigenvector misalignment angle using Equation (7) and thus parameterize the galaxy-eigenvector alignment strength using the deviation of $\langle \cos \theta \rangle$ from 0.5 (i.e., the deviation from random alignments):

$$\Delta \langle \cos \theta \rangle \equiv \langle \cos \theta \rangle - 0.5.$$ (9)

Note that the significance of a model with $-\Delta \langle \cos \theta \rangle$ is identical to the significance of a model with $\Delta \langle \cos \theta \rangle$ because the spins and eigendirections are headless vectors invariant under the transformation $\theta \rightarrow \pi - \theta$. Therefore, we only plot significances as a function of positive $\Delta \langle \cos \theta \rangle$.

In Figure 6, we show the forecasted significance of the alignment signal between galaxies and $\hat{e}_1$, as a function of the sightline spacing, number of galaxies, expected redshift error, and errors on the galaxy position angle and inclination. Our fiducial values for these quantities are $(d_s) = 2.5 h^{-1}$ Mpc, 10,000 coeval galaxies, redshift errors of 100 km s$^{-1}$, and position angle and inclination errors of 10°. A different random seed is used in each panel, leading to very slight differences between the fiducial case in different panels. The 1σ error on $\Delta \langle \cos \theta \rangle$ of $\sim 0.01$ for the fiducial measurement of alignment with $\hat{e}_1$ is somewhat larger than 1σ errors from alignment measurements using low-redshift galaxies ($\sim 0.005$ for similar galaxy sample sizes in Tempel & Libeskind 2013; Tempel et al. 2013; Pahwa et al. 2016).

Figure 6 shows the significance of alignment measurements between galaxy spins and $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$ as a function of the true alignment strength between galaxy spin and $\hat{e}_1$, $\hat{e}_2$ and $\hat{e}_3$. Consistent with Figure 3, alignments with $\hat{e}_1$ and $\hat{e}_2$ can be detected at similar levels of significance, while alignments with $\hat{e}_3$ will be detected with somewhat lower significance. We note that $\hat{e}_2$ alignments are detected at similar significance for both 2D and 3D measurements. We attribute this to redshift-space distortions in the map, which cause $\hat{e}_2$ to lie preferentially in the plane of the sky, because the directions of maximal and minimal compression ($\hat{e}_1$ and $\hat{e}_2$) are biased toward the line of sight due to compression and rarefaction from redshift-space distortions. Measuring alignments between real-space matter density eigenvectors and real-space $\delta_F^{cos}$ eigenvectors yields a similar reduction between 2D and 3D alignment measurements for $\hat{e}_1$, $\hat{e}_2$, and $\hat{e}_3$.

TTT predicts that galaxy spin is aligned with $\hat{e}_3$. Using an analytic quadratic alignment model (Lee & Pen 2000), Lee & Erdogdu (2007) derived a PDF for the misalignment angle as a function of $c$, a correlation parameter ranging from 0 (random alignments) to 1 (perfect spin-shear alignments). In the limit of small $\Delta \langle \cos \theta \rangle$, this PDF can be well approximated by Equation (7) via Taylor series expansion. For the fiducial $\hat{e}_2$ alignment measurement we find a 1σ error
on $\Delta \langle \cos \theta \rangle \sim 0.015$, which translates to a 1σ error on $c \sim 0.08$. Previous measurements at low redshift have achieved lower error bars: Lee & Pen (2002) found $c = 0.28 \pm 0.07$,9 Lee & Erdogdu (2007) found $c = 0.08 \pm 0.01$, and Lee & Pen (2007) found $c = 0.0 \pm 0.05$ for red galaxies and $c = 0.33 \pm 0.07$ for blue galaxies. If $c \sim 0.2-0.3$ at $z \sim 2.4$, IGM tomography surveys with $\langle d_f \rangle = 2.5 h^{-1}$ Mpc and 10,000 coeval galaxies will measure this alignment at $\sim 3\sigma$. However, nonlinear evolution is expected to decrease the alignment between spin and $\hat{e}_2$ over time (Porciani et al. 2002), leading to a larger value of $c$ at high redshift than low redshift. These results suggest that the combination of galaxy surveys at low redshift and IGM tomography surveys at high redshift may be able to constrain the redshift evolution of the alignment, providing a rigorous test of TTT.

Figure 6 shows the importance of varying different parameters of the IGM and galaxy observations. Varying the sightline spacing from $\langle d_f \rangle = 1.4 h^{-1}$ Mpc to $\langle d_f \rangle = 4 h^{-1}$ Mpc is equivalent to decreasing the number of sightlines by an order of magnitude. Thus, comparison of the top-center and top-right panels of Figure 6 shows that close to the fiducial sightline spacing of $2.5 h^{-1}$ Mpc, increasing the number of coeval galaxies is more important than increasing the number of background Lyα forest sightlines. However, the measured significance of the signal drops dramatically for sightline spacings $\langle d_f \rangle > 4 h^{-1}$ Mpc. This suggests that a wide-field survey such as PFS is preferable for measuring galaxy–cosmic web alignments, as it would be best positioned to deliver a large coeval galaxy sample, while the coarser sightline spacing of $4 h^{-1}$ Mpc only modestly lowers the significance compared to CLAMATO with $\langle d_f \rangle = 2.5 h^{-1}$ Mpc. However, the poor performance of the $\langle d_f \rangle = 6.5 h^{-1}$ Mpc survey suggests that PFS will require a supplemental tomography component to achieve the necessary sightline spacing to detect galaxy–cosmic web alignments.

Varying the fiducial position angle and inclination errors by a factor of two makes relatively little difference for measuring the alignment signal. We also test a model with a relatively large PA error of $40^\circ$, which may be more representative of the shape errors in a ground-based survey. In this case, much more of the constraining power comes from the inclination. If the survey is also unable to recover the inclinations due to large uncertainties in measuring the axis ratio, the significance of the alignment signal drops dramatically. Therefore, reasonably precise estimates of the position angle ($\sigma_{PA} < 30^\circ$) will be necessary to measure alignments between galaxy spin and the cosmic web.

The impact of spectroscopic redshift errors are quite modest, as Figure 6 shows little difference between a sample with redshift errors $\sim 100$ km s$^{-1}$ (e.g., redshifts measured from rest-frame optical nebular emission lines) and a sample with redshift errors $\sim 300$ km s$^{-1}$ (e.g., redshifts measured from rest-frame UV absorption lines). Even grism redshifts ($\sigma_v \sim 500$ km s$^{-1}$) lead to only modest degradation of the alignment signal.

At a fixed number density, a redshift error of $\sim 2000$ km s$^{-1}$ from the sample with randomized positions leads to a drastic reduction in the constraining power of the survey. However, photometric samples offer much greater number densities than spectroscopic samples due to the less stringent observational requirements. In Figure 7, we show that alignment measurements with the “photometric” sample (randomized galaxy positions) require 10,000 to 50,000 galaxies to achieve similar significant to alignment measurements with 600 spectroscopic galaxies ($\sigma_v = 100$ km s$^{-1}$). By comparison, the CLAMATO volume contains $\sim 600$ spectroscopic galaxies and $\sim 10,000$ photometric galaxies. The redshift error of the randomized sample is considerably smaller than either the photometric redshift accuracy in COSMOS ($\sim 9000$ km s$^{-1}$; Laigle et al. 2016) or optimistic forecasts for tomographic redshift accuracy ($\sim 3000$ km s$^{-1}$; Schmittfull & White 2016), suggesting that spectroscopic galaxy samples are preferable for measuring spin–cosmic web alignments.

We also explore the possibilities for constraining alignment models based on results from simulations. Simulations have measured a broad variety of alignments (e.g., between halo/galaxy spins/shapes and filaments/​$\hat{e}_1$) across a wide range of space.
redshifts. In general, simulations have found stronger alignments between halo shapes and the cosmic web than between halo spins and the cosmic web (Hahn et al. 2007a). While the discussion above is framed in terms of galaxy spin alignments, ultimately we are measuring the major axis of the galaxy image, which may be set by either the spin or the shape of the galaxy and ultimately the dark matter halo. Therefore, we consider alignment models from both galaxy spin and halo shape.

We use the simulation results of Hahn et al. (2007a) to create an alignment model based on halo shape. Hahn et al. (2007a) studied the alignment between halo shape and $\hat{e}_i$ at $z = 0$, 0.49, and 1.05. After accounting for the mass dependence by scaling by the mass scale of nonlinear collapse $M_h(z)$ they found no additional redshift dependence.

We extrapolate the results of Hahn et al. (2007a) to $z \sim 2.3$ to create an alignment model. Hahn et al. (2007a) parameterized the mass dependence of their result using $M_h/M_\star$ where $M_\star$ is the mass for which a 1σ fluctuation reaches the threshold for spherical collapse, $\delta_c = 1.686$. At $z \sim 2.3$, the typical halo ($M_h \sim 10^{12} M_\odot$) in the coeval galaxy sample has $M \gtrsim 100 M_\star$, leading to an extremely strong alignment signal, median $\cos \theta = 0.78$ ($\langle \cos \theta \rangle = 0.73$ assuming the PDF follows Equation (7)). More conservatively, it is possible that above $z \sim 1.05$ the alignment signal is constant with $M_\star$ rather than $M_h/M_\star$. In this case, the typical halo detected in our galaxy sample has $M \sim 10 M_\star z^{-1.05}$, leading to a slightly weaker median $\cos \theta = 0.7$ ($\langle \cos \theta \rangle = 0.64$) between $\hat{e}_i$ and halo shape.

To translate from halo shape alignments to galaxy shape alignments, we use the halo-galaxy misalignment model of Okumura et al. (2009), a Gaussian distribution of halo-galaxy misalignment angles with dispersion 35°. We find $\Delta(\cos \theta) = 0.092$ (0.054) for the Hahn et al. (2007a) model using $M_h/M_\star$ ($M_h$) to determine alignments.
In contrast to the shape measurements, several authors measured alignments between galaxy spins and the cosmic web using hydrodynamic simulations of the galaxies. These include Codis et al. (2015), who measured alignments between galaxy spin and \( \hat{e}_1 \) at \( z \sim 1.2 \), finding \( \Delta (\cos \theta) = 0.009 \). Similarly, Dubois et al. (2014) measure alignments between galaxy spin and filaments for galaxies between \( z \sim 1.2 \) and \( z \sim 3 \) and find \( \Delta (\cos \theta) = 0.02 \). These alignments are similar to alignments inferred from simulations of halo spin–cosmic web alignments (Hahn et al. 2007a; Trowland et al. 2013) with a galaxy–halo spin misalignment following Bett (2012). The spin-web alignment is considerably weaker than the shape–web alignment, consistent with results from dark matter halos (Hahn et al. 2007a) and possibly related to stronger shape–cosmic web alignments for early-type than late-type galaxies observed at low redshift (Tempel & Libeskind 2013; Pahwa et al. 2016) and the considerably stronger intrinsic alignments observed for early-type than late-type galaxies (Mandelbaum et al. 2006; Joachimi et al. 2013).

Figure 6 shows that IGM tomography surveys in tandem with wide-field galaxy surveys would be able to detect or rule out alignment models based on halo shape (e.g., from Hahn et al. (2007a) at high significance. Even the combination of the CLAMATO survey and zCOSMOS galaxy survey (with \( N_{\text{gal}} \sim 600 \) over the \( V \sim 10^7 h^{-1} \) Mpc\(^3 \) CLAMATO volume at \( 2.1 < z < 2.5 \)) will be sufficient to detect or rule out the most aggressive alignment models based on halo shape at \( \sim 2–3\sigma \). However, more realistic models with smaller alignments will require an order of magnitude more coeval galaxies for detection at a similar level. Figure 6 also shows that ground-based imaging should be sufficient to measure galaxy spins as long as position angles can be measured with an error \( \lesssim 20^\circ \).

Additional measurements besides spin-eigendirection correlations may yield further independent information. For instance, IGM tomography will be able to identify a large number of voids (Stark et al. 2015a), allowing measurement of the void-spin correlation (e.g., Trujillo et al. 2006; Slosar & White 2009; Varela et al. 2012). We can also use the eigenvalues to partition our map into voids, sheets, filaments, and nodes (Lee & White 2016) and measure spin-\( \hat{e}_1 \) alignments only in filaments, or spin-\( \hat{e}_3 \) alignments only in sheets, where they may be strongest (e.g., Hahn et al. 2007a).

4. Conclusions

Intrinsic alignments between galaxies and the underlying cosmic web have been predicted from both DM-only and hydrodynamical simulations, several of which predict increasing alignment strength at higher redshift (\( z \gtrsim 1 \)). At these redshifts, it becomes increasingly expensive to obtain spectroscopic redshifts with sufficiently high number densities to trace the cosmic web. Recently, tomographic reconstruction of the IGM as traced by high area densities of Ly\( \alpha \) forest sightlines has emerged as a promising method to map the cosmic web at \( z \sim 2–3 \).

In this paper, we studied the feasibility of IGM tomographic surveys, in conjunction with coeval galaxy redshift samples with measured structural parameters, to place constraints on galaxy–cosmic web alignments at \( z \sim 2.5 \). Using detailed hydrodynamical simulations based on the Nyx code, we first generated realistic mock data sets reflecting both ongoing and future IGM tomography surveys. The galaxy spin or shape distributions were "painted on" with respect to the underlying matter tidal tensor field using a simple alignment model parameterized by \( \Delta \langle \cos \theta \rangle \), i.e., the non-random excess alignment of the galaxies with respect to the eigenvectors of the matter tidal tensor. Future studies of galaxy–cosmic web alignments at \( z \sim 2 \) will benefit greatly from simulations combining both realistic IGM physics and galaxy formation (e.g., future versions of the Nyx simulations used in this paper).

First, we showed that IGM tomography with sightline separations of \( \langle d_i \rangle \lesssim 5 h^{-1} \) Mpc should be able to recover the eigenvectors of the tidal tensor, \( \hat{e}_1, \hat{e}_2, \) and \( \hat{e}_3 \), as determined from the large-scale distribution of matter in the universe (smoothed on \( 2 h^{-1} \) Mpc scales). The mean dot products between the eigenvectors as determined by the matter field and the eigenvectors from a mock observation with sightline spacing \( 2.5 h^{-1} \) Mpc, similar to the ongoing CLAMATO survey, are \([0.815, 0.722, 0.838]\) for \( \hat{e}_1, \hat{e}_2, \hat{e}_3 \). This builds
on our previous result showing that IGM tomography can recover eigenvalue–cosmic web classifications with a fidelity similar to $z \lesssim 0.7$ surveys (Lee & White 2016).

We then compared the eigenvectors recovered from the IGM tomography with the spins or shapes in coeval galaxy samples as a function of the alignment strength $\Delta(\cos \theta)$, and also considered the effect of uncertainties in the measurement of the galaxy position angles, inclinations, and redshift estimation. The largest factor in our ability to constrain the galaxy–cosmic web alignments is the size of the galaxy sample. Assuming a fiducial mean sightline separation of $\langle d_\perp \rangle = 5$ $h^{-1}$ Mpc, redshift errors of $\sigma_z = 500$ km s$^{-1}$, as well as errors of $\sigma_{PA} = 10^\circ$ and $\sigma_z = 10^\circ$ in the galaxy position angles and inclinations, respectively, we find that the ongoing CLAMATO Survey on the Keck I Telescope, in conjunction with $\sim 600$ coeval galaxies from zCOSMOS-Deep and other spectroscopic surveys, should be able to place $\sim 3\sigma$ limits on the most extreme alignment models with $\Delta(\cos \theta) \sim 0.1$ within the next few years. For most alignment models with $\Delta(\cos \theta) < 0.05$, however, coeval samples of at least several thousand galaxies with spectroscopic redshifts would be needed to make a $\sim 3-4\sigma$ detection. These results are not very sensitive to the mean sightline separation of the IGM tomography survey so long as $\langle d_\perp \rangle \lesssim 5$ $h^{-1}$ Mpc, nor on the accuracy of the galaxy structural parameters, although space-based imaging or very good quality ground-based imaging ($<0.5$ arcsec seeing) would be desirable for the latter. We find that alignment measurements using photometric redshifts will require samples at least 20 times larger than spectroscopic redshift samples, indicating that spectroscopic samples are preferable.

Since the primary limitation for this alignment measurement is the size of available galaxy redshift samples at $z \sim 2.5$, a relatively wide/shallow strategy would be optimal: at a fixed survey magnitude, the galaxy sample size $N_{\text{gal}}$ scales linearly with telescope time by expanding the survey area. On the other hand, increasing $N_{\text{gal}}$ by increasing survey depth within a small survey area would require exponential increases of telescope time. Since the tidal tensor eigenvector recovery does not degrade much with slightly coarser tomographic reconstructions relative to the fiducial $2.5$ $h^{-1}$ Mpc sightline spacing in CLAMATO, this argues that near-future wide-field instruments, i.e., Subaru PFS, which cover much larger areas than CLAMATO with the concomitantly larger $N_{\text{gal}}$, will deliver significantly improved spin–cosmic web or shape–cosmic web constraints. However, we did find a mean spacing of $\langle d_\perp \rangle < 5$ $h^{-1}$ Mpc is required for the Ly$\alpha$ forest sightlines, above which the eigenvector recovery degrades considerably. Since the $2 < z < 3$ LBG component currently planned for the $\sim 20–30$ sq deg PFS Galaxy Evolution Survey leads to a “free” IGM tomographic map with $\langle d_\perp \rangle \sim 6.5$ $h^{-1}$ Mpc, we advocate supplemental PFS spectroscopy to boost the sightline sampling to $\langle d_\perp \rangle \approx 4$ $h^{-1}$ Mpc. Based on the calculations of Lee et al. (2014b), this would require $\sim 5–6$ hr of additional exposure time per field, or $\sim 20$ nights over $\sim 25$ sq deg (including weather/seeing overheads). Such a program, along with the $\sim 10,000$ coeval galaxies also from PFS, should allow $3\sigma$ limits on alignments down to $\Delta(\cos \theta) \approx 0.03$. Constraints on even smaller $\Delta(\cos \theta)$, at the levels predicted by, e.g., Codis et al. (2015), would require even more ambitious surveys. However, it is conceivable that a new generation of massively multiplexed wide-field spectrographs on $>10$m-class telescopes could be available by the early 2030s (Dodelson et al. 2016; McConnachie et al. 2016; Najita et al. 2016), in time to provide priors on the intrinsic alignment systematics for the final LSST tomographic weak-lensing analyses.

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Footnote 10: Comoving volume of $V \sim 10^5$ $h^{-3}$ Mpc$^3$ over $2.1 < z < 2.5$ within the central square degree of the COSMOS Field.
