Galaxy evolution in the metric of the Cosmic Web

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ABSTRACT

The role of the cosmic web in shaping galaxy properties is investigated in the GAMA spectroscopic survey in the redshift range 0.03 ≤ z ≤ 0.25. The stellar mass, u − r dust corrected colour and specific star formation rate (sSFR) of galaxies are analysed as a function of their distances to the 3D cosmic web features, such as nodes, filaments and walls, as reconstructed by DisPerSE. Significant mass and type/colour gradients are found for the whole population, with more massive and/or passive galaxies being located closer to the filament and wall than their less massive and/or star-forming counterparts. Mass segregation persists among the star-forming population alone. The red fraction of galaxies increases when closing in on nodes, and on filaments regardless of the distance to nodes. Similarly, the star-forming population reddens (or lowers its sSFR) at fixed mass when closing in on filament, implying that some quenching takes place. Comparable trends are also found in the state-of-the-art hydrodynamical simulation HORIZON-AGN. These results suggest that on top of stellar mass and large-scale density, the traceless component of the tides from the anisotropic large-scale environment also shapes galactic properties. An extension of excursion theory accounting for filamentary tides provides a qualitative explanation in terms of anisotropic assembly bias: at a given mass, the accretion rate varies with the orientation and distance to filaments. It also explains the absence of type/colour gradients in the data on smaller, non-linear scales.

Key words: Cosmology: observations – Cosmology: large-scale structure of Universe – Galaxies: evolution – Galaxies: high-redshift – Galaxies: statistics.

1 INTRODUCTION

Within the Λ cold dark matter (ΛCDM) cosmological paradigm, structures in the present-day Universe arise from hierarchical clustering, with smaller dark matter halos forming first and progressively merging into larger ones. Galaxies form by the cooling and condensation of baryons that settle in the centres of these halos (White & Rees 1978) and their spin is predicted to be correlated with that of the halo generated from the tidal field torques at the moment of proto-halo collapse (tidal torque theory, TTT; e.g. Peebles 1969; Doroshkevich 1970; Efstathiou & Jones 1979; White 1984). However, dark matter halos, and galaxies residing within them, are not isolated. They are part of a larger-scale pattern, dubbed the cosmic web (Jøeveer et al. 1978; Bond et al. 1996), arising from the anisotropic collapse of the initial fluctuations of the matter density field under the effect of gravity across cosmic time (Zel’dovich 1970). This web-like pattern, brought to light by systematic galaxy
The TTT, naturally connecting the large-scale distribution of matter and the angular momentum of galactic halos (e.g. Jones & Efstathiou 1979; Barnes & Efstathiou 1987; Heavens & Peacock 1988; Porciani et al. 2002a,b; Lee 2004), in its recently revisited, conditioned formulation (Codis et al. 2015) predicts the angular momentum distribution of the forming galaxies relative to the cosmic web, which tend to first have their angular momentum aligned with the filament’s direction while the spin orientation of massive galaxies is preferentially in the perpendicular direction. Despite the difficulty to model properly the halo-galaxy connection, due to the complexity, non-linearity and multi-scale character of the involved processes, modern cosmological hydrodynamic simulations confirm such a mass dependent angular momentum distribution of galaxies with respect to the cosmic web (Dubois et al. 2014; Welker et al. 2014, 2017). On galactic scales, the dynamical influence of the cosmic web may have a strong effect on the efficiency of galaxy formation (see also Benítez-Llambay et al. 2013), Eardley et al. (2015) argue that there is no evidence of a direct influence of the cosmic web as these variations can be entirely driven by the underlying local density dependence. These discrepancies are partially expected: the present state of galaxies must be impacted by the effect of the past environment, which in turn does correlate with the present environment, if mildly so; but these environmental effects must first be distinguished from mass driven effects which typically dominate.

On the other hand, Alpaslan et al. (2015) find in the GAMA data that the most important parameter driving galaxy properties is stellar mass as opposed to environment (see also, Robotham et al. 2013). Similarly, while focusing on spiral galaxies alone, Alpaslan et al. (2016) do find variations in the star formation rate (SFR) distribution with large-scale environments, but they are identified as a secondary effect. Another quantity tracing different geometric environments that was found to vary is the luminosity function. However, while Guo et al. (2015) conclude that the filamentary environment may have a strong effect on the efficiency of galaxy formation (see also Benítez-Llambay et al. 2013), Eardley et al. (2015) argue that there is no evidence of a direct influence of the cosmic web as these variations can be entirely driven by the underlying local density dependence. These discrepancies are partially expected: the present state of galaxies must be impacted by the effect of the past environment, which in turn does correlate with the present environment, if mildly so; but these environmental effects must first be distinguished from mass driven effects which typically dominate.

The on-hand, there are evidences that the cosmic web affects galaxy properties. Void galaxies are found to be less massive, bluer, and more compact than galaxies outside of voids (e.g. Rojas et al. 2004; Bekgu et al. 2016); galaxies infalling into clusters along filaments show signs of some physical mechanisms operating even before becoming part of these systems, that galaxies in the isotropic infalling regions do not (Porter et al. 2008; Martínez et al. 2016); Kleiner et al. (2017) find systematically higher HI fractions for massive galaxies ($M_T > 10^{12} M_{\odot}$) near filaments compared to the field population, interpreted as evidence for a more efficient cold gas accretion from the intergalactic medium; Kuutma et al. (2017) report an environmental transformation with a higher elliptical-to-spiral ratio when moving closer to filaments, interpreted as an increase in the merging rate or the cut-off of gas supplies near and inside filaments (see also Aragon-Calvo et al. 2016); Chen et al. (2017) detect a strong correlation of galaxy properties, such as colour, stellar mass, age and size, with the distance to filaments and clusters, highlighting their role beyond the environmental density effect, with red or high-mass galaxies and early-forming or large galaxies at fixed stellar mass having shorter distances to filaments and clusters than blue or low-mass and late-forming or small galaxies, and Tojeiro et al. (2017) interpret a steadily increasing stellar-to-halo mass ratio from voids to nodes for low mass halos, with the reversal of the trend at the high-mass end, found for central galaxies in the Galaxy And Mass Assembly survey (Driver et al. 2009, 2011), as an evidence for halo assembly bias being a function of geometric environment. At higher redshift, a small but significant trend in the distribution of galaxy properties within filaments was reported in the spectroscopic survey VIPERS ($z \simeq 0.7$; Malavasi et al. 2017) and with photometric redshifts (0.5 < z < 0.9) in the COSMOS field (with a 2D analysis; Laigle et al. 2017). Both studies find important mass and type segregations, where the most massive or quiescent galaxies are closer to filaments than less massive or active galaxies, emphasising that large-scale cosmic flows play a role in shaping galaxy properties.

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tory results). What is less obvious is whether observed integrated scalar properties such as morphology or physical properties (star-formation rate, type, metallicity, which depend not only on the mass but also on the past and present gas accretion) are also impacted.

Theoretical considerations alone suggest that local density as a sole and unique parameter (and consequently any isotropic definition of the environment based on density alone) is not sufficient to account for the effect of gravity on galactic scale (e.g. Mo et al. 2010) and therefore capture the environmental diversity in which galaxies form and evolve: one must also consider the relative past and present orientation of the tidal tensor with respect to directions pointing towards the larger-scale structure principal axes. At the simplest level, on large scales, gravity should be the dominant force. Its net cumulative impact is encoded in the tides operating on the host dark matter halo. Such tides may be decomposed into the trace of the tidal tensor, which equals the local density, and its traceless part, which applies distortion and rotation to the forming galaxy. The effect of the former on increasing scales has long been taken into account in standard galaxy formation scenarios (Kaiser 1984), while the effect of the latter has only recently received full attention (e.g. Codis et al. 2015). Beyond the above-discussed effect on angular momentum, other galaxy’s properties could in principle be influenced by the large-scale traceless part of the tidal field, which modifies the accretion history of a halo depending on its location within the cosmic web. For instance, the tidal shear near saddles along the filaments feeding massive halos is predicted to slow down the mass assembly of smaller halos in their vicinity (Hahn et al. 2009; Borzyszkowski et al. 2016; Castorina et al. 2016). Bond & Myers (1996) integrated the effect of ellipsoidal collapse (via the shear amplitude), which may partially delay galaxy formation, in the Extended Press-Schechter (EPS) theory. Yet, in that formulation, the geometry of the delay imposed by the specific relative orientation of tides imposed by the large-scale structure is not accounted for, because time delays are ensemble-averaged over all possible geometries of the LSS. The anisotropy of the large-scale cosmic web – voids, walls, filaments, and nodes (which shape and orient the tidal tensor beyond its trace) should therefore be taken into account explicitly, as it impacts mass assembly. Despite of the above-mentioned difficulty in properly describing the connection between galaxies and their host dark matter halos, this anisotropy should have direct observational signatures in the differential properties of galaxies with respect to the cosmic web at fixed mass and local density. Quantifying these signatures is the topic of this paper. Extending EPS to account for the geometry of the tides beyond that encoded in the density of the field is the topic of the companion paper, Musso et al. (2017).

This paper explores the impact of the cosmic web on galaxy properties in the GAMA survey, using the DisPerSE Persistent Structure Extractor code (DisPerSE; Sousbie et al. 2011) to characterise its 3D topological features, such as nodes, filaments and walls. GAMA is to date the best dataset for this kind of study, given its unique spectroscopic combination of depth, area, target density and high completeness, as well as its broad multi-wavelength coverage. Variations in stellar mass and colour, red fraction and star formation activity are investigated as a function of galaxy’s distances to these three features. The rest of the paper is organised as follows. Section 2 summarises the data and describes the sample selection. The method used to reconstruct the cosmic web is presented in Section 3. Section 4 investigates the stellar mass and type/colour segregation and the star formation activity of galaxies within the cosmic web. Section 5 shows how these results compare to those obtained in the HORIZON-AGN simulation (Dubois et al. 2014). Section 6 addresses the impact of the density on the measured gradients towards filaments and walls. Results are discussed in Section 7 jointly with predictions from Musso et al. (2017). Finally, Section 8 concludes. Additional details on the matching technique and the impact of the boundaries to the measured gradients are provided in Appendix A and B, respectively. Appendix C investigates the effect of smoothing scale on the found gradients, Appendix D briefly presents the horizon-AGN simulation, Appendix F provides tables of median gradients, and a short summary of predicted gradient misalignments is presented in Appendix E.

Throughout the study a flat $\Lambda$CDM cosmology with $H_0 = 67.5 \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.31$ and $\Omega_\Lambda = 0.69$ is adopted (Planck Collaboration et al. 2015). All statistical errors are computed by bootstrapping, such that the errors on a given statistical quantity correspond to the standard deviation of the distribution of that quantity re-computed in 100 random samples drawn from the parent sample with replacement. All magnitudes are quoted in the AB system, and by log we refer to the 10-based logarithm.

2 DATA AND DATA PRODUCTS

The following section describes the observational data and derived products, namely the galaxy and group catalogues, that have been used in this work.

2.1 Galaxy catalogue

The analysis is based on the GAMA survey1 (Driver et al. 2009, 2011; Hopkins et al. 2013; Liske et al. 2015), a joint European-Australian project combining multi-wavelength photometry (UV to far-IR) from ground and space-based facilities and spectroscopy obtained at the Anglo-Australian Telescope (AAO, NSW, Australia) using the AAOmega spectrograph. GAMA provides spectra for galaxies across five regions, but this work only considers the three equatorial fields G9, G12 and G15 covering a total area of $180 \, \text{deg}^2$ ($12 \times 5 \, \text{deg}^2$ each), for which the spectroscopic completeness is $> 98\%$ down to a r-band apparent magnitude $m_r = 19.8$. The reader is referred to Wright et al. (2016) for a complete description of the spectro-photometric catalogue constructed using the LAMB-DAR2 code that was applied to the 21-band photometric dataset from the GAMA Panchromatic Data Release (Driver et al. 2016), containing imaging spanning the far-UV to the far-IR.

The physical parameters for the galaxy sample such as the absolute magnitudes, extinction corrected rest-frame colours, stellar masses and specific star formation rate (sSFR) are derived using a grid of model spectral energy distributions (SED; Bruzual & Charlot 2003) and the SED fitting code LePHARE3 (Arnouts et al. 1999; Ilbert et al. 2006). The details used to derive these physical parameters are given in the companion paper Treyer et al. (in prep.).

The classification between the active (star-forming) and passive (quiescent) populations is based on a simple colour cut at $u - r = 1.8$ in the rest-frame extinction corrected $u - r$ vs $r$ diagram that is used to separate the two populations. This colour cut is consistent with a cut in sSFR at $10^{-11.5} \, \text{yr}^{-1}$ (see Treyer et al. in prep.). Hence, in what follows, the terms red (blue) and quiescent (star-forming) will be used interchangeably.

1 http://www.gama-survey.org/
2 Lambda Adaptive Multi-Band Deblending Algorithm in R
3 http://cesam.lam.fr/lephare/lephare.html
The analysis is restricted to the redshift range $0.03 \leq z \leq 0.25$, totalling 97072 galaxies. This is motivated by the high galaxy sampling required to reliably reconstruct the cosmic web. Beyond $z \sim 0.25$, the galaxy number density drops substantially (to $2 \times 10^{-3}$ Mpc$^{-3}$ from $8 \times 10^{-3}$ Mpc$^{-3}$ at $z \leq 0.25$, on average), while below $z \sim 0.03$, the small volume does not allow us to explore the large scales of the cosmic web.

The stellar mass completeness limits are defined for the passive and active galaxies as the mass above which 90% of galaxies of a given type (blue/red) reside at a given redshift $z \pm 0.004$. This translates into mass completeness limits of $\log (M_*/M_\odot) = 9.92$ and $\log (M_*/M_\odot) = 10.46$ for the blue and red populations at $z \leq 0.25$, respectively.

### 2.2 Group catalogue

Since the three-dimensional distribution of galaxies relies on the redshift-based measures of distances, it is affected by their peculiar velocities. In order to optimise the cosmic web reconstruction, one needs to take into account these redshift-space distortions. On large scales, these arise from the coherent motion of galaxies accompanying the growth of structure, causing its flattening along the line-of-sight, the so-called Kaiser effect (Kaiser 1987). On small scales, the so-called Fingers of God (FOG; Jackson 1972; Tully & Fisher 1978) effect, induced by the random motions of galaxies within virialized halos (groups and clusters) causes the apparent elongation of structures in redshift space, clearly visible in the galaxy distribution in the GAMA survey (Figure 1, top panel). While the Kaiser effect tends to enhance the cosmic web by increasing the contrast of filaments and walls (e.g. Subba Rao et al. 2008; Shi et al. 2016), the FOG effect may lead to the identification of spurious filaments. Because the impact of the Kaiser effect is expected to be much less significant than that of the FOG (e.g. Subba Rao et al. 2008; Kuutma et al. 2017), for the purposes of this work, its correction is not attempted and the focus is on the compression of the FOG alone. To do so, the galaxy groups are first constructed with a use of an anisotropic Friends-of-Friends (FoF) algorithm operating on the projected perpendicular and parallel separations of galaxies, that was calibrated and tested using the publicly available GAMA mock catalogues of Robotham et al. (2011) (see also Merson et al. 2013, for details of the mock catalogues construction). Details on the construction of the group catalogue and related analysis of group properties can be found in the companion paper Treyer et al. (in prep.). Next, the centre of each group is identified following Robotham et al. (2011) (see also Eke et al. 2004, for a different implementation). The method is based on an iterative approach: first, the centre of mass of the group (CoM) is computed; next its projected distance from the CoM is found iteratively for each galaxy in the group by rejecting the most distant galaxy. This process stops when only two galaxies remain and the most massive galaxy is then identified as the centre of the group. The advantage of this method, as shown in Robotham et al. (2011), is that the iteratively defined centre is less affected by interlopers than luminosity-weighted centre or the central identified as the most luminous group galaxy. The groups are then compressed radially so that the dispersions in transverse and radial directions are equal, making the galaxies in the groups isotropically distributed about their centres (see e.g. Tegmark et al. 2004). In practice, since the elongated FoG effect affects mostly the largest groups, only groups with more than six members are compressed. Note that the precise correction of the FoG effect is not sought. What is needed for the purpose of this work is the elimi-
nation of these elongated structures that could be misidentified as filaments.

Figure 1 displays the whole galaxy population and the identified FoF groups (coloured by their richness) in the GAMA field G12. The top and bottom panels show the groups before and after correcting for the FoG effect. For the sake of clarity, only groups having at least five members are shown. The visual inspection reveals that most of the groups are located within dense regions, often at the intersection of the apparently filamentary structures.

3 THE COSMIC WEB EXTRACTION

With the objective of exploring the impact of the LSS on the evolution of galaxy properties, one first needs to properly describe the main components of the cosmic web, namely the high density peaks (nodes) which are connected by filaments, framing the sheet-like walls, themselves surrounding the void regions. Among the various methods developed over the years, two broad classes can be identified. One uses the geometrical information contained in the local gradient and the Hessian of the density or potential field (e.g. Novikov et al. 2006; Aragón-Calvo et al. 2007a,b; Hahn et al. 2007a,b; Sousbie et al. 2008a,b; Forero-Romero et al. 2009; Bond et al. 2010a,b), while the second exploits the topology and connectivity of the density field by using the watershed transform (Aragón-Calvo et al. 2010) or Morse theory (e.g. Colombi et al. 2000; Sousbie et al. 2008a; Sousbie 2011). The theory for the former can be built in some details (see e.g. Pogosyan et al. 2009), shedding some light on physical interpretation, while the latter avoids shortcomings of a second order Taylor expansion of the field and provides a natural metric in which to compute distances to filaments. Within these broad categories, some algorithms deal with discrete data sets, while others require that the density field must be first estimated (possibly on multiple scales). An exhaustive description of several cosmic web extraction techniques and a comparison of their classification patterns as measured in simulations are presented in Libeskind et al. (2017). While this paper found some differences between the various algorithms, which should in principle be accounted for as modelling errors in the present work, these differences remain small on the scales considered.

3.1 Cosmic web with DisPerSE

This work uses the Discrete Persistent Structure Extractor (DisPerSE; see Sousbie et al. 2011, for illustrations in a cosmological context), a geometric three-dimensional ridge extractor dealing directly with discrete datasets, making it particularly well adapted for astrophysical applications. It allows for a scale and parameter-free coherent identification of the 3D structures of the cosmic web as dictated by the large-scale topology. For a detailed description of the DisPerSE algorithm and its underlying theory, the reader is referred to Sousbie (2011); its main features are summarised below.

DisPerSE is based on discrete Morse and persistence theories. The Delaunay tessellation is used to generate a simplicial complex, i.e. a triangulated space with a geometric assembly of cells, faces, edges and vertices mapping the whole volume. The Delaunay Tessellation Field Estimator (DTFE; Schaap & van de Weygaert 2000; Caunt & van de Weygaert 2011) allows for estimating the density field at each vertex of the Delaunay complex. The Morse theory enables to extract from the density field the critical points, i.e. points with a vanishing (discrete) gradient of the density field (e.g. maxima, minima and saddle points). These critical points are connected via the field lines tangent to the gradient field in every point. They induce a geometrical segmentation of space, where all the field lines have the same origin and destination, known as the Morse complex. This segmentation defines distinct regions called ascending and descending k-manifolds. The morphological components of the cosmic web are then identified from these manifolds: ascending 0-manifolds trace the voids, ascending 1-manifolds trace the walls and filaments correspond to the ascending 2-manifolds with its extremities plugged onto the maxima (peaks of the density field). In addition to its ability to work with sparsely sampled data sets while assuming nothing about the geometry or homogeneity of the survey, DisPerSE allows for the selection of retained structures on the basis of the significance of the topological connection between critical points. DisPerSE relies on persistent homology theory to pair critical points according to the birth and death of a topological feature in the excursion set. The “persistence” of a feature or its significance is assessed by the density contrast of the critical pair chosen to pass a certain signal-to-noise threshold. The noise level is defined relative to the RMS of persistence values obtained from random sets of points. This thresholding eliminates less significant critical pairs, allowing to simplify the Morse complex, retaining its most topologically robust features. Figure 2 shows that filaments outskirt walls, themselves circumventing voids. The filaments are made of a set of connected segments and their end points are connected to the maxima, the peaks of the density field where most of clusters and large groups reside. Each wall is composed of the facets of tetrahedra from the Delaunay tessellation belonging to the same ascending 2-manifold. In this work, DisPerSE is run on the flux-limited GAMA data with a 3σ persistence threshold. Figure 3 illustrates the filaments for the G12 field, overplotted on the density contrast of the underlying galaxy distribution, 1 + δ, where the local density is estimated using the DTFE density estimator. Even in this 2D projected visualisation one can see that filaments trace the ridges of the 3D density field connecting the density peaks between them.

3.2 Cosmic web metric

Having identified the major cosmic web features, let us now define a new metric to characterise the environment of a galaxy, that will be referred to as the “cosmic web metric” and into which galaxies are projected. Figure 4 gives a schematic view of this framework. Each galaxy is assigned the distance to its closest filament, D_{skel}. The impact point in the filament is then used to define the distances along the filament toward the node, D_{node}, and toward the saddle point, D_{saddle}. Similarly, D_{wall} denotes the distance of the galaxy to its closest wall. In the present work, only distances D_{node}, D_{skel} and D_{wall} are used. Other investigations of the environment in the vicinity of the saddle points are postponed to a forthcoming work.

The accuracy of the reconstruction of the cosmic web features is sensitive to the sampling of the dataset. The lower the sampling the larger the uncertainty on the location of the individual components of the cosmic web. To account for the variation of the sampling throughout the survey, unless stated differently, all the distances are normalised by the redshift dependent mean inter-galaxy
Figure 2. Illustration of the walls and filaments in the G12 field. For the sake of clarity and for the illustrative purposes, only the cosmic web features detected above a persistence threshold of 5σ are shown. Filaments are coloured in black, with the most persistent ones (> 6σ) plotted in red, while walls are colour coded randomly. Note how DisPerSE is capable of recovering the important features of the underlying cosmic field by identifying its (topologically) most-robust features. In particular, it extracts filaments as a set of connected segments, which outskirt walls, themselves circumventing voids.

Figure 3. Illustration of the filamentary network (black lines) extracted with the DisPerSE code within the ±1.2° of the central declination of the G12 field. The persistence threshold with which the filamentary network and the associated structures, used in this work and shown here, are extracted is 3σ. Also shown is the density contrast of the underlying galaxy distribution, measured with the small-scale adaptive DTFE estimator (see text) and averaged over cells of 2.3 \times 2.3 \text{ Mpc}^2 (white colour is used for empty cells). In spite of the projection effects, the visual inspection reveals that filaments follow the ridges of the density field which connect the peaks together.

separation \( \langle D_z \rangle \), defined as \( \langle D_z \rangle \equiv n(z)^{-1/3} \), where \( n(z) \) represents the number density of galaxies at a given redshift \( z \). For the combined three fields of GAMA survey, \( \langle D_z \rangle \) varies from 3.5 to 7.7 Mpc across the redshift range \( 0.03 \leq z \leq 0.25 \), with a mean value of \( \sim 5.6 \text{ Mpc} \).

4 GALAXY PROPERTIES WITHIN THE COSMIC WEB

In this section, the dependence of various galaxy properties, such as stellar mass, \( u - r \) colour, sSFR and type, with respect to their location within the cosmic web is analysed. First, the impact of the nodes, representing the largest density peaks, is investigated. Next, by excluding these regions, galaxy properties are studied within the
intermediate density regions near the filaments. Finally, the analysis is extended to the walls.

4.1 The role of nodes via the red fractions

Let us start by analysing the combined impact of nodes and filaments on galaxies through the study of the red fractions. The red fraction, defined as the number of passive galaxies with respect to the entire population, is analysed as a function of the distance to the nearest filament, $D_{\text{skel}}$, and its distance to the closest wall, $D_{\text{node}}$. $D_{\text{saddle}}$ and $D_{\text{node}}$ represent the distances from the impact point to the node and saddle along the corresponding filament, respectively.

This analysis is restricted to galaxies more massive than $\log(M_*/M_\odot) \gtrsim 10.46$, as imposed by the mass limit completeness of the passive population (see Section 2). The stellar mass distributions of the passive and star-forming populations are not identical, with the passive galaxies dominating the high mass end. Therefore, to prevent biases in the measured gradients introduced by such differences, the mass-matched samples are used. The detailed description of the mass-matching technique can be found in Appendix A1.

In Figure 5 the red fraction of galaxies is shown as a function of $D_{\text{skel}}$ in three different bins of $D_{\text{node}}$. While the fraction of passive galaxies is found to increase with decreasing distances both to the filaments and nodes, the dominant effect is the distance to the nodes. At fixed $D_{\text{skel}}$, the fraction of passive galaxies sharply increases with decreasing distance to the nodes. Recalling that the mean inter-galaxy separation ($D_{\text{skel}}$) is $\sim 5.6$ Mpc, a 20 to 30% increase in the fraction of passive galaxies is observed from several tens of Mpc away from the nodes to less than $\sim 500$ kpc. This behaviour is expected since the nodes represent the loci where most of the groups and clusters reside and reflects the well known colour-density (e.g. Blanton et al. 2003; Baldry et al. 2006; Barden et al. 2009) and star formation-density (e.g. Lewis et al. 2002; Kauffmann et al. 2004) relations. However, the gradual increase suggests that some physical processes already operate before the galaxies reach the virial radius of massive halos. At fixed $D_{\text{node}}$, the fraction of passive galaxies increases with decreasing distance to filaments, but this increase is milder compared to that with respect to nodes: an increase of $\sim 10\%$ is observed regardless of the distance to the nodes. These regions with intermediate densities appear to be a place where the transformation of galaxies takes place as emphasised in the next section.

4.2 The role of filaments

In order to infer the role played by filaments alone in the transformation of galactic properties, the impact of nodes, the high density regions has to be mitigated. By construction, nodes are at the intersection of filaments: they drive the well known galaxy type-density as well as stellar mass-density relations. To account for this bias, Gay et al. (2010) and Malavasi et al. (2017) adopted a method where a given physical property or distance of each galaxy was down-weighted by its local density. Laigle et al. (2017) adopted a more stringent approach by rejecting all galaxies that are too close to the nodes. This method allows to minimise the impact of nodes, avoiding the difficult-to-quantify uncertainty of the residual contribution of the density weighting scheme. The latter approach is therefore adopted. As shown in Appendix B1, this is achieved by rejecting all galaxies below a distance of 3.5 Mpc from a node.

4.2.1 Stellar mass gradients

Figure 6 shows the normalised probability distribution functions (PDFs) of the distance to the nearest filament $D_{\text{skel}}$ in three stellar mass bins for the entire population and star-forming galaxies alone (top left and right panels, respectively). The medians of the PDFs,
shown by vertical lines, are listed together with the corresponding error bars in Table 1. The significance of the observed trends is assessed by computing the residuals between the distributions in units of $\sigma$ (bottom panels), defined as $\Delta_{1-2}/\sqrt{\sigma_1^2 + \sigma_2^2}$, where $\Delta_{1-2}$ is the difference between the PDFs of the populations 1 and 2, and $\sigma_1$ and $\sigma_2$ are the corresponding standard deviations.

For the entire population (left panels), differences between the PDFs of the three stellar mass bins are observed: the most massive galaxies ($\log(M_*/M_\odot) \geq 11$) are located closer to the filaments than the intermediate population ($11 > \log(M_*/M_\odot) \geq 10.7$), while the population with the lowest stellar masses ($10.7 > \log(M_*/M_\odot) \geq 10.46$) is found furthest away from the filaments. The significances of the difference between the most massive and the two lowest stellar mass bins are shown in the bottom panel.
Between the most extreme stellar mass bins (purple line), the difference exceeds $4\sigma$ close to the filament and $2\sigma$ at larger distances. It is slightly less significant between the intermediate and lowest stellar mass bins (orange line), but still in excess of $2\sigma$ close to the filament. The differences between the PDFs can be also quantified in terms of their medians, where the differences between the highest and lowest stellar mass bins is significant at a $\sim 10\sigma$ level (see Table 1). These results confirm previous claims of a mass segregation with respect to filaments, where the most massive galaxies are located near the core of the filaments, while the less massive ones tend to reside preferentially on their outskirts (Malavasi et al. 2017; Laigle et al. 2017). As the impact of the nodes has been minimised, it is established that this stellar mass gradient is driven by the filaments themselves and not by the densest regions of the cosmic web.

The mass segregation is also found among the star-forming population alone (right panels), such that more massive star-forming galaxies tend to be closer to the geometric core of the filament than their less massive counterparts. Note that the mass bins for star-forming galaxies differ from mass bins used for the entire population. The completeness stellar mass limit allows us to decrease the lowest mass bin to $\log(M_*/M_\odot) = 9.92$ when considering the star-forming galaxies alone (see Section 2). The significance of these stellar mass gradients between the extreme stellar mass bins exceeds $4\sigma$ near the filaments, while the difference of the medians reaches a $\sim 8\sigma$ level (see Table 1).

### 4.2.2 Type gradients

Let us now investigate the impact of the filamentary network on the type/colour of galaxies. To do so, galaxies are split by type between star-forming and passive galaxies based on the dust corrected $u-r$ colour as discussed in Section 2.1. As for the analysis of the red fraction (Section 4.1), the sample is restricted to galaxies with $\log(M_*/M_\odot) \geq 10.46$ and the star-forming and passive populations are matched in stellar mass. Figure 7 shows the PDFs of the normalised distances $D_{\text{skel}}$ within the mass-matched samples of star-forming and passive populations, which by construction have the same number of galaxies. Galaxies are found to segregate according to their type such that passive galaxies tend to reside in regions located closer to the core of filaments than their star-forming counterparts. The significance of the stellar mass gradients between the two populations exceeds $3\sigma$ near filaments while the difference between the medians reaches a $\sim 4\sigma$ level (see Table 1).

### 4.2.3 Star formation activity gradients

To explore whether the impact of filaments on the star formation activity of galaxies can be detected beyond the red fractions and type segregation reported above, the focus is now on the star-forming population alone through the study of their (dust corrected) $u-r$ colour and sSFR.

Both these quantities are known to evolve with stellar mass which itself varies within the cosmic web (see above). To remove this mass dependence, the offsets of $u-r$ colour and sSFR, $\Delta u-r$ and $\Delta sSFR$ respectively, from the median values of all star-forming galaxies at a given mass are computed for each mass. Figure 8 shows the medians of $\Delta u-r$ and $\Delta sSFR$ as a function of $D_{\text{skel}}$. Both quantities are found to carry the imprint of the large-scale environment. At large distances from the filaments ($D_{\text{skel}} \gtrsim 5$ Mpc), star-forming galaxies are found to be more active than the average.

![Star-forming vs passive](image)

**Figure 7.** Top: Differential distributions of the distances to the nearest filament, $D_{\text{skel}}$ (normalised by $D_z$), the redshift-dependent mean inter-galaxy separation) for star-forming and quiescent galaxies that have been matched in mass (see text for details). To highlight an effect specific to the filaments, the contribution of node is minimised (see text for details). The vertical lines indicate the medians of the distributions and their values together with associated error bars are listed in Table 1. The numbers of galaxies in different considered bins are indicated in each panel. The error bars are calculated from 100 bootstrap samples. Galaxies are found to segregate, relative to filaments, according to their type: quiescent galaxies tend to be preferentially located closer to the filaments compared to their star-forming counterparts. Bottom: Residuals in units of $\sigma$ between the star-forming and passive galaxies.

At intermediate distances ($0.5 \lesssim D_{\text{skel}} \lesssim 5$ Mpc), star formation activity of star-forming galaxies do not seem to evolve with the distance to the filaments, while in the close vicinity of the filaments ($D_{\text{skel}} \lesssim 0.5$ Mpc), they show signs of a decrease in star formation efficiency (redder colour and lower sSFR). The significance of these results will be discussed in Section 7.

### 4.3 The role of walls in mass and type gradients

Let us now investigate the impact of walls on galaxy properties. Figures 9 and 10 show the PDFs of the distances to the closest wall $D_{\text{wall}}$ for the same selections as in Figures 6 and 7, respectively. The distances are again normalised by the redshift dependent mean inter-galaxy separation ($D_z$). The values of medians with corresponding error bars are listed in Table 1. As for filaments, one seeks signatures induced by a particular environment solely, walls in this case. Given that filaments are located at the intersections between walls, in addition to the contamination by nodes, which is of concern for filaments, one has to make sure that the contribution of filaments themselves is minimised as well. Following the method adopted in Section 4.2.1, Appendix B2 shows that this can be achieved by removing from the analysis galaxies having distances to the nodes smaller than 3.5 Mpc and distances to the closest filaments less than 2.5 Mpc.
The derived trends are qualitatively similar to those measured with respect to filaments. Massive galaxies are located closer to walls compared to their low-mass counterparts; star-forming galaxies preferentially reside in the outer regions of walls; and mass segregation is present also among star-forming population of galaxies with more massive star-forming galaxies having smaller distances to the walls than their low-mass counterparts. Since the walls typically embed smaller-scale filaments, the net effect of transverse gradients perpendicular to these filaments should add up to transverse gradients perpendicular to walls.

The significance of the measured trends, in terms of the residuals between medians (see Table 1), is above $3\sigma$ for all considered gradients, slightly lower than for the gradients towards filaments. The deviations of $\sim 10\sigma$ and $\sim 5\sigma$ are detected between the highest and lowest stellar mass bins among the whole and star-forming population alone, respectively, while between the star-forming and passive galaxies it reaches $\sim 4\sigma$, as in the case of gradients towards filaments.

5 COMPARISON WITH THE HORIZON-AGN SIMULATION

In this section, a qualitative support for the results on the mass and star-formation activity segregation is provided via the analysis of the large-scale cosmological hydrodynamical simulation HORIZON-AGN (Dubois et al. 2014). Note that the main purpose of such an analysis is to provide a reference measurement of gradients in the context of a large-scale “full physics” experiment. The construction of the GAMA-like mock catalogue is not performed because the geometry of HORIZON-AGN does not allow us to recover the entire GAMA volume and the flux-limited sample requires a precise modelling of fluxes in different bands.

A brief summary of some of the main features of the simulation can be found in Appendix D. Here, the results on the mass and sSFR gradients towards filaments and walls are presented. The HORIZON-AGN simulation is analysed at low redshift ($z \sim 0.1$), comparable to the mean redshift studied in this paper, and the same analysis is performed as in the GAMA data. The filamentary network and associated structures are extracted by running the DisPerSE code with the persistence threshold of $3\sigma$.

Figure 11 shows the mass (left panels) and sSFR (right panels) gradients towards filaments (figure a) and walls (figure b) as measured in the HORIZON-AGN simulation. The impact of the nodes and filaments on the measured signal is minimised by removing from the analysis galaxies that are closer to the node than 3.5 Mpc and closer to the filament than 1 Mpc. The detailed description of the method used to identify these cuts in distances can be found in Appendix B1. Consistently with the measurements in GAMA, galaxies in HORIZON-AGN are found to segregate by stellar mass, with more massive galaxies being preferentially closer to both the filaments and walls than their low-mass counterparts. Similarly, the presence of the sSFR gradient, whereby less star-forming galaxies tend to be closer to the cores of filaments and walls than their more star-forming counterparts, is in qualitative agreement with the type/colour gradients detected in the GAMA survey. Note that the three bins of sSFR are used to separate out the highly star-forming galaxies, with $\log(sSFR/\text{yr}^{-1}) > 10.4$, from passive ones, with $\log(sSFR/\text{yr}^{-1}) < -10.8$, in order to compare with the type gradients in the observations. In the simulation, sSFR is a more reliable parameter for type than the colour.

The significance of the trends is measured, as previously, in terms of the residuals between medians (see Table 1). For the gradients towards filaments, the difference of $\geq 6\sigma$ is found between the most extreme, both mass and sSFR, bins, while it drops to $\sim 2 - 3\sigma$ between the intermediate and lowest bins. For the gradients towards walls, the deviation between the most extreme bins is $\sim 10$ and $4\sigma$ for mass and sSFR bins, respectively, while there is only a little to no difference between intermediate and lowest stellar mass and sSFR bins, respectively. The gradients are slightly less significant than in the GAMA measurements, most likely due to the low numbers of galaxies per individual bins in HORIZON-AGN, but qualitatively similar as in GAMA.

6 THE RELATIVE IMPACT OF DENSITY

Let us now address the following questions: what is the specific role of the geometry of the large-scale environment in establishing mass and type/colour large-scale gradients? Are these gradients driven solely by density, or does the large scale anisotropy of the cosmic web provide a specific signature?

A key ingredient in answering these questions is the choice of the scale at which the density is inferred. The properties of galaxies at a given redshift are naturally a signature of their past lightcone. This lightcone in turn correlates with the galaxy’s environment: the larger the scale is, the longer the look-back time one must consider, the more integrated the net effect of this environment. This past environment accounts for the total accreted mass of the galaxy, but may also impact the geometry of the accretion history and more generally other galactic properties such as its star formation efficiency, its colour or its spin. At small scales, the density correlates with the most recent and stochastic processes, while going to larger scales allows taking the integrated hence smoother history of galaxies into account. Since this study is concerned about the statistical impact of the large scale structure on galaxies, it is natural to consider scales large enough to average out local recent events they
Figure 9. Top row: As in Figure 6, but for the distances to the nearest wall, \( D_{\text{wall}} \). To minimise the contribution of nodes and filaments to the measured signal, galaxies located closer to a node than 3.5 Mpc and closer to a filament than 2.5 Mpc are removed from the analysis. There is a mass segregation of galaxies with respect to walls of the entire as well as star-forming population: more massive galaxies tend to be preferentially located closer to the filaments compared to their lower-mass counterparts. Bottom row: Residuals in units of \( \sigma \) as in Figure 6.

Table 2. Medians for the PDFs displayed in Figure 11.

| selection | bin | \( D_{\text{abul}} \) [Mpc] | \( D_{\text{wall}} \) [Mpc] |
|-----------|-----|----------------|----------------|
| Mass      | \( \log(M_*/M_\odot) \geq 10.8 \) | 1.34 \( \pm \) 0.09 | 0.79 \( \pm \) 0.04 |
|           | \( 10.8 > \log(M_*/M_\odot) \geq 10.4 \) | 1.73 \( \pm \) 0.08 | 1.14 \( \pm \) 0.03 |
|           | \( 10.4 > \log(M_*/M_\odot) \geq 10 \) | 1.97 \( \pm \) 0.04 | 1.22 \( \pm \) 0.02 |
| sSFR      | \( -10.8 > \log(sSFR/\text{yr}^{-1}) \) | 1.46 \( \pm \) 0.07 | 1.02 \( \pm \) 0.03 |
|           | \( -10.4 > \log(sSFR/\text{yr}^{-1}) \geq -10.8 \) | 1.88 \( \pm \) 0.06 | 1.18 \( \pm \) 0.03 |
|           | \( \log(sSFR/\text{yr}^{-1}) \geq -10.4 \) | 2.0 \( \pm \) 0.04 | 1.18 \( \pm \) 0.02 |

\( ^* \) panels of Figure 11

\( ^b \) medians of distributions as indicated in Figure 11 by a vertical line; errors are computed as in Table 1

\( ^c \) only galaxies with stellar masses \( \log(M_*/M_\odot) \geq 10 \) are considered

May have encountered, such as binary interactions, mergers, outflows. Therefore in the discussion below, the density is computed at the scale of 8 Mpc, the “smallest” scale at which the effect of the anisotropic large-scale tides can be detected.

In practice, in order to try to disentangle the effect of density from that of the anisotropic large-scale tides, the following reshuffling method (e.g. Malavasi et al. 2017) is adopted. For mass gradients, ten equipopulated density bins are constructed and in each of them the stellar masses of galaxies are randomly permuted. By construction, the underlying mass-density relation is preserved, but this procedure randomises the relation between the stellar mass and the distance to the filament or the wall. For the type/colour gradients, in each of ten equipopulated density bins, ten equipopulated stellar mass bins are constructed. Within each of such bins, \( u - r \) colour of galaxies are randomly permuted. Thus by construction, this preserves the underlying colour-(mass)-density relation, but breaks the relation between the colour/type and the distance to the particular environment, the filament or wall.

In order to account for the variation of the density through the survey, the density contrast, defined as \( 1 + \delta = n/n(z) \), where \( n(z) \) corresponds to the mean redshift dependent number density, is used in logarithmic bins. The number density \( n \) is computed in the Gaussian kernel and every time five reshuffled samples are constructed.

In Figure 12 (a), the mass and type gradients towards filaments, as measured in GAMA and previously shown in Figures 6 and 7, are compared with the outcome of the reshuffling technique. The original signal is found to be substantially reduced after the reshuffling of masses and colours of galaxies. For the mass gradients, the deviation between the most extreme bins before reshuffling exceeds 3\( \sigma \), while after the reshuffling, the signal gets reduced, with typical deviations of \( \sim 1\sigma \). The original signal for the type/colour gradients is weaker than in the case of the mass gradi-
Let us first discuss the observational findings of the previous section in the framework of existing work (Section 7.1) and then focus on a recent extension of anisotropic excursion set which is developed in the companion paper (Section 7.2). The latter will allow us to explain why colour gradients prevail at fixed density.

### 7.1 Cosmic web metric: expected impact on galaxy evolution

In the current framework for galaxy formation, in which galaxies reside in extended dark matter halos, it is quite natural to split the environment into the local environment, defined by the dark matter halo and the global large-scale anisotropic environment, encompassing the scale beyond the halo’s virial radius. The anisotropy of the cosmic web is already a direct manifestation of the generic anisotropic nature of gravitational collapse on larger scales. It provides the embedding in which dark halos and galaxies grow via accretion, which will act upon them via the combined effect of tides, the channeling of gas along preferred directions and angular momentum advection onto forming galaxies.

The observations and simulations presented in Sections 4, 5 and 6 provide a general support for this scenario. While rich clusters and massive groups are known to be environments which induce major galaxy transformations, the red fraction analysis presented in Section 4.1 (Figure 5) reveals that the fraction of passive galaxies in the filaments starts to increase several Mpc away from the nodes and peaks in the nodes. This gradual increase suggests that some “pre-processing” already happens before the galaxies reach the virial radius of massive halos and fall into groups or clusters (e.g. Porter et al. 2008; Martinez et al. 2016). The above mentioned morphological transformation of elliptical-to-spiral ratio when getting closer to the filaments (see also Kuutma et al. 2017) can be interpreted as the result of mergers transforming spirals into passive elliptical galaxies along the filaments when migrating towards nodes as suggested by theory and simulations (Codis et al. 2012; Dubois et al. 2014). These findings show that filamentary regions, corresponding to intermediate densities, are important environments for galaxy transformation. This is also confirmed by the segregation found in Sections 4.2 (Figures 6 and 7). More massive and/or passive galaxies are found closer to the core of filaments than their less massive and/or star-forming counterparts. These differential mass gradients persist among the star forming population alone. In addition to mass segregation, star-forming galaxies show a gradual evolution in their star formation activity (see Figure 8). They are bluer than average at large distances from filaments ($D_{skel} \gtrsim 5$ Mpc), in a “steady state” with no apparent evolution in star formation activity at intermediate distances ($0.5 \leq D_{skel} \leq 5$ Mpc) and they show signs of decreased star formation efficiency near the core of the filaments ($D_{skel} \lesssim 0.5$ Mpc). These results are in line with the picture where on the one hand more massive/passive galaxies lay in the core of filaments and merge while drifting towards the nodes of the cosmic web. On the other hand, the low mass/star-forming galaxies tend to be preferentially located in the outskirts of filaments, a vorticity rich regions (Laigle et al. 2015), where galaxies acquire both their angular momentum (leading to a spin parallel to the filaments) and their stellar mass via essentially smooth accretion (Dubois et al. 2012b; Welker et al. 2017, also relying on HORIZON-AGN). The steady state of star formation in these regions can reflect the right balance between the consumption and refuelling of the gas reservoir by the cold gas controlled by their surrounding filamentary structure (as shown by Codis et al. 2015, following Pichon et al. 2011, the outskirts of filaments are the loci of most efficient heliocoidal infall of cold gas). This may not be true anymore when galaxies fall in the core of the filaments. The decline of star formation activity can in part be due to the higher merger rate...
but also due to a quenching process such as strangulation, where the supply of cold gas is halted (Peng et al. 2015). It could also find its origin in the cosmic web detachment (Aragon-Calvo et al. 2016), where the turbulent regions inside filaments prevent galaxies to stay connected to their filamentary flows and thus to replenish their gas reservoir.

7.2 Link with excursion set theory

The distinct transverse gradients found for mass, density and type or colour may also be understood within the framework of conditional excursion set theory. Qualitatively, the spatial variation of the (traceless part of the) tidal tensor in the vicinity of filaments will
delay infall onto galaxies, which will impact differentially galactic colour (at fixed mass), provided accretion can be reasonably converted into star formation efficiency.

7.2.1 Connecting gradients to constrained excursion set

The companion paper (Musso et al. 2017) revisits excursion set theory subject to conditioning the excursion to the vicinity of a filament. In a nutshell, the main idea of excursion set theory is to compute the statistical properties of the initial (over-)density – a stochastic variable – enclosed within spheres of radius $R$, the scale which, through the spherical collapse model, can be related to the final mass of the object (should the density within the sphere pass the threshold for collapse). Increasing the radius of the sphere provides us with a proxy for “evolution” (larger sphere, larger mass, smaller variance, later formation time) and a measure of the impact.
of the environment (different sensitivity to tides for different, larger, spheres). The expectations associated to this stochastic variable can be re-computed subject to the tides imposed by larger-scale structures, which are best captured by the geometry of a filament-saddle point, \( S \), providing the local natural “metric” for a filament (Codis et al. 2015). These large-scale tides will induce distinct weighting in the conditional PDF \( \delta, \partial_H \delta(S) \) for the over-density \( \delta \), and its successive derivatives with respect to scale, \( \partial_H \delta \) etc. (so as to focus on collapsed accreting regions). Indeed, the saddle will shift both the mean expectation of the PDFs but also importantly their co-variances (see Musso et al. 2017, for details). The derived expected (dark matter) mean density \( \rho(r, \theta, \phi) \), Press-Schechter mass \( M(r, \theta, \phi) \) and typical accretion rate \( \dot{M}(r, \theta, \phi) \) then become explicit distinct functions of distance \( r \) and relative orientation to the closest (oriented) saddle point. Within this model, it follows that the orientation of the mass, density and accretion rate gradients differ. The misalignment arises because the various fields weight differently the constrained tides, which will physically e.g. delay infall, and technically involve different moments of the aforementioned conditional PDF (see Appendix E for more quantitative information on contour misalignment). This is shown in Figure 13 which displays a typical longitudinal cross section of those three maps in the frame of the saddle, with the filament along the \( Oz \) axis, in Lagrangian space. This line of argument explains environmentally driven differential gradients, yet there is still a stretch to connect it to the observed gradients. While there is no obvious consensus on the detailed effect of large-scale (dark matter) accretion onto the colour or star formation of galaxies at fixed mass and density, one can expect that the stronger the accretion, the stronger the AGN feedback, the stronger the quenching. Should this (reasonable) scaling hold true, the net effect in terms of gradients would be that colour gradients differ from mass and density ones. This is qualitatively consistent with the findings of this paper.

Figure 13. Isocontours of constant typical redshift \( z = 0 \) mean density (filled contours), mass (dotted lines) and accretion rate (dashed lines) in the frame of a filament (along the \( Oz \) axis) in Lagrangian space (initial conditions) from low (light colours) to high values (dark colours). The saddle is at coordinate (0,0) while the induced peak and void are at coordinates (0,±7) and (±8,0) Mpc/h, respectively. As argued in the main text, this figure shows that the contours, hence the gradients of the three fields are not parallel (the contours cross). The choice of scale sets the units on the \( x \) and \( z \) axis (chosen here to be 5 Mpc/h), while the mass and accretion rates are computed for a local smoothing of 0.5 Mpc/h. At lower redshift/smaller scales, one expects the non-linear convergence of the flow towards the filament to bring those contours together, aligning the gradients (see Figure 14).

Table 3. Medians for the PDFs displayed in Figure 12: large-scale density

| selection | bin | median original | reshuffling | matching |
|-----------|-----|----------------|-------------|----------|
| All galaxies | \( \log (M_* / M_\odot) \geq 11 \) | 0.379 ± 0.009 | 0.441 ± 0.009 | 0.379 ± 0.01 |
| | \( 11 > \log (M_* / M_\odot) > 10.7 \) | 0.456 ± 0.007 | 0.463 ± 0.006 | 0.44 ± 0.009 |
| | \( 10.7 > \log (M_* / M_\odot) \geq 10.46 \) | 0.505 ± 0.007 | 0.475 ± 0.006 | 0.486 ± 0.01 |
| SF galaxies | \( \log (M_* / M_\odot) \geq 11 \) | 0.459 ± 0.01 | 0.541 ± 0.015 | 0.459 ± 0.011 |
| | \( 11 > \log (M_* / M_\odot) > 10.4 \) | 0.534 ± 0.007 | 0.543 ± 0.007 | 0.514 ± 0.012 |
| | \( 10.4 > \log (M_* / M_\odot) \geq 9.92 \) | 0.578 ± 0.007 | 0.552 ± 0.007 | 0.549 ± 0.012 |
| Types | star-forming | 0.503 ± 0.007 | 0.491 ± 0.007 | 0.498 ± 0.007 |
| | passive | 0.462 ± 0.007 | 0.476 ± 0.007 | 0.467 ± 0.006 |

* panels of Figure 12
b medians of distributions as indicated in Figure 12 by a vertical lines; errors are computed as in Table 1
c as in Table 1 for \( D_{\text{h}0} / (D_c) \)
d reshuffling is done in bins of density computed at 8 Mpc (see the text for details)
e medians for the density-matched sample, where the density considered is computed at 8 Mpc
f only galaxies with stellar masses \( \log (M_* / M_\odot) \geq 10.46 \) are considered

5 This companion paper does not capture the strongly non-linear process of dynamical friction of sub-clumps within dark matter halos, nor strong deviations from spherical collapse. We refer to Hahn et al. (2009) which captures the effect on satellite galaxies, and to Ladlow et al. (2014); Borzyszkowski et al. (2016); Castorina et al. (2016) which study the effect of the local shear on halos forming in filamentary structures. This requires adopting a threshold for collapse that depends explicitly on the local shear. The shear-dependent part of the critical density (and its derivative) correlates with the shear of the saddle, and introduces an additional anisotropic effect on top of the change of mean values and variances of density and slope.
Typical dark halo mass simulation (e.g., Sousbie et al. 2008a), or predicted at the level of the saddle smoothed on the corresponding scale, but where the use of the small scale density tracer does not allow to disentangle between the effects of the local density and that of cosmic web, suggesting that at such scale, they are closely correlated through the small-scale processes.

7.2.3 Relationship to wall gradients

When measured relative to the walls, galaxy properties are found to exhibit the same trends as for filaments, in that more massive and/or quiescent galaxies are found closer to the walls than their low mass and/or star-forming counterparts. This result is again in qualitative agreement with the idea of walls being, together with the filaments, the large-scale interference patterns of primordial fluctuations capable of inducing anisotropic boost in over-density together with the corresponding tides, and consequently imprinting their geometry in the measured properties of galaxies. The gradients measured for walls have the same origin as those inducing the differential gradients near the filament-type saddles, but are sourced by the geometry of the tides near the wall-type saddles (Codis et al. 2015, Appendix B). The main difference between the two saddles lies in the transverse curvatures, which is steeper for wall-type than for filament-type saddles (when considering the mean, eigenvalue weighted, eigenvalues of the curvature tensor with the relevant signatures) leading to weaker differences between the different gradients when considering walls. This is consistent with the findings of Section 4.3.

In closing, note that the (resp. Eulerian and Lagrangian) interpretations presented in Section 7.1 and 7.2 are complementary, but fall short in explaining in details the origin of quenching. Nevertheless, in view of both observation and theory, the cosmic web metric appears as a natural framework to understand galaxy formation beyond stellar mass and local density.

8 SUMMARY AND CONCLUSIONS

This paper studies the impact of the large-scale environment on the properties of galaxies, such as their stellar mass, dust corrected $u - r$ colour and sSFR. The discrete persistent structure extractor (DisPerSE) was used to identify the peaks, filaments and walls in the large-scale distribution of galaxies as captured by the GAMA survey. The principal findings are the following.

(i) **Mass segregation.** Galaxies are found to segregate by stellar mass, such that more massive galaxies are preferentially located closer to the cores of filaments than their lower mass counterparts. This mass segregation persists among the star-forming population. Similar mass gradients are seen with respect to walls in that galaxies with higher stellar mass tend to be found closer to the walls compared to galaxies with lower mass and persisting even when star-forming population of galaxies is considered alone.

(ii) **Type/colour segregation.** Galaxies are found to segregate by type/colour, both with respect to filaments and walls, such that passive galaxies are preferentially located closer to the cores of filaments or walls than their star-forming counterparts.

(iii) **Red fractions.** The fraction of passive galaxies increases with both decreasing distance to the filament and to the node, i.e., at fixed distance to the node, the relative number of passive galaxies (with respect to the entire population) increases as the distance to the filament decreases and similarly, at a given distance to the filament, this number increases with decreasing distance to the node.
(iv) Star formation activity. Star-forming galaxies are found to carry an imprint of large-scale environment as well. Their dust corrected $u-r$ and sSFR are found to be more enhanced and reduced, respectively, in the vicinity of the filaments compared to their outskirts.

(v) Consistency with cosmological simulations. All the found gradients are consistent with the analysis of the HORIZON-AGN "full physics" hydrodynamical simulation. This agreement suggests that what drives the gradients is captured by the implemented physics.

(vi) Connection to excursion set theory. The origin of the distinct gradients can be qualitatively explained via conditional excursion set theory subject to filamentary tides (Musso et al. 2017).

This work has focused on filaments, nodes and in somewhat lesser details on walls. Similar observational results were recently reported at high redshift by using the cosmic web filamentary structures in the VIPERS spectroscopic survey (Malavasi et al. 2017) and when using projected filaments in photometric redshift slices in the COSMOS field (Laigle et al. 2017). These observations are of intrinsic interest as a signature of galactic assembly; they also confirm theoretical expectations which point towards distinct gradients for colour, mass and density with respect to the cosmic web. The tides of the large-scale environment plays a significant specific role in the evolution of galaxies, and are imprinted in their integrated physical properties, which vary as a function of scale and distance to the different components of the cosmic web in a manner which is specific to each observable.

These observations motivates a theory which eventually should integrate the anisotropy of the cosmic web as an essential ingredient to i) describe jointly the dynamics and physics of galaxies, ii) explain galactic morphological diversity, and iii) mitigate intrinsic alignment in upcoming lensing dark energy experiments, i.e. ii) explain galactic morphological diversity, and iii) mitigate intrinsic alignment in upcoming lensing dark energy experiments, once a proper modelling of the mapping between galaxies and their halos (allowing e.g. to convert the DM accretion rate into colour of galaxy) becomes available.

Future large scale spectrographs on 8 meter class telescopes (MOONS6; Cirasuolo et al. 2014; Cirasuolo & MOONS Consortium 2016, PFS; Sugai et al. 2015) or space missions (WFIRST7; Spergel et al. 2013, 2015, and Euclid8; Laureijs et al. 2011, the deep survey for the latter) will extend the current analysis at higher redshift ($z \geq 1$) with similar samplings, allowing to explore the role of the environment near the peak of the cosmic star formation history, an epoch where the connectivity between the LSS and galaxies is expected to be even tighter, with ubiquitous cold streams. Tomography of the Lyman-$\alpha$ forest with PFS, MOONS, ELT-HARMONI (Thatte et al. 2010) tracing the intergalactic medium will make the study of the link between galaxies and this large scale gas reservoir possible (Laigle et al. in prep.).

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6 Multi-Object Optical and Near-infrared Spectrograph
7 Prime Focus Spectrograph; http://pfs.ipmu.jp/
8 Wide-Field Infrared Survey Telescope; http://wfirst.gsfc.nasa.gov
9 http://sci.esa.int/euclid/, http://www.euclid-ec.org
APPENDIX A: MATCHING TECHNIQUE

A1 Mass matching

First the mass distributions of the two populations are cut so that they cover the same stellar mass range, i.e. they have the same minimum and maximum value of stellar mass. Then, in each stellar mass bin, the population with lower number of galaxies is taken as the reference sample and $N_{\text{match}}$ samples of galaxies are extracted in the other population, such that their mass distribution is the same as the one of the reference sample. In practice, for each galaxy in the reference sample, the corresponding galaxy of the larger sample is sought among galaxies whose mass difference with respect to the reference mass is smaller than $\Delta M_*$, in logarithmic space. If there is no galaxy in the larger sample satisfying this condition, the galaxy of the reference sample is removed from the analysis. In each of $N_{\text{match}}$ samples every galaxy of the larger sample is considered only once, however repetitions are allowed across all samples. By construction, after applying this procedure, one ends up with $N_{\text{match}}$ samples consisting of the same number of star-forming and passive galaxies and having very similar stellar mass distributions.

If not stated differently, 20 mass-matched samples are typically constructed using ten equipopulated stellar mass bins for each and choosing a value of 0.1 for $\Delta M_*$ parameter. Varying the values of $N_{\text{match}}$, $\Delta M_*$ and the number of stellar mass bins within the reasonable range does not alter our conclusions.

A2 Density matching

This Appendix provides details on the density matching procedure. First, let us describe how the mass-density matched samples are constructed. The galaxy sample is first divided into three logarithmic stellar mass bins for each and choosing a value of 0.1 for $\Delta M_*$ parameter. Varying the values of $N_{\text{match}}$, $\Delta M_*$ and the number of stellar mass bins within the reasonable range does not alter our conclusions.

The contribution of nodes to mass gradients towards filaments is measured by randomising distances to the filament, $D_{\text{skel}}$, in bins of distances to the node, $D_{\text{node}}$. By construction, gradients towards nodes are preserved. 20 samples are constructed in each of which this reshuffling method is applied in 20 equipopulated logarithmic bins. As shown by the dashed lines in Figure A1 and values of medians listed in Table F1, the reshuffling cancels the gradients towards filaments for $D_{\text{node}} \leq 3.5$ Mpc.

In addition, following Laigle et al. (2017), it can be shown that in the regions sufficiently faraway from nodes, gradients towards nodes and those towards filaments are independent. It was checked that the mass gradients towards nodes, present for the entire galaxy sample, are substantially reduced once galaxies for which distances to the node $D_{\text{node}} \leq 3.5$ Mpc are excluded. This time, the distances to the node, $D_{\text{node}}$, were randomised in bins of distances to the filament, $D_{\text{skel}}$, i.e. by construction, gradients towards filaments were preserved. Again, 20 samples were constructed using 20 equipopulated logarithmic bins. After reshuffling, weak gradients at the level of at most 1σ are still present, but note that additional increase in $\Delta M_*$ does not reduce them further.

This analysis allows us to conclude that by removing from our sample galaxies that are closer to nodes than 3.5 Mpc, the impact of nodes to the measured gradients towards filaments is minimised, and even if weak gradients towards nodes still exist, these are independent of gradients towards filaments, i.e. gradients towards filaments and gradients towards nodes can be disentangled.

Let us finish this section with two remarks. First, note that distances to the node considered here are 3D euclidian distances. Curvilinear distances along the filaments could have been used instead of the Euclidean distance, but the adoption of such a measure would have led to similar conclusions.

APPENDIX B: THE IMPACT OF COSMIC BOUNDARIES

It was stated in Sections 4.2.1 and 4.3 that the measured gradients towards filaments (Figures 6 and 7) and walls (Figures 9 and 10) are not simply due to gradients towards nodes in the former and due to gradients towards nodes and filaments in the latter case. This Appendix presents the performed tests that allowed us to reach such a conclusion.

B1 Gradients towards filaments

Let us start by considering the gradients towards filaments. In order to probe these gradients without being substantially contaminated by the contribution from nodes, galaxies that are closer to nodes than 3.5 Mpc are removed from the analysis. The choice of this distance $D_{\text{node}}^{\min}$ is motivated by the compromise between eliminating the most of the gradient coming from nodes while keeping enough objects to have a statistically significant sample. Note that the distance of 3.5 Mpc is greater than the typical size of groups, which is $\sim 1.5$ Mpc in the redshift range considered in this work, measured as a median (or mean) projected group radius. The value of median (and mean) is insensitive to the definition of the group radius (see Robotham et al. 2011, for various definitions considered).

In Figure A1, the solid lines show the mass gradients towards filaments for the entire sample (left panel) on the one hand and after excluding galaxies with distances to the node $D_{\text{node}} \leq 3.5$ Mpc (right panel).

In addition, following Laigle et al. (2017), it can be shown that in the regions sufficiently faraway from nodes, gradients towards nodes and those towards filaments are independent. It was checked that the mass gradients towards nodes, present for the entire galaxy sample, are substantially reduced once galaxies for which distances to the node $D_{\text{node}} \leq 3.5$ Mpc are excluded. This time, the distances to the node, $D_{\text{node}}$, were randomised in bins of distances to the filament, $D_{\text{skel}}$, i.e. by construction, gradients towards filaments were preserved. Again, 20 samples were constructed using 20 equipopulated logarithmic bins. After reshuffling, weak gradients at the level of at most 1σ are still present, but note that additional increase in $\Delta M_*$ does not reduce them further.

This analysis allows us to conclude that by removing from our sample galaxies that are closer to nodes than 3.5 Mpc, the impact of nodes to the measured gradients towards filaments is minimised, and even if weak gradients towards nodes still exist, these are independent of gradients towards filaments, i.e. gradients towards filaments and gradients towards nodes can be disentangled.
instead (as illustrated in Figure 4). This alternative choice of the
distance does not alter our conclusions. Secondly, instead of using
distances to the node \(D_{\text{node}}\), one could have considered dis-
tances normalised by the redshift-dependent mean inter-galaxy sep-

tation, \(D_{\text{node}}/\langle D_z \rangle\). These two approaches give consistent results

not only qualitatively, but also quantitatively.

### B2 Gradients towards walls

As with filaments, when measuring the gradients towards walls, one
should investigate whether the gradient is not dominated by
other component of the environments. As filaments are regions
where walls intersect, these represent on top of nodes an addi-
tional source of contamination for the measured gradients towards
walls. Figure B1 shows the mass gradients towards walls for the
galaxy sample outside the zone of influence of nodes parametris-
ed by \(d_{\text{min}}^{\text{node}} = 3.5\) Mpc (left panel) and after applying an additional cri-
terion by excluding galaxies with distances to the closest filament
\(D_{\text{skel}} \leq d_{\text{min}}^{\text{skel}}\), with \(d_{\text{min}}^{\text{skel}} = 2.5\) Mpc (right panel). The contribu-
tion of filaments to the mass gradients towards walls is measured
by randomising distances to the wall, \(D_{\text{wall}}\), in bins of distances to the
filament, \(D_{\text{skel}}\). By construction, the gradients towards fil-
aments are preserved. Here 20 samples are constructed in each of
which the reshuffling method is applied in 20 equipopulated loga-

tithmic bins. As shown by the dashed lines in Figure B1 and values
of medians listed in Table F2, the reshuffling cancels the gradients
towards walls for \(d_{\text{min}}^{\text{skel}} = 2.5\) Mpc.

Following the method used in Appendix B1 it was verified (but
not shown here) that the mass gradients towards filaments after ran-

domisation of the distances \(D_{\text{skel}}\) in bins of distances to the nearest

wall \(D_{\text{wall}}\) are substantially reduced. Only a very weak mass gra-
dient (at a \(1\sigma\) level at most) is detected after randomisation even
for \(d_{\text{min}}^{\text{skel}} = 2.5\) Mpc. Similarly to what was found in Section B1,

increasing this parameter does not induce any substantial reduction of
the gradient. Thus this distance was chosen as the limit for the
exclusion region around filaments.

### APPENDIX C: SMALL SCALE DENSITY-COSMIC WEB RELATION

In this Appendix, the impact of the small-scale density estimator on

the mass and type/colour gradients is presented. The density used
here is DTFE, i.e. the density computed at the smallest possible scale.\(^{10}\) As in the Section 6, the reshuffling and
density-matching, are applied.

Figure C1 shows the differential distributions of the distances

to the nearest filament, \(D_{\text{skel}}\) (normalised by \(\langle D_z \rangle\), for the same se-
lections as in Figure 12. The contribution of the nodes to the mea-
sured signal is minimised, by removing from the analysis galaxies
located closer to a node than 3.5 Mpc. Star-forming and passive

galaxies have been matched in mass, as described in Appendix A1.
The vertical lines indicate the medians of the distributions, whose
values together with the error bars are listed in Table F3.

In Figure (a), the mass and type gradients are shown before

(solid lines, as in 12) and after (dashed lines) applying the reshu-
flying of galaxies in the bins of over-density \(1 + \delta\), where the num-
ber density corresponds to the DTFE density. The result conforms
to the expectations. The reshuffling does not remove the observed
mass and type/colour gradients, i.e. the distributions before and af-

ter the reshuffling are almost identical, suggesting that at the small

\(10\) There is no specific scale associated to the DTFE: it is a local adap-
tive method which determines the density at each point while preserving its
multi-scale character.
scale, traced by DTFE, the density and cosmic web are closely correlated through the small-scale processes.

Figure (b) illustrates the PDFs for samples that have been matched in over-density $1 + \delta$, as described in Appendix A2, where the density considered is DTFE. The density-matching technique yields qualitatively similar result than the above used reshuffling in that almost no mass and type gradients are detected when galaxies matched in the DTFE density.

Qualitatively same results are obtained for both methods when applied to the measurements of gradients with respect to the walls (not shown).

APPENDIX D: THE HORIZON-AGN SIMULATION

This Appendix is dedicated to presenting the large-scale cosmological hydrodynamical simulation HORIZON-AGN (Dubois et al. 2014). First, some of the main features of the simulation are briefly summarised. The reshuffling method is then implemented on the simulation, as defined in Section 6, and shown to yield qualitatively similar results to those obtained in GAMA for both large- and small-scale density tracers.

D1 Simulation summary

The detailed description of the HORIZON-AGN simulation\footnote{http://www.horizon-simulation.org} can be found in Dubois et al. (2014), here only its brief summary is given. The cosmological parameters used in the simulation correspond to those found in Dubois et al. (2014), here only its brief summary is given. H$_0$ = 70.4 km s$^{-1}$ Mpc$^{-1}$, and $n_s = 0.967$ compatible with the WMAP-7 data (Komatsu et al. 2011).

The simulation was run with the Adaptive Mesh Refinement code RAMSES (Teyssier 2002) in a box of length $L_{box} = 100$ Mpc containing $10^{25}$ dark matter (DM) particles, with a DM mass resolution of $M_{DM, res} = 8 \times 10^7 M_\odot$, and initial gas resolution of $M_{gas, res} = 1 \times 10^7 M_\odot$.

The collisionless DM and stellar components are evolved using a particle-mesh solver. The dynamics of the gaseous component are computed by solving Euler equations on the adaptive grid using a second-order unsplit Godunov scheme.

The refinement is done in a quasi-Lagrangian manner starting from the initial coarse grid down to $\Delta x = 1$ proper kpc (seven levels of refinement) as follows: each AMR cell is refined if the number of DM particles in a cell is more than eight, or if the total baryonic mass in a cell is eight times the initial DM mass resolution code. This results in a typical number of $7 \times 10^9$ gas resolution elements (leaf cells) in the HORIZON-AGN simulation at $z = 0$.

Heating of the gas from a uniform UV background takes place after redshift $z_{reion} = 10$ following Haardt & Madau (1996). Gas is allowed cool down to $10^4$ K through H and He collisions with a contribution from metals using a Sutherland & Dopita (1993) model.

The conversion of gas into stars occurs in regions with gas density exceeding $\rho_g = 0.1$ H cm$^{-3}$ following the Schmidt (1959) relation of the form $\dot{\rho}_* = 1.0 \epsilon_s (\rho_g/\rho_{crit})^\alpha$, where $\dot{\rho}_*$ is the star formation rate density, $\rho_{crit}$ the gas mass density, $\epsilon_s = 0.02$ the constant star formation efficiency, and $\rho_{crit}$ the local free-fall time of the gas.

Feedback from stellar winds, supernovae type Ia and type II are included into the simulation with mass, energy and metal release. HORIZON-AGN simulation takes also into account the formation of black holes (BHs) that can grow by gas accretion at a Bondi-Hoyle-Lyttleton rate capped at the Eddington accretion rate when
they form a tight enough binary. The AGN feedback is a combination of two different modes (the so-called quasar and radio mode) in which BHs release energy in the form of heating or jet when the accretion rate is respectively above and below one per cent of Eddington, with efficiencies tuned to match the BH-galaxy scaling relations at $z = 0$ (see Dubois et al. 2012a, for details).

Galaxies are identified using the updated method (Tweed et al. 2009) of the AdaptaHOP halo finder (Aubert et al. 2004) directly operating on the distribution of stellar particles. Only galactic structures with a minimum of $N_{\text{min}} = 100$ stellar particles are considered, which typically selects objects with masses larger than $2 \times 10^8 M_\odot$.

D2 Density reshuffling

Let us finally present the impact of the reshuffling method, as defined in Section 6, and the choice of the density tracer in the HORIZON-AGN simulation.

Figure D1 illustrates that the result of reshuffling depends on the scale at which the density is computed. As expected, when using the small-scale density tracer, such as e.g. the DTFE density (Figure a), both mass and sSFR gradients are almost unchanged, while on sufficiently large scales, the gradients tend to cancel out (Figure b). The numerical value of the scale at which this happens is $\sim 5$ Mpc. This is again in a qualitative agreement with the scale required in the GAMA survey, corresponding to the $\sim 1.5 \times$ mean inter-galaxy separation.
Galaxy evolution in the metric of the Cosmic Web

Figure D1. Top rows: As in Figure 11 for the distances to the nearest filament, $D_{\text{skel}}$. The contribution of the nodes is minimized by removing galaxies located within 3.5 Mpc around them from the analysis. The dashed lines correspond to the distributions after the application of the reshuffling method using two different density tracers, a large (Figure a) and small-scale (Figure b) estimators. The numerical values of medians, shown as a vertical line, are listed in Table F4. In qualitative agreement with the results obtained with the observed data, in order to cancel the gradients, density at sufficiently large scale has to be considered. This corresponds to 5 Mpc in the HORIZON-AGN simulation, representing $\sim 1.5\times$ mean inter-galaxy separation, again in agreement with the value found in observations. Bottom rows: As in Figure 11 before (solid lines) and after (dashed lines) the reshuffling.

APPENDIX E: GRADIENT MISALIGNMENTS

In the context of conditional excursion set theory subject to a saddle $\mathcal{S}$ at some finite distance $(r, \theta, \phi)$ from a forming halo, let us consider the Hessian of the potential, $q_{ij} \equiv \partial^2 \psi / \partial r_i \partial r_j$, smoothed on the saddle scale $R_S$ and normalized so that $\langle |q|^2 \rangle = 1$. The anisotropic shear is given by the traceless part $q_{ij}^\ast \equiv q_{ij} - \delta_{ij} \text{tr} q/3$, which deforms the region by slowing down or accelerating the collapse along each axis. At finite separation, this traceless shear modifies in an anisotropic way the statistics of the smooth mean density (and of its derivative with respect to scale). The variations are modulated by $Q = \sum_{i,j} \tilde{r}_i \delta_{ij} f_j$, with $\tilde{r}_i = r_i/r$, i.e. by the relative orientation of the separation vector, $r$, in the frame set by the tidal tensor of the saddle. This extra degree of freedom, $Q(\theta, \phi)$, provides a supplementary vector space, beyond the radial direction, over which to project the gradients, with statistical
weight depending on each specific observable (mass, accretion rate, etc.). These quantities have thus potentially different iso-surfaces from each other and from the local mean density, a genuine signature of the impact of the traceless part of the tidal tensor. Indeed, for each observable, the conditioning on \( S \) introduces a further dependence on the geometry of the environment (the height of the saddle and its anisotropic shear \( \tilde{q}_{ij} \)) and on the position \( r \) of the halo with respect to the saddle point. This dependence arises because the saddle point condition modifies the mean and variance of the stochastic process \( (\delta, \theta, \varphi) \) – the height and slope of the excursion set trajectories – in a position-dependent way, making it more or less likely to form halos of given mass and assembly history within the environment set by \( S \). The expectation of the process becomes anisotropic with respect to the saddle point. This dependence arises because the saddle point condition modifies the mean and variance of the stochastic process \( (\delta, \theta, \varphi) \). The companion paper (Musso et al. 2017) shows that the Taylor expansion in the anisotropy for the angular variation, \( Q \), of \( M_* \) and \( M_* \) at fixed distance \( r \) from the saddle scales like

\[
\Delta M_* \propto \xi(r) \bar{Q}(\theta, \phi), \tag{E2}
\]

and

\[
\Delta M_* \propto \begin{bmatrix} \xi(r) - \frac{\sigma}{\sigma^2 - \xi} \xi \end{bmatrix} \bar{Q}(\theta, \phi), \tag{E3}
\]

in terms of the variance

\[
\sigma^2(M) = \int \frac{k^2 P(k)}{2\pi^2} W^2(kR), \tag{E4}
\]

and the radius dependent vectors

\[
\xi(r) = \{\xi_0(r), \sqrt{3} \xi_{11}(r) r/R_5, \sqrt{5} \xi_{20}(r)\}, \tag{E5}
\]

\[
\xi'(r) = \{\xi'_{00}(r), \sqrt{3} \xi'_{11}(r) r/R_5, \sqrt{5} \xi'_{20}(r)\}, \tag{E6}
\]

where

\[
R_5^2 \equiv \int dk \frac{P(k)}{2\pi^2} \frac{W^2(kR_5)}{\sigma_S^2}, \tag{E7}
\]

with \( P(k) \) the underlying power spectrum, \( W(k) \) the top-hat filter in Fourier space, \( \sigma_S = \sigma(R_S) \), while the finite separation correlation functions, \( \xi_{\alpha\beta}(r, R, R_S) \) and \( \xi'_{\alpha\beta}(r, R, R_S) \) are defined as

\[
\xi_{\alpha\beta}(r, R, R_S) \equiv \int dk \frac{k^2 P(k)}{2\pi^2} W(kR) \frac{W(kR_S) J_0(kr)}{\sigma_S}, \tag{E8}
\]

\[
\xi'_{\alpha\beta}(r, R, R_S) \equiv \int dk \frac{k^2 P(k)}{2\pi^2} W'(kR) \frac{W'(kR_S) J_0(kr)}{\sigma_S}, \tag{E9}
\]

where \( J_0(x) \) are the spherical Bessel functions of the first kind and prime denote derivative with respect to \( \sigma \). Note that Equation (E3) clearly highlights the shifted variance, \( \sigma^2 - \xi : \xi \) which contributes to the difference between \( \Delta M_* \) and \( \Delta \dot{M}_* \). From Equation (E3), since the square bracket is not proportional to \( \xi_{20} \) as in equation (E2), it follows that the cross product in Equation (E1) is non zero, which in turn implies that the contours of mass and accretion rate differ.

**APPENDIX F: MEDIANS OF DISTRIBUTIONS**

This Appendix gathers Tables of medians with corresponding error bars used in previous sections.
**Table F1. Medians of $D_{\text{skel}}/\langle D_s \rangle$ for Figure A1**

| selection<sup>a</sup> | mass bin | median<sup>b</sup> $D_{\text{skel}}/\langle D_s \rangle$ before reshuffling<sup>c</sup> | after reshuffling<sup>c</sup> |
|------------------------|----------|-------------------------------------------------|-----------------|
| all galaxies           | log ($M_*/M_\odot$) $\geq$ 11 | 0.27 ± 0.01 | 0.33 ± 0.02 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.36 ± 0.01 | 0.37 ± 0.01 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.40 ± 0.01 | 0.38 ± 0.01 |
| $D_{\text{node}}$ = 3.5 Mpc | log ($M_*/M_\odot$) $\geq$ 11 | 0.38 ± 0.01 | 0.46 ± 0.02 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.46 ± 0.01 | 0.47 ± 0.01 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.51 ± 0.01 | 0.47 ± 0.01 |

<sup>a</sup> panels of Figure A1  
<sup>b</sup> medians of distributions as indicated in Figure A1 by a vertical lines; errors are computed as in Table 1  
<sup>c</sup> randomisation of $D_{\text{skel}}$ in bins of $D_{\text{node}}$

**Table F2. Medians of $D_{\text{wall}}/\langle D_s \rangle$ for Figure B1**

| selection<sup>a</sup> | mass bin | median<sup>b</sup> $D_{\text{wall}}/\langle D_s \rangle$ before reshuffling<sup>c</sup> | after reshuffling<sup>c</sup> |
|------------------------|----------|-------------------------------------------------|-----------------|
| $D_{\text{node}}$ = 3.5 Mpc | log ($M_*/M_\odot$) $\geq$ 11 | 0.234 ± 0.005 | 0.258 ± 0.011 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.279 ± 0.003 | 0.278 ± 0.005 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.295 ± 0.003 | 0.292 ± 0.004 |
| $D_{\text{node}}$ = 3.5 Mpc, $D_{\text{node}}$ = 2.5 Mpc | log ($M_*/M_\odot$) $\geq$ 11 | 0.334 ± 0.007 | 0.379 ± 0.028 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.381 ± 0.004 | 0.386 ± 0.011 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.403 ± 0.004 | 0.398 ± 0.008 |

<sup>a</sup> panels of Figure B1  
<sup>b</sup> medians of distributions as indicated in Figure B1 by a vertical lines; errors are computed as in Table 1  
<sup>c</sup> randomisation of $D_{\text{wall}}$ in bins of $D_{\text{node}}$

**Table F3. Medians for the PDFs displayed in Figure C1: small-scale density**

| selection<sup>a</sup> | bin | median<sup>b</sup> $D_{\text{skel}}/\langle D_s \rangle$ matching<sup>c</sup> |
|------------------------|-----|-------------------------------------------------|-----------------|
| All galaxies           | log ($M_*/M_\odot$) $\geq$ 11 | 0.379 ± 0.009 | 0.378 ± 0.01 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.456 ± 0.007 | 0.453 ± 0.009 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.505 ± 0.006 | 0.495 ± 0.006 |
| SF galaxies            | log ($M_*/M_\odot$) $\geq$ 10.8 | 0.459 ± 0.012 | 0.489 ± 0.016 |
|                        | 10.8 > log ($M_*/M_\odot$) $\geq$ 10.3 | 0.534 ± 0.007 | 0.541 ± 0.006 |
|                        | 10.3 > log ($M_*/M_\odot$) $\geq$ 9.92 | 0.578 ± 0.007 | 0.567 ± 0.007 |
| Types                  | star-forming | 0.504 ± 0.008 | 0.493 ± 0.006 |
|                        | passive | 0.462 ± 0.007 | 0.458 ± 0.007 |

<sup>a</sup> panels of Figure C1  
<sup>b</sup> medians of distributions as indicated in Figure C1 by a vertical lines; errors are computed as in Table 1  
<sup>c</sup> randomisation of $D_{\text{skel}}$ matching small-scale density with $D_{\text{skel}}$

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**Table F4. Medians of $D_{\text{skel}}/\langle D_s \rangle$ for Figure D1**

| selection<sup>a</sup> | mass bin | median<sup>b</sup> $D_{\text{skel}}/\langle D_s \rangle$ before reshuffling<sup>c</sup> | after reshuffling<sup>c</sup> |
|------------------------|----------|-------------------------------------------------|-----------------|
| all galaxies           | log ($M_*/M_\odot$) $\geq$ 11 | 0.27 ± 0.01 | 0.33 ± 0.02 |
|                        | 11 > log ($M_*/M_\odot$) $\geq$ 10.7 | 0.36 ± 0.01 | 0.37 ± 0.01 |
|                        | 10.7 > log ($M_*/M_\odot$) $\geq$ 10.46 | 0.40 ± 0.01 | 0.38 ± 0.01 |

<sup>a</sup> panels of Figure D1  
<sup>b</sup> medians of distributions as indicated in Figure D1 by a vertical lines; errors are computed as in Table 1  
<sup>c</sup> randomisation of $D_{\text{skel}}$ in bins of $D_{\text{node}}$
Table F4. Medians for the PDFs displayed in Figure D1

| selection$^a$ | bin | median$^b$ $D_{skel}$ [Mpc] | after reshuffling$^d$ |
|---------------|-----|-----------------------------|-----------------------|
|               |     | original$^c$ | DTFE | G5Mpc |
| Mass          |     |               |     |       |
| $\log (M_*/M_\odot) \geq 10.8$ | $1.34 \pm 0.09$ | $1.26 \pm 0.08$ | $1.72 \pm 0.1$ |
| $10.8 > \log (M_*/M_\odot) \geq 10.4$ | $1.73 \pm 0.08$ | $1.71 \pm 0.06$ | $1.82 \pm 0.06$ |
| $10.4 > \log (M_*/M_\odot) \geq 10$ | $1.97 \pm 0.04$ | $2.0 \pm 0.05$ | $1.86 \pm 0.04$ |
| sSFR          |     |               |     |       |
| $-10.8 > \log (sSFR/yr)$ | $1.46 \pm 0.07$ | $1.61 \pm 0.07$ | $1.74 \pm 0.08$ |
| $-10.4 > \log (sSFR/yr) \geq -10.8$ | $1.88 \pm 0.06$ | $1.89 \pm 0.06$ | $1.81 \pm 0.06$ |
| $\log (sSFR/yr) \geq -10.4$ | $2.0 \pm 0.04$ | $1.9 \pm 0.05$ | $1.91 \pm 0.06$ |

$^a$ panels of Figure D1

$^b$ medians of distributions as indicated in Figure D1 by a vertical lines; errors are computed as in Table 1

$^c$ as in Table 2 for $D_{skel}$ (corresponding to the solid lines in Figure D1)

$^d$ reshuffling is done in the bins of the DTFE density and the density computed at the scale of 5 Mpc (corresponding to the dashed lines in Figures a and b, respectively)