We introduce an algorithm aimed to identify large-scale filaments founded on the conception that these structures are bridges of matter that connect high density peaks. Our method is based on two standard tools, the Minimal Spanning Tree (MST) and the Friends of Friends (FoF) algorithm. Briefly, the complete process consists of five stages. Initially, we use the FoF algorithm to select intermediate density regions to stave off underdense zones (voids). Next, we build the MST by restricting it only to the regions defined in the previous step. Then the tree is pruned according to the length of its branches keeping the most dominant and discarding the more tenuous ones. Finally, the filaments are individualised according to the mass of the ends and smoothed using a B-spline fitting routine.

To assess the results of the filament finder we apply it to a cosmological simulation. By focusing our analysis on those filaments whose halos at the ends have large masses, we found that the radial density profile, at scales around $1h^{-1}\text{Mpc}$, follow a power law function with index -2. Even though the method only relies on halo positions, it is capable to recover the expected velocity field in filamentary structures. Large infall velocities coming from low density environment approach perpendicularly to the filaments and diverges toward to the ends. By studying the transverse velocity dispersion, we estimate the dynamical linear density following Eisenstein et al. (1997), finding a good correspondence between that and the actual mass per unit length of the filaments.

Key words: methods: numerical, methods: statistical, large-scale structure of the Universe - Numerical Simulations

1 INTRODUCTION

The distribution of matter in the Universe at large scales forms a complex pattern that is known as the cosmic web (Bond et al. 1996). It is composed of dense compact clusters, elongated filaments, sheetlike walls and low density regions called voids. The most prominent and defining features of the cosmic web beyond the halos are the filaments (van Haarlem & van de Weygaert 1993; Colberg et al. 1999). They are the key to understand how the material is gradually transported and assembled towards the knots within the cosmic web (Bond et al. 2010; González & Padilla 2010; Aragón-Calvo et al. 2010; Cautun et al. 2014; Libeskind et al. 2018).

The study and characterisation of filaments are interesting for different reasons. The cosmological simulations reveal the role of filaments over their environment. Several authors confirm the influence of these structures on the alignment of the angular momentum and the shape of dark matter halos and their large-scale surrounding. (Altay et al. 2006; Hahn et al. 2007a,b; Aragón-Calvo et al. 2007b; Zhang et al. 2009; Libeskind et al. 2013; Aragón-Calvo & Yang 2014; Ganeshaiah Veena et al. 2018, 2019). Studies based on galaxy catalogs show evidence of correlations between the orientation and/or shape of the galaxies and the spine of the nearby filaments. (Jones et al. 2010; Tempel et al. 2013; Tempel & Libeskind 2013; Zhang et al. 2013, 2015; Chen et al. 2019). The analysis of properties of galaxies at low and high redshift shows that the fraction of passive galaxies increases with decreasing distances to the spine of filaments and nodes of the cosmic web (e.g. Martínez et al. 2016; Alpaslan et al. 2016; Malavasi et al. 2017; Chen et al. 2017; Kraljic et al. 2018; Laigle et al. 2018; Salerno et al. 2019). In addition, the filamentary network plays an important role in the evolution of groups and their central galaxies (Poudel et al. 2017). Guo et al. (2015) found that groups in filaments have more
satellites than those that are outside of filamentary environments. Following this work, Tempel et al. (2015) explored the alignment of satellite galaxies with respect to filaments, finding that the satellites tend to be aligned with them. They suggest that the alignment signal may be a consequence of how satellites accrete matter via streams along the direction of the filaments.

In this context, filament identification plays a fundamental role in conducting these studies. However, the detection of these objects represents a great challenge due to the complexity of their interconnected structures, as well as the wide range of densities found in their distribution of matter. Different techniques have been recently developed in the literature for this purpose e.g. the Multiscale Morphology Filter (Aragón-Calvo et al. 2007a), FINE (González & Padilla 2010), Bisous model (Stoica et al. 2010; Tempel et al. 2014), DisPerSE (Sousbie 2011; Sousbie et al. 2011), NEXUS/NEXUS+ (Cautun et al. 2013). Adapted Minimal Spanning Tree (Alpaslan et al. 2014), SCMS (Chen et al. 2015), MultiStream Web Analysis (Ramachandra & Shardar 2015). A comprehensive comparison of different filament finding methods can be found in (Libeskind et al. 2018). Most of these methods perform a reconstruction of the underlying density field and/or the velocity field that this induces, which makes them very effective in detecting different types of structures. These algorithms are usually quite sensitive to the specific density field reconstruction method, which can be computationally expensive and also makes them difficult to implement in observational data sets.

Based on the assumption that filaments are bridges of matter linking high density peaks, we introduce a new method for filament detection. This algorithm is based on the graph construction known as minimal spanning tree (MST, hereafter) and the friend of friend (FoF, hereafter).

The organisation of this paper is as follows: in §2 we describe in detail the filaments identification method, which we have called Semita1. Afterwards, in §3, we apply this filament finder on a dark matter only cosmological simulation and analyse global properties of the extracted structures. In §4 we study dynamical and structural properties focusing our analysis on the stacked density field and the transverse velocity dispersion. Finally, we summarise our results and discuss future works in §5.

2 METHOD

In this work we will adopt the general definition of filaments embraced by several authors (Pimbblet 2005; Colberg et al. 2005; González & Padilla 2010; Martínez et al. 2016) according to whom the filaments are bridges of matter that connect high density peaks (cluster-cluster bridges). In order to analyse the results of our finding algorithm, we will focus our method on cosmological numerical simulations using dark matter halos as tracers of matter.

The proposed algorithm has five steps:

- Apply a FoF algorithm to extract the halos and the intermediate density regions in which the filaments are embedded.
- Use the MST technique to link the halos restricting us to the intermediate density regions.
- Prune the tree to remove minor branches.
- Select filaments chopping the branches according to the mass of the halos at their ends.
- Smooth the spine of each filament using B-spline technique.

Below we describe in detail each one of these procedures.

2.1 Friends-of-friends algorithm

As mentioned above, we use halos as mass tracers, consequently, the first step of our method is to identify the halos in the simulation. For this purpose we use a FoF algorithm which puts into a single group all particles linked in pairs whenever their separation is less than a certain value (linking length). In our case, we select regions with an overdensity \( \delta = 200 \) (with \( \delta = \rho/\bar{\rho} - 1 \) where \( \rho \) is the local density and \( \bar{\rho} \) is the mean density of the universe) which corresponds to the overdensity of a virialized halo and is associated to a standard linking length of \( l_t = 0.17 n^{-1/3} \), where \( n \) is the mean number density of particles in the simulation. The most relevant of this stage is the application of the FoF to extract intermediate density regions corresponding to an overdensity of \( \delta = 1 \) (linking length \( l_t = 0.79 n^{-1/3} \)) which is larger than the overdensity associated to the walls (\( \delta \approx 0.4 \). (Cautun et al. 2013)) but much smaller than that related to the halos or filaments. The purpose of this run is to avoid those regions of very low density.

2.2 Minimal Spanning Tree

The MST is a technique borrowed from graph theory. In this work, we follow the definitions of Barrow et al. (1985) which were also previously used by other authors (see e.g. Colberg 2007; Park & Lee 2009; Alpaslan et al. 2014). A graph \( G \) is a collection of nodes and edges (straight lines that join nodes) each of which has an associated weight, edges (straight lines joining nodes), and weights for each of these edges. A spanning tree of \( G \) is defined as a network connecting all the nodes on the graph. The MST is the unique tree (if there are not two equal weights) connecting all the nodes in \( G \) so that the sum of weights is minimal and there are no closed loops on it.

A key property of the MST scheme is the degree of a given node, which is defined as the number of edges incident to the node. Another important concept is the definition of a \( k \)-branch. It is defined as a path of \( k \) edges connecting a node of the degree 1 with another one of degree 3 or more, with all intermediate nodes of degree 2.

We will use the FoF halos as the nodes of the graph \( G \). In order to define the edges of that graph, we construct a Voronoi tessellation of the simulation volume based on the positions of the nodes. For each FoF halo, we look for his Voronoi neighbours within the same intermediate density regions associated with the linking length \( l_t \). The Voronoi tessellation over nodes is computed using the public library VORO++ (Rycroft 2009). Since the main physical process

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1 named after the Latin word for “a path”
involved in the formation and evolution of the filaments is gravity, we decided to use a Newtonian form for the weight:

$$w_{12} = \frac{M_1 \cdot M_2}{r_{12}^2}$$  (1)

Even though this weight is not derived from first principles, the criterion behind this choice is to emphasise the relative importance of the most massive and closest nodes. At this point it is worth mentioning that, strictly speaking, we have an MST for each intermediate density region, but for simplicity, we will continue our description as if there is only one MST, since each of these regions are disjoint.

The MST of graph $G$ is constructed employing the Kruskal’s algorithm (Kruskal 1956). Briefly, we arrange the edges of $G$ by its weight in increasing order. After that, we sequentially select the lightest edge that do not produce closed loops on the tree. Under the hypothesis that there are not two equal weights, which is a good assumption in our case, the selected edges represent the unique MST.

### 2.3 Pruning, classification and smoothing of filaments

Most massive halos ($M > 10^{14} h^{-1} M_\odot$) are classified as residing in knot environments. These halos are usually connected by the most prominent filaments (Colberg et al. 2005; González & Padilla 2010; Aragón-Calvo et al. 2010; Libeskind et al. 2018). Therefore, taking into account these considerations we use the threshold mass $M_{th} = 10^{13} h^{-1} M_\odot$ to characterise our filaments. To delineate the final structure, we process the MST by pruning the minor branches. By definition we say that a tree is "pruned" to level $p$ when all $k$-branches with $k \leq p$ have been removed. In this work, we pruned our MST to level $p = 4$. This "pruning" method allows us to remove the minor branches that weakly contribute to the main filamentary pattern. It should be emphasised that we avoid pruning those branches that contained a halo with a mass greater than or equal to $M_{th}$. Due to this restriction, values larger than $p = 4$ do not cause significant modifications.

Once the pruning process is applied, we individualise the different branches according to the mass of the halos at their ends. To do this, we first trim those paths of the MST that connect two halos with masses greater than $M_{th}$ (type-2 filaments). Next, from the remaining tree, we extract those paths that connect the nodes of grade 1 with the nodes $M_{th}$ (type-1 filaments). Finally, all remaining branches are classified as type-0 filaments. Note that by construction, the identified filament network does not have intermediate halos with mass greater than or equal to $M_{th}$.

At this point we already have a catalogue of individualised filaments but since they are forced to pass through all the nodes, the filaments are rather uneven. Consequently, we use a order 3 B-spline fitting routine from the FITPACK library (Dierckx 1993) to define the spine of the filament. This is a curve that connects the halos at the ends and passes near all the intermediate nodes in the filament path. Fig. 2 illustrates one of the type-2 detected filaments represented as a tube of $1 h^{-1} \text{Mpc}$ radius following the spine of the filament.

A schematic view of our identification method can be seen on figure 1. Upper-left panel shows a slice of $10 h^{-1} \text{Mpc}$, for clarity, we display only 1% of the dark matter particles of the intermediate density region. In the upper-right panel we show (blue lines) the MST built in this slice. As expected, there are more edges close to the high density peaks, since, by construction, the MST links all the nodes within this
intermediate density region. The lower-left panel emphasises the role of pruning of the MST. In general, it can be seen that the main filamentary structure is maintained, while most minor branches have been removed. Finally, in the lower-right panel shows the individualised and smoothed filaments, in red, green and blue lines, corresponding to types -2, -1 and -0, respectively.

3 PROPERTIES OF FILAMENTS

3.1 Data

In this work we use the last snapshot (redshift zero) of a dark matter only simulation of 1600$^3$ particles in a periodic box of 400$h^{-1}\text{Mpc}$ side with cosmological parameters $\Omega_m = 0.31$ and $\Omega_\Lambda = 0.69$ and $h = 0.68$ given by Planck Collaboration results (Planck Collaboration et al. 2018). The particle mass resolution is $1.18 \times 10^6 h^{-1}M_\odot$, the force resolution is $7.68 h^{-1}\text{Kpc}$ and the normalisation parameter is $\sigma_8 = 0.811$. The simulation was evolved using the public version of GADGET-2 code (Springel 2005).

We identified approximately $6.8 \times 10^6$ dark-matter halos with at least 20 particles using a FoF algorithm with a linking length $l_\text{f}$ (see §2.1). The resulting halos distribution is characterised by a minimum mass of $M_{\text{min}} = 2.36 \times 10^{10} h^{-1} M_\odot$, and a maximum mass of $M_{\text{max}} = 1.57 \times 10^{15} h^{-1} M_\odot$. We have a total of 22574 halos with $M > 10^{11} h^{-1} M_\odot$. The mass contained inside $l_2$ regions represents approximately 70% of the total mass.

3.2 Global properties of filaments

In this section, we present an analysis of the global properties of our filaments, separated according to the defined types. For this purpose we define four basic properties for each filament: length, elongation, quotient between the masses of the halos at the ends and the mass. Length is the most basic and general property of the filaments, and we define it as the sum of the lengths of all smoothed edges that constitute the filament. Hereafter, we will only consider filaments longer than $10 h^{-1}\text{Mpc}$ and shorter than $100 h^{-1}\text{Mpc}$. The upper-left panel of fig. 3 shows the length distributions for filaments type-0, -1 and -2 in blue, green and red colours respectively. Given the hierarchical nature of the large scale structure formation, it is expected that type-0 filaments dominate in number as shown in the figure. The total sample distribution (black histogram) exhibit the same exponential behaviour found by Bond et al. (2010); Tempel et al. (2014) for the SDSS data set and González & Padilla (2010) for dark matter simulations.

The next property is the elongation, defined as the ratio of the distance between the ends and the length of the filament. By construction, this is a dimensionless parameter, and its values range between 0 and 1. The straight filaments have an approximate elongation value of 1, whereas twisted filaments have values close to 0. The upper right panel of fig. 3 shows that type-0 filaments are straighter than the other types. This is because these filaments are preferably shorter.

The third basic property we define is the quotient $q = M_1/M_2$, between the masses of the halos at the ends of the filament, with $M_2 > M_1$. This property is related with the saddle point of the filament, helping us to characterise it. The $q$ parameter distribution is shown at the bottom-left panel of fig. 3. As expected the number of filaments with small $q$ is larger for type-0.

Finally, the bottom-right panel of fig. 3 shows the mass distribution of filaments, which is estimated by counting the dark matter particles inside a tube with a radius of $2 h^{-1}\text{Mpc}$ (Colberg et al. 2005; Aragón-Calvo et al. 2010; González & Padilla 2010; Cautun et al. 2014) along the filament spine. Since the filaments by construction have massive halos at their ends, we decided to exclude the particles within two virial radius of them. As it can be seen, type-2 filaments are more massive than type-1. This is to be expected since type-2 filaments have two massive halos with mass greater than or equal to $M_2$ in their extremes and therefore, those filaments define the stronger bridges of the cosmic web.

Looking at the histograms of fig. 3, it can be seen that type-0 filaments are shorter and much less massive than the other types. This is expected since these filaments may have halos with masses as small as $M_{\text{min}} = 2.36 \times 10^{10} h^{-1} M_\odot$ at their ends. Therefore, they probably do not fit our definition of filament (cluster-cluster bridges). That is why we will not include them in our subsequent analyses.

An important feature that we can use to assess whether the identified objects are well defined structures is the average overdensity enclosure in a tube with a radius of $2 h^{-1}\text{Mpc}$. As can be seen in the left panel of fig. 4, the overdensities are typically around 10 for type-2 filaments (red dots) and this value is quite independent of the length, meanwhile type-1 filaments (green dots) present smaller values of $\delta$. This result is comparable with Cautun et al. (2014) that obtains similar results. For completeness and comparison, we also calculate the relationship between mass and length (right panel of fig. 4) which, as expected shows a linear positive dependence on length with a slope of approximately 1.3. Although this slope does not match that of Cautun et al. (2014) ($M \propto L^{1.2}$), it should be taken into account that the way of calculating the masses are completely different.

4 DYNAMICAL AND STRUCTURAL PROPERTIES OF FILAMENTS

In this section, we study the average density and velocity fields of the filaments by means of a stacking technique. As previously mentioned, type-2 filaments are the most significant bridges in the large scale structure, therefore, for the sake of clarity, hereafter we concentrate our studies on these filaments, even so, the results for type-1 filaments are similar. The coordinates of a particle tracer around a given filament will be given by two distances adapted to the geometry of the spine of the filament. One coordinate, denoted with $r$, is distance from the tracer particle to its closest point in the spine. The other coordinate, is the distance from this point to the less massive halo measured along the curved filament, indicated with $z$. The stacking technique simply consists in normalising $z$ to the length of the filament $l$ and averaging all the physical properties in bins in both $z/l$ and $r$ coordinates, for a given set of filaments. Since we are interested on volume-weighted quantities, we need to compute the volume of each bin. However, due to the wavy nature of filaments,
The normalised stacking plot for the overdensity (Fig. 5) shows the typical shape of a filament (e.g. Kraljic et al. 2019) with high-density peaks at the extremes, indicating the position of clusters, and a matter bridge linking them. The coloured contours represent the overdensity levels and the position of clusters, and a matter bridge linking them.

2019) with high-density peaks at the extremes, indicating

The two density peaks at the extremes of the filament are the most noticeable features in this figure. The nature of the stacking method leads the filaments to always have a massive halo at the ends, therefore it is expected the signal increases in these points. Meanwhile, the bridge of matter between them is formed by halos less massive than $M_{\delta}$ and diffuse matter whose signal is averaged in the stacking process. Even though the filaments are non-virialised and irregular structures, it can be observed that an overdensity of $\delta + 1 \approx 10$ encloses almost the filamentary structure, in good agreement with Cautun et al. (2013). In the direction perpendicular to the filament, the overdensity reaches values as high as $\delta + 1 = 100$ near the spine, decreasing to values of approximately $\delta + 1 \approx 1$ at distances greater than $5 \ h^{-1} \ Mpc$.

The signal shown on the left and right outside the filament reflects the nature of the cosmic web, in the sense that there are no isolated filaments, and the extremes are connected with other filamentary structures, which are diluted when stacked.

In addition to the normalised overdensity stacking we also calculate the radial density profile. It is estimated in concentric cylindrical shells around the spine of the filament.
in the coordinate space $z/l - r$. Figure 6 shows the density profile at 20 equal logarithmically spaced bins between 0.1 and 10.0 $h^{-1}$Mpc. The different curves represent the profile estimated for 4 subsamples of $\mu$, where $\mu = M/l$ is the mass per length unit, it is worth remembering that in the estimation of the filament mass the halos at the ends are excluded. The error bars are computed using the jackknife technique. The filaments with larger $\mu$ are denser towards the centre, while they are also wider. In agreement with previous works (Colberg et al. 2005; Dolag et al. 2006; González & Padilla 2010; Aragón-Calvo et al. 2010) in intermediate scales (0.5 to 2.0 $h^{-1}$Mpc), the profile approximately follows a $r^{-2}$ power law (solid grey line). As expected, on large scales, all the curves tend to the local background density of the Universe independently of $\mu$. It should be noted that despite the difference of amplitude between the four profiles, all shapes are similar. Comparing our density profile with those obtained by Cautun et al. (2013), it can be seen that our filaments show a similar behaviour to their larger diameter samples, nevertheless, our profiles are sharper towards the centre. As stated at the beginning of this section, we are showing results only for type-2 filaments, however it should be stressed that similar profiles to those showed in fig. 6 are obtained for type-1 filaments with slightly smaller amplitudes. The flattening towards the centre may not correspond to a physical property of the filaments, but rather could be related to the smoothing technique or to the difficulty of establishing a well defined axis in this type of such irregular objects.

### 4.2 Velocity field

The dynamical processes involved in filament formation have a key role in the genesis of properties of dark matter halos and galaxies (e.g. Jones et al. 2010; Codis et al. 2015; Laigle et al. 2018; Kraljic et al. 2018, 2019). This motivates us to characterise the velocity field around the filaments and, to do so, we will separate it into its parallel $v_\parallel$ and perpendicular $v_\perp$ components with respect to the spine of the filament. In the case of the perpendicular component, we will define as positive the direction that points away from the filament axis, while for the parallel component it will be the direction that points to the most massive halo. In order to subtract bulk motion, we refer all velocities to that of the centre of mass of the halos at the extremes of each filament.

As mentioned previously, the stream lines in fig. 5 show the stacked velocity field. There it can be seen that at large distances matter falls perpendicularly to the filaments and as it gets closer, its velocity decreases in magnitude and becomes parallel. In agreement with the scenario presented in previous works (e.g. Bond et al. 1996; Colberg et al. 2005; Aragón-Calvo et al. 2010; Kraljic et al. 2018, 2019), the flow of particles within the filaments moves towards the ends and the saddle point where the stream lines diverge towards the extremes can be neatly distinguished.

Figure 7 shows the parallel component of the average velocity field in quartiles of the $q$ parameter for filaments with length $\in (19.21, 30.88) h^{-1}$Mpc. The blue and red colours represent the negative and positive velocity component, respectively. The orange contour represents the iso-overdensity $\delta + 1 = 10$.
If the filaments are distribution of matter where the gravitational collapse occurs towards a line, it is expected that they generate a potential with the same geometric features, and therefore we should expect that, in the linear regime, the perpendicular component of the velocity increases towards the axis of the filament. The averaged perpendicular component of the velocity field is shown in fig. 8 where it can be seen that although at great distances there is a fall towards the filament when we approach to the axis, the average perpendicular velocity decreases due to the beginning of a virtualisation process. Another characteristic that can be observed in this figure is that the perpendicular infall does not depend on the parameter $q$, which would indicate that the gravitational potential would be determined by the mass of the filament itself and not by the halos at the ends. The high infall speeds away from the filaments are consistent with the expansion velocities at the boundaries of empty voids (Ceccarelli et al. 2013).

### 4.2.1 Saddle points

According to our definition of filament, these are a matter bridge that joins two high density peaks. From this definition it follows that at some point in the middle of the peaks there must be a saddle point where the density reaches a minimum and the velocities become divergent. This point plays an important role in the internal structure of the filaments, since it corresponds to the position of dynamic equilibrium along its spine (Pogosyan et al. 2009; Codis et al. 2015; Laigle et al. 2015; Kraljic et al. 2019) and that is why a variety of finding algorithms use this feature to identify filaments (Novikov et al. 2006; Sousbie et al. 2008). Our method makes no assumptions about this, and yet the saddle point arises naturally as observed in the above. It is expected that the position of this point depends on the parameter $q$ since the dynamics within the filament is affected by the halos at the ends. Figure 9 shows the relation between parameter $q$ and the distance from the less massive end of the filament to the saddle point for four samples of different lengths. As expected, there is a direct relationship between them and the saddle point approaches the centre of the filament as the mass of the ends resemble each other. In addition, this behaviour seems to be independent of length. The bars represent the errors estimated by the jackknife technique and the mean standard deviation for the position and the value of $q$, respectively. The position of the saddle point is estimated by inspecting the averaged parallel velocity field and looking for the point where there is a change in the sign of such velocity component.
4.2.2 Transverse velocity dispersion

As stated above, the filaments are structures that are in the process of formation and, therefore, have not yet reached dynamic equilibrium. They are not structures supported by the radial velocity dispersion as is the case with the halos. However, towards the centre of them, it can be seen that the dispersion of the velocity perpendicular to the axis is greater than in the surrounding regions, as can be seen in Figure 10. This can be explained mainly by two processes: (i) the filaments have a certain degree of virtualisation in the direction perpendicular to them; (ii) the dispersion of the velocity is due to the encounter between the material that is accreting in the filament and material that is making the first shell-crossing. In this complex scenario, both processes could be happening simultaneously. It should be noted that the filaments contain diffuse material as well as virialised halos.

In order to understand the nature and dynamic of filaments, Eisenstein et al. (1997) propose a theoretical relation to estimate, from observational data, the mass per unit length $\mu$ of filaments. Specifically, assuming that filaments are axisymmetric, isothermal structures virialised along the perpendicular direction, they found an analytical relation between $\mu$ and the transverse velocity dispersion $\sigma_z$ of the filaments.

$$\mu = \frac{\sigma_z^2}{G} = 3.72 \times 10^{13} \, \text{M}_\odot \, \text{Mpc}^{-1} \left(\frac{\sigma_z}{400 \, \text{km} \, \text{s}^{-1}}\right)^2$$

Equation 2 differs from equation 13 of these authors by a factor of 2, because their equation considers that the velocity dispersion is measured along a line-of-sight. Figure 11 shows the comparison between the true mass per unit length $\mu_{\text{true}}$ and the dynamical mass $\mu_{\text{dyn}}$ estimated using equation 2. The best linear fit and the identity relation are shown in solid and dashed lines, respectively. The value of $\mu_{\text{true}}$ is calculated as the quotient between the total mass inside a cylinder of radius $2h^{-1}\text{Mpc}$ along the filament spine and its total length. The different colour points represent these values for each type-2 filament on quartiles of length. As it can be seen, the relation is independent of the length of the filament.

Despite the assumptions made to deduce the equation, our results show a good agreement with the theoretical predictions. This would suggest that the filaments are partially virialised in the direction perpendicular to the axis. Strengthening this hypothesis, it is worth mentioning that the crossing time in the perpendicular direction of the filaments is shorter than the Hubble time. However, the data has a high dispersion, which may be due to the fact that the filaments, in general, do not have a regular cylindrical shape, as assumed to deduce the relationship 2. In addition, they are not relaxed structures but are continually disturbed by the infall of matter. Another effect that should be considered is the presence of substructure that tends to overestimate the mass of the filaments Eisenstein et al. (1997).

5 SUMMARY AND CONCLUSION

In this paper, we introduce a new algorithm to identify filaments in cosmological simulations. Briefly, our finding process consists of successively extracting branches of a Minimal Spanning Tree (MST) constructed from the Friends of Friends halos (FoF) identified in the simulation. To avoid false identifications, we restrict the tree to the regions enclosed by an overdensity $\delta = 1$. In this way, each filament is a contiguous path of halos embedded in those intermediate overdensity regions. To construct the filament catalogue, we additionally prune the MST keeping only those branches with order $k >= 4$ and apply a smoothing filter to the resulting paths.

Our algorithm individualises three types of filaments according to the mass at the ends. If both halos have masses greater than a given mass threshold ($M_a$), the filament is classified as type-2. We define a filament as type-1 if only...
one halo at the ends has a mass greater than the threshold, whereas if neither of the two halos exceed it we denote it as type-0. Accordingly to previous works (Colberg et al. 2005; González & Padilla 2010; Aragón-Calvo et al. 2010), we use in this work an $M_\text{th} = 10^{14} h^{-1} \text{M}_\odot$.

We analyse the performance of the algorithm by applying it over a cosmological box of $400 h^{-1} \text{Mpc}$ side and a mass resolution of $1.18 \times 10^9 h^{-1} \text{M}_\odot$. Our results show a good agreement with the general picture of the cosmic web where filaments are bridges of matter connecting high density peaks (cluster-cluster bridges) and delineate the underdense basins. The stacked density field of these structures shows a "thighbone-like" shape surrounded by a typical overdensity $\delta \approx 10$.

By construction, type-0 filaments are conformed by low mass halos, therefore in agreement with the hierarchical formation scenario, we found that they are typically short, straight, and more numerous structures of the filamentary network. On the other hand, type-2 filaments are the most dominant bridges of the cosmic web in agreement with previous works.

We find that the average overdensity within a $2 h^{-1} \text{Mpc}$ tube along the axis of these filaments has an approximately constant value over a wide range of lengths. Notwithstanding the dispersion around the mass-length relation is quite large, which may be since filaments do not follow a regular geometric shape, we found that this can be well described by a power-law $M \propto L^{1.3}$. The slope greater than 1 suggests that long filaments are well-defined structures instead of concatenated short filaments.

We measure the transverse density profile of filaments up to $10 h^{-1} \text{Mpc}$. It shows that filaments with larger linear density are thicker and denser towards the spine of filament. In intermediate scales, the density profile follows a $r^{-2}$ power law. Meanwhile, on large scales they asymptotically tend to the mean density value.

Although our method does not impose any restrictions on the velocity field, we are able to determine the location of the saddle point along the axis of the filaments, defined as the place where the velocity flow diverges. The vicinity of the saddle point is a region of particular interest because it is closely related to the rotation of dark matter halos, as well as to the processes of galaxy formation (Codis et al. 2015; Laigle et al. (2015); Kraljic et al. (2019); López et al. (2019)). This topic will be investigated in a forthcoming work.

The pattern showed by the streamlines of the velocity field shows the ideal scenario where matter flow from low density environments to the intermediate density of filaments, to ultimately infall into the halos at the ends. Even though it should be stressed that our results also indicate that the magnitude of the velocity field along filaments is significantly smaller than field in low density regions. In other words, most of the matter is accreted along filaments, however particles infalling into the halos directly form low density regions have the largest velocities (Ceccarelli et al. 2011). The analysis of the perpendicular component of the velocity field strengthens the idea that the filament produces a cylindrical-like potential since the average velocity values decrease towards the axis while the dispersion increases.

Although filaments are structures in a quasi-linear formation regime, we observed that at the centre of them the transverse velocity dispersion is higher than in the environment. This could be indicating that filaments have a certain degree of virtualisation. In this sense, we analyse the relationship between the transverse velocity dispersion and the linear density. We found a good agreement with the theoretical relation proposed by Eisenstein et al. (1997). The observed dispersion can be ascribed to different factors, e.g., filaments are not isolated nor are they smoothed structures, they have a wide range and varieties of substructures.

As a final remark, we stress that given the flexibility and simplicity of the methodology presented in this work, because we use dark matter halos as tracers of matter, our algorithm does not require any smoothing scale and it adapts well to even large cosmological simulations. As well as it can be extended with certain modifications, to identify filaments in galaxy catalogues. This will be work for a future publication (Rosti et al., in prep.).

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REFERENCES

Alpaslan M., et al., 2014, Mon. Not. R. Astron. Soc., 438, 177
Alpaslan M., et al., 2016, MNRAS, 457, 2287
Altay G., Colberg J. M., Crock R. A. C., 2006, MNRAS, 370, 1422
Aragón-Calvo M. A., Yang L. F.,, 2014, MNRAS, 440, L46
Aragón-Calvo M. A., Jones B. J. T., van de Weygaert R., van der Hulst J. M., 2007a, Astron. Astroph., 474, 315
Aragón-Calvo M. A., van de Weygaert R., Jones B. J. T., van der Hulst J. M., 2007b, ApJ, 655, L5
Aragón-Calvo M. A., van de Weygaert R., Jones B. J. T., 2010, MNRAS, 408, 2161
Barrow J. D., Bhavsar S. P., Sonoda D. H., 1985, Mon. Not. R. Astron. Soc., 216, 17
Bond J. R., Kolman L., Pogosyan D., 1996, Nature, 380, 603
Bond N. A., Strauss M. A., Cen R., 2010, MNRAS, 409, 156
Cautun M., van de Weygaert R., Jones B. J. T., 2013, MNRAS, 429, 1286
Downes L., van de Weygaert R., Jones B. J. T., Frenk C. S., 2014, MNRAS, 441, 2923
Ceccarelli L., Paz D. J., Padilla N., Lambas D. G., 2011, MNRAS, 412, 1778
Ceccarelli L., Paz D., Lares M., Padilla N., Lambas D. G., 2013, MNRAS, 434, 1435
Chen Y.-C., Ho S., Freeman P. E., Genovese C. R., Wasserman L., 2015, MNRAS, 454, 1140
Chen Y.-C., et al., 2017, MNRAS, 466, 1880
Chen Y.-C., Ho S., Blazek J., He S., Mandelbaum R., Melchior P., Singh S., 2019, MNRAS, 485, 2492
Codis S., Pichon C., Pogosyan D., 2015, MNRAS, 452, 3369
Colberg J. M., 2007, Mon. Not. R. Astron. Soc., 375, 337
Colberg J. M., White S. D. M., Jenkins A., Pearce F. R., 1999, MNRAS, 308, 593
Colberg J. M., Krughoff K. S., Connolly A. J., 2005, MNRAS, 359, 272
Dierckx P., 1993, Curve and surface fitting with splines. Claredon Press
Dolag K., Meneghetti M., Moscardini L., Rasia E., Bonaldi A., 2006, MNRAS, 370, 656
Eisenstein D. J., Loeb A., Turner E. L., 1997, ApJ, 475, 421
