The abundance and environment of dark matter haloes

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8 April 2018

ABSTRACT

An open question in cosmology and the theory of structure formation is to what extent does environment affect the properties of galaxies and haloes. The present paper aims at shedding light on this problem. The paper focuses on the analysis of a dark matter only simulation and it addresses the issue of how the environment affects the abundance of haloes, which are are assigned four attributes: their virial mass, an ambient density calculated with an aperture that scales with \( R_{\text{vir}} (\Delta M) \), a fixed-aperture \((\Delta R)\) ambient density, and a cosmic web classification (i.e. voids, sheets, filaments, and knots, as defined by the V–web algorithm). \( \Delta M \) is the mean density around a halo evaluated within a sphere of a radius of 5 \( R_{\text{vir}} \), where \( R_{\text{vir}} \) is the virial radius. \( \Delta R \) is the density field Gaussian smoothed with \( R = 4 h^{-1} \) Mpc, evaluated at the center of the halo. The main result of the paper is that the difference between haloes in different web elements stems from the difference in their mass functions, and does not depend on their adaptive-aperture ambient density. A dependence on the fixed-aperture ambient density is induced by the cross correlation between the mass of a halo and its fixed-aperture ambient density.

Key words: large-scale structure of Universe — galaxies: evolution — galaxies: haloes

1 INTRODUCTION

Galaxies know about their neighbourhood. Namely, there are correlations between a galaxy’s properties and its environment. Arguably, the most striking correlation is the one between the morphological type of a galaxy and its ambient density (Dressler 1980), which a theory of galaxy formation ought to be able to explain. The morphology—density relation provides an important clue and insight into a comprehensive theory of galaxy formation. A number of models exist to explain the environmental dependencies of galaxy properties. Many of these suggest that environment can regulate the gas supply available to galaxies for star formation; processes such as harassment (wherein galaxy morphology is transformed due to frequent high speed encounters; e.g. Moore et al. 1996), strangulation (wherein the hot gas supply is slowly removed, thereby gradually reducing a galaxy’s star formation rate; e.g. Balogh, Navarro & Morris 2000), stripping via e.g. ram pressure (Gunn & Gott 1972) or tidal effects (King 1962), and mergers (that transform spirals into ellipticals; e.g. Toomre & Toomre 1972), are a number of “quenching” effects that are triggered by changes in a galaxy’s environment (e.g. van den Bosch et al. 2008). Given the uncertainties associated with the numerical implementation of the baryonic physics at play, one may look into dark matter (DM) haloes as a crude and ‘first order’ proxy for galaxies and as the site of galaxy formation. Such an approach has motivated us to study the abundance of DM haloes in cosmological N–body simulations and its dependence on their environment.

The study of the halo mass function plays a major role in the development of a theory of structure and galaxy formation, starting with the seminal work by Press & Schechter (1974). It is by now clear that the efficiency of halo formation depends on the environment in which the halo resides. Dense environments are more efficient in producing massive haloes than less dense ones, resulting in a mass function that is skewed towards more massive haloes (Maulbetsch et al. 2007; Lemson & Kauffmann 1999). This has prompted an intensive study as to how to define and quantify the notion of environment.

Muldrew et al. (2012) conducted a thorough comparison of 20 different algorithmic approaches for the definition of the environment. These authors correctly stated that almost all methods are based on either nearest–neighbour statistics or on an evaluation of the ambient density in fixed 2– or 3–dimensional volumes. Both approaches provide a scalar mea-
sure of the environment, namely they do not define preferred directions. However, visual inspection of the distribution of (observed) galaxies and (simulated) DM haloes gives rise to an intricate structure of vast voids, planar sheets, long filaments and dense and compact knots - the so-called ‘cosmic web’ (Bond, Kofman & Pogosyan 1996). The notion of the cosmic web does not only provide a link between the local density of a region and the topography of its environment, but also defines preferred directions. The sequence of web elements, ranging from voids, to sheets, to filaments, and to knots, corresponds to a sequence of: a. increasing local density (e.g. Hoffman et al. 2012); b. increasing mass of DM haloes (e.g. Metuki et al. 2015); c. by implication, the increasing local density leads to an increasing ratio of early to late type galaxies. An important question arising from this is what is the main mechanism behind these correlations?

In the context of the present paper we adopt a rather limited view of DM haloes, and characterize each halo by the following properties: its virial mass, its web environment, and the ambient density within which it resides. A short and incomplete review of these properties of haloes is presented here. The abundance of haloes will be studied here in the framework of such a characterization.

Hahn et al. (2007a) analyzed the properties of haloes with respect to the cosmic web, defined by the eigenvalues of the Hessian of the gravitational potential, and showed that the halo mass function varies with web classification. They also showed that the high mass end of the halo mass function increases as the web sequence goes from voids to knots. Alonso, Eardley & Peacock (2015) have recently studied the dependence of the halo mass function on both the ambient density and on the cosmic web (as defined by Forero-Romero et al. 2009), and concluded that “…to a good approximation, the abundance of haloes in different environments depends only on their densities, and not on their tidal [web] structure.” Eardley et al. (2015) have investigated the dependence of galaxy luminosity on the cosmic web and local density within the GAMA survey. These authors found that the modulation of the luminosity function with environment can be accounted for by the luminosity function’s dependence on density, and found “no evidence of a direct influence of the cosmic web on the galaxy luminosity function”.

Metuki et al. (2015) studied the dependence of properties of simulated galaxies in a suit of gas-dynamical cosmological simulation on the cosmic web (as defined by Hoffman et al. 2012) and found a strong dependence of the halo and galaxy properties on the cosmic web, but showed that this dependence can be virtually accounted for by the dependence of the haloes’ mass function on the web.

Bond, Kofman & Pogosyan (1996) were the first to introduce the concept of the ‘cosmic web’, yet the idea that the matter distribution can be characterized by voids, sheets (called at the time pancakes), filaments, and knots dates back to the seminal work of Zel’dovich (1970). Since then many methods and algorithms have been proposed to developing a mathematical description of the cosmic web.

We follow here a path that started with Hahn et al. (2007a,b) and was further extended by Forero-Romero et al. (2009) (see also the NEXUS algorithm of Cautun, van de Weygaert & Jones 2013). Common to all of these methods is that the web is classified according to the number of eigenvalues of the Hessian of a scalar field (such as the gravitational potential, the matter density, or the velocity potential, namely the velocity shear tensor) which are larger than some threshold. The number of eigenvalues larger than said threshold at a given point assigns a web classification - 0 (voids), 1 (sheets), 2 (filaments) and 3 (knots) - and the eigenvectors endow preferred directions. The tidal web (Hahn et al. 2007b; Forero-Romero et al. 2009) has been improved upon by Hoffman et al. (2012), who have replaced the gravitational tidal tensor by the velocity shear tensor, and thereby improved the spatial resolution. The velocity shear tensor based web (V–web) resolves the cosmic web down to sub–Megaparsec scales (in numerical simulations), and has been used to examine halo spins (Libeskind et al. 2012), halo alignment (Libeskind et al. 2013), subhalo accretion (Libeskind et al. 2014) and planes of satellites (Libeskind et al. 2015). The V–web is adopted here as a measure of the cosmic web.

The aim of the present paper is to study the dependence of the abundance of haloes on their mass, cosmic web environment and the ambient density. The present analysis bears some resemblance to previous work (Alonso, Eardley & Peacock 2015; Eardley et al. 2015) but it also differs from those studies in a fundamental way. A distinction is made here between the fixed-aperture and adaptive-aperture approaches. The V–web is calculated in a multi–scale fashion, in which the spatial resolution of the V–web of a given halo scales with its virial radius (Libeskind et al. 2014; Metuki et al. 2015). The ambient density is calculated here in both fashions - an adaptive-aperture one (in which the width of the kernel scales with the virial radius) and a fixed-aperture one (calculated with a fixed kernel, in a similar manner to Alonso, Eardley & Peacock 2015; Eardley et al. 2015). Our goal is to shed light on the complex relation between the mass, web environment, and the fixed- and adaptive- aperture ambient densities of haloes, and in particular address the issue of how these properties affect the abundance of haloes.

The paper is organized as follows. The methodology of the paper is presented in §2 and the results are described in §3. A general summary and discussion conclude the paper (§4).

2 METHODS

The methodology employed here consists of extracting DM haloes from a DM–only N–body simulation by means of a halo finder. The environment within which a halo resides is defined by means of the cosmic web and by the local density field. The abundance of the haloes is expressed by mass and density functions. The aim of the paper is the study of the dependence of these functions on the mass, local density, and cosmic web environment of DM haloes.

2.1 Simulation

The DM–only N–body simulation employed here has been performed as part of the Multimessenger Approach for Dark Matter Detection (MultiDark) project, and is dubbed the Small MultiDark Planck (Klypin et al. 2016, SMDP;) simulation. The cosmological parameters have the following values - a cosmological constant density parameter $\Omega_\Lambda = 0.693$,
a matter density parameter $\Omega_m = 0.307$, a Hubble constant of $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$, a spectral index of primordial density fluctuations given by $n_s = 0.96$, and a $\sigma_8 = 0.829$ normalization of the power spectrum. The simulation spans a box of side length $400 \ h^{-1}\text{Mpc}$ with $3840^3$ particles, achieving a mass resolution of $\sim 9.6 \times 10^7 h^{-1}\text{M}_\odot$. DM haloes are defined by the BDM halo finder (Klypin & Holtzman 1997; Riebe et al. 2013), with their virial radius, $R_{\text{vir}}$, defined as the radius within which the density is equal to $360 \times \rho_m$, where $\rho_m$ is the average density in the universe.

### 2.2 Ambient density

The dark matter density ($\rho$) field is evaluated on a $400^3$ Cartesian grid by the “clouds in cells” (CIC) algorithm, corresponding to a unit grid length of $1 h^{-1}\text{Mpc}$. The density field is denoted here by $\Delta_{\text{CIC}} = \rho/\bar{\rho}$, where $\bar{\rho}$ is the mean cosmological density. The raw CIC field is smoothed with a Gaussian kernel of width $R$, yielding $\Delta_{\text{CIC}}^R$. The smoothing length is taken here to be $R = 1 h^{-1}\text{Mpc}$, a length scale larger than the virial radius of all but a small fraction of the most massive haloes in the simulation.

Note that the relative total volumes of the different web elements are purposefully left out of the density computations, as we are interested in calculating the different properties as they may appear to an observer.

When dealing with the local density a halo resides in, namely its ambient density, one needs to ensure that the local density is smoothed on a scale larger than the halo’s virial radius, $R_{\text{vir}}$, so as to reflect the halo’s environment and not its internal structure. Two approaches are followed here - a fixed-aperture approach and a adaptive-aperture one. In the fixed-aperture approach the density field, $\Delta_R$, is the smoothed density, $\Delta_{\text{CIC}}^R$ with $R = 4 h^{-1}\text{Mpc}$, evaluated at the center of the halo. The adaptive-aperture ambient density associated with a halo of mass $M_{\text{vir}}$, $\Delta_M$, is defined to be the mean value of $\Delta_{\text{CIC}}$ within a top–hat sphere of $5 R_{\text{vir}}$, where $R_{\text{vir}}$ is the halo’s virial radius (as defined in 2.1). It follows that a halo is endowed with two ambient densities, $\Delta_M$ and $\Delta_R$.

### 2.3 Cosmic web

The normalized velocity shear tensor is defined at each grid point as (Hoffman et al. 2012):

$$
\Sigma_{\alpha\beta} = -\frac{1}{2H_0} \left( \frac{\partial v_\alpha}{\partial r_\beta} + \frac{\partial v_\beta}{\partial r_\alpha} \right), \quad \alpha, \beta = x, y, z
$$

(1)

Here $H_0$ denotes Hubble’s constant and the minus sign is introduced so as to associate positive eigenvalues with a converging flow. Spatial derivatives are calculated by means of the Fast Fourier Transform (FFT) algorithm. Eigenvalues ($\lambda_i$, $i = 1, 2, 3$) of the shear tensor are evaluated at each grid point, and assume the standard convention of $\lambda_1 > \lambda_2 > \lambda_3$. The $V$–web is defined by introducing a threshold value, $\lambda_{th}$, and by counting the number ($\mu$) of eigenvalues larger than $\lambda_{th}$. It follows that $\mu = 0, 1, 2, 3$ correspond to a $V$–web classification of voids, sheets, filaments, and knots, respectively (Hoffman et al. 2012). The $V$–web is defined by the (Gaussian) smoothing length used for calculating the shear tensor and by $\lambda_{th}$. A halo inherits its web type ($\mu$) from the web classification of the CIC cell where its center lies. The $V$–web is introduced here as a measure of the environment of haloes, hence care needs to be taken to make sure that the web classification depicts the environment of a halo and not...
its internal structure, which is highly non-linear and where the web classification formalism does not apply. For that reason, the small fraction (< 0.01%) of haloes with $R_{\rm vir}$ greater than the basic smoothing length ($1\,h^{-1}\text{Mpc}$) have their web classification drawn from a calculation of the cosmic web done over a density grid that is smoothed over $2\,h^{-1}\text{Mpc}$, which is larger than the virial radius in the simulation. Following Hoffman et al. (2012) we adopt here a threshold value of $\Lambda_{\text{th}} = 0.45$.

2.4 Abundance of haloes: mass and density functions

DM haloes are characterized by their virial mass ($M_{\text{vir}}$), ambient fixed- and adaptive- aperture densities ($\Delta_{\text{R}}$ and $\Delta_{\text{M}}$), and V–web type ($\mu$). Let $n_\mu(M_{\text{vir}}, \Delta_X)$ be the total number of haloes per unit volume, as a function of the virial mass $M_{\text{vir}}$ and ambient adaptive- or fixed- aperture densities (with $X = M, R$), of a given web type $\mu$. Following Jenkins et al. (2001, and references therein) the function $\eta_\mu(M_{\text{vir}}, \Delta_X)$, which describes the abundance of haloes as a function of their mass, ambient (adaptive- or fixed- aperture) density, and web classification, is defined by:

$$\eta_\mu(M_{\text{vir}}, \Delta_X) = M_{\text{vir}} \Delta_X \frac{d^2 n_\mu(M_{\text{vir}}, \Delta_X)}{d M_{\text{vir}} \, d \Delta_X}$$  \hspace{1cm} (2)

Conditional functions are defined here by:

$$\eta_\mu(M_{\text{vir}}|\Delta_X) = M_{\text{vir}} \times \frac{d n_\mu(M_{\text{vir}}, \text{within a given range of } \Delta_X)}{d M_{\text{vir}}}$$  \hspace{1cm} (3)

$$\eta_\mu(\Delta_X|M_{\text{vir}}) = \Delta_X \frac{d n_\mu(\text{within a given range of } M_{\text{vir}}, \Delta_X)}{d \Delta_X}$$  \hspace{1cm} (4)

The mass and ambient density functions, $\eta_\mu(M_{\text{vir}})$ and $\eta_\mu(\Delta_X)$, are obtained by marginalizing over the other parameter.

3 RESULTS

Our analysis commences with the evaluation of the abundance of CIC cells with Gaussian smoothed density $\Delta_{\text{R,CIC}}^\mu$ as a function of the web attribute $\mu$. Fig. 1 presents the CIC density function, $\eta_\mu(\Delta_{\text{R,CIC}}) = d n_\mu(\Delta_{\text{R,CIC}})/d \ln \Delta_{\text{R,CIC}}$. While there is a significant overlap in the density distributions of the different web elements, the plot reproduces the well known correlation between the cosmic web classification and the density (Hoffman et al. 2012, and references therein). The voids are populated predominantly by low density cells and the transition from voids, through sheets and filaments, to knots, corresponds to a systematic shift from low to high density of the CIC cells.

Fig. 2 reproduces another well known relation, namely the correlation between the mass of haloes and their web environment (Cautun et al. 2014; Metuki et al. 2015, and references therein). It shows the mass function, $\eta_\mu(M_{\text{vir}})$, for the four web environments. The tendency of low mass haloes to reside in voids, and the more massive ones to be found, progressively, in sheets, filaments and knots, is clearly visible here.

The analysis shifts here to include the effects of the ambient density. Fig. 3 presents the conditional, by the adaptive-aperture (left frame) and fixed-aperture (right frame) ambient density, mass function. Each panel (i.e. quadrant of the frame) presents the mass function of haloes of a given ambient density interval as a function of their mass and web attribute. Bins of $\Delta_{\text{M}}$ and $\Delta_{\text{R}}$ have been selected to have an equal number of haloes in each bin. The figure clearly shows that at a given ambient density cut the mass function varies significantly with web classification. This holds for both the adaptive- and fixed- aperture densities.

Fig. 4 presents again the conditional mass function, but the role of the ambient density (adaptive-aperture, left frame, and fixed-aperture, right frame) and the web attribute, $\mu$, is reversed. Each panel corresponds to a given web attribute (voids, sheets, etc.) and the different curves correspond to different intervals of the ambient density. The curves here are essentially the same as those shown in Fig. 3, yet grouped and presented differently for clarity. The left frame of Fig. 4 shows that for a given web environment the variation of the adaptive-aperture ambient density does not change the mass function. A modest variation is found for the fixed-aperture case for high mass knot and filament haloes.

Next, the conditional ambient density function, namely $\eta_\mu(\Delta_X|M_{\text{vir}})$ (where $X = M, R$), is considered. Fig. 5 depicts the adaptive-aperture (left frame) and fixed-aperture (right frame) ambient density functions. Individual panels show $\eta_\mu(\Delta_X|M_{\text{vir}})$ at a given mass range for the full range of web types. The $\eta_\mu(\Delta_{\text{M}}|M_{\text{vir}})$ curves, at a given mass interval, are virtually independent of the web type. Namely, the number of haloes as a function of their adaptive-aperture ambient density, at a given mass range, does not vary with the web environment. This is not the case for the fixed-aperture ambient density (right panel of Fig. 5), where the mass function shows a significant dependence on the environment.

Figs. 4 and 5 manifest a decoupling between adaptive-aperture ambient density and the web environment of haloes. The number of haloes as a function of their mass depends on the web environment but is independent of $\Delta_{\text{M}}$. The number of haloes as a function of $\Delta_{\text{M}}$ depends on the mass but is independent of the environment. These trends are not as strong in the fixed-aperture ambient density case, where some difference is clearly seen between the curves. A summary of the dependence, or lack of it, of the various functions is presented in Table 1.

Recall that the main difference between the adaptive- and fixed- aperture ambient densities is that the former is calculated within a radius that scales with the virial radius of a halo while the latter is calculated within a fixed radius. It follows that a trivial correlation is induced between the mass and $\Delta_{\text{R}}$ - a sphere of a radius of $R = 4\,h^{-1}\text{Mpc}$ that contains a $10^{13}\,h^{-1}\text{M}_\odot$ halo is (statistically) bound to have a higher density than the one that contains a $10^{11}\,h^{-1}\text{M}_\odot$ halo. This dependence introduces a leakage of the mass dependence of the mass function to a dependence on $\Delta_{\text{R}}$. Such a dependence is not expected for the adaptive-aperture ambient density for haloes of mass below $M_*$, the characteristic
Figure 3. The mass function conditioned by the ambient adaptive-aperture (left frame) and fixed-aperture (right frame) density of haloes is plotted for the different web elements, $\eta_{\mu}(M_{\text{vir}}|\Delta X)$ (where $X = M$ or $R$).

Table 1. A summary of the dependence of the various conditional functions on the four attributes of the DM haloes: mass ($M$), web classification ($\mu$), fixed-aperture ($\Delta R$) and adaptive-aperture ($\Delta M$) ambient densities.

| Function | $M$ | web type ($\mu$) | $\Delta R$ | $\Delta M$ |
|----------|-----|-----------------|----------|--------|
| $\eta(M_{\text{vir}}|\mu)$ (Fig. 2) | + | + | |
| $\eta_{\mu}(M_{\text{vir}}|\Delta M)$ (Figs. 3 & 4) | + | + | - |
| $\eta_{\mu}(M_{\text{vir}}|\Delta R)$ (Figs. 3 & 4) | + | + | + |
| $\eta_{\mu}(\Delta M|M_{\text{vir}})$ (Fig. 5) | - | + | + |
| $\eta_{\mu}(\Delta R|M_{\text{vir}})$ (Fig. 5) | + | + | + |

mass of the mass function, beyond which the self-similarity of the mass function breaks. This is clearly illustrated by Figs. 6 and 7. Fig 6 presents the mean adaptive-aperture (left frame) and fixed-aperture (right frame) ambient densities as a function of the virial mass for the different web environments. The mean values of the adaptive-aperture ambient density remain constant. The fixed-aperture ambient density, on the other hand, shows a clear departure from this constancy, and is changing both with halo mass and with web environment. Fig. 7 shows the full distribution of the haloes in the $M_{\text{vir}} - \Delta X$ ($X = R, M$), plotted separately for each web environment. The distribution is shown by means of a scatter and contours plots. The figure clearly shows the virtual invariance of the distribution along the vertical (ambient density) axis for $\Delta M$, while for $\Delta R$ the distribution depends both on the virial mass and the web environments.

4 SUMMARY AND DISCUSSION

Dark matter haloes serve as the building blocks of the large scale structure of the universe, and a very crude and biased proxy for galaxies. An open question in cosmology and the theory of structure formation is to what extent does environment affect the properties of galaxies and haloes. The present paper aims at shedding light on the problem from a structure, rather than galaxy formation, standpoint. The paper focuses on the analysis of DM–only simulations and addresses the issue of how the environment affects the abundance of DM haloes. Haloes are assigned four attributes: their virial mass, their fixed- and adaptive-aperture ambient densities (termed $\Delta R$ and $\Delta M$ and defined as the Gaussian smoothed density within $4h^{-1}\text{Mpc}$ and the top–hat smoothed within 5 virial radii, respectively), and their cosmic web classification (i.e. voids, sheets, filaments, and knots) according to the eigenvalues of the velocity shear tensor. The main result of the paper is that the mass function of haloes, namely the abundance of haloes as a function of their mass, depends on the haloes’ web environment and not on their adaptive-aperture ambient density. The weak dependence on the fixed-aperture ambient density is induced by the cross correlation between the mass of a halo and its fixed-aperture ambient density.

Is this result in conflict with Alonso, Eardley & Peacock (2015), and their statement on the dependence of the halo abundance on the ambient density? Technically speaking, no. Those authors used the fixed-aperture method to calcu-
Figure 4. The mass function conditioned by the four web types \( \eta_{\mu}(M_{\nu}, |\Delta X|) \), where \( X = M \) (left) and \( R \) (right): Each frame shows the mass function of a given web type, with the different curves corresponding to different adaptive-aperture (left frame) and fixed-aperture (right frame) ambient density ranges. Here the line styles correspond to different density ranges (given as legends in the plots), with the solid line depicting the mass function of all haloes in this web element, regardless of ambient density.

Figure 5. The adaptive-aperture (left frame) and fixed-aperture (right frame) ambient density functions, \( \eta_{\mu}(\Delta X | M) \) (where \( X = M, R \)), conditioned by the virial mass of haloes, is plotted for the different web elements.

late the densities, and evaluated the tidal tensor with a the same fixed smoothing kernel; they also took into account the difference in the total mass of each web element when calculating their mass functions. This makes comparison with our results problematic. When a adaptive-aperture ambient density is used, the dependence of the mass function on the ambient density vanishes, leaving the sole dependence to be on the web environment.

The present work, together with Metuki et al. (2015), leads to a coherent picture regarding how galaxies are affected by their neighbourhood. This earlier work, in which hydrodynamical simulations of galaxy formation were studied, suggested that the halo mass is the dominant parameter that shapes the fate of the baryons in their parent haloes. Here we show that the abundance of haloes as a function of their mass is closely correlated with their web environment,
leaving no room for further dependence on their (adaptive-aperture) ambient density. So it is this strong mass–web dependence that drives the apparent dependence of the galaxy properties on the environment, and it is an environment defined by the cosmic web, and not by the (adaptive-aperture) ambient density.

Acknowledgments

NIL is supported by the Deutsche Forschungs Gemeinschaft.

YH has been partially supported by the Israel Science Foundation (1013/12).

The authors would also like to thank Dr. David Alonso for helpful explanations and Prof. John Peacock for a very insightful report.

REFERENCES

Alonso D., Eardley E., Peacock J. A., 2015, MNRAS, 447, 2683
Balogh M. L., Navarro J. F., Morris S. L., 2000, ApJ, 540, 113
Bond J. R., Kofman L., Pogosyan D., 1996, Nature, 380, 603
Cautun M., van de Weygaert R., Jones B. J. T., 2013, MNRAS, 429, 1286
Cautun M., van de Weygaert R., Jones B. J. T., Frenk C. S., 2014, MNRAS, 441, 2923
Dressler A., 1980, ApJ, 236, 351
Eardley E. et al., 2015, MNRAS, 448, 3665
Förero-Romero J. E., Hoffman Y., Gottlöber S., Klypin A., Yepes G., 2009, MNRAS, 396, 1815
Gunn J. E., Gott, III J. R., 1972, ApJ, 176, 1
Hahn O., Carollo C. M., Porciani C., Dekel A., 2007a, MNRAS, 381, 41
Hahn O., Porciani C., Carollo C. M., Dekel A., 2007b, MNRAS, 375, 489
Hoffman Y., Metuki O., Yepes G., Gottlöber S., Förero-Romero J. E., Libeskind N. I., Knebe A., 2012, MNRAS, 425, 2049
Jenkins A., Frenk C. S., White S. D. M., Colberg J. M., Cole S., Evrard A. E., Couchman H. M. P., Yoshida N., 2001, MNRAS, 321, 372
King L., 1962, AJ, 67, 471
Klypin A., Holtzman J., 1997, ArXiv e-prints, astro-ph/9712217
Klypin A., Yepes G., Gottlöber S., Prada F., Heß S., 2016, MNRAS
Lemson G., Kauffmann G., 1999, MNRAS, 302, 111
Libeskind N. I., Hoffman Y., Förero-Romero J., Gottlöber S., Knebe A., Steinmetz M., Klypin A., 2013, MNRAS, 428, 2489
Libeskind N. I., Hoffman Y., Knebe A., Steinmetz M., Yepes G., 2012, MNRAS, 421, L137
Libeskind N. I., Hoffman Y., Tully R. B., Courtois H. M., Pomarède D., Gottlöber S., Steinmetz M., 2015, MNRAS, 452, 1052
Libeskind N. I., Knebe A., Hoffman Y., Gottlöber S., 2014, MNRAS, 443, 1274
Maulbetsch C., Avila-Reese V., Colin P., Gottlöber S., Khlatyan A., Steinmetz M., 2007, ApJ, 654, 53
Metuki O., Libeskind N. I., Hoffman Y., Crain R. A., Theuns T., 2015, MNRAS, 446, 1458
Moore B., Katz N., Lake G., Dressler A., Oemler A., 1996, Nature, 379, 613
Muldrew S. I. et al., 2012, MNRAS, 419, 2670
Press W. H., Schechter P., 1974, ApJ, 187, 425
Rieke K. et al., 2013, Astronomische Nachrichten, 334, 691
Toomre A., Toomre J., 1972, ApJ, 178, 623

Figure 6. The mean adaptive-aperture (left frame) and fixed-aperture (right frame) ambient density of haloes plotted against the virial mass, for the different web environment.
Figure 7. Scatter plots of the haloes in the parameter space of their ambient adaptive-aperture (left frame) and fixed-aperture (right frame) density and their virial mass. The coloured contours indicate the number density of haloes in that parameter space, and are present in order to point out the shape of the distributions; the actual numerical values are of no significance to our results.

van den Bosch F. C., Aquino D., Yang X., Mo H. J., Pasquali A., McIntosh D. H., Weinmann S. M., Kang X., 2008, MNRAS, 387, 79

Zel’dovich Y. B., 1970, A&A, 5, 84