How do galaxies populate haloes in high-density environments? 
An analysis of the Halo Occupation Distribution in future virialized structures

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ABSTRACT

Context. There are hints suggesting that properties of galaxy populations in dark matter haloes may depend on their large-scale environment. Recent works point out that very low-density environments influence halo occupation, however there is not a similar analysis focused on high-density environments. Here we use a simulated set of future virialized superstructures (FVS) to analyse the occupation of galaxies in haloes within these high globally dense regions.

Aims. Our main goal is to explore the different characteristics of the galaxies populating haloes in FVS to those in general.

Methods. We use a publicly available simulated galaxy set constructed with a semi-analytical model to identify FVS in the simulation. Then, we computed the halo occupation distribution within these superstructures for different absolute magnitude thresholds and make several analysis including the comparison to the global halo occupation results. We study the dependence on the results on properties of the FVS such as density and volume as well as consider the morphology of galaxies. We also analysed the properties of the stellar content of galaxies and the formation time of the haloes inside FVS and confronted them to those of the general populations.

Results. We find a significant increase in the halo occupation distribution inside FVS. This result is present for all absolute magnitude thresholds explored. The effect is larger in the densest regions of FVS, but does not depend on the volume of the superstructure. We also find that the stellar-mass content of galaxies considerably differs inside the superstructures. Low mass haloes have their central and satellite galaxies with a higher stellar mass content (∼ 50%), and exhibit mean star ages (∼ 20%) older than average. For massive haloes in FVS we find that only the stellar mass of satellite galaxies varies considerably corresponding to a decrease of ∼ 50%. We find a significant statistical difference between the formation times of haloes in FVS and the average population. haloes residing in superstructures formed earlier, a fact that leads to several changes in the HOD and their member galaxy properties.

Key words. large-scale structure of Universe – Galaxies: haloes – Galaxies: statistics – Methods: data analysis – Methods: statistics

1. Introduction

Galaxy formation and evolution inside dark matter haloes involves a great diversity of astrophysical mechanisms. These processes make it difficult to unequivocally determine how galaxies populate haloes, a key process to understand the formation and evolution of the large-scale structure of the Universe. Nevertheless, relating the properties of galaxies to the large-scale environment could provide clues to improve our understanding of these processes.

In this context, a powerful tool to connect galaxies and dark matter haloes is the halo occupation distribution (HOD). It describes the probability distribution $P(N|M_{\text{halo}})$ that a virialized halo of mass $M_{\text{halo}}$ contains $N$ galaxies with a specified set of characteristics. The HOD assumes, in the first order, that the population of galaxies in a halo depends only on its mass. This approximation has been analysed in several works using simulations and observations (e.g., Jing et al. 1998; Ma & Fry 2000; Peacock & Smith 2000; Seljak 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Cooray & Sheth 2002; Zheng et al. 2005; Yang et al. 2007; Rodriguez et al. 2015; Rodriguez & Merchán 2020). Besides this simple dependence, some authors have found signs of correlation between the HOD and the environmental density in galaxy catalogues constructed using both, semi-analytic models (Zehavi et al. 2018), and hydrodynamic cosmological simulations (Artale et al. 2018).

In recent work, Alfaro et al. (2020) showed that the HOD differs significantly inside cosmic voids. These results are consistently obtained in two synthetic catalogues, one based on a semi-analytic approach derived from the MDPL2-SAG catalogue (Knebe et al. 2018), and other extracted from the hydrodynamic simulation Illustris TNG300-1 (Marinacci et al. 2018; Naiman et al. 2018; Nelson et al. 2018; Pillepich et al. 2018; Springel et al. 2018). Analysing both simulations, the authors consistently found a significant decrease in the number of galaxies residing in void haloes compared with the overall behaviour of the HOD in the simulations. These studies show evidence of the large-scale environment influence on the population of galaxies in dark matter haloes in these extremely low-density regions.

As it is well known, the cosmic web that constitutes the large-scale structure of the Universe is the result of the mass accretion process dominated mainly by gravity. In this process, mass flows from the low-density environments, i.e., voids, to high-density regions, namely filaments and walls. The intersections of these last two structures can form nodes that become the densest environments in the large-scale structure. Under the current Λ-CDM cosmological model, some of these overdense regions will become bound and virialised structures in the future (Luparello et al. 2011 and references therein), hence we refer to these as Future Virialized Structures (FVS). In order to deepen...
our understanding of the influence of large-scale environments on the galaxy population of dark matter haloes, in this work we focus on superstructures, in particular on FVS.

On the observational side, it is also well known that galaxy properties are strongly influenced by their local environment. However, there are several studies focused on the large-scale influence on the formation and evolution of galaxies, groups and clusters. As stated by the assembly bias scenario (Lacerna & Padilla 2011), the most massive groups and clusters are located in the highest density global environments (i.e. superstructures and superclusters) (Einasto et al. 2003, 2005; Luparello et al. 2011; Croft et al. 2012). Furthermore, for a given group r-band luminosity (considered as a mass proxy) a group residing in a superstructure exhibits larger stellar mass content and higher velocity dispersion as compared to a group of the same luminosity, in a less dense environment. We stress the fact that groups in FVS may have formed earlier than groups elsewhere in a less dense environment. We stress the fact that groups in superstructure exhibits larger stellar mass content and higher velocity dispersion as compared to a group of the same luminosity, in a less dense environment. We stress the fact that groups in FVS may have formed earlier than groups elsewhere (Luparello et al. 2013). So, the effects determining intrinsic properties of galaxies within groups in different environments are linked to both host halo mass as well as to its assembly history, Luparello et al. (2015) find that large-scale environment may only affect the most luminous galaxy in groups; this influence is not very significant and strongly depends on galaxy morphological type. Late-type brightest group galaxies show higher luminosities and stellar masses, redder $(u-r)$ colours, lower star formation activity and larger star–formation time–scale when embedded in superstructures, regardless of the group local environment. Also, the authors find the impact on the properties of galaxies beyond rank three in luminosity is completely negligible.

Similarly, there is also a recent analysis discussing the influence of large-scale filaments in galaxy properties (Kuitma et al. 2020, and references therein). They find slight deviations between the brightest group galaxy properties inside and outside filaments in terms of stellar mass, colour, the 4000Å break, specific star formation rates and morphology. However, these effects are marginal and the differences are negligible compared to the effects arising from local environment density.

It is worth to mention that the previous works on galaxy properties and the large-scale structure reviewed above were based mainly on observational data. In this paper, and with the aim of reproducibility of the results in observational data, we use the FVS identification method presented in Luparello et al. (2011) used to identify FVS in the observational galaxy catalogue Sloan Digital Sky Survey Data Release 7 (Stoughton et al. 2002; Abazajian et al. 2009). As discussed, there are hints of the influence of superstructure on galaxy groups. Nevertheless, the effects of the large-scale structure on the intrinsic galaxy properties are not completely unveiled. Therefore in this context, the analysis of semi-analytic galaxies from numerical simulations can be extremely useful, allowing us to access information that is not yet available in observational data, deepening our understanding of the astrophysical processes involved.

This paper is organised as follows. In Sec. 2, we describe the simulated galaxy catalogues obtained from a semi-analytic model and detail the algorithms to identify the FVS. In Sec. 3, we present the main properties of our FVS catalogue. In Sec. 4 we describe the methodology used to determine the HOD inside the FVS and other definition of high-density regions. We present and compare the results of the HOD measurements for these two different regions. In this section, we also explore the dependence of the results within the FVS volume and the properties of the galaxies such as their magnitude and morphology. In Sec. 5, we study the galaxies stellar mass distribution as a function of the total dark matter halo mass and compared the mean age of the stellar population of the galaxies inside the FVS with the general results. In Sec. 6, we compare the halo formation time inside FVS with the overall results and with the other high-density regions. Finally, in Sec. 7, we present our summary and conclusions.

2. Data

In this section, we present the simulated galaxy catalogue used in this work. We also present a brief description of the FVS-identification algorithm.

2.1. The MDPL2-SAG galaxy catalogue

We made use of the publicly available MDPL2-SAG galaxy catalogue (Knebe et al. 2018), which was constructed using the dark matter haloes of the MultiDark Plank 2 cosmological simulation (MDPL2, Riebe et al. 2013; Klypin et al. 2016) and the semi-analytic model of galaxy formation Semi-Analytic Galaxies (SAG, Cora et al. 2018).

The MDPL2 simulation follows the evolution of 3840$^3$ dark matter particles in a cubic box with $L_{\text{box}} = 1000h^{-1}$Mpc of side length and with a mass resolution per particle of 1.5$\times$10$^8M_\odot/h$. The adopted cosmology corresponds to a flat ΛCDM model consistent with Plank results (Planck Collaboration et al. 2014, 2016), with cosmological parameters given by $\Omega_m = 0.307$, $\Omega_b = 0.048$, $\sigma_8 = 0.823$, $h = 0.678$ and $n = 0.96$. Haloes and subhaloes in the simulation were identified using Rockstar (Behroozi et al. 2013a), and their corresponding merger-trees were constructed with ConsistentTrees (Behroozi et al. 2013b).

The SAG model use as backbone the haloes and subhaloes, and their respective merger-trees, to populate the MDPL2 simulation with galaxies. This model includes all the relevant processes relative to galaxy formation and evolution, such as: radiative cooling of hot gas (both in central and satellite galaxies), star formation triggered by galaxy mergers (quiescent mode) and by disc instabilities (burst mode), feedback by supernovae explosions and stellar winds, mechanism of hot gas ejection and reincorporation, feedback by AGN and growth of super-massive black holes, ram pressure, tidal stripping and a detailed treatment of the chemical evolution in gas and stars. For each dark matter system, the SAG model provides three types of galaxies: the central galaxy of the main halo (type 0), galaxies inhabiting subhaloes which are satellites of the main halo (type 1) and galaxies that have lost their subhalo as it cannot be identified anymore (type 2, also named orphan galaxies). In particular, the selection of this model is based on its reliable treatment of orphan galaxies. This is relevant for the HOD determination in high–density environments because includes a large fraction of these galaxies. The SAG model integrates analytically the orbits of orphan galaxies taking into account dynamical friction and tidal stripping effects. This implementation provides a more realistic estimation of the satellite galaxies final positions and, therefore, a high precision determination of an orphan satellite galaxy membership to a main dark matter halo. In this work, we consider satellite galaxies both type 1 and 2, without distinction. For a detailed description of all the mechanisms modelled and implemented in SAG, we refer to the reader to Cora (2006), Lagos et al. (2008), Tecce et al. (2010), Padilla et al. (2014), Ruiz et al. (2015), Gargiulo et al. (2015), Cora et al. (2018), Collacchioni et al. (2018), Cora et al. (2019) and Delfino et al. (2021).

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Both MDPL2-SAG galaxy catalogue and MDPL2 (sub)halo catalogue are publicly available at the CosmoSim database. From the complete MDPL2-SAG catalogue at $z = 0$, we selected all galaxies with absolute magnitudes in the $r$-band $M_r \leq -16$, stellar masses $M_\ast \geq 5 \times 10^{10} h^{-1} M_\odot$, and host haloes with masses $M_{200c} \geq 5 \times 10^{10} h^{-1} M_\odot$, where $M_{200c}$ corresponds to the mass enclosed within an over-density of 200 times the critical density of the Universe. With this approach, our smaller haloes are made of ~ 30 mass particles. The final catalogue comprises 41986893 galaxies.

2.2. FVS identification

Observationally, galaxies are biased tracers of the matter distribution. In large scales, the luminosity follows the matter density of a bound structure defined by Dünner et al. (2010; Liivamägi et al. 2012), the identified structures have a high degree of arbitrariness.

Particularly, the FVS identification procedure is based on the construction of a luminosity density field (Einasto et al. 2007) from which the highest density regions can be selected by fixing a minimum luminosity overdensity. This process associates the FVS with the highest values of a smoothed luminosity density field constructed from the convolution between the spatial distribution of galaxies with a kernel function weighted by the galaxies luminosity. The luminosity threshold was calibrated in Luparello et al. (2011), according to the theoretical criterion for the mass density of a bound structure defined by Einasto et al. (2006). The smoothed luminosity density field was obtained for a cubic grid with a resolution of $1 h^{-1}$ Mpc on a side. By assuming a constant mass-luminosity ratio and considering the minimum mass overdensity necessary for a structure to remain bound in the future, the suitable and previously computed threshold results in $\rho_{\text{num}}/\rho_{\text{num}} = 5.5$, where $\rho_{\text{num}}$ represents the luminosity density of each cell and $\rho_{\text{num}}$ is the mean luminosity density of the sample. Then, by means of a percolation algorithm, the highest luminosity density groups of cells are identified. Hence, the FVS are defined as the densest regions in the Universe that will remain bound and virialized in the future evolution of the Universe. Also, to avoid contamination of smaller systems, a lower limit for the total luminosity of a structure is applied at $L_{\text{FVS}} > 10^{12} h^{-2} L_\odot$. These criteria provide a suitable compromise of high completeness and low contamination for the FVS sample.

3. Properties of FVS in MDPL2-SAG

In this section, we briefly describe the main properties of our FVS catalogue, which help us to understand these extreme regions. The properties analysed here will be related with the population of dark matter haloes and galaxies which inhabit the FVS in the next section (Sec. 4).

The identification algorithm described in Sec. 2.2 was applied to the MDPL2-SAG catalogue, finding 3219 structures composed by a total of 1422683 galaxies. The top panel of Fig. 1 shows the distribution of FVS volumes (solid line) and its cumulative fraction $V_{\text{FVS}}/V_{\text{box}}$ (dashed line), where $V_{\text{FVS}}$ is the volume occupied by FVS and $V_{\text{box}} = L_{\text{box}}^3 = 10^9 h^{-3} \text{Mpc}^3$ is the complete MDPL2 simulation volume. As can be seen, the FVS covers a wide range of volumes from $\sim 50 h^{-3} \text{Mpc}^3$ to $\sim 2.3 \times 10^4 h^{-3} \text{Mpc}^3$, although, the 99.5 percent are below $10^4 h^{-3} \text{Mpc}^3$. The integrated volume of all FVS in our catalogue is $\sim 5.65 \times 10^6 h^{-3} \text{Mpc}^3$. However, as shown in dashed line, this represents a tiny part of the total volume of the simulation box, just a 0.56 per cent.

In addition, besides the FVS volumes, we also study their luminosities. In the bottom panel of Fig. 1 we show the distribution of FVS luminosities (solid line) and the cumulative fraction $L_{\text{FVS}}/L_{\text{tot}}$ (dashed line), where $L_{\text{FVS}}$ is the luminosity of the FVS and $L_{\text{tot}}$ the total luminosity of our FVS catalogue. Just like the volume behavior, the FVS luminosity covers a wide range from $10^{12} h^{-2} L_\odot$ to $\sim 4.66 \times 10^{13} h^{-2} L_\odot$, being the 99.5 percent of the sample below $2 \times 10^{13} h^{-2} L_\odot$.

![Figure 1](https://www.cosmosim.org)

**Fig. 1.** Top panel: FVS volume distribution (solid line) and the cumulative fraction of the volume occupied by FVS with respect to the total volume of the simulation (dashed line). Bottom panel: FVS luminosity distribution (solid line) and the cumulative fraction of luminosity with respect to the total luminosity of the FVS catalogue (dashed line).

It is worth to mention that although the total volume occupied by FVS covers a small fraction of the simulation, we find 898 of the 1000 galaxies with the largest stellar mass content residing in FVS. This is also evident by inspection to the stellar–mass distribution in the top panel of Fig. 2 for all the galaxies (solid black line) and FVS galaxies (red dashed line). As it can be seen, galaxies in FVS show a significant difference only in the high stellar mass end.

Regarding to the dark matter content of FVS, we show in bottom panel of Fig. 2 the distribution of the halo mass $M_{200c}$ in these structures (red dashed line) compared to that corresponding to the full simulation (solid black line). As it can be seen, FVS present an excess of high mass haloes $M_{200c} \geq 10^{13} h^{-1} M_\odot$, consistent with the excess of high luminosity galaxies.

We find that this trend remains in general when we split the galaxy sample into centrals and satellites: 893 and 795 of the
1000 central and satellite galaxies, respectively, with the largest stellar mass galaxies residing in FVS. The top panel of Fig. 3 corresponds to the stellar mass distribution for satellite galaxies inside FVS (red dashed line) and the complete catalogue (dark solid line). The bottom panel show the same quantities but for central galaxies. For satellite galaxies, we find an excess for all stellar mass ranges. This behaviour is consistent with the result of Dragomir et al. (2018) for the stellar mass distribution of galaxies in different mass density regions. Concerning central galaxies, we find an excess for high stellar masses, consistent with the large fraction of galaxies with the highest stellar mass content residing in FVS. On the other hand, central galaxies in FVS with \( M_\star < 11 \times 10^{10} h^{-1} M_\odot \) have lower stellar mass than average. We conclude that FVS are superstructures suitable to study a variety of HOD dependence on large-scale high-density environments. Our results for central galaxies in FVS may be analysed in both, different galaxy formation models and observational data, fostering our understanding of galaxy formation and evolution.

4. HOD analysis in high density environments

To determine the HOD is necessary to compute the mean number of galaxies in haloes of a given mass, \( \langle N_{\text{gal}} \mid M_{\text{halo}} \rangle \), being \( M_{\text{halo}} = M_{200c} \). Since in the simulation the membership of galaxies to dark matter haloes is available, the HOD is computed just binning the sample in halo mass and calculating the average number of galaxies in each bin.

To study the HOD in FVS, we follow the same procedure described above but using only those haloes which are inside an FVS. It is worth to mention that the FVS were identified using the luminosity of galaxies as tracers of the large-scale structure. Whether part of a halo is inside of an FVS, all of his galaxies are taking into account in the HOD estimate. As the FVS volumes are larger than halo volumes by orders of magnitude (see Sec. 3), this criterion does not affect noticeably our FVS boundaries. We also compute the HOD using all the galaxies in the catalogue, in order to compare the results obtained for FVS and the general behaviour. To determine the variance in HOD estimations, we follow the jackknife procedure (Efron 1982). We used 50 equal volume sub-samples and computed HOD differences when any of these sub-samples are not taking into account. We tested the results using 10, 50, 100, 150 and 1000 sub-samples, but we found that the variance stabilizes from 50 sub-samples.

To further study large-scale environmental effects on the population of dark matter haloes, we have used a different high-density measure following Dragomir et al. (2018) environment definition. For this aim, we constructed spheres with \( 8 h^{-1} \text{Mpc} \) radii around the position of each dark matter halo and we count the number of galaxies with \( M_\star > 5 \log_{10}(h) < -20.1 \) within these spheres to derive a local density given by the number of galaxies divided by the volume of the sphere, i.e. \( \rho_{\text{loc}} = N_{\text{gal}} / V_{\text{sphere}} \). Fig. 4 show the distribution of the \( \rho_{\text{loc}} \) for the complete galaxy and the median value \( \rho_{\text{loc}} = 0.00774 \).

We have considered two density thresholds in Dragomir et al. (2018) prescription: a) haloes with \( \delta_\text{c} > 0.7 \) and b) haloes with \( \delta_\text{c} > 4 \). In case a), about one in five of high-density sphere haloes reside in FVS, whereas \( \sim 90\% \) of case b) are included in FVS. Thus, for the highest densities, Dragomir et al. (2018) definitions of large-scale environment are comparable to FVS, whereas when this restriction to high density is relaxed, it can substantially differ. These issues deserve consideration when analysing high-density environment definitions in HOD studies.

For the haloes in the highest density spheres (case b), the results are indistinguishable from FVS, showing that irrespective of the definition of high-density environment, when considering a similar fraction of high-density haloes, the results are unchanged regarding the HOD.
As expected, a more relaxed restriction reflects a lower difference concerning the global values. In order to show this issue, we have considered the HOD of a sample of haloes (S8+) using the condition $0.7 < \delta_S$. Fig. 5 shows in a red solid line the ratio between the HOD measured for the complete catalogue and the HOD inside FVS. Red dashed lines correspond to the ratio between the overall HOD and the HOD measured for the S8+ sample. We only present the result for galaxies with $M_r - 5 \log_{10}(h) < -17$, but this does not vary for other magnitude thresholds. With both environment definitions, haloes in the highest density regions show HOD with larger values with respect to the average, although this effect is stronger for FVS.

Taking into account the previous results, in our analysis, we have considered FVS as a suitable measure of high–density environments, entirely consistent with the highest density threshold in Dragoni et al. (2018) work.

**4.1. Luminosity density dependence**

The FVS are identified through the construction of a luminosity density field. During this process (see Sec. 2.2) we assign to each galaxy two parameters that characterize the luminosity density of the surrounding environment: $\delta_{\text{loc}}$, the local luminosity density within a cube of $1h^{-1}\text{Mpc}$ side, and $\delta_{\text{glob}}$, the global luminosity density in a cube with $13h^{-1}\text{Mpc}$ side, both centred in the galaxy position. These parameters are expressed in terms of the mean luminosity density of the MDPL2-SAG catalogue, $1.87 \times 10^8 h_\odot/\text{Mpc}^3$, By definition, all galaxies in FVS have a $\delta_{\text{loc}} > 5.5$, but their $\delta_{\text{glob}}$ can have lower or higher values, depending on the FVS region where the galaxy is located. A galaxy with $\delta_{\text{glob}} < 5.5$ likely inhabit in the border of the FVS, while a galaxy with $\delta_{\text{glob}} > 5.5$ generally is located near the nucleus.

In Fig. 6 we show the FVS HOD for different values of $\delta_{\text{glob}}$ (red dashed lines), the results for all FVS sample (solid red line) and the complete catalogue HOD (black line). We perform this analysis for four absolute magnitude thresholds: $M_r - 5 \log_{10}(h) = -17, -18, -19$ and $-20$. Although in principle the upper panels do not significant differences are observed, when we plot in bottom panels the ratio between the FVS HOD and the HOD of the complete catalogue, a clear tendency appears: regions with higher luminosity density present differences up to $\sim 20$ per cent with respect to the general behaviour.

These results point out that haloes in extremely dense environments are populated with more galaxies than the average. As can be seen, this dependence is present for all magnitude limits and for haloes with masses higher than $10^{14}h^{-1}\odot$. It is important to note that, for low halo masses, there are no significant differences in the HOD inside the FVS with respect to the general behaviour. On the other hand, it is reasonable that there will be no differences for the highest masses (greater $2 \times 10^{14}h^{-1}\odot$) since these haloes will be preferentially in regions of high density and less likely outside of FVS.

We present in Fig. 7 the ratio between the HOD inside the FVS and the HOD of the complete sample of haloes. It can be seen that there is no appreciable difference between the different magnitude thresholds, indicating that the increase of the HOD inside the FVS is equal for both faint and bright galaxies. The fact that there is no dependence on luminosity is remarkable. Although the most luminous galaxies may have some relationship with the definition of the environment, faints objects do not affect the FVS identification and, nevertheless, the results are consistent in the entire range of magnitudes studied.

**4.2. Dependence on FVS volume**

In the previous section we have shown that there are differences between the HOD inside the FVS when compared with the general behaviour and, even more, we show that these differences depend on the luminosity density of the large-scale environment. For this reason, in this section, we aim to explore a possible dependence on the HOD with the size of the FVS.

We divide the FVS sample into three volume bins and computed the HOD for each one. The FVS sub-samples are defined as: $V_{\text{FVS}} < 2500 h^{-3}\text{Mpc}^3$, $2500 h^{-3}\text{Mpc}^3 < V_{\text{FVS}} < 5000 h^{-3}\text{Mpc}^3$ and $5000 h^{-3}\text{Mpc}^3 < V_{\text{FVS}}$. We analyse the be-
The HOD measured for different luminosity thresholds. The different panels show the results for magnitude limits $M_r - 5 \log(h)$ ranging from -17 to -20. Black solid lines represent the overall HOD, meanwhile, the red solid line the HOD measured inside the complete FVS catalogue. Red dashed lines are the HOD in FVS as a function of the global overdensity of luminosity, $\delta L_{\text{glob}}$. For each magnitude bin, the ratio between FVS HODs and overall HOD (solid black line in the main panels) are shown at the bottom of each panel. The uncertainties are calculated by the standard jackknife procedure.

For simplicity in Fig. 8 we only show the results for galaxies with $M_r - 5 \log(h) < -18$, within uncertainties. We perform this for the same absolute magnitude thresholds of the previous section and we found that the behaviour is the same for all samples. It is clear from the figure that there is not a significant correlation of the HOD behaviour and FVS volume in spite of the large-scale density dependence.

This is somewhat expected given that our FVS are regions with a great variety of volumes and luminosities (Sec. 3). Thus, for the same volume we can have structures with several luminosity densities. The volume of the FVS does not seem to be the parameter which defines the behaviour of the HOD, is their luminosity density.
4.3. Dependence on morphology of galaxies

As shown earlier in this section, for a dark matter halo in a certain mass range the number of galaxies that inhabit there is greater than average when the halo resides in an FVS. Now, we are interested in the study if these galaxies excess have a particular feature. In Luparello et al. (2015), the authors analysed the different morphological types of group central galaxies inside FVS, finding that most massive groups with a late-type central host a larger number of satellites when they reside in FVS. These central galaxies are more luminous and have a larger stellar mass content. Besides, these objects are redder and show a lower star formation activity and a longer star–formation time–scale. These results motivate us to study the behaviour of the HOD for different galaxy morphology in FVS.

We define the morphological type of a galaxy using the ratio between the stellar mass of the bulge, $M_*^{\text{bulge}}$, and the total stellar mass of the galaxy, $M_*^{\text{total}}$. Elliptical galaxies are defined as those with $M_*^{\text{bulge}} / M_*^{\text{total}} > 0.85$ and spiral galaxies as those with $0 < M_*^{\text{bulge}} / M_*^{\text{total}} < 0.85$. All galaxies with $M_*^{\text{bulge}} = 0$ are classified as irregulars. In Fig. 9 we show the resulting morphological fractions as a function of the stellar mass for MDPL2-SAG galaxies (solid lines), compared with the observational results obtained by Conselice (2006) (circles with errorbars) for the Third Reference Catalogue of Bright Galaxies (RC3, de Vaucouleurs et al. 1991). Elliptical galaxies are shown in red, spirals in blue and irregulars in green. As can be seen in the figure, there is an overestimation in the number of irregular galaxies for low stellar masses. Since morphology is not expected to be well defined in semi–analytic models, particularly for low resolution, we decide to use only galaxies with $M_* > 5 \times 10^9 h^{-1} M_\odot$ to address observational morphological type fractions.

Once defined the morphological samples, we compute the HOD for the complete catalogue and for galaxies in FVS. Results for four different magnitude thresholds are shown in Fig. 10, where the red lines correspond to elliptical galaxies, blue lines to spiral galaxies and green lines to irregular galaxies. In solid lines we show the results for the complete sample of haloes and in dashed lines for the FVS sample. The resulting HOD are presented in upper panels, meanwhile, bottom panels show the ratios between the measurements of FVS galaxies and the complete catalogue.

As expected, in the upper panels of Fig. 10, it can be seen that when fainter absolute magnitude thresholds are considered, haloes have a large population of spiral (late type) galaxies rather than elliptical (early type) galaxies; however, this tendency is reversed when we look at brightest absolute magnitudes. The behaviour of irregular galaxies across the absolute magnitude thresholds is also expected given the high $M_*^{\text{bulge}}$ threshold considered, which only has a significant population for the most massive haloes. The HOD of irregular galaxies are particularly low for $M_r - 5 \log_{10}(h) < -19$ and $-20$. 
In bottom panels of Fig. 10 can be appreciated that all morphological types follow similar behaviours for halo masses greater than $\sim 10^{13} h^{-1} M_\odot$, showing an excess of the HOD for galaxies inside FVS, and being this excess consistent with those presented in Fig. 6, where no morphological cuts were performed. We also notice a systematic excess in the fraction of spiral versus elliptical galaxies respective of the absolute magnitude thresholds. However, this is not statistically significant and it is consistent with Luparello et al. (2015) results where late-type central galaxies are those more affected when residing in FVS. We believe that these results require further analysis in observational data to address properly the interplay between HOD, environment and galaxy morphology.

5. Stellar content

The results presented in the previous sections indicate that, for a dark matter halo with a given mass above $\sim 10^{13} h^{-1} M_\odot$, the mean number of galaxies increases up to $\sim 20\%$ if the halo resides inside an FVS. In this section, we aim to investigate if galaxies inside these structures show different stellar content than the average. For our analysis, we split our sample into central galaxies and satellite galaxies, considering as satellite galaxies both type 1 and 2, as mentioned in Sec. 2.1, and we explore the mass and age of the stellar content from both galaxy samples.

5.1. Stellar mass content

For both the central galaxy and the satellite population we computed the mean stellar mass content for galaxies in haloes of a given mass: $\langle M_\star | M_{\text{halo}} \rangle$. This quantity was calculated for both central and satellites using all haloes with $M_\text{vir} < 5 \log_{10}(h) < -17$. Since we are interested in exploring the properties of central and satellite galaxies as a function of the total dark matter halo mass, we adopt the same $M_{\text{halo}}$ value corresponding to $M_{200c}$ (we do not use the subhalo mass for the satellites).

Fig. 11 shows, in the upper panel, the results from all central galaxies (solid red line), FVS central galaxies (red dashed line), all satellite galaxies (solid blue line) and FVS satellite galaxies (dashed blue line). Lower panel shows the ratio between the results considering only FVS galaxies and the complete sample. It can be seen that for the case of central galaxies, the results are consistent with Behroozi et al. (2010). We found that within dark matter haloes with a mass lower than $\sim 10^{13} h^{-1} M_\odot$ both central and satellite galaxies have up to $\sim 45\%$ more stellar mass when the halo is inside of a FVS. In haloes with mass above $\sim 10^{13} h^{-1} M_\odot$ the central galaxies have approximately the mean stellar mass regardless if the halo is in an FVS. On the other hand, satellite galaxies in FVS have a stellar content considerably lower than the average of the complete satellites sample, decreasing up to $\sim 50\%$. This difference in stellar content can be explained by the galactic harassment suffered by satellite galaxies in high-density regions (Gunn & Gott III 1972; Larson et al. 1980; Van Gorkom 2004; Pasquali & Nachname 2015). It is worth recalling that environmental effects on satellite galaxies are incorporated in SAG model via a gradual starvation of the hot gas halo driven by the combination of ram pressure and tidal stripping effects (Cora et al. 2018).

5.2. Mean age of stellar population

Another way to characterize the galaxy stellar population is through the parameter $T_\star$ provided by the semi-analytic model, which corresponds to the mean age of the stellar population of each galaxy at a given redshift. To explore a possible difference in the galaxies inside the FVS respect to the complete galaxy sample, we compute the distribution of this parameter on both samples. The results are shown in Fig. 12, where we can see that, in general, galaxies in FVS (red dashed line) have older stars than the global distribution (black solid line).

With the aim to explore if the differences between $T_\star$ distributions are produced by lower or higher mass haloes, we used the galaxies with $M_\text{vir} < 5 \log_{10}(h) < -17$ to compute the mean $T_\star$ in haloes of a given mass: $\langle T_\star | M_{\text{halo}} \rangle$. Again, for this analysis, we divide our galaxies sample in centrals and satellites.

Fig. 13 shows that for haloes with masses lower than $\sim 10^{13} h^{-1} M_\odot$, both FVS central (red dashed line) and satellite galaxies (dashed blue line) have stellar populations up to $\sim 25\%$ older than the overall results (solid red and blue lines, respectively). For haloes with masses greater than $\sim 10^{13} h^{-1} M_\odot$, there is no significant differences in the values of the mean $T_\star$ for galaxies in FVS and elsewhere.

6. Halo formation time in FVS

The dependence of a halo formation time on the environment has been previously reported by several works (e.g., Sheth & Tormen 2004; Maulbetsch et al. 2007). Even in a previous work Alfaro et al. (2020) show that for dark matter haloes residing in a cosmic void, the HOD is lower than the average. These haloes also presented slightly upper formation time than the mean. Now we have seen that HOD inside the FVS shows an increase compared to the overall behaviour. To explore a possible cause of the variation, in this section we studied the distribution of $z_{\text{form}}$, defined as the redshift in which a halo accreted the half of its maximum mass for the first time. As opposite to the behaviour in voids, we expect that the distribution of this parameter is above of the average for the haloes inside the FVS. Similarly, the high density regions analyzed in Sec. 4 should present an early halo formation compared to the mean, albeit later than in FVS.

We use the formation redshift given by the MDPL2 data, which corresponds to the redshift where each halo reached half of the peak mass over accretion history. The top panel of the Fig. 14 shows the cumulative fraction of $z_{\text{form}}$ from the haloes inside the FVS (red dashed line), from the S8+ sample (red dashed line) and from the complete catalogue (black solid line). The results show that the haloes inside FVS reach half of their maximum mass at larger redshifts than elsewhere. Similar findings are obtained for S8+ haloes, albeit with smaller differences with respect to average. This result is consistent with those obtained in Alfaro et al. (2020) for haloes inside cosmic voids, indicating that there is a correlation between the variation of the HOD and the particular formation history of the dark matter halo in extreme environments. We further explore this issue by analyzing the number of galaxies for the halo mass range $10^{14} - 5 \times 10^{14} M_\odot h^{-1}$ as a function of their formation redshift. As it can be seen in the bottom panel of Fig. 14 the number of galaxies residing in FVS and S8+ are significant larger than the overall values, a difference which increases at recent formation times.

In order to test whether the differences in the $z_{\text{form}}$ distribution is due to an excess of high mass haloes in densest regions, we also computed $z_{\text{form}}$ for different $M_{\text{halo}}$ bins. Fig. 15 shows the $z_{\text{form}}$ as a function of $M_{\text{halo}}$ for the complete halo catalogue (dark solid line), the FVS haloes (red solid line) and the S8+ haloes (red dashed line). We conclude that in general, $M_{\text{halo}} < 10^{13} h^{-1} M_\odot$ haloes residing in the densest regions were
formed before. This difference is more important for haloes in FVS than in the S8+ environments.

7. Summary and conclusions

HOD is a powerful tool linking galaxies to their host dark matter halo. Throughout this work, we have studied its behaviour in FVS, superstructures with the highest luminosity spatial densities in the Universe. For this purpose, we used FVS identified in MDPL2-SAG simulated galaxy catalogue where galaxies populate dark matter haloes of the MDPL2 cosmological simulation through the SAG semi-analytic model of galaxy formation and evolution.

We find that supersuctures defined as FVS host approximately 90 per cent of the 1000 first ranked galaxies in stellar mass content. This is a considerable effect taking into account that the total volume of the FVS catalogue is only ~ 0.56 per cent of the total simulated box. Furthermore, when we separate our galaxy samples into centrals and satellites this result persists for both populations.
We find a statistically significant difference in the HOD of haloes residing in FVS with respect to the average simulation values. This difference increases in the central regions of the FVS, where the value of the $\delta_{\text{glob}}$ parameter increases towards the densest regions. This indicates that the effect is directly related to the luminosity density of the large-scale environment. We find that haloes with masses lower than $\sim 10^{13} h^{-1} M_\odot$ do not present significant variations in their HOD. This indicates that for these haloes, the formation of the central galaxy is nearly independent of the large-scale environment density. This fact is consistent with the lack of dependence of the low mass HOD in voids found by Alfaro et al. (2020). For larger masses, haloes in overdense regions require less mass than the average to host a larger number of satellites. This effect does not depend on the FVS volume nor on galaxy luminosity.

With the aim of analysing the behaviour of different morphological types residing in haloes within FVS, we use the ratio $M_{\text{bulge}}/M_{\text{total}}$ to separate the samples. By imposing a minimum stellar mass threshold of $5 \times 10^9 h^{-1} M_\odot$, we obtain a distribution of morphological fractions consistent with the observational data. As shown in Sec. 4.3 the differences of HOD inside FVS with respect to the global behaviour are present for all morphological types. For haloes with $M_{\text{halo}} \gtrsim 10^{13} h^{-1} M_\odot$ residing in FVS we find an excess of galaxies of all morphological types, more important for spiral and irregulars. For lower halo masses, the number of irregulars is marginally lower, although this may be due to the stellar mass cutoff.

We argue that the reproduction of this analysis in observational data may be important since previous results (Luparello et al. 2015) show differences in galaxy properties when considering their different morphological types inside the FVS.

The results of Sec. 5 show that in the FVS, the lower mass haloes (less than $\sim 10^{13} h^{-1} M_\odot$) have a higher mean stellar mass per galaxies than average. For FVS haloes with masses above $\sim 10^{13} h^{-1} M_\odot$, satellite galaxies show a mean stellar mass content considerably lower than average. On the other hand, in the most massive haloes, the mean stellar mass of central galaxies do not present significant variations. We find that the distribution of the $T_\star$ parameter of galaxies in massive haloes residing in FVS is more extended than average. For lower mass haloes, both central and satellites show stars with a mean age up to $\sim 20\%$ higher
than average. This difference decreases considerably for the most massive haloes.

Regarding the formation times, the results of Sec. 6 show that FVS haloes exhibit higher $\zeta_{form}$ values. Besides for a representative mass range, we find that a given formation time, haloes residing in FVS are more densely populated by galaxies than elsewhere.

If different definition of high-density environment is used, we find remarkably similar HOD and halo properties under the restriction that these different characterizations correspond to a similar fraction of objects at high density.

We conclude that the differences found in this work regarding to the population of haloes residing in FVS is relevant for further studies of the galaxy–halo connection. Our results suggest that assembly bias would have a significant impact on HOD, in particular, when we take into account the large scale density environment.

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Fig. 14. Top panel: Cumulative fraction of the formation redshift of haloes, $\zeta_{form}$, for haloes inside FVS (red dashed line), all haloes (black solid line) and S8+ haloes (red dashed line). Bottom panel: Mean number of galaxies for the halo mass range $10^{14} - 5 \times 10^{14} M_{\odot} h^{-1}$ as function of the formation redshift. The line types are the same as in the top panel.

Fig. 15. Halo formation redshift, $\zeta_{form}$, in function of halo mass. The black solid line correspond to the complete halo catalogue, the dashed red line to the S8+ haloes and the solid red line to haloes inside of a FVS.
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