The impact of galaxy formation on satellite kinematics and redshift-space distortions

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ABSTRACT

Galaxy surveys aim to map the large-scale structure of the Universe and use redshift space distortions to constrain deviations from general relativity and probe the existence of massive neutrinos. However, the amount of information that can be extracted is limited by the accuracy of theoretical models used to analyze the data. Here, by using the L-Galaxi1es semi-analytical model run over the MXXL N-body simulation, we assess the impact of galaxy formation on satellite kinematics and the theoretical modelling of redshift-space distortions. We show that different galaxy selection criteria lead to noticeable differences in the radial distributions and velocity structure of satellite galaxies. Specifically, whereas samples of stellar mass selected galaxies feature satellites that roughly follow the dark matter, emission line satellite galaxies are located preferentially in the outskirts of halos and display net infall velocities. We demonstrate that capturing these differences is crucial for modelling the multipoles of the correlation function in redshift space, even on large scales. In particular, we show how modelling small scale velocities with a single Gaussian distribution leads to a poor description of the measure clustering. In contrast, we propose a parametrization that is flexible enough to model the satellite kinematics, and that leads to an accurate description of the correlation function down to sub-Mpc scales. We anticipate that our model will be a necessary ingredient in improved theoretical descriptions of redshift space distortions, which together could result in significantly tighter cosmological constraints and a more optimal exploitation of future large datasets.

Key words: galaxies:high-redshift – galaxies:evolution – methods:numerical

1 INTRODUCTION

The gravitational law and the amount of matter in the Universe are fundamental aspects of the cosmological model. A key topic in observational cosmology is to probe these by measuring the growth of structure encoded in the parameter $f = \frac{d}{d \ln a}$, where $D$ is the linear growth factor at the scale factor $a = (1+z)^{-1}$. The value of the growth rate, $f$, and its evolution with redshift has been used to constrain departures from General Relativity and explore alternative gravity theories (Guzzo et al. 2008). Additionally, $f$ can also be employed to constrain the presence of massive neutrinos, which introduces a scale-dependent growth of structure (Beutler et al. 2014).

The most accurate measurements of cosmic growth rate originate from the observed anisotropy in the two-dimensional correlation function of galaxies. Distances to galaxies are inferred from their redshift, a combination of the Hubble expansion and their peculiar velocity. Thus, galaxy clustering along the line of sight differs from that on the perpendicular direction, the former being distorted by the velocity field (Jackson 1972; Sargent & Turner 1977). This, in turn, depends on the growth rate. This anisotropy in the clustering, known as redshift-space distortions (RSDs), is therefore sensitive to the value of $f$.

Early attempts at interpreting the anisotropic clustering signal have shown the feasibility of the measurement and the power of RSDs as a cosmological probe (e.g. Peacock et al. 2001; Hawkins et al. 2003). To date, the best constraints on $f$ were obtained by analyses of the Baryon Oscillation Spectroscopic Survey (BOSS). The combination $f\sigma_8$, with $\sigma_8$, the root-mean-square linear fluctuation of the mass distribution on scales of $8\, \text{Mpc}/h$, was measured with a precision of $\sim 6\%$ at the redshifts $z = 0.38, 0.51$, and $0.61$ (Alam et al. 2016). At higher redshifts, the best constraints were placed by VIPERS with a $\sim 11 \sim 20\%$ precision at $z = 0.86$ (de la Torre et al. 2016; Mohammad et al. 2017). Given the accuracy of the measurements, the constraints are fully consistent with the predictions of general relativity and massless neutrinos.

In the near future, a new generation of multi-object spectroscopic surveys, such as HETDEX, 4MOST, DESI, PFS and eBOSS (Hill et al. 2008; de Jong et al. 2012; Weinberg et al. 2013; Takada et al. 2014; Delubač et al. 2017), and the space missions Euclid and WFIRST (Laureijs et al. 2010; Spergel et al. 2015), will aim at significantly improving current measurements. The goal is to map a larger number of galaxies, over bigger volumes, and at redshifts...
above 1. The larger volume will reduce the statistical errors, and the extended redshift coverage should help distinguishing different cosmologies and/or gravity models (see, e.g. Linder 2016). For an optimal exploitation of these datasets, upcoming surveys require an accurate modelling of the density and velocity fields as traced by galaxies, as well as how these are affected by galaxy formation physics.

Over the last couple of years, there has been significant progress on improving the theoretical models of RSDs for dark matter and halos (Scoccimarro 2004; Tinker 2007; Okumura et al. 2015; Wang 2016; Kopp et al. 2016; Bose & Koyama 2017). As a result, scales much smaller than those described by linear theory are used in cosmological analysis. For instance, Sanchez et al. (2016) claims to obtain cosmological constraints with BOSS data on scales above $s \gtrsim 20$ Mpc$/h$, consistent with the limit found with dark matter simulations in White et al. (2015). In the future, advances in numerical simulations, emulators and perturbation theory will likely improve the theoretical descriptions of clustering, allowing to reach even smaller scales.

The next frontier in the modelling of RSDs will be to understand the galaxy scale-dependent bias and their velocity field, specifically satellite kinematics. Currently, there is widespread use of simplified treatments to account for small-scale velocities (Bianchi et al. 2015; Uhlemann et al. 2015; Bianchi et al. 2016; Zheng et al. 2017). However, as we will show in this paper, this is inaccurate and not physically motivated, but instead shaped by galaxy formation processes.

The role of galaxy formation is enhanced by the varied selection criteria of future surveys. A common target of future surveys are the so-called emission-line galaxies (ELGs). ELGs are abundant at high redshifts, and their redshift can be precisely measured by identifying narrow strong emission lines in their spectra. However, ELGs are comparatively much less understood than the Luminous Red Galaxies (LRGs) targeted by BOSS. These objects are highly biased, abundant galaxies with a similar stellar mass and an accurate redshift determination, provided by a 4000Å break spectral feature typical of old stellar populations (Padmanabhan et al. 2007). Instead, ELGs are expected to have lower bias, sample a wider range of stellar masses, and possibly be more affected by environmental effects such as ram pressure stripping and by assembly bias.

In this scenario, the upcoming data is presenting a serious challenge for its optimal interpretation: to significantly improve the theoretical understanding of the structure of the velocity fields over the widest possible range of scales, and, in particular, regarding its connection to galaxy formation physics. This is the problem we address here.

In this paper we study how the redshift space clustering and kinematics of galaxies is shaped by galaxy formation processes. For this, we make use of a semi-analytical model of galaxy formation embedded in a very large N-body simulation. Therefore, the relation between the location and velocity of a dark matter structure and the properties of the galaxy it hosts, is a direct prediction of an ab initio modelling of galaxy formation physics. This includes tracking the evolution from hot gas in halos to detailed star-formation histories, feedback processes, mergers and instabilities triggering starbursts, etc. Rather than attempting to predict the correct clustering of a particular galaxy population, we aim at exploring how different galaxy populations deviate from a simple prescription, and identify the ingredients that can help improving the description of galaxies for probing cosmology incorporating the small-scale regime.

We illustrate the differences in clustering expected between ELGs and LRGs. In particular, we show that ELGs are hosted by lower mass halos and have lower satellite fractions. Interestingly, these satellites are preferentially located in the outermost parts of halos and feature a net infall velocity component. We propose a physically-motivated parametrization of the intra-halo velocity field that can capture accurately these aspects and show that this is sufficient to model the first three non-zero multipoles of the correlation function down to $\sim 1$ Mpc$/h$.

This paper is organized as follows: Section 2 describes the tools and strategy we use throughout this work. Section 3 discusses the overall properties, host halo mass distributions, number density profiles, and clustering of galaxy samples. Section 4 compares different descriptions of intra-halo velocities in terms of their performance in clustering analysis for galaxy surveys. In Section 5 we discuss applications and possible extensions of our work. Finally, we summarize our main findings in the conclusions.

2 METHODOLOGY

In this section we discuss the tools and strategy used in this work to explore the impact of galaxy formation on redshift-space distortions. We start by describing how we obtain theoretical predictions for the distribution and properties of galaxies (§2.1), and then describe the selection criteria we employ to define ELGs and LRGs samples (§2.2). Finally, we move on to detailing how we estimate the 2-point correlation function and its covariance matrix (§2.3).

2.1 The joint numerical modelling of galaxies and their dark matter halos

The results presented in this work are based on a galaxy formation model applied over the merger history of dark matter structures extracted from a very large N-body simulation. Before describing these two ingredients separately, we emphasize that throughout this paper we do not focus on developing a new galaxy formation model to improve the agreement with observational data. Such exercise is beyond the scope of this paper. Instead, we make use of a state-of-the-art galaxy formation model to develop a model description that incorporates the impact of galaxy formation processes in the clustering of galaxies.

The simulation used in this work is the Millennium-XXL (MXXL) run, described in full detail in Angulo et al. (2012). This is a dark matter only simulation of 6720$^3$ particles over a cubic volume of $27(\text{Gpc}/h)^3$. The particle mass resolution is $m_p = 6.1 \times 10^9 M_\odot/h$. The cosmological parameters are identical to those of earlier Millennium runs, i.e. a flat cosmology with $h = 0.73, \Omega_m = 0.25, \Omega_k = 0.75, n = 1$ and $\sigma_8 = 0.9$.

The galaxy formation used is a variant of the L-Galaxies semi-analytical model presented in Guo et al. (2011). Briefly, the semi-analytical technique models the growth and evolution of galaxies in a hierarchical universe by following the evolution of gas, stars and metals throughout the merger histories of dark matter halos. The main physical processes included are: the shock-heating of gas in dark matter halos followed by radiative cooling, which forms a cold gas component that settles into a rotating disk at the bottom of the gravitational potential well; the subsequent formation of stars, metals and the chemical enrichment of the gas, all modulated by feedback mechanisms such as those caused by supernovae and by the energy released by an active galactic nucleus (AGN); spheroid formation as a result of galaxy merger and disk instability.
episodes; the growth of a supermassive black hole in the centre of each galaxy; and the computation of observed properties by combining the star-formation histories of individual galaxies with a stellar population synthesis code. The free parameters of the model are set by matching a diverse set of observations that do not include RSDs. It is thus worth emphasizing that our predictions for the velocity field of galaxies are a result of physical assumptions.

The mass resolution of the MXXL is a factor of \( \sim 8 \) worse than that of the Millennium simulation (Springel et al. 2005). Hence, some modifications were needed to improve numerical convergence with those obtained with the same variant of the code over the Millennium simulation. Briefly, these corrections are: i) A galaxy drawn from the Millennium simulation, hosted by a halo at the same redshift and mass, is placed in newly formed halos (i.e. those that up-cross the detection threshold for the first time); ii) merger trees are extended to lower halo masses to account for the effect of minor mergers that are unresolved in the MXXL. The details and convergence tests of these two corrections are discussed in length in Angulo et al. (2014). Here we simply recall that the real-space correlation function of stellar-mass selected galaxies shows good agreement with that computed from the Millennium simulation.

We apply further modifications to improve convergence of the satellite galaxy population in redshift space. L-Galaxies identifies galaxies as type 0 (i.e. central galaxies), type 1 (satellites with a sub-halo), and type 2 (orphans, i.e. satellites without a sub-halo). The latter type occurs when a galaxy’s sub-halo has vanished at a particular snapshot of the simulation, due to mass disruption events or resolution effects. In the variant of the model run over the Millennium simulation, the position and velocity of type 2 galaxies are assigned by tracking the most-bound particle of the last resolved sub-halo structure. Unfortunately, due to huge data storage requirements, there is no particle information stored for the MXXL simulation. The type 2 positions are thus calculated from the last time their sub-halo was identified, after which point it is assumed that their radial distance to the host halo centre shrinks as the square root of the elapsed dynamical friction timescale. Additionally, the velocity of type 2 galaxies are frozen to the last recorded value for the sub-halo and then its direction randomized relative to the centre of the main host halo (assuming that these objects lie within the virial radius \( R_{\text{vir}} \), see section 2.2).

We have checked that these modifications result in better agreements with the statistics measured from the Millennium simulation. Specifically, in the Appendix we show that the detailed spatial and velocity distribution of our galaxy samples converge for scales above \( r \approx 100 \text{kpc}/h \).

### 2.2 Construction of the galaxy samples

Employing the theoretical galaxy catalogues described in the previous section, we can build samples that mimic the selection criteria for current and future surveys.

The previous generation of cosmological galaxy surveys targeted mostly red and massive galaxies. To mimic such samples, we rank order our galaxies according to the predicted stellar mass and select objects with a global number density \( n = 10^{-3} h^3 \text{Mpc}^{-3} \). Future surveys will, however, also target galaxies with strong emission lines originated by ionizing radiation from young massive stars. These stars are short-lived, thus these samples can be regarded as selected by star formation rate. Other astrophysical properties, such as the gas-phase metallicity and ionization parameter of H\( \text{ii} \) regions also determine the strength of a nebular emission line (Orsi et al. 2014). However, they introduce relatively minor dependencies and are neglected here. Therefore, to mimic samples of ELGs we simply select galaxies in a ranked ordered list according to the predicted star formation rate.

We note that by selecting galaxies according to a given abundance, we can compare both galaxy samples more directly and also reduce the sensitivity of our results to possible mismatches between the predicted and observed stellar mass functions or star formation rates. Additionally, we note that we consider only the \( z = 1 \) snapshot, motivated by the target redshift of upcoming surveys, however, our results can be qualitatively extended to any redshift range.

Finally, additional observational constraints, such as colour selections, contamination fractions and other instrumental features would be necessary to fully mimic a survey selection. However, we neglect these effects here as our goal is to illustrate how the main physical features (e.g. stellar-mass vs. star-formation rate) translate into different clustering properties. The construction of detailed mock catalogues representing large cosmological surveys is out of the scope of this paper, but such calculation can be found elsewhere (see, e.g. Orsi et al. 2010; Merson et al. 2013).

### 2.3 Clustering measurements

We characterize the clustering of the galaxy samples using the two-point correlation function. Since the simulation box is periodic, we can compute the 2-point auto-correlation function \( \xi(r) \) using the direct estimator:

\[
\xi(r) = \frac{DD(r)}{\bar{n} \Delta V(r)} - 1, \tag{1}
\]

where \( DD(r) \) stands for the number of pairs of objects within a radial bin centered at \( r \) normalized by the total number of pairs, \( \bar{n} \) is the number density of objects in the simulation box, and \( \Delta V(r) \) is the volume of a spherical shell centered at \( r \).

To estimate errors in the measurements, we construct a covariance matrix using the sub-sample method. This consists in subdividing the full simulation box into smaller boxes and computing the clustering in each of these. We divide the simulation into \( N_t = 216 \) sub-boxes of length 500 Mpc/\( h \). The covariance matrix elements are thus estimated as:

\[
C_{ij} = \frac{1}{N_t} \left\{ \frac{1}{N_i - 1} \sum_k \left[ (w_i - \bar{w})(w_j - \bar{w}) \right] \right\}, \tag{2}
\]

where each \( w \) corresponds to a vector that contains a series of clustering measurements concatenated over a given scale range. Since now each sub-box is not periodic, we compute the auto-correlation function using the Landy & Szalay estimator (Landy & Szalay 1993):

\[
\xi(r) = \frac{DD(r) - 2DR(r) + RR(r)}{RR(r)}, \tag{3}
\]

where \( RR(r) \) is the number of pairs of objects from a random catalogue at distance \( r \), and \( DR(r) \) is the number of random objects around data objects. Finally, we scale the resulting covariance matrix with the inverse of the volume of interest (Klypin & Prada 2017).

Throughout this work, we focus on the anisotropic clustering signal that results from the line-of-sight velocities of galaxies distorting their apparent redshift. We assume the distant observer ap-
proximation, and define the line-of-sight redshift-space coordinate \( s \) as:

\[
s = r_z + \frac{v_z}{aH(z)},
\]

where \( r_z \) is an arbitrary cartesian coordinate representing the line-of-sight direction, \( v_z \) is the peculiar velocity component along this direction, \( a = (1+z)^{-1} \) and \( H(z) \) is the Hubble parameter at redshift \( z \).

The anisotropic redshift-space correlation function is obtained by computing the two-point correlation function as a function of perpendicular \( r_z \) and parallel \( r_t \) positions, \( \xi(r_z, r_t) \). This can be expressed as a multipole expansion in Legendre polynomials \( L(\mu) \). Each multipole term of order \( \ell \) is computed as:

\[
\xi(\ell) = -\frac{2\ell + 1}{2} \left( \frac{\pi}{2} \right)^{\ell/2} \int_0^\infty \left( 1 - \mu^2 \right)^{\ell/2} L(\mu) \mu d\mu,
\]

where \( \mu = s/r_z = \cos \theta, s = \sqrt{r_z^2 + r_t^2}, \) and \( \theta \) is the angle of \( s \) with respect to the line-of-sight direction. We note that, in linear theory, the redshift-space clustering is fully characterized by the monopole (\( \ell = 0 \)), quadrupole (\( \ell = 2 \)) and hexadecapole (\( \ell = 4 \)).

3 THE PROPERTIES OF LRG AND ELG GALAXY SAMPLES

In this section we explore the overall properties of our galaxy samples. We start by presenting differences in the distribution of host halo masses for LRGs and ELGs (§3.1) and the radial distribution of satellites inside these halos (§3.2). We then show how these differences propagate to the real-space correlation function (§3.3) and to the multipoles of the redshift-space correlation function (§3.4).

3.1 The halo occupation distributions

The two galaxy samples described before populate dark matter halos of different masses and properties. Fig. 1 shows the halo mass distribution of the LRG and ELG galaxy samples. Both samples span roughly the same halo mass range but the LRG sample is typically hosted by more massive halos than the ELG sample. The average host halo mass is \( \langle M_{\text{halo}} \rangle = 4.8 \times 10^{12} M_\odot/h \) for the LRG sample, and \( \langle M_{\text{halo}} \rangle = 7.8 \times 10^{11} M_\odot/h \) for the ELG sample. Additionally, the bottom panel of Fig. 1 shows the satellite fraction \( f_{\text{sat}} \) of both galaxy samples as a function of the host halo mass. Below \( M_{\text{halo}} \sim 10^{12} M_\odot/h \), the ELG sample is almost exclusively made up of central galaxies, whereas above that threshold almost all galaxies are satellites, \( f_{\text{sat}} \sim 1 \), with a slight decrease at higher masses. On the other hand, a much more gradual increase in the satellite fraction can be seen in the LRG sample: the transition from \( f_{\text{sat}} \sim 0 \) to 1 occurs over two orders of magnitude in mass. Table 1 summarizes the main properties of both galaxy samples.

The above trends can be understood in terms of the galaxy formation physics shaping the star formation and build up of stellar mass of central and satellite galaxies. At first order, the stellar mass of a galaxy reflects the total amount of baryons it had available throughout its life to transform into stars. Thus, the features seen in the LRG sample reflect those of a population of dark-matter mass selected halos and satellite subhalos: as we consider halos of higher masses, their abundance decreases smoothly while their number of satellites increases.

On the other hand, the star formation of a galaxy is modulated by feedback and environmental effects. Massive galaxies in large halos are expected to be more frequently under strong star formation regulating mechanisms (e.g. AGN feedback) and thus, present low star formation rates. Additionally, low star formation rates are also expected in galaxies hosted by low mass halos due to a combination of other quenching mechanisms (e.g. supernova feedback) and the smaller amounts of baryons available. For these reasons most of central galaxies are located in halos of \( \sim 10^{12} M_\odot/h \). Satellite galaxies, on the other hand, will be additionally quenched by tidal and ram-pressure stripping of their hot gaseous halo. The timescale for these is relatively short, nevertheless, while still active, these satellite galaxies dominate the number counts over the more massive but low-star forming centrals, which drives the satellite fraction close to unity above masses \( \sim 10^{13} M_\odot/h \).

3.2 The number density profiles of satellite galaxies

The physical processes discussed above not only affect the host halo mass distribution, but also the regions in the halo preferentially occupied by different galaxies. As an example, Fig. 2 shows the radial distribution of satellites within host halos of mass \( \log M_{\text{halo}} [M_\odot/h] = 13.5 \pm 0.5 \). The LRG sample features a high density of satellites towards smaller radii, whereas the ELG sample peaks at the outskirts of their host halo, \( r \sim 0.5 Mpc/h \). Although

| Galaxy sample property | LRG | ELG |
|------------------------|-----|-----|
| Min. stellar mass, \( M_{\text{stellar}}^{\text{min}} M_\odot/h \) | \( 3.2 \times 10^{10} \) | \( 1.4 \times 10^9 \) |
| Min. star-formation rate, SFR_{\text{min}} M_\odot/yr | 0.0 | 9.1 |
| Mean stellar mass, \( \langle M_{\text{stellar}} \rangle M_\odot/h \) | \( 4.5 \times 10^{10} \) | \( 2.3 \times 10^{10} \) |
| Mean star-formation rate, \( \langle \text{SFR} \rangle M_\odot/yr \) | 4.22 | 14 |
| Mean halo mass, \( \langle M_{\text{halo}} \rangle M_\odot/h \) | \( 4.8 \times 10^{12} \) | \( 7.8 \times 10^{11} \) |
| Total satellite fraction, \( f_{\text{sat}} \) | 0.22 | 0.12 |
| Clustering bias, \( b \) | 1.84 | 1.02 |
not shown here, this qualitative picture is found on halos of all masses.

The origin of such difference is the same physics discussed before: satellite galaxies can present high star formation rates only for a short period after the relatively fast-acting tidal and ram pressure stripping has starved the galaxy of its gas reservoir. Therefore, satellite ELG will be preferentially located in the outskirts of the halo where recently accreted subhalos are found. The stellar mass, on the other hand, is more resilient to these effects and a galaxy can pass our LRG selection threshold even after several dynamical times after accretion.

To show this explicitly, we split satellites according to the infall time to their host halo. Those sub-halos accreted within the past \( \sim 680 \) Myr (green shaded regions in Fig. 2), have not experienced their first pericenter passage and make up for a significant fraction of the ELG sample. Naturally, these objects are preferentially located in the outskirts of their host halo. On the other hand, galaxies accreted recently are less common in the LRG sample and can be located also in the central regions of the halo.

We stress that we expect our results to be qualitatively correct regardless of the assumptions and parameters of our semi-analytic galaxy formation model. Quantitatively, however, the lack of star forming galaxies in the center of halos is determined by poorly constrained satellite quenching timescales; the cupiness of LRGs radial distribution is given by how efficient tidal stripping of stars. This is only approximately treated in our model after the stripping of dark matter in subhalos. Nevertheless, we anticipate that all the relevant ingredients will be modelled and constrained better in the future thanks to observational estimates of quenching timescales (e.g. Wetzel & White 2010), and comparing to more accurate hydrodynamical simulations (e.g. Springel et al. 2017).

3.3 Assembly bias in the galaxy samples

Halo clustering is not only a function of the mass, but it also depends on other properties such as formation time, concentration, spin (see, e.g. Gao et al. 2005; Wechsler et al. 2006; Gao & White 2007; Angulo et al. 2008; Lacerna & Padilla 2011; Hearin et al. 2016; Zehavi et al. 2017) – an effect usually referred to as assembly bias. The physical processes discussed before can preferentially select for host halos with certain properties besides their mass. Therefore, our galaxy samples could display clustering statistics that amplify or suppress assembly bias.

Fig. 3 shows the distribution of formation redshifts (defined as the redshift when half of the mass was first acquired) of the host halos of central and satellite galaxies in our samples. We show results for two host halo mass ranges and for ELGs and LRGs, as indicated by the legend. Each of our measured distributions (green histograms) is compared with a control sample computed using a random set with the exact same distribution of halo masses (orange histograms).

Central LRGs are preferentially in halos older than the average. This can be a consequence of the higher-than-average stellar mass of central galaxies in older halos owing to the longer times those galaxies have had to build their stellar content. This effect is less pronounced at high halo masses, reflecting the fact that almost all of those high mass halos will contain galaxies that pass our selection criteria. Central ELGs in low mass halos have very similar formation redshifts as those of the control sample, suggesting that the quenching of central galaxies at a fixed halo mass is a somewhat stochastic process. At high masses, on the other hand, ELGs are preferentially in younger halos, which is expected because of the connection between mass accretion and star formation rates.

Satellite galaxies of both types, and in host halos mass ranges explored, are preferentially found on halos more recently formed than those in the control samples. Additionally, there does not ap-
appear to be significant differences between the formation times selected by our ELG and LRG criteria. Therefore, the preference appears to be a consequence of younger halos having a more abundant satellite population reflecting a larger fraction of their mass to be recently acquired through mergers (e.g. Zentner et al. 2005; Chaves-Montero et al. 2016; Zehavi et al. 2017; Contreras et al. 2017).

Because of lower satellite fractions and a weaker correlation between formation time and star formation rate in central galaxies, we expect assembly bias to be less important for ELGs than for LRGs. A detailed quantification and characterization of this effect is beyond the scope of this work. Nevertheless, the effects discussed above illustrate how galaxy formation couples to halo properties and is expected to leave imprints in the galaxy clustering on all scales. Thus, these effects should be incorporated for an accurate and complete modelling of galaxy clustering.

### 3.4 The real-space clustering of galaxies

The differences in the distribution of host halo mass, formation times, and radial profiles discussed above result in differences in galaxy clustering. This is shown in Fig. 4, where the correlation function of both galaxy samples is displayed normalized by their respective linear bias parameter squared (making both curves match at large scales), and multiplied by the scale $s^2$ to enhance features. Operationally, we compute the bias parameter by taking the average of the ratio between the real-space correlation functions of each galaxy sample over the correlation function of the dark matter at scales $40 < r [\text{Mpc}/h] < 70$.

The LRG sample features a higher bias, $b = 1.86$, than the ELG sample, $b = 1.04$, owing to the higher abundance of massive host halos compared (c.f. Fig. 1). On large scales, $r > 40 \text{Mpc}/h$, both galaxy samples are a linearly scaled version of the linear dark matter correlation function. On intermediate scales, however, differences are clearly visible owing to nonlinear galaxy biases with ELG showing the larger deviations. On small scales, $r < 10\text{Mpc}/h$ the differences are enhanced due to the different typical host halo masses and radial distributions: the larger host halos and steeper number density profiles of LRG produce a correlation function with a much more pronounced 1-halo term.

### 3.5 The redshift-space clustering of galaxies

The clustering in redshift space is affected by the properties discussed above and also by the peculiar velocity of galaxies along the line of sight. We show this in Fig. 5, which compares the monopole ($\ell = 0$), quadrupole ($\ell = 2$), and hexadecapole ($\ell = 4$) of the redshift-space correlation function of our two galaxy samples. Note that we display the correlation function times $\ell^2 s^2$ to enhance the dynamic range shown.

The differences in satellite fractions and host halo mass can explain part of the differences we see in Fig. 5: the higher bias of the LRG sample implies monopole and quadrupole with larger amplitude compared to those of the ELG samples. The differences on smaller scales and for $\ell \neq 0$ multipoles, however, are mostly caused by the differences in the satellite kinematics, as we will show next.

#### 3.5.1 The importance of satellite kinematics

To quantify the role of satellite kinematics for RSDs, we will compare the clustering of samples with different distributions of satellite velocities relative to that of the host halo (thereafter “intra-halo”) velocities but that are identical otherwise.

We start by computing a correlation function, $\xi_{3D} = 0$, where all intra-halo velocities were set to zero. In redshift space, by construction this sample of objects displays no Fingers-of-God effect, since all velocities are coherent inside a halo. We then convolve $\xi_{3D}$ with different intra-halo velocity distribution functions, $P(v_{los})$:

$$\xi_{i}(r_{50}, r_{78}) = \int_{-\infty}^{\infty} dv_{los} \xi_{3D}(r_{50}, r_{78}, v_{los}) P(v_{los}) \xi_{3D}(r_{50}, r_{78}, v_{los}) \xi_{3D}(r_{50}, r_{78}, v_{los}) \xi_{3D}(r_{50}, r_{78}, v_{los})$$

and compute the respective multipoles following Eq. 5.

We consider three different $P(v_{los})$:

i) The first one corresponds to a model with zero intra-halo velocity, i.e. $P(v_{los}) = \delta_{G}(0)$.

ii) The second one describes intra-halo velocities as a Gaussian variate, i.e. $P(v_{los}) = \mathcal{N}(0, \sigma_{v})$.

iii) The third one follows a model that will be presented in forthcoming sections and that it captures non-zero net infall velocities, host halo mass dependencies, and anisotropies.

To illustrate the impact of intra-halo velocities, in Fig. 5 we compare the clustering of these three cases (lines) with the multipoles measured in our original catalogues (symbols). We can see that the case with no intra-halo velocities is a fairly good description of the ELGs multipoles but performs poorly for the LRG sample. This is because the larger satellite fraction and higher halo mass typical of LRGs compared to ELGs imply higher typical velocities relative to that of the host halo (thereafter “intra-halo”) velocities but that are identical otherwise.

The second case, where we set $\sigma_{v}$ to the standard deviation measured in our catalogues (170 and 97 km/s for the LRG and ELG samples, respectively), produces correlation functions that differ strongly from the true ones. We highlight that modelling small-scale velocities as Gaussian deviates is a widely-spread practice in large-scale structure and RSD analyses. Our results, however, indicate that a Gaussian is a very poor description of the true velocity distributions. In fact, neglecting intra-halo velocities altogether is a better assumption because most galaxies in a sample will be centrals and, thus, are expected to be at rest with respect to the host halo.

As an additional test, we have repeated our analysis using the value of $\sigma_{v}$ that best fits the measured multipoles ($\sigma_{v} \sim 50 \text{ km/s}$ for the LRG sample and $\sigma_{v} \sim 0$ for the ELG sample). In this way, the
Gaussian model can provide a reasonable description of the clustering but only on scales above $s \sim 10 - 20 \text{Mpc}/h$. In general, we expect its performance to depend on the details of the sample: redshift range, selection criteria, galaxy formation physics, etc, as well as on the combination of multipoles and minimum scale used in the fit. The dependence on these details is simply because considering these velocities as random Gaussian deviates is not accurate, and neither physically-motivated, as we will show later.

The above illustrates that intra-halo velocities imprint significant features in the multipoles of the correlation function, and that a more sophisticated modelling given the accuracy and importance of RSD measurements is needed. In the upcoming sections we will focus on developing a minimal but physically-motivated description of intra-halo velocities. The resulting correlation functions of this model are shown by the solid lines in Fig. 5, where we can see that it can correctly capture the behavior in both ELG and LRG samples down to 1 Mpc$/h$. Next we will motivate and discuss the ingredients of the model and show that it is not only accurate but also flexible enough to capture the expected diversity induced by different galaxy selection criteria.

4 AN IMPROVED DESCRIPTION OF SATELLITE KINEMATICS

The analysis of the previous section indicated that an accurate model of the redshift-space galaxy clustering should incorporate a correct description of the small-scale velocities. In particular, we showed that modelling these intra-halo velocities as Gaussian variables with zero mean produces correlation functions that differ systematically from the true ones. We now explore the reason behind this.

In Fig. 6 we show the distribution of the line-of-sight component of intra-halo velocities, $P(v_{los})$, for ELGs and LRGs as blue and red histograms, respectively. Since the fraction of satellites is in both cases small, the distributions are dominated by a strong peak at zero\(^1\). Therefore, the term $\sigma_v$ in Eq. (6) cannot be directly related to the actual intra-halo velocity dispersion but to a mixture of velocity dispersions weighted by satellite fractions. All this explains why the Gaussian model did not agree well with the measured multipoles and why completely neglecting intra-halo velocities lead to a more accurate model (c.f. Fig. 5).

A simple extension of the Gaussian model is to describe the distribution of intra-halo velocities as a mixture of a Dirac delta function (representing central galaxies) and a Gaussian (capturing satellite kinematics):

\[^1\] In our model, central galaxies have the velocity of the host subhalo. Note that there are indications that the central galaxy might not be at rest relative to the host (see, e.g. Guo et al. 2015a). The expected velocity bias is, however, small compared to the virial velocity of the host halo, thus we expect this to only slightly broaden the distribution of $v_{los}$.
Figure 7. The line-of-sight velocity distribution of the LRG (top) and the ELG samples (bottom) for satellite galaxies in three host halo mass bins centered in log($M_h$) = 13, 13.5, 14.0, shown by the coloured histograms, with colours according to the legend. The solid gray lines correspond to Model C. The dashed gray line results from fitting a Gaussian to the distribution of velocities of each galaxy sample.

\[
\mathcal{P}(v_{\text{los}}) = (1 - f_{\text{sat}}) \delta_P(0) + f_{\text{sat}} \mathcal{G}(\mu = 0, \sigma),
\]  

(7)

where $f_{\text{sat}}$ is the satellite fraction, $\delta_P$ is the Dirac’s delta, $\mathcal{G}(\mu, \sigma)$ represents a Gaussian distribution of mean $\mu$ and standard deviation $\sigma$. The dashed lines in Fig. 6 show that this model reasonably matches most of the velocity distribution with only two free parameters ($f_{\text{sat}}$ and $\sigma$). In the following, we refer to this description of intra-halo velocities as “Model A”.

One limitation of this model is that those galaxies with zero velocities are not necessarily placed at the centres of halos, neither it is guaranteed to have only one of those galaxies per halo. A more accurate model can thus be obtained if both terms in Eq (7) are associated to their respective galaxy type, assigning zero velocities for central galaxies and drawing velocities from $\mathcal{G}$ for satellites. In the next section we discuss this improved description, which we refer to as “Model B”.

On the other hand, we see that $\mathcal{P}(v_{\text{los}})$ has a longer tail than expected for a Gaussian. In Fig. 7 we show $\mathcal{P}(v_{\text{los}})$ for satellites inside three disjoint host halo mass bins, and the respective best fit Gaussian is indicated by dotted lines. We can see that satellites are described by Gaussians of different width, as expected from the correlation between the velocity dispersion and the mass of halos (see, e.g. Wu et al. 2013). This naturally creates an extended tail, as the one seen in Fig. 8 which is made up by the mixture of many distribution functions of different widths weighted by the respective number of satellites.

Although considering the dependence of $\sigma_r$ with host halo mass is an improved description of the global $\mathcal{P}(v_{\text{los}})$, we see that within each mass bin there are significant deviations from a Gaussian shape. To explore this further, we decompose the intra-halo velocity $v$ into a radial and a tangential component, $v_r$ and $v_\phi$, respectively:

\[
v = -v_r \hat{e}_r + v_\phi \hat{e}_\phi + v_\theta \hat{e}_\theta.
\]

(8)

The velocity along the line-of-sight, $v_{\text{los}}$ is therefore

\[
v_{\text{los}} = -v_r \mu + v_\phi (1 - \mu^2)^{1/2},
\]

(9)

where $\mu$ is the cosine of the angle between the line-of-sight and radial directions, $\mu = \hat{e}_r \cdot \hat{e}_{\text{LOS}}$. By construction, $v_\theta$ is chosen to vanish along the line-of-sight direction.

Fig. 8 shows the distribution of $v_r$ and $v_\phi$ for satellite galaxies in host halos of mass $M_h = 10^{13} \pm 0.125 M_\odot/h$. Tangential velocities are consistent with a single distribution centered at zero, with a somewhat narrower peak for the LRG sample. In contrast, for both LRGs and ELGs, radial velocities appear to be the mixture of two distinct distributions: one centered at zero velocity, and another centered at $v_r \sim 500$ km/s (i.e. a net velocity towards the centre of the halo). The latter distribution is barely noticeable in the LRG sample, but dominant for the ELG sample.

To clarify the origin of the two populations shown in Fig. 8, we have highlighted in green the contribution of galaxies that were accreted over the past 680 Myr. This shows that the non-zero peak of the radial velocity is created by a sub-population of recently accreted galaxies. Consistent to what is shown in Fig. 2, short quenching timescales favor the ELG sample to be made up significantly by
where tangential velocities are independent, the distribution of velocities is:

\[ \mathcal{P}(v_{\text{LOS}}, M) = \alpha f_1((v_{r,1}), (v_{\phi,1}), (v_{\sigma,1})) + (1 - \alpha) f_2((v_{r,2}), (v_{\phi,2}), (v_{\sigma,2})), \]

where \( \alpha \) is the relative amplitude of the Gaussians used to describe the infall velocities, and \( f((v_{r}), (v_{\phi}), (v_{\sigma})) \) corresponds to

\[ f_i(v_r, \sigma_r) = \frac{1}{2} \int_1^1 \frac{du}{(2\pi)^{1/2} \sigma_r(\mu, M)} \exp \left[ -\frac{(v_{\text{LOS}} + \mu v_r(M))^2}{2\sigma_r^2(\mu, M)} \right]. \]

where

\[ \sigma_r^2(\mu, M) = \mu^2 \sigma_r^2(M) + (1 - \mu^2) \sigma_\phi^2(M). \]

Note that in the case with no net infall velocities and \( \sigma_r = \sigma_\phi \), the description of line of sight velocities is reduced to a single Gaussian.

We plot the results of this model as solid lines in Fig. 5 and Fig. 7. For computing the parameters of our model, we split our galaxy samples in log bins of halo mass with \( \Delta \log M = 0.25 \), and then fit two Gaussian components to the infall velocity and a single one to the tangential velocity components. An example of the quality of the fits is shown in Fig. 8. The model is able to reproduce remarkably well the line-of-sight velocity distribution for both galaxy samples, the agreement being slightly better with the LRG sample, with the velocities in the ELG sample being slightly overestimated at the tail of the distribution. In the following we refer to this description of intra-halo velocities as “Model C”.

A particular case of Model C is when only one population is considered but it is allowed to have a nonzero net radial velocity. This case was considered by Hikage & Yamamoto (2016) to describe a mass-selected sample of dark matter subhalos. Fig. 7 shows the performance of this description against the line-of-sight velocity distribution of the two galaxy samples studied here (note that we have fitted again the parameters of the model). For the LRG sample, this parametrization results in a reasonable fit, slightly overestimating the tails of the distribution. However, for the ELG sample the resulting velocity distributions are a poor fit to the ones in our simulation. This again illustrates how galaxy formation physics combined with different observational selection criteria preferentially selects satellites in certain regions in phase space, and thus, that it is necessary to develop flexible and physically motivated models for satellite kinematics.

Fig. 9 shows a schematic cartoon that summarizes the differences between satellite galaxies in the LRG and ELG samples. Namely, both galaxy satellites are distributed in a different way within their host halos, and they also display different intra-halo velocities. Environmental mechanisms that quench the star-formation in satellite galaxies are responsible for ELG satellites populating the outskirts of their host halo. Also, the same mechanisms, stronger in massive halos, make these galaxies to populate less massive halos compared to galaxies in the LRG sample.

The global picture suggested by Fig. 9 and detailed throughout this section is robust against the specific modelling of the Guo et al. (2011) semi-analytical model. Although environmental processes are modelled differently across different galaxy formation models, and are not robustly constrained by observational data, there is strong observational evidence for galaxy transformations...
triggered in dense regions (see, e.g. Hashimoto et al. 1998; Kauffmann et al. 2004). Moreover, the description of intra-halo velocities presented in Eq. (10) is controlled by parameters that can accommodate a wide range of variations from our baseline model, the Guo et al. (2011) semi-analytical model. Therefore, we expect that our model for intra-halo velocities to be flexible and robust enough for interpreting future observations.

### 4.1 The clustering accuracy with different descriptions of intra-halo velocities

In the previous subsection we explored different models for the intra-halo velocities, which we summarize in Table 2. We now quantify the accuracy with which they can describe the multipoles of the correlation function. Fig. 10 shows $\Delta \xi$, the difference between the true correlation function and that predicted by different models for $\mathcal{P}(v_{\text{los}})$, scaled by $(s/b)^2$ to enhance the dynamic range shown.

First, we test the accuracy of Model A, i.e. a global velocity distribution for each galaxy sample. Operationally, instead of drawing velocities from the functional form of Eq. (7), we shuffle all intra-halo velocities in our catalogues regardless of the galaxy type or halo mass, and compute the clustering. Overall, Fig 10 shows that this model is accurate to within 1% in scales down to $s \approx 10$ Mpc/$h$ for the monopole of both galaxy samples. The quadrupole and hexadecapole are poorly described in scales below $s \approx 20 - 30$ Mpc/$h$. Despite its simplicity, it already performs substantially better than the case where intra-halo velocities are modeled as a single Gaussian deviate.

Next we test Model B. We do this by shuffling the intra-halo velocities of all satellites in the galaxy samples, leaving central galaxies unaltered. As a result, the clustering improves significantly for both samples, specially for the quadrupole and hexadecapole. In particular, the accuracy of the monopole increases by roughly factors of two on scales below 10 Mpc/$h$.

Finally, we test Model C, which accounts for the halo mass dependence and the infalling velocity component of satellites. This description of intra-halo velocities is strikingly accurate within 1% down to scales of $s \approx 1$ Mpc/$h$ for the monopole of both galaxy samples. The quadrupole of both samples is also accurate except in an intermediate region between $s \sim 3 - 10$ Mpc/$h$ where the accuracy drops above 10%. The discontinuity of the shaded regions showing the fractional accuracy around this range in Fig 10 arises from the quadrupole value crossing zero in this range. The hexadecapole obtained is also fairly accurate, although significantly noisier than the other two multipoles.

Although not shown here, we have also checked the performance of the special case of simplifying the description of infall velocities with a single Gaussian, as in Hikage & Yamamoto (2016). This results in slightly worse multipoles for the LRG sample, yet reach a similar accuracy in scales $s \gtrsim 2$ Mpc/$h$. However, this model performs significantly worse for the ELG sample, producing the multipoles only within 5% of of accuracy at scales of $s \approx 2$ Mpc/$h$ for the monopole, and within 10% for the quadrupole and hexadecapole for the same scale.

### 4.2 Possible improvements

Although the accuracy of our Model C is already high, we have nevertheless explored different paths for improving further its performance:

i) The upper limit in accuracy for Model C is obtained by employing the exact line-of-sight velocity distribution. We test for this by shuffling the line-of-sight component of the intra-halo velocities of satellites among halos of the same mass. However, we have confirmed that this results in only a slight improvement compared to what is obtained with Eq. (10).

ii) An additional level of sophistication is obtained by incorporating the radial dependence of the intra-halo velocity distribution. We have tested this idea by shuffling the line-of-sight velocity distribution of satellites in bins of mass and also three bins of $r/r_{200}$. The improvement in clustering accuracy of this model is negligible compared to what is obtained without considering the radial dependence.

iii) Another possible improvement of our model is to consider correlations with the large-scale velocity field (e.g. Guo et al. 2015a,b) We have tested this by constructing a sample of galaxies in which the direction of the intra-halo velocity of each galaxy is randomized, thus preserving their amplitude, and any correlation between this velocity and the super-halo environment. This, however, resulted in only a slight improvement on the LRG sample for scales of $s \lesssim 2$ Mpc/$h$.

iv) Finally, we explored a description of velocities in which the anisotropy of the intra-halo velocity distribution is preserved. The anisotropy of the velocity dispersion has been shown to be key to interpret and model kinematic mass data (Wojtak et al. 2013; Kafle et al. 2014) and can thus lead to further corrections in the amplitude of fingers of god, especially if the anisotropy depends on the properties of the galaxy samples. To construct these galaxy samples we preserve the radial component of the intra-halo velocity of each galaxy, and randomize the direction of the tangential component. For the LRG sample, preserving the anisotropy results in clustering measurements accurate to within 0.1% down to scales of 1 Mpc/$h$. The quadrupole and hexadecapole of this model description is consistent to what is found with the catalogue that randomizes the direction of the full velocity vector. For the ELG sample preserving the anisotropy also results in no significant improvement over Model C described by Eq. (10).

The relatively minor improvements obtained by the above modifications suggests that the current version of Model C is already describing most of the uncorrelated aspects of the intra-halo velocity distributions. A possible direction where more significant gains could be achieved concerns the correlations among the velocity of satellites: For instance, some satellites are expected to

| Name | Equation | Description |
|------|----------|-------------|
| Model $\sigma_v$ | Eq. (6) | A Gaussian centered at zero with standard deviation $\sigma_v$. |
| Model A | Eq. (7) | Fit to the global line-of-sight velocity distribution. |
| Model B | $\mathcal{P}(v)$ (type) = \begin{cases} 0 & \text{if central} \\ Eq. (7) & \text{if satellite} \end{cases}$ | Zero velocities to centrals, a global Gaussian to satellites. |
| Model C | $\mathcal{P}(v)$ (type, $M_h$) = \begin{cases} 0 & \text{if central} \\ Eq. (10) & \text{if satellite} \end{cases}$ | A two-Gaussian fit to radial velocities and one-Gaussian fit to tangential velocities. |
be accreted in groups (e.g. Angulo et al. 2009), thus their velocity should be highly correlated. We have not attempted to extend our models to accommodate for such given that implementing them in theoretical models of RSDs is not straightforward.

5 DISCUSSION

In the previous section we have proposed several models for the intra-halo velocity dispersion of satellite galaxies. All of these models resulted in accurate but different predictions for the multipoles of the redshift-space correlation function. We now compare and quantify the improvements by means of the minimum scale, $s_{\text{min}}$, above which they would deliver a good fit to the measured correlation functions. In practice, we first compute

$$\chi^2(s) = \frac{1}{3N_p - N_f} \sum_{i,j,k} \left[ w_j^{\text{meas}} - w_j^{\text{mod}} \right] C_{ij}(V) \left[ w_i^{\text{meas}} - w_i^{\text{mod}} \right]^T,$$

where $N_f$ corresponds to the number of measurements in each multipole, $N_p$ the number of free parameters of the model, $w_i^k = [\xi(x_i), \eta(x_i), \varphi(x_i)]$ with $k$ referring to either a galaxy sample or a model. $C_{ij}(V)$ is the inverse of the covariance matrix computed according to Eq. (2) rescaled to a volume $V$. Then, we find the value of $s_{\text{min}}$ as $\chi^2(s) < 1$ for all $s > s_{\text{min}}$. Therefore, $s_{\text{min}}$ represents the smallest scale that can be consider before an hypothetical fit starts delivering biased constrains.

Fig. 11 shows $s_{\text{min}}$ computed for different models as a function of the comoving volumes. Small differences between the model and the measured clustering become more important as the volume of the survey increases since the elements of the covariance matrix decrease, resulting in an increase of the value of $\chi^2$ at a fixed minimum scale $s_{\text{min}}$.

For all models, the minimum scale providing a good fit is smaller for the ELGs than for the LRG sample. Since the ELG sample contains a smaller fraction of satellites, any inaccuracy on the description of intra-halo velocities has a greater impact on the LRG sample. Consequently, the models for the ELG sample display overall a higher accuracy, as shown also in Figs. 10.

For any given volume, Model C reaches smaller scales with good fits compared to all the other models. This is particularly true for the model of the ELG sample. For a survey with $V = 10(\text{Gpc}/h)^3$, comparable to DESI at $z = 1 \pm 0.1$ (Weinberg et al. 2013), these limits become $s_{\text{min}} \approx 25, 50 \text{ Mpc}/h$ for the ELG and LRG samples, respectively.

For illustration, we compare the performance of our models against Model $\sigma_v$. This shows the common strategy in which intra-halo velocities are described by a single Gaussian with standard deviation $\sigma_v$ (Eq. 5). The value of $\sigma_v$ is chosen to provide an overall good fit to all multipoles between $s = 5 - 90 \text{ Mpc}/h$. Fig. 11 shows that this model performs poorly, with values of $s_{\text{min}}$ systematically larger by a factor 2x and more compared to Models B and C. Moreover, for volumes larger than $V \approx 1(\text{Gpc}/h)^3$, this model delivers $\chi^2 \gg 1$ at all scales. The regime of large volumes where Model $\sigma_v$ breaks down is precisely the one that is expected to be probed by future surveys. Model constraints with $\chi^2 > 1$ represent a sub-optimal exploitation of the measurements.

In contrast, the values obtained for $s_{\text{min}}$ with Model A span $10 - 30 \text{ Mpc}/h$ for small volumes, but reach to $\approx 70 \text{ Mpc}/h$ for the LRG sample for large volumes, $V \sim 10(\text{Gpc}/h)^3$. On the other hand, Model B and C perform similarly. This is explained because at large scales both models deliver similar accuracies, as shown in Fig. 10.

As discussed before, even though our models assume the correct satellite fraction, halo occupation distribution, host halo velocities, and radial distributions, these are still erroneous on small scales given the huge accuracy of upcoming surveys. Even though
Galaxy formation is a complex process which ever, the predictions for the different models as a function of the volume probed. The dotted green line corresponds to a constant $\sigma_v$ value that best fits the redshift-space clustering. The dashed orange, dotted-dashed purple and solid brown lines correspond to Models A, B and C, respectively. The top and bottom panels correspond to the LRG and ELG samples, respectively.

Finally, we would like to emphasize that our results are based on the semi-analytical model, which represents the state-of-the-art in galaxy formation models. This model captures all the key physical processes that are expected to shape the evolution of galaxies, and shows a remarkable agreement with the many observed statistical properties of galaxy populations. However, the predictions for the differences between the LRG and ELG samples are expected to vary in detail across different galaxy formation models (see, e.g. Knebe et al. 2015, for a detailed comparison between models). Galaxy formation is a complex process which combines astrophysical mechanisms spanning different dynamical ranges to account for observed properties. Thus, important ingredients to our analysis, such as the strength of ram-pressure stripping or feedback processes are not robustly constrained. Moreover, some of the parameters controlling different physical mechanisms can be degenerate (Bower et al. 2010; Lu et al. 2011; Henriques et al. 2013; Ruiz et al. 2013).

Despite this quantitative limitation of the models, our descriptions of intra-halo velocities are general enough to accommodate the relevant features of the galaxy sample targeted. For instance, regardless of the accuracy of the gas stripping prescription in Guo et al. (2011), an ELG galaxy selection is likely to result in a population of recently infalling satellites in haloes with a dominating infall velocity. Such population should be well described with Eq. (10) to model the distribution of line-of-sight intra-halo velocities in the real Universe.

The free parameters of models A, B and C can be constrained jointly with cosmological parameters using anisotropic clustering measurements. However, extending the analysis to smaller scales may not necessarily result in improved cosmological constraints given the number of free parameters. In particular, for current survey volumes, the gain of models B and C over A is marginal. However, as Fig. 11 illustrates, the gain becomes substantial when volumes exceed $\sim 10^{12}$ and improvements over models with a single Gaussian become necessary. In addition, current progress on perturbation theory models and numerical approaches are likely to improve the current accuracy of the real-space clustering towards smaller scales (Dodelson et al. 2016).

Additional priors to the nuisance parameters of our model descriptions can be obtained with theoretical galaxy formation models or by independent datasets. For instance, one such technique is
6 CONCLUSIONS

The next generation of cosmological galaxy surveys requires a significant improvement of theoretical descriptions of galaxy clustering. The exploitation of cosmological surveys can currently be considered sub-optimal, meaning that only linear or mildly non-linear scales are used to constrain cosmological parameters, and only an approximate treatment of the galaxy velocities are considered. As a result, small scales that are measured with the greatest precision are discarded from the analysis.

Current efforts towards improving theoretical models have focused mostly on improving the description of the density and velocity field for dark matter and halos. In this paper we show that such approaches will be limited by the particular features imprinted by galaxy formation physics. Future experiments will target very different types of galaxies to perform cosmological analysis, which will increase the importance of understanding the impact of galaxy formation.

In this paper we studied the impact of galaxy selection on satellite kinematics and redshift-space clustering. We made use of a state-of-the-art semi-analytical galaxy formation model (Guo et al. 2011) run over one of the largest N-body simulations to date (M-XXL, Angulo et al. 2012). We build two galaxy samples at $z = 1$ with a fixed number density, $n = 10^{-3} (\text{Mpc}/h)^{-3}$ and a selection criteria based on stellar mass and star-formation rate limited samples. These samples represent proxies for LRGs and ELGs, respectively. These galaxy samples feature different halo mass distributions and satellite fractions (Fig. 1). The star-formation rate is typically quenched in satellite galaxies by gas-stripping processes such as ram-pressure. Environmental processes thus largely reduce the abundance of satellite galaxies in the ELG sample and prevent them from populating massive haloes, where these effects have a stronger impact. Their typical halo mass is, thus $M_h \approx 7 \times 10^{10} M_{\odot}/h$. On the other hand, the stellar mass is tightly correlated with the parent dark matter halo mass, and it is not affected strongly by environmental effects. As a result, the LRG sample is characterized by massive dark matter haloes and a higher satellite fraction.

The clustering in real space of these two galaxy samples can be characterized by their clustering bias. At large, linear scales, a constant bias parameter is sufficient to describe their clustering accurately. However, at smaller scales, $r \lesssim 20\text{Mpc}/h$ their clustering differs significantly on each galaxy sample, as shown in Fig. 4.

In redshift-space, the clustering depends also on the peculiar velocities of galaxies. Our galaxy formation model predicts that galaxy samples have different peculiar velocities. In particular, the distribution of intra-halo velocities of the different galaxy samples has a strong impact on the clustering in scales well beyond the 1-halo term.

One of key differences between the LRG and ELG samples is a population of recently accreted satellites infalling into their parent halo. These objects are fairly ubiquitous in the ELG sample because they have not been significantly affected by environmental effects that quench their star-formation yet. The satellite galaxies in the ELG sample are thus comprised of two populations with different properties: one corresponds to objects affected by gas stripping processes but still forming stars at a rate that allows them to be included in our selection criteria. These objects have infall velocities well described by a Gaussian centered at zero, and occupy a broad range of radial positions within their parent halo. The other population corresponds to recently accreted satellites populating the outskirts of their parent halo (see Fig. 2) with a dominant infalling velocity component (see Fig. 8).

We develop a description of intra-halo velocities that can account for two populations with different infall velocity distributions. Eq. (10) describes the line-of-sight velocity distribution of satellites as a function of mass of their parent halo. Fig. 7 shows that this description can successfully reproduce the intra-halo line-of-sight velocity distribution of the LRG and ELG samples. More importantly, we show that this description results in a predicted redshift-space clustering that is remarkably accurate. For the monopole of the redshift-space correlation function, this description is accurate to within 1% in scales of $s = 1 - 90\text{Mpc}/h$.

In contrast, the standard approach to account for the impact of intra-halo velocities in the redshift-space clustering consists in applying a Gaussian smoothing to the clustering, with a velocity dispersion term taken as a nuisance parameter. This approach is shown to result in poor fits to small scales. Even when considering a model in which both the positions and velocities of galaxies are exact, except for intra-halo scales, this description limits the accuracy to scales $s \approx 20 - 30 \text{Mpc}/h$. Further improvements to this simplistic model include modelling the true distribution of line-of-sight intra-halo velocities, which features a strong peak at zero velocities corresponding to central galaxies. This extension of the model can improve the accuracy of the clustering to scales of $s \approx 10 \text{Mpc}/h$ for the monopole. Further improvements are obtained by separating galaxies in centrals and satellites, and drawing their intra-halo velocities as a function of parent halo mass. More detailed improvements, such as preserving the anisotropy of the velocities in haloes do not improve the accuracy of the clustering in redshift space significantly.

Implementing these ideas is not trivial in the standard framework of models used to interpret clustering measurements. For instance, analytical models typically do not distinguish satellites and centrals, and so the velocity dispersion term introduced effectively affects the whole galaxy sample used (e.g. Reid et al. 2012). A more accurate modelling technique could be achieved by means of constructing quick galaxy samples with an halo occupation distribution or sub-halo abundance matching technique that incorporate the ideas described above. In this way, the non-linear dynamics would be accurately accounted for by creating galaxy samples from an ensemble of N-body simulations of varying cosmological parameters or by re-scaling techniques that modify the cosmology in a simulation (Angulo & White 2010). These ideas will be investigated further in a future work.

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APPENDIX A: VALIDATION OF OUR RESULTS AGAINST THE MILLENNIUM SIMULATION.

In section 2.1 we discussed the corrections that were necessary to account for the limited mass resolution of the catalogues based on the M-XXL run. Several quantities have been compared and adjusted to retrieve consistent results with the same model run in the Millennium simulation. Such tests are described in Angulo et al. (2014).

However, a key quantity throughout this paper, the distribution of intra-halo velocities, has not been confronted against the Millennium simulation before. Hence, we compare the intra-halo velocity distributions predicted by the Guo et al. (2011) model based on the M-XXL simulation to those from the Millennium simulation. To access the model predictions of the latter, we make use of the Millennium database (Lemson & Virgo Consortium 2006).

Fig. A1 shows the intra-halo line-of-sight velocity distribution of the two galaxy samples for different host halo masses. The same distribution is computed in both simulations. The results between both catalogues match remarkably well. Evidently, due to the smaller volume, the histograms obtained from the Millennium simulation are more noisy, but there is not any systematic deviation between both predictions. Therefore, this comparison validates our predictions for the shape of the line-of-sight velocity distribution against resolution effects.

To explore the predicted intra-halo velocities in more detail, Fig. A2 shows the velocity distribution split into their infall and tangential components. Due to its large size, particles in the M-XXL simulation were not stored. Thus, there is no information in the simulation to assign velocities to the galaxies once they become type 2 (orphans). This creates an artificial peak of positive infall velocities not related with the population of recently accreted satellites, as discussed in Fig. 8, but instead with the moment in which those subhalos were disrupted in the simulation to an extent that they could not be identified anymore. Randomizing the direction of the velocity vector results in a remarkable match of these two velocity components with what is obtained with the Millennium simulation.

In summary, both tests described above show that the velocity distributions and the results over which this paper is based on are not sensitive to the limited resolution of the M-XXL simulation.

Finally, the lack of information in the simulation to assign positions for type 2 galaxies also arises in the overall radial distribution of satellites. Fig. A3 shows the radial distribution of satellites for the LRG and ELG samples obtained with the Millennium and M-XXL simulations. Here type 2 galaxies are shown with pink shaded areas. Unlike the previous cases discussed before, the radial distribution of type 2 galaxies differs significantly between the two simulation results. This is particularly important for the LRG sample, where the population of type 2 galaxies dominates over small distances. Interestingly, the Guo et al. (2011) model run over the Millennium simulation predicts a NFW-like profile for the distribution of satellites in the LRG sample, but is consistent with our finding for ELG galaxies. The discrepancy in the radial distributions for the
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Figure A3. The radial distribution of LRG (red) and ELG (blue) samples, similarly to Fig. 2. The left panels show the results obtained using the Guo et al. (2011) model run over the Millennium simulation, and the right panels over the MXXL simulation (this work). The pink dotted region corresponds to type 2 satellites.

LRG sample arises in scales well below 1 Mpc/h. Hence, this difference is likely to affect the clustering in a small range of scales.

Furthermore, throughout this paper we tested different descriptions of intra-halo velocities by retaining everything else about the galaxy population. In particular, the radial distribution of galaxies in the galaxy samples was preserved among different galaxy catalogues with different intra-halo velocity descriptions. Therefore, our conclusions about the impact of different intra-halo velocity descriptions are robust to resolution effects on the radial distribution of type 2 galaxies.

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