Semi-analytic galaxy formation in \( f(R) \)-gravity cosmologies

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ABSTRACT

Modifications of the equations of general relativity at large distances offer one possibility to explain the observed properties of our Universe without invoking a cosmological constant. Numerous proposals for such modified gravity cosmologies exist, but often their consequences for structure formation in the non-linear sector are not yet accurately known. In this work, we employ high-resolution numerical simulations of \( f(R) \)-gravity models coupled with a semi-analytic model (SAM) for galaxy formation to obtain detailed predictions for the evolution of galaxy properties. The \( f(R) \)-gravity models imply the existence of a ‘fifth-force’, which is however locally suppressed, preserving the successes of general relativity on solar system scales. We show that dark matter haloes in \( f(R) \)-gravity models are characterized by a modified virial scaling with respect to the \( \Lambda \)CDM scenario, reflecting a higher dark matter velocity dispersion at a given mass. This effect is taken into account in the SAM by an appropriate modification of the mass–temperature relation. We find that the statistical properties predicted for galaxies (such as the stellar mass function and the cosmic star formation rate) in \( f(R) \)-gravity show generally only very small differences relative to \( \Lambda \)CDM, smaller than the dispersion between the results of different SAM models, which can be viewed as a measure of their systematic uncertainty. We also demonstrate that galaxy bias is not able to disentangle between \( f(R) \)-gravity and the standard cosmological scenario. However, \( f(R) \)-gravity imprints modifications in the linear growth rate of cosmic structures at large scale, which can be recovered from the statistical properties of large galaxy samples.

Key words: galaxies: formation - galaxies: evolution - galaxies: fundamental properties

1 INTRODUCTION

Our knowledge of the basic properties of the Universe has seen considerable advances in recent decades, culminating in the accurate determination of the key cosmological parameters (see e.g. Planck Collaboration et al. [2013]; Komatsu et al. [2009]). Measurements of the accelerated expansion and of the curvature and matter content of the Universe have led to the conclusion that some unknown form of Dark Energy (DE, hereafter) accounts for \( \sim 70 \) per cent of its energy density today. In the standard \( \Lambda \)CDM model, the dark energy is described by a classical cosmological constant, and so far, available experiments have been unable to decide whether the true nature of the dark energy differs from a cosmological constant, something that is generally expected on theoretical grounds. Numerous scenarios, ranging from scalar field theories (e.g. quintessence) to modifications of the equations of general relativity, have been proposed as alternatives to the standard cosmological constant model, where a homogeneous and static energy field fills the whole Universe at any cosmic epoch.

Future wide galaxy surveys (like EUCLID, Laureijs et al. [2011]) have been proposed as powerful experiments to constrain the basic properties of DE and disentangle different proposed scenarios. However, the success of these missions hinges on a precise understanding of the relationship between the physical processes responsible for galaxy formation and evolution, and the assembly of the cosmic large-scale structure. While the non-linear evolution of virialized structures in a variety of cosmological scenarios has been explored by means of high-resolution \( N \)-body simulations (see e.g. Grossi & Springel [2009] for quintessence models; Schmidt [2009]; Khoury & Wyman [2009]; Li et al. [2012] for modified gravity models; Baldi [2012] for coupled DE models), their influence on the properties of galaxies has not yet been explored in much detail. This is a question of fundamental importance, since the envisaged tests for constraining the properties of DE ultimately depend on our...
understanding of how galaxies trace the distribution of dark matter (DM) on large scales.

Semi-analytic models (SAMs, hereafter) of galaxy formation, and hydrodynamic numerical simulations alike, resort to simplified yet physically grounded, analytical approximations to describe the relevant physical mechanisms (such as gas cooling, star formation, black hole accretion, feedbacks) and their interplay, as a function of the physical properties of the simulated objects (e.g. stellar mass, gas content) and/or their environment (e.g. host halo mass). This approach intrinsically involves a phenomenological parameter space, which is constrained by means of a calibration procedure against a selected subset of (mainly) low-redshift observations. The current generation of models has been shown to successfully reproduce a large number of observational evidences. Nevertheless, our detailed knowledge of the chain of physical processes responsible for galaxy formation and evolution is still limited, even for a standard ΛCDM cosmology. A number of well known discrepancies between the predictions of theoretical models and observational constraints still exist. Due to the considerable complexity of the coupled non-linear physical processes of the baryonic gas and due to the significant level of degeneracy among the relevant parametrizations (see e.g. Henriques et al. 2009), this can however not easily be translated into constraints of the underlying cosmological model. It is thus a high priority in the framework of future space missions to identify any modification in model predictions that can be directly and robustly ascribed to the effect of a given DE scenario. An important goal is to quantify the performance of different cosmological tests based on statistical galaxy properties, marginalized over the uncertainties of galaxy formation physics.

This paper is the second of a series aimed at studying the impact of alternative DE cosmologies on the properties of galaxy populations, as predicted by SAMs. In the first paper (Fontanot et al. 2012, hereafter Paper I), we considered a specific class of DE cosmologies, namely the Early Dark Energy (EDE) models, in which the DE constitutes a small but finite fraction of the total energy density at the time of matter-radiation equality, leading to an earlier formation of structures with respect to the standard ΛCDM cosmology. A number of well known discrepancies between the predictions of theoretical models and observational constraints still exist. Due to the considerable complexity of the coupled non-linear physical processes of the baryonic gas and due to the significant level of degeneracy among the relevant parametrizations (see e.g. Henriques et al. 2009), this can however not easily be translated into constraints of the underlying cosmological model. It is thus a high priority in the framework of future space missions to identify any modification in model predictions that can be directly and robustly ascribed to the effect of a given DE scenario. An important goal is to quantify the performance of different cosmological tests based on statistical galaxy properties, marginalized over the uncertainties of galaxy formation physics.

This paper is organized as follows. In Section 2, we introduce the cosmological numerical simulations and semi-analytic models we use in our analysis. We then present the predicted galaxy properties and compare them among different cosmologies in Section 3. Finally, we discuss our conclusions in Section 4.

2 MODELS

2.1 $f(R)$-gravity parametrization

In this paper, we focus on a particular class of modified gravity cosmologies, namely $f(R)$-gravity models. In particular, we consider the same class of modified gravity models studied in Puchwein et al. (2013), with a parametrization first introduced by Hu & Sawicki (2007). We assume a modification of the Einstein-Hilbert action of the form

$$S = \int d^4 x \sqrt{-g} \left[ R + f(R) \frac{1}{16\pi G} + \mathcal{L}_m \right],$$

where $R$ is the Ricci scalar and $\mathcal{L}_m$ the matter Lagrangian. Hu & Sawicki (2007) argued that the functional form for $f(R)$ is constrained by high- and low-redshift observational data, and proposed a general class of broken power law models to parameterize $f(R)$ in the form

$$f(R) = -m^2 \frac{c_1(R/m^2)^\eta}{c_2(R/m^2)^\eta + 1},$$

where $m^2 = H_0^2 \Omega_m$ and $\eta$, $c_1$ and $c_2$ are free parameters. It is possible to derive relations between these free parameters by requiring the model to closely reproduce a flat ΛCDM cosmic expansion history, which yields

$$\frac{c_1}{c_2} \approx \frac{6}{\Omega_m} \Omega_m$$

and

$$f_R = \frac{df(R)}{dR} = -\eta \frac{c_1}{c_2} \left( \frac{m^2}{R} \right)^{\eta+1}.$$
Table 1. Cosmological parameters of our simulation set. The columns list from left to right: total dark matter density, dark energy content at $z = 0$, present-day expansion rate, power spectrum normalization, equation of state parameter, and the quantities describing the early dark energy or the $f(R)$ gravity modification, respectively.

| Model   | $\Omega_{m0}$ | $\Omega_{\Lambda0}$ | $h$  | $\sigma_8$ | $w_0$ | $\Omega_{de,0}$ | $\eta$ | $|f_{\text{red}}|$ |
|---------|---------------|---------------------|-----|------------|-------|----------------|-------|----------------|
| LCDM    | 0.272         | 0.728               | 0.704 | 0.809      | -1.0  | —              | —     | —              |
| EDE3    | 0.272         | 0.728               | 0.704 | 0.809      | -0.93 | $2 \times 10^{-3}$ | —     | —              |
| FoR1    | 0.272         | 0.728               | 0.704 | 0.809      | -1.0  | —              | 1.0   | $10^{-4}$      |

consider it to maximize the impact of $f(R)$-gravity models on the statistical properties of galaxy populations.

2.2 Numerical Simulations

In this work we consider a set of numerical $N$-body simulations of DM only runs (see Table 1). We use a $f(R)$-gravity run and, for comparison, also consider two additional cosmological runs, assuming a standard $\Lambda$CDM cosmology and an EDE model, respectively. The former model has been taken from the EDE runs considered in Paper I, and is named EDE3 following the same labelling convention as in Paper I. In all simulations, we assume a flat universe with matter density parameter $\Omega_m = 0.272$. Hubble parameter $h = 0.704$. Gaussian density fluctuations with a scale-invariant primordial power spectrum with spectral index $n = 1$, and a normalization of the linearly extrapolated $z = 0$ power spectrum equal to $\sigma_8 = 0.8$.

We generate initial conditions for all the simulations using the N-GENIC code and run the simulation using the cosmological code GADGET-3 (last described in Springel 2005). For the EDE3 run, we employ the same code version as in Grossi & Springel (2009) to account for EDE cosmologies with a redshift-dependent equation of state. Finally, we perform the FoR1 run with $f(R)$-gravity using the new MG-GADGET code developed by Puchwein et al. (2013). This code augments the usual algorithms of GADGET for ordinary gravity with a multigrid-accelerated Newton-Gauss-Seidel relaxation solver on an adaptive mesh to efficiently solve for perturbations in the scalar degree of freedom of the modified gravity model. All simulations have been run in periodic boxes 100 $h^{-1}$Mpc on a side, using $512^3$ particles (corresponding to a mass resolution of $5.62 \times 10^7 h^{-1} M_\odot$). We use initial conditions with the same phases and mode amplitudes in the $\Lambda$CDM and $f(R)$-gravity runs to ensure a similar realization of the large scale structure and allow an object-by-object comparison. It is worth stressing that, at variance with Paper I, we do not constrain the $\Lambda$CDM and $f(R)$-gravity simulations to have similar matter power spectrum at $z = 0$: instead we require the initial conditions for these runs to share the same amplitude of the initial power spectrum at the last scattering surface.

For each run, 64 simulation snapshots were produced at the same output redshifts used in the Millennium simulation project (Springel et al. 2005) and in Paper I. Group catalogues have been constructed using the friend-of-friend (FOF) algorithm with a linking length of 0.2 in units of the mean particle separation. Each group has then been decomposed into gravitationally bound substructures using SUBFIND (Springel et al. 2001), and the resulting subhalo catalogues were used to construct merger history trees as explained in detail in Springel et al. (2005). Only subhaloes that retained at least 20 bound particles after the gravitational unbinding procedure were kept for the tree construction.

2.3 Semi-Analytic Models

In this paper, we use the same approach as proposed in Paper I. We consider three different versions of $f$ -GALAXIES, based on the code originally developed by Springel et al. (2005), namely the versions and corresponding models presented in Guo et al. (2011), De Lucia & Blaizot (2007), and Croton et al. (2006). These models share the same code structure and were designed to work on Millennium-like merger trees. They thus represent a coherent set of models that can be used to study the intra-model variance induced by different choices for the approximation of galaxy formation physics. A comparison of the corresponding systematic model uncertainties to the changes in the predictions when the underlying cosmology is changed is quite informative for assessing how easily these differences could be detected. We refer the reader to the original papers for a more detailed discussion of the modelling of the relevant physical mechanisms in each model. All SAMs have been calibrated by requiring them to reproduce a well-defined set of low-redshift reference observations. The difference in the treatment of physical processes in these SAM versions are large enough to require a general re-calibration of the main model parameters.

In Paper I, the Guo et al. (2011) model has been modified to run self-consistently on EDE cosmologies. In this work we extend these modifications to include $f(R)$-gravity models. For the remainder of this paper, whenever we refer to the Guo et al. (2011) model, we actually refer to our modified code. The first change in the code follows closely from Paper I, as we implement in the SAM a tool to specify the Hubble function $H(a)$ through an external file containing a user-generated expression, thus taking into account the possible variation of the expansion rate connected to a DE cosmology. A second relevant modification comes from the analysis of the properties of DM haloes in the FoR1 simulation. In Figure 1 we show the virial scaling relation between the total DM mass inside a sphere with interior mean density 200 times the critical density at a given redshift, $M_{200}(z)$, and the one-dimensional velocity dispersion $\sigma_{200}$ inside the same radius. Evrard et al. (2008) showed that haloes in a $\Lambda$CDM cosmological run follow with good approximation the theoretical relation (dashed line):

$$\sigma_{200} \propto \left[ h(z) M_{200}(z) \right]^{1/3}.$$  

(5)

We find that haloes in $f(R)$-gravity are generally offset from this relation, and only haloes massive enough for the screening effect to be effective lie on the expected relation for the $\Lambda$CDM cosmology. A simple estimate of the halo mass or halo velocity dispersion scale on which the Chameleon mechanism screens modifications

The main differences between the three models are: (a) the treatment of dynamical friction and merger times, the stellar initial mass function and the dust model (from Croton et al. 2005 to De Lucia & Blaizot 2007); (b) the modeling of supernovae feedback, the treatment of satellite galaxy evolution, tidal stripping and mergers (improved from De Lucia & Blaizot 2007 to Guo et al. 2011).
of gravity as a function of redshift can be obtained by comparing the background value of the scalar degree of freedom $f_R(z)$ to the depth of a halo potential well. More precisely, screening happens in deep potential wells roughly when

$$|\phi_N| > \frac{3c^2|f_R(z)|}{2},$$

where $|\phi_N|$ represents the Newtonian potential (see, e.g., Hu & Sawicki 2007, Cabrè et al. 2012). In virial equilibrium the square of the three-dimensional velocity dispersion is approximately equal to the gravitational potential: ignoring the difference between the actual gravitational potential and the Newtonian gravitational potential we can thus get a simple estimate of the velocity dispersion above which the Chameleon mechanism is active. Using these assumptions, we find that modifications of gravity are screened in halos with:

$$\frac{4}{3} - 1 \approx 15\%$$

This should not be off by more than a factor $4/3$, which is the maximum enhancement of gravity in $f(R)$-models, and translates into a shift smaller than $\sqrt{4/3} - 1 \approx 15$ per cent in the velocity dispersion.

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Figure 1. Virial scaling relation $M_{200}-\sigma_{200}$ for the haloes in the FoR1 run. Solid and dashed lines show the best fit formulae for the relations in FoR1 and $\Lambda$CDM cosmologies, respectively (see text for more details).
Figure 2. A collection of SAM predictions in different cosmological scenarios. In each panel the solid black/blue/red lines refer to our SAM predictions in \( \Lambda \)CDM, Early Dark Energy (EDE3) and \( f(R) \)-gravity (FoR1) cosmologies, respectively. Black dashed and dotted lines refer to the predictions of the De Lucia & Blaizot (2007) and Croton et al. (2006) SAMs for the \( \Lambda \)CDM cosmology, respectively. Upper Panel: redshift evolution of the predicted stellar mass function. Grey points refer to the stellar mass function compilation from Fontanot et al. (2009, see references herein). Lower Panel: redshift evolution of the cosmic star formation rate density. Grey points refer to a cosmic star formation density compilation from Hopkins (2004, see references herein).

\[ \sigma_{200} \approx \sqrt{\frac{c^2 |f_R(z)|}{2}} \]  

In Figure II we mark with an horizontal dotted line the redshift dependent velocity dispersion threshold separating screened and unscreened systems. We then consider unscreened \( > 10^{12} M_\odot \) DM haloes and we show that they follow the same scaling relation as in Eq. 5, with a different normalization (solid line). We have thus modified L-GALAXIES to rescale the assumed virial relations of unscreened haloes to account for this mean offset in \( f(R) \)-gravity runs. We defer a more detailed study of the changes of the virial properties of DM haloes as a function of \( |f_{\beta 0}| \) to a forthcoming paper (Arnold et al., in preparation).

In the following, we refrain from discussing possible changes in the model calibrations, instead we prefer to highlight differences induced by changes in the cosmology alone, holding all other ingre-
Figure 3. Redshift evolution of the galaxy bias in different cosmological models. Only model galaxies with $M_* > 10^9 M_\odot$ have been considered. Models are labelled with the same line types and colours as in Fig. 2.

dients fixed. As we retain the original parameter choices, this implies that only for the $\Lambda$CDM run the models are tuned to perform best when compared to observational constraints. Nonetheless, this approach seems best suited to assess the size of the expected effects from modified gravity cosmologies alone.

## 3 RESULTS AND DISCUSSION

In Figure 2 we compare the redshift evolution of a selection of galaxy properties as predicted by the different SAMs discussed in the previous section. We choose the same quantities as in Paper I and we compare them over a common redshift range: the galaxy stellar mass function (upper panel) and the cosmic star formation rate (lower panel). Whenever model predictions are compared to observational constraints, we convolve them with an adequate estimate of the typical observational error (e.g. a lognormal error distribution with amplitude $0.25$ and $0.3$ for stellar masses and star formation rates respectively, see Fontanot et al. [2009]). Moreover, the predictions of the Croton et al. (2006) model have been converted from a Salpeter to a Chabrier IMF by assuming a constant shift of $0.25$ dex in stellar mass and $0.176$ dex in star formation rate. In the following, only galaxies with $M_* > 10^9 M_\odot$ have been considered.

In all panels, black lines refer to the 1-GALAXIES prediction in the $\Lambda$CDM simulation, with solid, dashed and dotted lines referring to the Guo et al. (2011), De Lucia & Blaizot (2007) and Croton et al. (2006) SAMs, respectively. We stress again that the differences in this set of predictions are driven by the different treatment of physical processes and varying calibration sets among the 3 models (see also Paper I), and represent a fair estimate of the intra-SAM variance. Predictions relative to the Guo et al. (2011) model in different cosmologies are instead shown as coloured lines: black, blue and red refer to the $\Lambda$CDM, EDE3 and FoR1 runs, respectively. For a full analysis of the comparison between the $\Lambda$CDM and EDE models we refer the reader to Paper I, while here we focus on the FoR1 run to see how it complements our conclusion in Paper I. The SAM predictions for the FoR1 run show smaller deviations relative to the $\Lambda$CDM model than a moderate EDE model (like EDE3). Moreover, these deviations do not grow with redshift (as in the EDE3 model), but remain of small amplitude over the whole redshift range under scrutiny. The similarity of $z = 0$ predictions between the $\Lambda$CDM and $f(R)$-gravity runs is particularly important, since it justifies our choice of keeping the same SAM parameters in the two runs, despite the two simulations are not constrained to have the same matter power spectrum at $z = 0$.

An interesting difference with respect to EDE models lies in the differential effect of $f(R)$-gravity on the stellar mass function at different mass scales, as highlighted in the lower row, using the ratio between the mass function in a given cosmology and the corresponding mass function in the $\Lambda$CDM run. In fact, while the EDE cosmologies predict an enhancement of the space density at all mass scales (as a consequence of the earlier structure formation epoch), in the FoR1 run the space density of low-mass galaxies is systematically increased at all redshifts, this effect being slightly larger at higher redshifts. At the high mass end, the $f(R)$-gravity simulation predicts a higher space density of DM haloes than in the $\Lambda$CDM run (see e.g. Li & Hu [2011] and Zhao et al. [2011]), but this effect is at most weakly reflected in the space density of massive galaxies. We indeed find a small excess of massive galaxies at the highest mass bin probed by our volume, but we also find a weak deficiency around the knee of the mass function. In the 1-GALAXIES model, the position of the knee is largely determined by the 'radio'-mode AGN feedback parametrization, which assumes an explicit dependence on the virial properties of the hosting DM halo. Given the larger virial velocities in $f(R)$-gravity at fixed halo mass (Figure 1 and our choice to not modify the SAM parameters, we expect AGN feedback to become effective at relatively smaller halo masses, thus explaining this finding. Nonetheless, it is worth stressing that these effects are predicted to be smaller than the assumed uncertainty in the stellar mass determination (and definitively smaller than the intra-model dispersion of SAMs in $\Lambda$CDM models). It is also interesting to note that they go in the opposite direction than required for solving the well known discrepancies between observed and theoretically predicted mass functions (see e.g. Weinmann et al. [2012]).

In Paper I, we also proposed galaxy bias as a relevant discriminant between $\Lambda$CDM and EDE models. The same conclusion does not hold in $f(R)$-gravity models (Figure 3). SAMs predict similar levels of galaxy bias for both the FoR1 run and the $\Lambda$CDM box, especially at scales accessible with present and future experiments (i.e. larger than a few Mpc).

It is well known that the redshift-space clustering of galaxies carries an imprint of the growth of structure, providing fundamental information about the nature of gravity (Kaiser [1987], Zhang et al. [2007], Guzzo et al. [2008], Reyes et al. [2010], Jennings et al. [2012]). Standard techniques to extract this information are traditionally based on measurements of the anisotropy of the redshift-space correlation function $\xi_{\perp}(r_\parallel, r_\perp)$, where $r_\parallel$ and $r_\perp$ represent the com\footnote{Galaxy bias has been defined as the ratio between the galaxy autocorrelation function $\xi_{\text{gal}}$ and the auto-correlation function $\xi_{\text{lin}}$ for a randomly selected subsample of DM particles corresponding to 1 per cent of the total particles in the cosmological box.}
Figure 4. Pairwise galaxy velocity distribution along the line of sight for different models at four different redshifts. Velocities have been rescaled to comoving distances by the conformal Hubble function $H = aH$. Each sub-panel represents different values of the galaxy separation ($r_∥, r_⊥$), parallel and perpendicular to the line of sight, respectively (as labelled). As in Fig. 2, the solid black/blue/red lines refer to our SAM predictions in $\Lambda$CDM, Early Dark Energy (EDE3) and $f(R)$-gravity (FoR1) cosmologies, while the black dashed and dotted lines refer to the predictions of the De Lucia & Blaizot (2007) and Croton et al. (2006) SAMs for the $\Lambda$CDM cosmology.

Components of galaxy separation parallel and perpendicular to the line of sight, respectively. In this work, the volume of the simulated cosmological boxes is too small and the cosmic variance too large to reliably apply this technique. Nonetheless, it can still be of interest to look at the behaviour of gravity-driven large scale coherent motions, which are a direct consequence of the growth of structure. Given the real-space correlation function $\xi_r$, the corresponding $\xi_z$ is fully determined by the pairwise galaxy velocity distribution along the line of sight $P(v_∥, r_∥, r_⊥)$, measured at each given separation $r_∥, r_⊥$ (Scoccimarro 2004). In Figure 4 we show the behaviour of this distribution in our simulations for a few fixed values of $r∥, r⊥$, using galaxies with $M_*>10^9M_\odot$. The velocities have been rescaled to comoving distances by the conformal Hubble function $H = aH$ so that the distribution actually represents the statistical displacement of galaxy pairs from real to redshift space. We adopt the convention that the pairwise velocity is neg-
ative when galaxies are approaching each other and vice versa. As expected, there is a clear statistical difference between the shapes of the distributions corresponding to the FoR1 run and all other SAMs. In particular, \( f(R) \)-gravity (red lines) predicts a larger variance in the distribution. This discrepancy is more relevant for larger parallel and perpendicular separations, almost vanishing on small scales (bottom left of each panel), thus stressing the case for large surveys as cosmological probes of gravity and dark energy.

4 CONCLUSIONS

In this work, we analysed an updated version of the L-GALAXIES semi-analytic model, specifically designed to run self-consistently on high-resolution N-body simulations of \( f(R) \)-gravity scenarios (Puchwein et al. 2013). With respect to the \( \Lambda \)CDM version of the code, our modifications include the implementation of a user-defined Hubble function and adjusted DM halo virial scalings that account for the expected change of the mass–temperature relation (directly calibrated on the \( f(R) \)-gravity simulation of interest). This allows us to predict the properties of galaxy populations for a \( f(R) \)-gravity model and compare them with comparable models for \( \Lambda \)CDM and EDE cosmologies. Even though we adopted a relatively large \( \bar{f}_{\text{to}} \) value (already in tension with local test of gravity), we find that \( f(R) \)-gravity has only a subtle impact on the predicted galaxy properties, leading to deviations from \( \Lambda \)CDM of a size comparable to the uncertainties in the determination of physical quantities (stellar masses and star formation rates) from observations, and smaller than the intra-SAM variance at fixed cosmology.

The weak constraints on cosmology coming from predicted galaxy properties are consistent with our conclusions in Paper I, and also with the documented response of SAMs against small variations of the \( \Lambda \)CDM cosmological parameters (see e.g. Guo et al. 2011). In order to break some of these degeneracies, we considered the imprint of \( f(R) \)-gravity on the large scale structure assembly. We have tested the galaxy pairwise velocity distribution along the line of sight at different separations, and have shown the potential of a significant galaxy sample to detect deviations from general relativity on large scales using such statistics.

These results extend our previous findings for quintessence cosmologies (Fontanot et al. 2012), and represent a step forward in a quantitatively more accurate understanding of the relation between cosmological scenarios and the physics of galaxy formation. This question is indeed of fundamental importance in order to identify a set of reliable and orthogonal observational tests able to discriminate between the many proposed alternative cosmological theories (Amendola et al. 2012). A case in point for our approach is that in Paper I we showed that galaxy bias is a sensitive probe for detecting an evolution of the DE equation of state (e.g. quintessence models), while in this work we show that this probe is almost insensitive to the effect of \( f(R) \)-gravity models. On the other hand, the analysis of the velocity distribution suggests that the anisotropy of redshift-space correlation function and/or power spectrum as measured from galaxy samples is a sensible probe for \( f(R) \)-gravity models, but it is not able to differentiate between \( \Lambda \)CDM and EDE cosmologies. Overall, this initial exploration of the coupling of semi-analytic models with full non-linear N-body models of non-standard cosmologies shows the power of this approach in helping to make full use of the wealth of information expected from future wide galaxy surveys (like the EUCLID mission, Laureij et al. 2011). In forthcoming work, we plan to extend the approach further by considering other cosmological models with alternative DE scenarios (see, e.g. Baldi 2012), as well as considering larger box-size simulations to improve the statistical power of the models, particularly on large scales.

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