Semi-analytic galaxy formation in early dark energy cosmologies

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ABSTRACT

We study the impact of early dark energy (EDE) cosmologies on galaxy properties by coupling high-resolution numerical simulations with semi-analytic modeling (SAM) of galaxy formation and evolution. EDE models are characterized by a non-vanishing high-redshift contribution of dark energy, producing an earlier growth of structures and a modification of large-scale structure evolution. They can be viewed as typical representatives of non-standard dark energy models in which only the expansion history is modified, and hence the impact on galaxy formation is indirect. We show that in EDE cosmologies the predicted space density of galaxies is enhanced at all scales with respect to the standard ΛCDM scenario, and the corresponding cosmic star formation history and stellar mass density is increased at high-redshift. We compare these results with a set of theoretical predictions obtained with alternative SAMs applied to our reference ΛCDM simulation, yielding a rough measure of the systematic uncertainty of the models. We find that the modifications in galaxy properties induced by EDE cosmologies are of the same order of magnitude as intra-SAM variations for a standard ΛCDM realization (unless rather extreme EDE models are considered), suggesting that is difficult to use such predictions alone to disentangle between different cosmological scenarios. However, when independent information on the underlying properties of host dark matter haloes is included, the SAM predictions on galaxy bias may provide important clues on the expansion history and the equation-of-state evolution.

Key words: early Universe – cosmology: theory – cosmology: cosmological parameters – galaxies: formation – galaxies: evolution – galaxies: fundamental properties

1 INTRODUCTION

The last decade has seen considerably advances in our understanding of the properties of our Universe as a whole, in particular thanks to the accurate measurement of the most important cosmological parameters (see e.g. Komatsu et al. 2009 and references herein). One of the most surprising discoveries of this "precision cosmology" epoch is that some unknown form of *Dark Energy* (DE, hereafter) accounts for more than 70% of the energy density of the present-day Universe, and is responsible for its accelerated expansion today (see e.g., Perlmutter et al. 1999). The physical nature of DE, together with its origin and time evolution, is one of the most enigmatic puzzles in modern cosmology.

In the standard ΛCDM cosmological model, DE is treated as a classic cosmological constant (following Einstein's original conjecture) where a homogeneous and static energy density fills the whole Universe. This simple assumption, however, gives rise to a number of theoretical problems, such as the high degree of "fine-

tuning" required to accommodate the present day value of Ω_Λ (see Weinberg 1989 for a review). For this reason, many alternative scenarios to explain DE and the accelerated expansion have been proposed, ranging from scalar field models such as quintessence to radical modifications of the laws of gravity. Most observational efforts currently concentrate on constraining effective parametrisations of the DE equation of state (see e.g. Wetterich 1988; Ratra & Peebles 1988), which is adequate for 'non-coupled' dark energy models in which the dark energy can be approximated as uniform and influences structure formation only through a modification of the cosmic expansion rate.

An interesting sub-class of these models are scenarios that involve a non-negligible DE contribution at early times during recombination and primordial structure formation, which also implies non-negligible modifications of the cosmic microwave background (Doran et al. 2001), of big-bang nucleosynthesis (Müller et al. 2004) and of large-scale structure formation (Bartelmann et al. 2006). The non-linear structure formation predicted in such early dark energy (EDE) models has been studied through high-resolution N-body simulation (Baldi 2012;

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Grossi & Springel 2009). In particular, the impact on the statistical properties of dark matter (DM) haloes (such as the abundance of high-redshift galaxy clusters) as a function of cosmic time has been compared with the corresponding predictions for the standard ΛCDM cosmology, with the aim of identifying observational tests that are able to disentangle between the different cosmologies based on future surveys (like the EUCLID satellite, Laureijs et al. 2011).

In contrast, the influence of modified DE models on the properties and the evolution of galaxy populations has not yet been explored in full detail, even though many cosmological tests for constraining the DE equation of state ultimately rely on a precise understanding of how galaxies trace mass. This can in part be understood as a result of our limited present understanding of galaxy formation even in the ΛCDM cosmology, which is hampered by several long-standing discrepancies between the predictions of theoretical models and observations, as seen, for example, in the redshift evolution of the galaxy stellar mass function (see e.g. Fontanot et al. 2009), the properties of the Milky Way satellites (see e.g. Macciò et al. 2010; Boylan-Kolchin et al. 2012), the low baryon fraction in galaxy clusters (see e.g. McCarthy et al. 2007), or in the shallow DM profiles associated with different galaxy populations ("cusp-core" problem, see e.g. Moore 1994). This in turn fuels some interest in exploring both the possibility that these discrepancies may be reduced by assuming an evolving DE, and in finding observational tests based on statistical galaxy properties that could potentially distinguish between different DE scenarios (which one may also hope to be easier to perform compared with tests working purely in the "dark sector").

The catch of course is that galaxy evolution is a complex process, involving a non-linear blend of many different physical processes acting on the baryonic gas. All models of galaxy formation on cosmological scales (both semi-analytic models, SAMs hereafter, and numerical simulations alike) need to simplify this intrinsic complexity by means of quite coarse, yet physically grounded, analytic approximations (in SAMs) or sub-grid models (in simulations). In SAMs, these analytic approximations are meant to describe the physical processes acting on the baryonic gas (such as gas cooling, star formation and feedback) as a function of the physical properties of model galaxies (like their cold gas and stellar content). This then yields a convenient parametrisation of the physics, which is calibrated against a small subset of low-redshift observations. The ability of modern models of this kind to successfully match a large and diverse set of observations not used in the calibration can be viewed as a powerful confirmation of the viability of the basic paradigm of hierarchical galaxy formation.

However, it has also been shown that the SAM approach entails a significant level of degeneracies among the different parameters (e.g. Henriques et al. 2009), and the theoretical uncertainty is exacerbated by the fact that different models tend to adopt different parametrizations for the physical processes acting on the baryonic gas. Even though the comparison of different model predictions shows a reassuring level of consistency in many cases (see e.g. Fontanot et al. 2009), there is hence a certain degree of systematic uncertainty in this approach. Therefore, in order to assess the role of modified DE on galaxy evolution and, viceversa, to use galaxy formation to constrain DE models, it is important to not only quantify the impact of modified cosmologies on galaxy formation within a specific model, but also to check how the size of the changes in the model predictions compares to the intra-model variance for a fixed ΛCDM cosmology.

This paper is organized as follows. In Section 2, we introduce

Table 1. Cosmological Parameters and Model definition.

	Ω_m	$\Omega_\Lambda, 0$	h	σ_8	w_0	$\Omega_{\mathrm{de,e}}$
ΛCDM	0.25	0.75	0.73	0.9	-1.0	—
CWDE	0.25	0.75	0.73	0.9	-0.6	—
EDE1	0.25	0.75	0.73	0.9	-0.93	2×10^{-4}
EDE3	0.25	0.75	0.73	0.9	-0.93	2×10^{-3}
EDE5	0.25	0.75	0.73	0.9	-0.93	2×10^{-2}

the cosmological numerical simulations and semi-analytic models we use in our analysis. We then compare the various predictions in Section 3. Finally, we discuss our conclusions in Section 4.

2 MODELS

2.1 Dark energy parametrisation

In this paper, we focus on a specific class of DE cosmologies, called *Early Dark Energy* (EDE) models. In these cosmologies, DE constitutes an observable fraction of the total energy density at the time of matter-radiation equality (in contrast to the cosmological constant scenario). A natural outcome of these models is to predict an earlier formation of structures with respect to the ΛCDM cosmology for an equal amplitude of the present-day clustering strength. In fact, in EDE models the high-z cluster population grows considerably relative to ΛCDM, helped also by a lowered value of the critical linear density contrast needed for collapse (Bartelmann et al. 2006); as a result, EDE models predict a slower evolution of the halo population than the standard ΛCDM cosmology.

In particular, we consider similar EDE models as in Grossi & Springel (2009), as originally introduced by Wetterich (2004). These models are characterized by a low but non-vanishing dark energy density at early times, and by a low redshift value of Ω_Λ consistent with CMB constraints. The equation of state parameter $w(z)$ varies with time according to the equation

$$w(z) = \frac{w_0}{1 + b \ln^2(1 + z)}, \tag{1}$$

where

$$b = -\frac{3 w_0}{\ln\left(\frac{1 - \Omega_{\mathrm{de,e}}}{\Omega_{\mathrm{de,e}}}\right) + \ln\left(\frac{1 - \Omega_{\mathrm{m,0}}}{\Omega_{\mathrm{m,0}}}\right)}. \tag{2}$$

In the previous equations, w_0 and $\Omega_{\mathrm{de,0}} = 1 - \Omega_{\mathrm{m,0}}$ represent the present-day equation of state parameter and amount of dark energy, respectively, while $\Omega_{\mathrm{de,e}}$ gives the average energy density parameter at early times. For sufficiently low $\Omega_{\mathrm{de,e}}$, EDE models reproduce the accelerated cosmic expansion observed in the local Universe.

We examine a set of different EDE models by changing w_0 and $\Omega_{\mathrm{de,e}}$ (Table 1). In particular, we vary the $\Omega_{\mathrm{de,e}}$ parameter over two orders of magnitude; it is worth stressing, however, that in our EDE5 model we assume a value for $\Omega_{\mathrm{de,e}}$ which is rather extreme for this class of models (Hollenstein et al. 2009).

2.2 Numerical simulations

We have performed a series of numerical N-body simulations of DM-only runs for all our EDE models. For comparison, we also run a simulation in a standard ΛCDM cosmology configuration and we consider a model with constant equation of state $w = -0.6$
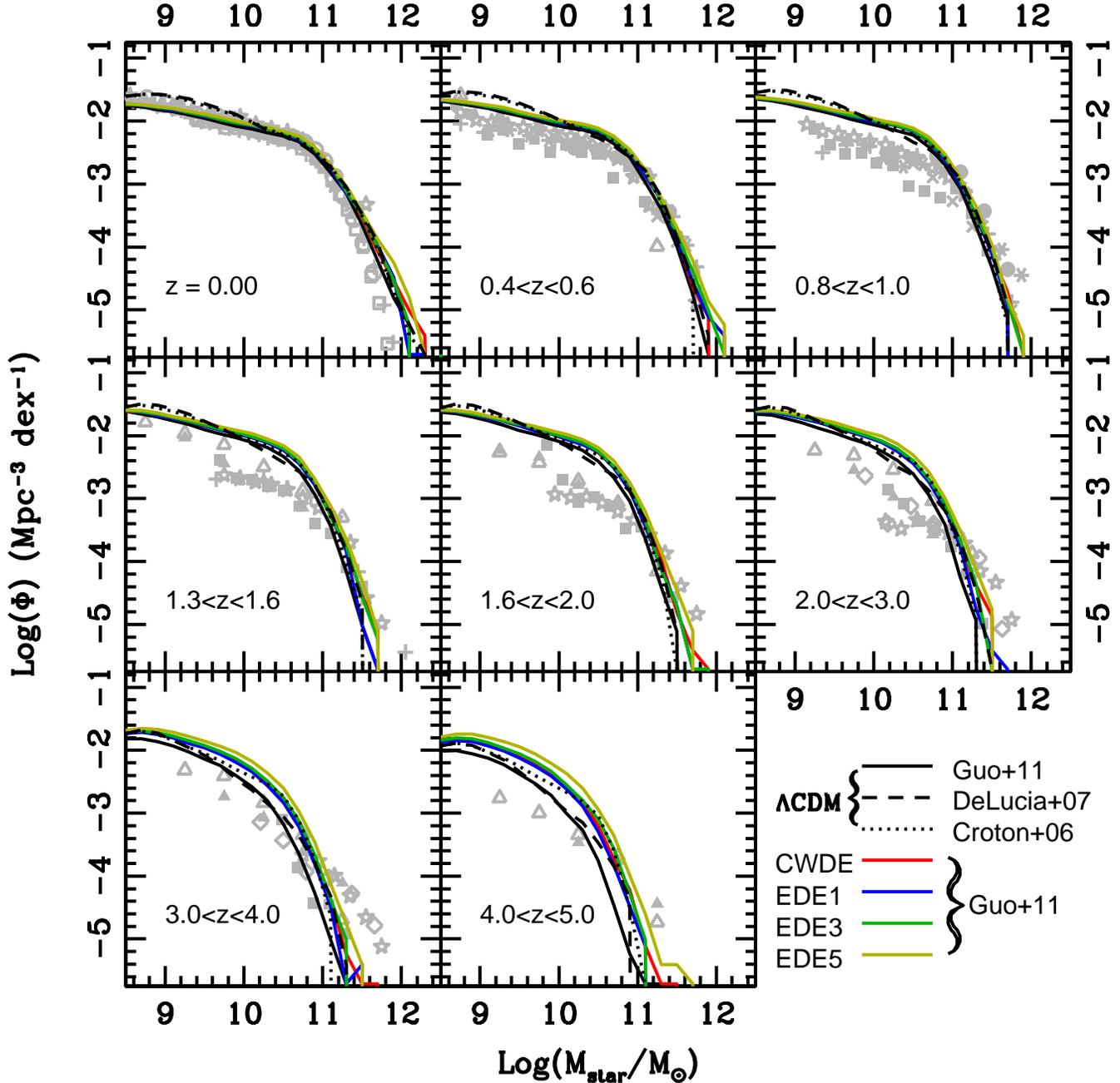
Figure 1. Redshift evolution of the galaxy stellar mass function in different cosmological models, and for different SAMs in the same ΛCDM model. Various line styles and colours distinguish the different models, as labeled in the legend. Grey points refer to the stellar mass function compilation from Fontanot et al. (2009, see references herein).

(CWDE) as well. In all simulations, we assume a flat universe with matter density parameter $\Omega_m = 0.25$, Hubble parameter $h = 0.73$, and Gaussian density fluctuations with a scale-invariant primordial power spectrum with spectral index $n = 1$. The normalization of the linearly extrapolated $z = 0$ power spectrum is taken to be $\sigma_8 = 0.9$ for all simulations.

We generate initial condition for all the cosmological models using the N-GENIC code and have run the simulations using the cosmological code GADGET-3 (last described in Springel 2005). For both codes we employ the versions modified by Grossi & Springel

(2009) to account for EDE cosmologies with a redshift-dependent equation of state. All simulations have been run using 432^3 particles in periodic boxes $100\,h^{-1}\mathrm{Mpc}$ on a side, corresponding to a mass resolution of $1.18 \times 10^9\,h^{-1}M_\odot$. For each box, 64 simulation snapshots were saved, at the same redshifts used in the Millennium project (Springel et al. 2005), facilitating a straightforward comparison. 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
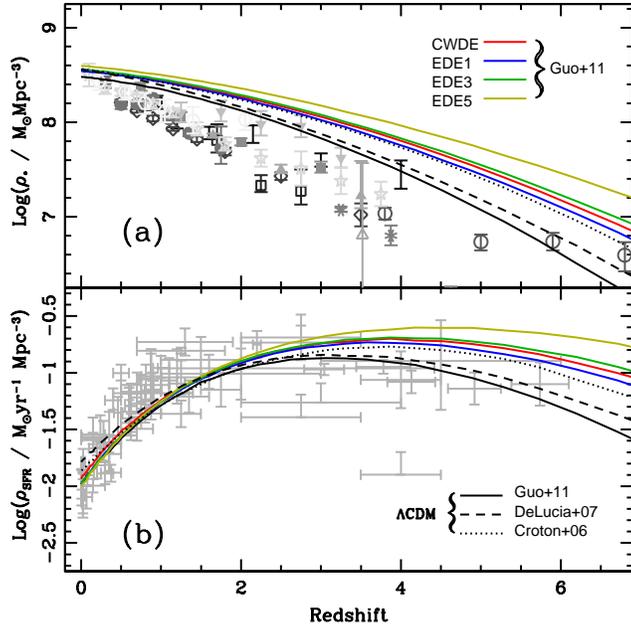
Figure 2. Redshift evolution of (a) the stellar mass density, and (b) the cosmic star formation rate density. Grey points refer to a stellar mass density compilation from Santini et al. (2012, see references herein) and to a cosmic star formation density compilation from Hopkins (2004, see references herein), respectively. Our models are shown with the same lines types and colours as in Fig. 1, as labeled.

Figure 3. Deviation of the galaxy auto-correlation functions in our model cosmologies with respect to the Guo et al. (2011) model applied to the ΛCDM simulation ($\xi_{\mathrm{G}\Lambda}$). The lines types and colours are the same as in Fig. 1.

SUBFIND (Springel et al. 2001). The resulting subhaloes are then used to construct merger history trees as explained in detail in Springel et al. (2005). Only subhaloes that retain at least 20 bound particles after the gravitational unbinding procedure are kept for the tree construction, thus implying a subhalo detection threshold of $2.36 \times 10^{10} \, h^{-1} M_\odot$.

As a consistency check, we have measured the matter power spectrum of the different simulation models at various redshifts, finding consistent results with respect to Grossi & Springel (2009, their Fig. 5). Similarly, our results for the halo mass functions reproduce their findings.

2.3 Semi-analytic models

In this paper, we mainly consider the most recent implementation of the *Munich* model (Guo et al. 2011), based on the L-GALAXIES code originally developed by Springel et al. (2005). We also consider two previous versions of the same code, namely the Croton et al. (2006) and De Lucia & Blaizot (2007) models. The use of different SAMs implemented on top of the same underlying code structure allows an assessment of the intra-model variance induced by different choices for the approximation of galaxy formation physics. This yields a course estimate of systematic model uncertainties, which can in turn be compared to the size of changes in the predicted galaxy properties due to EDE cosmologies. The chosen set of SAM models is particularly suitable for this approach as it represents a coherent set of models designed to work on Millennium-like merger trees, such that complications such as merger tree conversions can be avoided.

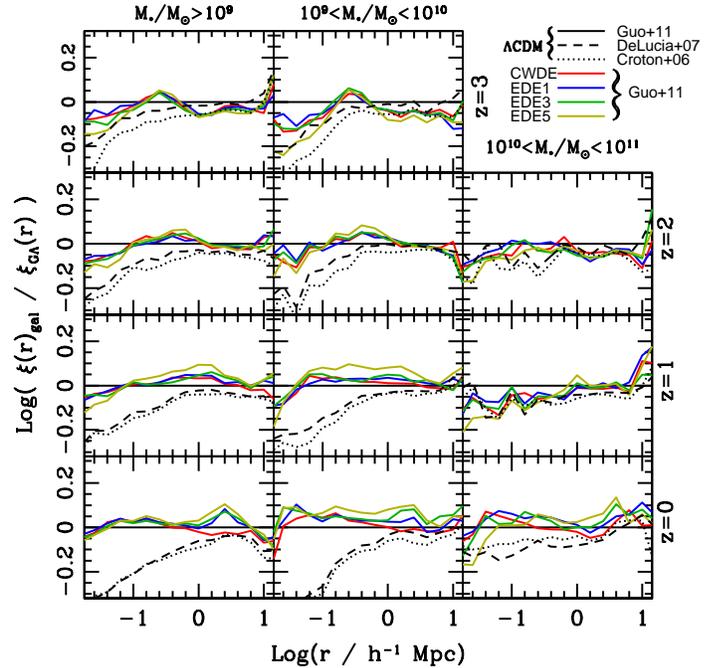In the interest of conciseness, we refrain in the following from

discussing all the details of the modeling of different physical processes in each of the SAMs (we refer the reader to the original papers for a full specification). However, we want to point out where the main differences between the three models lie: (a) in the treatment of dynamical friction and merger times, the stellar initial mass function and the dust model (from Croton et al. 2006 to De Lucia & Blaizot 2007); (b) in 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). In all cases, these major changes in the physical recipes involved a re-calibration of the most relevant model parameters.

We note that we have modified the code used in the Guo et al. (2011) model in order to have it run self-consistently on EDE cosmologies, by including the EDE contribution in the expression for the Hubble expansion rate:

$$H(a) = H_0 \sqrt{\frac{\Omega_{\mathrm{m},0}}{a^3} + \Omega_{\mathrm{de},0} \, e^{-3 \int [1+w(a)] d \ln a}}. \quad (3)$$

This equation is a generalisation of the usual Hubble function definition employed in L-GALAXIES, and it naturally simplifies to the correct forms when dealing with the CWDE and ΛCDM cosmologies ($w(a) = -1$). In the following, whenever we discuss results based on the Guo et al. (2011) model, we actually refer to this modified code.

All SAMs have been calibrated by requiring them to reproduce a well-defined set of low-redshift reference observations. In this paper, we do not discuss possible changes in the model calibrations, rather we prefer to retain the original parameter choices, in order to allow a direct comparison to the published models and to highlight differences induced by changes in the cosmology alone, for physics models that are kept fixed. As far as the EDE and CWDE cosmologies are concerned, this implies that these mod-
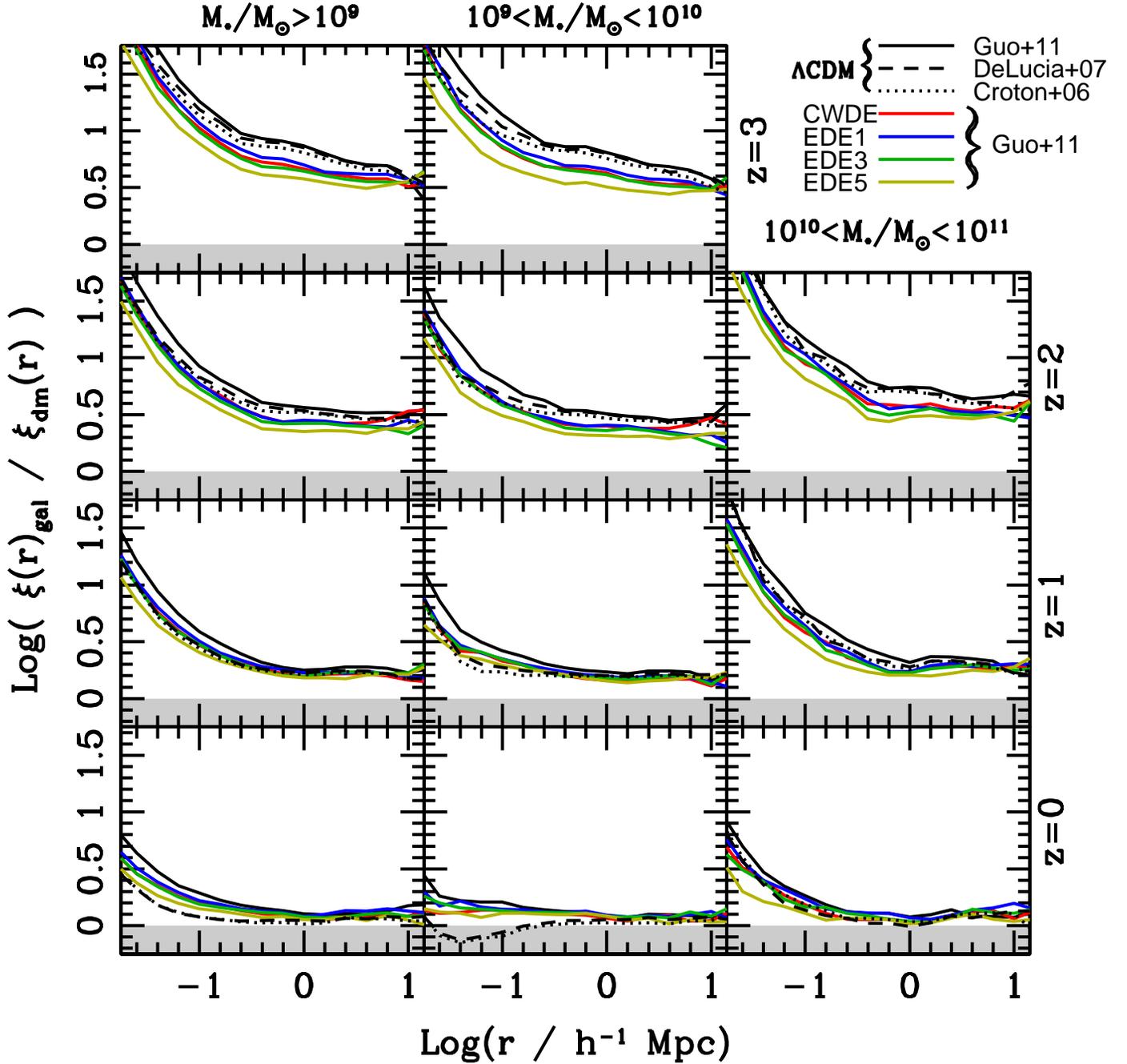
Figure 4. Redshift evolution of the galaxy bias in different cosmological models. The lines types and colours are as in Fig. 1.

els are not necessarily tuned to perform best, as in the ΛCDM case. Nonetheless, since we require our numerical simulations to provide consistent statistical properties for $z = 0$ DM haloes by construction, we expect the variations between SAM predictions in the different cosmologies to be small at the lowest redshifts. In any case, our choice of keeping the parameter choices used in the Guo et al. (2011) model the same also in different dark energy cosmologies is instrumental for testing the effective change in model predictions due to a variation of the assumed Hubble function *alone*, a distinctive feature of EDE models.

3 RESULTS & DISCUSSION

We begin by comparing the redshift evolution of some of the most basic global properties of the galaxy populations predicted by our SAMs, namely the galaxy stellar mass function (Fig. 1), and the evolution of the cosmic star formation rate and stellar mass density (Fig. 2).

In all the figures, the black lines show the different L-GALAXIES models in a ΛCDM cosmology. In particular, the solid lines refer to the Guo et al. (2011) implementation of the model, while dashed and dotted lines refer to the De Lucia & Blaizot (2007) and Croton et al. (2006) versions, respectively. The differ-

ences between the predictions of the different SAMs applied to the same cosmological simulations are mainly driven by the different calibration sets employed by the different authors. For example, the Guo et al. (2011) model has been especially designed to reproduce the low-mass end of the stellar mass function at $z = 0$. Coloured lines, on the other hand, give the predictions of the Guo et al. (2011) model in different cosmologies. Red lines refer to the CWDE simulation, whereas blue, green and yellow lines refer to the different EDE realizations, as labelled in the legend.

We point out that the agreement of the Guo et al. (2011) predictions among the different cosmologies is satisfactory at $z = 0$. When a comparison to observational constraints is made, the model predictions have been convolved 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). 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.

As expected, the earlier structure formation epoch in EDE cosmologies directly translates into an increase of the space density of galaxies at all redshifts (Fig. 1). The strength of this effect and the redshift range involved increase with the $\Omega_{\rm de,e}$ value, as then the dark energy contribution to the total energy density of the Universe becomes more relevant. Nonetheless, it is worth noting that this increase in space density is not limited to the massive end of the stellar mass function, but is present at all mass scales. The well-known problem of an overprediction of intermediate-to-low mass galaxies in theoretical models of galaxy formation (Fontanot et al. 2009) is thus not reduced, but even enhanced in EDE cosmologies. Following this argument, we also expect that a number of known tensions between model predictions and the properties of galaxies in the Milky-Way environment should not be solved but exacerbated, although dedicated higher resolution simulations are needed to firm up this conclusion. However, when we consider the predictions of the other two L-GALAXIES versions based on the same ΛCDM cosmology, we find a small spread in the predictions of different SAM models computed for the same cosmology. This "systematic uncertainty" in the theoretical modelling is of the same order as the size of the differences seen in the predictions of a single SAM model applied to different cosmologies.

Similar conclusions can be drawn by considering integrated quantities, like the cosmic stellar mass density and mean star formation rate density (Fig. 2). In these quantities, the different redshift evolution among different cosmologies and models is even more clear: out to redshift $z \sim 4$, it is difficult to separate the impact of different cosmologies from the effect of a different modeling of physical processes and/or different model calibrations, while at higher redshift, EDE models effectively predict somewhat higher star formation rates and accumulated stellar mass density. Anyhow, also in this case, only rather extreme models differ significantly from the locus of considered ΛCDM SAMs.

The galaxy auto-correlation function $\xi_{\rm gal}$ represents another potentially useful discriminant between different cosmologies. We consider auto-correlation functions corresponding to different intervals of stellar mass. The predicted galaxy auto-correlation functions for our models show good consistency among each other over a wide redshift range, so they provide no direct way to disentangle between different cosmologies. In Fig. 3, we show the resulting auto-correlation functions normalised to the predicted values for the Guo et al. (2011) model in the ΛCDM realization ($\xi_{G\Lambda}$), for all galaxies more massive than $10^9 M_\odot$ and in two different mass

bins. Similar trends are seen in all cosmologies, with no relevant deviations from the reference model in most cases. Most notably, the strongest deviations are seen for the Croton et al. (2006) and De Lucia & Blaizot (2007) predictions at very small scales. This is clearly due to the different treatment of satellite galaxy evolution in Guo et al. (2011). For the theoretical predictions on these small scales, the physical mechanisms acting on baryonic gas dominate over the cosmological effects.

Nonetheless, these results can provide interesting insights when coupled with additional information on the underlying distribution of DM particles. In particular, for each cosmology, we have computed the auto-correlation function $\xi_{\rm dm}$ of the mass for a randomly selected subsample of DM particles (corresponding to 1% of the total particles in the cosmological box, for computational convenience – a larger fraction would not change the results). As expected, the redshift evolution of $\xi_{\rm dm}$ shows large deviations among different cosmologies. We combine these complementary informations into an estimate of the galaxy bias, defined as $\xi_{\rm gal}/\xi_{\rm dm}$ (Fig. 4). In all stellar mass intervals we consider, it is in principle possible to distinguish between the different cosmological models with the help of the bias, by considering the intermediate to large scales (i.e. larger than a few tenths of a Mpc) at $z > 0$. In fact, at these scales, there is a concordance of the predictions for the bias from the different ΛCDM based SAMs, while, at the same time, the deviations of EDE models from a standard ΛCDM cosmology become progressively larger at increasing redshift and for larger stellar mass. At smaller scales, the intrinsic intra-model dispersion between SAM predictions due to the different treatments of the satellite galaxy physics hampers firm cosmological conclusions.

4   CONCLUSIONS

In this paper we discuss the expected impact of Early Dark Energy (EDE) cosmologies on the properties of galaxy populations, as predicted by semi-analytic models. We consider the latest version of the L-GALAXIES model (Guo et al. 2011), modified to account for time-dependent variations of the equation of state parameter w. We also consider earlier versions of the same SAM (Croton et al. 2006; De Lucia & Blaizot 2007) to compare the size of differences in galactic properties induced by changes in the underlying dark energy model with the intra-model variance due to differences in the modeling of the baryonic physics. The extension of our approach to consider other cosmological models with alternative dark energy scenarios (see e.g. Baldi 2012) is in principle straightforward, provided high-resolution N-body simulations of such scenarios can be calculated. The latter has very recently become possible even for more complicated theories of gravity, such as DGP or $f(R)$-gravity (see e.g. Oyaizu 2008; Schmidt 2009; Khoury & Wyman 2009; Li et al. 2012), such that our method can be fruitfully used to connect such scenarios with observations of galaxies. We plan to expand our present results into this direction in forthcoming work.

Our results highlight that EDE cosmologies lead to important modifications in the galaxy properties with respect to a standard ΛCDM universe. Nonetheless, they also show that these deviations are of the same order of magnitude as those induced by different assumptions in the modeling of physical properties and/or by parameter recalibrations in a homologous set of ΛCDM-based SAMs (see also Guo et al. 2012). Stronger effects are seen at higher redshift ($z > 4$), but these redshifts correspond to a cosmic epoch where direct observational constraints on galaxies are extremely difficult to

obtain and where we expect SAM predictions to be comparatively uncertain (given that their usual calibration samples are selected at lower redshifts). This behaviour is mainly due to our still limited understanding of the physical properties acting in the baryonic sector, and to the high level of degeneracy between the analytic approximations employed in different SAMs. We thus conclude that predicted galaxy properties alone provide only weak constraints on disentangling a standard ΛCDM cosmology from an Early Dark Energy model. These results are consistent with studies that analysed the response of SAMs against variations of cosmological parameters (corresponding to the best constraints from different data releases of the WMAP satellite) in the ΛCDM Universe (see e.g Wang et al. 2008; Guo et al. 2012).

We have also shown that some of these degeneracies are broken if additional information on the properties and distribution of the underlying DM field became available. The combination of the stronger evolutionary patterns expected for the "dark sector" and the definition of galactic populations with suitably stable properties in SAMs indeed leads to the identification of reliable cosmological tests. In particular, we show the potential of a measurement of galaxy bias on scales larger than a few tenths of Mpc as a cosmological discriminant. Future observational efforts aimed at constraining w and its redshift evolution, like the EUCLID mission (Laureijs et al. 2011), are indeed devised in order to provide, at the same time, constraints on the DM distribution (via weak lensing) and on the properties of large galaxy populations (via spectroscopy and photometry). We stress however, that this mission is designed to primarily focus on the $z \sim 1$ diagnostics, where the predicted effects of EDE cosmologies on galaxy bias are smaller than at higher redshifts.

While we confirm that the combination of these different probes is indeed one of the most promising methods to achieve constraints on the dark energy component of our Universe, we also would like to emphasise the power of the particular simulation approach taken here, which is able to accurately predict galaxy bias in non-standard cosmologies as a function of scale, epoch, and galaxy type. The combination of high-resolution dark matter simulations and semi-analytic galaxy formation models used in this paper should also be highly useful to explore and understand generic effects of galaxy formation on cosmological constraints, for instance those derived from BAO or redshift space distortion measurements (Angulo 2012). This would ultimately lead to an optimal and accurate exploitation of the next generation of galaxy surveys.

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