Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **447,** 3361–3367 (2015) doi:10.1093/mnras/stu2705

Semi-analytic galaxy formation in massive neutrino cosmologies

Fabio Fontanot,[1★] Francisco Villaescusa-Navarro,[1,2] Davide Bianchi[3] and Matteo Viel[1,2]

[1] *INAF – Astronomical Observatory of Trieste, via G.B. Tiepolo 11, I-34143 Trieste, Italy*
[2] *INFN – Sezione di Trieste, Via Valerio 2, I-34127 Trieste, Italy*
[3] *INAF – Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (LC), Italy*

Accepted 2014 December 18. Received 2014 December 16; in original form 2014 September 22

ABSTRACT

The constraints on neutrino masses led to the revision of their cosmological role, since the existence of a cosmological neutrino background is a clear prediction of the standard cosmological model. In this paper, we study the impact of such background on the spatial distribution of both dark matter (DM) and galaxies, by coupling *N*-body numerical simulations with semi-analytic models (SAMs) of galaxy formation. Cosmological simulations including massive neutrinos predict a slower evolution of DM perturbations with respect to the Λ cold dark matter (ΛCDM) runs with the same initial conditions and a suppression on the matter power spectrum on small and intermediate scales, thus impacting on the predicted properties of galaxy populations. We explicitly show that most of these deviations are driven by the different σ_8 predicted for cosmologies including a massive neutrino background. We conclude that independent estimates of σ_8 are needed, in order to unambiguously characterize the effect of this background on the growth of structures. Galaxy properties alone are a weak tracer of deviations with respect to the ΛCDM run, but their combination with the overall matter distribution at all scales allows us to disentangle between different cosmological models. Moreover, these deviations go on opposite directions with respect to competing models such as modified gravity, thus weakening any detectable cosmological signal. Given the ubiquitous presence of a neutrino background, these effects have to be taken into account in future missions aimed at constraining the properties of the 'Dark' components of the Universe.

Key words: galaxies: evolution – galaxies: formation – cosmology: theory.

1 INTRODUCTION

The accurate measurement of the value of cosmological parameters from the cosmic microwave background (CMB; Hinshaw et al. 2013; Planck Collaboration XVI 2014) opened a completely new window on the study of the basic properties of our Universe. In particular, the role of the so-called Dark components, i.e. dark matter (DM) and dark energy (DE), as the main contributors to the current energy density of the Universe has raised considerable debate. Despite the undisputed successes of the standard Λ cold dark matter (ΛCDM) cosmological scenario at physical scales ranging from the Galactic to the large-scale structure (LSS hereafter), the still unknown properties of the 'Dark' components remain a challenge to our understanding of the Universe as a whole.

Numerous scenarios have been proposed in an attempt to explain the origin and rise of such components: as an example, generalized DE models overcome the theoretical difficulties related to the simplest scenario based on a cosmological constant Λ (see e.g. Amendola et al. 2013, for a review of the different DE scenarios). Besides, different models have been suggested to explain the nature of the DM particle, based on some assumptions on its phase-space density and/or interaction properties, including extensions of the Particles Standard Model (e.g. axions, supersymmetric or weakly interacting massive particles). Present constraints based on CMB measurements are in better agreement with $\Omega_{\rm m}$ being dominated by a non-baryonic 'cold' DM particle (i.e. characterized by non-relativistic velocities). It is worth stressing that, as long as the 'cold' component dominates, a small contribution from a different DM species, with 'hotter' properties, is possible. In these mixed or 'warm' DM scenarios (see e.g. Macciò et al. 2013; Viel et al. 2013, and references herein), the growth of structures in both the linear and non-linear regime is affected by the hottest component, due to its relatively large free-streaming scale. Conversely, the evolution of the LSS of the Universe provides strong constraints on the maximum contribution of these hot species to the total DM budget.

The standard cosmological big bang theory predicts the existence of a neutrino background (see e.g. Lesgourgues & Pastor 2006) and

★ E-mail: fontanot@oats.inaf.it

neutrinos contribute to the total radiation energy density in the early Universe, thus affecting the early nucleosynthesis of light elements. Commonly considered as massless particles, the cosmological role of neutrinos as DM candidates has been revived by the discovery of the neutrino oscillation phenomenon (Cleveland et al. 1998; Fogli et al. 2012; Forero, Tórtola & Valle 2012), which proved that at least two of the three neutrino families should have a mass. It is worth stressing that these experiments only provide information on the mass square difference between the different neutrino families, which is then converted into constraints on their total mass. In addition, CMB experiments and galaxy surveys studied the shape of the matter power spectrum and were able to put upper limits on the total neutrino mass of the order of $\sum_i m_{\nu_i} < 0.3$ eV (see e.g. Xia et al. 2012; Costanzi et al. 2014; Riemer-Sørensen, Parkinson & Davis 2014, and references herein). At variance with warm DM cosmologies, which can be viewed as 'exotic' models meant to solve a number of inconsistencies in the standard cosmological model (such as those related to halo profiles and subhalo abundances), massive neutrinos are nowadays regarded as a fundamental element in cosmology and constraining their masses is a key target in order to explore physics beyond the standard model.

This paper is the third of a series aimed at the study of the properties of galaxy populations as predicted by semi-analytic models (SAMs) of galaxy formation and evolution in non-ΛCDM cosmologies. In the first two papers, we consider early DE (Fontanot et al. 2012b, hereafter Paper I) and *f*(*r*)-Gravity (Fontanot et al. 2013, hereafter Paper II) cosmologies, and we discuss which observables are the most suitable to distinguish these scenarios from a standard ΛCDM universe. In this paper, we expand this suite of mock galaxy catalogues coupling SAMs with numerical simulations of massive neutrino cosmologies. In the SAM framework (and in hydrodynamical simulations as well), the relevant physical mechanisms acting on the baryonic component and responsible for galaxy formation and evolution (gas cooling, star formation, black hole accretion, feedbacks) are modelled using simplified analytic prescriptions, which describe the main dependences, as a function of the physical properties of model galaxies (stellar, gas and metal content, morphology), environment (parent halo mass) and hierarchy (central or satellite). Such models are thus characterized by a number of free parameters, usually calibrated against a well-defined set of low-redshift observations. This approach is flexible enough to test different prescriptions for the relevant processes and their interplay, thus providing key insight in our understanding of the complex processes leading to the built up of the different galaxy populations. However, a number of tensions between model predictions and observational constraints are still present (see e.g. McCarthy, Bower & Balogh 2007; Boylan-Kolchin, Bullock & Kaplinghat 2012; Weinmann et al. 2012; Henriques et al. 2013; Wilman et al. 2013, among others) pointing to the need for a revision of some key ingredients. Moreover, the SAM approach implies a relevant level of intrinsic degeneracy among the different parameters (Henriques et al. 2009), which is exacerbated by the fact that different groups made different choices for the (equally plausible) modelling of the main processes. The predictions of independently developed SAMs show reasonable agreement for a number of key quantities (see e.g. Fontanot et al. 2009, 2012a). None the less, it is of fundamental importance, in the context of future space missions aimed at a better characterization of DE and DM (such as the *EUCLID* mission; Laureijs et al. 2011), to identify modifications of galaxy properties that can be uniquely associated with the different cosmological frameworks and define suitable statistical tests based on galaxy populations able to disentangle such models from the standard cosmological model. In fact, most of the key cosmological probes proposed in the context of such missions, ultimately rely on the spatial distribution of galaxy populations, used as tracers of the underlying LSS at different redshifts.

This paper is organized as follows. In Section 2, we introduce the cosmological numerical simulations and SAMs 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 Massive neutrino cosmologies

Massive neutrinos affect the growth of cosmological LSS at different scales. At the linear order, they shift the matter-radiation equality time, stretching out the radiation-dominated epoch, while in the matter-dominated era they slow down the growth of matter perturbations. The combination of these two effects determines a suppression of the matter power spectrum on small scales (Lesgourgues & Pastor 2006). In the fully non-linear regime, on the other hand, massive neutrinos induce a variety of effects and in order to properly characterize their impact on the matter power spectrum *N*-body simulations have been used (see e.g. Brandbyge et al. 2008; Viel, Haehnelt & Springel 2010; Agarwal & Feldman 2011; Bird, Viel & Haehnelt 2012; Wagner, Verde & Jimenez 2012). Those works have pointed out that the suppression of power is higher in the fully non-linear regime than in linear theory. However, unlike the linear case, the suppression is redshift- and scale dependent.

At the decoupling time, the momentum distribution of the neutrinos is expected to follow the Fermi–Dirac distribution: thus, a small fraction of the cosmic neutrinos will have velocities low enough to cluster within the DM haloes (see e.g. Brandbyge et al. 2010; Ichiki & Takada 2012; LoVerde 2014, and reference herein) and form, via gravitational collapse, haloes of neutrinos. These structures modify the total matter density profile and in principle may be detected via gravitational lensing in future surveys (Villaescusa-Navarro et al. 2011).

Recently, in a series of works (Costanzi et al. 2013; Castorina et al. 2014; Villaescusa-Navarro et al. 2014) it has been shown that massive neutrinos induce a scale-dependent bias on large scales. In particular, Castorina et al. (2014) pointed out that the scale-dependence almost disappears if the bias is defined as the ratio between the halo power spectrum and the CDM power spectrum. Massive neutrinos have also an impact on the halo mass function, as the same authors have shown that in massive neutrino cosmologies this constraint can be entirely, and universally, described in terms of the properties of the CDM field alone (see also Brandbyge et al. 2010, where this aspect has been suggested for the first time). Additional signatures of the presence of a massive neutrino background are also expected on the Lyα forest (Viel et al. 2010; Villaescusa-Navarro et al. 2013; Rossi et al. 2014), on the Sunyaev–Zel'dovich and X-ray properties of galaxy clusters (Roncarelli, Carbone & Moscardini 2015), on the redshift-space distortions (Marulli et al. 2011), and on the cosmic voids statistics (Villaescusa-Navarro et al. 2013).

The first attempt to populate DM haloes with galaxies in massive neutrino cosmologies has been carried out in Villaescusa-Navarro et al. (2014) using a halo occupation distribution model. In this paper, we plan to extend this study and we investigate the distribution and properties of different galaxy populations, as predicted by SAMs. It is well known that the effects induced

Table 1. Cosmological parameters for the cosmological simulation suite.

	Ω_Λ	$\sum_i m_{\nu_i}$	Ω_ν	Ω_m	Resolution (h^{-1} M$_\odot$)	h	σ_8
ΛCDM	0.6825	0.0 eV	0.0	0.3175	6.57×10^8	0.6711	0.834
NU03	0.6825	0.3 eV	0.0072	0.3175	6.42×10^8	0.6711	0.763
NU06	0.6825	0.6 eV	0.0143	0.3175	6.27×10^8	0.6711	0.692
N3s8	0.6825	0.3 eV	0.0072	0.3175	6.42×10^8	0.6711	0.834
N6s8	0.6825	0.6 eV	0.0143	0.3175	6.27×10^8	0.6711	0.834

by massive neutrinos, through a non-vanishing value of Ω_ν, can be mimicked by a standard cosmological model with a different normalization of the matter power spectrum: this is the so-called Ω_ν–σ_8 degeneracy. In this paper, we will also explore whether this degeneracy can be broken by means of mock galaxy catalogues.

2.2 Numerical simulations

In this paper, we consider a set of numerical simulations similar to those used in Villaescusa-Navarro et al. (2014), using a modified version of the cosmological code GADGET3: in order to follow the evolution of the LSS on non-linear scales, these runs employ the so-called *particle method*, which explicitly incorporates neutrinos in the simulations as particles. In all simulations, we assume a flat universe consistent with Planck cosmology (Planck Collaboration XVI 2014), with matter density parameter $\Omega_m = 0.3175$, Hubble parameter $h = 0.6711$ and with Gaussian density fluctuations with a scale-invariant primordial power spectrum with spectral index $n = 0.9624$. We generate initial conditions for all the simulations using a modified version of the N-GENIC code: we set them to have the same matter power spectrum at the last scattering surface, and we impose the same phases and mode amplitudes to force a similar realization of the LSS and allow a proper object-by-object comparison. Since Ω_m is kept constant in all runs, simulations with larger Ω_ν have smaller Ω_{cdm}. We thus run a set of simulations with varying total neutrino masses including $\sum_i m_{\nu_i} = 0.0$ eV (i.e. a standard vanilla ΛCDM), 0.3 eV (NU03), 0.6 eV (NU06). In this reference simulation suite, the normalization of the power spectrum at early times is the same as in a ΛCDM universe with $\sigma_8 = 0.834$; none the less, the presence of a massive neutrino component changes the linear structure growth as a function of redshift and scale, and the actual σ_8, measured at $z = 0$ will be different from the corresponding ΛCDM value. In an attempt to break the degeneracy between $\sum_i m_{\nu_i}$ and σ_8 we also run additional simulations with $\sum_i m_{\nu_i} = 0.3$ eV and 0.6 eV where we vary the amplitude of the initial fluctuations to obtain the same σ_8 value at $z = 0$ as in the ΛCDM realization (N3s8, N6s8).

We set up our simulations of periodic boxes of 100 h^{-1} Mpc on a side using 512^3 CDM and 512^3 neutrino particles, corresponding to a mass resolution of $6.57 \times 10^8\ h^{-1}$ M$_\odot$ for the ΛCDM realization (and slightly lower for the other runs, see Table 1). For each run, 63 simulations snapshots were stored at the same redshifts used in the Millennium simulation (Springel et al. 2005) and in Papers I and II. Group catalogues have been constructed using a Friend-of-Friend algorithm with a linking length of 0.2 (in mean particle separation units), and gravitationally bound substructures have been defined using SUBFIND (Springel et al. 2001) (only subhaloes that retain at least 32 particles after the gravitational unbinding procedure were considered). We then use the subhalo catalogues to define the merger tree histories as in Springel et al. (2005).

2.3 Semi-analytic models

In this work, we use the same approach we used in the previous papers of this series. We consider three different versions of the L-GALAXIES SAM, based on the code originally developed by Springel et al. (2005): those are, in historical order, the versions described in Croton et al. (2006), De Lucia & Blaizot (2007) and Guo et al. (2011). All these models share a common code structure and are designed to run on the same merger tree histories defined in the previous section. Moreover, they provide a representative set of models characterized by different choices in the modelling of the relevant galaxy formation physics,[1] which typically require a general re-calibration of the main model parameters, against comparable sets of low-redshift reference observations. Therefore, when these models are applied to the same ΛCDM cosmological simulation, we expect the scatter in their predictions to be representative of the variance of SAM predictions.[2]

Our reference version of the model is the same as proposed in the original Guo et al. (2011) paper: the presence of a massive neutrino component affects mainly the growth of LSS (at variance with Papers I and II we do not expect any effect neither in the Hubble function nor in the baryonic physics) and this information is completely defined in the different merger tree histories. We will thus focus mainly in understanding the effect of massive neutrino scenarios on galaxy properties (such as the assembly of stellar mass, the cosmic star formation rate and galaxy clustering).

As in Papers I and II, we do not consider possible re-calibrations of the Guo et al. (2011) model and we rather prefer to keep the original parameter set: this choice allows a direct comparison to the published models and to highlight differences induced by changes in the cosmology alone. This implies that the models with an increasingly large contribution of neutrinos are not necessarily tuned to perform best, as in the ΛCDM case.

3 RESULTS

As in Papers I and II, we compare the redshift evolution of selected statistical properties of mock galaxy populations in the different

[1] From the Croton et al. (2006) to the De Lucia & Blaizot (2007) version, the main differences lie in the treatment of dynamical friction and merger times, the initial mass function (from Salpeter to Chabrier) and the dust modelling; from the De Lucia & Blaizot (2007) to the Guo et al. (2011) version, the main changes involve the modelling of supernovae feedback, the treatment of satellite galaxy evolution, tidal stripping and mergers. In the following, the predictions of the Croton et al. (2006) model have been converted to a Chabrier IMF by applying a constant shift (0.25 dex in stellar mass and 0.176 dex in star formation rate) to the original, Salpeter IMF calibrated, predictions.

[2] We note that, since all models we consider use Millennium-like merger trees, we get rid of any additional source of noise due to the different merger tree formats used in the SAM framework, see e.g. Knebe et al. (in preparation).

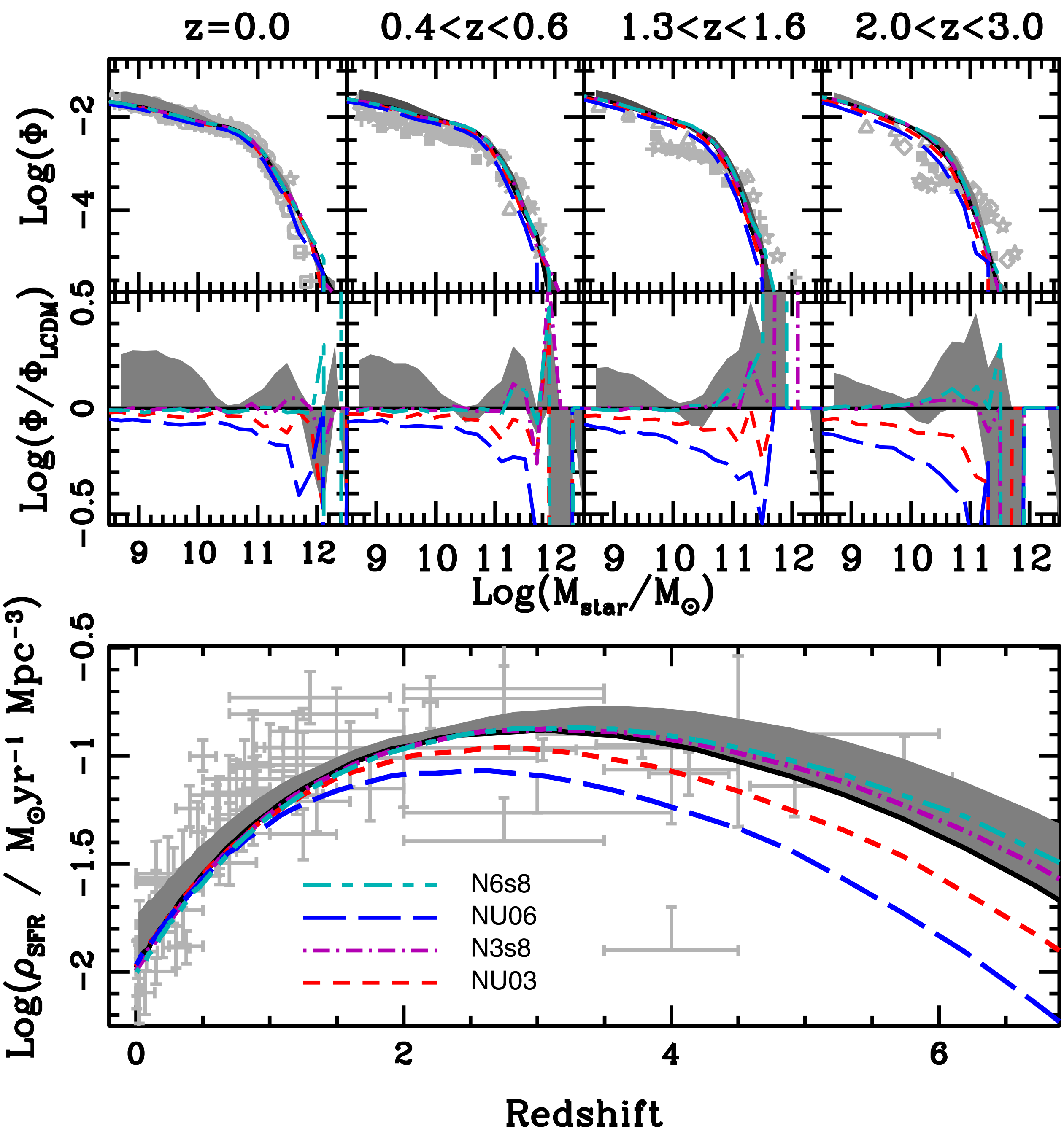

Figure 1. SAM predictions in different massive neutrino cosmological scenarios for the redshift evolution of the predicted stellar mass function (upper panel – light grey points refer to the compilation from Fontanot et al. 2009) and for the cosmic star formation rate density (lower panel – light grey points refer to the compilation from Hopkins 2004). In each panel, the solid black, long-dashed red, dot–dashed violet, short-dashed blue and short-long-dashed light blue lines refer to SAM predictions in ΛCDM, NU03, N3s8, NU06 and N6s8 cosmologies, respectively, as labelled. Dark grey areas mark the distribution in the predictions between the Guo et al. (2011), De Lucia & Blaizot (2007) and Croton et al. (2006) SAMs for ΛCDM cosmology.

cosmologies. In particular, we consider the galaxy stellar mass function (Fig. 1, upper panel), the cosmic star formation rate (Fig. 1, lower panel), the galaxy bias (both in real and redshift space, Fig. 2) and the pairwise velocity distribution (Fig. 3). In the following, only galaxies with $M_\star > 10^9\,\mathrm{M}_\odot$ have been considered and in Fig. 1, model predictions are convolved with an estimate of the error associated with observational constraints (i.e. a lognormal distribution with amplitude 0.25 and 0.3 for stellar masses and star formation rates, respectively). In all figures, shaded areas represent the locus span by the predictions of the three different SAMs when applied to the same ΛCDM box, the black solid line being the prediction of the Guo et al. (2011) model: as we discussed in the previous sections, we consider the shaded area as representative of the variance between SAMs. The predictions of the Guo et al. (2011) model applied to massive neutrino realizations are highlighted by different line types and colours: long dashed red, dot–dashed violet, short dashed blue and long-short-dashed cyan refer to the NU03, N3s8, NU06 and N6s8 runs, respectively.

Massive neutrino cosmologies induce systematic deviations in galaxy properties with respect to ΛCDM: in particular, the slower

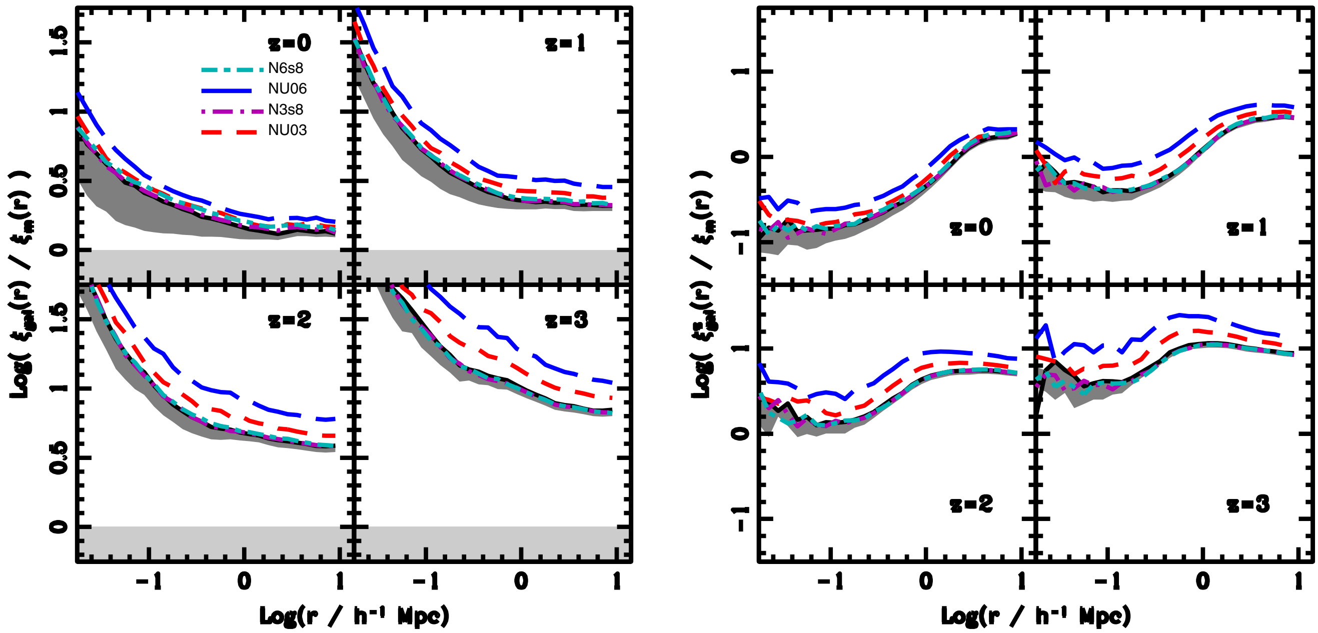

Figure 2. Redshift evolution of galaxy bias in real (left-hand panel) and redshift space (right-hand panel) for different massive neutrino cosmologies. In each panel, only model galaxies with $M_\star > 10^9\,\mathrm{M}_\odot$ have been considered while computing the galaxy two-point correlation functions. Models are labelled with the same line types, colours and shades as in Fig. 1.

growth of structures is reflected in a smaller space density of galaxies at all mass scales and redshifts, i.e. in a lower cosmic star formation rate. The differences with respect to ΛCDM are larger at the high-mass end of the stellar mass function, and tend to be small or negligible at the low-mass end: this implies that the dwarf overproduction problem (Fontanot et al. 2009) is not reduced in massive neutrino cosmologies. In realistic cases ($\sum_i m_{\nu_i} \simeq 0.3$ eV), these deviations are of the same order of the intra-SAM variance, and only models with relatively large values of $\sum_i m_{\nu_i}$ show relevant deviations. None the less, it is worth stressing that similar trends are expected also for standard ΛCDM realizations with different σ_8 (see e.g. Wang et al. 2008; Guo et al. 2013). Indeed, the results for the N3s8 and N6s8 runs clearly show that most of the difference between massive neutrino cosmologies and ΛCDM are washed out, if we force the former runs to have the same σ_8 at $z = 0$: as a consequence they became indistinguishable from a standard cosmological model. Therefore, an independent estimate of σ_8 at different redshifts is needed in order to use our results as constraints for massive neutrino cosmologies.

In the left-hand panel of Fig. 2, galaxy bias is estimated from the ratio between the auto-correlation function of galaxies in real space ξ_{gal} and the auto-correlation function of total matter distribution in real space ξ_{m}, using the Landy & Szalay (1993) estimator. The latter quantity has been computed combining the auto-correlation function of CDM and neutrino and the cross-correlation among them (see equation 12 in Villaescusa-Navarro et al. 2014), and using a subsample of 10^6 CDM particles and 10^6 neutrino particles randomly extracted from the corresponding simulations. From the analysis of this plot, we reach similar conclusions with respect to Fig. 1: massive neutrino cosmologies show a clear increase in the bias at all scales with respect to ΛCDM model with the same power spectrum at recombination. Moreover, it is possible to define a range of physical scales and redshifts where the cosmological signal is clearly larger than the variance between different SAM predictions. However, most of these effects are connected to the different σ_8 evolution. The same conclusions hold when galaxy bias is computed in redshift space (using the ratio between the auto-correlation function for galaxies in redshift space ξ^z_{gal} and the auto-correlation function of total matter distribution in real space, Fig. 2, right-hand panel), showing that the analysis in redshift space disentangles different massive neutrino cosmologies as efficiently as in the real space.

Finally, in Fig. 3 we show the redshift evolution of the pairwise galaxy velocity distribution along the line of sight $\mathcal{P}(v_\parallel, r_\parallel, r_\perp)$, measured considering fixed components of galaxy separation parallel ($r_\parallel$) and perpendicular ($r_\perp$) to the line of sight (see e.g. Scoccimarro 2004). The actual choice of reference separations (1 and 15 Mpc h^{-1}) has been motivated by the limited cosmological volume considered in our boxes. Only galaxies with $M_\star > 10^9\,\mathrm{M}_\odot$ have been considered and their velocities[3] have been rescaled using the conformal Hubble function $\mathcal{H} = aH$ in order for the distribution to represents the statistical displacement of galaxy pairs from real to redshift space. The pairwise velocity distribution is a reliable tracer of the anisotropy of redshift-space correlation functions and the assembly and growth of LSS. As expected, given the different growth history in massive neutrino cosmologies, there is some statistical difference between SAM predictions relative to NU03 and NU06 and all other realizations; however, the effect is rather small for realistic cases ($\sum_i m_{\nu_i} \sim 0.3$ eV).

By comparing Figs 2 and 3 with the corresponding plots in Papers I and II, we noticed that the combined deviations are clearly different from those predicted in the case of early DE or $f(r)$-gravity runs, showing that in principle it should be possible to disentangle between these cosmologies using these tests. Moreover, it is worth stressing that, since massive neutrino cosmologies imprint opposite trends with respect to the other models, the existence of a neutrino

[3] As in Paper II, we assume that the pairwise velocity is negative when galaxies are approaching each other and positive when they are receding.

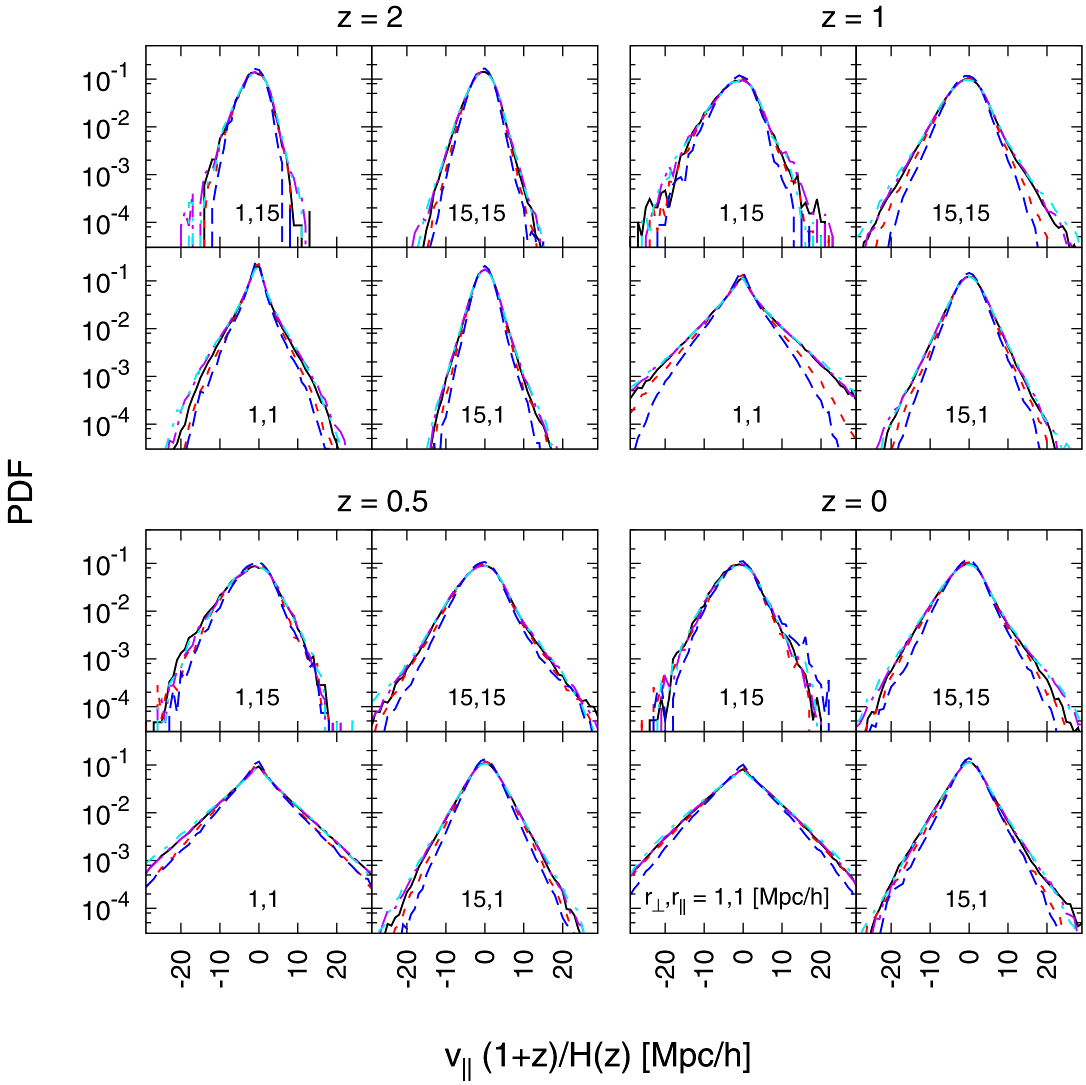

Figure 3. Pairwise galaxy velocity distribution along the line of sight for the massive neutrino cosmologies at four different redshifts. Velocities have been rescaled to comoving distances using the conformal Hubble function $\mathcal{H} = aH$. Each panel represents a different combination for values of the galaxy separation ($r_\perp$,$r_\parallel$), perpendicular and parallel to the line of sight, respectively (as labelled). Different cosmological models are marked by different line types and colour as in Fig. 1.

background (as predicted by the standard cosmological model) has the net effect of smoothing any signal coming from these. This has indeed been already pointed out by simulations combining massive neutrinos and *f*(*r*)-gravity (see e.g. Baldi et al. 2014).

4 CONCLUSIONS AND DISCUSSION

In this paper, we study the impact of cosmologies including massive neutrinos on the properties of galaxy populations, as predicted by SAMs. This work has important implications, since the existence of a neutrino background (and its role in early nucleosynthesis) is a robust prediction of the standard cosmological model, and given the evidences in favour of massive neutrinos (Cleveland et al. 1998; Fogli et al. 2012; Forero et al. 2012). In this paper, we couple a suite of *N*-body CDM+neutrinos simulations with the L-GALAXIES model (in the Guo et al. 2011, version). We also consider earlier L-GALAXIES versions to constrain the variance in the SAM predictions when applied to the same ΛCDM realization. Our results are compatible with our previous findings (see Papers I and II) and similar studies based on coupling warm DM simulations with SAMs (Kang, Macciò & Dutton 2013): the presence of an additional, but subdominant, hot/warm DM component leads to small but systematic deviations in the global properties of galaxy populations. It is worth stressing that most of the effects we find are mainly driven by the lower σ_8 values predicted for cosmological boxes including massive neutrinos with respect to ΛCDM, and due to the requirement that the amplitude of matter power spectrum at recombination to be the same in all runs. Therefore, it is of fundamental importance to have an independent and firm estimate of σ_8 at different redshifts coming from other cosmological constraints, in order to break the degeneracy. Given this estimate, our results show the effects on structure formation of including massive neutrinos in theoretical models of galaxy formation. None the less, for $\sum_i m_{\nu_i}$ values compatible with present observational constraints, these changes are of the same order of magnitude as the variance between the predictions of different SAMs applied to the same ΛCDM realization and due to the different modelling of the relevant physical processes.

Stronger constraints on the cosmological models are indeed accessible, should detailed information on the overall DM field be available. In particular, we show that both galaxy bias and the pairwise velocity distribution are sensitive to the presence of massive neutrinos (the effects being larger with larger $\sum_i m_{\nu_i}$); more interestingly both diagnostics show deviations in the opposite direction with respect to early DE and/or $f(r)$-gravity models. Tests based on these observables are thus able not only to disentangle runs including massive neutrinos from ΛCDM, but also to discriminate between different non-ΛCDM cosmologies. On the other hand, since a neutrino background is expected to be present in all cosmological models based on the big bang theory, we expect it to weaken any signal coming from an early DE or $f(r)$-gravity cosmology (see e.g. Baldi et al. 2014).

Overall, the results presented in this work complement our previous claims about the effect of cosmological models which deviates from a standard ΛCDM model in the 'dark sector', given different assumptions on the nature and properties of DE or DM. Such analysis confirms the relevance of studying the modifications induced in galaxy properties by alternative cosmologies, in order to tailor effective cosmological tests to be performed with galaxy surveys. Forthcoming planned space missions such as *EUCLID* (Laureijs et al. 2011) are indeed designed to describe the LSS, using both weak lensing and slitless spectroscopy techniques, and compare it with the spatial distribution of galaxies. In this framework, it is crucial to build mock catalogues covering as many cosmologies as possible: in a forthcoming work, we plan to further extend this approach by considering other cosmological models such as the coupled DE scenarios (see e.g. Baldi 2012). Finally, in this series of papers we consider cosmological volumes best suited to study the galaxy mass function over a wide range of stellar and halo masses (i.e. from $\sim 10^9$ to $\sim 10^{12}$ $M_{\odot}$): we plan to extend the analysis using larger box-size simulations to improve the statistical power of our approach, especially at large scales (i.e. galaxy clusters).

ACKNOWLEDGEMENTS

We thank Carmelita Carbone for enlightening discussions. FF acknowledges financial contribution from the grants PRIN MIUR 2009 'The Intergalactic Medium as a probe of the growth of cosmic structures' and PRIN INAF 2010 'From the dawn of galaxy formation'. FVN and MV are supported by the ERC Starting Grant 'cosmoIGM' and partially supported by INFN IS PD51 'INDARK'. We acknowledge partial support from 'Consorzio per la Fisica - Trieste'.

REFERENCES

Agarwal S., Feldman H. A., 2011, MNRAS, 410, 1647
Amendola L. et al., 2013, Living Rev. Relativ., 16, 6
Baldi M., 2012, MNRAS, 422, 1028
Baldi M., Villaescusa-Navarro F., Viel M., Puchwein E., Springel V., Moscardini L., 2014, MNRAS, 440, 75
Bird S., Viel M., Haehnelt M. G., 2012, MNRAS, 420, 2551
Boylan-Kolchin M., Bullock J. S., Kaplinghat M., 2012, MNRAS, 422, 1203
Brandbyge J., Hannestad S., Haugbølle T., Thomsen B., 2008, J. Cosmol. Astropart. Phys., 8, 20
Brandbyge J., Hannestad S., Haugbølle T., Wong Y. Y. Y., 2010, J. Cosmol. Astropart. Phys., 9, 14
Castorina E., Sefusatti E., Sheth R. K., Villaescusa-Navarro F., Viel M., 2014, J. Cosmol. Astropart. Phys., 2, 49
Cleveland B. T., Daily T., Davis R., Jr, Distel J. R., Lande K., Lee C. K., Wildenhain P. S., Ullman J., 1998, ApJ, 496, 505
Costanzi M., Villaescusa-Navarro F., Viel M., Xia J.-Q., Borgani S., Castorina E., Sefusatti E., 2013, J. Cosmol. Astropart. Phys., 12, 12
Costanzi M., Sartoris B., Viel M., Borgani S., 2014, J. Cosmol. Astropart. Phys., 10, 081
Croton D. J. et al., 2006, MNRAS, 365, 11
De Lucia G., Blaizot J., 2007, MNRAS, 375, 2
Fogli G. L., Lisi E., Marrone A., Montanino D., Palazzo A., Rotunno A. M., 2012, Phys. Rev. D, 86, 013012
Fontanot F., De Lucia G., Monaco P., Somerville R. S., Santini P., 2009, MNRAS, 397, 1776
Fontanot F., Cristiani S., Santini P., Fontana A., Grazian A., Somerville R. S., 2012a, MNRAS, 421, 241
Fontanot F., Springel V., Angulo R. E., Henriques B., 2012b, MNRAS, 426, 2335 (Paper I)
Fontanot F., Puchwein E., Springel V., Bianchi D., 2013, MNRAS, 436, 2672 (Paper II)
Forero D. V., Tórtola M., Valle J. W. F., 2012, Phys. Rev. D, 86, 073012
Guo Q. et al., 2011, MNRAS, 413, 101
Guo Q., White S., Angulo R. E., Henriques B., Lemson G., Boylan-Kolchin M., Thomas P., Short C., 2013, MNRAS, 428, 1351
Henriques B. M. B., Thomas P. A., Oliver S., Roseboom I., 2009, MNRAS, 396, 535
Henriques B. M. B., White S. D. M., Thomas P. A., Angulo R. E., Guo Q., Lemson G., Springel V., 2013, MNRAS, 431, 3373
Hinshaw G. et al., 2013, ApJS, 208, 19
Hopkins A. M., 2004, ApJ, 615, 209
Ichiki K., Takada M., 2012, Phys. Rev. D, 85, 063521
Kang X., Macciò A. V., Dutton A. A., 2013, ApJ, 767, 22
Landy S. D., Szalay A. S., 1993, ApJ, 412, 64
Laureijs R. et al., 2011, preprint (arXiv:1110.3193)
Lesgourgues J., Pastor S., 2006, Phys. Rep., 429, 307
LoVerde M., 2014, Phys. Rev. D, 90, 083518
McCarthy I. G., Bower R. G., Balogh M. L., 2007, MNRAS, 377, 1457
Macciò A. V., Ruchayskiy O., Boyarsky A., Muñoz-Cuartas J. C., 2013, MNRAS, 428, 882
Marulli F., Carbone C., Viel M., Moscardini L., Cimatti A., 2011, MNRAS, 418, 346
Planck Collaboration XVI, 2014, A&A, 571, A16
Riemer-Sørensen S., Parkinson D., Davis T. M., 2014, Phys. Rev. D, 89, 103505
Roncarelli M., Carbone C., Moscardini L., 2015, MNRAS, 447, 1761
Rossi G., Palanque-Delabrouille N., Borde A., Viel M., Yèche C., Bolton J. S., Rich J., Le Goff J.-M., 2014, A&A, 567, A79
Scoccimarro R., 2004, Phys. Rev. D, 70, 083007
Springel V., White S. D. M., Tormen G., Kauffmann G., 2001, MNRAS, 328, 726
Springel V. et al., 2005, Nature, 435, 629
Viel M., Haehnelt M. G., Springel V., 2010, J. Cosmol. Astropart. Phys., 6, 15
Viel M., Becker G. D., Bolton J. S., Haehnelt M. G., 2013, Phys. Rev. D, 88, 043502
Villaescusa-Navarro F., Miralda-Escudé J., Peña-Garay C., Quilis V., 2011, J. Cosmol. Astropart. Phys., 6, 27
Villaescusa-Navarro F., Vogelsberger M., Viel M., Loeb A., 2013, MNRAS, 431, 3670
Villaescusa-Navarro F., Marulli F., Viel M., Branchini E., Castorina E., Sefusatti E., Saito S., 2014, J. Cosmol. Astropart. Phys., 3, 11
Wagner C., Verde L., Jimenez R., 2012, ApJ, 752, L31
Wang J., De Lucia G., Kitzbichler M. G., White S. D. M., 2008, MNRAS, 384, 1301
Weinmann S. M., Pasquali A., Oppenheimer B. D., Finlator K., Mendel J. T., Crain R. A., Macciò A. V., 2012, MNRAS, 426, 2797
Wilman D. J., Fontanot F., De Lucia G., Erwin P., Monaco P., 2013, MNRAS, 433, 2986
Xia J.-Q. et al., 2012, J. Cosmol. Astropart. Phys., 6, 10

This paper has been typeset from a TEX/LATEX file prepared by the author.