High-z massive clusters as a test for dynamical coupled dark energy

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ABSTRACT

The recent detection by Jee et al. of the massive cluster XMMU J2235.3–2557 at a redshift $z \approx 1.4$, with an estimated mass $M_{200} = (6.4 \pm 1.2) \times 10^{14} M_\odot$, has been claimed to be a possible challenge to the standard ΛCDM cosmological model. More specifically, the probability to detect such a cluster has been estimated to be $\sim 0.005$ if a ΛCDM model with Gaussian initial conditions is assumed, resulting in a $3\sigma$ discrepancy from the standard cosmological model. In this Letter we propose to use high-redshift clusters as the one detected in Jee et al. to compare the cosmological constant scenario with interacting dark energy models. We show that coupled dark energy models, where an interaction is present between dark energy and cold dark matter, can significantly enhance the probability to observe very massive clusters at high redshift.

Key words: cosmology: observations – cosmology: theory.

1 INTRODUCTION

One of the main challenges of present cosmology is to use observations to distinguish between a cosmological constant scenario and dynamical dark energy. More generally, it is a crucial task to devise new observational tests capable of detecting possible failures of the standard Lambda cold dark matter (ΛCDM) model, also in view of future observations, and to constrain the parameter space of alternative scenarios. The existence of massive clusters at high redshift has been recently used to test ΛCDM cosmologies. In particular, weak lensing observations in a survey of 11 deg² (Jee et al. 2009; Rosati et al. 2009) have recently detected a cluster of mass $M_{200} = (6.4 \pm 1.2) \times 10^{14} M_\odot$ [MC20 = (7.3 ± 1.3) $\times 10^{14} M_\odot$] at a redshift $z \approx 1.4$. The observation of such a massive cluster at high redshift represents an extremely rare event in the context of hierarchical structure formation. More specifically, the probability to detect such a cluster within a ΛCDM model with Gaussian initial conditions in the volume considered by the survey presented in Jee et al. (2009) and Rosati et al. (2009) has been estimated by the same authors to be $\sim 0.005$, resulting in a $3\sigma$ discrepancy with the assumed model. Naturally, this discrepancy can indicate that either initial conditions are not perfectly Gaussian, or that the ΛCDM model itself has to be modified. Some analyses have already been carried out in order to test the former possibility and the detection of high-z massive clusters has been used to constrain the level of primordial non-Gaussianity (Grossi et al. 2007; Jimenez & Verde 2009; Cayon, Gordon & Silk 2010; Holz & Perlmutter 2010; Hoyle, Jimenez & Verde 2010; Sartoris et al. 2010). In this Letter, instead, we investigate the second option: we point out that the presence of high-z massive clusters can be used to test the cosmological constant scenario as compared to dynamical coupled dark energy models. We therefore keep Gaussian initial conditions and instead allow for the possibility that dark energy is not a cosmological constant but rather a dynamical scalar field that can interact with CDM. We carry out N-body simulations for a set of models of interacting dark energy with either constant or time dependent couplings. We then compute the cumulative halo mass functions of the structures that form within these theories at different redshifts, and compare them with the outcomes of the standard ΛCDM model. In this way we are able to show that the probability of finding massive clusters at high redshifts is significantly enhanced in coupled dark energy cosmologies with respect to ΛCDM.

2 COUPLED DARK ENERGY

We consider coupled dark energy models where the acceleration of the Universe is driven by a scalar field $\phi$ (Ratra & Peebles 1988; Wetterich 1988) interacting with the CDM fluid according to the equations:

$$\rho_c' + 3H\rho_c = -\beta\phi'\rho_c$$

(1)

$$\rho_\phi' + 3H\rho_\phi = +\beta\phi'\rho_c$$

(2)

with $\rho_c$ the energy density of CDM and where a prime denotes a derivative with respect to conformal time. The dimensionless function

$$\beta \equiv -\frac{d\ln m_c}{d\phi}$$

(3)

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where $m_p$ is the mass of a CDM particle, fully specifies the interaction. Note that we define densities as $\rho \equiv 8\pi G\rho$ and that the scalar field $\phi$ is normalized in units of the reduced Planck mass $M = (8\pi G)^{-1/2}$. The scalar field energy density is $\rho_\phi = (\phi^2/2a^2) + U(\phi)$ and we consider two choices of potentials

$$U(\phi) = U_0e^{-\phi},$$

$$U(\phi) = U_0e^{-\alpha\phi},$$

where $U_0$ and $\alpha$ are constants. In the present work we limit our investigation to the models specified in Table 1: one model with a potential given by (4) and with a constant coupling $\beta = 0.2$, labelled as ‘RP’, and two models with an exponential potential (5) with constant coupling $\beta = 0.2$ and variable coupling $\beta(\phi) = 0.4e^{\phi}$, labelled ‘EXP005’ and ‘EXP010a2’, respectively (see Baldi 2010, for a detailed discussion on variable coupling models).

Coupled dark energy models have been widely studied in the literature (Wetterich 1995; Amendola 2000; Mangano, Miele & Pettorino 2003; Pettorino & Baccigalupi 2008, and references therein). The interaction imparts specific features on the growth of cosmic structures, as it has been shown both within spherical collapse models (Mainini & Bonometto 2006; Wintergerst & Pettorino 2010) and at the non-linear level by means of $N$-body simulations for constant (Macciò et al. 2004; Baldi et al. 2010) and variable couplings $\beta(\phi)$ (Baldi 2010). In particular, the interaction determines an enhancement of structure formation due to the presence of a long range fifth-force acting between coupled massive particles. In addition to this effect, conservation of momentum turns into an extra acceleration directly proportional to the peculiar velocity of coupled particles; at the non-linear level, it has been shown that this velocity dependent term can determine a reduction of the concentration of haloes if the coupling function $\beta(\phi)$ is positive (see again Baldi 2010; Baldi et al. 2010). These effects are encoded in the modified Newtonian acceleration equation for coupled dark matter particles:

$$p_i = \frac{1}{a} \left[ \beta \frac{\phi}{M} a p_i + \sum_{j \neq i} \tilde{G}_{ij} m_j x_{ij} / |x_{ij}|^3 \right],$$

where $i$ and $j$ are indices that span over all the particles of the simulation, $p$ is the momentum of the $i$th particle and $\tilde{G}_{ij}$ is the effective gravitational constant between the $i$th and the $j$th coupled particles $\tilde{G}_{ij} = G_N[1 + 2\beta(\phi)]$,

where $G_N$ is the usual Newtonian value.

### 3 SIMULATIONS

In this letter, we estimate how the probability of finding very massive clusters comparable to the XMMU J2235.3−2557 detection by Jee et al. (2009) and Rosati et al. (2009) at $z \sim 1.4$ is modified in the presence of a coupling between dark energy and CDM as compared to the standard $\Lambda$CDM case. With this aim, we use the modified version of the cosmological $N$-body code GADGET-2 (Springel 2005) presented in Baldi et al. (2010) and Baldi (2010), to which we refer for further details, to investigate non-linear structure formation within the models described in Table 1. We make use of the following sets of simulations:

(i) Two of the high-resolution hydrodynamical simulations presented in Baldi et al. (2010) for the case of a scalar field with an inverse-power-law self-interaction potential with a constant coupling $\beta = 0.2$ and for a reference $\Lambda$CDM model, both with cosmological parameters in accordance with five-year Wilkinson Microwave Anisotropy Probe (WMAP5) results (Komatsu et al. 2009).

(ii) Three new simulations at lower resolution in a larger cosmological box for the case of an exponential self-interaction potential with either constant ($\beta = 0.2$) or variable ($\beta = 0.4 \cdot e^{\phi}$) coupling and for a reference $\Lambda$CDM cosmology, all with cosmological parameters in accordance with WMAP7 results (Komatsu et al. 2010).

The former set of simulations includes the cosmological fraction of uncoupled baryons on which hydrodynamical forces are computed with the Smoothed Particle Hydrodynamics (Springel & Hernquist 2002; Springel 2005) algorithm, while the latter ones are pure CDM simulations.

The two sets of simulations start at $z = 60$ with exactly the same initial conditions for each set of runs. This is a conservative set-up, since the effects of enhanced growth that we are investigating would be more pronounced if a normalization at decoupling ($z \sim 1100$) had been adopted. We remark that this normalization is different from the one adopted in most of the simulations discussed in Baldi et al. (2010) and Baldi (2010): in these works the amplitude of linear density fluctuations was normalized in order to have the same $\sigma_8$ at the present time. In the present study, instead, we choose all the models with the same initial normalization of the power spectrum, which will necessarily result in different values of $\sigma_8$ at $z = 0$ for the different cosmological models. It is important to notice that all our models start at high redshift with a normalization of the power spectrum which is in full accordance with the latest WMAP7 determination of the scalar perturbations amplitude from CMB data alone (Komatsu et al. 2010).

Given this set-up, we study the halo mass function at different redshifts for the groups identified in each simulation with a Friends-of-Friends (FoF) algorithm with a linking length $\lambda = 0.2 \times \bar{d}$, where $\bar{d}$ is the mean particle spacing. We show that the interaction between dark energy and CDM results in a significantly larger number of massive haloes at any epoch, with respect to $\Lambda$CDM.

### 4 RESULTS

In Fig. 1 we show the evolution of the halo mass function at different redshifts in the three low-resolution simulations described in Table 1. The bottom panel of each plot shows the enhancement of halo number density in coupled dark energy models with respect to $\Lambda$CDM. As it clearly appears in all the plots, the number density of haloes of any mass is larger in coupled dark energy models, both for constant and variable couplings, as compared to $\Lambda$CDM, and the effect significantly grows with mass [the decreasing behaviour found in Manera & Mota (2006) can be explained in view of Wintergerst & Pettorino (2010)]. In particular, at $z \sim 1.5$ the halo number density at the high-mass end of our simulated mass functions exceeds the $\Lambda$CDM value by a factor of $\sim 10$ and $\sim 3$ for constant and variable couplings, respectively.

In Fig. 2 we plot the same quantities for our hydrodynamical high-resolution simulations, which confirm the trend found in the larger simulation box, although the enhancement is slightly weaker in this case due to the inclusion of the fraction of uncoupled baryons.

For all simulations, the most massive halo forming in the simulated box has a higher mass for coupled dark energy cosmologies than for $\Lambda$CDM. In this respect, it is important to stress once more here that all the simulations start from the very same initial conditions, and therefore this effect is due only to the different physics.
Table 1. List of the different simulations discussed in the present work, performed with our modified version of GADGET-2. The low-resolution simulations include only CDM particles while the two high resolution runs include uncoupled baryons with hydrodynamical forces. The last column of the table reports the gravitational softening $\epsilon_s$ used in each simulation.

| Model          | $U(\phi)$ | $\alpha$ | $\beta$ | Box size ($h^{-1}$ Mpc) | Number of particles | $M_0$ ($h^{-1}$ M$_{\odot}$) | $M_{CDM}$ ($h^{-1}$ M$_{\odot}$) | $\epsilon_s$ ($h^{-1}$ kpc) |
|----------------|------------|----------|---------|-------------------------|---------------------|-----------------------------|-------------------------------|-----------------------------|
| $\Lambda$CDM (low) | – – 0     | 320      | 256$^3$ | –                       | 1.47 x $10^{11}$    | 25.0                        | 2.3 x $10^8$                 | 3.5                         |
| $\Lambda$CDM (high) | – – 0     | 80       | 2 x $512^3$ | 4.7 x $10^7$  | 2.3 x $10^8$        | 2.3 x $10^8$                | 2.3 x $10^8$                 | 3.5                         |
| RF             | $\phi^{\alpha}$ | 0.143  | 0.2     | 320                     | 256$^3$             | –                          | 1.47 x $10^{11}$             | 25.0                        |
| EXP005         | $e^{-\alpha \phi}$ | 0.1      | 0.2     | 80                      | 256$^3$             | –                          | 1.47 x $10^{11}$             | 25.0                        |
| EXP010a2       | $e^{-\alpha \phi}$ | 0.1      | 0.2     | 80                      | 256$^3$             | –                          | 1.47 x $10^{11}$             | 25.0                        |

Figure 1. Cumulative mass functions for the low-resolution simulations of the coupled DE models with constant (red) and variable (green) couplings, and for the standard $\Lambda$CDM cosmology (black). The four plots correspond to different redshifts and show in the bottom panel the ratio of the halo number density to the $\Lambda$CDM case. The mass functions are based on the groups identified with a FoF algorithm and the masses quoted in the plots are FoF masses. Each plot also reports the mass of the most massive halo found at a given redshift in each simulation, which clearly shows how more massive structures are expected to form at any cosmological epoch in coupled dark energy models as compared with $\Lambda$CDM.

induced by the coupling and is not affected by statistical differences in the random realization of the initial density fields. Due to our normalization choice, the different models will also be characterized by different values of $\sigma_8$ at $z = 0$. In order to quantify this effect we have computed $\sigma_8(z = 0)$ from our two hydrodynamical simulations. The maximum increase in $\sigma_8$ is obtained, as expected, for the highest value of the coupling: $\sigma_8(\beta = 0.2) \sim 0.91$. Compared to the $\Lambda$CDM value $\sigma_8(\Lambda$CDM) $\sim 0.76$, this corresponds to a maximum relative increase of roughly 20 per cent, still in reasonable agreement with present available...
measurements of $\sigma_8$ at $z = 0$ (see e.g. Mantz et al. 2010; Vikhlinin et al. 2009). We stress again that different values of $\sigma_8$ at the present time arise from the same normalization at high redshift. In other words, different couplings are able to evolve the same initial normalization into different $\sigma_8$ today. As a consequence, a mismatch between the value of the perturbations amplitude at CMB and local measurements of $\sigma_8$ based solely on low-redshift probes, could provide a further possible observational test for coupled dark energy models, breaking degeneracies with $\Lambda$CDM cosmologies. Interestingly, some mismatch between the value of $\sigma_8$ extrapolated from CMB data under the assumption of a standard $\Lambda$CDM cosmology and pure local measurements has been recently claimed by e.g. Feldman et al. (2003); Reichardt et al. (2009); Watkins, Feldman & Hudson (2009), although still with a low statistical significance.

We also note that the effect is expected to be model dependent and possibly weaker for other viable models as e.g. variable coupling scenarios.

5 CONCLUSIONS

We conclude that coupled dark energy can significantly increase the probability to detect massive clusters at high redshift with respect to a $\Lambda$CDM model. The effect shows a quite strong dependence on the halo mass and is found to be larger for higher halo masses. Note that similar coupled dark energy models may also predict the existence of structures at very large scales (Wintergerst et al. 2010).

For the case of a constant coupling we have assumed the largest possible value of the coupling which is allowed according to present constraints for this class of models (Bean et al. 2008; La Vacca et al. 2009; Baldi & Viel 2010). In this case the number density of haloes at $z \sim 1.5$ is found to be at least a factor of $\sim 10$ higher than in $\Lambda$CDM cosmologies for haloes of masses larger than $M \approx 10^{12}$ $M_\odot$. This is a conservative estimate and the enhancement could increase in case the models were normalized further in the past (e.g. at decoupling) rather than at $z \sim 60$ as considered in the present simulations.

We have also presented results for one choice of variable coupling models. Despite the large value of the interaction strength at recent cosmological epochs, such models have a weaker impact on the background expansion history as compared to constant coupling models and are therefore easier to reconcile with present cosmological constraints. For the specific choice of variable coupling that we have considered in this work, which has recently been shown to also mitigate other possible tensions between the $\Lambda$CDM cosmology and observations at small scales (e.g. the cluster baryon fraction or the so called ‘cusp-core’ problem, see Baldi 2010), the total effect on the number counts is found to be somewhat weaker than in the constant coupling scenario, due to the low value of the coupling at early times. Nevertheless, also in this model the probability of finding massive clusters at $z \sim 1.4$ is enhanced by at least a factor of 2–3 with respect to $\Lambda$CDM.

These estimates are based on the ratio of the simulated halo mass functions at their high-mass end in the different models. Although the most massive groups found in our simulations at $z \sim 1.4$ do not reach the mass of the high-$z$ cluster XMMU J2235.3–2557 identified by Jee et al. (2009) and Rosati et al. (2009), the extrapolation to slightly higher masses of the enhancement found in the number density at the high-mass end of our halo catalogues is a conservative approach since the effect is found to be quite strongly increasing with mass (see Figs 1 and 2). It is also interesting to notice that the mass of the most massive halo forming in coupled dark energy cosmologies, both for constant and variable couplings, is systematically larger than for the corresponding $\Lambda$CDM cosmology. The related increase of $\sigma_8$ does not exceed 20 per cent for the largest possible coupling and could be significantly reduced for other viable scenarios or by performing an optimization of the full set of cosmological parameters. In any case, such an increase concerns only the value of $\sigma_8$ at low redshifts, while all the models are consistent at high redshift with the present CMB data. One may want to compare the effects found in the present analysis for coupled dark energy with those of a $\Lambda$CDM model with a higher $\sigma_8$; we have noted that such a degeneracy may be broken by directly measuring the redshift evolution of $\sigma_8$, thereby providing an additional observational test for coupled dark energy as compared to $\Lambda$CDM.

We have therefore shown that both constant and variable coupling models, also for different scalar potentials, enhance at any cosmological epoch the cumulative halo mass function – and consequently the probability to detect haloes of any given mass in volume limited surveys – with respect to the standard $\Lambda$CDM cosmology. Future detection of massive clusters at high redshift can therefore be used to disentangle a cosmological constant from dynamical coupled dark energy models.

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Figure 2. Cumulative mass function at $z = 1.5$ for the coupled DE model RP of Table 1 (orange) compared to $\Lambda$CDM (black). From a high-resolution hydrodynamical simulation in a box of $80 \, h^{-1}$ comoving Mpc. The enhancement of the mass function in this set of simulations is slightly lower than in pure CDM simulations due to the presence of a fraction of uncoupled baryons. The bottom panel shows the enhancement of halo number density relative to $\Lambda$CDM.
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