Hydrodynamical simulations of coupled and uncoupled quintessence models – I. Halo properties and the cosmic web

Edoardo Carlesi,1* Alexander Knebe,1 Geraint F. Lewis,2 Scott Wales2,3 and Gustavo Yepes1

1Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Cantoblanco, Madrid, Spain
2Sydney Institute for Astronomy, School of Physics A28, The University of Sydney, NSW 2006, Australia
3ARC Centre of Excellence for Climate System Science, School of Earth Sciences, The University of Melbourne, VIC 3010, Australia

Accepted 2014 January 20. Received 2014 January 17; in original form 2013 September 28

ABSTRACT

We present the results of a series of adiabatic hydrodynamical simulations of several quintessence models (both with a free and an interacting scalar field) in comparison to a standard Λ cold dark matter cosmology. For each we use $2 \times 10^{24}$ particles in a $250 \, h^{-1}\, \text{Mpc}$ periodic box assuming 7-year Wilkinson Microwave Anisotropy Probe cosmology. In this work we focus on the properties of haloes in the cosmic web at $z = 0$. The web is classified into voids, sheets, filaments and knots depending on the eigenvalues of the velocity shear tensor, which are an excellent proxy for the underlying overdensity distribution. We find that the properties of objects classified according to their surrounding environment show a substantial dependence on the underlying cosmology; for example, while $V_{\text{max}}$ shows average deviations of $\approx 5$ per cent across the different models when considering the full halo sample, comparing objects classified according to their environment, the size of the deviation can be as large as 20 per cent. We also find that halo spin parameters are positively correlated to the coupling, whereas halo concentrations show the opposite behaviour. Furthermore, when studying the concentration–mass relation in different environments, we find that in all cosmologies underdense regions have a larger normalization and a shallower slope. While this behaviour is found to characterize all the models, differences in the best-fitting relations are enhanced in (coupled) dark energy models, thus providing a clearer prediction for this class of models.

Key words: galaxies: haloes – cosmology: theory – dark matter.

1 INTRODUCTION

Over more than 15 yr, since observations of high-redshift Type Ia supernovae (see Riess et al. 1998; Perlmutter et al. 1999) first indicated that the Universe is undergoing an accelerated expansion, a large number of cosmological probes, including cosmic microwave background (CMB) anisotropies (Larson et al. 2011; Sherwin et al. 2011), weak lensing (Huterer 2010), baryon acoustic oscillations (BAO; Beutler et al. 2011) and large-scale structure (LSS) surveys (Abazajian et al. 2009), have confirmed this startling claim and shown that the Universe is spatially flat. To explain these diverse observation, cosmology requires the presence of a fluid, called dark energy (DE), which permeates the whole Universe and exerts a negative pressure, eventually overcoming the gravitational pull that would otherwise dominate. The standard model of cosmology, referred to as Λ cold dark matter (ΛCDM), provides the simplest possible explanation for DE, assuming that DE is played by a constant called Λ which possesses a constant equation of state, such that $p_\Lambda = -\rho_\Lambda$. However, despite its simplicity and observational viability, ΛCDM still lacks of appeal from a purely theoretical point of view, due to fine tuning and coincidence problems; the first refers to the fact that, if we assume that Λ is the zero-point energy of a fundamental quantum field, to be compatible with the aforementioned cosmological constraints its density requires an unnatural fine-tuning of several tens of orders of magnitude. The second problem arises from the difficulty in explaining in a satisfactory way the fact that matter and DE densities today have comparable values, although throughout most of the cosmic history their evolutions have followed completely different patterns.

It is thus natural to explore the possibility that DE does not take the form of a cosmological constant, Λ, but is instead a dynamical component of the universe, whose energy density evolves with time, eventually dominating in the present epoch. In this sense, a large number of different models, such as Chaplygin gas (Kamenshchik, Moschella & Pasquier 2001), vector DE (Beltrán Jiménez...
2 PREREQUISITES

Here, we will briefly recall the basic properties of quintessence models and their implementation into a cosmological N-body algorithm. We refer the reader to the works of Wetterich (1995), Amendola (2000), Amendola & Quercellini (2003), Pettorino et al. (2012), Chiba, De Felice & Tsujikawa (2013) for discussions on the theoretical and observational properties of (coupled) quintessence models, and to Macciò et al. (2004), Baldi et al. (2010), Li & Barrow (2011a) for a thorough description of the numerical approaches.

2.1 The models

In quintessence models the role of DE is played by a cosmological scalar field $\phi$ whose Lagrangian can be generally written as

$$L = \int \, \mathrm{d}^4x \sqrt{-g} \left( -\frac{1}{2} \partial_{\mu} \phi \partial^{\mu} \phi + V(\phi) + m(\phi) \psi_m \psi_m \right), \quad (1)$$

where in principle $\phi$ can interact with the dark matter field $\psi_m$ through its mass term, meaning that, in general, dark matter particles will have a time-varying mass. With a suitable choice of the potential $V(\phi)$, quintessence cosmologies can account for the late time accelerated expansion of the universe both in the interacting and non-interacting case. In the present work we have focused on the so-called Ratra–Peebles (see Ratra & Peebles 1988) self-interaction potential:

$$V(\phi) = V_0 \left( \frac{\phi}{M_p} \right)^{-\alpha}, \quad (2)$$

where $M_p$ is the Planck mass, while $V_0$ and $\alpha$ are two constants whose values can be fixed by fitting the model to observational data (see Wang, Chen & Chen 2012; Chiba, De Felice & Tsujikawa 2013).

In equation (1), we allowed for the scalar field to interact with matter through the mass term $m(\phi) \psi \psi$; a popular choice (see Pettorino et al. 2012) for the function $m(\phi)$ is

$$m(\phi) = m_0 \exp \left( -\beta(\phi) \frac{\phi}{M_p} \right), \quad (3)$$

which is also the one assumed in this paper.

In the following, we have taken into account a constant interaction term $\beta(\phi) = \beta_0$, which from equation (3) implies an energy flow from the dark matter to the DE sector and thus a diminishing mass for dark matter particles. In Table 1 we list the values for $V_0$, $\alpha$ and $\beta$ of equations (2) and (3) as used in the four non-standard cosmologies under investigation – an uncoupled dark energy (uDE) model and three coupled dark energy (cDE) ones. The latter differ only by the choice of the coupling and have been named accordingly. The particular values used in all the implementations have been selected according to the CMB constraints discussed in Pettorino et al. (2012), to ensure the cosmologies under investigation to be compatible with the 7-year Wilkinson Microwave Anisotropy Probe (WMAP7) data set (Komatsu et al. 2011). However, more recent results obtained using Planck data (see Pettorino 2013) provide even tighter constraints on the free parameters of these models, which shall be the object of subsequent investigation.

Table 1. Values of the coupling and potential used for the uDE and cDE models.

| Model  | $V_0$  | $\alpha$ | $\beta$ |
|--------|--------|----------|---------|
| uDE    | $10^{-7}$ | 0.143 | $-$      |
| cDE033 | $10^{-7}$ | 0.143 | 0.033   |
| cDE066 | $10^{-7}$ | 0.143 | 0.066   |
| cDE099 | $10^{-7}$ | 0.143 | 0.099   |
2.2 Numerical implementation

The first simulations of interacting DE models were performed by Macciò et al. (2004), who described the basic steps for implementing interacting quintessence into the AMR code. In our case, we built our implementation on P-GADGET-2, a modified version of the publicly available code GADGET-2 (Springel, Yoshida & White 2001; Springel 2005). This version has first been developed to simulate vector DE models (see Carlesi et al. 2011, 2012) and was then extended to generic dynamical DE as well as CDE cosmologies. The algorithm used is based on the standard TREE-PM solver with some modifications added to take into account the additional long-range interactions due to the coupled scalar field which effectively act as a rescaling of the gravitational constant. For the implementation of these features non-standard models we followed closely the recipe described in Baldi et al. (2010), to which the reader is referred.

This approach requires that a number of quantities, namely

(i) the full evolution of the scalar field \( \phi \) and its derivative \( \dot{\phi} \),
(ii) the variation mass of cold dark matter particles \( \Delta m(\zeta) \) and
(iii) the background expansion \( H(\zeta) \),

have to be computed in advance and then interpolated at run time. We therefore implemented background and first-order Newtonian fluctuation equations into the publicly available Boltzmann code CMBEASY (Doran 2005) to generate the tables containing the aforementioned quantities. The starting background densities were chosen in order to ensure the same values at \( \zeta = 0 \) for the cosmological parameters listed in Table 2; linear perturbations have been solved assuming adiabatic initial conditions.

Finally, in the case of non-standard cosmologies it is necessary to properly generate the initial conditions of the \( N \)-body simulations taking into account not only the different matter power spectra but also the altered growth factors and logarithmic growth rates, respectively. These are in fact the necessary ingredients to compute the initial particles’ displacements and velocities on a uniform Cartesian grid using the first-order Zel’dovich approximation (Zel’dovich 1970). We implemented these changes into the publicly available N-GENIC\(^1\) MPI code, which is suitable for generating GADGET format initial conditions. Again, the matter power spectra, growth factors \( D(\zeta) \) and logarithmic growth rates \( f = d \ln D(\zeta)/d \ln a \) have been computed for the four non-standard cosmologies using the modified CMBEASY package.

All the above changes have been carefully tested against theoretical predictions and the previous results existing in the literature to ensure the consistency and reliability of our modifications.

### Table 2. Cosmological parameters at \( \zeta = 0 \) used in the \( \Lambda \)CDM, uDE, cDE033, cDE066 and cDE099 simulations.

| Parameter  | Value |
|------------|-------|
| \( h \)    | 0.7   |
| \( n \)    | 0.951 |
| \( \Omega_{\text{dm}} \) | 0.224 |
| \( \Omega_b \) | 0.046 |
| \( \sigma_8 \) | 0.8 |

### Table 3. \( N \)-body settings and cosmological parameters used for the three simulations.

| Parameter  | Value |
|------------|-------|
| \( L_{\text{box}} \) | 250 \( h^{-1} \) Mpc |
| \( N_{\text{dm}} \) | 1024\(^2\) |
| \( N_{\text{gas}} \) | 1024\(^2\) |
| \( m_{\text{dm}} \) | \( 9.04 \times 10^8 \) \( h^{-1} \) M\(_{\odot} \) |
| \( m_{\text{b}} \) | \( 1.85 \times 10^8 \) \( h^{-1} \) M\(_{\odot} \) |
| \( z_{\text{start}} \) | 60 |

### 3 THE SIMULATIONS

#### 3.1 Settings

Our set of \( N \)-body simulation has been devised in order to allow us to compare and quantitatively study the peculiarities of the different models in the physics of galaxy clusters and the properties of the cosmic web. To do this, we have chosen a box of side length 250 \( h^{-1} \) Mpc (comoving) where we expect to be able to analyse with adequate resolution a statistically significant (\( \gtrsim 100 \)) number of galaxy clusters \( (M > 10^{14} \) \( h^{-1} \) M\(_{\odot} \)) as well as the properties of the different cosmic environments, classified as voids, sheets, filaments and knots. The parameters chosen to set up the simulations, which are common to all the six models under investigation, are listed in Table 3.

In this series of simulations we implemented adiabatic SPH only, thus neglecting the effects of all sources of radiative effects (Monaghan 1992; Springel 2010) This way we are able to establish a clear basis for the differences induced on baryons by the different cosmologies, without the need to take into account the additional layer of complexity introduced of radiative physics, which in itself requires a substantial degree of modelling. The publicly available version of GADGET-2 performs a Lagrangian sampling of the continuous fluid quantities using a set of discrete tracer particles. Gas dynamics equations are then solved using the SPH entropy conservation scheme described in Springel (2005). In our case, continuous fluid quantities are computed using a number of smoothing neighbours \( N_{\text{sp}} = 40 \). Gas pressure and density are related through the relation \( P \propto \rho^\gamma \), where \( \gamma = \frac{4}{3} \) under the adiabatic assumption.

In addition to the four quintessence models (whose parameters have been given in Table 1) we simulated a \( \Lambda \)CDM cosmology, which we use as a benchmark to pinpoint deviations from the standard paradigm. The initial conditions for all the simulations have been generated using the same random phase realization for the Gaussian fluctuations, which enables us to consistently cross-correlate properties enforcing the same values at present time for \( \Omega_b \) and \( \sigma_8 \) (cf. Table 2), across different simulations.

#### 3.2 Halo identification

We identified haloes in our simulation using the open source halo finder AHF\(^2\) described in Knollmann & Knebe (2009); this code improves the MSH halo finder (Gill, Knebe & Gibson 2004) and has been widely compared to a large number of alternative halo finding methods (Knebe et al. 2011, 2013; Onions et al. 2012). AHF computes the density field and locates the prospective halo centres at the local overdensities. For each of these density peaks, it

\(^{1}\)http://www.mpa-garching.mpg.de/gadget/

\(^{2}\)AHF stands for Amiga Halo Finder, which can be downloaded freely from http://www.popia.ft.uam.es/AHF.
determines the gravitationally bound particles, retaining only peaks with at least 20 of them, which are then considered as haloes and further analysed.

The mass is computed via the equation

\[ M_\Delta = \Delta \rho_c(z) \frac{4\pi}{3} R_h^3, \]  

so that \( M(R) \) is defined as the total mass contained within a radius \( R \) at which the halo matter overdensity reaches \( \Delta \) times the critical value \( \rho_c \). Since the critical density of the universe is a function of redshift, we must be careful when considering its definition, which reads

\[ \rho_c(z) = \frac{3H^2(z)}{8\pi G} \]  

as the evolution of the Hubble parameter, \( H(z) \) differs at all redshifts in the five models. In the latest version of AHF this problem is solved reading the \( H(z) \) for the cDE and uDE models in from a pre-computed table, which then allows to compute the \( \rho_c(z) \) consistently in each case. For all models we assume \( \Delta = 200 \).

### 3.3 Classification of the cosmic web

As we intend to correlate halo properties with the environment, it is necessary to introduce the algorithm used for the classification of the cosmic web into voids, sheets, filaments and knots. Using the term cosmic web (Bond, Kofman & Pogosyan 1996) we refer to the complex visual appearance of the LSS of the universe, characterized by thin linear filaments and compact knots crossing regions of very low density (Massey et al. 2007; Kitaura et al. 2009; Jasche et al. 2010).

The exact mathematical formulation for describing the visual impression of the web is highly non-trivial and can be implemented using two different approaches, the geometric one and the dynamic one. The first one relies on the spatial distribution of haloes in simulations (Novikov, Colombi & Doré 2006; Aragón-Calvo et al. 2007) disregarding the dynamical context. The second approach starts with the classification of Hahn et al. (2007), where they identified the type of environment using the eigenvalues of the tidal tensor (i.e. the Hessian of the gravitational potential), rather than studying the matter density distribution.

However, these particular approaches are unable to resolve the web on scales smaller than a few megaparsecs (Forero-Romero et al. 2009). While retaining the original idea of dynamical classification, Hoffman et al. (2012) proposed to replace the tidal tensor with the velocity shear, showing that this approach has a much finer resolution on the smaller scales while reproducing the large scale results of the other approach. Defining the velocity shear tensor as

\[ \Sigma_{\alpha\beta} = -\frac{1}{2H_0} \left( \frac{\partial u_\alpha}{\partial r} - \frac{\partial u_\beta}{\partial r} \right) \]  

and diagonalizing it, we obtain the eigenvalues \( \lambda_1, \lambda_2 \) and \( \lambda_3 \). Taking the trace of \( \Sigma_{\alpha\beta} \) we obtain

\[ \text{Tr}(\Sigma_{\alpha\beta}) = \sum_i \lambda_i = -\nabla \cdot V \propto \delta_m \]  

from which we see that there is indeed a direct relationship between the eigenvalues of the velocity shear tensor and the matter overdensity. In practice the eigenvalue \( \lambda_i \) is related to the intensity of the inflow (outflow) of matter along the \( i \)th axis in the base where \( \Sigma_{\alpha\beta} \) is diagonal.

We therefore proceed to classify the cosmic web ordering the eigenvalues \( \lambda_1 > \lambda_2 > \lambda_3 \) and defining the different points on the web as (Hoffman et al. 2012; Libeskind et al. 2012, 2013)

(i) voids, if \( \lambda_1 < \lambda_{th} \),
(ii) sheets, if \( \lambda_1 > \lambda_{th} > \lambda_2 \),
(iii) filaments, if \( \lambda_2 > \lambda_{th} > \lambda_3 \),
(iv) knots, if \( \lambda_3 > \lambda_{th} \).

where \( \lambda_{th} \) is a free threshold parameter (to be specified below).

The computation of the eigenvalues has been performed on a regular 256^3 grid, corresponding to a cell size of 0.97 h^{-1} Mpc. We use a triangular-shaped cloud (TSC) prescription for the assignment of the particles (Hockney & Eastwood 1988) and then compute the overdensity and the eigenvalues of the velocity shear tensor for every grid cell. Using the AHF catalogues, we assign every halo to the nearest grid point hence providing us with a measure of environment for every object.

At this stage we still have not explicitly classified the cosmic web, as we lack a clear theoretical prescription for the value of \( \lambda_{th} \). In our case, we have fixed \( \lambda_{th} \) to the highest value which ensures that no halo with \( M > 10^{14} h^{-1} M_\odot \) belongs to a void in any simulation. At a first glance, this kind of constraint might seem redundant, as it would be implied in any standard definition of void as an underdense region. However, we must recall here that our definition of the cosmic web relies solely on the dynamical properties of the matter distribution (being related to the magnitude of its inflow or outflow in a given node) and may in principle overlook its net density content. It is thus necessary to enforce this principle explicitly tuning our free parameter to \( \lambda_{th} = 0.1 \), which is the value which in this case satisfies the aforementioned condition and has been used in Section 5. For a more elaborate discussion of \( \lambda_{th} \) we refer the reader to Hoffman et al. (2012); we only note that our choice is close to their proposed value.

### 4 LARGE-SCALE CLUSTERING AND GENERAL PROPERTIES

Before presenting the results relative to the properties of the cosmic web and the correlation of halo properties to the environment, we will describe some aspects of LSS and general halo properties in our simulations. This should give a more traditional overview of the effects of (coupled) DE models.

#### 4.1 Halo mass function

The halo mass function (HMF) in cDE cosmologies has already been studied by Macciò et al. (2004), Nusser, Gubser & Peebles (2005), Baldi et al. (2010), Li & Barrow (2011b), Cui, Baldi & Borgani (2012) so that we will only briefly comment on the topic. Our results reproduce the earlier findings of Baldi’s in the overlapping regions of mass and \( k \)-space, thus providing an additional proof of the correct functioning of our modified implementation.

In Fig. 1 we show the cumulative mass (left) and velocity functions (right) as well as the ratio to \( \Lambda \)CDM for the four quintessence models. Singling out the region from \( 10^{10} \) to \( 10^{14} h^{-1} M_\odot \), and neglecting the higher mass end, where the statistics is unreliable due to the low number of objects, we can see that the largest difference in number counts amounts to \( \approx 7 \) per cent for the strongest coupled models, gradually decreasing for smaller couplings. In the velocity function, this suppression reaches 10 per cent, thus slightly enhancing the magnitude of the effect.
We can compare our results for the HMF with those of Cui et al. (2012), who modelled the Jenkins et al. (2001) and Tinker et al. (2008) mass functions for a series of similar cDE models, using friends-of-friends (FoF) and spherical overdensity (SO) algorithms to build up their halo catalogues. Even though in their simulations they used different $\sigma_8$ normalizations, fitting the analytical HMFs to the numerical results they were able to extend the predictions for cDE cosmology to arbitrary $\sigma_8$ values. Using the same $\Lambda$CDM $\sigma_8$ normalization, then they also found a 5–10 per cent suppression of the number of objects produced at redshift $z = 0$ compared to $\Lambda$CDM (neglecting the higher mass ends, which are affected by a very low statistics).

Although not shown here, we have also verified that these $z = 0$ results match the analytical prediction of the Tinker mass function (Tinker et al. 2008), provided the correct input power spectra and normalizations are used. We can safely conclude that the presence of coupled and uncoupled quintessence of the kind described here is expected to produce differences from $\Lambda$CDM predictions up to a factor of 10 per cent in present day’s HMF. Remarkably, this estimate is qualitatively independent of the algorithm used for the halo identification as we have seen comparing our results to the work of Cui et al. (2012).

4.2 Halo properties

To study internal halo properties (such as spin parameter and concentration) we first need to define a statistically sound sample of objects, in order to reduce the impact of spurious effects on the results. This means that we need to constrain our analysis to structures which satisfy some conditions on both resolution and relaxation.

The first condition means that we have to restrict our analysis to objects with a number of particles above a given threshold, taking into account the existing trade-off between the quality and the size of the halo sample. The second criterion needs to be applied as we want to focus on structures as close as possible to a state of dynamical equilibrium. In fact, many phenomena, such as infalling matter and major mergers, may take place, driving the structure out of equilibrium. In this case, then, the determination of quantities such as density profiles and concentrations becomes unreliable (see for instance Macciò et al. 2007; Muñoz-Cuartas et al. 2011).

Following Prada et al. (2012), we will define as relaxed only the haloes that obey to the condition

$$\frac{2K}{U} - 1 < 0.5$$

without introducing other selection parameters; for alternative ways of identifying unrelaxed objects we refer for instance to Macciò et al. (2007), Bett et al. (2007), Neto et al. (2007), Knebe & Power (2008), Prada et al. (2012), Muñoz-Cuartas et al. (2011) and Power, Knebe & Knollmann (2012). For the moment, we neglect the impact of uDE and cDE on the definition of the virial ratio since this effect is of just a few per cent (Abdalla, Abramo & de Souza 2010; Pace, Waizmann & Bartelmann 2010) and is thus subleading in our case, where we are removing objects off by more than 50 per cent from the standard relation.

Now that we have established the rules that will shape our halo sample, we proceed to study some internal properties of dark matter haloes, namely, spin and concentration – as a function of halo mass – enforcing one additional criterion for the halo selection: the number of particles in it (see Table 4). When studying the spin parameter, we will restrict ourselves to haloes with $M_{200} > 3 \times 10^{13} \, h^{-1} \, M_\odot$, i.e. composed of at least $\approx$600 baryon and dark matter particles, following the choices of Bett et al. (2007), Macciò et al. (2007), Muñoz-Cuartas et al. (2011) and Prada et al. (2012). In the case of halo concentrations, we applied a stricter criterion, using $M_{200} > 1 \times 10^{12} \, h^{-1} \, M_\odot$ (or $\approx$2000 particles), due to the fact that the computation of halo concentration requires a better resolution of the central regions, as we will discuss in the dedicated subsection.
Table 4. Total number of haloes found in each simulation corresponding to our applied mass cuts of $M > 3 \times 10^{11} \, h^{-1} M_\odot$ and the $M > 10^{12} \, h^{-1} M_\odot$, respectively.

| Mass cut       | $\Lambda$CDM | uDE      | cDE033   | cDE066   | cDE099   |
|----------------|--------------|----------|----------|----------|----------|
| $M > 3 \times 10^{11} \, h^{-1} M_\odot$ | 138,211     | 139,288  | 135,613  | 130,877  | 130,812  |
| $M > 10^{12} \, h^{-1} M_\odot$     | 46,196       | 46,179   | 44,943   | 44,363   | 43,749   |

Figure 2. Average value of the spin parameter per mass bin. We can see that the spin parameter has a weak positive correlation to the mass until $\approx 8 \times 10^{12} \, h^{-1} M_\odot$ and a negative one after that threshold. Further, haloes in cDE models have an average value which is slightly larger than uncoupled ones.

4.2.1 Spin parameter

We can study the rotational properties of haloes introducing the so-called spin parameter $\lambda$ (e.g. Barnes & Efstathiou 1987; Warren et al. 1992), a dimensionless number that measures the degree of rotational support of the halo. Following Bullock et al. (2001), we define it as

$$\lambda = \frac{L_{200}}{\sqrt{2}M_{200}V_{200}R_{200}},$$

where the quantities the total angular momentum $L$, the total mass $M$, the circular velocity $V$ and the radius $R$ are all taken as defined by equation (4), with $\Delta = 200$; in cosmological simulations, the distribution of this parameter is found to be described as lognormal (e.g. Barnes & Efstathiou 1987; Warren et al. 1992; Cole & Lacey 1996; Bullock et al. 2001; Gardner 2001; Macciò et al. 2007; Macciò, Dutton & van den Bosch 2008; Muñoz-Cuartas et al. 2011):

$$P(\lambda) = \frac{1}{\lambda \sigma^2 \sqrt{2\pi}} \exp \left[ -\frac{\ln^2(\lambda/\lambda_0)}{2\sigma^2} \right],$$

even though some authors (e.g. Bett et al. 2007) claim that this should be slightly modified.

Because of the non-Gaussian nature of this distribution, instead of the average value we plot in Fig. 2 the median value of the spin parameter $\lambda$, as a function of halo mass. A weak negative correlation of spin to the halo mass can be observed here for haloes above $8 \times 10^{12} \, h^{-1} M_\odot$ (as noted for instance by Macciò et al. 2007; Knebe & Power 2011) while the relation is positive below that threshold. However, cDE models have on average a higher value (per mass bin) compared to uDE and $\Lambda$CDM. Albeit small, this increase in $\lambda$ is clearly a coupled related effect, the magnitude of which is directly proportional to the value of $\beta$. Given the small error bars (due to the large number of objects used in this analysis) we are confident that this is a real effect. Moreover, a similar result has been found by Hellwing et al. (2011), that also claimed to have observed a link between fifth force and larger $\lambda$.

A deeper investigation of the physical link between the coupling and increased rotational support is left to an upcoming work (Carlesi et al., in preparation) where the evolution of different parameters under different cosmologies will be analysed. For the moment it is important to note that there appears to be some evidence of a link between the coupling strength of the fifth force and the corresponding degree of rotational support in dark matter haloes.

4.2.2 Concentration

Dark matter density profiles can be described by a Navarro–Frenk–White (NFW) profile (Navarro, Frenk & White 1996) of the form

$$\rho(r) = \frac{\rho_0}{r \left(1 + \frac{r}{r_s}\right)^2},$$

where the $r_s$, the so-called scale radius, and the density $\rho_0$ are in principle two free parameters that depend on the particular halo structure. Using equation (11) we can define

$$c = \frac{r_{200}}{r_s},$$

which is the concentration of the halo, relating the radius $r_{200}$ to the scale radius $r_s$. Fitting equation (11) to our halo sample we observe that no substantial difference can be seen in the different simulations, that is, the NFW formula describes (on average) equally well dark matter halo profiles in $\Lambda$CDM as in the other (coupled) DE models. While this is in contrast with the early findings of Macciò et al. (2004), it is however in good agreement with the subsequent works of Baldi et al. (2010) and Li & Barrow (2011b), who also found the NFW profile to be a valid description of DM haloes in interacting cosmologies. Thus, defining concentrations using equation (12) will not pose any problems nor introduce any systematic effect due to the fact that the NFW profile might only be valid for $\Lambda$CDM dark matter haloes.

In Fig. 3 we now show the median concentration for objects in a certain mass bin: cDE cosmologies have a smaller concentration than $\Lambda$CDM, i.e. the larger the $\beta$ the smaller the $c$; whereas the opposite is true for the uDE model. This can partly be explained by the fact that concentrations are related to the formation time of the halo, since structures that collapsed earlier tend to have a more compact centre due to the fact that it has more time to accrete matter from the outer parts. Dynamical DE cosmologies generally imply larger $c$ values as a consequence of earlier structure formation, as found in works like those by Dolag et al. (2004), Bartelmann, Doran & Wetterich (2006) and Grossi & Springel (2009). In fact, since the presence of early DE usually suppresses structure growth, in order to reproduce current observations we need to trigger an earlier start of the formation process, which on average yields a higher value for the halo concentrations. However, as explained in Baldi et al. (2010), smaller concentrations in cDE models are not related to the formation time of dark matter haloes, but to the fact...
that one of the effects of coupled quintessence is to effectively act as a positive friction term. This means that dark matter particles have an increased kinetic energy, which moves the system out of virial equilibrium and causes a slight expansion, resulting in a lowering of the concentration.

In the hierarchical picture of structure formation, concentrations are usually inversely correlated to the halo mass as more massive objects form later; N-body simulations (Dolag et al. 2004; Muñoz-Cuartas et al. 2011; Prada et al. 2012) and observations (Comerford & Natarajan 2007; Okabe et al. 2010; Sereno & Zitrin 2012) have in fact shown that the relation between the two quantities can be written as a power law of the form

$$c(M) = c_0 \left( \frac{M_{200}}{10^{12} M_\odot h^{-1}} \right)^\gamma,$$

(13)

where $\gamma$ and $c_0$ can have explicit parametrizations as functions of redshift and cosmology (see Neto et al. 2007; Muñoz-Cuartas et al. 2011; Prada et al. 2012). When we fit our halo sample to this relation using $c_0$ and $\gamma$ as free parameters we obtain the best-fitting values as shown in Table 5. Our values are qualitatively in good agreement with the ones found by, for instance, Macciò et al. (2008) and Muñoz-Cuartas et al. (2011) for $\Lambda$CDM; but we do find some tension with the findings of Prada et al. (2012). However, since they use a different algorithm for the determination of $c$ (which, according to them, leads to higher concentration values) and a different $\sigma_8$ normalizations we cannot directly compare our results to theirs. On the other hand, uDE values are generally in agreement with Dolag et al. (2004), De Boni et al. (2013) although in both cases there are again some discrepancies in the $c_0$ best-fitting result, most probably due to the much different $\sigma_8$ used in their simulations. For cDE we cannot directly compare our concentration–mass relation to the one obtained by Baldi et al. (2010) since they do not provide any fit to equation (13).

### 5 PROPERTIES OF THE COSMIC WEB

We now turn to the study of the cosmic web, as defined in Section 3.3, in $\Lambda$CDM, uDE, cDE033, cDE066 and cDE099. In Figs 4 and 5 we give a visual impression of the web classification (left) and the underlying dark matter density field (right) for a slice of thickness one cell (i.e. 0.97 $h^{-1}$ Mpc) using a logarithmic colouring scheme for the density. From Figs 4 and 5 it is evident that there is, in general, a very close correspondence between $\delta > 1$ and filamentary and knot-like regions; just like between $\delta < 1$ and void and sheet-like ones, so that the kinetic classification does provide in general a faithful description of the underlying density distribution – as shown in Hoffman et al. (2012). Nonetheless, a minor number of cells do indeed violate this principle. In fact, as also noted by Hoffman et al. (2012), in a very limited number of cases it happens that, for cells placed in the interior of a of a large dark matter halo, the velocity field will be determined by the motion of its virialized particles and not reflecting the cosmic web, respectively. On top of that, we must not forget that the freedom in the choice of the threshold $\lambda_{th}$, and the fixed spacing of the grid account for the fact that on scales smaller than 0.97 $h^{-1}$ Mpc we cannot properly resolve the complex shape of the web, which would probably require a more flexible grid implementation (Platen et al. 2011). However, all these shortcomings do not seriously invalidate this description, as the number of such cells is generally small (e.g. points defined as voids with $\delta > 1$ sum up to less than 1 per cent of the total in all simulation, and independent of the simulation). In fact, the latter is the most important condition that we need to ensure, so that the existence of small biases disappears when considering ratios to $\Lambda$CDM, which is at the core of the analysis we are carrying.

In Tables 6–8 we show the mass and volume filling fractions as a function of cell type and cosmologies. These values are estimated simply summing all masses and volumes contained in cells belonging to the same kind of environment. What is clear by looking at these results is that the general structure of the cosmic web is almost left unchanged across models. In fact, discrepancies among different cosmologies are much less than 1 per cent in this regard, thus making it hard to detect deviations from $\Lambda$CDM by simply considering the volume and the mass associated with the various kinds of environment. The same conclusion can be drawn if we look at Fig. 6, which shows the distributions of the three $\lambda_{1,2,3}$ eigenvalues of $\Sigma_{\text{avg}}$ that appear to be identical and thus provide no leverage to distinguish the models under investigation here.

The gas distribution through the different node types seems also to be largely unaffected by the different cosmology: as we can see from Table 7, the mass fractions of gas are substantially identical throughout all the models, without any significant discrepancy. Comparing to the distribution of dark matter, we do notice a slight increase in the fraction of gas belonging to sheets and filaments paralleled by its reduction on knots, a pattern which is observable in all the models to the same extent.

We remark that our results for uDE agree with Bos et al. (2012), who also found that quintessence cosmologies with Ratra–Peebles potentials do not lead to significant changes in the general properties of the cosmic web. We also emphasize that our findings relative to
void regions are largely independent of the choice of $\lambda$. Using different threshold values we have been able to test this and see that void distributions are affected to the same degree in all the different models, confirming this particular result does not depend on our $\lambda_{th}$.

6 HALO PROPERTIES IN DIFFERENT ENVIRONMENTS

We now turn to the study of halo properties classified according to their environment; this kind of analysis has already been done for $\Lambda$CDM using both geometrical (e.g. Avila-Reese et al. 2005; Macciò et al. 2007) and dynamical (e.g. Hahn et al. 2007; Libeskind et al. 2012, 2013) web classifications, finding in general a correlation between halo properties such as spin and shape to its surrounding environment.

Using the information from the halo catalogues we proceed to assign each halo to the nearest grid point and build up four different halo samples, one for each cell type. Then we repeat the analysis presented in Section 4 for the halo counts (velocity and mass), spin and concentrations. We will see that this kind of separation of haloes enhances some of the differences already seen in general among different cosmological models and is therefore of great importance when trying to constrain more effectively coupled and uncoupled scalar field cosmologies.

Voids and sheets are readily identified with underdense regions, as has also been confirmed by the analysis presented in Section 5. And the fact that for these cells at most one eigenvalue of the shear tensor has a value above $\lambda_{th}$ means that in two or more spatial directions there is a net outflow of matter, which is in turn associated with a matter density below the average. For overdense regions (i.e. filaments and knots) there is a net inflow of matter towards the centre of the cell from at least two directions. Following this we partition the subsequent study into underdense regions on the one hand (using voids and sheets) and overdense regions (i.e. filaments and knots) on the other (see Fig. 7).

Underdense regions in $\Lambda$CDM are usually associated with lower spins and slightly larger halo concentrations (Macciò et al. 2007), raising the question whether this still holds for (coupled) DE cosmologies.
Figure 5. Same as Fig. 4 for cDE033 (upper panel), cDE066 (middle panel) and cDE099 (lower panel).
Fraction of total dark matter mass for different node type

| Cell type | ΛCDM | cDE | cDE033 | cDE066 | cDE099 |
|-----------|------|-----|--------|--------|--------|
| Void      | 0.103| 0.103| 0.102  | 0.103  | 0.102  |
| Sheet     | 0.343| 0.343| 0.344  | 0.344  | 0.343  |
| Filament  | 0.437| 0.438| 0.443  | 0.442  | 0.443  |
| Knot      | 0.116| 0.115| 0.109  | 0.111  | 0.118  |

Fraction of total gas mass for different node type in each simulation.

| Cell type | ΛCDM | cDE | cDE033 | cDE066 | cDE099 |
|-----------|------|-----|--------|--------|--------|
| Void      | 0.103| 0.103| 0.103  | 0.104  | 0.102  |
| Sheet     | 0.349| 0.348| 0.348  | 0.347  | 0.346  |
| Filament  | 0.449| 0.450| 0.450  | 0.449  | 0.453  |
| Knot      | 0.097| 0.097| 0.097  | 0.098  | 0.098  |

Volume filling fractions of different cell types for all the simulation set.

| Cell type | ΛCDM | cDE | cDE033 | cDE066 | cDE099 |
|-----------|------|-----|--------|--------|--------|
| Void      | 0.337| 0.338| 0.338  | 0.337  | 0.334  |
| Sheet     | 0.460| 0.456| 0.460  | 0.460  | 0.461  |
| Filament  | 0.185| 0.184| 0.185  | 0.185  | 0.186  |
| Knot      | 0.017| 0.017| 0.017  | 0.017  | 0.018  |

### 6.1 Halo number counts

Even though, by definition, underdense regions are less populated, non-negligible fractions of the total halo count can be still found in voids and sheets, as shown in Table 9, ensuring that the samples used are reasonably large, and allow us to draw credible conclusions.

#### 6.1.1 Underdense regions: voids and sheets

We notice that in underdense regions (i.e. voids and sheets, shown in the upper two plots) the trend persists that the number of objects is smaller for cDE models than for ΛCDM, something also observed for the general halo sample. However, it is important to remark that singling out and counting the objects belonging to the underdense parts only, we end up observing larger differences among the models. This effect also appears to be much stronger in cDE than in uDE. In fact, whereas the differences in number counts of objects does not exceed 7 per cent, when restricting halo counts to void regions only, we can see that cDE models’ underprediction is much larger and peaks at 20 per cent (ignoring the higher mass ends, where only a small number of objects is found). It is also clear from Fig. 8 that while the sign of the effect is very similar in both voids and sheets, its strength is slightly reduced in the latter type of web, suggesting that there exists at least a mild dependence of this phenomenon on the specific kind of environment. Although we are not showing it here, we have also carefully checked that this result is substantially independent from the kind of $\lambda_{th}$ chosen. In fact, repeating our computation using higher threshold values, we see that the magnitude of the effect does not change substantially. The physical mechanism behind this effect is understood and provides a consistent framework for interpreting our results. In fact, as first explained by Keselman, Nusser & Peebles (2010) and subsequently confirmed by Li & Barrow (2011b), fifth forces enhance the gravitational pull towards the overdense regions, quickly evacuating matter from underdense regions. This causes these environments to have less structures, so that in the end the number of haloes left in voids will be comparatively smaller than in the non-interacting cases, as found in our simulations.

However, we need to make an additional remark on this result before proceeding to the next section. In fact, we note that our choice of the $\sigma_8$ normalization, which is taken to be the same at $z = 0$, plays an important role in the result just described. It is in fact known (see e.g. Baldi & Pettorino 2011) that using a different normalization prescription (for instance, at the redshift of the CMB for the matter density fluctuations), coupled models end up predicting (in total) more objects than ΛCDM. Hence, at this stage we cannot completely disentangle the influence of our choice of the normalization of the initial conditions from the genuine influence of the additional interaction.

#### 6.1.2 Overdense regions: filaments and knots

Like in the case of underdensities, we notice for overdense regions (shown in the lower two plots) that the trend of suppression which characterizes the general halo counting still holds, even though now the strength of this effect is slightly smaller across all cosmologies. This is not unexpected, since the effect seen in the HMF discussed in Section 4 has to be obtained from a combination of both underdense and overdense structures, and should therefore result in an intermediate value for cDE halo underproduction. Again, we have checked that the chosen threshold for the eigenvalues of the velocity shear tensor does not substantially affect this conclusion.

We can therefore state that there is a progression towards smoothing out the differences among different cosmologies while moving to increasingly higher density regions. This is a very important result that indicates that underdense regions should be the target...
of choice when searching for the effects of additional long range gravitational-like forces.

This result is in line with what has been already found for other fifth-force cosmologies (see Martino & Sheth 2009; Keselman, Nusser & Peebles 2010; Li, Zhao & Koyama 2012; Winther, Mota & Li 2012), where the environmental dependence and in particular the properties of voids were stressed as powerful tests for additional interactions and modifications of standard Newtonian gravity. It is in fact well known that void properties are extremely sensitive to cosmology (Lee & Park 2009; Lavaux & Wandelt 2010; Bos et al. 2012; Sutter et al. 2012) and hence provide a powerful probe of alternative models. In particular, when the extra coupling in the dark sector is weak (as in the cases analysed here) the complex evolution and phenomena that characterize the overdense regions may conceal its imprints, while void regions, whose dynamics is comparatively simpler, are expected to be more directly linked to the underlying cosmology.

6.2 Spin and concentration

We now turn to the non-dimensional spin parameter, $\lambda$, and dark matter halo concentrations, investigating how they will change across different environments and cosmologies. In the latter case, we will also pay particular attention to the environment-related changes to the $c$–$M$ relation of equation (13). In both cases we refer to the definitions introduced in Section 4.

6.2.1 Underdense regions: voids and sheets

Looking at the median spin parameters shown in the upper panel of Fig. 9 we can again draw the conclusion that, just like in the general case, cDE cosmologies lead to larger spins and that this increase is proportional to the coupling parameter $\beta$. On the other hand, the value of $\bar{\lambda}$ for haloes in uDE cosmologies is, on average, indistinguishable from $\Lambda$CDM. We can therefore confirm the observation that underdense region contain haloes with lower spins, just as found by Macciò et al. (2007). However, the reduction in the median value is of the same order in all models, so that combining the information of the environment does not put tight constraints on the parameters of the model.

Concentrations, too, show a remarkable behaviour for haloes belonging to underdense regions. In Table 10 we show the results of fitting the median concentration per mass bin to a power law, i.e. equation (13). The first thing we observe is that the correlation between $c$ and $M$ (as measured by the power-law index $\gamma$) is weaker than what we observed in the general case. This, combined with

| Environment | $\Lambda$CDM | uDE | cDE033 | cDE066 | cDE099 |
|-------------|-------------|-----|--------|--------|--------|
| Void        | 0.128       | 0.131 | 0.127  | 0.123  | 0.124  |
| Sheet       | 0.431       | 0.432 | 0.431  | 0.429  | 0.428  |
| Filament    | 0.384       | 0.382 | 0.387  | 0.392  | 0.391  |
| Knot        | 0.055       | 0.054 | 0.053  | 0.055  | 0.056  |
the fact that in the lower mass bins median concentration do not change with respect to the general case, in turn leads to observed larger values for $c_0$, although the errors are also large due to the small number statistics. However, some care must be taken when considering this relation for void haloes since the fit is based upon a small mass range only and also gives more weight to lower mass objects (Prada et al. 2012; De Boni et al. 2013).

6.2.2 Overdense regions: filaments and knots

In the bottom panels of Figs 9 and 10 we plot the spin and concentration–mass relation; the best-fitting values to equation (13) are again provided in Table 10.

In the case of spins, we find that dark matter haloes in coupled cosmologies tend to be characterized by larger values of $\lambda$. However, haloes located in filamentary structures show, at least in the lower mass bins, sharper differences between cDE models and $\Lambda$CDM than what is revealed by knots. This is also due to the smaller number of low-mass haloes living in knots, which visibly affects the statistics of the parameter.

Concentrations instead show two slightly different patterns in filaments and in knots. In the former environment, all cosmologies seem to be characterized by a flatter slope, which averages around $-0.06$ and seems not to be connected to the underlying model. In the latter environment, a steeper correlation is found, with $\gamma \approx -0.09$ – much closer to the general case discussed in Section 4. Not only the slope but also the normalization $c_0$ of equation (13) changes when considering filamentary or knot-like environments: in the former case we find that this parameter is substantially larger than in the latter.

**Table 10.** Best-fitting values for the concentration–mass equation (13) relation for haloes belonging to voids (v) sheets (s) filaments (f) and knots (k).

| Parameter | $\Lambda$CDM | cDE | cDE033 | cDE066 | cDE099 |
|-----------|--------------|-----|--------|--------|--------|
| $c_0(v)$  | 5.1 ± 0.5    | 5.36 ± 0.5 | 4.5 ± 0.2 | 4.5 ± 0.3 | 4.3 ± 0.3 |
| $\gamma(v)$ | -0.03 ± 0.01 | -0.03 ± 0.01 | -0.04 ± 0.01 | -0.04 ± 0.01 | -0.03 ± 0.01 |
| $c_0(s)$  | 4.8 ± 0.1    | 5.1 ± 0.2    | 4.5 ± 0.1    | 4.3 ± 0.2    | 4.2 ± 0.1    |
| $\gamma(s)$ | -0.034 ± 0.007 | -0.037 ± 0.009 | -0.04 ± 0.01 | -0.04 ± 0.01 | -0.036 ± 0.008 |
| $c_0(f)$  | 4.41 ± 0.05  | 4.42 ± 0.03  | 4.26 ± 0.05  | 4.15 ± 0.04  | 3.98 ± 0.05  |
| $\gamma(f)$ | -0.052 ± 0.01 | -0.059 ± 0.006 | -0.07 ± 0.01 | -0.064 ± 0.008 | -0.058 ± 0.005 |
| $c_0(k)$  | 4.06 ± 0.07  | 4.38 ± 0.08  | 4.02 ± 0.06  | 3.74 ± 0.06  | 3.67 ± 0.07  |
| $\gamma(k)$ | -0.087 ± 0.009 | -0.093 ± 0.008 | -0.085 ± 0.005 | -0.093 ± 0.009 | -0.092 ± 0.007 |
Figure 9. Median of the spin parameter for haloes located in voids (upper left-hand panel), sheets (upper right-hand panel), filaments (lower left-hand panel) and knots (lower right-hand panel).

Figure 10. Average concentration for haloes located in voids (upper left-hand panel), sheets (upper right-hand panel), filaments (lower left-hand panel) and knots (lower right-hand panel).
Our results therefore indicate that the concentration–mass relation is not only affected by the cosmological model but also by the environment the haloes under consideration live in: $y$ gets flatter while $c_{\rm z}$ increases for decreasing densities. However, at odds with what we found for halo number counts, we find here that environment does not play a role in strengthening the magnitude of model-dependent properties of haloes. While the effect of DE can still be clearly seen in the higher spins and lower concentrations of dark matter haloes, these cDE-induced characteristics are not enhanced by the environment. In fact, whereas the halo content of the different regions depends on the model and reinforces the trends observed in Section 4.2, the properties of the haloes themselves, while still being correlated to the underlying cosmology, seem to be shifted by the same amount as $\Lambda$CDM. This suggests that environmental effects, in these cases, influence to the same extent both quintessential and standard models, and do not provide a stronger model-specific kind of prediction.

7 CONCLUSIONS

In the present work – which forms part of a series of studies of (coupled) DE models – we have discussed the properties of LSSs and the cosmic web as they emerge in a series of different quintessence models, systematically comparing the results of a coupled scalar field to those obtained for a free field and the standard $\Lambda$CDM cosmology.

We performed the following three-fold analysis:

(i) we studied HMF and general halo properties (mass, spin and concentrations);
(ii) we investigated the general properties of the cosmic web, using a kinetic classification algorithm;
(iii) we correlated halo properties to the environment.

First, we have studied several aspects of cDE and uDE cosmologies looking at the full halo sample. At this stage, our results proved to be in line with those of Baldi et al. (2010), Li & Barrow (2011b) and Cui et al. (2012), finding that the analytical formulae for the HMFs and dark matter profiles are valid also in this class of models.

Examining concentrations we found that while uDE cosmology is characterized by haloes with higher values for $c_z$, for cDE models the opposite is in general the case – in accordance with the results of Baldi et al. (2010) and De Boni et al. (2013). Interestingly, in the case of spin parameters we observe a weak dependence on the coupling, since we can see that their value is mildly enhanced by larger values of $\beta$, as was also noted by Hellwing et al. (2011) in the context of other fifth force cosmological models.

The cosmic web investigated as part of this study is characterized by the eigenvalues of the velocity shear tensor, a novel method recently proposed by Hoffman et al. (2012) and successfully applied to various simulations by Libeskind et al. (2012). Computing the fraction of total mass and volume belonging to each type of environment in our cosmologies, we find that the structure of the cosmic web itself does not reveal any particular difference among the models. The same conclusion can be drawn when investigating the global distribution of the shear tensor eigenvalues.

This notwithstanding, the classification of the cosmic web can be extremely useful when married with the halo catalogue. Combining the two, in fact, we were able to show that many of the differences observed in some halo properties when studying a global sample of relaxed structures above a threshold mass are in fact due to objects belonging to a certain type of environment. This happens in particular in voids and sheets, where the differences among cDE and $\Lambda$CDM are up to three times as large as they are in the general case. We have been able to verify how the magnitude of this effect is closely dependent on the coupling: while cDE cosmologies’ underproduction of haloes in these regions is largely amplified, the overproduction that characterizes the uDE model investigated here is only weakly enhanced. This means that

(i) one should focus on voids and sheets (underdense regions) when looking for signatures of (coupled) DE, and
(ii) the magnitude of the deviations from $\Lambda$CDM allows us to place constraints on cDE cosmologies, or even detect them.

We have also seen how the standard concentration–mass relation is substantially affected when fitted for halo samples classified according to the environment they are located in. While the standard functional form of equation (13) still holds in underdense regions for all the models, it does so with a much steeper slope (the change is from an average of $-0.9$ to $-0.4$) and a substantial increase in the average concentration. In addition to this, we note again an amplification of the difference between the $c_{\rm z}$ values in cDE and $\Lambda$CDM obtained when fitting equation (13) in voids and sheets (up to 15 per cent) with respect to the global one ($\approx 7$ per cent).

The fact that these results are mostly visible when restricting the halo sample to underdense environments tells us the importance of the relative weights to be attached when performing global analyses. Indeed, when referring to halo properties in general, we do in fact hide a large number of peculiar features which can be seen only in a narrower subset. In the particular case of cDE we have seen how structures in voids play a major role, in the same direction of Li & Barrow (2011b), who also highlighted the importance of underdense regions in the context of similar cosmological models.

As a concluding remark, we would like to emphasize that a great amount of effects observed here still deserve a more in-depth study. In particular, the analysis of the temporal evolution of halo parameters will shed more light on the mechanisms that result in the previously discussed differences at $z = 0$ and increase the observational features that can be used to constrain quintessence models. We shall turn to these in future contributions in this series.

ACKNOWLEDGEMENTS

EC is supported by the Spanish Ministerio de Economía y Competitividad (MINECO) under grant no. AYA2012-31101, and MultiDark Consolider project under grant CSD2009-00064. He further thanks Georg Robbers for providing an updated, non-public version of CMBEASY.

This work was undertaken as part of the Survey Simulation Pipeline (SSimPL: ssimpluniverse.tk) and GFL acknowledges support from ARC/DP 130100117. AK is supported by the Spanish Ministerio de Ciencia e Innovación (MICINN) in Spain through the Ramón y Cajal programme as well as the grants AYA 2009-13875-C03-02, CSD2009-00064, CAM S2009/ESP-1496 (from the ASTROMADRID network) and the Ministerio de Economía y Competitividad (MINECO) through grant AYA2012-31101. He further thanks Emily for reflect on rye.

GY acknowledges support from MINECO under research grants AYA2012-31101, FPA2012-34694, Consolider Ingenio SyeC CSD2007-0050 and from Comunidad de Madrid under ASTROMADRID project (S2009/ESP-1496).

The authors thankfully acknowledge the computer resources, technical expertise and assistance provided by the Red Española de Supercomputación.
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