1. INTRODUCTION

The concordance cosmological model—based on a family of non-relativistic massive particles possibly weakly interacting with the standard sector of particle physics (cold dark matter particles, CDM hereafter) and on the cosmological constant $\Lambda$—very successfully accounts for a large wealth of observational data, but poses significant theoretical puzzles and requires an extreme fine-tuning of its basic parameters. In this context, alternative scenarios have been explored, such as, e.g., the possibility that the cosmological constant $\Lambda$ being replaced by a dark energy (DE) component represented by a classical dynamical scalar field $\phi$ evolving in a self-interaction potential (Wetterich 1988; Ratra & Peebles 1988). A further step in the exploration of alternative cosmological models has been recently proposed, speculating about a possible direct interaction between the DE and the CDM sectors of the universe (Wetterich 1995; Amendola 2000; Amendola 2004). Such coupled dark energy (cDE) models have been widely investigated in recent years concerning their background evolution and their effects on structure formation (e.g., by Mainini & Bonometto 2006; Pettorino & Baccigalupi 2008; Abdalla et al. 2009; Wintergerst & Pettorino 2010) by means of specifically designed $N$-body algorithms aimed at exploring the nonlinear evolution of cosmic structures within these alternative scenarios (Macciò et al. 2004; Baldi et al. 2010; Baldi 2011; Li & Barrow 2011). These studies have led to the highlight of some distinctive features in the evolved matter density fields of cDE models and have shown how the properties of nonlinear collapsed objects can be significantly affected by the dark interactions in a potentially observable way (Baldi & Viel 2010; Baldi & Pettorino 2011). Therefore, one of the most important tasks in the present investigation of these alternative models consists in linking the predictions obtained for the CDM density distribution to directly observable quantities.

Lee (2010) very recently brought up a speculative idea, namely, that the dark sector interaction might be probed by measuring the alignment between galaxy and matter distributions in triaxial clusters. In $\Lambda$CDM cosmology, the spatial correlations of the large-scale tidal fields yield the strong alignments of the satellite galaxies in the clusters with the cluster dark matter distributions (e.g., Zentner et al. 2005; Altay et al. 2006). Lee (2010) claimed that the alignment of the cluster galaxies with the underlying CDM distribution would be weaker in the cDE models than in $\Lambda$CDM since the spatial correlations of the tidal fields inside the clusters would be less strong due to the existence of a fifth force. If this is really the case, the alignment between galaxy and matter distributions in triaxial clusters would provide a unique probe of the cDE scenarios, especially because the alignment angle is insensitive to the other cosmological parameters.

To back up the speculative idea of Lee (2010), it is essential to examine numerically whether or not the cDE scalar field truly makes a detectable difference on the cluster galaxy–matter alignment. The goal of this paper is to use high-resolution $N$-body simulations to study how the alignment between satellites and the underlying dark matter distribution in galaxy clusters changes in cDE models as compared to $\Lambda$CDM (Komatsu et al. 2011).

2. SIMULATIONS AND DATA ANALYSIS

The dark interaction between the DE scalar field $\phi$ and CDM which characterizes cDE models affects the growth of cosmic structures in manifold ways. First of all, the background expansion history of the universe is changed with respect to the standard $\Lambda$CDM evolution by the dynamical nature of the DE scalar field $\phi$. Furthermore, the mass of CDM particles changes in time due to the exchange of energy with the DE sector, and the...
Figure 1. CDM projected density (gray scale) and location of the 30 most luminous substructures (colored squares) within $R_{200}$ for the most massive cluster formed in our simulated ΛCDM (left), EXP005 (middle), and EXP010e2 (right) cosmologies, respectively. (A color version of this figure is available in the online journal.)

In order to compare the results of our numerical simulations with observations, we need to assign to each (sub)halo a stellar mass. For this purpose, we use the recently derived stellar-to-halo mass relationship presented in Moster et al. (2010). In this paper, the authors give a series of simple fitting formulae to derive the stellar mass of the galaxy hosted by a given dark matter halo as a function of the virial mass (for central galaxies) or as a function of the maximum mass over the halo’s history (for satellite galaxies). For all our substructures, we therefore build a full merger tree and we assign to each subhalo a stellar mass based on the latter criterion by using the formulae of Moster et al. (2010).

However, these formulae have been derived by comparing the observed galaxy luminosity function with the halo mass function in a ΛCDM universe. This implies that we cannot directly apply them in the case of cDE models. In order to overcome this issue, we first find a function $f(M, z)$ able to map the cDE mass function onto the ΛCDM one and then we apply the Moster et al. (2010) fitting equations. The CDM density and the location of the 30 most luminous substructures inside two virial radii for the same massive cluster within the three different cosmologies under investigation are plotted in the three panels of Figure 1, where a stronger tendency of alignment between the CDM distribution and the selected substructures in the ΛCDM model as compared to cDE scenarios is already visible.

3. ALIGNMENT BETWEEN GALAXY AND MATTER DISTRIBUTIONS IN CLUSTERS

From each cluster catalog obtained from the simulations for the ΛCDM and cDE cosmologies, we select those cluster halos which have five or more galaxies within some cutoff radius $r_c (\leq R_{200})$ from the halo center. Then, we measure the alignment angles between the galaxy and dark matter distributions of each selected cluster halo through the following procedure. First, the inertia tensor of the galaxy distribution of each selected cluster halo, $I^G_{ij}$, is evaluated as

$$I^G_{ij} = \sum_{\beta} m_{*,\beta} x_{\beta,i} x_{\beta,j},$$

where $m_{*,\beta}$ is the stellar mass of the $\beta$th galaxy and $(x_{\beta,i})$ is the position vector of the $\beta$th satellite galaxy relative to the center of the stellar mass of the galaxy distribution. Weighting the satellites by stellar mass is important for a comparison with observations since in practice the shapes of galaxy distributions are often obtained from the luminosity-weighted satellites.
Finding the unit eigenvector of \((I^M_{ij})\) corresponding to the largest eigenvalue, we determine the major axis, \(e_M\), of the galaxy distribution of each selected halo. Similarly, we evaluate the inertia tensor, \((I^M_{ij})\), of the CDM distribution of each selected cluster halo as

\[
I^M_{ij} = \sum_a x_{a,i} x_{a,j},
\]

where \((x_{a,i})\) is the position vector of the \(a\)th dark matter particle relative to the halo center. The summation in Equation (3) goes over all dark matter particles located within the halo virial radius \(R_{\text{vir}}\). Finding the unit eigenvector of \((I^M_{ij})\) corresponding to the largest eigenvalue, we determine the major axis, \(e_M\), of the CDM distribution of each selected cluster halo. The alignment angle, \(\theta\), between dark matter and galaxy distributions of each selected halo is now calculated as \(\cos \theta = |e_M \cdot e_G|\), where \(\cos \theta\) is in the range of \([0, 1]\). Binning the values of \(\cos \theta\) and counting the number of the halos belonging to each \(\cos \theta\)-bin, we derive the probability density distribution, \(p(\cos \theta)\), for the ΛCDM and cDE cosmologies, separately. When the cutoff radius \(r_c\) for the satellite galaxies is set at \(0.8 R_{\text{vir}}\), the total number of the selected cluster halos which have five or more galaxies within \(r_c\) is found to be 186 and 116 for the ΛCDM and cDE cosmologies, respectively.

Before making a comparison between the probability distributions of \(\cos \theta\) from the two cosmologies, it is worth examining how robust our measurement of \(\cos \theta\) is. If the dark matter distribution of a given halo is spherically symmetric, then the determination of the major principal axis of its inertia tensor would be quite ambiguous. Therefore, the robustness of the measurement of \(\cos \theta\) of a given halo critically depends on how spherical its dark matter distribution is. The sphericity of a given halo is conventionally defined as \(S \equiv \sqrt{u_3/u_1}\), where \(u_1\) and \(u_3\) are the largest and the smallest eigenvalues of the inertia tensor of the dark matter distribution, respectively. Using this definition, we measure the sphericity of each selected halo for both cosmologies. Figure 2 plots the number distribution of the selected halos versus their sphericity for cDE and ΛCDM cosmologies as solid and dashed histogram, respectively. As it can be seen, for the case of cDE there is no halo whose sphericity is larger than 0.9, while for ΛCDM there is only one halo whose sphericity exceeds 0.9. Thus, our measurement of \(\cos \theta\) is robust, free from the ambiguity caused by the spherically symmetric dark matter distribution.

Given that our samples of the halos for both cosmologies are not large enough to be fully representative of the true parent populations, we perform the bootstrap error analysis to estimate the uncertainties in the measurement of \(p(\cos \theta)\) (Wall & Jenkins 2003). We first construct 1000 bootstrap resamples and measure \(p(\cos \theta)\) from each resample. The bootstrap error, \(\sigma_b\), at each bin is then calculated as one standard deviation among the 1000 remeasurements, \(\sigma_b\equiv \langle [p(\cos \theta_i) - \langle p(\cos \theta) \rangle]^2 \rangle^{1/2}\), where the ensemble average is taken over the 1000 resamples and \(\langle p(\cos \theta_i) \rangle\) represents the bootstrap mean value at the \(i\)th bin. The top panel of Figure 3 plots the resulting \(p(\cos \theta)\) with the bootstrap errors for cDE and ΛCDM cosmologies as square and triangle dots, respectively. For this plot, the cutoff radius \(r_c\) for the satellite galaxies is set at \(0.8 R_{\text{vir}}\).

As shown in Figure 3, the probability density distribution increases with \(\cos \theta\) in both cosmologies, which indicates that the major axes of the galaxy and dark matter distributions in clusters tend to be strongly aligned. However, we note a difference between the two cosmologies: \(p(\cos \theta)\) increases less rapidly in the cDE model. At the fourth \(\cos \theta\)-bin (corresponding to \(0.6 \leq \cos \theta \leq 0.8\)), the difference between the two models exceeds \(\sigma_b\). The bottom panel of Figure 3 plots the ratio between the two probability density distributions: \(p_{\text{cDE}}(\cos \theta)/p_{\Lambda\text{CDM}}(\cos \theta)\), which demonstrates clearly that the ratio deviates from unity and the degree of the deviation reaches the maximum at the fourth bin.

Now that we find a difference between the two cosmologies in the tendency of the cluster galaxy–matter alignment, we would like to investigate how the result depends on the cutoff radius \(r_c\). In fact, it is naturally expected that as \(r_c\) decreases the alignment tendency would decrease. The major axes of the dark matter distribution are determined at \(R_{\text{vir}}\) while the major axes of the galaxy distribution are measured at \(r_c\). Therefore, the difference \(R_{\text{vir}} - r_c\) represents the distance by which the inner and outer
tide fields are separated. As $r_c$ decreases, the spatial correlations between the two tidal fields would decrease, which would be manifested by the decrease of the strength of the alignment between the major axes of the galaxy and matter distributions in clusters.

Repeating the whole process described above, we calculate the probability density at the fourth bin, $p(0.6 < \cos \theta < 0.8)$, for five different choices for $r_c$. The top panel of Figure 4 plots the result for cDE and $\Lambda$CDM as square and triangle dots, respectively. The bottom panel of Figure 4 plots the ratio of the square points to the triangle points at each bin are plotted as a solid line in the bottom panel.

To make a direct comparison with observations, it may be more useful to find the probability density distribution of the two-dimensional projected alignment angles, $\theta_{2d}$. For each cosmological model, we project $\mathbf{e}_x$ and $\mathbf{e}_y$ of each selected halo cluster onto the $xy$, $yz$, and $zx$ planes and calculate the two-dimensional alignment angle $\theta_{2d}$ between the projected major axes of dark matter and galaxy distributions for all three projection cases and determine the probability density distribution, $p(\theta_{2d})$, by taking the average over the three cases. To estimate the uncertainties in the measurement of $p(\theta_{2d})$, we also perform the bootstrap error analysis. The top panel of Figure 5 plots the $p(\theta_{2d})$ with the bootstrap errors for cDE and $\Lambda$CDM cosmologies as square and triangle dots, respectively. As one can see, the two-dimensional projection does not dilute the difference in the alignment tendency between the two models. The probability density distribution, $p(\theta_{2d})$, decreases less rapidly as $\theta_{2d}$ increases in the cDE model than in the $\Lambda$CDM model. Note that for a three-dimensional distribution, it is $p(\cos \theta)$ that is expected to be uniformly distributed in case of no alignment while for the two-dimensional case, it is $p(\theta_{2d})$.

To quantify the statistical significance of the difference in the galaxy–matter alignments between $\Lambda$CDM and cDE cosmologies, we perform a Wald test for the ratio, $\xi \equiv p_{\text{cDE}}(\cos \theta) / p_{\text{CDM}}(\cos \theta)$. In the null hypothesis $H_0$ that the two probability density distributions shown in Figures 3 and 5 are in fact from the same parent population, the expectation value of $\xi$ is unity at all bins. Taking into account the possible cross-correlations of $p(\cos \theta)$ between the different bins, we calculate the generalized $\chi^2$ defined in terms of the full covariance matrix as

$$\chi^2 \equiv (\xi_i - 1) C^{-1}_{ij} (\xi_j - 1).$$  

Here, $C^{-1}_{ij}$ is the inverse of the covariance matrix, $C_{ij} \equiv \langle (\xi_i - \bar{\xi}_i)(\xi_j - \bar{\xi}_j) \rangle$, where the ensemble average is taken over the 1000 bootstrap resamples and $\bar{\xi}_i$ denotes the mean value of $\xi$ averaged over the bootstrap resamples at the $i$th bin. In Equation (4), $(\xi_i - 1)$ expresses how much the numerical result of $\xi$ at the $i$th bin deviates from the expectation value of unity. We find $\chi^2 = 15.08$ and 14.97 for the three- and two-dimensional case, respectively. Since the number of degrees of freedom for $\chi^2$ is 5, its value corresponds to the null hypothesis being rejected at the 98.9% confidence level for both cases.

4. DISCUSSION AND CONCLUSIONS

Using data from high-resolution $N$-body simulations, we have shown that the $\Lambda$CDM and cDE cosmologies yield different
strengths of the alignments between satellite galaxy and matter distributions in triaxial clusters. As speculated by Lee (2010), it is found that the alignment is less strong in cDE cosmologies than in the standard ΛCDM scenario. The null hypothesis that the two cosmologies give the same alignment tendency is rejected at the 98.9% confidence level through a Wald test based on the generalized χ² statistics.

The differences in the satellite distributions between ΛCDM and cDE models may be understood as follows. There are two possible mechanisms for explaining the alignments between the dark matter and galaxy distributions (Altay et al. 2006). The first one is the spatial correlations between the large-scale external tidal fields and the internal tidal fields due to the cluster potentials which affect the non-spherical shapes of dark matter components of galaxy clusters and the anisotropic distributions of their satellite galaxies, respectively. The second one is the preferential accretion of satellites along filaments, often closely aligned with the major axis of the host halo (Zentner et al. 2005).

In the ΛCDM cosmology, the tidal fields evolve nonlinearly only via gravity. In cDE cosmologies, instead, the coupling between DE and dark matter generates additional tidal effects within the clusters, which weaken the spatial correlations between the external and internal tidal fields and also redistribute previously accreted satellites. This redistribution mechanism is mainly provided by the “modified inertia” that characterizes cDE models, which is a consequence of the simultaneous variation of CDM particles mass and of a velocity-dependent acceleration for CDM particles. The combination of these two effects, which has been shown to have a significant impact on the internal dynamics of virialized objects (Baldi et al. 2010), can alter the orbits of satellite structures and contribute to modify their spatial distribution within the cluster main halo.

Recently, Oguri et al. (2010) compared the observed distribution of satellite galaxies in clusters with the shape of the cluster dark matter distribution determined from weak lensing, finding a very weak alignment (Lee 2010). Due to the small sample (composed of only 13 clusters), it is difficult to say at the moment whether or not this observational signal supports the cDE scenario. In any case, a crucial implication of our results is that the alignment between galaxy and matter distributions in clusters is in principle a unique probe of dark sector interactions.

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