THE SPIN ALIGNMENTS IN GALAXY PAIRS AS A TEST OF BOUNCING COUPLED DARK ENERGY

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ABSTRACT

We investigate the effect of coupled dark energy (cDE) on the spin alignments in isolated pairs of galactic halos using the publicly available data from the hydrodynamic cDE simulations (H-CoDECs) that were run for various cDE models such as EXP001, EXP002, EXP003 (with exponential potential and constant coupling), EXP008e3 (with exponential potential and exponential coupling), and SUGRA003 (with supergravity potential and negative constant coupling), as well as for a standard ΛCDM cosmology (with the WMAP7 parameters). Measuring the cosines of the angles between the spin axes in isolated pairs of galactic halos for each model and determining its probability density distribution, we show that for the SUGRA003 model with bouncing cDE the null hypothesis of no spin alignment in pairs of galactic halos is rejected at a 99.999% confidence level. In contrast, the ΛCDM cosmology yields no significant signal of spin alignment, and the other four cDE models also exhibit only weak signals of spin alignments. The strength of the spin alignment signal is found to be almost independent of the total halo mass and separation distance in galaxy pairs. Showing also that no signal is detected from the Sloan Digital Sky Survey DR 7, we conclude that the spin alignments in galaxy pairs are in principle a unique test of bouncing cDE models.

Key words: cosmology: theory – large-scale structure of universe – methods: statistical

Online-only material: color figures

1. INTRODUCTION

Recent observations have warned us that the ΛCDM (Λ + cold dark matter) cosmology might not be the ultimate truth of the universe even though it works well on the large scale. The increasing amount of observational evidence against the ΛCDM model on the (sub-)galactic scale that has been accumulated for the past decade should no longer be dismissed nor overlooked under the shield of unknown complicated baryonic physics (see, e.g., Perivolaropoulos 2008; de Blok 2010; Peebles & Nusser 2010; Kroupa et al. 2010; Kuzio de Naray & Spekkens 2011, and references therein).

The mismatches of the theoretical predictions based on the ΛCDM model with the observations on the (sub-)galactic scales have so far been routinely attributed to our lack of knowledge about all complicated baryonic processes involved in the formation of galaxies. But the recent rapid progresses in observational and numerical studies have indicated that taking into account highly nonlinear baryon effects may not fully rescue the ΛCDM cosmology. For example, the observed flat density cores of the dark-matter-dominated low surface brightness galaxies (LSBGs; see de Blok 2010 for a comprehensive review) have been regarded as one of the more serious observational challenges to the ΛCDM cosmology on the sub-galactic scale, which predicts the cuspy density cores (Navarro et al. 1996). The recent work of Kuzio de Naray & Spekkens (2011) revealed by comparing thoroughly the simulated disk galaxies in hydrodynamic simulations with the observed LSBGs that the baryonic processes are unlikely to flatten the density cores of the LSBGs.

Nevertheless, there is a good reason that the ΛCDM model is still regarded as the standard one. Although many authors have so far made strenuous endeavors to devise a better (and hopefully more fundamental) cosmological theory, expecting it to work as well as the ΛCDM model on the large scale while simultaneously resolving all of the (sub-)galactic scale tensions of the ΛCDM cosmology with observations, no alternative theory has so far been capable of defeating the ΛCDM model. The difficulty in coming up with a viable alternative lies in the fact that the small-scale agreements of a model tend to be achieved only at the cost of its large-scale agreements and vice versa. To make matters worse, when a model has been found to be consistent with the observations on the large scales, it has then turned out to be indistinguishable from the ΛCDM cosmology.

An unprecedentedly ample amount of high-quality data recently available from observations and hydrodynamic simulations, however, gives us hope that it might be possible to eventually distinguish between the candidate cosmological models and to finally rule some of them out. The key question is what statistical property of the universe on the (sub-)galactic scale would be the most useful tool to achieve this goal. Here, we suggest the spin alignments in isolated galaxy pairs as a unique tool to test coupled dark energy (cDE) models, one of the currently popular alternatives to the ΛCDM cosmology, in which the acceleration of the universe is driven by a dynamic scalar field dark energy (DE), coupled to the non-baryonic CDM under the influence of scalar self-interaction potential $U(\phi)$ (Ratra & Peebles 1988; Wetterich 1995; Amendola 2000, 2004).

In the cDE picture, the long-range fifth force generated by the DE-CDM coupling plays a role in enhancing the density and velocity perturbations in the linear regime relative to the ΛCDM case (Baldi 2011b, 2012b; Lee & Baldi 2011), which eventually leads to the earlier formation and faster merging of dark halos (Mangano et al. 2003; Macciò et al. 2004; Mainini & Bonometto 2006; Pettorino & Baccigalupi 2008; Baldi et al. 2010; Wintergerst & Pettorino 2010; Baldi & Viel 2010; Baldi 2012a, and references therein). Since the galaxy angular momentum depends strongly on both the density and velocity perturbations in the linear regime, the relative spin orientations in galaxy pairs would differ among the candidate cDE models, which are characterized by different shapes of the coupling function $\beta(\phi)$ and self-interaction potential $U(\phi)$.
The following two recent additions to the literature have motivated us to do this work. The first one is Cervantes-Sodi et al. (2010), who showed that there are no significant spin alignments in pairs of late-type galaxies from the seventh data release of the Sloan Digital Sky Survey (Abazajian et al. 2009, hereafter, SDSS DR7). The second one is Baldi (2012b), who performed high-resolution hydrodynamic simulations (H-CoDECS) for various cDE models and released the data to the public very recently. Analyzing the H-CoDECS halo catalogs at $z = 0$, we find it possible in principle to test the cDE models by comparing their predictions of the spin alignments in galaxy pairs with the observational result.

The outline of this paper is as follows: In Section 2, a brief description of the halo and subhalo catalogs from H-CoDECS is provided. In Section 3, we explain how the spin alignments in isolated pairs of galactic halos identified using H-CoDECS data are determined, how the probability density distribution of the alignment angles is derived at $z = 0$ for each cDE model, and how the spin alignment signals depend on the total mass and separation distance in galaxy pairs. In Section 4, the spin alignments in pairs of late-type galaxies from the SDSS DR7 are calculated, and its probability density distribution is compared with the numerical results from the H-CoDECS. In Section 5, the possibility of testing bouncing cDE model with the spin alignments in galaxy pairs is discussed and a final conclusion is stated.

2. DATA FROM THE H-CoDECS

Baldi (2012b) conducted a series of H-CoDECS (Hydrodynamic Coupled Dark Energy Simulations) with the modified GADGET-2 code (Springel 2005; Springel & Hernquist 2002; Baldi et al. 2010) on a periodic box of volume $0.512 h^{-3} \text{Gpc}^3$, which contains approximately 134,217,728 gas particles in addition to the same number of CDM particles. The individual gas and CDM particle mass are $M_\text{h} = 4.78 \times 10^7 h^{-1} M_\odot$ and $M_{\text{CDM}} = 2.39 \times 10^9 h^{-1} M_\odot$ at $z = 0$, respectively. Using the SPH (Smooth Particle Hydrodynamics) technique incorporated in the GADGET-2 code (Baldi et al. 2010), the adiabatic hydrodynamic forces were computed in each H-CoDECS run to track the dynamic evolution of the gas particles.

Released to the public were all the numerical data from the H-CoDECS for five different cDE models, namely, EXP001, EXP002, EXP003, EXP008e3, and SUGRA003, as well as the standard ΛCDM model. The simulation runs for all six models started from the same initial conditions consistent with the WMAP7 parameters, and the linear power spectra of all models were also normalized to have the same amplitudes at the epoch of decoupling. The first three cDE models have the exponential form of the scalar self-interaction potential (Lucchin & Matarrese 1985; Ratra & Peebles 1988; Wetterich 1988), $U(\phi) \propto e^{-\beta \phi^2}$, and constant coupling functions: $\beta = 0.05$, $0.1$, and $0.15$ for EXP001, EXP002, and EXP003, respectively, which are all within the current limits on the cDE coupling strength from observations (Bean et al. 2008; Xia 2009; Baldi & Viel 2010; Baldi & Salucci 2012).

The EXP008e3 model has the same exponential potential, $U(\phi) \propto e^{-0.08 \phi}$, but with the time-dependent coupling function $\beta = 0.4 e^{-3 \phi}$ (Baldi 2011a). On the other hand, SUGRA003 is a bouncing cDE model characterized by supergravity potential (Brax & Martin 1999), $U(\phi) \propto \phi^{-a} e^{\beta \phi^2 / 2}$, and by a negative value of constant coupling $\beta = -0.15$. See Baldi (2012b), who provides a much more comprehensive introduction of general cDE cosmologies as well as more detailed explanations of the above six specific cDE models (see also Amendola 2000, 2004; Pettorino & Baccigalupi 2008; Baldi et al. 2010, 2011; Baldi 2011a, 2012a, and references therein).

The bound halos and their subhalos are identified by applying the standard friends-of-friends (FoF) with a linkage parameter of 0.2) and the SUBFIND algorithm to the H-CoDECS, respectively, for each cosmological model (Davis et al. 1985; Springel 2005). The H-CoDECS halo catalog provides information about the number of subhalos ($N_s$) and the FoF mass, position, and velocity of each halo, while information on the numbers of particles ($N_p$), masses ($m$), positions, and specific angular momenta ($\vec{J}$) of all the subhalos belonging to each halo is available in the H-CoDECS substructure catalog. Here, the halo mass corresponds to the collapsed mass measured at $z = 0$ as the sum of all the gas and CDM particles belonging to the same FoF groups. Thus, the halo mass has the same meaning in the six cosmological models since the mass of each individual particle has the same value at $z = 0$ in all six models (e.g., see Baldi 2012a). For more detailed explanations on the H-CoDECS project and its halo/substructure catalogs, see Baldi (2012b) and visit the CoDECS Web site.¹

3. SPIN ALIGNMENTS IN ISOLATED PAIRS OF GALACTIC HALOS

Analyzing the halo and subhalo catalogs at $z = 0$ from H-CoDECS for each cosmological model, we identify those halos that have only two subhalos ($N_s = 2$) without belonging to any larger halos; we regard the two subhalos in each identified halo as an isolated galaxy pair. To avoid those poorly resolved subhalos whose specific angular momentum vectors are likely to suffer from inaccurate measurements, we select only those halos among the identified ones in which each of the two subhalos has 100 or more particles. We focus here only on the isolated pairs of galactic halos located in low-density regions to control the environmental effect on the spin orientations to the minimum level, which helps single out the cDE effect.

Table 1 lists the number ($N_{\text{pair}}$) of the selected galaxy pairs, the median mass of the halo ($M_{\text{med}}$), and the median masses of the two subhalos ($m_{1,\text{med}}$ and $m_{2,\text{med}}$ in decreasing order) in pairs for the six cosmological models. As can be seen, the six samples have almost the same median masses. The maximum difference in $M_{\text{med}}$ and $m_{\text{med}}$ among the six models is less than 10%.

Figure 1 plots the probability density distributions of the total mass of the selected galaxy pairs, $p(M_T)$, for the six cosmological models. As can be seen, the distributions $p(M_T)$ are very similar to one another with almost the same width.

Table 1

| Model  | $N_{\text{pair}}$ | $M_{\text{med}}$ | $m_{1,\text{med}}$ | $m_{2,\text{med}}$ |
|--------|------------------|------------------|-------------------|-------------------|
| ACDM   | 948              | 2.28             | 1.72              | 0.35              |
| EXP001 | 914              | 2.38             | 1.82              | 0.34              |
| EXP002 | 860              | 2.35             | 1.79              | 0.35              |
| EXP003 | 774              | 2.52             | 1.86              | 0.34              |
| EXP008e3 | 783          | 2.53             | 1.86              | 0.34              |
| SUGRA003 | 1003        | 2.33             | 1.82              | 0.35              |

¹ http://www.marcobaldi.it/web/CoDECS.html
Figure 1. Probability density distributions of the total mass of the galaxies in pairs for the six models. (A color version of this figure is available in the online journal.)

Figure 2. Probability density distributions of the separation distance between the galaxies in pairs for the six models. (A color version of this figure is available in the online journal.)

height, and location of the maximum value of $p(M_T)$ at $(3 \times 10^{11} h^{-1} M_\odot)$ among the six models. This result confirms that our six samples of isolated galaxy pairs are comparable to one another in mass. In fact, this result should be naturally expected since the same algorithm was employed to find the isolated galaxy pairs for each model case. Figure 2 plots the probability density distributions of the separation distance in galaxy pair, $p(r)$. As can be seen, the distributions are also quite similar to one another, having the characteristic small-$r$ tail and reaching their maximum values at $r \approx 150 h^{-1}$ kpc.

For each selected galaxy pair, we calculate the cosine of the angle, $\cos \theta$, between the two specific angular momentum vectors as $\cos \theta \equiv |\hat{J}_1 \cdot \hat{J}_2|/(\hat{J}_1 \cdot \hat{J}_2)$, where $\hat{J}_i \equiv |\hat{J}_i|$. Here we restrict the range of the angle $\theta$ to $[0, \pi/2]$ since what matters are not the signs of the two angular momentum vectors but their relative orientations. Binning the values of $\cos \theta$ in the range of $[0, 1]$ and counting the number of the selected galaxy pairs belonging to each $\cos \theta$ bin, we determine the probability density distribution, $p(\cos \theta)$, for each cosmological model. If the two specific angular momentum vectors in galaxy pairs have a strong tendency to be aligned with each other, then the probability distribution $p(\cos \theta)$ is expected to increase as $\cos \theta$ increases. If there is no alignment tendency, then it must be uniform, $p(\cos \theta) = 1$, over the range of $0 \leq \cos \theta \leq 1$. The stronger alignment tendency will be manifest as the higher degree of the deviation of $p(\cos \theta)$ from the uniform distribution.

Figure 3 plots the probability density distributions of $\cos \theta$ for the six models. As can be seen, for the $\Lambda$CDM case, the probability density $p(\cos \theta)$ is almost uniform. For the case of the constant coupling, the larger the coupling constant $\beta$ is, the more severely the probability density $p(\cos \theta)$ seems to deviate from the uniform distribution. Nevertheless, even for the extreme case of EXP003 (with $\beta = 0.15$), the degree of the deviation of $p(\cos \theta)$ from the uniform distribution is not so high as in the SUGRA003 model, which exhibits the highest degree of deviation.

To estimate the statistical significance of the alignment signals detected for the cDE model cases, we perform the bootstrap error analysis. Figure 4 plots the same as Figure 3 but in the separate panels, showing the bootstrap errors, $\sigma_{\text{boot}}$, calculated as one standard deviation of $\cos \theta$ among the 10,000 bootstrap resamples. In each panel the horizontal dotted line corresponds to the uniform probability density for the case of no alignment. As can be seen for the $\Lambda$CDM case, $p(\cos \theta)$ is almost perfectly consistent with the uniform distribution. For the SUGRA003 case, the alignment signal is as significant as $4\sigma_{\text{boot}}$ in the first and the fifth bins. For the other cDE model cases, the alignment signal is not as significant as for the SUGRA003 case.

To test the null hypothesis of $p(\cos \theta) = 1$, we also calculate $\chi^2$ with $N_{\text{bin}} - 1$ degrees of freedom as

$$\chi^2 = \sum_{i=1}^{N_{\text{bin}}} \frac{[p(\cos \theta_i) - 1]^2}{\sigma_{\text{boot}}^2},$$

where $N_{\text{bin}}$ is the number of bins.

**Figure 3.** Probability density of the cosines of the angles between the spin axes of the galaxies in pairs for the six models. (A color version of this figure is available in the online journal.)

**Figure 4.** Probability density of the cosines of the angles between the spin axes of the galaxies in pairs for the six models with bootstrap errors. (A color version of this figure is available in the online journal.)
where $N_{\text{bin}}$ is the number of the $\cos \theta$ bin and $p(\cos \theta_i)$ represents the value of the probability density distribution at the $i$th $\cos \theta$ bin. Figure 5 plots the values of $\chi^2$ versus the models. The horizontal dotted line corresponds to the value of $\chi^2$ with which the null hypothesis is rejected at the 99% confidence level (Wall & Jenkins 2003). It is found that for the SUGRA003 model the null hypothesis of no spin alignment in the galaxy pairs is rejected at the 99.999% confidence level.

Now, we would like to investigate whether there is any dependence of the spin alignment signal on the mass $M_T$. This issue may be important to address since it has been recently reported that the degree of the shape alignments of the galaxy groups with the large-scale structures depends on the mass scale (Paz et al. 2011). Figure 6 plots $\cos \theta$ versus $M_T$ for the six models in the separate panels. As can be seen, there exists no obvious correlation between $\cos \theta$ and $M_T$. To address this issue more quantitatively, we calculate the correlation coefficient, $\xi$, of $\cos \theta$ and $M_T$ as (Wall & Jenkins 2003)

$$\xi(\cos \theta, M_T) = \frac{\langle (\cos \theta - \langle \cos \theta \rangle)(M_T - \langle M_T \rangle) \rangle}{\sqrt{\langle (\cos \theta - \langle \cos \theta \rangle)^2 \rangle \langle (M_T - \langle M_T \rangle)^2 \rangle}}^{\frac{1}{2}},$$

where the average is taken over all the selected galaxy pairs and the value of $\xi$ ranges between $-1$ and 1. If there is a strong correlation (anti-correlation) between $\cos \theta$ and $M_T$, then $\xi$ will be close to 1 ($-1$). If there is no correlation between the two quantities, $\xi$ will be zero. The weaker the correlation between $\cos \theta$ and $M_T$, the closer to zero the value of $\xi$ becomes. Figure 7 plots $\xi$ versus the models. As can be seen, for each model the
value of \( \xi \) is less than 0.1, which clearly demonstrates that the spin alignment signal in an isolated galaxy pair hardly depends on its total mass.

Similarly, we examine whether there is any correlation between \( \cos \theta \) and the separation distance between the pair galaxies, \( r \). The values of the correlation coefficient, \( \xi(\cos \theta, r) \), are calculated by substituting \( r \) for \( M_T \) into Equation (2) for the six models, the results of which are plotted in Figure 8. As can be seen, the value of \( \xi \) is very close to zero, confirming that there is basically no correlation between \( \cos \theta \) and \( r \).

### 4. COMPARISON WITH OBSERVATION FROM SDSS DR7

As mentioned in Section 2, it was Cervantes-Sodi et al. (2010) who for the first time showed that no significant degree of alignment exists between the spin axes in galaxy pairs, analyzing the 255 pairs of late-type galaxies in a redshift range of \([0.01, 0.2]\) identified using a spectroscopic sample from the SDSS DR7. Intriguing as their result may be, their analysis definitely has some room for improvement. For example, they assumed that the angle between the spin axes in a galaxy pair equals the difference between the position angles, which is not necessarily true. Besides, considering a relatively wide redshift interval to find galaxy pairs, they measured the relative spin orientations without accounting for the fact that the spin axes of bulges (Lee 2011).

In this section, we present a more robust and thorough analysis for the measurements of the spin alignments in pairs of the SDSS late-type galaxies. First, we utilize the spectroscopic catalog of the SDSS DR7 galaxies compiled by Huertas-Company et al. (2011), in which a total of 698,420 galaxies at \(0 \leq z \leq 0.16\) are all classified by means of the Bayesian statistics into five Hubble types, \{E, Ell, S0, Sab Scd\}; each of them is assigned five corresponding probabilities \( P(\text{E}), P(\text{Ell}), P(\text{S0}), P(\text{Sab}), P(\text{Scd}) \). Out of this catalog, we construct a sample for our analysis, selecting only those nearby large late-type galaxies that satisfy the conditions of \( z \leq 0.02 \), \( D \geq 7.92 \) arcsec and \( P(\text{Scd}) = \max \{P(\text{E}), P(\text{Ell}), P(\text{S0}), P(\text{Sab}), P(\text{Scd}) \} \), where \( D \) denotes the diameter of a given late-type galaxy (Lee 2011). That is, we focus only on the nearby large late-type galaxies since their spin axes are relatively accurately measurable owing to their small bulges and large extended disks (Lee 2011).

Taking each galaxy from the sample as a target, we find its nearest neighbor galaxy in the same sample. Let \( d_e \) and \( \Delta z \) be the separation distance and redshift difference between a target and its nearest neighbor, respectively. If the nearest neighbor galaxy has no galaxy within the distance of \( d_e \) other than the target galaxy and if \( d_e \leq 1 h^{-1} \) Mpc and \( \Delta z \leq 0.001 \), then the target galaxy and its nearest neighbor are regarded as an isolated pair system composed of the SDSS late-type galaxies.

A total of 84 pairs of the late-type galaxies are identified from our sample, and the directions of the two spin axes in each galaxy pair are determined up to two-fold ambiguity (accounting for both the clockwise and counterclockwise spinning) with the help of the circular thin disk approximation as (Pen et al. 2000; Lee & Pen 2001; Lee & Erdogdu 2007; Lee 2011).

\[
\hat{J}_x = \pm \cos I \cos \delta \cos \alpha + \sqrt{1 - \cos^2 I} \sin I \sin \delta \cos \alpha \\
- \sqrt{1 - \cos^2 I} \cos P \sin \alpha, \quad (3)
\]

\[
\hat{J}_y = \pm \cos I \cos \delta \sin \alpha + \sqrt{1 - \cos^2 I} \sin I \sin \delta \sin \alpha \\
+ \sqrt{1 - \cos^2 I} \cos P \cos \alpha, \quad (4)
\]

\[
\hat{J}_z = \pm \cos I \sin \delta - \sqrt{1 - \cos^2 I} \sin P \cos \delta, \quad (5)
\]

where \( I \) is the inclination angle, \( P \) is the position angle, and \((\alpha, \delta)\) are the right ascension and declination of each late-type disk galaxy in pair. The inclination angle of each late-type galaxy is determined as \( \cos^2 I = (q^2 - u^2)/(1 - u^2) \), where \( q \) is the axial ratio and \( u \) is the intrinsic flatness parameter introduced by Haynes & Giovanelli (1984). Following the Bayesian approach, the value of \( u \) for the selected late-type galaxies is calculated as \( u = u_{Sa} P(Sa) + u_{Sbc} P(Sbc) + u_{Scd} P(Scd) \), with \( u_{Sa} = 0.23 \), \( u_{Sbc} = 0.2 \), \( u_{Scd} = 0.1 \). For a detailed description of the measurements of the minor axes of the spiral galaxies with the intrinsic parameter, see Haynes & Giovanelli (1984) and Lee (2011).

Using the same procedure described in Section 3, we derive the probability density distribution of the cosines of the angles between the two spin axes in the selected galaxy pairs. Note that the two-fold ambiguity in the measurement of \( \hat{J} \) produces the four-fold ambiguity in the determination of \( \cos \theta \). In other words, for each galaxy pair, we end up having four different values of \( \cos \theta \). Regarding the four values as different realizations of the alignment angles for each galaxy pair, we calculate the probability density distributions of \( p(\cos \theta) \) using the \( 3\times(=4 \times 4) \) realizations of the spin alignment.

The result is plotted as square dots in Figure 9. The errors are again calculated as one standard deviation scatter among 10,000 bootstrap resamples. As can be seen, the observed probability density distribution, \( p(\cos \theta) \), is almost perfectly uniform, indicating no spin alignments in pairs of the late-type galaxies from SDSS DR7, which is consistent with the result of Cervantes-Sodi et al. (2010).
numerical samples include all isolated pairs of the galaxies. However, we have already shown in Section 3 that there is very little, if any, correlation between the spin alignment signal and the total halo mass in the galaxy pair system. We think that although our observational sample is biased, these systematics are unlikely to contaminate severely the spin alignment signal. In other words, the result of no spin alignment from the SDSS galaxy pair sample is unlikely to be due to the systematics caused by selectively including only those large spiral galaxies (which must be biased toward large halo mass) in the sample.

There is another difference between the observational data analysis and the numerical data. The measurement of the alignment angle between the spin directions in each SDSS galaxy pair unavoidably suffers from the four-fold ambiguity, which effectively adds to $p(\cos \theta)$, lowering the significance of spin alignment signal. Here, we would like to examine whether or not the spin alignment signal seen in the SUGRA003 model remains significant when the same assumption is applied to the model. Reversing the signs of the radial components of the unit spin vectors of the two galaxies, we construct two new unit spin vectors per galaxy pair. Using the two unit spin vectors (the original one and the one newly constructed through reversing the sign of the radial component of the original spin vector) of each galaxy pair, we calculate four times the cosines of the spin alignment angles per galaxy pair. Then, we redetermine $p(\cos \theta)$, regarding the four values of $\cos \theta$ per galaxy pair as four different realizations.

Figure 10 plots the newly determined probability density distribution of the cosines of the spin alignment angles (solid line) for the SUGRA003 case with the bootstrap errors and compares it with the original distribution (dashed line). As can be seen, the spin alignment signal becomes weaker, as expected, while the sizes of the bootstrap errors shrink. Note that although the alignment signal is weaker than the original one, it is still statistically significant. We find $\chi^2 = 15.23$ even when four-fold ambiguity is assumed, which still rejects the null hypothesis of $p(\cos \theta) = 1$ at the 99.8% confidence level. In other words, for the SUGRA003 case, the signal of the spin alignment in isolated galaxy pairs is so strong and robust that its statistical significance survives the application of four-fold ambiguity.

5. DISCUSSION AND CONCLUSION

In the linear tidal torque theory, the angular momentum of a galactic halo originates from the tidal interaction with the surrounding matter at its proto-galactic stage (Peebles 1969; Doroshkevich 1970; White 1984). The gas clouds in proto-galaxies are believed to share the same specific angular momentum with the CDM particles, provided that they were well mixed with each other at the initial stage (Fall & Efstathiou 1980). If the galaxies kept the initial memory of the tidal influence, then the spin axes in galaxy pairs would align well with each other since both spin axes are correlated with the principal axis of the same local tidal field (Doroshkevich 1970; White 1984; Catelan & Theuns 1996; Lee & Pen 2000; Pen et al. 2000; Porciani et al. 2002). In reality, however, the galaxies gradually lose their initial tendencies of the spin alignments during the nonlinear evolutionary processes after decoupling from the Hubble flows (e.g., Lee & Erdogdu 2007; Lee 2011). Henceforth, the degree of the spin alignments in galaxy pairs would be determined by the competition between the constructive tidal influence and the destructive nonlinear effect.

In cDE models, the integrated effect of the DE–DM interaction enhances the linear perturbations in the matter (gas+CDM) density and velocity fields relative to the ΛCDM case (Balbi 2011b; Lee & Baldi 2011). Our original idea was that the enhanced linear density and velocity perturbations in cDE models might result in augmenting the constructive effect of the initial tidal interaction, helping the galaxies better keep the initially induced spin alignments. Here, we have confirmed this idea through quantitatively investigating the effect of cDE on the spin alignments in isolated pairs of galactic halos identified using the publicly available data from the H-CoDECS for the five specific cDE models, EXP001, EXP002, EXP003, EXP008e3, SUGRA003, as well as for the ΛCDM model.

For the case of the ΛCDM model, no signal of the spin alignment in galaxy pairs has been found, which is consistent with the observational result obtained using the pairs of the
SDSS late-type galaxies (see also Cervantes-Sodi et al. 2010). The highest degree of spin alignments in isolated pairs of galactic halos has been found in the SUGRA003 model, where the linear velocity perturbations are enhanced before $z_{\text{inv}} \approx 6.8$ but lowered after $z_{\text{inv}}$, relative to the ΛCDM case. Here the redshift $z_{\text{inv}}$ corresponds to the epoch when the cDE bounces on the Λ-barrier of $P_\phi/\rho_\phi = -1$, inverting its direction of motion (see Baldi 2012a, 2012b for a detailed explanation). Given the peculiar dynamics of the SUGRA003 cDE, the strongest spin alignments exhibited by this model can be understood as follows: The enhanced velocity perturbations before $z_{\text{inv}}$ augment the constructive tidal effect of aligning the spin orientations in pairs, while the lowered velocity perturbations after $z_{\text{inv}}$ diminish the destructive nonlinear effect of erasing the tidally induced alignments.

In fact, bouncing cDE models have recently attracted sharp attention since several observational tensions of the ΛCDM model have been found to be alleviated in bouncing cDE models. For instance, Baldi (2012a) showed that the bouncing cDE accelerates the formation of massive clusters and increases their abundance at high redshifts without affecting their abundance at low redshifts. Lee & Baldi (2011) also showed that the pairwise speeds of the colliding clusters are significantly enhanced due to the effect of bouncing cDE; thus, finding a bullet-like cluster is no longer an exceptionally rare event in the SUGRA003 model (see also Lee & Komatsu 2010).

It is intriguing to see that our result presented in this paper might be used to rule out SUGRA003 as a viable cDE model. The strong signal of spin alignments in pairs of galactic halos predicted by the SUGRA003 model is in direct conflict with there being no observational signal of spin alignment in the pairs of spiral galaxies from SDSS DR7. What our result truly predicts by the SUGRA003 model is in direct conflict with the observable minor axes of the luminous disks.

As a final conclusion, since the degree of the spin alignments in isolated pairs of galactic halos is found to depend sensitively on the strength of coupling and shapes of the self-interaction potential, it can be in principle used as a unique and powerful test of cDE cosmologies, provided that it is understood how well the angular momentum vectors of the galactic halos are aligned with the observable minor axes of the luminous disks.

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