The Misalignments between Matter and Galaxy Distributions in Triaxial Clusters: A Signature of a Possible Fifth Force?

Jounghun Lee

Department of Physics and Astronomy, FPRD, Seoul National University, Seoul 151-747, Korea

jounghun@astro.snu.ac.kr

ABSTRACT

The standard structure formation model based on a ΛCDM cosmology predicts that the galaxy clusters have triaxial shapes and that the cluster galaxies have a strong tendency to be located preferentially along the major axes of host cluster’s dark matter distributions due to the gravitational tidal effect. The predicted correlations between dark matter and galaxy distributions in triaxial clusters are insensitive to the initial cosmological parameters and to the galaxy bias, and thus can provide a unique test-bed for the nonlinear structure formation of the ΛCDM cosmology. Recently, Oguri et al. determined robustly the dark matter distributions in the galaxy clusters using the two dimensional weak lensing shear fitting and showed that the orientations of the cluster galaxy distributions are only very weakly correlated with those of the underlying dark matter distributions determined robustly, which is in contrast to with the ΛCDM-based prediction. We reanalyze and compare quantitatively the observational result with the ΛCDM-based prediction from the Millennium Run simulation with the help of the bootstrap resampling and generalized χ²-statistics. The hypothesis that the observational result is consistent with the ΛCDM-based prediction is ruled out at the 99% confidence level. A local fifth force induced by a non-minimal coupling between dark energy and dark matter might be responsible for the observed misalignments between dark matter and galaxy distributions in triaxial clusters.

Subject headings: cosmology:theory — large-scale structure of universe

1. INTRODUCTION

Although the dark energy that is responsible for the present cosmic acceleration is known to occupy more than 70% of the energy budget of the Universe (e.g., Komatsu et al. 2010),
its nature is still shrouded in deep mystery. The simplest candidate for the dark energy is the cosmological constant (Λ) that Einstein introduced in his field equation a century ago and called the fundamental constant of Nature (Einstein 1917), which has been interpreted as the vacuum energy that is completely homogeneous in space, does not evolve with time, non-interacting, chemically inert, and has a constant equation of state (see Carroll et al. 1992, for a review).

Over the past two decades, the cosmologists have witnessed and enjoyed the practical success of the ΛCDM (cosmological constant + cold dark matter) cosmology in explaining the large-scale properties of the Universe, which have left little doubt on the validity of the ΛCDM as a standard model. Nevertheless, an increasing number of literatures have been devoted to seeking for viable alternatives that could compete with and hopefully replace the ΛCDM (Alcaniz 2006, for a review). The main motivation of the alternative dark energy models is to explain naturally the cosmic coincidence that the densities of dark energy and dark matter have the same order of magnitude of unity, which issue the standard ΛCDM is incapable of addressing (Amendola 2000; Chiba 2001; Chimento et al. 2003).

An intriguing idea that was motivated by a fundamental particle physics and has gained a lot of popularity recently in the field of large scale structure is that dark energy is a scalar field having a non-minimal coupling with dark matter (Amendola 2000; Farrar & Peebles 2004; Alcaniz 2006, and references therein). The distinct feature of this fascinating idea is that a possible fifth force can be generated by the propagation of dark matter inhomogeneities into the scalar field due to the non-minimal coupling. The strength, range and potential form of a possible fifth force depends on how to model the coupling in the dark sector (dark energy+dark matter). The reason for the recent sharp attention on the coupled scalar field models is that the inclusion of a fifth force generated by the dark sector interaction may be able to explain several observational phenomena (Macciò et al. 2004; Nusser et al. 2005; Peebles & Nusser 2010; Baldi et al. 2010), which have been suggested as mismatches to the theoretical predictions of the ΛCDM cosmology such as the abundance of galaxy satellites, the speed of bullet cluster, and the clear-out of void dwarfs (Klypin et al. 1999; Peebles 2001; Farrar & Rosen 2007; Lee & Komatsu 2010).

In this Letter, we present another observable that exhibits an obvious mismatch with the numerical prediction based on the standard structure formation based on a ΛCDM cosmology: the misalignments between matter and galaxy distributions in triaxial galaxy clusters. In conventional approaches the shapes of dark matter distribution in galaxy clusters were often determined by measuring the member galaxy distributions (e.g., Binggeli 1982; Flinn 1987; Rhee & Katgert 1987; West et al. 1995; Chambers et al. 2002; Plionis & Basilakos 2002; Hashimoto et al. 2008; Evans & Bridle 2009). Recent progress in weak lensing shear
analysis, however, has allowed us to determine the shapes of clusters directly from dark matter distributions (Okabe et al. 2010; Oguri et al. 2010), which has revealed that the cluster dark matter distributions are only very weakly aligned with the cluster galaxy distributions.

Noting that the standard structure formation model based on ΛCDM cosmology predicts very strong correlations between the shapes of galaxy and dark matter distributions (Lee et al. 2008), we make a quantitative comparison between the observed trend and the ΛCDM-based prediction, and make a robust test of the hypothesis that the observed trend is consistent with the ΛCDM-based prediction with the help of the bootstrap resampling and generalized χ² statistics. We speculate that the observed misalignments between dark matter and galaxy distributions in triaxial clusters might be a new observational signature of a dark sector interaction.

2. NUMERICAL RESULT BASED A ΛCDM COSMOLOGY

The correlations between the major axes of dark matter and satellite galaxy distributions in dark halos have been investigated by Lee et al. (2008) using the data from the mili-Millennium simulation that was run on a periodic box size of 62.5 h⁻¹Mpc for a flat ΛCDM cosmology with Ω_m = 0.25, Ω_Λ = 0.75, h = 0.73, σ_8 = 0.9, and n_s = 1 (Springel et al. 2005). The dark halos and their substructures were identified from the mili-Millennium data by applying the Friends-of-Friends (FoF) and the SUBFIND algorithm, respectively (Springel et al. 2001). The luminosities of the satellite galaxies residing in the dark halo substructures were determined according to the semi-analytic model of galaxy formation (Croton et al. 2006). For a detailed description of the mili-Millennium simulation and the semi-analytic galaxy catalog, we refer the readers to Springel et al. (2005).

Selecting those mili-Millennium halos which have five or more satellite galaxies, Lee et al. (2008) ended up having a sample of 277 dark halos with mass M ≥ 1.3 × 10¹³ h⁻¹M⊙ at z = 0. They determined the major axes of the selected 277 halos using two different schemes. The first scheme is based on the dark matter distribution of each halo. They calculated the inertia momentum tensor of each halo using the constituent dark matter particles (each of which has mass 8.6 × 10⁸ h⁻¹M⊙) and determine the major axis as the eigenvector of the inertia momentum tensor corresponding to the largest eigenvalue. In the second scheme the major axis of the inertia momentum tensor of each halo was calculated by using the satellite galaxies weighted by their luminosity.

The correlations between the major axes determined by the two different schemes were quantified in terms of the distribution of the alignment angle: Basically, they measured the
angle between the two major axes in range of \([0, 90^\circ]\) for each halo. Binning the alignment angles and counting the number of halos whose alignment angles belong to each bin, they calculate the number fraction distribution as a function of the angle between the two major axes of dark matter and satellite galaxy distributions (see Figure 1 in Lee et al. 2008). Very strong correlations between the two major axes were found, which proved that the satellite galaxies in the massive halos tend to be located near the major axes of the dark matter distributions.

The correlations between matter and galaxy distributions in halos are usually ascribed to the effect of the external tidal fields: According to the cosmic web theory based on a cold dark matter paradigm (Bond et al. 1996), the coherence and non-linear sharpening of the gravitational tidal fields induce the shape-alignments between the large-scale structures such as cluster-supercluster alignments, void-supercluster alignments and the inclination of the galaxy spin axes onto the sheets (e.g., Navarro et al. 2004; Kasun & Evrard 2005; Altay et al. 2006; Trujillo et al. 2006; Lee & Evrard 2007; Park & Lee 2007).

The gravitational tidal effects also cause the galaxy clusters to have triaxial shapes and induce the correlations between matter and satellite galaxy distribution in the triaxial clusters since the merging and accretion of matter and galaxies onto the clusters occur preferentially along the primary filaments that are aligned with the directions of the minimal matter compression, i.e., the minor principal axes of the gravitational tidal fields (West et al. 1995; Bailin et al. 2005; Bailin & Steinmetz 2005). After anisotropic merging along the primary filaments, however, the secondary infall and subsequent nonlinear evolution inside the clusters would modify the spatial distributions of the member galaxies (Dubinski 1999). For instance, Lee & Kang (2006) have shown that as the clusters become more relaxed, the correlations between the principal axes of dark matter and substructures tend to decrease. They also found that the correlations increase with redshift and cluster mass.

In observations, the correlations between the major axes of dark matter and galaxy distributions are often measured in the two dimensional projected planes. Therefore, for a direct comparison with the observational result, it is necessary to predict numerically the correlations of the projected major axes of dark matter and satellite galaxy distributions. Adopting the same mili-Millennium Run data used by Lee et al. (2008) and assuming the flat-sky approximation, we investigate here the correlations between the projected major axes of dark matter and galaxy distributions. Measuring and binning the angles \(\phi\) of the projected major axes of dark matter and satellite galaxy distributions of the selected 277 halos in the two dimensional plane, we find the number fraction of dark halos as a function of \(\phi\).

The left, middle and right panel of Figure 1 plots the results for the case that the
projection was done onto the xy, yz, and zx plane, respectively. The errors include both of
the sample variance as well as the Poisson noise. The sample variance is calculated as one
standard deviation among the 1000 bootstrap resamples. As one can see, the distributions
has a sharp peak at the first bin $0^\circ \leq \phi \leq 10^\circ$, as in the three dimensional case, which
proves that projections onto the two dimensional planes do not diminish the correlations
between the major axes of matter and satellite galaxy distributions. In the following section,
we compare this numerical prediction with the observational result and test the hypothesis
that the observational result is consistent with the numerical prediction based on a ΛCDM
cosmology.

2.1. NUMERICAL VS. OBSERVATIONAL

Performing two dimensional analysis of the weak lensing shear maps constructed with
high-quality Subaru/Supreme-cam [Miyazaki et al. 2002], Oguri et al. (2010) have measured
the two dimensional projected shapes and orientations of dark matter distributions in the
galaxy clusters from the Local Cluster Substructure Survey (Okabe et al. 2010). Using a
subsample of 18 galaxy clusters for which the weak lensing shear maps are well fitted to the
elliptical density profiles (Jing & Suto 2002), they determined the longest axis of the dark
matter distribution and measured its position angle for each cluster (see Table 1 in Oguri et
al. 2010).

Selecting those member galaxies whose r-band magnitudes are brighter than 22 mag,
they also fitted the member galaxy distribution (confined to the same region) in each cluster
to an elliptical power law profile and determined the positions angle of the longest axis of
galaxy distributions (see Table 2 in Oguri et al. 2010). According to Oguri et al. (2010),
the fitting of the dark matter and member galaxy distribution in each cluster was done at
the square region $20' \times 20'$, around cluster’s center chosen to be the location of the brightest
cluster galaxy, where $20'$ corresponds to approximately 2-3 Mpc for the selected clusters in
a redshift range of $0.1 < z < 0.3$. For a detailed description of the two dimensional fitting
of weak lensing shear field and the cluster sample, see Oguri et al. (2010).

By comparing the position angles of dark matter and galaxy distributions in each cluster,
they found only very weak correlations between the two. They considered several possible
systematics such as galaxy bias, dilution effect, fitting area and field-galaxy contamination
but found no systematics significant enough to explain the observed trend. Although
Oguri et al. (2010) asserted that the ellipticity distribution of dark matter distributions in
the observed galaxy clusters agrees well with the theoretical prediction based on a ΛCDM
cosmology (Jing & Suto 2002), they did not recognize that the observed misalignments be-
tween the longest axes of dark matter and member galaxy distributions in the clusters are inconsistent the ΛCDM prediction.

To make a parallel comparison of the observational result with the ΛCDM prediction given in §2, here we determine the distributions of the angles $\phi$ between the projected major axes of dark matter and galaxy distributions using the observational data of the 18 clusters given in Oguri et al. (2010). The angle $\phi$ for each cluster is determined by subtracting the position angle of the galaxy distribution from that of dark matter distribution and taking its absolute value. If the position angle difference exceeds $\pi/2$, then we take $\pi - \phi$. Then, we bin the values of $\phi$ and count the number of the clusters belonging to each bin.

Figure 2 plots the result as open squares. The dotted line represents the uniform distribution corresponding to the case that there is no correlation between the major axes of dark matter and galaxy distributions. The errors include the sample variance and the Poisson noise. As in §2, the sample variance is calculated as $1\sigma$ scatter among the 1000 bootstrap resamples. For comparison, we also plot the numerical prediction of the ΛCDM cosmology obtained in §2 as thick solid line (projection onto xy plane) while the thin solid lines represent the $\pm 1\sigma$ bootstrap errors of the numerical results.

As it can be seen, the observational result deviates significantly from the numerical result based on a ΛCDM prediction and the semi-analytic galaxy formation model. To quantify the deviation, we employ the generalized $\chi^2$-statistics which accounts for the correlations between the neighbor $\phi$-bins due to the errors in the measurement of cluster’s position angles:

$$\chi^2 = \Sigma_{i,j} \Delta f_j C_{ij}^{-1} \Delta f_i$$

Here $C_{ij}$ is the covariance matrix defined as $C_{ij} \equiv \langle \Delta f_i \Delta f_j \rangle$ and $\Delta f_i$ is the difference between the observed and predicted value of the cluster number fraction at the $i$-th bin given as $\Delta f_i \equiv f_{i}^{\text{obs}} - f_{i}^{\text{the}}(\phi_i)$. The bracket in the definition of $C_{ij}$ (Equation 1) represents the ensemble average over the 1000 bootstrap resamples. Noting that in the large $\phi$ section (beyond the third bins) the Poisson noises dominate over the bootstrap errors and the signals of the numerical results are confined to the first two bins, we consider the first three bins $(0^\circ \leq \phi \leq 30^\circ)$ for the calculation of $\chi^2$ (i.e., the degree of freedom is 3).

Putting the numerical results obtained in §2 into $f^{\text{the}}(\phi_i)$ for the calculation of $\chi^2$, we test the hypothesis that the observational result is consistent with the ΛCDM prediction and found that the hypothesis is rejected at the 99% confidence level. Meanwhile, putting the uniform distribution into $f^{\text{the}}(\phi_i)$, we also test the null hypothesis that there is no correlation between the major axes of dark matter and galaxy distributions and have found that the null hypothesis is rejected only at the 23% confidence level.

Excluding those clusters whose position angles suffer from large uncertainties, we end up
with a smaller subsample of 13 clusters and redetermined the number fraction distribution as a function of $\phi$. Figure 3 plots the results. As it can be seen, the distribution has a higher peak at the second bin but still deviates significantly from the numerical result based on a $\Lambda$CDM cosmology and the semi-analytic galaxy formation model. The recalculation of $\chi^2$ for this case rejects the hypothesis that the observational result from the 13 clusters is consistent with the numerical result is rejected at the 95% confidence level.

It is worth mentioning the differences in the redshift range between the numerical and observational data used for the above comparison: The numerical result has been obtained at $z = 0$ while the observational results have been drawn from the galaxy clusters at $0.1 < z < 0.3$. This difference in the redshift range, however, would even worsen the disagreement between the numerical and the observational result for the following reason. As mentioned in §2 and as shown by N-body simulations (e.g., Bailin & Steinmetz 2005; Bailin et al. 2005; Altay et al. 2006; Lee & Kang 2006), the correlations between the major axes of dark matter and satellite galaxy distributions tend to be stronger at higher redshifts. In other words, the predicted strength of the correlations used for the comparison with the observational result is underestimated.

One might think that the selection bias in the measurements of galaxy distributions should be responsible for the disagreement between theory and observation since in the analysis of Oguri et al. (2010) only those bright galaxies with $mag > 22$ at r-band are used unlike in the numerical analysis. Recall, however, that we used the luminosity-weighted galaxy distributions in the numerical analysis to determine the major axes, which should minimize the expected selection bias.

Another difference lies in the values of the cosmological parameters used for the mili-Millennium Run simulations. Especially, the value of $\sigma_8$ chosen by the Millennium Run simulation has been known to be higher than the WMAP value (Komatsu et al. 2010). The correlations between dark matter and satellite galaxy distributions in triaxial clusters, however, are unlikely to be significantly affected by the initial cosmological conditions, since it represents a nonlinear observable rather than a linear one.

### 3. DISCUSSION

Now that we have found the observed misalignments of the projected major axes of dark matter and galaxy distributions in the galaxy clusters to be inconsistent with the numerical prediction based on a $\Lambda$CDM cosmology and the semi-analytic galaxy formation model, we would like to discuss the possible physical origin of the misalignments. A usual suspect would
be some hydrodynamic gas physics involved in the galaxy formation that was not included in the Millennium Run simulation and semi-analytic galaxy catalog. If this is really the case, then our result indicates that the semi-analytic galaxy formation model has to be improved to account for the observed deviations of the orientations of cluster galaxy distributions relative to that of dark matter distributions.

An intriguing new possibility is that the orientations of member galaxy distributions have deviated from that of dark matter distributions due to the existence of the fifth force that is non-zero only in massive halos. In some dark energy model where the scalar field is coupled both to the dark matter particles and the second relativistic particle species, a fifth force is short ranged, having non-zero values only on the scales smaller than the typical cluster sizes (∼1Mpc) (e.g., Farrar & Peebles 2004; Nusser et al. 2005).

According to recent simulation results (e.g., Nusser et al. 2005; Keselman et al. 2009; Baldi et al. 2010), in these models with a local fifth force the cluster galaxies (i.e., the galactic halos in dense environments) tend to form earlier and evolve more nonlinearly than in the standard ΛCDM model. In addition, a local fifth force also tend to affect the mutual interactions between the satellite galaxies, which would result in an internal tidal field different from the gravitational external tidal field. Whereas, the dark matter particles which constantly accrete onto the host clusters at relatively later epochs than the member galaxies along the primary filaments from the surroundings would be less affected by the existence of a local fifth force and thus would keep the memory of the external gravitational tidal fields. Overall, a fifth force would play a role of diminishing the expected strong alignments between dark matter and galaxy distributions in clusters.

This new idea also suggests that it might be possible to constrain the range and strength of a local fifth force by measuring the misalignments between dark matter and galaxy distributions in clusters. This goal calls for making a quantitative prediction of the coupled dark energy model on the correlations between dark matter and galaxy distribution using detailed N-body and hydrodynamic simulations.

The Millennium Run simulation used in this paper was carried out by the Virgo Supercomputing Consortium at the Computing Centre of the Max-Planck Society in Garching, which are available at http://www.mpa-garching.mpg.de/millennium. We thank M.Oguri for useful comments. This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST, No.2010-0007819).
REFERENCES

Adami, C., Mazure, A., Katgert, P., Biviano, A. 1998, A&A, 336, 63

Alcaniz, J. S. 2006, Brazilian Journal of Physics, 36, 1109

Amendola, L. 2000, Phys. Rev. D, 62, 043511

Altay, G., Colberg, J. M., & Croft, R. A. C. 2006, MNRAS, 370, 1422

Baldi, M., Pettorino, V., Robbers, G., & Springel, V. 2010, MNRAS, 403, 1684

Bailin, J., et al. 2005, ApJ, 627, L17

Bailin, J., & Steinmetz, M. 2005, ApJ, 627, 647

Basilakos, S., Plionis, M., Yepes, G., Gottlöber, S., & Turchaninov, V. 2006, MNRAS, 365, 539

Binggeli, B. 1982, A&A, 107, 338

Bond, J. R., Kofman, L., & Pogosyan, D. 1996, 380, 603

Carroll, S. M., Press, W. H., & Turner, E. L. 1992, Annu. Rev. Astron. Astrophys., 30, 499

Chambers, S., Melott, A., & Miller, C. 2002, ApJ, 565, 849

Chiba, T. 2001, Phys. Rev. D, 64, 103503

Chimento, L. P., Jakubi, A. S., Pavon, D., & Zimdahl, W. 2003, Phys. Rev. D, 67, 083513

Croton, D. J., et al. 2006, MNRAS, 365, 11

de Theijji, P. A. M., Katgert, P., van Kampen, E. 1995, MNRAS, 273, 30

Dubinski, J. 1999, Galaxy Dynamics - A Rutgers Symposium, 182, 491

Einstein, A. 1917, Sitz. Preuss. Akad. Wiss., 142, 121

Evans, A. K. D., & Bridle, S. 2009, ApJ, 695, 1446

Farrar, G. R., & Peebles, P. J. E. 2004, ApJ, 604, 1

Farrar, G. R., & Rosen, R. A. 2007, Physical Review Letters, 98, 171302

Flin, P. 1987, MNRAS, 228, 941
Hashimoto, Y., Henry, J. P., & Boehringer, H. 2008, MNRAS, 390, 1562
Jing, Y. & Suto, Y. 2002, ApJ, 574, 538
Kasun, S. F. & Evrard A. E. 2005, ApJ, 629, 781
Keselman, J. A., Nusser, A., & Peebles, P. J. E. 2009, Phys. Rev. D, 80, 063517
Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. 1999, ApJ, 522, 82
Komatsu, E., et al. 2010, ApJ, in press
Lee, J., & Kang, X. 2006, ApJ, 637, 561
Lee, J., & Evrard, A. E. 2007, ApJ, 657, 30
Lee, J., Springel, V., Pen, U.-L., & Lemson, G. 2008, MNRAS, 389, 1266
Lee, J. & Komatsu, E. 2010, ApJ, 717, 6
Macciò, A. V., Quercellini, C., Mainini, R., Amendola, L., & Bonometto, S. A. 2004, Phys. Rev. D, 69, 123516
Miyazaki, S., et al. 2002, PASJ, 54, 833
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563
Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2004, ApJ, 613, L41
Nusser, A., Gubser, S. S., & Peebles, P. J. 2005, Phys. Rev. D, 71, 083505
Oguri, M., Takada, M., Okabe, N., & Smith, G. P. 2010, MNRAS, 405, 2215
Okabe, N., Takada, M., Umetsu, K., Futamase, T., & Smith, G. P. 2010, PASJ, in press
Olivares, G., Atrio-Barandela, F., & Pavón, D. 2006, Phys. Rev. D, 74, 043521
Park, D. & Lee, J. 2007, ApJ, 665, 96
Peebles, P. J. E. 2001, ApJ, 557, 495
Peebles, P. J. E., & Nusser, A. 2010, Nature, 465, 565
Rhee, G., & Katgert, P. 1987, A&A, 183, 217
Plionis, M. & Basilakos, S. 2002, MNRAS, 329, L47
Springel, V., et al. 2001, MNRAS, 328, 726

Springel, V., et al. 2005, Nature, 435, 629

Trujillo, K., Carretero, C., & Patiri, S. 2006, ApJ, 640, L111

West, M., Jones, C., & Forman, W. 1995, ApJ, 451, L5
Fig. 1.— The fraction of the dark halos as a function of the angles between the major axes of the cluster halos and the spatial distributions of the member galaxies projected into the $x$-$y$, $y$-$z$ plane and $z$-$x$ plane (in the left, middle and right panel, respectively).
Fig. 2.— Comparison of the Λ prediction (solid line) with the observational result (open squares) obtained from Oguri et al. (2010). The error-bars include the sample variance as well as the Poisson noise. The thin solid lines represent the ±1σ bootstrap scatters.
Fig. 3.— Same as Figure 2 but including in the observational results only those clusters which do not show larger uncertainties in the measurement of the major axis directions.