Distinguishing between ΛCDM and \( f(R) \) gravity models using halo ellipticity correlations in simulations

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ABSTRACT

There is a growing interest in utilizing intrinsic alignment (IA) of galaxy shapes as a geometric and dynamical probe of cosmology. In this paper, we present the first measurements of IA in a modified gravity model using the gravitational shear-intrinsic ellipticity correlation (GI) and intrinsic ellipticity-ellipticity correlation (II) functions of dark-matter halos from \( f(R) \) gravity simulations. By comparing them with the same statistics measured in ΛCDM simulations, we find that the IA statistics in different gravity models show distinguishable features, with a trend similar to the case of conventional galaxy clustering statistics. Thus, the GI and II correlations are found to be useful in distinguishing between the ΛCDM and \( f(R) \) gravity models. More quantitatively, IA statistics enhance detectability of the imprint of \( f(R) \) gravity on large scale structures by ~ 40\% when combined with the conventional halo clustering in redshift space. We also find that the correlation between the axis ratio and orientation of halos becomes stronger in \( f(R) \) gravity than that in ΛCDM. Our results demonstrate the usefulness of IA statistics as a probe of gravity beyond a consistency test of ΛCDM and general relativity.

Key words: methods: statistical – cosmology – dark energy – large-scale structure of Universe.

1 INTRODUCTION

The origin of the cosmic acceleration has been one of the most profound mysteries for decades (Weinberg et al. 2013). Many studies have explored it by considering dark energy as a source of the cosmic acceleration. Modifying the law of gravity at cosmological scales is an alternative way to explain the acceleration (Wang & Steinhardt 1998; Linder 2005). Conventionally, galaxy clustering observed in redshift surveys has been extensively exploited for this purpose (e.g., Guzzo et al. 2008; Reyes et al. 2010; Okumura et al. 2016).

Intrinsic alignment (IA) of galaxy shapes, originally focused as a contaminant to gravitational lensing signals (Croft & Metzler 2000; Heavens et al. 2000; Hirata & Seljak 2004; Mandelbaum et al. 2006; Hirata et al. 2007; Okumura et al. 2009; Okumura & Jing 2009; Blazek et al. 2011; Troxel & Ishak 2015; Tonegawa & Okumura 2022), has been drawing attention as a new dynamical and geometric probe of cosmology (e.g., Chisari & Dvorkin 2013; Okumura et al. 2019; Taruya & Okumura 2020; Kurita et al. 2021; Okumura & Taruya 2021; Reischke et al. 2022). However, such a possibility has been explored merely by forecast studies or numerical simulations based on the ΛCDM model. Thus, we still do not know how the observed IA looks like in gravity models beyond general relativity (GR).

In this paper, we present the first measurements of IA statistics of dark-matter halos in modified gravity using N-body simulations of the \( f(R) \) gravity model. We then show that the IA statistics are indeed useful to tighten the constraint on gravity models by combining with the conventional galaxy clustering statistics.

This paper is organized as follows. In Section 2, we briefly review the statistics of IA used in this paper. Section 3 describes N-body simulations under the ΛCDM and \( f(R) \) gravity models. In Section 4, we present measurements of the halo clustering and alignment statistics. We investigate how well one can improve the distinguishability between the ΛCDM and \( f(R) \) gravity models by considering the IA statistics in section 5. Our conclusions are given in Section 6.

2 INTRINSIC ALIGNMENT STATISTICS

This section provides a brief description of the three-dimensional alignment statistics following Okumura & Taruya (2020). In this paper, we measure all the statistics in redshift space, and thus the halo overdensity field \( \delta_h \) below is sampled in redshift space and suffers from redshift-space distortions (RSD Kaiser 1987).

To begin with, orientations of halos or galaxies projected onto the sky are quantified by the two-component ellipticity, given as

\[
\gamma_{(+,\times)}(x) = \frac{1 - q^2}{1 + q^2} (\cos(2\theta), \sin(2\theta)),
\]

where \( \theta \), defined on the plane normal to the line-of-sight, is the angle between the major axis projected onto the celestial sphere and
the projected separation vector pointing to another object, $q$ is the minor-to-major axis ratio on the projected plane ($0 \leq q \leq 1$).

In this paper, together with the halo density correlation function, $\xi_{hh}$, abbreviated as the GG correlation, we study two types of IA statistics, the intrinsic ellipticity (II) correlation functions, $\xi_\ell$ and $\xi_\delta$. (Croft & Metzler 2000; Heavens et al. 2000), and the gravitational shear-intrinsic ellipticity (GI) correlation functions, $\xi_{gh}$ (Hirata & Seljak 2004). These IA statistics are concisely defined as

$$\xi_X(r) = \langle \{ 1 + \delta_h(x_1) \} \{ 1 + \delta_h(x_2) \} W_X(x_1,x_2) \rangle,$$

(2)

where $X = \{ h+, +, - \}$ and $r = x_2 - x_1$. The GI and II correlation functions are characterized by the function $W_X(x_1,x_2)$ $= \gamma_x(x_2)$ and $W_X(x_1,x_2) = \gamma_x(x_1)\gamma_x(x_2) \pm \gamma_y(x_1)\gamma_y(x_2)$ for the GI and II correlation functions, respectively. For the II correlation, when we specifically refer to $\xi_\delta$ and $\xi_\ell$, they are abbreviated as the II (+) and II (−) correlations, respectively. Throughout this paper, we assume the distant-observer approximation so that $\hat{x}_1 = \hat{x}_2 \equiv \hat{x}$, where a hat denotes a unit vector.

## 3 F(R) GRAVITY SIMULATIONS

In $f(R)$ gravity theories, we replace the Ricci scalar $R$ in the Einstein-Hilbert action by some general function of $R$, $f(R)$, to mimic the effect of the cosmological constant $\Lambda$ (Starobinsky 1980; De Felice & Tsujikawa 2010; Nojiri & Odintsov 2011). We adopt the functional form of $f(R)$ introduced by Hu & Sawicki (2007), where the deviation of the law of gravity from GR is characterized by $f(R) = f_0 + f_1/R$. The parameter $f_0$ is the gravitational run, we choose the value of $f_0 = 10^{-1}$, and the lower mass threshold is adopted for $\Lambda$CDM halos to make the number densities equivalent with the former.

The error bars shown only for the $f(R)$ gravity results represent the Poisson error.

In measuring the redshift-space density field and the projected shape field, we rotate the simulation box and regard each direction of the axis ratio $q$.

Figure 1. Distributions of minor-to-major axis ratios of projected halo shapes for $\Lambda$CDM and $f(R)$ gravity simulation runs. The solid and dashed curves show the results at $z = 0$ and 1, respectively. The left panel shows the distributions of all the particle members project on the celestial plane. $I_{ij} = \sum \Delta x_i \partial^2 / \partial x_j$, where $\Delta x_i$ is the $i$th spatial component of the vector $\Delta x_i$, the difference between the positions of the halo center and $k$-th member particles, and the sum is over all the particles within the virial radius of the halo. The two ellipticity components of each halo, projected along the third axis for instance, are estimated as (Valdes et al. 1983; Miralda-Escude 1991; Croft & Metzler 2000)

$$\gamma_{(+,\times)} = \frac{1}{I_{11} + I_{22}} (I_{11} - I_{22}, 2I_{12}).$$

In measuring the redshift-space density field and the projected shape field, we rotate the simulation box and regard each direction along the three axes of the box as the line of sight. We thus have three realizations for each of the $\Lambda$CDM and $f(R)$ simulations, though they are not fully independent. Thus, in the following, all the quantities are averaged over the three projections.

Fig. 1 shows the distributions of minor-to-major axis ratios of projected halo shapes at $z = 0$ and 1 for $\Lambda$CDM and $f(R)$ gravity simulation runs. As mentioned above, the averages are averaged over the three realizations. By comparing the two distributions at $z = 1$, one can see that halo shapes in $f(R)$ gravity are more elongated than those in $\Lambda$CDM. This could be because more masses undergo infalling along the filaments into halo centers in $f(R)$ gravity than in $\Lambda$CDM. Toward $z = 0$ where the structure growth becomes more nonlinear, the difference of the axis ratio distributions between $f(R)$ gravity and $\Lambda$CDM models becomes less prominent. These trends at $z = 0$ and 1 are totally consistent with the earlier finding of L’Huillier et al. (2017). In the following sections, we analyze the halo catalogs of $z = 0$ only.
4 CORRELATION FUNCTIONS IN $f(R)$ GRAVITY

4.1 Correlation function measurements

Here we measure the GG, GI and II statistics in the $N$-body simulations. Since all these statistics have explicit angular dependences (Hamilton 1992; Okumura & Taruya 2020), we consider their multipole expansions in terms of the Legendre polynomials, $P_{\ell}$,

$$\xi_{X,\ell}(r) = \frac{2\ell + 1}{2} \int_{-1}^{1} \xi_X(r) P_{\ell}(\mu_r) d\mu_r,$$

where $X = \{hh, h+, h-, h\}$ and $\mu_r = \hat{r} \cdot \hat{x}$ with a hat denoting a unit vector. In linear perturbation theory all the four correlation functions, $\xi_{X,\ell}$, have non-zero values only for $\ell = 0, 2$ and 4. We thus consider only these three multipoles for each correlation function, and hence the number of the total statistics is $4 \times 3 = 12$.

Our estimators for the multipoles, $\hat{\xi}_{X,\ell}$, are expressed as (Okumura et al. 2020)

$$\hat{\xi}_{X,\ell}(r) = \frac{2\ell + 1}{2} \frac{1}{RR(r)} \sum_{j,k} W_{X,jk} P_{\ell}(\mu_{jk}),$$

where $RR$ is the pair counts from the random distribution, which can be analytically computed because we place the periodic boundary condition on the simulation box. For the GG, GI and II correlations, $W_{hh,jk} = 1 - \delta_{jk}^{K} RR(r)/DD(r)$, $W_{h+,jk} = \gamma_{h}(x_j)$, and $W_{h-,jk} = \gamma_{-}(x_j)$, respectively, where $\gamma_{\ell}(x_j)$ is redefined relative to the separation vector $r$ projected on the celestial sphere, $\delta_{jk}^{K}$ is the Kronecker delta and $DD(r)$ is the pair counts of halos at given separation $r$. Clustering of halos in $f(R)$ gravity has been investigated in literature using $N$-body simulations (Arnalte-Mur et al. 2017; Hernández-Aguayo et al. 2019; Alam et al. 2021; García-Farieta et al. 2021) and hydrodynamical simulations (Arnold et al. 2020).
Here we investigate how well one can improve the distinguishability between the ΛCDM and f (R) gravity models by considering the IA effect. The purpose of this work is, however, to see how much adding the IA effect improves the distinguishability of different gravity models compared to the galaxy clustering analysis only, rather than the distinguishability itself. Thus, we do not expect that our conclusion is affected by the underestimation of the covariance matrix.

5 RESULTS AND DISCUSSION

5.1 Distinguishing gravity models with IA

Here we investigate how well one can improve the distinguishability between the ΛCDM and f (R) gravity models by considering the IA effect. The purpose of this work is, however, to see how much adding the IA effect improves the distinguishability of different gravity models compared to the galaxy clustering analysis only, rather than the distinguishability itself. Thus, we do not expect that our conclusion is affected by the underestimation of the covariance matrix.

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add subscripts to $A$ depending on which statistics to be used for the constraints, e.g., $A_{GG}$, $A_{GI}$ and $A_{II}$ for the GG-, GI- and II-only analyses, respectively, and $A_{GG+GI+II}$ for their combination. We adopt a simple $\chi^2$ statistic to constrain the parameter $A$ which is given by

$$\chi^2(A) = \sum_{i,j,f,X,X'} \Delta^X_{ij} (C^{-1})_{ij} X_{i,j} X'_{i,j} \Delta^X_{ij},$$

where $\Delta^X_{ij} = \xi_{X,i}(r) - A \xi^G_{X,i}(r)$. The covariance of the correlation functions in $f(R)$ gravity, $C_{ij}$, is the $120 \times 120$ matrix, and for the single-statistics analysis of the GG or GI correlation, the covariance is reduced to a $30 \times 30$ submatrix, while the analysis of the II correlation, $II(+)\text{ and } II(-)$, needs the $60 \times 60$ submatrix. Table 1 summarizes the degree of freedom for each choice of the statistics. Note that the constant model above is too simple and in reality the deviation of $A$ from unity is scale-dependent. We perform a qualitative investigation of the scale dependence using a simple model in $f(R)$ gravity in the next subsection. To properly take into account the scale dependence, however, the detailed modeling of IA statistics in modified gravity models is required. Furthermore, the amount of the deviation from unity is not necessarily equivalent between different statistics. Thus, we do not focus on the best-fitting values of $A$ but are rather interested in how well we can exclude the possibility of the correlation functions under the two models being equal, namely $A = 1$, and whether the constraint gets tighter by combining the IA statistics with the clustering statistics.

Fig. 4 shows $\Delta \chi^2 = \chi^2 - \chi^2_{\text{min}}$ as a function of $A$, where $\chi^2_{\text{min}}$ is the minimized $\chi^2$ value with the best-fitting $A$. The black-dotted, yellow-dot-dashed and blue-long-dashed curves are the constraints from the GG, GI and II correlations, respectively. While the GG correlation gives the tightest constraint as expected, the GI and II correlations also provide meaningful constraints. The best-fitting parameter $A_{GG}$ is shown as the horizontal lines in the second, third and fourth rows on the leftmost column of figure 2. Similarly, $A_{GI}$ is shown on the second leftmost column and $A_{II}$ is on the third and fourth columns.

We study how well one can improve the distinguishability between the $\Lambda$CDM and $f(R)$ gravity models by combining the IA statistics with the conventional clustering statistics. The constraint using the combination of GI and II correlations is shown as the red curve in Fig. 4. It is interesting to see that though the constraint from the conventional GG-correlation analysis is stronger and excludes the case of $\xi_{hh,\ell} = \xi^G_{hh,\ell}$ with $3.9\sigma$ C.L., one can achieve the meaningful constraint from GI+II (4.51$\sigma$). Once we combine all the statistics, namely 12 multipoles, the distinguishability reaches 5.63$\sigma$. Note that the analysis is based on various assumptions and simplifications, and thus these numbers do not have much importance. Rather, the amount of the improvement ($\sim 40\%$) matters. All the obtained numerical values are summarized in table 1.

5.2 Linear alignment model in $f(R)$ gravity

As a demonstration, we calculate the model prediction of the GG, GI and II correlations in $f(R)$ gravity using linear perturbation theory. In Fourier space, the halo density field in redshift space, $\delta_h(k)$, is linearly related to the underlying matter density field in real space, $\delta_m(k)$, via the Kaiser factor (Kaiser 1987), $\delta_h(k) = (b_h + f \mu^2_h) \delta_m(k)$, where $\mu = \hat{k} \cdot \hat{x}$ and $b_h$ is the linear halo bias. The superscript $R$ denotes a real-space quantity. The growth rate, $f$, is defined as $f(z) = -d \ln D(z)/d ln (1 + z)$, with $D(z)$ being the growth factor. Different gravity models predict different values of $D(z)$ and $f(z)$. For the IA statistics, we adopt the linear alignment (LA) model (Catelan et al. 2001; Hirata & Seljak 2004), which relates the ellipticity field linearly to the tidal gravitational field, described in Fourier space as

$$\gamma+(k) = b_K (k^2 - k_s^2) \delta_m(k)/k^2, \quad \gamma-(k) = b_K (k^2 + k_s^2) \delta_m(k)/k^2,$$

where $b_K$ is the shape bias parameter. Following Okumura & Taruya (2020) we introduce the expression,

$$\Xi_{f}(r) = \frac{1}{2\pi^2} \int_0^\infty k^{2-\eta} dk P_m^{R}(k)f(k,r),$$

where $P_m^{R}(k)$ is the matter power spectrum in real space. We can then write all the IA statistics in the LA model in terms of $\Xi_f$, similarly to the case of the GG correlation (Hamilton 1992; Okumura & Taruya 2020). In the following, we compute $P_m^{R}(k)$ in two ways.

First, we use the CAMB code (Lewis et al. 2000) to compute $P_m^{R}(k)$ in the $\Lambda$CDM model and obtain the correlation functions, $\xi^G_{X,i}$. We then multiply it by the best-fitting value of $A$ obtained in Section 5.1 to have the prediction for $f(R)$ halos, $\xi_{X,i} = A \xi^G_{X,i}$. The bias parameter $b_h$ for the halos in $\Lambda$CDM is determined as $b_h^{GR} = 1.40$ by fitting the ratio of the GG correlation function to the matter correlation function $\xi_{m} = \Xi_0$, $b_h^{GR} = \xi_{hh,0}/\xi_{m}^{GR}$, to the measurement in the $f(R)$ simulation on large scales. Similarly, $b_K$ is determined as $b_K^{GR} = 0.46$ by fitting $b_K^{GR} = (15/8)\xi_{X,i}^{GR}/\xi_{m}$. Second, to take into account the scale dependence induced by the
modification of gravity, we compute $f_R$ directly in the $f(R)$ gravity model using the MGCAMB code (Zhao et al. 2009; Hojjati et al. 2011; Zucca et al. 2019). Similarly to the first case above, we determine the two biases, $b_h$ and $b_K$, by taking the ratios of the real-space correlation functions of halos measured from the $f(R)$ gravity simulation and the matter correlation function from the MGCAMB. They are determined as $b_h = 1.34$ and $b_K = 0.42$, lower than the values for the ΛCDM model, as expected. Different gravity models predict different values of the growth rate, $f(z)$. Furthermore, $f(z)$ can become scale dependent in modified gravity models, which arise from the effective gravitational constant (Narikawa & Yamamoto 2010). Thus, the GG and GI correlation functions induce a further scale dependence due to $f(z)$ in the Kaiser factor.

In the top row of Fig. 2, we show the two LA predictions for halo statistics in $f(R)$ gravity explained above, one with the correlation function in ΛCDM multiplied by the best-fitting parameter $A$ obtained in section 5.1 (dotted curves), and another with the correlation function in $f(R)$ gravity directly computed using the MGCAMB code (dashed curves). Note that they are not fitting results of the LA model predictions: the parameter $A$ is constrained by the measured ratio of $\xi_{X,i}/\xi_{GR,i}$ and the bias parameters are also determined by the simulation measurements. Nevertheless, we can see the LA model qualitatively explains the measured correlation functions of halos in $f(R)$ gravity. A close look at the small scale behavior of the correlation functions shows that the prediction based on the MGCAMB gives better agreement, particularly for the GG and GI correlation functions. It is important to note that the difference between the two model curves comes from the scale dependence of the growth factor $D(z)$ and its growth rate $f(z)$ which was not considered in section 5.1. Properly taking into account the effect will help improve the distinguishability between ΛCDM and $f(R)$ gravity models.

5.3 Correlation of halo shape and its orientation

Is there additional information encoded in the halo shape and orientation to distinguish different gravity models? To answer this, we consider normalized alignment statistics, which were introduced in Okumura & Jing (2009). The normalized GI and II correlation functions are defined as

$$\tilde{\xi}_{h+}(r;q) = \left(\frac{1-q^2}{1+q^2}\right)^{-1} \xi_{h+}(r;q),$$

$$\tilde{\xi}_{e}(r;q) = \left(\frac{1-q^2}{1+q^2}\right)^{-2} \xi_{e}(r;q),$$

where $\left(1-q^2/1+q^2\right)$ is the value averaged over all the halos used for our analysis and $\xi_X(r;q)$ are the same as $\xi_X(r)$ in equation (2) but the dependence on $q$ is explicitly written. These normalized alignment statistics are useful because if there is no correlation between axis ratios and orientations, we simply expect $\tilde{\xi}_X(r;q) = \xi_X(r;0)$. Namely, even though the axis-ratio distributions were different between two models as shown in figure 1, it would not affect the distinguishability of gravity models if the normalized statistics were used.

In Fig. 5, we show the ratio of the multipoles, $\tilde{\xi}_{X,\ell}(r;q)/\tilde{\xi}_{X,\ell}(r;0)$. In all the statistics the ratios tend to be greater than unity, which implies that there are non-negligible correlations between the halo shape and orientation, consistent with the finding of Okumura & Jing (2009). Interestingly, for most of the statistics, the correlation is stronger in $f(R)$ gravity than in ΛCDM. This indicates that if properly modeled, considering the correlation between halo shapes and orientations potentially helps improve the distinguishability between ΛCDM and $f(R)$ gravity models. Blazek et al. (2011) studied the correlation in ΛCDM based on the LA model. We leave the study of the correlation between halo ellipticity and orientation for the $f(R)$ gravity model as future work.

6 CONCLUSIONS

In this paper, we have presented the first measurements of IA in a gravity model beyond GR using the two types of IA statistics, the GI and II correlation functions of halo shapes from $f(R)$ gravity simulations. By comparing them with the same statistics measured in ΛCDM simulations, we found that the IA statistics in different gravity models show distinguishable features, with a trend similar to the case of conventional galaxy clustering statistics. Quantitatively, IA
statistics enhance detectability of the imprint of \( f(R) \) gravity on large scale structures by \( \sim 40\% \) when combined with the conventional halo clustering. We also found that the correlation between the axis ratio and orientation of halos becomes stronger in \( f(R) \) gravity than that in \( \Lambda CDM \).

Our constraints on different gravity models have been made assuming that the effect of the modified gravity on the clustering and IA statistics can be perfectly modeled. However, in the analysis of actual observations of IA, one needs to model the present statistics from linear to quasi non-linear scales. While there are several theoretical studies of IA beyond linear theory in GR (e.g., Blazek et al. 2019; Vlah et al. 2020), such predictions need to be carefully tested and extended to gravity models beyond GR. Furthermore, in real surveys, one observes shapes of galaxies, not of halos, thus misalignment between the major axes of galaxies and their host halos (Okumura et al. 2009) would degrade the detection significance of IA even in a modified gravity scenario. As a result, the distinguishability between different gravity models would be degraded compared to the results obtained in this paper. On the other hand, in this work we used only the amplitude of the multipole moments of the clustering and IA statistics, not the full shape of the underlying matter power spectrum which contains ample cosmological information but is more severely affected by the nonlinearities. Therefore, constraining power could eventually be either enhanced or suppressed. The more detailed and realistic analysis of clustering and IA statistics beyond a consistency test of GR will be performed in our future work.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding authors.

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