Galaxy infall kinematics as a test of modified gravity

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ABSTRACT

Infrared modifications of General Relativity (GR) can be revealed by comparing the mass of galaxy clusters estimated from weak lensing to that from infall kinematics. We measure the 2D galaxy velocity distribution in the cluster infall region by applying the galaxy infall kinematics (GIK) model developed by Zu & Weinberg to two suites of f(R) and Galileon-modified gravity simulations. Despite having distinct screening mechanisms, namely, the Chameleon and the Vainshtein effects, the f(R) and Galileon clusters exhibit very similar deviations in their GIK profiles from GR, with $\sim 100-200 \text{ km s}^{-1}$ enhancement in the characteristic infall velocity at $r = 5 h^{-1}$ Mpc and $50-100 \text{ km s}^{-1}$ broadening in the radial and tangential velocity dispersions across the entire infall region, for clusters with mass $\sim 10^{14} h^{-1} \text{ M}_{\odot}$ at z = 0.25. These deviations are detectable via the GIK reconstruction of the redshift-space cluster–galaxy cross-correlation function, $\xi_{cg}^s(r_p, r_\pi)$, which shows $\sim 1-2 h^{-1}$ Mpc increase in the characteristic line-of-sight distance $r_{\pi,c}$ at $r_p < 6 h^{-1}$ Mpc from GR predictions. With overlapping deep imaging and large redshift surveys in the future, we expect that the GIK modelling of ξ_{cg}^s , in combination with the stacked weak lensing measurements, will provide powerful diagnostics of modified gravity theories and the origin of cosmic acceleration.

Key words: galaxies: kinematics and dynamics - large-scale structure of Universe.

1 INTRODUCTION

The late-time acceleration of the Universe can be explained by modifying General Relativity (GR) on cosmological scales, avoiding the need of invoking a cosmological constant Λ or an exotic repulsive fluid (a.k.a., dark energy). Many popular modified gravity (MG) theories rely on an extra scalar field ψ to mediate a fifth force,¹ making the distributions and motions of galaxies different from those predicted by GR (see Jain & Khoury 2010, and references therein). In particular, the coherent infall of galaxies on to massive clusters will exhibit systematic deviations due to the enhanced gravitational forces. Zu & Weinberg (2013, hereafter ZW13) demonstrated that in Λ CDM+GR simulations the velocity distribution of galaxies in the virial and infall regions of clusters (hereafter abbreviated GIK for galaxy infall kinematics) is well described by a two-component velocity distribution model, which can be reconstructed from measurements of the redshift-space cluster-galaxy cross-correlation function, ξ_{cg}^s . In this paper, we apply GIK modelling to two suites of different MG simulations and investigate the possible signals of MG imprinted on the redshift-space distribution of galaxies around clusters, using dark matter particles and haloes as proxies for galaxies. For more general discussions of clusters as tests of cosmic acceleration theories, we refer readers to Weinberg et al. (2013), and for a succinct discussion of distinguishing MG from dark energy to Hu (2009).

While deviations from GR may be welcomed on cosmological scales, a 'screening' mechanism must be invoked in MG theories to recover GR in high-density regions like the Solar system, where GR has passed numerous stringent tests (e.g. Baeßler et al. 1999; Bertotti, Iess & Tortora 2003). Current viable screening mechanisms generally fall into two classes.

(i) The Chameleon-like mechanism, in which the selfinteractions of the scalar field are regulated by a potential $V(\psi)$ (Buchdahl 1970; Khoury & Weltman 2004). Objects are screened when their gravitational potential $|\phi_{\text{grav}}|$ is larger than $\bar{\psi}/\alpha$, where $\bar{\psi}$ is the cosmic mean of ψ and $\alpha \sim \mathcal{O}(1)$ is the coupling between matter and ψ . In other words, the effective scalar charge Q that responds to ψ is reduced by the ambient gravitational potential. This type of screening operates in f(R) (Capozziello, Carloni & Troisi 2003; Nojiri & Odintsov 2003; Carroll et al. 2004), symmetron (Pietroni 2005; Olive & Pospelov 2008; Hinterbichler & Khoury

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¹ Theories such as the braneworld and massive/resonant gravity models can be reduced to scalar–tensor theories in the 'decoupling limit' (Luty, Porrati & Rattazzi 2003; de Rham et al. 2011a; Hinterbichler 2012).

2010), and dilaton (Brax et al. 2011) theories. In this paper, we will focus on the Chameleon mechanism within f(R), where the Ricci scalar, R, in the Einstein–Hilbert action is replaced by R + f(R) where f(R) is an arbitrary function of R.²

(ii) The Vainshtein mechanism, in which the self-interactions of the scalar field are determined by the derivatives of ψ , which suppress the scalar field and fifth force in high-density regions (Vainshtein 1972; Babichev & Deffayet 2013). Scalar fields that exhibit Vainshtein screening are generally called 'Galileons' because of an internal Galilean symmetry (Nicolis, Rattazzi & Trincherini 2009). For an isolated spherical source, the force transition happens at a characteristic radius $r_* = (r_s r_c^2)^{1/3}$ (called the Vainshtein radius), where r_s is the Schwarzschild radius of the source and r_c in models of interest is of the order of the Hubble radius cH_0^{-1} . Within r_* , the scalar field is suppressed ($\psi \propto \sqrt{r}$), forming a 'sphere' of screened region around the source. This mechanism is at play in the Dvali-Gabadadze-Porrati (DGP; Dvali, Gabadadze & Porrati 2000) and massive gravity (de Rham, Gabadadze & Tolley 2011b) theories. For our purpose, we simplify this class of model as a theory with a Λ cold dark matter (Λ CDM) background cosmology and an extra Galileon-type scalar field that manifests Vainshtein screening (Wyman, Jennings & Lima 2013).

In both the f(R) and Galileon models, the maximum force enhancement is 4/3 times the normal gravity, but the 'fifth force' that produces this enhancement has different ranges in the two models. Since the Chameleon scalar field becomes Yukawa-screened, the fifth force does not have infinite range, i.e. it cannot reach to cosmological scales. Galileons, however, are never massive, so their force has an infinite range, thus having a much larger impact on linear perturbation theory than Chameleons do. In the local Universe, however, the Chameleon screening predicts a richer set of observational signatures that are detectable with astrophysical tests, because it is possible to have order unity violation of the macroscopic weak equivalence principle, i.e. extended objects do not fall at the same rate as in GR (Hui, Nicolis & Stubbs 2009). In environments of low background $|\phi_{grav}|$, objects with deep gravitational potential can self-screen, while those with shallow potential remain unscreened. For example, Jain & VanderPlas (2011) estimated that there could be up to $\sim 1 \, \text{kpc}$ separation of the stellar disc (composed of selfscreened objects) from the dark matter and gas (both unscreened) inside unscreened dwarf galaxies, using orbital simulations under f(R). In contrast, there is no analogous order one violation in the Vainshtein case, but the Vainshtein 'spheres'³ of individual objects interfere with each other. For example, in a two-body system where the separation is $\sim r_*$, the interference reduces the infall acceleration, and this reduction becomes most significant for two objects with equal masses (Belikov & Hu 2013).

The infall zone around clusters lies at the transition between the linear scale, where gravity is universally enhanced, and the local Universe where GR is frequently recovered, providing a unique avenue for distinguishing MG from GR. However, in both screening mechanisms the scalar ψ is coupled to density fluctuations via a non-linear field equation, which can only be solved jointly with the matter field using numerical simulations. Lam et al. (2013)

proposed a halo model-based approach to model the line-of-sight (LOS) velocity dispersions of galaxies in the infall region under both modified and normal gravities. In this study, we hope to provide a complete picture of the coherent motions and distributions of galaxies around clusters in the two MG theories and their systematic deviations from GR, fully taking into account the non-linearities that are intrinsic to the Chameleon and Vainshtein mechanisms.

The GIK model of ZW13 describes the average galaxy infall in cluster-centric coordinates in terms of a 2D velocity distribution at each radius, comprising a virialized component with an isotropic Gaussian velocity distribution and an infall component described by a skewed 2D *t*-distribution with a characteristic infall velocity $v_{r,c}$ and separate radial and tangential dispersions. The virialized component is confined within a 'shock radius' that is close to the virial radius of the cluster, so in the infall region (several to $20 h^{-1} \text{ Mpc})^4$ the GIK model reduces to a single infall component. ZW13 demonstrated that GIK profiles can be robustly recovered from the measurement of ξ_{cg}^{s} within the Millennium simulation (Springel 2005), and they applied the method to rich galaxy groups in the Sloan Digital Sky Survey (SDSS; York et al. 2000). In particular, the inferred $v_{\rm r,c}$ profile provides a promising way of estimating the average dynamical mass of clusters and is likely insensitive to baryonic physics and galaxy bias (Zu et al. in preparation). Although the ZW13 method is calibrated against GR simulations, we will show that the GIK model is also an excellent description of the infall behaviour in MG simulations. Studies have shown that the peculiar velocities are more distinctively affected by modifications to gravity than the matter density field alone (Wyman & Khoury 2010; Jennings et al. 2012; Li et al. 2013b; Wyman et al. 2013), and we expect the GIK to be a particularly acute test of MG theories and their screening mechanisms.

A virtue of using galaxy dynamics in the outskirts of clusters is that independent information on the average cluster mass profiles can be robustly extracted from stacked weak lensing (WL) experiments (Mandelbaum et al. 2006; Sheldon et al. 2009; Mandelbaum et al. 2010). Since photons do *not* respond to the extra scalar field,⁵ lensing mass estimates will be different from dynamical mass estimates if gravity is modified from GR on relevant scales (Zhang et al. 2007; Reyes et al. 2010; Zhao, Li & Koyama 2011b). However, implementing this test requires measuring mass profiles on scales where screening is inefficient, i.e. the cluster infall region rather than within the virial radius. For any given cluster sample detected by imaging, X-ray, or Sunyaev-Zel'dovich (SZ) experiments, one can either directly compare the average lensing mass and the GIKestimated dynamical mass or search for inconsistency between the measured ξ_{cg}^s and the GIK-predicted ξ_{cg}^s using lensing mass estimates and assuming $\Lambda CDM+GR$. Alternatively, a simplified test can be performed when WL measurements are unavailable. Since any volume-limited cluster sample is thresholded by some mass observable (i.e. galaxy richness, X-ray luminosity, or SZ decrement) that correlates with the true mass (with some scatter), we can estimate the corresponding threshold in true mass using the abundance matching (AM) technique. However, the uncertainties of AM may be large when the scatter in the mass observable-true mass relation is large or/and the completeness of the cluster sample is low. For the sake of simplicity, in this paper we concentrate on the AM-based

² In practice, the functional form of f(R) is tightly constrained by observations (Amendola et al. 2007; Amendola & Tsujikawa 2008).

³ Strictly speaking, the Vainshtein mechanism works best for spherically symmetric sources, and not at all for planar sources; in reality, the screened region always has a complicated geometry that emerges from the geometry of the source.

⁴ Here $h \equiv H_0 / 100 \,\mathrm{km \, s^{-1} \, Mpc^{-1}}$.

⁵ Though see Wyman (2011) for an interesting effect on lensing induced by MG.

We present the results of GIK modelling of the Chameleon and Galileon simulations separately in the paper, as the two simulation sets were run with different initial conditions, cosmic expansion histories, and box sizes and resolution. We first introduce the Chameleon simulations in Section 2, including the specific f(R) model, and halo statistics and kinematics. Section 3 presents the results of GIK modelling and the measurements of ξ_{cg}^s for the Chameleon clusters and compares that to GR. In Section 4, we presents a similar set of results for the Galileon clusters. We summarize and discuss the future prospects of our method in Section 5.

2 CHAMELEON SIMULATIONS

For the Chameleon modified gravity, we use a suite of large-volume f(R) simulations (1 h^{-3} Gpc³ box and 1024³ particles) evolved with the N-body code ECOSMOG (Li, Zhao & Koyama 2012b). The same set of simulations has been used to study the non-linear matter and velocity power spectra (Li et al. 2013b), redshift-space distortions (Jennings et al. 2012), and halo and void properties (Li et al. 2012a) in f(R) gravity. The large volume of the simulations allows us to derive robust statistics from a large number of massive clusters $(M > 10^{14} h^{-1} M_{\odot})$. We do not make distinctions between the main haloes and sub-haloes, but include all the bound groups of particles identified by the spherical density halo finder AHF (Amiga's Halo Finder; Knollmann & Knebe 2009). The halo mass is defined by $M \equiv M_{\rm vir} = \Delta_{\rm vir} \rho_{\rm m} V_{\rm sphere}(r_{\rm vir})$, where $\Delta_{\rm vir}$ is the overdensity for virialized haloes ($\Delta_{vir} \simeq 276$ at z = 0.25 for typical ACDM cosmology; Bryan & Norman 1998) and ρ_m is the mean density of the universe. We will briefly describe the f(R) models here and refer the readers to Li et al. (2012b) for more details on the simulations.

The simulations adopt a specific f(R) gravity model introduced by Hu & Sawicki (2007), with the functional form of f(R) as

$$f(R) = -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1},$$
(1)

where the mass scale $m^2 \equiv H_0^2 \Omega_m$, c_1 and c_2 are dimensionless parameters, and n controls the sharpness of the transition of f(R) from 0 in high-curvature limit $(R \rightarrow 0)$ to $-m^2 c_1/c_2$ in low-curvature limit $(R \rightarrow \infty)$. The corresponding scalar field in f(R) theory is $\frac{df(R)}{dR}$, commonly denoted as f_R (i.e. the scalaron). Matching to the expansion history of flat ACDM universes (e.g. $\Omega_{\rm m} = 0.24$ and $\Omega_{\Lambda} = 0.76$) requires an $R_0/m^2 \sim 41$ and a field value $f_{R0} \simeq -nc_1/c_2^2/(41)^{n+1} < 0$, where the subscript $_0$ represents the present day values. Therefore, the Hu & Sawicki model is effectively described by two parameters: n and f_{R0} . Models with $|f_{R0}| \lesssim 0.1$ are capable of evading Solar system tests. For cosmological tests of Chameleon theories, models with $|f_{R0}| > 10^{-4}$ are ruled out by cluster abundance constraints from Schmidt, Vikhlinin & Hu (2009b), and models with $|f_{R0}|$ below 10^{-6} are nearly indistinguishable from ACDM universes. We shall study two cosmologically interesting f(R) models with n = 1 and $f_{R0} = -10^{-5}$, -10^{-4} , which will hereafter be referred to as F5 and F4, respectively. Jain, Vikram & Sakstein (2013) reported constraints of $|f_{R0}| < 10^{-7}$ from other astrophysical tests, so these models may no longer be observationally viable, but they none the less provide useful illustrations of MG effects and a natural comparison for the Vainshtein screening model discussed later. The expansion history of the two f(R) simulations is matched to one flat ACDM simulation that evolves from the same initial conditions under normal gravity with $\Omega_{\rm m} = 0.24$, $\Omega_{\Lambda} = 0.76$, h = 0.73, and $\sigma_8 = 0.77$ (referred to as the 'GR' simulation). The

evolution of structure is the same in the three universes up to epochs around z = 49, which is the starting time of the simulations, since the fifth force in f(R) gravity is vastly suppressed until then. By studying the time evolution of the matter and velocity divergence power spectra in f(R), Li et al. (2013b) showed that different f(R)models are in different stages of the same evolutionary path at any given time, and that varying the model parameter f_{R0} mainly varies the epoch marking the onset of the fifth force. The exact epoch of onset in each model depends on the scale of interest, i.e. at higher redshift for smaller scales (see fig. 8 in Li et al. 2013b). We choose to focus on the z = 0.25 output of the simulations, mimicking the portion of the Universe most observed by existing and near-term future redshift surveys that contain large samples of clusters.

Fig. 1 compares the halo mass functions from the GR, F5, and F4 simulations. The bottom panel shows the fractional enhancement of the halo mass function in the f(R) simulations relative to the GR one. The shaded region $(M < M_{\text{lim}} \equiv 6.4 \times 10^{12} \, h^{-1} \, \text{M}_{\odot})$ indicates the mass range where the halo catalogues are incomplete and the bumps in the shaded area of the bottom panel are likely due to numerical effects. Although sub-haloes were included in the halo catalogues, at $M > M_{\text{lim}}$ the halo mass functions are mostly contributed by main haloes. The two f(R) models predict very similar halo abundances below $6 \times 10^{13} h^{-1} M_{\odot}$, enhanced by 10–30 per cent over the GR abundances. For haloes in this mass range, the fifth force was activated early enough that the structure formation has somehow converged in the two f(R) models. However, on the high-mass end, the halo mass function in the F4 model shows even stronger enhancement over GR, while in the F5 model the number of haloes becomes closer to the ACDM prediction with increasing mass. The divergence of the halo mass functions predicted by the two f(R) models beyond $\sim 10^{14} h^{-1} M_{\odot}$ indicates that the fifth force only started affecting the formation of massive clusters recently in the F5 model, producing smaller enhancement in the halo abundance compared to F4. For some very massive clusters in the F5 model (e.g.



Figure 1. Top panel: halo mass functions in GR (solid), F5 (dotted), and F4 (dashed) simulations. Bottom panel: Fractional differences in halo mass function between the f(R) simulations and the GR simulation. The shaded region in each panel indicates the mass scale where the halo catalogues are incomplete.

see fig. 3 in Li et al. 2012a), the gravitational potential has begun to dominate the background scalaron, activating the Chameleon mechanism to recover GR in the infall region, while in the F4 model the Chameleon screening likely never activates anywhere in the universe. Fig. 1 is in good agreement with the study of Schmidt et al. (2009a), where a series of smaller but higher resolution f(R)simulations are employed. Lombriser et al. (2013) modelled the halo mass functions measured from the same sets of f(R) simulations using environment- and mass-dependent spherical collapse model in combination with excursion set theory.

With neither well-resolved sub-haloes nor simulated galaxies in the simulations, the common prescription for constructing mock galaxy catalogues is through Halo Occupation Distributions (HODs; Jing, Mo & Boerner 1998; Peacock & Smith 2000; Seljak 2000; Scoccimarro et al. 2001; Berlind & Weinberg 2002; Zheng et al. 2005). However, the minimum required mass threshold for a complete halo sample in the Chameleon simulations, M_{lim} , is overly high for any meaningful HOD – galaxies similar to the Milky Way and M31 would be absent. Therefore, we simply use particles and haloes as our proxies for galaxies in the paper, and the behaviour of HOD galaxies should be intermediate between that of the 'particle' galaxies and 'halo' galaxies. Since we are focused on the relative behaviour of MG and GR simulations, the impact of choices for galaxy proxy on our conclusions should be small. We will usually refer simply to 'galaxies', when it is clear from context whether we are using particles or haloes as our proxies.

Before going into the statistical properties of galaxy infall, we hope to gain some intuitive understanding of the differences in infall between MG and GR by looking at Fig. 2. Taking advantage of the same initial condition shared by the f(R) and GR



Figure 2. Positions and velocities (in cluster-centric frame) of haloes around a massive cluster in the GR and F4 simulations. The dimension of the slice is $60 h^{-1}$ Mpc × $60 h^{-1}$ Mpc with a thickness of $30 h^{-1}$ Mpc, centred on a cluster of $M_h \sim 3.2 \times 10^{14} h^{-1}$ M_☉. The length of each arrow is v_{pec}/H_0 , in units of h^{-1} Mpc. The background grey-scale shows the density field of the GR simulation. Grey and red arrows show the velocities of haloes in the GR and F4 simulations, respectively, with larger circles and thicker arrows for haloes of $M > 10^{14} h^{-1}$ M_☉.

simulations, we locate at the frame centre two primary clusters $(M \sim 3.2 \times 10^{14} h^{-1} M_{\odot})$ at z = 0.25 that formed from the same seed in the initial density fluctuation field in the F4 (red, for which the fifth force is stronger) and GR (grey) simulations, respectively, and plot all haloes with mass above $6 \times 10^{12} h^{-1} \,\mathrm{M_{\odot}}$ as circles, with their relative velocities to the primary cluster indicated by the arrows. The dark matter density field in the GR simulation is illustrated by the grey-scale background, highlighting the three filamentary structures that funnel the infalling haloes. The radius of each circle is proportional to the halo mass, with the thick ones representing haloes more massive than $10^{14} h^{-1} M_{\odot}$. The length of each arrow is $v_{\rm nec}/H_0$, corresponding to the redshift-space displacement (in units of h^{-1} Mpc) that would be seen by a distant observer aligned with the velocity vector. Fig. 2 shows that the GIK around individual clusters is highly anisotropic, and while the difference in the spatial distribution between GR and F4 haloes is irregular and fairly mild, it is somewhat enhanced in redshift space. To avoid clutter, we do not show haloes from the F5 model, which should display smaller differences from GR because of its smaller impact from the fifth force. In the next section, we will show that by stacking individual frames like Fig. 2 for clusters of similar mass, the anisotropy goes away and the average infall kinematics can be well described by the GIK model proposed in ZW13, for both the f(R)and ACDM models. More importantly, the enhanced difference in the redshift space between MG and GR models can be captured by systematic differences in the parameters of the GIK model, namely, the characteristic infall velocity $v_{\rm r, c}$, the radial velocity dispersion $\sigma_{\rm rad}$, and the tangential velocity dispersion $\sigma_{\rm tan}$.

3 GALAXY INFALL KINEMATICS

The halo mass functions in Fig. 1 suggest that the fifth force became unscreened earlier in F4 than in F5, which gives it more time to affect the velocity field in the former. As a result, at z = 0.25clusters in both the F4 and F5 models should exhibit more enhanced galaxy infall compared to GR, but we expect the enhancement to be more substantial in the F4 model. For the small number of screened clusters in the F5 model, the infalling galaxies around Chameleon clusters should feel similar instantaneous accelerations as their counterparts around similar clusters in GR. However, the peculiar velocities of galaxies were enhanced by the fifth force when they were further away from the clusters. By the time they reached to the screened region, the peculiar velocities were already higher, so the infall stays stronger even though the underlying gravity recovers to GR. Our goal here is to quantify this modification to galaxy infall induced by f(R) gravities as function of f_{R0} within the framework of GIK modelling.

To compare the average GIK among the three simulations, we select dark matter haloes with $M_{\rm vir} \in 1-2 \times 10^{14} h^{-1} \,\mathrm{M_{\odot}}$ in the Λ CDM simulation as our fiducial GR cluster sample, and those with the same mass range in the f(R) simulations as the 'equalmass' (EM) cluster samples. As mentioned in the introduction, we also select specific halo samples in the f(R) simulations to have the same rank-order in mass as the fiducial GR clusters, i.e. the 'equalrank' (ER) cluster samples. The ER clusters generally have slightly larger masses than the EM ones, with $1.13-2.14 \times 10^{14} h^{-1} \,\mathrm{M_{\odot}}$ and $1.27-2.52 \times 10^{14} h^{-1} \,\mathrm{M_{\odot}}$ in F5 and F4 models, respectively. The ER sample thus resembles the set of clusters that formed from the same initial density peaks as the fiducial GR ones. In the limit of very rare, highly biased peaks, the large-scale cluster bias b_c , defined by the ratio between the cluster-matter correlation function and the matter autocorrelation $\xi_{\rm cm}/\xi_{\rm mm}$, is $\propto \sigma_8^{-1}$, yielding $\xi_{\rm cm} \propto 0$

3.1 Velocity field model

As mentioned in the introduction, the two-component GIK model is an excellent analytic description of the joint 2D distribution of radial and tangential velocities of galaxies in the cluster-centric frame, $P(v_r, v_t)$. Here, we will present the results of GIK modelling for the cluster samples defined above, and refer the readers to ZW13 for details on the GIK parametrization and fitting procedures.

Fig. 3 shows the best-fitting $P(v_r, v_t)$ for the GR (top), F5-EM (middle), and F4-EM (bottom) cluster samples at five different radial bins, using dark matter particles as proxy for galaxies. Negative v_r indicates falling towards clusters. Following ZW13, we define v_t as the tangential velocity component that is projected in the plane of LOS axis and galaxy position vector in the cluster-centric frame (see the 3D diagram in the fig. 2 of ZW13). Since the *average* galaxy motion around the cluster centre is isotropic, the probability distribution of v_t is symmetric about zero. Hereafter, we refer to v_t simply as the 'tangential velocity'. Note that the Hubble flow is subtracted when defining v_r , but it will be incorporated when modelling ξ_{cg}^s . The GIK of the three cluster samples in Fig. 3 show some generic trends with radius. (1) The distribution has two distinct components on very small scales (leftmost column) but only shows a single infall component on large scales; (2) the infall component is symmetric about the mean v_r near the turn-around radius, where infall velocity is comparable to Hubble flow (middle column); (3) the v_r distribution of the infall component is skewed towards positive velocities beyond the turn-around radius (two right-hand columns), but is negatively skewed below that radius (two left-hand columns).

The impacts of modified gravity on $P(v_r, v_t)$ are subtle but none the less visually apparent in Fig. 3 when comparing the three models at the same radial bin (i.e. within the same column). The solid vertical line in each panel indicates the most probable radial velocity, which shifts to more negative v_r with increasing $|f_{R0}|$ (i.e. from top to bottom) at each radius. Simultaneously, the dispersions of the infall component in the radial and tangential directions also increase as function of f_{R0} – the joint distributions in the F4 model are more extended than in GR. This increased width results in the decreased peak amplitude of the distributions (which are normalized to unity by definition).

To quantify the differences in GIK among the three simulations, we will focus on the impacts of modified gravity on three of the GIK parameters ($v_{r,c}$, σ_{rad} , and σ_{tan}). We ignore the other GIK parameters defined by ZW13 (seven in total), including two parameters describing the virialized component that are irrelevant to this paper, and two others that describe the skewness and the kurtosis of the infall component, which we found to be insensitive to modified gravity. Note that the characteristic radial velocity $v_{r,c}$ is not the mean, median, or mode of the radial velocity distribution, but is a characteristic velocity naturally associated with the definition of the skewed *t*-distribution used for describing the GIK infall component (see ZW13, equation 6).

Fig. 4 presents the best-fitting GIK parameters as functions of radius for the F5 (left) and the F4 (right) models, respectively.



Figure 3. Joint probability distributions of radial and tangential velocities from the best fit to the GR (top), F5 (middle), and F4 (bottom) simulations using our GIK model, in five different radial bins marked at the top of each panel (in units of h^{-1} Mpc), for clusters of $1-2 \times 10^{14} h^{-1}$ M_O in each simulation. In each panel, the vertical dashed line indicates the position of zero radial velocity while the solid line is the most probable radial velocity. The colour scales, indicating probability density in the (v_t , v_r) space, are identical across all panels (colour bars are thus not shown here).



Figure 4. Best-fitting characteristic infall velocity (top), radial velocity dispersion (middle), and tangential velocity dispersion (bottom) as functions of radius. Left- and right-hand columns compare the results of F5 and F4 simulations to that of GR, respectively. The shaded region in each panel indicates the scales below the maximum infall radius, where the GIK measurements are less robust. Haloes in the f(R) simulations are selected as either having equal mass (EM) or equal rank-order (ER) to the haloes of $1-2 \times 10^{14} h^{-1} M_{\odot}$ in the GR simulations. See text for details.

In each panel, we show the parameter profiles for all three types of cluster samples (GR, EM, and ER). The shaded region in each panel indicates the radial bins where GIK is dominated by the virialized component and the fit to the infall component is less robust. For the F5 model, the halo mass function is close to that of ACDM at high masses, so the EM and ER samples have little difference in mass and their GIK profiles look very similar. However, as expected from Fig. 3, the two F5 cluster samples in the f(R) simulation show stronger infall (top left) and larger velocity dispersions (centre and bottom left) compared to the GR sample. For the F4 model, the difference between the EM and ER samples is larger, especially in the $v_{r,c}$ profiles (top right), where the difference between the ER and GR profiles is almost double that between the EM and GR ones. For both samples, the F4 results are more easily distinguished from GR than the F5 results, as expected. Since we anticipate that ER comparisons will be more observationally relevant in most cases, we will focus henceforth on the GIK of ER cluster samples in the MG simulations.

We highlight the differences in GIK profiles between ER and GR clusters for both Chameleon models in Fig. 5. The characteristic infall velocity profiles exhibit significant effects from the Chameleon gravity on scales below $15 h^{-1}$ Mpc, showing ~ 100 and 200 km s^{-1} enhancement at $5 h^{-1}$ Mpc for the F5 and F4 models, respectively. Beyond $15 h^{-1}$ Mpc the $v_{r,c}$ profiles converge to the GR prediction. The dispersion profiles in f(R) models deviate from GR on all distance scales, with the differences almost constant and decreasing

with radius for σ_{rad} and σ_{tan} , respectively. The magnitude of the deviations we see here is very encouraging $- \sim 100 \text{ km s}^{-1}$ difference in both the $v_{r,c}$ and the dispersions is already detectable within 2σ in ZW13, where a preliminary GIK constraint is obtained using two samples of SDSS rich groups (with group number ~ 2000 and ~ 600 , respectively) and the SDSS DR7 main galaxy sample.

Using dark matter particles as proxy for galaxies effectively assumes that galaxies have the same density profile and velocity distribution as dark matter particles within haloes. In reality, we expect central galaxies to have low peculiar velocities relative to the halo centre of mass, and the spatial distribution may be less concentrated than the matter (see, e.g. Budzynski et al. 2012). To bracket the expectations for constraining GIK using realistic galaxy samples, we repeat the above experiment using haloes instead of particles as proxy for galaxies. This mimics the scenario where a Luminous Red Galaxy (LRG; Eisenstein et al. 2001) sample is employed, implying approximately one galaxy per halo as one extreme of the HOD (Zheng et al. 2009). Fig. 6 summarizes the result of this experiment. We denote the curves correspondingly as 'GR_h', 'F5_h', and 'F4_h' in the figure. The GIK profiles are much noisier because of the rarity of haloes, but the differences among the three samples are similar to those seen in Fig. 5, but smaller in magnitude by about a factor of 2. We infer that the difference in GIK seen in Fig. 5 using 'particle' galaxies has approximately equal contributions from two sources, Chameleon modifications to the random motions within haloes (i.e. '1-halo') and the impact of Chameleon gravity on the



Figure 5. Difference in GIK profiles between the f(R) and GR simulations, using clusters of ER.



Figure 6. Comparison of GIK profiles in the GR, F5, and F4 simulations, using haloes as proxy for galaxies instead of dark matter particles as in Figs 4 and 5.

bulk inflow of haloes (i.e. '2-halo'). Quantitative predictions for a particular galaxy sample will require simulations that resolve the host haloes and thus allow a full HOD model of the population, incorporating both one-halo and two-halo effects with appropriate weight.

3.2 Cluster-galaxy correlation function

The redshift-space cluster–galaxy cross-correlation function, ξ_{cg}^s , is a comprehensive characterization of the statistical relation between clusters and galaxies, influenced by both the real-space crosscorrelation ξ_{cg}^r and the peculiar velocities induced by the cluster gravitational potential. Mathematically, $\xi_{cg}^s(r_p, r_\pi)$, a function of projected cluster–galaxy separation r_p and LOS redshift separation r_π , can be derived by convolving the real-space $\xi_{cg}^r(r)$ with the Hubble flow-corrected LOS velocity distribution, which can be straightforwardly predicted from the GIK model (see equation 11 in ZW13). ZW13 demonstrated that the GIK can be extracted from the observed ξ_{cg}^s , by taking advantage of the non-degenerate imprint of each GIK element on the 2D pattern of ξ_{cg}^s . In this section, we will examine the impact of Chameleon gravity on the real and redshiftspace cluster–galaxy correlation functions in the f(R) simulations, using particles as proxy for galaxies.

For measuring ξ_{cg}^r , we count the numbers of particles around clusters in spherical shells of successive radii, ranging from 100 to 30 h^{-1} Mpc with logarithmic intervals, then average overall clusters in each bin and normalize by the particle numbers expected in a randomly located shell of equal volume. We measure ξ_{cg}^s in a sim-

ilar way, counting galaxies in cylindrical rings of successive LOS distance r_{π} for each projected separation $r_{\rm p}$ (assuming a distantobserver approximation so that the LOS is an axis of the box). Uncertainties in both measurements are estimated by Jackknife resampling the octants of each simulation box.

We start by showing the real-space cluster-galaxy correlation function ξ_{cg}^{r} for the GR, F4-ER, and F5-ER cluster samples in the left-hand panels of Fig. 7. In the top-left panel, all three correlation functions exhibit a break at $2-3 h^{-1}$ Mpc, marking the transition from the NFW-like density distribution (Navarro, Frenk & White 1997) within haloes to a biased version of the matter autocorrelation function on large scales (Hayashi & White 2008; Zu et al. 2014). The bottom-left panel shows the ratio of ξ_{cg}^{r} between the ER samples in f(R) simulations and the GR sample. On scales below the break radius, ξ_{cs}^{r} of the ER clusters show enhancement of 10 and 20 per cent in the F5 and F4 models, respectively, because they are intrinsically more massive than their counterparts in the ACDM simulation. On scales larger than $\sim 5 h^{-1}$ Mpc, the ER clusters have nearly the same large-scale clustering as the GR sample. Since we are measuring the cross-correlation with dark matter particles, these ξ_{cg}^{r} profiles also determine the cluster–galaxy WL profile (see, e.g. equation 13 of Zu et al. 2014).

On intermediate scales, there is a bump at $\sim 2 h^{-1}$ Mpc in the ratio between ξ_{cg}^r of the F4-ER and the GR samples, but not in the ratio curve for F5-ER. In the F4 model, the fifth force became unscreened from quite early time, so that the velocity field has been enhanced for a long time by z = 0.25. This means that the peculiar velocities are enhanced by roughly the same factor κ as



Figure 7. Left-hand panel: comparison of real-space correlation functions in the GR, F5, and F4 simulations, using particles as proxy for galaxies. Right-hand panel: characteristic LOS distances derived from the redshift-space correlation functions in Fig. 8.



Figure 8. Redshift-space correlation functions in the GR, F5, and F4 simulations.

the gravitational force, where κ is between unity and 4/3, and the kinetic energy of particles in F4 is thus κ^2 times that in GR; meanwhile, the gravitational potential in F4 is $\sim \kappa$ times as deep as in GR. The net result is that the MG effect on the particle kinetic energy dominates over its effect on the cluster potential, so that as a compromise the particles tend to move towards the outer parts of clusters. The situation is different in the F5 model, where the fifth force became unscreened quite late. By z = 0.25, the fifth force has become unscreened but only for a short period, so that particle velocities have not been significantly affected by it. On the other hand, due to the disappearance of the screening, the potential of the cluster suddenly became deeper. The result is a stronger MG effect on the potential than on the kinetic energy of particles, and particles tend to move towards the inner parts of clusters. These features have been observed in the halo density profiles of f(R) simulations before (e.g. Zhao, Li & Koyama 2011a), and similar ones have been found in coupled quintessence simulations. Using cluster WL measurements, Lombriser et al. (2012) exploited this small-scale enhancement of cluster density profiles in Chameleon gravity and

obtained a constraint of $|f_{R0}| < 3.5 \times 10^{-3}$ at 95 per cent confidence level.

Fig. 8 presents the redshift-space cluster–galaxy correlation functions for the three cluster samples, showing a stronger small-scale Fingers-of-God (FOG; Jackson 1972) effect with increasing $|f_{R0}|$, but with similar LOS squashing effect on large scales (a.k.a. Kaiser effect; Kaiser 1987). However, the most easily visible features of ξ_{cg}^s in Fig. 8 are driven by the radial gradient of cluster density profiles, which are fairly insensitive to the influence of Chameleon modifications to gravity according to the left-hand panel of Fig. 7. Modified gravity also changes the shape of ξ_{cg}^s at fixed r_p via its effects on the GIK, redistributing matter/galaxies along the r_{π} axis. To reveal this LOS distortion of ξ_{cg}^s by f(R), following ZW13, we compute the characteristic LOS distance $r_{\pi,c}(r_p)$ by fitting a powered exponential function to ξ_{cg}^s at each fixed r_p ,

$$\xi_{\rm cg}^{s}(r_{\rm p},r_{\pi})\simeq\xi_{\rm cg}^{s}(r_{\rm p},r_{\pi}=0)\exp\left\{-\left|\frac{r_{\pi}}{r_{\pi,\rm c}}\right|^{\beta}\right\},\tag{2}$$

where $r_{\pi,c}$ is the characteristic length-scale at which ξ_{cg}^s drops to 1/e of its maximum value at $r_{\pi} = 0$. The shape parameter β yields a Gaussian cut-off for $\beta = 2$ and simple exponential for $\beta = 1$, though any value is allowed in the fit. The results of this fitting are shown in the right-hand panel of Fig. 7. The $r_{\pi,c}$ versus r_p curves exhibit the characteristic U-shape discovered in ZW13 – FOG stretching at small r_p gives way to Kaiser compression at intermediate r_p which gives way to Hubble flow expansion at large r_p . Clearly, the ξ_{cg}^s distribution along the LOS is a sensitive probe of f(R) models at $r_p < 6 h^{-1}$ Mpc, becoming more extended with increasing $|f_{R0}|$ (e.g. $r_{\pi,c} = 7$, 8, and $9 h^{-1}$ Mpc at $r_p = 2 h^{-1}$ Mpc for GR, F5, and F4 models, respectively).

The detailed shape of $\xi_{cs}^{s}(r_{p}, r_{\pi})$ reflects a complex interplay among the four elements of the galaxy kinematics around clusters, including the three GIK profiles of the infall component ($v_{r,c}, \sigma_{rad}$, and σ_{tan}) and the virial component (see fig. 1 0 of ZW13 for an illustrative experiment). For the same reason, the increase of $r_{\pi,c}$ with f_{R0} has different origins at different projected distances. Below $r_{\rm p} \sim 1.5 \, h^{-1} \, {\rm Mpc}$, the response of $r_{\pi, c}$ to f_{R0} is uniform with $r_{\rm p}$, caused by the uniform increase of dispersion in virial motions. For $r_{\rm p} \sim 1.5-3 \, h^{-1}$ Mpc, the f_{R0} dependence of $r_{\pi, c}$ has two contributing sources, one being the increase of tangential velocity dispersions, the other the increase of maximum infall velocities, which transport high-speed matter/galaxies from one side of the cluster in real space to the opposite side in redshift space (i.e. the portion of the FOG effect caused by infall). For $r_{\rm p} \sim 3-6 h^{-1}$ Mpc, f_{R0} influences the $r_{\pi, c}$ profile mainly via the increase of tangential velocity dispersions. The radial velocity dispersions only enter into play at large $r_{\rm p}$, where the diagnostic power of $\xi_{c\sigma}^{s}$ is diminishing.

4 RESULTS FOR A GALILEON MODEL

Although Chameleon theories like the Hu & Sawicki f(R) model include the phenomenology of Λ CDM without a *true* cosmological constant, Wang, Hui & Khoury (2012) proved that the theories that invoke a Chameleon-like scalar to explain cosmic acceleration essentially rely on a form of dark energy rather than a genuine MG effect,⁶ even if they are initially described in terms of an altered gravitational action. Conversely, the Galileon class of theories is capable of accelerating the cosmic expansion even in the absence of any form of dark energy (e.g. de Rham et al. 2011a; Appleby & Linder 2012; Barreira et al. 2012; Gratia, Hu & Wyman 2012), i.e. they have so-called self-accelerating solutions. Here, we study the GIK for a simplified version of such kind of Galileon theories, where an extra Galileon-type scalar field that manifests the Vainshtein mechanism permeates a universe with the Λ CDM background cosmology.

We employ a suite of Galileon simulations with 512^3 particles on a 512^3 grid of $L_{box} = 400h^{-1}$ Mpc, evolved using the Particle Mesh code of Khoury & Wyman (2009), which was updated by Wyman et al. (2013; for other Galileon/DGP simulations, see, e.g. Chan & Scoccimarro 2009; Schmidt 2009; Barreira et al. 2013; Li, Zhao & Koyama 2013a). The simulations were first used by Wyman et al. (2013) for studying the statistics of matter clustering in real and redshift spaces. We will briefly introduce the Galileon implementation and parametrization here and refer the readers to Wyman et al. (2013) for details. As described in the Introduction, the Vainshtein mechanism has only one parameter, r_c , which is interpreted as the Compton wavelength associated with the graviton mass in massive gravity theories, so that the Vainshtein radius of a point mass with mass *M* is

$$r_*^{\rm p} \equiv (r_{\rm s} r_{\rm c}^2)^{1/3} \simeq 2.1 \left(\frac{M}{10^{14} \,{\rm M}_{\odot}}\right)^{1/3} \left(\frac{r_{\rm c}}{10^3 \,{\rm Mpc}}\right)^{2/3} \,{\rm Mpc}.$$
 (3)

For extended objects of the same mass M, the Vainshtein radii are generally several times larger than $r_*^p(M) - e.g.$ an NFW halo with $M = 10^{14} M_{\odot}$ has $r_* \sim 10$ Mpc, and galaxies generally have $r_* \sim 1$ Mpc. Therefore, whereas the cluster interior below the virial radius belongs to the strongly Vainshtein-screened regime, the cluster infall region is weakly screened, displaying complex interference among Galileon fields sourced by the primary cluster and the infalling galaxies and galaxy groups.

We make use of three simulations with the same expansion history and initial condition, one of them a flat ACDM universe evolved under normal gravity with $\Omega_{\rm m} = 0.24$, $\Omega_{\Lambda} = 0.76$, h = 0.73, and $\sigma_8 = 0.80$, and the other two immersed in Galileon scalar fields with $r_c = 1665$ and 1089 Mpc. In the figures, we refer to them simply as 'GR' (i.e. $r_c = +\infty$), $r_c = 1665$, and $r_c = 1089$, respectively, and a smaller r_c implies an earlier onset of the fifth force and an effectively stronger fifth force in the late Universe (see, e.g. fig. 5 of Wyman et al. 2013, for the change of linear growth rate as function of r_c). Note that the 'GR' simulation is different from what we used for comparing to the f(R) simulations, albeit with similar cosmology. Dark matter haloes are identified via a spherical overdensity finder with the halo mass defined by $M \equiv$ $M_{200} = \Delta_{200} \rho_{\rm m} V_{\rm sphere}(r_{200})$, different from the $M_{\rm vir}$ used for the Chameleon simulations. Since $\Delta_{200} < \Delta_{vir}$, a halo would have a higher M_{200} than $M_{\rm vir}$ (e.g. $M_{200} \sim 1.1 \times M_{\rm vir}$ for a $10^{14} \, h^{-1} \, {
m M_{\odot}}$ cluster at z = 0.25 in ACDM). The halo mass functions, halo bias functions, and matter power spectra of the three simulations can be found in Wyman et al. (2013). Targeting the same redshift range as in Section 2, we use the z = 0.20 output of the simulations (not z = 0.25 due to the different sets of recorded epochs in the two suites of simulations).

Since the volume of the Galileon simulations is only 6.4 per cent of that of the Chameleon simulations, we have to select samples with a wider mass bin size for robust GIK measurements. For the fiducial cluster sample in the GR simulation, we include clusters with $M_{200} \in$ $1-3 \times 10^{14} \, h^{-1} \, \mathrm{M_{\odot}}$, and similar to Section 2 we also select two ER cluster samples from respective Galileon simulations, with $M_{200} \in$ $1.15-3.52 \times 10^{14} h^{-1} \,\mathrm{M_{\odot}}$ and $M_{200} \in 1.23-3.87 \times 10^{14} h^{-1} \,\mathrm{M_{\odot}}$ in the $r_c = 1665$ and $r_c = 1089$ models, respectively. Unlike Section 2, we do not show the results from the EM cluster samples for the GR versus Galileon comparisons, as the relative difference between the EM and ER samples is similar to what we see in the Chameleon simulations. Because of the smaller volume, we can only afford to use dark matter particles as proxy for galaxies. Note that the Galileon cluster sample here comprises haloes that are intrinsically smaller than the one used in Section 2, due to different overdensity thresholds used in mass definitions.

Fig. 9 compares the GIK profiles of the two ER samples in the Galileon simulations to that of the fiducial GR cluster sample. As intrinsically less massive systems, the fiducial GR clusters show weaker infall velocities and velocity dispersions than the GR clusters used in the Chameleon comparison at all distances (e.g. comparing the black curves in the top panels of Fig. 9 to the black curves in Fig. 4). However, the relative difference between the MG and GR samples overall looks very similar to what we see in the Chameleon comparison (e.g. comparing the bottom panels of Fig. 9

⁶ For a 'genuine' MG effect, the cosmic acceleration should stem entirely from the conformal transformation from the Einstein frame to the Jordan frame. See Wang et al. (2012) for details.



Figure 9. Similar to Fig. 6, but for the Galileon simulations and using particles as proxy for galaxies, around clusters of ER.

to Fig. 5). As expected, $v_{\rm r,c}$, $\sigma_{\rm rad}$, and $\sigma_{\rm tan}$ all become stronger with decreasing $r_{\rm c}$ (i.e. stronger fifth force). Specifically, $v_{\rm r,c}$ shows ~50 and 100 km s⁻¹ enhancement at $r = 5 h^{-1}$ Mpc for the $r_{\rm c} = 1665$ and $r_{\rm c} = 1089$ models, respectively, which are comparable to the fractional enhancements in the F5 and F4 Chameleon models, respectively.

The only major difference between Fig. 9 and Fig. 5 appears in the bottom middle panel. The deviation of σ_{rad} profiles from the GR prediction decreases as function of distance, from 125/90 km s⁻¹ at $r = 30 h^{-1}$ Mpc to 60/50 km s⁻¹ at $r = 5 h^{-1}$ Mpc, whereas in the Chameleon comparison the deviation of σ_{rad} stays more or less constant with distance. This difference in σ_{rad} may be reflecting the different ranges of fifth force in the two models: the Galileon has infinite range, so the force is enhanced further way from clusters, whereas the Chameleon force is Yukawa-suppressed on large scales. However, the pattern of ξ_{cg}^s is insensitive to σ_{rad} at $r_p < 6 h^{-1}$ Mpc where the ξ_{cg}^s measurement is the most robust, making it an unpromising tool for distinguishing the two mechanisms. The GIK profiles of the EM cluster samples in the Galileon simulations closely follow those of their corresponding ER counterparts, albeit with slightly weaker amplitudes.

Fig. 10 compares the real-space cluster–galaxy cross-correlation function ξ_{cg}^r (left) and the characteristic LOS distance $r_{\pi,c}$ (right) measured for the three cluster samples. The shaded region indicates the scales below the force softening length of the simulations, where the correlation function and velocity dispersions are artificially suppressed. On small scales, the ratios between ξ_{cg}^r of the Galileon ER samples and fiducial GR sample (bottom left) display similar features to those in Fig. 7, including an enhancement interior to the virial radius because the ER clusters are more massive, and a bump around $2 h^{-1}$ Mpc, though this is only $\sim 1.2 h^{-1}$ Mpc away from the force resolution limit. To check whether the bump is a numerical artefact, we repeated the same measurements of ξ_{cg}^r using a suite of higher resolution (but smaller volume) Galileon simulations and



Figure 10. Similar to Fig. 7, but for the Galileon simulations. The shaded region indicates the distance scale below the force resolution in the simulations.

verified that the bump is physical. Similar to the f(R) case in the F4 model, the fast transition from Galileon force outside to normal gravity inside causes a sudden change of the depth of the potential well, but not the galaxy velocity (or kinetic energy), which has been experiencing enhancement well before infall. As the galaxies have excessive kinetic energy, they tend to move to the outer parts of haloes, making the density profile lower in the central region of clusters and higher near the edges.

On large scales, the ER samples in the Galileon simulations exhibit stronger clustering than the GR clusters. This enhancement in ξ_{cs}^{r} can be understood by starting from the findings of Wyman et al. (2013), which suggest that the halo mass function, the halo bias function, and the matter power spectrum of the Galileon simulations are like those of Λ CDM universes with higher σ_8 .⁷ For example, at z = 0 the $r_c = 1665$ and 1089 simulations resemble the Λ CDM universes with $\sigma_8 = 0.88$ and 0.92, respectively. Since the large-scale ξ_{cs}^{r} of ER clusters is almost linearly proportional to the effective σ_8 , we observe ~10 and 15 per cent enhancement in ξ_{co}^r at $\sim 10 h^{-1}$ Mpc for clusters in the $r_c = 1665$ and $r_c = 1089$ models, respectively. However, the possible enhancement in the clustering bias of clusters due to modified gravity can be determined by either the cluster WL measurement or the measurement of the projected cluster-galaxy cross-correlations, so there is no degeneracy between the reconstruction of GIK profiles and the effective changes in σ_8 .

For the redshift-space cluster–galaxy cross-correlation function, because the impact of the Galileon field on GIK is similar to that in the Chameleon models, the $r_{\pi,c}$ curves in Galileon simulations also exhibit similar deviations from the GR curves, as shown in the right-hand panel of Fig. 10. The lack of upturn of $r_{\pi,c}$ at small r_p is a consequence of force resolution suppressing velocity dispersions; we expect that simulations with higher force resolution would show the characteristic U-shape for all three models. The overall lower amplitude of $r_{\pi,c}$ compared to Fig. 7 is again the result of selecting intrinsically less massive haloes. When we select the Galileon clusters to have equal mass to the GR clusters, the enhancement in large-scale clustering (left-hand panel) disappears because the large-scale bias is steep function of mass, but the differences in GIK and $r_{\pi,c}$ remain.

5 CONCLUSIONS

We have investigated the impact of modified gravity on the galaxy infall motion around massive clusters by applying the GIK model developed in ZW13 to two suites of f(R) and Galileon *N*-body simulations. Both MG theories seek to explain cosmic acceleration by modifying GR on cosmological scales, but they recover GR in dense regions via two distinct 'screening' effects: the potential-driven Chameleon mechanism in f(R) and the density-driven Vainshtein mechanism in Galileon. However, within the range of parameter space probed by our simulations (i.e. $10^{-5} \le |f_{R0}| \le 10^{-4}$ for f(R) and 1089 Mpc $\le r_c \le 1665$ Mpc for Galileon), despite having quite different cosmic growth histories, the two theories exhibit strikingly similar GIK deviations from GR, with $\sim 100-200$ km s⁻¹ enhancement in the characteristic infall velocity at $r = 5 h^{-1}$ Mpc, and $\sim 50-100$ km s⁻¹ broadening in the radial and tangential velocity dispersions across the infall region, for clusters with mass $\sim 10^{14} h^{-1}$ M_{\odot}.

at z = 0.25. These deviations are detectable through GIK modelling of the redshift-space cluster–galaxy correlation function ξ_{cg}^s , especially when combined with cluster WL measurements. We highlight the imprint of MG on ξ_{cg}^s using the characteristic U-shaped curve of $r_{\pi,c}$, which increases by $\sim 1-2 h^{-1}$ Mpc at $r_p < 6 h^{-1}$ Mpc from the GR prediction. We find little difference between the GIK profiles predicted by the two screening mechanisms, except for slightly different trends of the radial velocity dispersion with distance.

It is unclear whether the similar signature of these two distinct modified gravity theories on GIK is a coincidence, or a generic result for any typical scalar-tensor theory that recovers the observed ACDM-like expansion history and reduces to normal gravity in the Solar system and binary pulsars. In either case, our findings imply that, in combination with WL, GIK offer a powerful non-parametric cosmological test of modified gravity. Ongoing galaxy redshift surveys will provide large samples of clusters with good statistics for measuring ξ_{cg}^{s} and inferring GIK out to large scales. The main systematic uncertainty arises from the imperfect understanding of the impact of galaxy formation physics on GIK. Within the context of GIK modelling and calibration, the infall behaviour of realistic galaxies could differ from that of tracers in cosmological simulations (e.g. haloes/sub-haloes in N-body simulations, post-processed galaxies in semi-analytical galaxy formation models, and simulated galaxies in hydrodynamic simulations, etc.; see Wu et al. 2013). However, we expect minimal impact on the characteristic infall velocity, which is our main tool of estimating the dynamical mass profiles of clusters, as any physical process that modifies galaxy kinematics within haloes likely only adds scatter to the velocity dispersions rather than changing the mean.

Within the context of testing gravity, the effects of galaxy formation physics could be partly degenerate with those of modified gravity. The observed properties of galaxies, including luminosity, morphology, colour, star formation, and clustering, are known to correlate with the environment (see, e.g. Goto et al. 2003; Hogg et al. 2003; Balogh et al. 2004; Kauffmann et al. 2004; Park et al. 2007; Zu et al. 2008; Zehavi et al. 2011; Guo et al. 2013), and MG theories also rely on the environment to mediate the strength of the fifth force. For example, a sample of preferentially blue, starforming galaxies may show enhanced infall velocities compared to a galaxy sample that is unbiased in colour in Λ CDM universes, and the enhancement could be mistaken as signal of modified gravity were the selection bias not properly accounted for. We will investigate the potential systematic uncertainties induced by galaxy formation physics in a future paper, using mock galaxy samples constructed from different HOD and semi-analytical model prescriptions. Redshift surveys that probe a range of galaxy types are especially valuable for those cosmological tests because one can check that different classes of galaxies lead to the same cosmological conclusions even though the galaxy samples themselves have different clustering and kinematics.

Our GIK modelling of ξ_{cg}^s is complementary to other semianalytical approaches based on the halo model (Lam et al. 2012, 2013), both seeking to model the velocity distribution around massive clusters for testing gravity (also see Tinker, Weinberg & Zheng 2006; Tinker 2007, for an alternative method of modelling galaxy redshift-space distortion based on HOD). The semi-analytical velocity model adopted in Lam et al. (2013) has three components: the empirical infall velocity from the spherical collapse model, the halo–halo pairwise velocity distribution, and the intra-halo velocities (assumed Maxwellian with constant scatter). While the model itself is highly informative, the accuracy is slightly lacking

⁷ Though they can be distinguished from Λ CDM by examining the Kaiser effect, where changing σ_8 cannot mimic the large-scale boost in the redshift-space clustering due to MG. See Wyman et al. (2013) for details.

compared to simulation predictions. We instead use the simulations as emulators for GIK, trading more computer time for better accuracy in the prediction of our model. In terms of observational applications, our method differs from Lam et al. (2013) in two significant aspects. First, they use the stacked redshift differences as the observable, but the model predicts the LOS velocity dispersion, so they are affected by the systematics in the subtraction of Hubble flow in the two-halo term; in our method, Hubble flow is naturally incorporated in the calculation of ξ_{cg}^s . Secondly, they consider the velocity distributions up to the second moment, while we are able to model the entire $P(v_r, v_t)$ including all higher moments.

Established as one of the most powerful probes of dark energy, stacked WL analysis of clusters requires deep imaging surveys that can simultaneously yield lensed background galaxies and foreground cluster sample. Forecasts for Stage III and Stage IV dark energy experiments predict cluster WL constraints that are competitive with supernovae, baryon acoustic oscillations, and cosmic shear (see Weinberg et al. 2013, sections 6 and 8.4). To complement WL as a cosmological test of gravity, GIK modelling of galaxy clusters requires overlap with a large galaxy redshift survey, such as the ongoing Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013), its higher redshift successor eBOSS (see Comparat et al. 2013), and the deeper surveys planned for future facilities such as BigBOSS (Schlegel et al. 2009), DESpec (Abdalla et al. 2012), the Subaru Prime Focus Spectrograph (Ellis et al. 2012), Euclid (Laureijs et al. 2011), and WFIRST (Green et al. 2012; Spergel et al. 2013). We expect that, in combination with the stacked cluster WL analysis, the redshift-space cluster-galaxy cross-correlations can reveal an accurate and complete picture of the average galaxy infall around clusters, allowing stringent tests of modified gravity theories for the origin of the accelerating expansion of the Universe.

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