Effective Dark Matter Halo catalog in $f(R)$ gravity

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We introduce the idea of effective dark matter halo catalog in $f(R)$ gravity, which is built using the effective density field. Using a suite of high resolution N-body simulations, we find that the dynamical properties of halos, such as the distribution of density, velocity dispersion, specific angular momentum and spin, in the effective catalog of $f(R)$ gravity closely mimic those in the ΛCDM model. Thus, when using effective halos, an $f(R)$ model can be viewed as a ΛCDM model. This effective catalog therefore provides a convenient way for studying the galaxy halo occupation distribution or even semi-analytical galaxy formation in $f(R)$ cosmologies.

Introduction. It has become well established that the Universe is currently undergoing a period of accelerated expansion [1][9]. The predominant explanation for this phenomenon is that it is driven by a non-zero cosmological constant, $\Lambda$, in the framework of General Relativity (GR). Together with the assumption that most of the matter in the Universe is cold and dark (non baryonic), this forms the current ΛCDM standard cosmological model. There are however theoretical arguments as to why such an explanation should be disfavoured, such as the discrepancy between the value of the cosmological constant measured astronomically and that predicted by quantum field theory (see, e.g., Ref. [10] for a review). An alternative explanation is that GR might not be accurate on cosmological scales and so some modification to it may be necessary to match observations.

A popular family of modified gravity models come under the umbrella of chameleon $f(R)$ gravity (so called because it replaces the Ricci scalar $R$ in the Einstein-Hilbert action in GR with some function $f(R)$; see, e.g., Ref. [11][12] for recent reviews). This function introduces an efficient cosmological constant which allows the Universe to expand in a way that mimics GR in environments such as our solar system and the early universe.

It therefore follows that a halo which has assembled under $f(R)$ gravity the properties of halos in ΛCDM [21]. Consequently, the virial temperature of gas in these halos is higher than in ΛCDM [21]. It therefore follows that a halo which has assembled under enhanced gravitational forces may have altered astrophysics and it should not be assumed that the processes which govern galaxy formation are the same in such a halo.

However, modifications to gravity increase the complexity of galaxy formation. In $f(R)$ gravity the properties of halos depend not only on their mass but also on their level of screening. For instance, the velocity dispersion is radically different in unscreened halos in $f(R)$ gravity compared to halos of equivalent mass in ΛCDM. Although semi-analytical models usually contain free parameters, their predictions are found to be in reasonable agreement with observations and the models are well motivated by underlining physics. It is therefore of particular interest to study semi-analytical galaxy formation models in $f(R)$ gravity.

In order to produce mock galaxy catalogs in modified cosmologies, it is necessary to have an understanding of galaxy formation and evolution. Although galaxies are extremely complicated objects and many details of the physical processes still remain poorly understood even within the ΛCDM paradigm, encouraging progress has been made in recent years. State-of-the-art hydrodynamical simulations such as ILLUSTRIS [18] and EAGLE [19], with proper modelling of subgrid astrophysics, are able to reproduce galaxy properties that are in good agreement with observations. Although hydrodynamical simulations can faithfully follow the "gastro-physics" in a gravitational field during the hierarchical process of structure formation, such simulations are computationally expensive and high resolution simulations in $f(R)$ gravity are not available currently. An alternative approach is to use semi-analytical galaxy formation models [20], which derive galaxy properties from dark matter simulations. Processes such as the cooling of gas, the formation of stars, feedback effects, and galaxy mergers closely relate to the properties of their host halos (e.g., halos mass, velocity dispersion and merger history). Although semi-analytical models usually contain free parameters, their predictions are found to be in reasonable agreement with observations and the models are well motivated by underlying physics.

In order to overcome these difficulties, in this paper we introduce the idea of the effective halo catalog, which is built using the effective density field in $f(R)$ gravity. We shall show that the dynamical properties of halos in this catalog closely resemble those in ΛCDM dark matter halos.

Setup. The formation of large-scale structure in $f(R)$ gravity is governed by the modified Poisson equation,

$$\nabla^2 \phi = \frac{16\pi G}{3} \frac{\delta \rho}{\delta R} ,$$

(1)
as well as an equation for the scalar field \( f_R \),

\[
\nabla^2 f_R = \frac{1}{3c^2} \left[ \delta R - 8\pi G \delta \rho \right],
\]

where \( \phi \) is the gravitational potential, \( \delta f_R \equiv f_R(R) - f_R(iR) \), \( \delta R \equiv R - R_i \), and \( \delta\rho \equiv \rho - \bar{\rho}. \) The overbar denotes the background value of quantities, and \( \nabla \) is the derivative with respect to physical coordinates. Combining Eq. (1) and Eq. (2), it follows that

\[
\nabla^2 \phi_N = 4\pi G \delta \rho ,
\]

where

\[
\phi_N \equiv \phi + \frac{c^2 \delta f_R}{2} ,
\]

is the standard Newtonian potential, which in \( f(R) \) gravity is also the lensing potential. The gravitational potential \( \phi \) is felt by massive particles and is therefore the potential associated with the dynamical properties of halos and the processes of galaxy formation in \( f(R) \) gravity.

We ran a suite of high-resolution N-body simulations using the ECOSMOG code [22], itself based on the publicly available N-body code RAMSES [23], to solve Eqs. (1) and (2). We studied an \( f(R) \) model which exactly reproduces the \( \Lambda CDM \) background expansion history [14]. Our simulations have a box size of \( L_{box} = 64h^{-1}\text{Mpc} \) and contain \( N = 256^3 \) particles. The background cosmology matches the Planck [8] best-fit \( \Lambda CDM \) model (\( \Omega^b_0 = 0.039, \Omega^b_0 = 0.267, \Omega^b_0 = 0.684, h = 0.671, n_s = 0.962, \) and \( \sigma_8 = 0.834) \). Initial conditions, at a redshift of \( z = 49 \), were generated using the MPERGRAFIC package [24]. Fourteen simulations were run in total, one realisation for \( f(R) \) models with \( f_{R0} = -10^{-6} \) and \( f_{R0} = -10^{-5} \), and five for \( f_{R0} = -10^{-5.5} \) (where \( f_{R0} \) is the present value of \( df/dR ) \). For each \( f(R) \) simulation we ran a \( \Lambda CDM \) one with the same initial conditions as a control.

**Effective halo catalog.** We define an effective density field \( \delta\rho_{\text{eff}} \) so that the modified Poisson equation, Eq. (1), in \( f(R) \) gravity can be cast into the same form as Eq. (3).

\[
\nabla^2 \phi = 4\pi G \delta\rho_{\text{eff}} ,
\]

where \( \delta\rho_{\text{eff}} \equiv \frac{4}{3} \frac{\delta R}{2\pi G \bar{\rho}} \). We identify halos in simulations using the true density field \( \delta\rho \) and the effective density field \( \delta\rho_{\text{eff}} \), respectively. The halo radius \( R_h \) is defined as the radius of a sphere within which the average density, \( \bar{\rho}_h \), is \( \Delta_h \) times the mean density, \( \bar{\rho}_m \). The total mass inside the halo is

\[
M_h = \frac{4\pi}{3} R_h^3 \Delta_h \bar{\rho}_m .
\]

We modified the AMIGA Halo Finder (AHF) [25] to identify dark matter halos and remove unbound particles taking into account the modification of gravity. Throughout this work we take \( \Delta_h = 328 \) and limit our study to halos containing more than 400 particles. We call the catalog of halos identified using the true density field \( \delta\rho \) the standard catalog. In contrast, we call the catalog of halos identified using the effective density field \( \delta\rho_{\text{eff}} \) the effective catalog. The standard and effective catalogs are two different catalogs. In each catalog, a halo has a well defined lensing mass \( M_L \equiv \int \delta\rho(\vec{x})dV \) and dynamical mass \( M_D \equiv \int \delta\rho_{\text{eff}}(\vec{x})dV \). However, there is not a one-to-one correspondence between the masses in the two catalogs: given the same halo radius, the lensing mass in the standard catalog is slightly different from that in the effective catalog. Further, it should be noted that \( M_L \) and \( M_D \) as defined above are not dependent on the shape of the halo. The dynamical mass \( M_D \) can be calculated accurately by our definition without the approximation that halos are spherical (e.g., in Refs. [26, 27]).

**Scaling relations.** After defining the standard and effective catalogs, we investigate the relationship between the mass and velocity dispersion, \( \sigma_v \), of halos in these two catalogs. The virial temperature of gas in virialized gaseous halos is related to the velocity dispersion via a power law, which also applies to \( f(R) \) gravity [21]. We can thus infer the virial temperature of gas in dark matter halos by studying the \( M-\sigma_v^2 \) relationship. The 3D velocity dispersion of a dark matter halo in the halo-rest frame is defined by

\[
\sigma_v^2 \equiv \frac{1}{N_p} \sum_i (\vec{v}_i - \bar{\vec{v}}_h)^2 ,
\]

where \( \bar{\vec{v}}_h \) and \( \bar{\vec{v}}_i \) are the halo and particle velocities, respectively, and \( N_p \) is the number of particles inside the halo.

Figure 1 shows the \( M-\sigma_v^2 \) relation for \( f(R) \) models with \( f_{R0} = -10^{-6}, -10^{-5.5}, -10^{-5} \) at \( z = 0 \). In the left-hand panels, the mass used is the lensing mass \( M_L \) from the standard catalog: in the right-hand panels, the mass is the dynamical mass \( M_D \) from the effective catalog. The points represent \( f(R) \) halos and the color indicates their level of screening, with the ratio \( M_D/M_L \) illustrated in the color bar to the right. The black crosses represent the halos in the \( \Lambda CDM \) simulations, and the red and black dashed lines represent the mean values. In the standard catalog (left-hand panels), we can see that the velocity dispersions of the well-screened halos (blue) overlap with \( \Lambda CDM \) halos of equivalent mass. For unscreened halos (red), which are in general less massive, the \( M-\sigma_v^2 \) relationship is different, with a \( \sqrt{A/3} \) enhancement in the velocity dispersion compared to the \( \Lambda CDM \) case. However, when we plot the velocity dispersion against the dynamical mass in the effective catalog (right-hand panels), the \( M-\sigma_v^2 \) relationship is the same as in \( \Lambda CDM \) for all halos.

Next, we investigate the relationship between halo mass and angular momentum, which is defined by

\[
\vec{J} = \sum_i m_i \vec{\Delta}\vec{r}_i \times \vec{\Delta}\vec{v}_i ,
\]

where \( \Delta\vec{r}_i \) and \( \Delta\vec{v}_i \) are the position and velocity of the \( i \)-th particle relative to the mean value of the halo. \( m_i \) is the true (inertial) mass of the \( i \)-th particle. The magnitude of the angular momentum is defined as \( J = (J_x^2 + J_y^2 + J_z^2)^{1/2} \). In the literature, people often use the specific angular momentum, \( j = J/M \), where \( M \) is the inertial mass of halos. Therefore we use the lensing mass \( M_L \) in the definition of \( j \) in \( f(R) \) gravity.

The upper panels of Fig. 2 show the scaling relation of the specific angular momentum \( j \) relative to the mass of halos for
FIG. 1. The scaling relation of velocity dispersions with respect to halo mass. The points represent \( f(R) \) models. The color represents the ratio \( M_D/M_L \). The black crosses represent the \( \Lambda \)CDM model. The red and black dashed lines are the averaged values. In the left panels, velocity dispersions in \( f(R) \) gravity do not scale as a power-law with the lensing mass. The scaling also depends on the screening. In the right panels, the scalings in \( f(R) \) gravity are the same as that in the \( \Lambda \)CDM model.

In \( f(R) \) gravity, \( \lambda \) also weakly depends on the halo mass. In the standard catalog, we use the definition of \( \lambda \) as

\[
\lambda = \frac{j}{\sqrt{2}VR},
\]

(6)

where \( j \) is the specific angular momentum and \( V \) is the circular velocity at radius \( R = R_h \). The lower panels of Figure 2 show \( \ln(\lambda) \) as a function of the halo mass. In \( \Lambda \)CDM, \( \lambda \) depends weakly on the halo mass [30]. Within the mass bin \([10^{11.5}, 10^{13.5}] M_\odot\]

The average spin parameter is very close to the \( \Lambda \)CDM value, \( \lambda \approx 0.0326 \), with a small relative difference of \( \Delta \lambda/\lambda_{\Lambda \text{CDM}} \approx 3\% \). Both standard and effective catalogs have approximately the same size of scatter, at \( \sigma_{\text{ln}\lambda} \approx 0.617 \).

Profiles. We now turn to the halo profiles of density, velocity dispersion, and specific angular momentum. Again, we...
focus our study to the $f(R)$ model with $f_{R0} = -10^{-5.5}$ at $z = 0$. We choose two different mass bins in which most dark matter halos are unscreened, $0.95 - 1.05 \times \{10^{12}, 10^{13}\} M_\odot$ (see Fig. 1). We only consider profiles at $r > 10 \, \text{kpc}/h$ since the accuracy of the halo profiles below this radius is affected by the limited resolution of our simulations.

The velocity dispersion as a function of the radius is defined as

$$
\sigma_v^2(r) = \frac{1}{\Delta N_p} \sum_{i \in \Delta r} (\vec{v}_i - \vec{v}_h)^2,
$$

in which $\Delta N_p$ is the number of particles within the spherical shell $\Delta r$ at a given radius $r$.

The top panels of Fig. 3 show the density profiles for halos in the two mass bins. The solid lines represent the mean values and the shaded regions represent the 1σ scatter. We can see that the density profiles of halos in $f(R)$ gravity and the $\Lambda$CDM model are indistinguishable in 1σ range of scatter. On the other hand, when we look at the velocity dispersion profiles (middle panels), we can see that in the standard catalog there is an enhancement in $f(R)$ gravity compared to $\Lambda$CDM. However, we can see that the velocity dispersion profiles are almost identical in both the effective and $\Lambda$CDM catalogs. Finally, in the bottom panels of Fig. 3 we show the specific angular momentum $j(< r)$ as a function of distance from the halo center. The halos from the effective catalog and the $\Lambda$CDM model show a good agreement in the distribution of $j$.

**Summary.** In the standard catalog of $f(R)$ gravity, halo properties depend not only on their masses but also on their level of screening. However, by introducing the effective dark matter halo catalog, we find that the relationships between the effective mass of a halo and its dynamical properties, such as the density profile (or equivalently potential profile), velocity dispersion, specific angular momentum and spin, closely resemble those in $\Lambda$CDM cosmology. These results can give us some basic insights into the galaxy formation in $f(R)$ gravity. On the scale of galaxies, the self-gravity of gas (which is the dominant baryonic component of galaxies) can be neglected, and so “gastrophysics” such as cooling and the accretion of gas, in an effective halo in $f(R)$ gravity should follow the same relationship with mass as halos in a $\Lambda$CDM cosmology. It can therefore be expected that galaxy halo occupation distribution models, designed to work in a $\Lambda$CDM cosmology, can be straightforwardly applied to the effective halo catalog in $f(R)$ gravity. Furthermore, although we demonstrated this idea for a specific $f(R)$ gravity model, it can be generalised to other modified gravity or coupled dark energy models, and therefore is expected to have a much wider application.

Of course, the baryonic physics inside galaxies can also be changed by modified gravity, especially in regions where the self-gravity of baryons dominates over the dark matter. The processes such as the formation of stars and feedback might be sensitive to the modification of gravity, and as a result galaxy properties such as color and luminosity may differ from the $\Lambda$CDM predictions. Although further studies on these topics are needed, we have seen that the introduction of effective halo catalog can greatly simplify the analysis of physical processes of galaxy formation in modified gravity and therefore will be a useful initial step in this direction.

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