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Structure Formation by the Fifth Force: Segregation of Baryons and Dark Matter

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In this paper we present the results of N-body simulations with a scalar field coupled differently to cold dark matter (CDM) and baryons. The scalar field potential and coupling function are chosen such that the scalar field acquires a heavy mass in regions with high CDM density and thus behaves like a chameleon. We focus on how the existence of the scalar field affects the formation of nonlinear large-scale structure, and how the different couplings of the scalar field to baryons and CDM particles lead to different distributions and evolutions for these two matter species, both on large scales and inside virialized halos. As expected, the baryon-CDM segregation increases in regions where the fifth force is strong, and little segregation in dense regions. We also introduce an approximation method to identify the virialized halos in coupled scalar field models which takes into account the scalar field coupling and which is easy to implement numerically. It is find that the chameleon nature of the scalar field makes the internal density profiles of halos dependent on the environment in a very nontrivial way.

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I. INTRODUCTION

The origin and nature of the dark energy [1] is one of the most difficult challenges facing physicists and cosmologists now. Among all the proposed models to tackle this problem, a scalar field is perhaps the most popular one up to now. The scalar field, denoted by φ, might only interact with other matter species through gravity, or have a coupling to normal matter and therefore producing a fifth force on matter particles. This latter idea has seen a lot of interests in recent years, in the light that such a coupling could potentially alleviate the coincidence problem of dark energy [2] and that it is commonly predicted by low energy effective theories from a fundamental theory.

Nevertheless, if there is a coupling between the scalar field and baryonic particles, then stringent experimental constraints might be placed on the fifth force on the latter provided that the scalar field mass is very light (which is needed for the dark energy). Such constraints severely limit the viable parameter space of the model. Different ways out of the problem have been proposed, of which the simplest one is to have the scalar field coupling to dark matter only but not to standard model particles, therefore evading those constraints entirely. This is certainly possible, especially because both dark matter and dark energy are unknown to us and they may well have a common origin. Another interesting possibility is to have the chameleon mechanism [3–6], by virtue of which the scalar field acquires a large mass in high density regions and thus the fifth force becomes undetectablly short-ranged, and so also evades the constraints.

Study of the cosmological effect of a chameleon scalar field shows that the fifth force is so short-ranged that it has negligible effect in the large scale structure formation [7] for certain choices of the scalar field potential. But it is possible that the scalar field has a large enough mass in the solar system to pass any constraints, and at the same time has a low enough mass (thus long range forces) on cosmological scales, producing interesting phenomenon in the structure formation. This is the case of some $f(R)$ gravity models [8, 9], which survives solar system tests thanks again to the chameleon effect [10–13]. Note that the $f(R)$ gravity model is mathematically equivalent to a scalar field model with matter coupling.

No matter whether the scalar field couples with dark matter only or with all matter species, it is of general interests to study its effects in cosmology, especially in the large scale structure formation. Indeed, at the linear perturbation level there have been a lot of studies about the coupled scalar field and $f(R)$ gravity models which enable us to have a much clearer picture about their behaviors now. But linear perturbation studies do not conclude the whole story, because it is well known that the matter distribution at late times becomes nonlinear, making the behavior of the scalar field more complex and the linear analysis insufficient to produce accurate results to confront with observations. For the latter purpose the best way is to perform full N-body simulations [14] to evolve the individual particles step by step.

N-body simulations for scalar field and relevant models have been performed before [15–22]. For example, in [21] the simulation is about a specific coupled scalar field model. This study however does not obtain a full solution to the spatial configuration of the scalar field, but

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