COSMOLOGICAL PROBES OF SCREENING MECHANISMS IN MODIFIED GRAVITY

C. LLINARES
Institute of theoretical astrophysics, University of Oslo,
Oslo, Norway

Several extensions of the standard cosmological model include scalar fields as new degrees of freedom in the underlying gravitational theory. A particular class of these scalar field theories include screening mechanisms intended to hide the scalar field below observational limits in the Solar System, but not on galactic scales, where data still gives the freedom to find possible signatures of their presence. Here I present two different results related to scalar-tensor theories for gravity. In the first place, I propose a particular observable that is sensitive to the underlying gravitational theory and thus can be used to test it. Secondly, I report results that were obtained in the context of N-body simulations and are related to the validity of the quasi-static approximation that is often employed when running such simulations.

1 Introduction

One of the most relevant open problems in present cosmology consists in the determination of the nature and origin of the dark energy responsible for the accelerated expansion of the Universe. Among the different possible solutions to this problem exist the idea of modifying the gravitational theory. Several alternative gravitational theories exist at this moment, all of them including extra degrees of freedom in the form of scalar, vector or even tensor fields.

Since Solar System tests show general relativity (GR) as a valid theory, any alternative theory has to behave as GR when scales, densities or accelerations are as in the Solar System. This gives rise to the concept of screening mechanism, which is mandatory for any universally coupled theory. The key feature of these screening mechanisms is to switch off the extra degrees of freedom inside matter overdensites (small scales), and to switch them on in the cosmological background (large scales). When the scalar fields are *on* a fifth force emerges between the matter particles. When it is *off* (the field is screened) the fifth force disappears and GR is recovered. The determination of observable quantities that are sensitive to this fifth force and therefore can be used as a test for its presence is a fundamental area of research in the context of modified gravity.

Here I present a new test for scalar-tensor theories for gravity which is based in the shape of the dark matter halos. We employed this technique to obtain constraints in the parameters of two different models: symmetron and chameleon. The models are representative of two different screening mechanisms. In the first case, the scalar field is screened by restoring a particular symmetry. On the other hand, the chameleon scalar field is screened by making it very massive and close to zero.

In the second part of this report, I show the consequence of relaxing the widely used quasi-static approximation in N-body simulations with modified gravity. This will be done by comparing results from static and non-static simulations that we run with our novel implementation of scalar fields in the code Ramses.

2 Shapes of clusters as a proof of screening mechanisms

Clusters of galaxies are not spherical, but have shapes that can be approximated with triaxial ellipsoids. The axial ratios of this ellipsoids can be determined observationally by employing three different techniques: optical observations (which gives information about the distribution of galaxies), gravitational lensing (which describes the distribution of the total dynamical mass) and X-ray emission of the intra-cluster medium. Here we are interested in this last observational technique since, under the assumption of hydro-static equilibrium, it gives direct information about the distribution of the total gravitational potential.

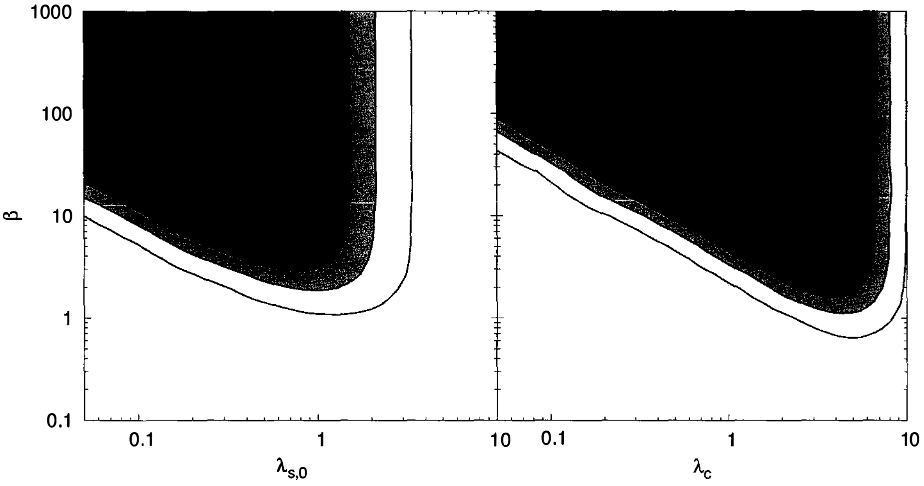

Figure 1 – Contours of relative difference $\Delta\epsilon/\epsilon_N$ between ellipticities that correspond to the modified models with respect to Newtonian gravity. Given the observed value for $\epsilon = 0.18 \pm 0.05$, we find that the set of parameters laying in the black regions are excluded by more than 3σ, while the white regions have ellipticities that lie within 1σ of the observed value (i.e. correspond to accepted values). The left and right panels correspond to symmetron and chameleon models respectively.

In standard gravity it is well known that the surfaces of constant gravitational potential are more spherical than the iso-density contours. In observational terms, this means that the ellipticity of the iso-contours of the X-ray maps are smaller than that of the lensing maps. In the scalar-tensor theories studied here, we found that this is not the case anymore. A simple way to see this, for instance in the chameleon model, consists in taking into account that in the regions where the scalar field is screened, the field is forced to stay close to the minimum of its effective potential. This minimum is uniquely determined by the local matter density thanks to the coupling between the scalar field and the density in the equation of motion. This implies that in the strong coupled limit, the iso-contours of the scalar field will be completely aligned with the contours of the matter density, no matter how the density is distributed. When taking into account this effect in the total gravitational force, we find that the ellipticity of the total iso-potentials is increased with respect to the standard gravity case.

We confirmed this hand waving arguments, by calculating numerically the shape of the iso-surfaces of the total gravitational potential (i.e. including the scalar field contribution) for fixed triaxial dark matter halos. This result can be used to obtain constraints in the model parameters since there will be a subset of the total parameter space for which the ellipticity will go beyond the observed value. In order to perform this test, we employed the value and error reported by Lau and collaborators[1]: $\epsilon = 0.18 \pm 0.05$. The figure 1 shows the constraints that we derived for the coupling constant β and the range of the field λ for the symmetron (left) and chameleon (right) models. Details of this constraints can be found in reference[2].

It is important to note that this calculation was made using a fixed dark matter density profile and that time evolution was not taken into account. As the shape of the dark matter halos are dominated by non-linear effects, N-body simulations are mandatory to make a complete treatment of the problem. We presented results obtained from N-body simulations in ref.[3]. By analyzing the shape of the dark matter halos in the simulations we found that the symmetron model gives results that are consistent with the static analysis (i.e. the ellipticity of the halos increases in the modified gravity case). On the other hand, the chameleon simulations show that the ellipticity can either increase or decrease depending of the model parameters and mass of the dark matter halos with respect to ΛCDM.

3 Cosmological simulations out of the static limit

In several scalar-tensor theories for gravity, the equation of motion for the extra degree of freedom ϕ takes the following form:

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} = f(\rho, \phi). \tag{1}$$

When running N-body simulations with this class of theories there is a universally adopted hypothesis which consist in neglecting the time derivatives in this equation. The approximation converts the Klein-Gordon equation in an elliptic equation which can be solved in every time step of an N-body simulation by means of well know multigrid techniques. Here I present results from the first non-static simulations that were run with the symmetron model.

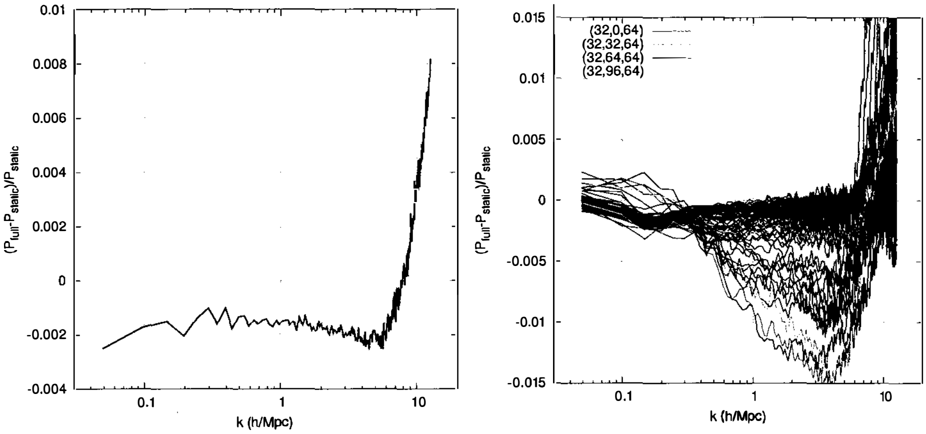

Figure 2 – Left: relative difference between the power spectra obtained from static and non-static cosmological simulations. Right: same as before, but for local power spectra which were obtained by passing the density distribution trough Gaussian filters centered at 64 different positions in the box. The four color lines correspond to four representative locations which are inside (red and green) and outside (light and dark blue) a domain wall.

The N-body code used for this simulations is a modified version of the code Ramses, to which we included static and non-static symmetron solvers for the Klein-Gordon equation. The modification for the non-static case consists in including a leap-frog scheme (similar to the one used to track the position and velocities of the particles) to follow the evolution of the scalar field and its time derivative. As the non-static scalar field solver has to track the very rapid oscillations of the scalar field (which can not be modeled with static codes), we also included a new time step in the code, much smaller than the usual time step used to follow the positions of the particles. Details on the simulations, as well as an extensive description of the code and the tests that were performed to it, can be found in reference[4].

In order to test the consequences of including non-static terms in the Klein-Gordon equation, we run different simulations using both static and non-static solvers. I present here the effects that non-static terms have in the power spectrum of density perturbations. The left panel of figure 2 shows the relative difference between the power spectrum of the static and non-static simulations. Non-static effects are below 1% in this particular quantity. However, it is possible to see that there is an offset of around 0.2% almost in the whole domain of studied frequencies. By running several simulations with different set ups, we found that the offset that appears in the low frequency region is a numerical artifact that can be reduced by using smaller time steps during the simulation. On the other hand, the high frequency offset is physical and related to the domain walls that characterize this particular model. These domain walls are produced by the fact that in the symmetron model the effective potential has two different minima. This produces a domain decomposition in a way that in some regions in space, the scalar field oscillates around positive values while in different regions it oscillates around a negative minimum. These domain walls (interface between different domains) have their own dynamics, which is independent of the evolution of the matter component. As a consequence, the position and shape of the domain walls can not be tracked by using static simulations. By comparing simulations in which the domain walls are present to those in which they are absent, we could confirm that the small scale offset in the power spectrum is produced by the perturbation in the matter distribution produced by the presence of the domain walls. In any case, the offset that appears in the power spectrum when the non-static equation is used is far beyond observational detection and thus, can be neglected (at least for the calculation of the power spectrum of density perturbations).

In order to better understand the effects that domain walls have in the matter distribution, we calculated the power spectrum locally by passing the over-density obtained from the distribution of particles through a Gaussian filter before calculating its Fourier transform. The filter was centered in 64 different positions given by a uniform grid of 4 nodes per dimension. The result can be found in the right panel of figure 2. In the regions that are far from the domain walls, the power spectrum appears unperturbed when non-static terms are included during the simulation. On the other hand, we found that the difference between static and non-static simulations can be up to 1.5% in the regions where the domain walls exist.

Acknowledgments

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