

Brane World Moduli and the CMB

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Abstract. The evolution of moduli fields, which naturally appear in higher dimensional models such as brane worlds, and their effects on the anisotropies of the cosmological microwave background radiation is discussed.

1 Introduction

Extra spatial dimensions appear naturally in models, which aim to combine the principles of Quantum Mechanics and General Relativity. Among the possible models, brane world scenarios have attracted a lot of attention recently [1]. The cosmological evolution of brane worlds are of considerable interest, because some scenarios predict observable consequences, such as the variation of the fine structure constant, the gravitational coupling or masses of particles. This is due to the existence of massless scalar degrees of freedom (moduli fields), which couple to the matter sector in the theory. Variations of masses or Newton's constant have an important impact in cosmology. In the following, the effects of moduli fields appearing in brane world scenarios on the anisotropies in the cosmic microwave background radiation are summarized (details can be found in [2]). As we will show, cosmological observations put stringent constraints on parameters in the low energy effective theory. As such, cosmological observations can be used complementarily to local experiments, i.e. experiments in the solar system, in order to constrain the coupling of scalar degrees of freedom to matter.

2 The low energy effective action

We begin by summarizing the properties of the low energy effective action of a two brane system with a bulk scalar field. At low energy, there are two scalar degrees of freedom. Their higher-dimensional interpretation is as follows: first, there is the bulk scalar field, which propagates in all spatial directions. The zero mode, i.e. the massless excitation of the bulk scalar field is one degree of freedom in the low energy effective action. The other scalar degree of freedom in the low energy effective action is the physical distance between the branes. These two scalar degrees of freedom generally evolve during the cosmological evolution. Apart from the two scalar degrees of freedom, there might be some forms of matter, confined on the individual branes.

There are different ways of obtaining the low energy effective action, see e.g. [3] and [4]. Here, we write down the effective action in the Einstein frame, obtained with the help of the moduli space approximation in [4]:

$$S_{\text{EF}} = \frac{1}{16\pi G_N} \int d^4x \sqrt{-g} \left[\mathcal{R} - \frac{12\alpha^2}{1+2\alpha^2} (\partial\varphi)^2 - \frac{6}{2\alpha^2+1} (\partial R)^2 - V(\varphi, R) \right], \quad (1)$$

and the matter action:

$$S_{\text{Matter}} = S_{\text{Matter},1}(\psi_1, A(\varphi, R)^2 g_{\mu\nu}) + S_{\text{Matter},2}(\psi_2, B(\varphi, R)^2 g_{\mu\nu}), \quad (2)$$

The moduli fields φ and R are non-trivial combinations of the bulk scalar field zero mode and the physical distance between the branes. The functions $A(\varphi, R)$ and $B(\varphi, R)$ describe the coupling of the two moduli fields to the matter fields confined on each branes. Because of the warping of the extra dimension, the functions A and B are generally different, i.e. matter on the individual branes couple differently to the matter on the branes. There is only one free parameter in the low energy effective theory which we will denote by α . This parameter has to be small in order for the theory to be consistent with local experiments [4]. For generality, we have included a potential energy, $V(\varphi, R)$, for the fields.

3 Moduli Evolution and the CMB

Solving the field equations derived from the action above, shows that the field R decays, i.e. it approaches zero in the matter dominated era. This is a valuable feature of the model as local experiments demand that the field value today has to be small [4].

Both fields evolve during the cosmological evolution and each will contribute to the expansion rate of the universe and the evolution of perturbations within the universe. We have studied the effect on the evolution of perturbations of each individual field [2], discussing one field at each time only. The cosmological parameters are chosen such that the cosmological model today is the Λ CDM model with $\Omega_{\text{CDM}} = 0.3$, $\Omega_{\Lambda} = 0.7$ and $h = 0.7$.

We begin first with the field φ , i.e. the field with constant coupling.

3.1 The case of constant coupling

In this case, the coupling of the field to matter is determined by the free parameter α . In Figure 1 we plot the unnormalized power spectra for different values of α . As it can be seen, both the amplitude as well as the positions of all peaks are affected. The case for $\alpha = 0$ corresponds to the Λ CDM model based on General Relativity.

It can be shown that the field contributes to the distance to the last scattering surface as well as to the scaling of the dark matter density [4]: whereas in the standard model $\rho_{\text{CDM}} \propto a^{-3}$, where a is the scale factor, this is no longer true in the case when α is not zero. Thus, at the time of last scattering the matter content is *different* from the standard case. As known, the matter content determines both the positions and the amplitude of the peaks [5]. We also found that the coupling has an impact on the magnitude of the integrated Sachs-Wolfe effect.

In Figure 2 we plot the COBE normalized curves. It can be seen that increasing the parameter α implies that there will be less power on small angular scales (i.e. large multipole number). Only on very large scales ($l \leq 10$) there is more power than in the model with $\alpha = 0$.

3.2 The case of field-dependent coupling

We now turn our attention to the field R , which coupling function depends on the field value. As already mentioned, if R is zero initially, it remains zero. However, deep in the radiation dominated epoch, it might well be that the field was different from zero.

In Figure 3 we plot the unnormalized power spectrum for different initial conditions of the field R . On large angular scales (low multipole number) one can see that the integrated Sachs-Wolfe effect is not as pronounced as in the case of constant coupling. This is because at low redshift ($z < 1.5$) the field value of R is quite small already, so that coupling to matter is small, too. We refer to [2] for details (see also [7] for a discussion on cosmological perturbations in some classes of dilatonic dark energy models).

In Figure 4 we plot the COBE normalized figures. The most obvious difference to the case of constant coupling (Figure 2) is the region $2 \leq l \leq 10$. This is because the integrated Sachs-Wolfe effect is not as pronounced as in the case of constant coupling.

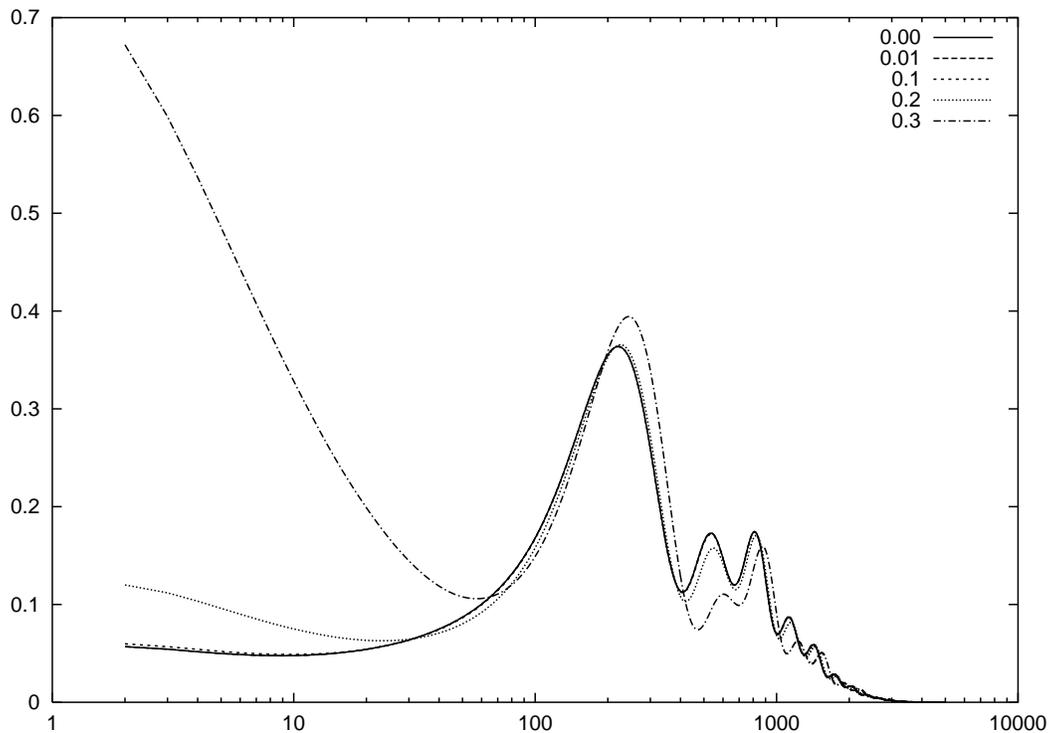


Figure 1: The temperature anisotropy power spectrum, $l(l+1)C_l/2\pi$, for the constant coupling case: the values in the legend are the values of α .

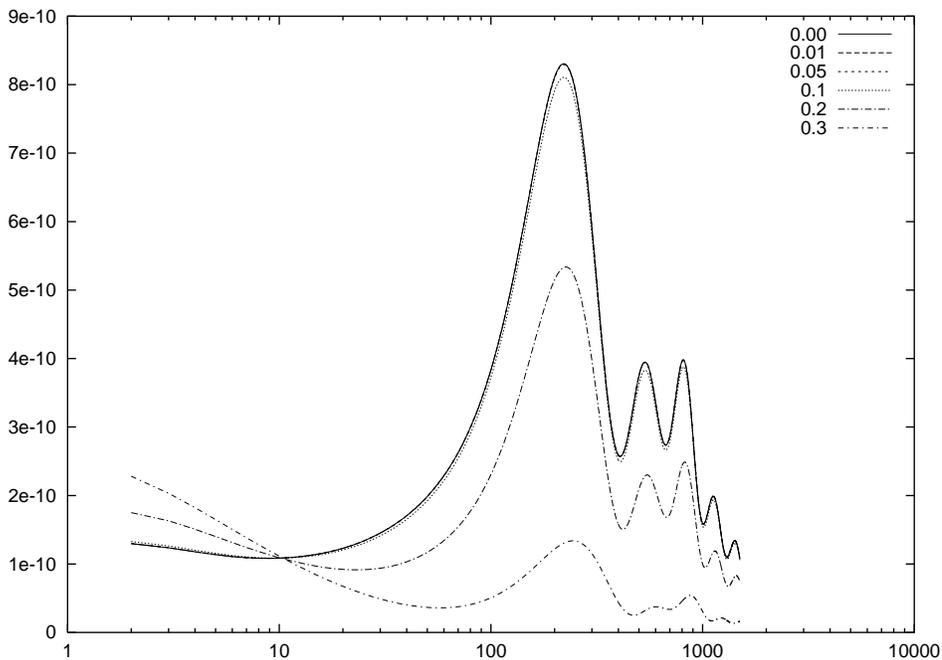


Figure 2: COBE-normalized temperature anisotropy $l(l+1)C_l/2\pi$ for the case of constant coupling. On small scales the COBE-normalized spectra are below the predictions for vanishing coupling due to the enhanced ISW.

4 Conclusions

Given that observations of anisotropies in the CMB will have very high accuracy, they will also provide vital constraints on models based on higher dimensions. In the case of brane world scenarios with

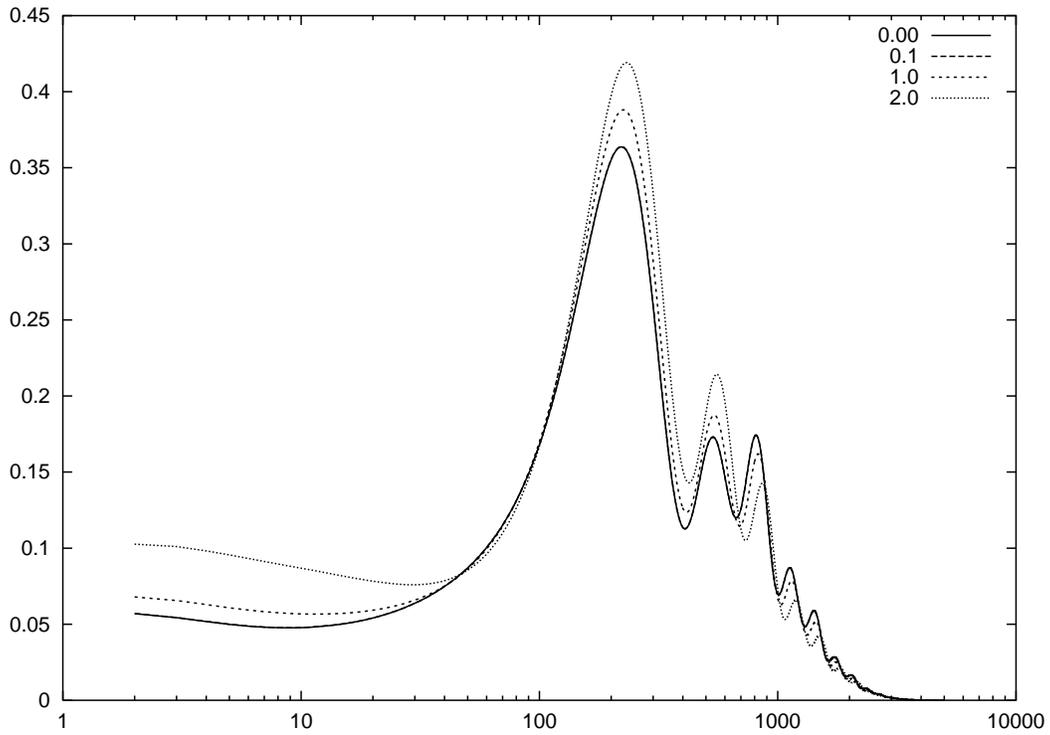


Figure 3: The temperature anisotropy power spectrum, $l(l+1)C_l/2\pi$, for the field-dependent coupling case: the values in the legend are for the initial values of the scalar field R .

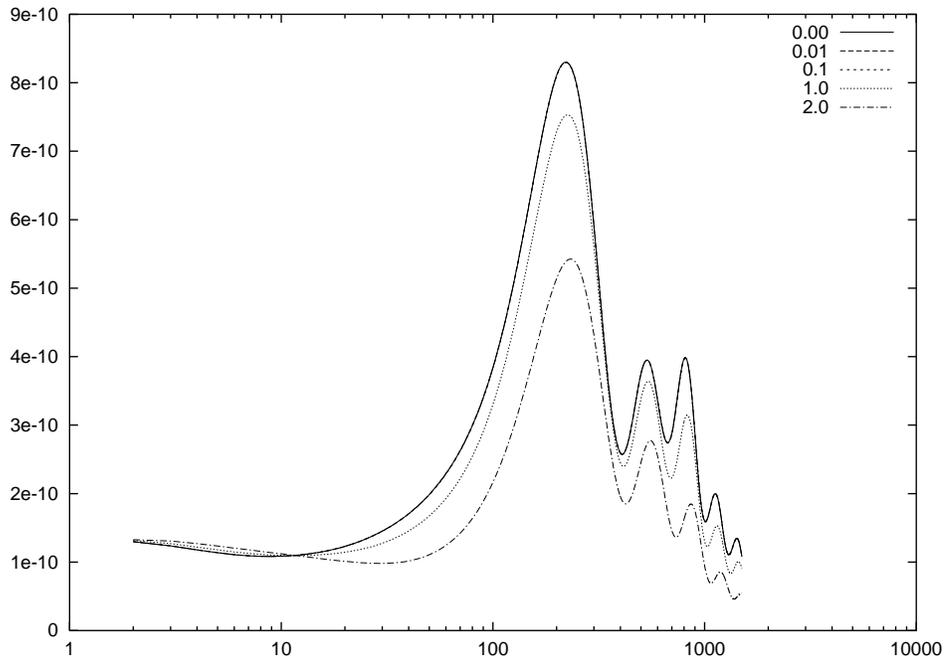


Figure 4: COBE-normalized temperature anisotropy $l(l+1)C_l/2\pi$ for the case of field-dependent coupling. Similar to the case in figure 2, on small scales the COBE-normalized spectra are below the predictions for vanishing coupling.

bulk scalar field it can be said that highly warped bulk geometries are favoured (which corresponds to small α , see [4]). Furthermore, the initial distance between the branes at the time of nucleosynthesis will be severely constrained by CMB experiments.

Both moduli fields affect the CMB. However, their effect is quite different, due the fact that in the case of the R -field the coupling to matter is decreasing in the cosmological history.

An interesting possibility would be to extend our analysis by giving the moduli fields a potential. They may then play the role of dark energy in the universe [6]. It is unlikely, however, that this can be done without fine tuning of some parameters in the potential. On the other hand, the origin of such a potential might come from a repulsion of the second brane from a singularity [4]. It would be interesting to investigate the effect of such a potential on the results presented here. In particular it would be important to investigate some possibilities: first, one could imagine a situation, where visible matter is located on our brane only, but dark matter only on the second brane. In this case, baryons and dark matter couple differently to dark energy. The second possibility is where dark matter and baryons live on our brane only, and the second brane is empty. This essentially the case studied here and in [2] for constant potential energy (i.e. cosmological constant). Finally, there might be two types of dark matter, one lives on our brane and the other dark matter type lives on the other. In this case, the masses of both types vary differently in time. This could imply some novel effects for structure formation not only on large scales.

Another effect neglected here is the variation of the fine structure constant α_{em} . If α_{em} varies, the Thomson cross section changes with time. Therefore the scattering between photons and free electrons is modified. It is known that this leaves an imprint in the CMB anisotropies. It might be interesting to investigate the magnitude of this effect in the theory presented here [8].

In conclusion, cosmological considerations will provide useful complementary information to local experiments about extra dimensions, especially about the size of extra dimensions. This will not only hold for the class of brane world models discussed here, but also for other, maybe more exotic, models. In any case, cosmology continues to play a significant role in constraining theories beyond the standard model of particle physics.

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