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Cosmic microwave background constraints on coupled dark matter

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A B S T R A C T

We study CMB constraints on a scenario where a fraction of dark matter is non-minimally coupled to a massless scalar field and dark energy is in the form of a cosmological constant. In this case, there is an extra gravity-like fifth force which can affect the evolution of the Universe enough to have a discernible effect on measurements of cosmological parameters. Using Planck and WMAP polarisation data, we find that up to half of the dark matter can be coupled. The coupling can also be several times larger than in models with a single species of cold dark matter coupled to a quintessence scalar field, as the scalar field does not play the role of dark energy and is therefore less constrained by the data.

1. Introduction

There is extensive observational evidence for the existence of dark matter, most of it favouring cold dark matter (CDM); see e.g. Ref. [1] for a review. In recent years there has been significant interest in models in which there are one or more species of DM coupled to a quintessence scalar field, which plays the role of dark energy (e.g. Refs. [2–6]). Since the quintessence field must be light, this leads to additional long-range forces on the DM, and the effects of such forces on structure formation and the cosmic microwave background (CMB) radiation have been studied [7–11]. If these long-range forces exist, but are neglected, they can affect measurements of the cosmological parameters [12,13].

It is possible that there is more than one species of DM (e.g. Ref. [14]). Brookfield et al. in Ref. [3] studied the phenomenology of multiple fluids interacting with different couplings to the dark energy scalar field, while Baldi in Ref. [5] looked at the case of two species of dark matter, with identical physical properties, but different couplings to the dark energy. In Paper I [15] we studied the cosmological evolution of a scenario with two species of DM, one of which is coupled to a scalar field. In contrast to, e.g., Ref. [3] we assume that the scalar field does not have a bare potential and the dark energy is in the form of a cosmological constant. This sort of set-up can, for instance, arise in higher dimensional compactifications [16]. This type of scenario can give rise to an abundance of scalar fields and, since the dark sector of our Universe is so poorly understood, there is plenty of scope for extra couplings to exist. It is therefore important to study the cosmological constraints on couplings in the dark sector, beyond just coupling of DM to quintessence (in particular since quintessence may actually introduce more fine-tuning problems than it solves, see Ref. [17] for a review). See Paper I for further details. We found that for the type of coupling studied in this paper, there is no longer a local minimum in the effective potential and there are no scalar field scaling solutions. Consequently the evolution of the Universe can deviate substantially from that of ΛCDM. We found that a relatively small fraction of coupled dark matter can significantly modify the angular power spectrum of the CMB. In this paper we use the Planck temperature and WMAP polarisation data to constrain the fraction of coupled DM and its coupling strength. In Section 2 we briefly review the set-up. The CMB constraints are presented in Section 3 and we conclude with discussion of the results in Section 4.

2. Overview of scenario

In this section we briefly overview the scenario which was introduced in Paper I [15]. The matter content of the Lagrangian can be divided into two components, one of which consists of baryons, radiation and uncoupled dark matter, and the other contains the remainder of the dark matter which is coupled to a massless scalar field, ϕ. The action then takes the form

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{16\pi G}(R-2\Lambda) - \frac{1}{2}(\nabla\phi)^2\right] + S_{\rm SM}[g_{\mu\nu},\ldots] + S_{\rm c}[g_{\mu\nu},\ldots] + S_q[\hat{g}_{\mu\nu},\psi_q], \quad (1)$$

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where g is the determinant of the metric $g_{\mu\nu}$, R is the corresponding Ricci scalar and ∇ is the covariant derivative. The action $S_{\rm SM}[g_{\mu\nu},\ldots]$ contains the photons, baryons, and massless neutrinos and $S_{\rm c}[g_{\mu\nu},\ldots]$ contains the uncoupled DM. The ellipses in $S_{\rm SM}[g_{\mu\nu},\ldots]$ denote the standard model fields, while the ellipses in $S_{\rm c}[g_{\mu\nu},\ldots]$ denote the uncoupled dark matter field. Neither the standard model fields nor the uncoupled dark matter couple directly to the scalar. The DM component that does couple directly to the scalar is described by the action $S_q[\hat{g}_{\mu\nu},\psi_q]$. The background evolution is governed by the Friedmann equation,

$$H^2=\frac{8\pi G}{3}\left(\rho_\Lambda+\rho_{\rm SM}+\rho_{\rm c}+\frac{1}{2}\dot{\phi}^2+\rho_{\rm q}\right), \tag{2}$$

where ρ_Λ, $\rho_{\rm SM}$, $\rho_{\rm c}$ and $\rho_{\rm q}$ are the densities of the cosmological constant, the standard model fields (baryons, photons and neutrinos), uncoupled DM and coupled DM, respectively, and the scalar field equation of motion

$$\ddot{\phi}+3H\dot{\phi}+\alpha\rho_q=0, \tag{3}$$

where α is the dimensionful coupling constant which determines the strength of the coupling between DM and the scalar field, $H=\dot{a}/a$ is the Hubble parameter and overdots represent differentiation with respect to cosmic time t. Perturbing Eqs. (2) and (3) along with the background gravitational field gives

$$\delta_q'=-\theta_q-\frac{1}{2}h'+\alpha\delta\phi', \tag{4}$$

$$\theta_q'=-\theta_q\mathcal{H}+\alpha\left(k^2\delta\phi-\phi'\theta_q\right), \tag{5}$$

where $\delta\phi$ is the perturbation in the scalar field and $\mathcal{H}=a'/a$, where prime denotes differentiation with respect to conformal time. The perturbations of the scalar field are governed by

$$\delta\phi''+2\mathcal{H}\delta\phi'+k^2\delta\phi+\frac{1}{2}h'\phi'=-\alpha a^2\delta\rho_q. \tag{6}$$

3. Results

We use the Monte Carlo Markov Chain [18,19] code CosmoMC [20] to constrain the fraction of coupled DM and its coupling strength using the Planck and WMAP polarisation data. We use the nine year WMAP polarisation (WP) data [21] since it provides a tighter constraint on the optical depth than Planck is able to do using probes of gravitational lensing from large scale structure [22]. Furthermore, the WMAP data is able to break some of the degeneracy between the matter density, $\Omega_{\rm m}=\Omega_{\rm b}+\Omega_{\rm c}+\Omega_{\rm q}$, and the Hubble constant [23]. We also use the same convergence criteria and sampling method as used in Ref. [22].

In addition to the six ΛCDM parameters (physical baryon density, $\Omega_{\rm b}h^2$, physical total cold dark matter density, $\Omega_{\rm c_{tot}}h^2=(\Omega_{\rm c}+\Omega_{\rm q})h^2$, one hundred times the angular size of the sound horizon at decoupling, $100\theta_*$, optical depth at reionisation, τ, scalar spectral index, $n_{\rm s}$ and primordial amplitude, $\ln(10^{10}A_{\rm s})$) we allow the density parameter of the coupled DM, $\Omega_{\rm q}$, and the coupling constant, α, to vary.[1] Our priors, all of which are flat, are given in Table 1. The density parameter of the coupled DM is allowed to vary in the range $0<\Omega_{\rm q}<0.16$ and the coupling in the range $0<\alpha<0.3$. It is not possible to calculate the CMB angular power spectra for arbitrarily large values of $\Omega_{\rm q}$ and α. As we saw in Ref. [15], there is no attractor solution for the scalar field. This means that small changes in the initial value of ϕ can lead to large changes in the present day densities, in particular for large α. For large values of α it is not, in general, possible to find suitable initial conditions for the scalar field and furthermore, if the coupling is large the background cosmology changes too much unless the amount of coupled CDM is very small [15]. Similarly for large $\Omega_{\rm q}$ the evolution of the background deviates too much from ΛCDM to provide a good fit to the CMB data unless the coupling α is very small [15]. These regimes (where either $\Omega_{\rm q}$ or α are vanishingly small) are not physically interesting; it will never be possible to exclude a scenario in the limit where it tends to ΛCDM.

Fig. 1 shows the one-dimensional (1D) marginalised probability distributions for the coupled dark matter density parameter, $\Omega_{\rm q}$, and coupling, α, while Fig. 2 shows the joint probability distribution of these parameters. The likelihood is maximised for non-zero values of $\Omega_{\rm q}$ and α, but there is no statistical preference for a non-zero coupled component. Large couplings and densities are, unsurprisingly, excluded and there is a degeneracy between α and $\Omega_{\rm q}$; an increase in one of the parameters can be countered by a decrease in the other. However, the probability distributions of both parameters decrease fairly rapidly as their values increase. The fall off for $\Omega_{\rm q}$ is more rapid than that for α. This is partly because, even for relatively small α, if $\Omega_{\rm q}$ is large then the increase in the coupled DM density at early times leads to a large Integrated Sachs–Wolfe (ISW) effect at low multipoles [15]. As dis-

Table 1
Priors used for parameters in CosmoMC.

Parameter	Prior range
$\Omega_{\rm b}h^2$	[0.005, 0.1]
$\Omega_{\rm c_{tot}}h^2$	[0.001, 0.99]
$100\theta_*$	[0.5, 10.0]
τ	[0.01, 0.8]
$n_{\rm s}$	[0.9, 1.1]
$\ln(10^{10}A_{\rm s})$	[2.7, 4.0]
$\Omega_{\rm q}$	[0.0, 0.16]
α	[0.0, 0.3]

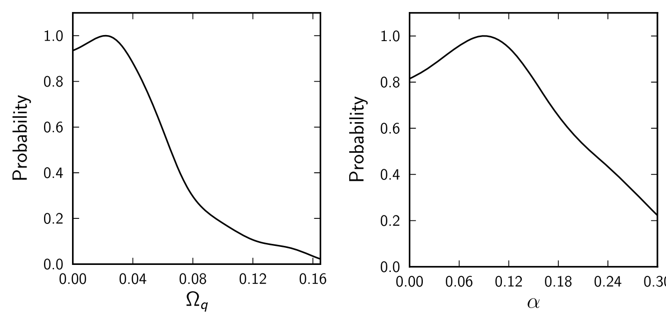

Fig. 1. 1D marginalised probability distributions for the coupled dark matter density, $\Omega_{\rm q}$ (left panel), and coupling constant, α (right panel).

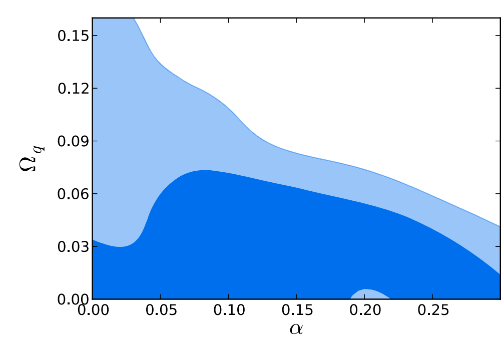

Fig. 2. Marginalised joint 68% and 95% confidence regions for $\Omega_{\rm q}$ and α.

[1] It would also be possible to vary $\Omega_{\rm c}h^2$ and $\Omega_{\rm q}$ instead of $\Omega_{\rm c_{tot}}h^2$ and $\Omega_{\rm q}$, and this would give physically equivalent results. We chose the later pair of parameters in order to facilitate comparison with parameter constraints from ΛCDM, as most cosmological/astronomical probes are sensitive to the total CDM density.