Cosmic microwave background constraints on coupled dark matter

Sophie C. F. Morris† and Anne M. Green‡
School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, UK

We study CMB constraints on a model with a cosmological constant and a fraction of dark matter non-minimally coupled to a massless scalar field. In this scenario, 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.

I. 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. However, the CDM particles have not yet been detected, and hence the nature of CDM is still to be understood. Therefore it is important to consider how the nature of the CDM, and in particular its couplings, can affect cosmological observations. 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. Ref. [2]–[5]). 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 [6]–[10]. If these long range forces exist, but are neglected, they can affect measurements of the cosmological parameters (as emphasised in Ref. [11] for the case of the dark energy equation of state).

It is possible that there is more than one species of DM (e.g. Ref. [12]). Ref. [3] studied the phenomenology of multiple fluids interacting with different couplings to the dark energy scalar field, while 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 [13] we studied the cosmological evolution of a model 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 [14]. In this case 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 and WMAP polarisation data to constrain the parameters of this model, in particular the fraction of coupled DM and its coupling strength. In Sec. II we briefly review the model. The CMB constraints are presented in Sec. III and we conclude with discussion of the results and model in Sec. IV.

II. OVERVIEW OF MODEL

In this section we briefly overview the model which was introduced in Paper I [13]. 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 which contains the remainder of the dark matter which is coupled to a massless scalar field, φ. The action then takes the form

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

(1)

where $g$ is the determinant of the metric $g_{\mu\nu}$, $R$ is the corresponding Ricci scalar and $\nabla$ is the covariant derivative. The action $S_{SM}[\varphi_{\mu\nu}, ...]$ contains the photons, baryons, and massless neutrinos and $S_c[\varphi_{\mu\nu}, ...]$ contains the uncoupled DM. The ellipses denote the standard model fields in $S_{SM}$ and the uncoupled dark matter field in $S_c$, none of which couple directly to the scalar. The DM component that does couple directly to the scalar is described by the action $S_q[\varphi_{\mu\nu}, \psi_q]$. The background evolution is governed by the Friedmann equation,

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

(2)

where $\rho_\Lambda$, $\rho_{SM}$, $\rho_c$ and $\rho_q$ 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

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

(3)

where $\alpha$ 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...
TABLE I: Priors used for parameters in CosmoMC.

| Parameter | Prior range |
|-----------|-------------|
| $\Omega_b h^2$ | [0.005, 0.1] |
| $\Omega_{c,\text{tot}} h^2$ | [0.001, 0.99] |
| $100\theta_s$ | [0.5, 10.0] |
| $\tau$ | [0.01, 0.8] |
| $n_s$ | [0.9, 1.1] |
| $\ln(10^{10} A_s)$ | [2.7, 4.0] |
| $\Omega_q$ | [0.0, 0.16] |
| $\alpha$ | [0.0, 0.3] |

overdots represent differentiation with respect to cosmic time $t$. Perturbing eqs. (2) and (3) along with the background gravitational field gives

$$\delta_q' = -\theta_q - \frac{1}{2} h' + \alpha \delta \phi', \quad (4)$$
$$\theta_q' = -\theta_q H + \alpha (k^2 \delta \phi - \phi' \theta_q), \quad (5)$$

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

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

III. RESULTS

We use the Monte Carlo Markov Chain [15, 16] code CosmoMC [17] to constrain the parameters of the coupled model described in Sec. II using the Planck and WMAP polarisation data. We use the nine year WMAP polarisation (WP) data [18] 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 [19]. Furthermore, the WMAP data is able to break some of the degeneracy between the matter density, $\Omega_m = \Omega_b + \Omega_c + \Omega_q$, and the Hubble constant [20]. We also use the same convergence criteria and sampling method as used in this reference.

In addition to the six $\Lambda$CDM parameters (physical baryon density, $\Omega_b h^2$, physical total cold dark matter density, $\Omega_{c,\text{tot}} h^2 = (\Omega_c + \Omega_q) h^2$, one hundred times the angular size of the sound horizon at decoupling, $100\theta_s$, optical depth at reionisation, $\tau$, scalar spectral index, $n_s$ and primordial amplitude, $\ln(10^{10} A_s)$) we allow the density parameter of the coupled DM, $\Omega_q$, and the coupling constant, $\alpha$, to vary. Our priors, all of which are flat, are given in Table I. The density parameter of the coupled DM is allowed to vary between $0 < \Omega_q < 0.16$. For larger $\Omega_q$ the evolution of the background deviates too much from $\Lambda$CDM to provide a good fit to the CMB data [13]. For large values of $\alpha$ it is not, in general, possible to find suitable initial conditions for the scalar field. As we saw in Ref. [13], there is no attractor solution for the scalar field. This means that small changes in the initial value of $\phi$ can lead to large changes in the present day densities, in particular for large $\alpha$. Furthermore, if the coupling is large the background cosmology changes too much unless the amount of coupled CDM is very small. This regime is not physically interesting (it will never be possible to exclude such a component making up a vanishingly small fraction of the Universe). Therefore we allow the coupling to vary in the range $0 < \alpha < 0.3$.

Fig. 1 shows the one-dimensional (1D) marginalised probability distributions for the coupled dark matter density, $\Omega_q$ (top panel) and coupling constant, $\alpha$ (bottom).
the probability distributions of both parameters decrease fairly rapidly as their values increase. The fall off for $\Omega_q$ is more rapid than that for $\alpha$. This is partly because, even for relatively small $\alpha$, if $\Omega_q$ 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 [13].

As discussed above, values of the coupling larger than 0.3 would produce an acceptable fit to the CMB data, but only if the amount of coupled DM is small.

Fig. 3 compares the constraints on the density parameters for our coupled CDM model with those for ΛCDM. It also shows the probability distributions of the derived parameters that have the most influence on the shape of the CMB angular power spectrum: the red-shift of matter radiation equality, $z_{eq}$, and $\theta_*$. The constraints on $z_{eq}$ are very tight and it is this, in addition to the ISW effect discussed above, which leads to the limits on the coupled DM density and coupling. As discussed in Paper I [13], if all other parameters are fixed, increasing the fraction of coupled dark matter increases the red-shift of equality. The red-shift of equality can in principle be reduced by lowering the total matter density. However, this leads to an increase in the value of the scalar field and hence the density of the coupled DM. For modest coupled DM densities and couplings this can be compensated for by small shifts in the densities of the other components. However, if the coupled DM density and coupling are too large then there is no combination of parameters which is compatible with the measured CMB peak heights and positions.

**IV. DISCUSSION**

We have studied the constraints from Planck and WMAP polarisation data on a model with two species of DM, one of which is coupled to a scalar field via a conformal coupling. There is a degeneracy between the density parameter of the coupled component and the coupling strength; a large coupling strength can be compensated for by a small density parameter and vice versa. The density parameter of the coupled DM is constrained to be $\Omega_q < 0.13$ at 95% confidence, which corresponds to roughly half of the total CDM density. It is not possible to place an upper limit on the coupling, as a large coupling would be compatible with CMB data if the amount of coupled DM is vanishingly small. However, for significant coupled DM fractions the coupling can be of order 0.1, larger than is allowed for a single DM species coupled to a dark energy scalar field [21][22].

Other data sets may place tighter upper bounds on the parameters of this model. For example, the exchange of kinetic energy between the scalar field and coupled CDM could affect the abundance of DM halos [23]. Some work has been done using N-body simulations to simulate the non-linear regime of structure formation in models with multiple species of dark matter [24]. These models with minimal coupling are essentially indistinguishable from ΛCDM when looking at large-scale structure formation, but the separation of the different dark matter components starts to cause a fragmentation of structure for higher couplings. N-body simulations may, therefore, be useful in constraining the parameter space of the model presented here, but are beyond the scope of this paper. Measurements of the Hubble parameter could also help to constrain this model. The forces between galaxies may change locally if the density of the coupled CDM varies from place to place, for example, an area containing many galaxies and an over density of charged dark matter will feel an extra repulsive force coming from the CDM coupling. This will affect the recession velocity in this area, thus causing deviations between different measurements of the Hubble parameter. The potential magnitude of this effect has been explored in more detail in Ref. [11]. Unfortunately the CMB data only places a constraint, in the context of coupled DM, $(64.1 < H_0 < 71.8)\text{km s}^{-1}\text{Mpc}^{-1}$ at 95% confidence, and this is consistent with the locally measured value of $H_0 = 73.8 \pm 2.4\text{km s}^{-1}\text{Mpc}^{-1}$ [25].

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FIG. 3: 1D marginalised probability distributions and corresponding 68% and 95% joint constraint contours for the total dark matter and baryon physical densities, $\Omega_{c_{\text{tot}}} h^2 = (\Omega_q + \Omega_c) h^2$ and $\Omega_b h^2$, the derived parameters $z_{\text{eq}}$ and $\theta_*$ and the matter and cosmological constant density parameters, $\Omega_m$ and $\Omega_{\Lambda}$, from the Planck and WMAP polarisation data for coupled DM (dark black curve) and $\Lambda$CDM (light red curve).

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