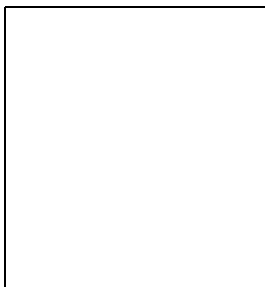


# EARLY QUINTESSENCE AND THE CMB

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We examine the cosmic microwave background (CMB) anisotropy for signatures of early quintessence dark energy – a non-negligible quintessence energy density during the recombination and structure formation eras. In contrast to a  $\Lambda$ CDM cosmology, early quintessence leads to a larger suppression of structure growth. Because of this influence on the clustering of dark matter and the baryon-photon fluid, we may expect to find trace signals in the CMB and the mass fluctuation power spectrum. In detail, we demonstrate that suppressed clustering power on small length-scales, as suggested by the combined Wilkinson Microwave Anisotropy Probe (WMAP) / CMB / large scale structure data set, is characteristic of early quintessence.

## 1 Introduction

There exists compelling evidence that the energy density of the Universe is dominated by dark energy as demonstrated by the recent high precision measurement of the cosmic microwave background (CMB) fluctuations by WMAP.<sup>1,2,3,4,5,6</sup> And yet, the nature of the dark energy remains elusive. A cosmological constant ( $\Lambda$ ), providing a simple phenomenological fix in the absence of better information, is consistent with current data including the latest WMAP results. Lessons from particle physics and cosmology, however, suggest a more attractive solution in the form of a dynamical dark energy<sup>7,8,9,10</sup> that continues to evolve in the present epoch — quintessence.

In the basic quintessence scenario, the dark energy enters only at late times, as required for cosmic acceleration. In a more realistic picture, the late appearance of the quintessence may not be the whole story. Scalar field models of quintessence with global attractor solutions<sup>7,8,11</sup> have been shown to “track” the dominant component of the cosmological fluid. One consequence is that just after inflation, the universe may contain a non-negligible fraction of the cosmic energy density. Through subsequent epochs, the quintessence energy density  $\rho_q$  lags behind the

dominant component of the cosmological fluid with a slowly varying  $\Omega_q$ , and an equation-of-state  $w_q \equiv p_q/\rho_q$  which is nearly constant. The field energy tracks the background until the current epoch, when the quintessence energy density crosses and overtakes the matter density. A non-negligible fraction of dark energy at last scattering,  $\Omega_q^{(ls)}$ , and during structure formation,  $\Omega_q^{(sf)}$ , then arises quite naturally. From the observational viewpoint, detection of any trace of “early quintessence” would give us a tremendous clue as to the physics of dark energy. For an extended discussion on “early quintessence” and its relation to the WMAP data, see Caldwell et al.<sup>12</sup>

In this work we concentrate on “early quintessence”, characterized by non-negligible values  $\Omega_q^{(ls)}, \Omega_q^{(sf)} \lesssim 0.05$ . Typical scalar field models exhibit an exponential form of the scalar potential in the range of the field relevant for early cosmology, with special features in the potential or kinetic term in the range governing the present epoch.<sup>13,14,15,16</sup> Our attention is drawn toward these models due to the recent claims of suppressed power on small scales in the combined WMAP / CMB / large scale structure data set. We are motivated precisely by the fact that the most prominent influence of a small amount of early dark energy is a suppression of the growth of dark matter fluctuations.<sup>17,18</sup> As we soon discuss, this influence can help to make the fluctuation amplitude extracted from galaxy catalogues or the Ly- $\alpha$  forest compatible with a relatively high amplitude CMB anisotropy. The effect of early quintessence on the mass fluctuation power spectrum can be understood simply as a suppression of the growth function for dark matter and baryonic fluctuations. Just as fluctuation growth is suppressed at late times with the onset of dark energy domination, so is the growth of linear modes slowed at early times due to non-negligible  $\Omega_q^{(ls)}, \Omega_q^{(sf)}$ . We emphasize that this results in a uniform suppression of the cold dark matter amplitudes for all modes that have entered the horizon since  $z_{eq}$ .

Now we turn to consider the implications of the CMB for quintessence.<sup>19</sup> For the case of quintessence, a degeneracy exists among the cosmological parameters,<sup>12</sup> for instance the equation-of-state can play off the Hubble constant to achieve an otherwise indistinguishable anisotropy pattern out to small angular scales.<sup>20</sup> As a means of proof by example, we identify a set of models in Table 1 with observationally indistinguishable CMB patterns, *i.e.* identical peak positions, but differing amounts of  $\Omega_q^{(ls)}, \Omega_q^{(sf)}$ , shown as Models (A,B) in Figure 1. Model (C) is WMAP’s best fit  $\Lambda$ CDM and Model (D) the best fit for an extended data set with  $\Lambda$ CDM and running spectral index.<sup>2</sup> Clearly, the CMB sky is consistent with a small amount of early quintessence in addition to  $\Omega_q^{(0)}$  insofar as the angular-diameter distance to the last scattering surface is preserved. For a more thorough treatment of the concordance regions see Caldwell & Doran.<sup>21</sup>

Table 1: Cosmological parameters of the models presented in this work.

	A	B	C	D
$\Omega_q^{(sf)}$	0.03	0.05	0	0
$\Omega_q^{(ls)}$	0.03	0.05	0	0
$w_q^{(0)}$	-0.91	-0.95	-1	-1
$n_s$	0.99	1.05	0.97	0.93
$h$	0.65	0.70	0.68	0.71
$\Omega_m h^2$	0.15	0.16	0.15	0.135
$\Omega_b h^2$	0.024	0.025	0.023	0.0224
$\tau$	0.17	0.26	0.1	0.17
$\sigma_8$	0.81	0.87	0.87	0.85
$\chi_{eff}^2/\nu$	1432/1342	1432/1342	1430/1342	1432/1342

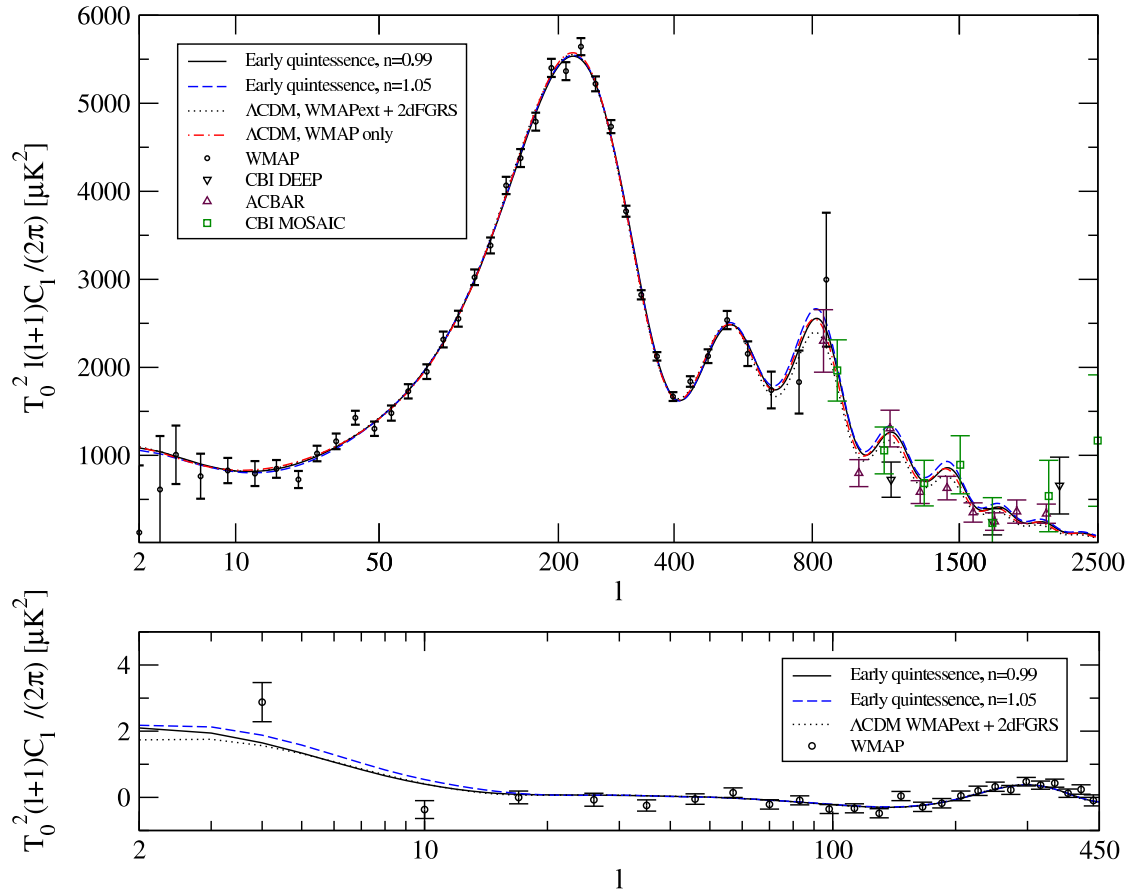


Figure 1: Temperature (TT) and Polarization (TE) as a function of multipole  $l$ . The WMAP data<sup>3,4</sup> are plotted alongside two early quintessence models with  $n_s = 0.99$  and  $n_s = 1.05$  (see Table 1 for the other cosmological parameters). For comparison, we plot WMAP-normalized spectra for the best fit  $\Lambda$ CDM model (no Ly- $\alpha$  data) with constant spectral index  $n = 0.97$  of Spergel et al.,<sup>2</sup> as well as the best fit  $\Lambda$ CDM model with running spectral index  $n_s = 0.93$ ,  $dn_s/d \ln k = -0.031$ . At large  $l$  we plot the CBI<sup>23,24</sup> and ACBAR<sup>25</sup> measurements.

We have computed the spectra in Figure 1 using CMBEASY<sup>22</sup> for a class of “leaping kinetic term quintessence”<sup>13</sup> models that feature early quintessence. The main features depend only on two parameters besides the present fraction of dark energy  $\Omega_q^{(0)}$  and the present equation of state  $w_q^{(0)}$ , namely the fraction of dark energy at last scattering,  $\Omega_q^{(ls)}$ , and during structure formation,  $\Omega_q^{(sf)}$ . In order to facilitate comparison with other effects of quintessence – for example the Hubble diagram  $H(z)$  for supernovae – we present a useful parametrization of quintessence<sup>16</sup> rather than detailed models. For  $a > a_{eq}$  and  $x \equiv \ln a = -\ln(1+z)$  we consider a quadratic approximation for the averaged equation-of-state ( $x_{ls} \approx -\ln(1100)$ )

$$\bar{w}_q(x) = -\frac{1}{x} \int_x^0 dx' w_q(x') = w_q^{(0)} + (\bar{w}_q^{(ls)} - w_q^{(0)}) \frac{x}{x_{ls}} + Ax(x - x_{ls}). \quad (1)$$

The time-dependent average equation of state  $\bar{w}_q(x)$  is directly connected to the time history of the fraction in dark energy  $\Omega_q(x)$  as one may verify. The parameter  $A$  is related to the average fraction of dark energy during structure formation. The parameters describing our models are (A):  $\bar{w}_q^{(ls)} = -0.188$ ,  $A = -0.0091$ ; (B):  $\bar{w}_q^{(ls)} = -0.172$ ,  $A = -0.015$ . Our models (A) and (B) are consistent with the large scale structure observations of the 2dFGRS survey<sup>26,27,28</sup> and all present bounds for  $H(z)$ , including type Ia supernovae.<sup>29,30,31,32,33</sup>

To summarize, we have demonstrated that models of early quintessence are compatible with the presently available data for a constant spectral index of primordial density perturbations. The presence of early quintessence results in a reduction in the spectrum of matter fluctuations on small scales, which may have significant consequences for the interpretation of combined CMB and large scale structure data.

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