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Structure formation in non homogeneous dark energy

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Abstract

The rate of structure formation in the Universe is different in homogeneous and clustered dark energy models. The degree of dark energy clustering depends on the magnitude of its effective sound speed $c^2_{eff} \equiv c_e$ *and for* $c_e = 0$ *dark energy will cluster in a similar fashion to dark matter while for* $c_e = 1$ *stays (approximately) homogeneous. In this paper we try to constrain the dark energy effective sound speed using current available data including SnIa, Baryon Acoustic Oscillation, CMB shift parameter (*Planck *and* WMAP*), Hubble parameter, Big Bang Nucleosynthesis and the growth rate of structures* $f\sigma_8(z)$.

1 Introduction

Dark energy (DE) affects the rate of structure formation in the universe. This is a secondary effect and can be used for distinguishing DE and modified gravity models. In particular, it has been shown that the homogeneous DE scenario fails to reproduce the observed concentration parameter of the massive galaxy clusters [1]. In this framework, [2] pointed out that CMB and LSS slightly prefer dynamical DE with $c_e \neq 1$ and recently [3] and [4] have shown that clustering DE reproduces the growth data better in the framework of the spherical collapse model. A similar conclusion was suggested also by [5]. In this paper we consider two distinct equations of state for the dark energy component, $w_d = const$ and $w_d = w_0 + w_{1}(z/1+z)$ with c_e as a free parameter and we try to constrain the dark energy effective sound speed.

2 Structure formation and data analyze

The growth rate $f = d\ln\delta/d\ln a$ is usually approximated by as first introduced by [6]. In this parametrization γ is the so called growth index and can be used to distinguish between DE and modified gravity models [7, 8]. It is well known that for a ΛCDM model γ is independent of redshift and equal to 6 /11. The DE sound speed in the framework of GR is given by [9]:

$$\frac{\delta p}{\delta \rho} = c_e + 3\mathscr{H}(1+w)(c_e - c_a^2)\frac{\theta}{\delta}\frac{1}{k^2}\,, \tag{1}$$

where c_e and c_a are effective and adiabatic DE sound speed. The evolution equation for DM and DE contrast are:

$$\frac{d^2\delta_m}{da^2} + A_m\frac{d\delta_m}{da} + B_m\delta_m = S_m\,, \tag{2}$$

$$\frac{d^2\delta_d}{da^2} + A_d\frac{d\delta_d}{da} + B_d\delta_d = S_d\,, \tag{3}$$

where the coefficients are given by:

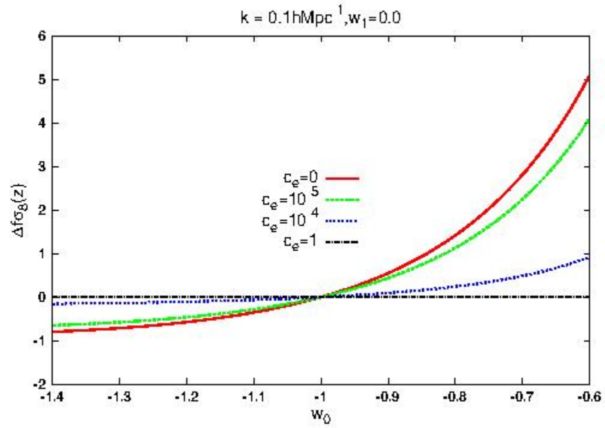

Figure 1: **Relative difference of $f\sigma_8$ at the present time as a function of EoS. The red solid curve is for $c_e = 0$. Results for $c_e = 10^{-5}$, $c_e = 10^{-4}$ and non-clustering DE are shown the by green dashed,blue dotted and black dashed-dotted line respectively.**

$$
\begin{aligned}
A_{\mathrm{m}} &= \frac{1}{a}\left(2+\frac{\mathscr{H}'}{\mathscr{H}^2}\right)=\frac{1}{a}\left(3+\frac{\dot{H}}{H^2}\right) , \\
B_{\mathrm{m}} &= 0 , \\
S_{\mathrm{m}} &= 3\frac{d^2\phi}{da^2}+\frac{3}{a}\left[2+\frac{\mathscr{H}'}{\mathscr{H}^2}\right]\frac{d\phi}{da}-\frac{k^2}{a^2\mathscr{H}^2}\phi , \\
A_{\mathrm{d}} &= \frac{1}{a}\left[2+\frac{\mathscr{H}'}{\mathscr{H}^2}+3c_{\mathrm{a}}-6w_{\mathrm{d}}\right] , \\
B_{\mathrm{d}} &= \frac{1}{a^2}\left[3\left(c_{\mathrm{e}}-w_{\mathrm{d}}\right)\left(1+\frac{\mathscr{H}'}{\mathscr{H}^2}-3w_{\mathrm{d}}+3c_{\mathrm{a}}-3c_{\mathrm{e}}\right)\right. \\
&+ \left.\frac{k^2}{\mathscr{H}^2}c_{\mathrm{e}}-3a\frac{dw_{\mathrm{d}}}{da}\right] , \\
S_{\mathrm{d}} &= \left(1+w_{\mathrm{d}}\right)\left[3\frac{d^2\phi}{da^2}+\frac{3}{a}\left(2+\frac{\mathscr{H}'}{\mathscr{H}^2}-3c_{\mathrm{a}}\right)\frac{d\phi}{da}\right. \\
&- \left.\frac{k^2}{a^2\mathscr{H}^2}\phi+\frac{3}{1+w_{\mathrm{d}}}\frac{d\phi}{da}\frac{dw_{\mathrm{d}}}{da}\right] ,
\end{aligned}
\tag{4}
$$

Where $\frac{\mathcal{H}'}{\mathcal{H}^2}$ is a function of scale factor and using the Friedmann equations we have

$$
\frac{\mathscr{H}'}{\mathscr{H}^2}=-\frac{1}{2}\frac{\Omega_{\mathrm{m}}+\Omega_{\mathrm{d}}(1+3w_{\mathrm{d}})}{\Omega_{\mathrm{m}}+\Omega_{\mathrm{d}}}=-\frac{1}{2}(1+3\Omega_{\mathrm{d}}w_{\mathrm{d}}) , \tag{5}
$$

Table 1: **The best value of parameters and their 1-σ uncertainty for the wCDM model.**

Parameters	Best (WMAP)	Best (Planck)
h	$0.6955^{+0.0040}_{-0.0037}$	$0.7064^{+0.0011}_{-0.0012}$
$\Omega^0_{\rm DM}$	$0.2273^{+0.0027}_{-0.0029}$	$0.2361^{+0.0010}_{-0.0010}$
$\Omega^0_{\rm b}$	$0.0470^{+0.0004}_{-0.0005}$	$0.0482^{+0.0003}_{-0.0002}$
w_0	$-0.9436^{+0.0144}_{-0.0141}$	$-0.9975^{+0.0055}_{-0.0053}$
$c_{\rm e}$	0.	0.001
$\Delta_{\rm d}(z=0)$	1.0×10^{-2}	4.3×10^{-4}

Table 2: **The best value of parameters and their 1-σ uncertainty for the w(t)CDM model.**

Parameters	Best (WMAP)	Best (Planck)
h	$0.7001^{+0.0040}_{-0.0038}$	$0.7070^{+0.0012}_{-0.0013}$
$\Omega^0_{\rm DM}$	$0.2234^{+0.0028}_{-0.0027}$	$0.2361^{+0.0012}_{-0.0011}$
$\Omega^0_{\rm b}$	$0.0474^{+0.0005}_{-0.0005}$	$0.0481^{+0.0003}_{-0.0003}$
w_0	$-1.0176^{+0.0128}_{-0.0124}$	$-0.95204^{+0.0060}_{-0.0058}$
w_1	$0.3289^{+0.0395}_{-0.0405}$	$-0.18512^{+0.0205}_{-0.0195}$
$c_{\rm e}$	0.002	0.
$\Delta_{\rm d}(z=0)$	1.2×10^{-2}	6.0×10^{-4}

To show how $f\sigma_8(z)$ changes with the DE sound speed, we compute $\Delta f\sigma_8(z) = \frac{f_h\sigma_{8,h}(z)-f\sigma_8(z)}{f\sigma_8(z)}\times 100$ as a function of the EoS parameter. In the above equations h stands for homogeneous DE. For the growth rate, results at present time is shown in Fig. (1).

For data used in this work, The overall likelihood function is given by the product of the individual likelihoods:

$$\mathcal{L}_{\rm tot} = \mathcal{L}_{\rm sn}\times\mathcal{L}_{\rm BAO}\times\mathcal{L}_{\rm CMB}\times\mathcal{L}_{H}\times\mathcal{L}_{\rm BBN}\times\mathcal{L}_{\rm fs}\ , \tag{6}$$

and the total chi-square $\chi^2_{\rm tot}$ is given by:

$$\chi^2_{\rm tot} = \chi^2_{\rm sn}+\chi^2_{\rm BAO}+\chi^2_{\rm CMB}+\chi^2_{H}+\chi^2_{\rm BBN}+\chi^2_{\rm fs}\ . \tag{7}$$

where *sn*, *BAO*, *CMB*, *H*, *BBN* and *fs* indicate SnIa, baryon acoustic osillation, cosmic microvave background, Hubble evolution big bang nucleosynthesis and growth rate data respectively.

We use MCMC algorithm to find the best value of parameters. The results are summarized in Tab.(1) and (2). In these Tabs. Δ_d stand for δ_d and show the amount of DE clustering. The DE sound speed tend to zero but can't constrain with data used in this work.

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