Did the dark energy always have a large Compton wavelength?

Bruce A. Bassett\textsuperscript{1}, Martin Kunz \textsuperscript{2}, David Parkinson\textsuperscript{1} and Carlo Ungarelli\textsuperscript{1,3}

\textsuperscript{1}Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth PO1 2EG
\textsuperscript{2}Astronomy Centre, CPES, University of Sussex, Brighton, BN1 9QJ, UK
\textsuperscript{3}School of Physics and Astronomy, University of Birmingham Edgbaston, Birmingham, B15 2TT, UK

Abstract. Until now all well-studied dark energy models proposed have very large Compton wavelengths, $\lambda_c > 100\text{Mpc}$ at all time and hence show no clustering on small scales. Evidence against this would disfavour both $\Lambda$CDM and quintessence. We show however, that large $\lambda_c$ is actually slightly favoured by current CMB, LSS and SN1a data by comparing quintessence with a condensate scenario with the same background dynamics. The condensate scenario has a very small $\lambda_c$ before making a transition to negative pressure and large $\lambda_c$ and therefore exhibits a rich CMB phenomenology which roughly interpolates between $\Lambda$CDM and flat CDM models.

1 Introduction

In quintessence models the current acceleration of the universe is due to potential-dominated evolution of a scalar field today. This typically implies that the potential is very flat today and hence that the Compton wavelength, $\lambda_c = (V'')^{-1/2}$, is very large. This makes standard quintessence models difficult to distinguish from the simple cosmological constant ($\Lambda$) \cite{1} since clustering will only occur on scales larger than $\lambda_c$. Moreover, quintessence models fulfill the condition of a large $\lambda_c$ at all times. Therefore two interesting questions are:

\begin{itemize}
  \item \textbf{(1)} Can we build models which are not associated with a large $\lambda_c$ either today or at earlier epochs?
  \item \textbf{(2)} Are such models favoured or disfavoured by cosmic data?
\end{itemize}

A strong affirmative to the second question would provide compelling evidence against both $\Lambda$CDM and quintessence. In answer to the first question we propose the idea of \textit{condensate dark energy}.\textsuperscript{1} In this scenario, part of the dark matter (which we take to be CDM) undergoes a transition to a condensate at some low redshift $z_1$, described by a scalar field with equation of state given by

\textsuperscript{1}Note that k-essence for example, can lead to a strong variation in the speed of sound, potentially leaving a detectable signal in the CMB \cite{2}.
Figure 1: A schematic illustration of the evolution of the Compton wavelength $\lambda_c \equiv (\nu''')^{-1/2}$, as a function of redshift. In condensation $\lambda_c$ jumps radically at the transition, $z_t$, while in metamorphosis or quintessence models it is almost unchanged in cosmological terms. In our specific implementation $\lambda_c \sim 0$ for $z > z_t$ since we consider a CDM condensate.

eq (1). Such condensate models have previously been envisaged [3], though with slightly different properties.

To isolate the effects of the Compton wavelength we must be sure that our models have the same background dynamics. We therefore use the model-independent parametrisation of the equation of state of [4] (and generalised in [5]):

$$w(z) = \frac{w_f}{1 + \exp((z - z_t)/\Delta)}$$

where $w_f$ is the final value of the equation of state, $z_t$ is the redshift at which $w(z)$ changes from 0 to $w_f$ and $\Delta$ controls the rapidity of the transition.

In the case of quintessence we can impose this equation of state to hold identically at all times. However, for condensation we require that for $z > z_t$ it hold only on average, i.e. $\langle w \rangle = 0$. This allows the potential to be very curved and hence for $\lambda_c$ to be small and allow clustering on small scales.

2 Results

To compare our models we use all recent CMB data sets (excluding Archeops), the LSS power spectra inferred from 2df, PSCz, Abell/ACO and the binned SN1a data as described in [4] and [6]. We compute likelihoods over the 4d grid $(\Omega_Q, z_t, w_f, H)$ where $H$ is the Hubble constant. We show the 1d marginalised likelihoods for our $w(z)$ parameters in fig (3) for both condensation and metamorphosis/quintessence. We also plot the same curves when we introduce a Gaussian prior for the Hubble constant coming from the HST key project result: $H = 72 \pm 8$ km s$^{-1}$ Mpc$^{-1}$.

Overall the condensate model has a better best-fit $\chi^2$ than the best $\Lambda$CDM model. Indeed, we found that for condensation the best-fit $\chi^2$ is 79.3 corresponding to $z_t = 5, w_f = -0.95, \Omega_Q = 0.75$, while for $\Lambda$CDM the best-fit $\chi^2$
Figure 2: The $C_\ell$ spectra for condensation as a function of $z_t$. In contrast to the case of quintessence and metamorphosis the effect of $z_t$ is rather non-trivial for $z_t < 1.5$, including an asymmetric offset pattern between the 2nd and 3rd peaks due to the induced change in $\Omega_b/\Omega_{cdm}$. For comparison pure CDM is the lowest curve at $\ell = 200$, $\Lambda$CDM the highest.

Figure 3: The total 1-d likelihood plots for condensation (top) and metamorphosis (bottom row) for the three variables $\Omega_Q, z_t$ and $w_f$. These likelihood plots are computed from current CMB, LSS and SN1a data, all marginalised over the Hubble constant (thick line with red points). The thin solid line corresponds to the case with a Gaussian prior $H = 72 \pm 8 \text{km s}^{-1} \text{Mpc}^{-1}$. Condensation strongly disfavours $z_t < 1.5$, while metamorphosis favours $z_t \approx 2$. 
is 84.9, (corresponding to $\Omega_\Lambda = 0.73$). The best fits for metamorphosis are even better with $\chi^2 = 78.8$ for $z_t = 1.5$ [4, 6].

To understand why condensation does not favour $z_t < 1.5$ we note that this is due both to the CMB and LSS. Unlike quintessence models which have an almost trivial effect on the CMB (see e.g. [4]), varying $z_t$ in condensation affects the CDM density at decoupling and hence alters the gravitational potential wells. This effect is only significant for $z_t < 2$ and boosts the height of the first acoustic peak relative to metamorphosis for $z_t = 0.5$ while giving an asymmetric off-set pattern to the 2nd and 3rd peaks.

The $C_\ell$ curves of fig. (2) can be understood by realising that they interpolate between standard flat CDM (small $z_t$) and pure $\Lambda$CDM models (high $z_t$). While the total energy density of the universe is continuous across the transition surface at $z_t$, the CDM density is not, since some of it is rapidly converted into dark energy. Hence the ratio $\Omega_b/\Omega_{cdm}$ is not constant in this model, but jumps across the transition at $z_t$. The smaller is $z_t$, the larger this jump is, and hence the smaller is $\Omega_b/\Omega_{cdm}$, and vice versa. This leads to the characteristic pattern of asymmetric 2nd and 3rd peaks seen for $z_t = 0.5$ due to the change in the gravitational potential wells at recombination [7].

The LSS disfavours low $z_t$ since the turnover in the power spectrum occurs at too large a $k$ value, inconsistent with current observations [6].

3 Discussion

In quintessence the Compton wavelength $\lambda_c$ of the scalar field is always very large, which implies that the transfer function of fluctuations is trivial on large scales. This is not necessary for a successful dark energy model however and dropping this constraint yields a richer phenomenology. We consider one of the simplest models with a large change in $\lambda_c$: condensation, and find that it is a worse fit to the data compared with quintessence models if $z_t < 2$ due to both CMB and LSS constraints [6].

It is important to realise that our conclusions with regard to condensation would be altered if we assumed a different value of $\lambda_c$ initially by choosing our dark matter to be warm instead of cold. In that case we would probably have a better fit to the data for $z_t < 2$, especially regarding LSS due to the well-documented problems of flat CDM models in fitting both COBE and $\sigma_8$ constraints. Perhaps the most interesting result of condensation is that it opens up the possibility of having dark energy which non-trivially alters the CMB and cluster-scale physics. Detailed analysis of condensation and comparison with quintessence/metamorphosis is reported elsewhere [6].

References

[1] Corasaniti P.S., Bassett B.A., Ungarelli C., and Copeland E.J., astro-ph/0210209 (2002)
[2] Erickson J. K., et al, Phys. Rev. Lett., 88, 121301 (2002).
[3] de la Macorra A., Stephan-Otto C., Phys. Rev. Lett. 87, 271301 (2001), astro-ph/0106316.
[4] Bassett B.A., Kunz M., Silk J., and Ungarelli C., MNRAS 336, 1217 (2002), astro-ph/0203383
[5] Corasaniti P.S. and Copeland E.J., astro-ph/0205544 (2002)
[6] Bassett B. A., Kunz M., Parkinson D., Ungarelli C., astro-ph/0211303, (2002)
[7] Hu W. and Sugiyama N., Ap. J 471, 542 (1996)