Early dark energy and its interaction with dark matter

Bo-Yu Pu, Xiao-Dong Xu, Bin Wang
Department of Physics and Astronomy, Shanghai Jiao Tong University, Shanghai 200240, China

Elcio Abdalla
Instituto de Física, Universidade de São Paulo, CEP 05315-970, São Paulo, Brazil

We study a class of early dark energy models which has substantial amount of dark energy in the early epoch of the universe. We examine the impact of the early dark energy fluctuations on the growth of structure and the CMB power spectrum in the linear approximation. Furthermore we investigate the influence of the interaction between the early dark energy and the dark matter and its effect on the structure growth and CMB. We finally constrain the early dark energy model parameters and the coupling between dark sectors by confronting to different observations and conclude that the early dark energy interacting with dark matter can contribute to alleviate the coincidence problem.

PACS numbers: 98.80.-k

I. INTRODUCTION

From astronomical observations, it is convincing that our universe is undergoing accelerated expansion. The driving force of this acceleration is dark energy (DE), which composes roughly 70% of the total energy budget of our universe. The physical nature of DE, together with its origin and time evolution, is one of the most enigmatic puzzles in modern cosmology. The simplest explanation of DE is the cosmological constant with equation of state (EoS) \( w = -1 \). Although the cosmological constant fits well to current observational data, it suffers serious theoretical problems. One is the cosmological constant problem, the fact that the quantum field theory prediction for the value of \( \Lambda \) is about hundred orders of magnitude larger than the observation \([1]\). Another problem, more closely related to the cosmological evolution itself, is the coincidence problem, namely why being a constant, the \( \Lambda \) value becomes important for the evolution of the universe just at the present moment \([2]\). Besides the cosmological constant, there are other alternative explanations for DE. But so far, the focus has been on the EoS of DE and in particular on its current value \( w_0 \).

It is rather the amount of DE, \( \Omega_{de} \), than the EoS, that influences the evolution of our universe. In this spirit, an interesting sub-class of DE models involving a non-negligible DE contribution at early times has been proposed. These models are called Early Dark Energy (EDE), and have been extensively studied recently. EDE models can potentially alleviate the coincidence problem. Furthermore, they can influence the cosmic microwave background \([3,4]\), big-bang nucleosynthesis \([5]\) and large-scale structure formation \([6,7]\). For now, it would be fair to say that there are no strong observational constraints on the EDE models, and it is especially difficult to discriminate EDE models which have \( w = -1 \) at present from the \( \Lambda \)CDM model.

In this paper, we will focus on a specific EDE model, which is similar to that originally introduced by Wetterich \([16]\) and further examined in \([13]\). This model is characterized by a low but non-vanishing DE density at early times with the EoS varying with time in the form

\[
\begin{align*}
    w(z) &= \frac{w_0}{1 + b \ln(1 + z)^2}, \\
    b &= - \frac{3w_0}{\ln \left( \frac{1 - \Omega_{de,e}}{\Omega_{de,e}} \right) + \ln \left( \frac{1 - \Omega_{m,0}}{\Omega_{m,0}} \right)}
\end{align*}
\]

where \( w_0 \) and \( \Omega_{de,0} = 1 - \Omega_{m,0} \) represent the present-day EoS and amount of DE, respectively, while \( \Omega_{de,e} \) gives the average energy density parameter at early times. The impact of this EDE cosmology on galaxy properties has been studied by coupling high-resolution numerical simulations with semi-analytic modeling of galaxy formation and evolution \([12]\). The available results highlight that such EDE model leads to important modifications in the galaxy properties with respect to a standard \( \Lambda \)CDM universe.

We use this dynamical EDE parametrization to further discuss the influence of this specific model on the cosmic microwave background radiation (CMB) and compare with the \( \Lambda \)CDM prediction. For dynamical DE models, in contrast with \( \Lambda \)CDM, they possess DE fluctuations. In the linear regime, these fluctuations for usual DE models, for example quintessence, are usually several orders of magnitude smaller than that of dark matter (DM), so that DE fluctuations are usually neglected in studies of CMB and structure formations in the linear approximation. It would be interesting to examine the presence of the EDE fluctuation and its impact on the DM perturbations and CMB, and compare with the usual assumption of nearly homogeneous EDE and \( \Lambda \)CDM models. This can help to
It is clear that DM and DE are two main components of our universe, which compose almost 95% of the total universe. It is a special assumption that these two biggest components existing independently in the universe. A more natural understanding, in the framework of field theory, is to consider that there is some kind of interaction between them. It has been shown that the interaction between DM and DE is allowed by astronomical observations and can help to alleviate the coincidence problem, see for example [17–21] and references therein. It would be of great interest to extend the previous studies to the interaction between EDE and DM. With the non-negligible DE energy density at high redshift, the interaction between dark sectors will start to play the role earlier. To investigate the influence of the interaction between EDE and DM on the structure growth and CMB signals is our second objective of this paper.

The outline of the paper is the following. In the next section, we will first present the background evolution of the EDE model and discuss the influence of the interaction between dark sectors on the background dynamics. And then we will study evolutions of linear perturbations of a system with EDE and pressureless matter and calculate the growth of structure. We will examine the effect of the interaction between EDE and DM on the linear perturbations. Section III is devoted to the study of the CMB power spectrum. In Section IV we will present the constraint of the EDE model from fittings to current observational data and in the last section we will present our conclusions.

II. ANALYTICAL FORMALISM

We are here investigating the EDE model presented in [1] with a low but non-vanishing DE density at early times. We examine the influences of the EDE on the background evolution, linear perturbation and CMB power spectrum by performing analysis for two models ‘EDE1’ and ‘EDE2’, which have $w_0 = -0.93, \Omega_{de,e} = 2 \times 10^{-4}(b = 0.29, \Omega_{m,0} = 0.25)$ and $w_0 = -1.07, \Omega_{de,e} = 2 \times 10^{-4}(b = 0.33, \Omega_{m,0} = 0.25)$, respectively.

Figure 1 shows the evolutions of EoS in EDE models that we examine in this work. The amount of DE at early times is non-negligible and EDE models approach to the cosmological constant scenario at recent times. The EDE1 model has EoS always above $-1$, while EDE2 EoS can cross $-1$ and stay below $-1$ at present.

In the spatially flat Friedmann-Robertson-Walker (FRW) universe, the evolutions of the energy densities of DE and DM in the background spacetime are governed by

\[ \rho'_{dm} + 3H \rho_{dm} = aQ_{dm} \]
\[ \rho'_{de} + 3H(1 + w)\rho_{de} = aQ_{de}, \]

where $H$ is the Hubble constant and $\mathcal{H} = aH$ with $a$ the scale factor of the universe. $Q_{\alpha}$ indicates the interaction between dark sectors, where the subscript ‘$\alpha$’ refers to ‘$dm$’ or ‘$de$’ respectively. We show the evolution of the DE fractional energy density when there is no interaction between DE and DM in Figure 2. In the left panel of Figure
we compare the $\Omega_{de}$ for EDE1 with constant EoS DE and cosmological constant. We can distinguish that for the model EDE1, the DE started to play the role earlier, which is required to alleviate the coincidence problem. We also compare the evolution of $\Omega_{de}$ for different EDE models with that of the cosmological constant in the right panel of Figure 2. The evolution of $\Omega_{de}$ shows that the model EDE1 is favorable to ease the coincidence problem.

![Figure 2: The evolutions of DE fractional energy densities for different DE models when there is no interaction between dark sectors. In the right panel, "EDE3" refers to $w_0 = -1.302$, $\Omega_{de,c} = 1.25 \times 10^{-5}$.](image)

Since we know the nature of neither DM nor DE, it is hard to describe the interaction between them, although there are some attempts to perform this task [23–26]. Our study on the interaction between dark sectors will concentrated on the phenomenological descriptions. We assume there is energy flow due to the interaction between dark sectors where the coupling vector is defined in the form $Q^\nu = (\frac{2}{3}, 0, 0, 0)^T$ [19], and $Q$ takes the phenomenological form $Q = 3\lambda_1 H \rho_{dm}$ or $Q = 3\lambda_2 H \rho_{de}$, where $\lambda_1$ and $\lambda_2$ refer to the strength of the respective couplings. With the interaction between dark sectors, we plot the evolution of the DE fractional energy density in Figure 3. In the left panel, we choose the interaction as being proportional to the energy density of DM. For the EDE model, with the positive coupling proportional to the DM energy density ($\lambda_1 > 0$), the influence of DE in the universe evolution appeared much earlier. The positive coupling, in our notation, describes the energy flow from DE to DM [17–21]. For the same amount of DE today, with the positive coupling, it implies that DE density was higher in the past. In the right panel, we show the case where the interaction is proportional to the DE density. We see that for the EDE1 model with positive coupling ($\lambda_2 > 0$), there was more EDE at high redshift if the present DE amount is the same as that of $\Lambda$CDM model, what we also argued to have consequences related to DM phenomenology in accordance to results of BOSS [22]. But comparing with the left panel, the influence of the coupling is weaker in the right panel. This is easy to understand, because in the right panel the interaction is proportional to the DE density, which was weaker than that of DM at early times in the universe.

Besides the background dynamics, we can extend the study to the linear relativistic evolution of the system of DE and DM. The gauge invariant linear perturbation equations of the system were derived in [13, 23] and using the phenomenological form of the energy transfer between dark sectors defined above, the equations yield

$$D'_{dm} = -k U_{dm} + 3H\Psi(\lambda_1 + \lambda_2/r) - 3(\lambda_1 + \lambda_2/r)\Phi' + 3H\lambda_2(D_{de} - D_{dm})/r,$$

$$U'_{dm} = -\dot{H}U_{dm} + k\Psi - 3\dot{H}(\lambda_1 + \lambda_2/r)U_{dm};$$

$$D'_{de} = -3\dot{H}(C_e^2 - w)D_{de} + (3w' - 9\dot{H}(w - C_e^2)(\lambda_1 r + \lambda_2 + 3 + w)\Phi,$$

$$- 9\dot{H}^2(C_e^2 - C_a^2)\frac{U_{de}}{k} + 3(\lambda_1 r + \lambda_2)\Phi' - 3H\Psi(\lambda_1 r + \lambda_2) + 3H\lambda_1 r(D_{de} - D_{dm})$$

$$- 9\dot{H}^2(C_e^2 - C_a^2)(\lambda_1 r + \lambda_2)\frac{U_{de}}{(1 + w)k} - kU_{de},$$

$$U'_{de} = -\dot{H}(1 - 3w)U_{de} - 3kC_e^2(\lambda_1 r + \lambda_2 + 3 + w)\Phi + 3H(C_e^2 - C_a^2)(\lambda_1 r + \lambda_2)\frac{U_{de}}{(1 + w)}$$

$$+ 3(C_e^2 - C_a^2)H U_{de} + kC_e^2 D_{de} + (1 + w)k\Psi + 3H(\lambda_1 r + \lambda_2)U_{de},$$

where $\Psi, \Phi$ are gauge invariant gravitational potentials, $D_\alpha = \delta_\alpha - \frac{\rho_{de}}{\rho} \Phi$ is the gauge invariant density contrast,
\[ U_{\alpha} = (1 + w_{\alpha})V_{\alpha}, \quad V_{\alpha} \] is the gauge invariant peculiar velocity, and \( r \equiv \rho_{dm}/\rho_{de} \) is the energy density ratio of DM and DE. \( C_{a} \) is the adiabatic sound speed of DE and \( C_{c} \) is the effective sound speed of DE which we will set to be 1 in this work. Having these perturbation equations, we are in a position to discuss the evolutions of DE and DM density perturbations.

Assuming \( \lambda_1 = \lambda_2 = 0 \) in (3), we display the evolution of the DE perturbation in Figure 4. In contrast to the DE models with constant EoS, which always have very small DE fluctuations, we see that although the fluctuation of EDE decays to zero as its EoS approaches to the cosmological constant, at early times, when EDE started to play a significant role, its fluctuation was not too small. It would be interesting to investigate how the EDE perturbation influences the growth of DM perturbations. We display the result in Figure 5(a) where we show the evolution of the DM perturbation when there is different kinds of DE. It is clear that the earlier presence of non-negligible DE fractional density in the background suppresses the growth in the DM perturbation. To see more closely, we have compared the evolution of the DM perturbation to the standard ΛCDM model in Figure 5(b). DM perturbations were suppressed compared with ΛCDM model if DE is described by EDE2, constant \( w = -1.1 \). The only exception is when DE has a constant EoS \( w = -1.1 \). The difference in the structure growth from that of the ΛCDM model can be mainly attributed to the differences in the background DE fractional energy density from the standard ΛCDM model. The suppression of the growth of perturbations was caused by the excessive amount of DE than that in the ΛCDM model at early epoch, which hindered gravitational attraction and weakened the growth of DM perturbations. For the EDE models, especially EDE1, the further excess of \( \Omega_{de} \) at early times suppresses the structure growth even more. The solid lines indicate the models having DE perturbation, while the dashed lines are for the homogeneous DE models where the DE perturbations are neglected. For the DE models with constant EoS, the difference of effects on the DM perturbations caused by homogeneous and inhomogeneous DE are negligible. This can be further seen in Figure 5(c). But for EDE models, we clearly see the differences between the solid and dashed lines for the inhomogeneous and homogeneous DE. Figure 5(c) shows this property much clearer. This is understandable for the DE with constant EoS, the DE perturbation itself is tiny. However for the EDE models, we clearly see that different from the homogeneous DE model, the DE perturbations do have impact on DM perturbations.

Considering the interaction between dark sectors, the study becomes more complicated. To see clearly the influence of the interaction in dark sectors on the linear perturbations, we concentrate on the DE model EDE1. Similar property can also be found for EDE2. In Figure 6(a), we see that at the present moment for the model with energy decay from EDE to DM, the DM perturbation is smaller, which is different from the case with energy decay in the opposite direction. This is easy to understand, because for the positive coupling the background \( \Omega_{de} \) was bigger in the past, which hindered the structure growth. In Figure 6(b), we present the comparison of the DM perturbations between the interacting EDE model and the ΛCDM model. It is clear that comparing with ΛCDM model, EDE interacting with DM allows weaker DM perturbations. For the interaction between dark sectors proportional to the energy density of DM, the effect of interaction showed up earlier. A positive \( \lambda_1 \) implies more DE in the past, bringing further suppression in the DM perturbations at early time. For the interaction between dark sectors proportional to the density of DE, the effect showed up later when the DE started to dominate. A positive \( \lambda_2 \) indicates the energy flow from EDE to DM, which implies that there was more DE in the past, preventing the DM perturbations further. This explains why the line in Figure 6(b) with positive \( \lambda_2 \) drops faster. For the negative \( \lambda_2 \), the energy flows from DM to
DE. To have the observed amount of DM now, we must have more DM in the past, which would imply further growth of DM perturbation. Since this effect of interaction started to appear when DE became important and became more influential in the process of the acceleration of the universe, we see the lines with positive and negative \( \lambda \) accordingly in Figure 6(b). The solid and dashed lines in Figure 6(b) are for inhomogeneous and homogeneous DE, respectively. We see that DM perturbations differ by including the DE perturbations or not. This can be seen much clearer in Figure 6(c). Comparing with Fig. 5(c) we see that when energy flows from DE to DM, the difference in the DM perturbations caused by the inhomogeneous DE and homogeneous DE is enlarged. Also from Figure 6(c) we see that the difference in the DM perturbations between inhomogeneous and homogeneous DE is more sensitive to the coupling if it is proportional to the energy density of DM.

III. CMB POWER SPECTRUM

Once we have the understanding of the linear perturbations for DM and DE, we can proceed to study the effects of DE models on the CMB. On large scales, the CMB power spectrum is composed of the ordinary Sachs-Wolfe (SW) effect and the Integrated SW (ISW) effect. The SW effect indicates the photons’ initial condition when it left the last scattering surface while the ISW effect is the contribution due to the change of the gravitational potential when photons passing through the universe on their way to earth. The gauge invariant gravitational potential in the absence of anisotropic stress can be given by the Poisson equation \( k^2 \Phi = -\frac{4\pi G}{a^2} \delta \rho \). Its derivative in DM plus DE universe, which is the source term for the ISW contribution, is given by \( k^2 \Phi' = -\frac{4\pi G}{a^2} \left[ a^2 (\delta \rho_{dm} + \delta \rho_{de}) \right] \). Thus the large scale CMB power spectrum depends on the evolution of the density perturbations of DE and DM. However it should be noted that ISW effect is complicated. Besides density perturbations in DM and DE, other cosmological parameters such as the EoS of DE, background energy densities and \( H_0 \) etc. also have influence on it. Only for the same background evolution, the large scale CMB power spectrum can be interpreted in terms of the evolution of the density perturbations for DE and DM.

Neglecting the interaction between dark sectors, for the DE with constant EoS \( w = -0.9 \), we show the CMB power spectrum in Figure 7(a). Comparing with the ΛCDM model, there is little difference in CMB at small \( l \) ISW effect. The ISW effect difference relates to the gravitational potential varying in time, which presents basically very little difference between the DE with constant EoS and the ΛCDM. For the DE with constant EoS, the CMB power spectrum keeps the same no matter we include the DE fluctuations in the computation or not. The DE fluctuations do not show up in the CMB power spectrum. This is because for DE with constant EoS, the DE perturbation is negligible. And the result at large scale CMB power spectrum agrees with what disclosed in the growth of DM perturbation in the previous section where the DE fluctuations do not show up for the DE with constant EoS. Thus including the DE fluctuations, the CMB power spectrum is just described the same as we do not take perturbations into account.
FIG. 5: (a) The evolutions of DM perturbations. (b) The comparison of DM perturbation evolutions with that of $\Lambda$CDM model. (c) The comparison of DM perturbation evolutions with and without DE perturbations. The solid lines refer to models taking into account DE perturbations. The dashed lines refer to the models assuming homogenous DE.

For the EDE models, we observe some interesting results in CMB. We considered both cases where EDE is homogeneous and inhomogeneous in Figures 8. Besides a slight shift in the CMB peak position, the power spectrum at small $l$ is different if we compare the situations with or without DE perturbations. For a homogeneous EDE neglecting the DE fluctuations, the small $l$ spectrum is suppressed as compared with the $\Lambda$CDM, while for the inhomogeneous EDE by considering DE fluctuations, we observe an enhanced power spectrum at low $l$ with respect to the $\Lambda$CDM. For a given EDE model, the evolutions of background cosmological parameters are the same, the differences in the large scale CMB power spectrum can be attributed to the evolutions of DE and DM density perturbations. In the last section, we learnt that the inhomogeneity in EDE will have an impact on the DM perturbations. For the inhomogeneous EDE, the DM perturbation is stronger. The inhomogeneous EDE perturbation also evolves with time. These effects result in a change of the gravitational potential and the variation of the gravitational potential in time leads to the differences in the ISW effect in CMB.

Including interaction between dark sectors, we have a richer physics in CMB. In the left panel of Figure 9, we present the CMB power spectrum for the interaction proportional to the energy density of DM. With a positive interaction, we see that the difference at low $l$ CMB between homogeneous and inhomogeneous EDE is enlarged compared with the zero coupling case. This can be attributed to the enlarged differences in the EDE perturbations together with the DM perturbations caused by whether we include the EDE fluctuations or not in the presence of
the interaction between dark sectors. Besides the difference we observe at low $l$, at the first peak the differences between homogeneous and inhomogeneous EDE for the same coupling is small. In the right panel we show the influence of interaction proportional to the energy density of DE. With inhomogeneous EDE, the interaction makes the power spectrum higher (the blue solid line) at low $l$. But with homogeneous EDE, the power spectrum at small $l$ drops lower (the blue dashed line). The interaction between dark sectors enlarge the differences in the small $l$ CMB power spectrum between homogeneous and inhomogeneous EDE. Making the strength of the interaction stronger ($\lambda_2 = 0.05$), we see the clear enhancement of the first peak.

To disclose the influence of different forms and strength of the interaction, we show the CMB power spectrum for EDE1 with various interactions as well as $\Lambda$CDM in Figure 10. DE is assumed inhomogeneous in the computations. We see that when the interaction is proportional to the density of DM, its signature shows up not only at small $l$ but also at the first peak of CMB. A larger $\lambda_1$ accommodates the suppression at low $l$ spectrum but also the enhancement of the first peak. If the interaction is proportional to the energy density of DE, the coupling $\lambda_2$ presents consistent behaviors both at low $l$ and the first peak: a larger $\lambda_2$ leads to the enhancement of the power spectrum. For the EDE models, the influences of the interaction between dark sectors present the same qualitative influence on CMB.


FIG. 7: CMB power spectrum and potential change for DE with constant EoS $w = -0.9$

FIG. 8: CMB power spectrum for DE models EDE1 in (a) and EDE2 in (b). For the EDE models, the solid lines refer to inhomogeneous DE and the dashed lines refer to homogeneous DE.

as compared with the DE with constant EoS [19, 29].

IV. FITTING RESULTS

In this section we fit the EDE models using Markov chain Monte Carlo (MCMC) analysis. For each model, the fittings are carried out using two datasets: the CMB observations from Planck [30–32] and a combined dataset of Planck+BAO [33, 34, 35]+SN [36]+$H_0$ [37]. We try to use these observational data to distinguish between homogeneous and inhomogeneous EDE models. Moreover we constrain the interaction between EDE and DM. In our numerical fittings, we set the priors of different cosmological parameters as in Table I.

We first assume that DE and DM evolve independently in the MCMC analysis. For the inhomogeneous EDE, with Planck data alone, we show the results in Table II. The likelihoods for parameters $w_0$ and $b$ in the EDE model are
FIG. 9: CMB power spectrum for EDE1 coupling with DM. In (a) $\lambda_2 = 0$. In (b) $\lambda_1 = 0$. For the EDE models, the solid lines refer to inhomogeneous DE and the dashed lines refer to homogeneous DE.

FIG. 10: CMB power spectrum for EDE1 when DE interacting with DM. In (a) $\lambda_2 = 0$. In (b) $\lambda_1 = 0$. DE fluctuations are taken into account in the computations.

shown in the upper panel of Figure 11. Using the combined dataset, we can see how the constraints improve. We list the results in Table III and exhibit the likelihoods in the lower panel of Figure 11. It is easy to see that the addition of the complementary data clearly enhances the constraints on the EDE model. This is because the parameters which could be degenerate with the EDE parameters in CMB power spectrum, such as the Hubble parameter, are well-constrained by other observations.

We next look at the case where DE perturbations are neglected. Performing an analysis with Planck data alone, we show the fitting results in Table III and likelihoods for the EDE model parameters in the upper panel of Figure 12. We find that for a homogeneous EDE, its CMB constraint is better than that of an inhomogeneous EDE. This can be understood because homogeneous EDE leads to the suppression in the low $l$ CMB power spectrum, which is consistent with the Planck data. The result of the joint analysis is reported in Table III and the lower panel of Figure 12. We find that although $w_0$ is similar to that in an inhomogeneous EDE model, the EDE parameter $b$ is rather
different. For the homogeneous EDE, the constrained $b$ is bigger and its lower bound is far away from zero, instead of closing to zero as for the inhomogeneous EDE model. From (1), it is clear that the EDE was more important at early times if $b$ is bigger. Thus the homogeneous EDE exhibits more earlier influence of DE in the universe.

Considering the interaction between DE and DM, we carry out the MCMC analysis again. We show the likelihoods in Figures 13 and 14 for using the combined datasets for inhomogeneous and homogeneous EDE respectively. The best fitting values and $1\sigma$ ranges are listed in Table IV and Table V. We noticed that both the DE perturbation and the suitable coupling between dark sectors can influence the low $l$ CMB power spectrum. But between these two factors, we observed in the above theoretical discussions that the small $l$ CMB power spectrum is more sensitive to the interaction between dark sectors. For this reason, including the coupling between dark sectors, we find similar fitting results of the EDE parameters and the coupling strength for homogeneous and inhomogeneous DE. DE perturbations have little influence if the coupling is present. In the inhomogeneous EDE, the coupling between dark sectors is mostly favored to be positive in the $1\sigma$ constraint range, which is independent of the form of the interaction. For a homogeneous EDE, the coupling is constrained to be nearly positive in the $1\sigma$ range, if it is proportional to the energy density of DM. However, if the interaction between dark sectors is proportional to the energy density of DE, its $1\sigma$ range straddles zero, which implies no coupling from the global fitting.

To examine whether the EDE models allowed by the observations is effective to alleviate the coincidence problem, we plot in Figure 15 the ratio of DM energy density to DE energy density in the best-fit EDE models of the joint analysis and compare them with the $\Lambda$CDM prediction. It is easy to see that for the homogeneous EDE model, it has longer period for DE and DM to be comparable compared with the inhomogeneous EDE model. This property is valid no matter whether there is interaction between dark sectors or not. Comparing two forms of interactions between dark sectors, we find that if the interaction is proportional to the energy density of DM, the ratio is more flattened than that if there is no interaction and if the interaction is proportional to the energy density of DE. So for this kind of interaction, the coincidence problem is less acute. We conclude that the EDE model is compatible with observations and it is effective to alleviate the coincidence problem.

| Parameter | Prior |
|-----------|-------|
| $\Omega b^2$ | $[0.005, 0.1]$ |
| $\Omega_{dm} h^2$ | $[0.001, 0.5]$ |
| $100\theta$ | $[0.5, 10]$ |
| $\tau$ | $[0.01, 0.8]$ |
| $n_s$ | $[0.9, 1.1]$ |
| $\log(10^{10} A_s)$ | $[2.7, 4]$ |
| $w_0$ | $[-3, -0.3]$ |
| $b$ | $[0.01, 1]$ |
| $\lambda_1$ | $[-0.5, 0.5]$ |
| $\lambda_2$ | $[-0.5, 0.5]$ |

| Parameter | Planck | Planck+BAO+SN+H0 |
|-----------|--------|------------------|
| $w_0$ | $-0.852$ | $-0.852$ |
| $b_0$ | $0.825$ | $0.825$ |

| Parameter | Planck | Planck+BAO+SN+H0 |
|-----------|--------|------------------|
| $w_0$ | $-1.343$ | $-1.343$ |
| $b_0$ | $0.896$ | $0.896$ |
FIG. 11: Fitting results of the inhomogeneous EDE model. The upper panel is from the Planck data alone, while the lower panel is from the combined dataset.

### TABLE IV: Best fit values and 68% C.L. constraints on inhomogeneous EDE models with interaction using the combined dataset of Planck+BAO+SN+$H_0$

| Parameter | $w_0$ | $b_0$ | $\lambda_1$ | $\lambda_2$ |
|-----------|-------|-------|--------------|--------------|
| $w_0$     | -1.318 | -1.220 | -0.0002295   | -            |
| $b_0$     | 0.101  | 0.103 | 0.00002295   | -            |
| $\lambda_1$ | 0.00002295 | 0.00002295 | -0.000232 | -            |
| $\lambda_2$ | -      | -     | -            | 0.01111     |

### TABLE V: Best fit values and 68% C.L. constraints on homogeneous models with interaction using the combined dataset of Planck+BAO+SN+$H_0$

| Parameter | $w_0$ | $b_0$ | $\lambda_1$ | $\lambda_2$ |
|-----------|-------|-------|--------------|--------------|
| $w_0$     | -1.293 | -1.236 | -1.252       | -0.019       |
| $b_0$     | 0.566  | 0.631 | 0.495        | -            |
| $\lambda_1$ | 0.000616 | 0.000445 | -0.000498 | -            |
| $\lambda_2$ | -      | -     | -            | 0.0474      |
V. CONCLUSIONS AND DISCUSSIONS

In this paper we have studied the influence of the EDE on the DM perturbations. We have observed that, different from DE models with constant EoS, DM perturbation is larger in inhomogeneous EDE models than in homogeneous EDE model in which DE fluctuation is neglected. We have also disclosed the effects of inhomogeneous and homogeneous EDE on the large scale CMB power spectrum. It is expected that the observations of growth of large scale structure and CMB angular power spectrum can help to distinguish between homogeneous and inhomogeneous EDE models.

Furthermore we have extended our discussion by including the interaction between EDE and DM. We have observed that a coupling between EDE and DM can also show up in the DM perturbations and the small $l$ CMB power spectrum, which may degenerate with the effect of the DE fluctuations. Comparing these effects, we have found that the interaction between EDE and DM influences more on the DM perturbations and the ISW effect in the large scale CMB.

We have confronted the EDE models to Planck data and a combined dataset of Planck+BAO+SN+$H_0$. The analysis showed that the coincidence problem in all allowed EDE models we have interest in are less severe than in ΛCDM model. For the homogeneous EDE, there is a longer period for DE and DM to be comparable than the case for the inhomogeneous EDE. This holds no matter whether there is interaction between EDE and DM or not. The positive coupling between EDE and DM proportional to the energy density of DM is an effective factor to alleviate the coincidence problem.

FIG. 12: Fitting results of the homogeneous EDE model. The upper panel is from the Planck data alone, while the lower panel is from the combined dataset.
FIG. 13: Global fitting results of the inhomogeneous EDE model with interaction. The upper panel is for the interaction proportional to the energy density of DM, while the lower panel is for the interaction proportional to the energy density of DE.

FIG. 14: Global fitting results of the homogeneous EDE model with interaction. The upper panel is for the interaction proportional to the energy density of DM, while the lower panel is for the interaction proportional to the energy density of DE.
FIG. 15: Ratio of DM energy density to DE energy density of best-fit EDE models. The solid lines refer to models taking into account DE perturbations. The dashed lines refer to the models assuming homogenous DE.

It is interesting to further examine whether the disclosed impacts of the DE fluctuations and the interaction between DE and DM on observables are specific to EDE models. A lot of efforts on this problem are called for.

Acknowledgments

We acknowledge financial supports from National Basic Research Program of China (973 Program 2013CB834900) and National Natural Science Foundation of China. E.A. acknowledges financial support from CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico) and from FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo).

[1] S. Weinberg, Rev. Mod. Phys. 61 1(1989).
[2] L. P. Chimento, A. S. Jakubi, D. Pavon, and W. Zimdahl, Phys. Rev. D67, 083513 (2003), arXiv: astro-ph/0303145 [astro-ph].
[3] M. Doran, M. Lilley, J. Schwindt, C. Wetterich, ApJ. 559 501(2001)
[4] U. Alam, ApJ. 714 1460, arXiv: 1003.1259(2010)
[5] M. Doran, K. Karwan, C. Wetterich, JCAP. 0511 007(2005), arXiv: astro-ph/050813
[6] P. Wu, H. Yu, Phys. Lett. B643 315(2006), arXiv: astro-ph/0611507
[7] J. Bielefeld, W.L.Kimmy Wu, R.R. Caldwell, O. Dore, Phys.Rev. D88 103004(2013), arXiv: 1305.2209
[8] J.Q Xia, M. Viel, JCAP. 0904 002(2009), arXiv: 0901.0605
[9] C.M. Müller, G. Schäfer, C. Wetterich, Phys.Rev. D70 083504(2004)
[10] M. Bartelmann, M. Doran, C. Wetterich, A&A. 454 27(2006)
[11] U. Alam, Z. Lukic, S. Bhattacharyya, ApJ. 727 87(2011)
[12] F. Fontanot, V. Springel, R. E. Angulo, B. Henriques, MNRAS. 426 2335(2012)
[13] M. Grossi, V. Springel, MNRAS. 394 1559(2009)
[14] R. C. Batista, F. Pace, JCAP. 1306 044(2013)
[15] M. Baldi, MNRAS. 422 1028(2012)
[16] C. Wetterich, Phys.Lett. B594 17(2004)
[17] A.A. Costa, X.D. Xu, B. Wang, E.G.M. Ferreira, E. Abdalla, Phys.Rev. D89 103531(2014)
[18] X.D. Xu, B. Wang, P.J. Zhang, F. Atrio-Barandela, JCAP, 1312 001(2013), arXiv: 1308.1475
[19] J.H. He, B. Wang, E. Abdalla, Phys.Rev. D83 063515(2011), arXiv: 1012.3904
[20] J.H. He, B. Wang, E. Abdalla, D. Pavon, JCAP. 1012 022(2010), arXiv: 1001.0079
[21] E. Abdalla, L. R. W. Abramo, J. Sodre, L., B. Wang, Phys.Lett. B673 107(2009), arXiv: 0710.1198
[22] E. Abdalla, E.G. M. Ferreira, J. Quintin and Bin Wang, arXiv: 1412.2777
[23] E. Abdalla, L. Graef, B. Wang, Phys.Lett. B726 786(2012), arXiv: 1202.0499
[24] S. Micheletti, E. Abdalla, B Wang, Phys.Rev. D79 123506(2009)
[25] S. Micheletti, JCAP. 1005 009(2010)
[26] O. Bertolami, P. Carrilho, J. Paramos, Phys.Rev. D86 103522(2012)
[27] J.H. He, B. Wang, E. Abdalla, Phys.Lett. B671 139(2009), arXiv: 0807.3471
[28] J.H. He, B. Wang, Y.P. Jing, JCAP. 0907 030(2009), arXiv: 0902.0660
[29] J.H. He, B. Wang, P.J. Zhang, Phys.Rev. D80 063530(2009), arXiv: 0906.0677
[30] Planck Collaboration I. A&A 571, A1(2014), arXiv: 1303.5062
[31] Planck Collaboration XVI. A&A 571, A16(2014), arXiv: 1303.5076
[32] Planck Collaboration XV. A&A 571, A15(2014), arXiv: 1303.5075
[33] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, et al., MNRAS. 416 3017(2011), arXiv: 1106.3366
[34] N. Padmanabhan, X. Xu, D. J. Eisenstein, R. Scalzo, A. J. Cuesta, et al., MNRAS. 427 2132(2012), arXiv: 1202.0090
[35] L. Anderson, E. Aubourg, S. Bailey, D. Bizyaev, M. Blanton, et al., MNRAS. 427 3435(2013), arXiv: 1203.6594
[36] N. Suzuki, D. Rubin, C. Lidman, G. Aldering, R. Amanullah, et al., Apj. 746 85(2012), arXiv: 1105.3470
[37] A. G. Riess, L. Macri, S. Casertano, H. Lampeitl, H. C. Ferguson, et al., Apj. 730 119(2011), arXiv: 1103.2976