Constraining interacting dark energy with CMB and BAO future surveys.

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We perform a forecast analysis on the ability of future baryonic acoustic oscillation (BAO) and cosmic microwave background (CMB) experiments in constraining interacting dark energy models using the well known Fisher-matrix formalism. We consider a Euclid-like experiment, in which BAO measurements is one of its main goals, to constrain the cosmological parameters of alternative cosmological models. Moreover, we include in the analysis a future ground-based CMB experiment mainly designed to measure the polarization signal with high precision. In the interacting dark energy scenario, a coupling between dark matter and dark energy modifies the conservation equations such that the fluid equations for both constituents are conserved as the total energy density of the dark sector. In this context, we consider three phenomenological models which have been deeply investigated in literature in the past years. We find that the combination of both CMB and BAO can break degeneracies among the parameters for all three models, in particular for the parameters related to the dark sector. We found powerful constraints on, for example, the coupling constant when comparing it with present limits for two of the models, and their future statistical 3-σ bounds could potentially exclude the null interaction for the combination of probes that is considered.

Keywords: Dark energy, dark matter, BAO, CMB

1. Introduction

Considering the standard cosmological model, the dark energy assumes its simplest form as the cosmological constant Λ, leading to the so-called ΛCDM model. Despite of successfully explaining the observations [1], the the standard model faces some difficulties, especially in the dark sector. The dark matter particles are far from detection, and its physics is still unknown. The cosmological constant theoretical predictions estimate the value of a vacuum energy density orders of magnitude larger than its actual observed value. In addition, the present values of the dark matter and dark energy densities are at the same other of magnitude even though they do not share the same cosmological evolutionary behaviour, problem known as cosmic coincidence [2]. To overcome some of these problems, models where dark matter and dark energy interact started to be considered, becoming very useful to alleviate this coincidence problem. An interacting dark matter and dark energy scenario would affect the overall evolution of the universe and its expansion history, thus observationally distinguishable from the ΛCDM model. The interaction can then be constrained by the data, becoming a testable theory for the universe.The present observations, however, are not able to confidently distinguish between these alternative interacting dark energy models and the ΛCDM. Our goal is to test their ability to constraint the interacting dark energy models described in the next section.

2. The interacting dark energy models

In the standard cosmological model the energy density of radiation, baryons, cold dark matter and dark energy is conserved separately, for each component. Conversely, in an interacting dark energy model, the fluid equations for the dark energy and dark matter are not conserved individually, but together as the total energy density of the dark sector such that $\dot{\rho}_{DM} + 3H\rho_{DM} = +Q$ and $\dot{\rho}_{DE} + 3H(1+\omega_{DE})\rho_{DE} = -Q$, where H is the Hubble parameter, ρ_{DM} and ρ_{DE} are the energy densities for dark matter and dark energy, respectively, and $\omega_{DE} = P_{DE}/\rho_{DE}$ is the dark energy EoS. Q represents the interaction kernel that can be written phenomenologically as $Q = 3H(\xi_1\rho_{DM} + \xi_2\rho_{DE})$, being the coupling coefficients (ξ_1 and ξ_2) constants to be determined by observations [4, 5]. The energy flow from dark energy to dark matter is defined by $Q > 0$, and the opposite for $Q < 0$. Considering the stability of the model (see, for instance, [6]), two choices are made: The first, $\xi_1 = 0$ and $\xi_2 \neq 0$, satisfying a constant dark energy EoS within the range $-1 < \omega_{DE} < 1$ (described as model 1), or $\omega_{DE} < -1$ (model 2). The second, $\xi_2 = 0$ and $\xi_1 \neq 0$ for $\omega_{DE} < -1$, defining our third considered model. For all three models, the other components follow the standard conservation equations. For a review on the topic refer to [7].

3. The fisher formalism

The baryonic acoustic oscillation (BAO) is an important observable currently used to constrain the cosmological parameters, more efficiently in combination with other probes, such as the CMB. The information stored in the BAO present in the matter power spectrum can precisely determine the Hubble parameter $H(z)$ and the angular diameter distance $Da(z)$ as a function of the redshift, which subsequently enables the calculation of the dark energy parameters constraints (for details on this methodology see [8]). The energy densities for dark matter and dark energy for the models considered here can be found in [9]. For the matter power spectrum obtained from galaxy surveys, generated using a modified version of CAMB software package [10], the Fisher matrix is given by [11]

$$F_{ij} = \int_{-1}^{1} \int_{k_{\min}}^{k_{\max}} \frac{\partial \ln P(k,\mu)}{\partial p_i} \frac{\partial \ln P(k,\mu)}{\partial p_j} V_{\text{eff}}(k,\mu) \frac{2\pi k^2 dk d\mu}{2(2\pi)^3}. \tag{1}$$

being V_{eff} the effective volume of the survey. We present the expected cosmological implications of the BAO measurements for an Euclid-like survey (for specifications on Euclid, see, for example, [12]).

Furthermore, we use the CMB information as a second probe to forecast the parameters of the interacting dark energy models described here. We do not consider primordial $B-$mode. We then construct the Fisher matrix for the CMB temperature anisotropy and polarization [13].

$$F_{ij} = \sum_{l} \sum_{XY} \frac{\partial C_l^X}{\partial p_i} (Cov_l^{-1})_{XY} \frac{\partial C_l^Y}{\partial p_j}, \tag{2}$$

being C_l^X the power in the l-th multipole, X stands for TT (temperature), EE (E-mode polarization), TE (temperature and E-mode polarization cross-correlation) and $(Cov_l^{-1})_{XY}$ the covariance matrix. For the definition and the elements of the covariance matrix refer to [13]. We consider the Advanced Atacama Cosmology telescope (ACTadv) instrumental setup as described in [14]. The ACTadv is supposed to obtain precise measurements of the CMB small-scale polarization, which can lead on probing alternative cosmological models.

4. Results and conclusions

We combine the Fisher matrices for the BAO and CMB future measurements from Euclid and ACTadv surveys, respectively. The marginalised error for the dark energy EoS in model 1 improves drastically for the combined analysis, being $\sigma(\omega) = 0.026$ for Euclid, $\sigma(\omega) = 0.028$ for the ACTadv and $\sigma(\omega) = 0.0044$ for their combination: an improvement by a factor of ~ 6 when compared with each individual probe. The constraint on the dark matter density improves by a factor of ~ 3 for the combined analysis ($\sigma(h^2\Omega_c) = 0.00053$), compared with Euclid alone ($\sigma(h^2\Omega_c) = 0.0017$). A similar improvement occurs for the coupling constant, where we find $\sigma(\xi_2) = 0.0037$ for Euclid alone and $\sigma(\xi_2) = 0.0019$ for ACTadv + Euclid. Such stringent constraint would exclude the null interaction correspondent to the ΛCDM model with high confidence. Present constraints on $h^2\Omega_c$, ω and ξ_2 for a combination of probes (Planck+BAO+SNIa+H0) show $h^2\Omega_c = 0.0792^{+0.0348}_{-0.0166}$, $\omega = -0.9191^{+0.0222}_{-0.0839}$ and $\xi_2 = -0.1107^{+0.085}_{-0.0506}$ [3]. The constraints on model 1 from the present datasets are affected by the degeneracies among the parameters, more evident between $h^2\Omega_c$ and ξ_2. It is clear by our analysis that Euclid information can help break the degeneracies between these parameters, therefore providing tight constraints on $h^2\Omega_c$, ω and ξ_2.

The same occurs for model 2. The combined result leads to stringent constraints on $\sigma(h^2\Omega_c)$, $\sigma(\omega)$ and $\sigma(\xi_2)$, the latter being $\xi_2 = 0.03798 \pm 0.00310$ at 1σ. A zero positive interaction is excluded by [3] with $\xi_2 = 0.02047^{+0.00565}_{-0.00667}$ at 1σ. The future combination of ACTadv and Euclide-like surveys would be able to improve this constraint by a factor of ~ 2.

As for model 3, degeneracies between the dark sector parameters do not play such an important role compared with models 1 and 2. However, the significance on the ξ_1 constraint is low at the current observational stage, being $\xi_1 = 0.0007127^{+0.000256}_{-0.000633}$

at 1σ, considering a combination of probes: Planck, SNIa, BAO, H_0 [3]. We found $\xi_2 = 0.0007273 \pm 0.00034$ (ACTadv + Euclid), which does not improve the actual best constraint. For this model, a combination of other probes is still needed in order to tighten the present limits.

It is well known the advantages of combining different observational probes in constraining cosmological parameters, and its implication to interacting dark energy models has been widely addressed. In our context, for models 1 and 2, stringent constraints were found in the dark sector parameters for the combined probes, especially for the coupling constant, being the $1-\sigma$ bound of $\xi_2 = -0.0929 \pm 0.0019$ and $\xi_2 = 0.03798 \pm 0.00310$, respectively. Future CMB and BAO experiments combined, such as presented here, would be able to exclude the null interaction with more than 3σ C.L. The present dataset and the future CMB information alone are affected by degeneracies that can be broken by the addition of Euclid BAO measurements, thus tighten the constraints on the dark sector cosmological parameters, and enabling a deeper discussion on these interacting dark energy scenarios. Conversely, the constraint on the coupling constant for model 3 is not improved by the combination of future CMB and BAO information compared with its constraint derived by present dataset. Extra information is still necessary for probing this model.

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