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Constraints on parameterized dark energy properties from new observations with principal component analysis

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ABSTRACT

For dark energy, the equation of state (EoS) is a critical parameter to depict its physical properties. In this paper, we mainly give constraints on the EoS of dark energy w with the latest observations of cosmic microwave background radiation (CMB) from Planck satellite, JLA Type Ia supernovae (SNIa) sample, baryon acoustic oscillation (BAO) and Hubble parameter measurements. We introduce a kind of parameterized dark energy model called "constant $bin-w$", in which the whole redshift range is divided into several bins, and EoS w in each bin is assumed as an independent constant. The results show that EoS in all of the redshift bins are comparable with ΛCDM in the 2σ confidence regions, but some weak deviations from $w=-1$ are still indicated. In particular, in the framework of 7 bins, a slight oscillation behavior is shown in the redshift $0 < z < 0.75$, especially around the range of *4th* bin ($0.25 < z < 0.35$) and *5th* bin ($0.35 < z < 0.51$). Additionally, we adopt the principal component analysis (PCA) method to do the model-independent analysis, which includes normal PCA and localized PCA methods. By implementing so called normal PCA method, the original oscillation behavior of EoS indicated in the framework of 7 bins becomes more significant after the best reconstruction, but such result still supports ΛCDM within the margin of 2σ errors. To further reduce the errors of constraints on EoS, and confirm such deviations from the cosmological constant scenario, we hope for more precise observational data in the future.

1. Introduction

The discovery of the acceleration of cosmic expansion poses a primary issues to fundamental physics and modern cosmology: what is the behind cause of driving the acceleration? Within the framework of Einstein's general relativity (GR), the acceleration expansion is ascribed to a mysterious component called dark energy (DE), which comprises about 70% of the energy density of the universe and provides a exotic repulsive pressure. Until now, we almost know nothing about the nature of dark energy, so a variety of assumptions have been proposed to explain its physics, which include the vacuum energy, and some kinds of dynamical scalar field, such as quintessence [1–4], phantom [5], quintom [6–10] and so on. These different DE models can be identified by the value of the equation of state (EoS) w, which is defined as the ratio of pressure and energy density of DE. For the simplest DE candidate, the vacuum energy has a constant EoS of $w=-1$ with no time evolution, while EoS is unlikely to be a constant in those generally dynamical models. Therefore, in order to examine the properties of DE, conventionally one need directly solve for $w(z)$ in the whole redshift range of evolution, or indirectly probe the redshift (or time) variation of EoS. In a word, the information of EoS is very crucial in distinguishing different DE models and understanding the underlying fundamental physics behind the phenomenon.

To extract the information of w, in most cases one needs to do parameterization and confront the parameterized models to observation. For the observation, in recent years, many kinds of observational data have been updated and got a large amount of accumulation. For instance, the JLA compilation, as a large sample of type Ia supernovae (SNIa), has been presented, which includes the data of luminosity distance vs. redshift from 740 SNIa and covers the redshift from 0 to 1.3 [11]. Also, Planck satellite has published its full-mission observations of temperature and polarization anisotropies of cosmic microwave background radiation (CMB) in 2015 [12]. This is the most precise measurements on CMB to date, which can provide us a lot of information about early universe and improve the power of SNIa survey to probe w. In addition, some new baryon acoustic oscillation (BAO) data extracted from Large Scale Structure (LSS) surveys has also been given, and so on. These new and high quality data can help to achieve better constraints on w when adopting more general types of parameterization.

For the parameterization, the relatively simple case is assuming the value of EoS in the whole redshift range as a constant w,

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namely fixing its redshift variation to zero. Such parameterization can be considered as a zero-order approximation to the true EoS. Although it can be fit for many data sets, constant w is after all a strong and insufficient prior, which may obscure the physics behind the DE [13]. Another widely used parameterization is linear $w(z)$ or CPL model [14,15], which gives a linear evolution form of EoS by setting a constant value of redshift or cosmic scale factor variation of w, and it can be seen as a first-order approximation to the true EoS. Such parameterization can be easily used to study the time variation of dark energy at linear order and many constraints work have been done on it [16–18], however, it still specifies an *ad hoc* form of EoS in a global redshift range and this may cause bias in the data fitting analysis. Given such problems, we adopt a more generalized parameterization about w, which is just based on the above "zero-order approximation": Instead of setting EoS as a globally constant value, we divide the whole redshift interval into several pieces, and keep EoS in each redshift piece as a locally constant w_i with no time variation, which is just the conventional piecewise constant EoS parameterization [19–23], and there have been many research about it.

To further treat the results of piecewise constant w in a model-independent way, one can usually adopt the method of principal component analysis (PCA). PCA, as a standard tool in data analysis, have been used more and more in the field of modern cosmology, such as in dealing with the cosmic reionization history [24], power spectra of CMB fluctuations and large scale structure data [25,26], and parameters related to the properties of dark energy. It is a relatively simple method for extracting essential information from confusing datasets. With the help of PCA, one can find patterns in data of high dimension and reduce the complex data set to a lower dimension to reveal the hidden, simplified structures but without much loss of information [27,28]. The traditional PCA method was first applied to dark energy by Huterer and Starkman in 2003 [20], in which they expanded the EoS $w(z)$ by using a series of orthogonal eigenfunctions that were determined by observational data. By retaining only some good patterns, they realized the dimension reduction of parameter space. In addition, some other variant types of PCA method have also been proposed and applied to cosmology, e.g., the localized PCA, which was first taken by Huterer and Cooray in 2005 [29], and widely used in dealing with the properties of dark energy [30–32].

In this paper, we study the constraints on piecewise constant EoS, which is done by using the observational data of Planck temperature and low-ℓ polarization power spectra, the JLA SNIa sample, the BAO measurements and the Hubble parameter data. We also adopt the PCA method. Our article is organized as follows: In Section 2, we describe the method for global fitting and the observational datasets used in the numerical analysis; Section 3 contains the results and discussions about our constraints on bin EoS; The result of PCA and its discussion occur in Section 4; The last Section 5 is the conclusions.

2. Method and data

2.1. Numerical method

First, we perform a global analysis by employing the publicly available MCMC package `CosmoMC` [33,34]. We assume the purely adiabatic initial conditions and a flat universe. The pivot scale is set at $k_{s0} = 0.05$ Mpc^{-1}. The following basic cosmological parameters are allowed to vary with top-hat priors: the physical cold dark matter energy density parameter $\Omega_c h^2 \in [0.001, 0.99]$, the physical baryon energy density parameter $\Omega_b h^2 \in [0.005, 0.1]$, the scalar spectral index $n_s \in [0.8, 1.2]$, the primordial amplitude $\ln[10^{10}A_s] \in [2, 4]$, the ratio (multiplied by 100) of the sound horizon at decoupling to the angular diameter distance to the last scattering surface $100\Theta_s \in [0.5, 10]$, and the optical depth to reionization $\tau \in [0.01, 0.8]$. In this paper, we focus on the study of dark energy, so, besides these six basic parameters, we should introduce relevant parameters for EoS of corresponding dark energy model. In dealing with the dark energy, we adopt the following parameterized models called constant $bin - w$: we divide the redshift interval $(0, z_{\max})$ into N bins and assume EoS $w(z)$ to be constant in each bin, while the neighboring bins are treated as independent ones. Then the parameters $\{w_i\}$ for EoS of dark energy $w(z)$ can be summarized in the following equations,

$$w(z) = w_1 + \sum_{i=1}^{N-1} \frac{w_{i+1} - w_i}{2} \left[1 + \tanh\left(\frac{z - z_{i+1}}{\eta}\right)\right], \tag{1}$$

where w_i stands for the value of EoS in the ith bin, z_i and z_{i+1} respectively denote the redshifts of the start and end points of the ith bin (note $z_1 = 0$), and the tanh function is adopted to link the neighbor two bins EoS transition smoothly. The parameter η is used to control the transition width of tanh, and in our calculation we keep that such transition between two bins is sharp. This treatment guarantees that $w(z)$ can be handled as a smooth function, and the value of EoS in each bin can be approximately considered as a constant w_i. For such EoS of piecewise constant bins, the energy density of dark energy component evolves as

$$\rho_X(z) = \rho_X(z=0) \left(\frac{1+z}{1+z_j}\right)^{3(1+w_j)} \prod_{i=1}^{j-1} \left(\frac{1+z_{i+1}}{1+z_i}\right)^{3(1+w_i)} \tag{2}$$

when z lies in the jth EoS bin. The $\rho_X(z)$ and $\rho_X(z=0)$ denotes the energy density of dark energy at redshift z and present respectively. Under this kind of parameterization, we set the EoS parameter $\{w_i\}$ in each bin as an extended free parameter, and give it the scale of $w_i \in [-12, 10]$.

The property of continuity in our parameterized dark energy models ensures that it is safe and convenient to handle dark energy perturbations (DEP), which plays a crucial role in the parameter estimation when using the global fitting strategy to constrain the cosmological parameters. In this paper we use the method provided in refs. [35,36] to treat DEP, and we set the value of sound speed square of dark energy perturbations $c_s^2 \equiv \delta p/\delta\rho$ in the rest frame to unity. Therefore, the most general parameter space in our analyses is:

$$\{\Omega_b h^2, \Omega_c h^2, \Theta_s, \tau, n_s, A_s, w_i\}. \tag{3}$$

2.2. Current observational data

In our analysis, we consider the following cosmological probes: i) CMB temperature power spectrum and low-ℓ polarization data; ii) luminosity distance of Type Ia supernovae; iii) the baryon acoustic oscillation in the galaxy power spectra; iv) the direct measurements on Hubble parameter at different redshifts.

For the CMB data, we combine the 2015 release of Planck high-ℓ ($30 \le \ell \le 2508$) and low-ℓ ($2 \le \ell \le 29$) CMB temperature power spectra data (denoted "Planck TT") with low-ℓ ($2 \le \ell \le 29$) TE, EE, BB polarization data (denoted "Planck lowP"). These data can be considered into fitting by using the low-ℓ temperature-polarization likelihood (*lowTEB*) and the high-ℓ temperature likelihood (*PlikTT*) provided by Planck [37]. Like our previous work, we do not include the CMB lensing data [38]. We denote the CMB data mentioned above as "*Planck*".

The luminosity distance of SNIa data is a powerful probe in studying the properties of dark energy for its influence on the cosmic expansion history. In our work, we adopt the JLA ("joint light-curve analysis") sample [11]. JLA sample is a larger joint compilation of type Ia supernovae to date compared with other SNIa datasets, which gives the Hubble diagram of 740 SNIa and provides