No Evidence for Dark Energy Dynamics from a Global Analysis of Cosmological Data

Paolo Serra1, Asantha Cooray1, Daniel E. Holz2, Alessandro Melchiorri1,3, Stefania Pandolfi1,4, Devdeep Sarkar1

1Center for Cosmology, Department of Physics and Astronomy, University of California, Irvine, CA 92697
2Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545
3Physics Department and Sezione INFN, University of Rome, “La Sapienza,” P.le Aldo Moro 2, 00185 Rome, Italy
4Physics Department and International Centre for Relativistic Astrophysics, University of Rome, “La Sapienza,” P.le Aldo Moro 2, 00185 Rome, Italy
5Physics Department, University of Michigan, Ann Arbor, MI 48109

(Dated: August 21, 2009)

We use a variant of principal component analysis to investigate the possible temporal evolution of the dark energy equation of state, \( w(z) \). We constrain \( w(z) \) in multiple redshift bins, utilizing the most recent data from Type Ia supernovae, the cosmic microwave background, baryon acoustic oscillations, the integrated Sachs-Wolfe effect, galaxy clustering, and weak lensing data. Unlike other recent analyses, we find no significant evidence for evolving dark energy; the data remains completely consistent with a cosmological constant. We also study the extent to which the time-evolution of the equation of state would be constrained by a combination of current- and future-generation surveys, such as Planck and the Joint Dark Energy Mission.

I. INTRODUCTION

One of the defining challenges for modern cosmology is understanding the physical mechanism responsible for the accelerating expansion of the Universe [1–3]. The origin of the cosmic acceleration can be due to a new source of stress-energy, called “dark energy”, a modified theory of gravity, or some mixture of both [4, 6]. Careful measurement of the expansion history of the Universe as a function of cosmic epoch is required to elucidate the source of the acceleration. In particular, existing data already allows direct exploration of possible time-variation of the dark energy equation of state.

While several recent papers have investigated the possibility of constraining the temporal evolution of dark energy (see, e.g., [8]), here we present an analysis improving and/or complementing existing work in two ways: first, we incorporate important recent data releases, including Type Ia supernovae samples (“Constitution” and “Union” datasets) and baryon acoustic oscillation data (SDSS Data Release 7). This new data provide significant improvements in the dark energy constraints. Second, we utilize principal component analysis techniques to constrain the dark energy in a model independent manner, leading to more robust and unbiased constraints.

In the absence of a well-defined and theoretically motivated model for dark energy, it is generally assumed that the dark energy equation of state (the ratio of pressure to energy density) evolves with redshift with an arbitrary functional form. Common parameterizations include a linear variation, \( w(z) = w_0 + w_a z \) [9], or an evolution that asymptotes to a constant \( w \) at high redshift, \( w(z) = w_0 + w_a z (1 + z) \) [10, 11]. However, given our complete ignorance of the underlying physical processes, it is advisable to approach our analysis of dark energy with a minimum of assumptions. Fixing an ad hoc two parameter form could lead to bias in our inference of the dark energy properties.

In this paper we measure the evolution history of the dark energy using a flexible and almost completely model independent approach, based on a variant of the principal component analysis (PCA) introduced in [12]. We determine the equation of state parameter, \( w(z) \), in five uncorrelated redshift bins, following the analysis presented in [13, 14, 19, 20]. To be conservative, we begin by using data only from geometric probes of dark energy, namely the cosmic microwave background radiation (CMB), Type Ia supernovae (SNe) and baryon acoustic oscillation data (BAO). We perform a full likelihood analysis using the Markov Chain Monte Carlo approach [34]. We then consider constraints on \( w(z) \) from a larger combination of datasets, including probes of the growth of cosmological perturbations, such as large scale structure (LSS) data. An important consideration for such an analysis is to properly take into account dark energy perturbations, and we make use of the prescription introduced in [18]. We also generate mock datasets for future experiments, such as the Joint Dark Energy Mission (JDEM) and Planck, to see how much they improve the constraints.

The paper is organized as follows: in the next section we describe our methods and the data used in our analysis; in Sec. III we present our results, and in Sec. IV we summarize and conclude.
II. ANALYSIS

The method we use to constrain the dark energy evolution is based on a modified version of the publicly available Markov Chain Monte Carlo package CosmoMC [34], with a convergence diagnostics based on the Gelman-Rubin criterion [35]. We consider a flat cosmological model described by the following set of parameters:

\[
\{w_i, \omega_b, \omega_c, \Theta_s, \tau, n_s, \log[10^{10} A_s]\},
\]  

where \(\omega_b (\equiv \Omega_b h^2)\) and \(\omega_c (\equiv \Omega_c h^2)\) are the physical baryon and cold dark matter densities relative to the critical density, \(\Theta_s\) is the ratio of the sound horizon to the angular diameter distance at decoupling, \(\tau\) is the optical depth to re-ionization, and \(A_s\) and \(n_s\) are the amplitude of the primordial spectrum and the spectral index, respectively.

As discussed above, we bin the dark energy equation of state in five redshift bins, \(w_i(z)(i = 1, 2, \ldots, 5)\), representing the value at five redshifts, \(z_i \in [0.0, 0.25, 0.50, 0.75, 1.0]\). We have explicitly verified that the use of more than five bins does not significantly improve the dark energy constraints. We need \(w(z)\) to be a smooth, continuous function, since we evaluate \(w'(z)\) in calculating the DE perturbations (and their evolution with redshift). We thus utilize a cubic spline interpolation to determine values of \(w(z)\) at redshifts in between the values \(z_i\).

For \(z > 1\) we fix the equation of state parameter at its \(z = 1\) value, since we find that current data place only weak constraints on \(w(z)\) for \(z > 1\). To summarize, our parameterization is given by:

\[
w(z) = \begin{cases} 
  w(z = 1), & z > 1; \\
  w_i, & z \leq z_{\text{max}}, z \in \{z_i\}; \\
  \text{spline}, & z \leq z_{\text{max}}, z \notin \{z_i\}. 
\end{cases}
\]

When fitting to the temporal evolution of the dark energy equation of state using cosmological measurements that are sensitive to density perturbations, such as LSS or weak lensing, one must take into account the presence of dark energy perturbations. To this end, we make use of a modified version of the publicly available code CAMB [15], with perturbations calculated following the prescription introduced by [18]. This method implements a Parameterized Post-Friedmann (PPF) prescription for the dark energy perturbations following [16, 17].

Moreover, the dark energy equation of state parameters \(w = w_i\) are correlated; we follow [13, 14] to determine uncorrelated estimates of the dark energy parameters. We calculate the covariance matrix \(C = (w_i - \langle w_i \rangle)(w_j - \langle w_j \rangle)^T \equiv \langle w w^T \rangle - \langle w \rangle\langle w^T \rangle\), using CosmoMC; we then diagonalize the resulting Fisher matrix \(F \equiv C^{-1}\), which can be written as \(F = O^T \Lambda O\), where \(\Lambda\) is the diagonalized inverse covariance of the transformed bins. The vector of uncorrelated dark energy parameters, \(q_i\) is then obtained...
TABLE I: Mean values and marginalized 68% confidence levels for the cosmological parameters. The set of $w(z)_i$ represent the measured values of the dark energy equation of state in uncorrelated redshift bins.

| Parameter | WMAP+UNION+BAO | WMAP+Constitution+BAO | all dataset | future datasets |
|-----------|----------------|------------------------|-------------|----------------|
| $\Omega_b h^2$ | 0.02281 ± 0.00057 | 0.02278 ± 0.00058 | 0.02304 ± 0.00056 | 0.02270 ± 0.00015 |
| $\Omega_c h^2$ | 0.1128 ± 0.0059 | 0.1144 ± 0.0060 | 0.1127 ± 0.0018 | 0.1100 ± 0.0012 |
| $\Omega_{\Lambda}$ | 0.728 ± 0.018 | 0.715 ± 0.017 | 0.728 ± 0.016 | 0.751 ± 0.008 |
| $n_s$ | 0.964 ± 0.014 | 0.963 ± 0.014 | 0.971 ± 0.014 | 0.962 ± 0.004 |
| $\tau$ | 0.085 ± 0.017 | 0.084 ± 0.016 | 0.088 ± 0.017 | 0.084 ± 0.05 |
| $\Delta^2_T (z)$ & $(2.40 ± 0.10) \cdot 10^{-9}$ & $(2.40 ± 0.10) \cdot 10^{-9}$ & $(2.40 ± 0.10) \cdot 10^{-9}$ & $(2.40 ± 0.10) \cdot 10^{-9}$ |
| $w(z = 1.7)$ | -- | -- | -- | $-1.55^{+0.46}_{-0.44}$ |
| $w(z = 1)$ | $-1.72^{+0.73}_{-0.81}$ | $-1.68^{+0.73}_{-0.85}$ | $-1.07^{+0.21}_{-0.20}$ | $-1.03 ± 0.10$ |
| $w(z = 0.75)$ | $-0.71^{+0.44}_{-0.47}$ | $-0.47^{+0.34}_{-0.33}$ | $-0.86^{+0.025}_{-0.26}$ | $-0.98 ± 0.08$ |
| $w(z = 0.5)$ | $-0.65^{+0.29}_{-0.30}$ | $-1.06^{+0.41}_{-0.40}$ | $-0.86 ± 0.14$ | $-1.00 ± 0.05$ |
| $w(z = 0.25)$ | $-1.05 ± 0.10$ | $-1.04 ± 0.07$ | $-1.00 ± 0.07$ | $-1.00 ± 0.02$ |
| $w(z = 0) | -0.97 ± 0.22 | -0.86 ± 0.13 | $-1.02^{+0.17}_{-0.18}$ | $-0.99 ± 0.05$ |
| $\sigma_8$ | 0.814 ± 0.055 | 0.815 ± 0.057 | 0.810 ± 0.024 | 0.811 ± 0.012 |
| $\Omega_{m}$ | 0.272 ± 0.018 | 0.285 ± 0.017 | 0.272 ± 0.016 | 0.249 ± 0.008 |
| $H_0$ | 70.7 ± 2.0 | 69.4 ± 1.7 | 70.8 ± 2.0 | 73.1 ± 1.0 |
| $z_{reion}$ | 10.8 ± 1.4 | 10.8 ± 1.4 | 11.0 ± 1.5 | 10.7 ± 0.4 |
| $t_0$ | 13.65 ± 0.14 | 13.67 ± 0.15 | 13.67 ± 0.13 | 13.60 ± 0.06 |

from $q = Ow$. If we now define $W$ so that $W^T W = F$, then, as emphasized by [43], there are infinitely many choices for the matrix $W$; following [13], we write the weight transformation matrix as $W = O^T A^4 O$ where the rows are summed such that the weights from each band add up to unity, and we apply this transformation matrix to obtain our uncorrelated estimates of dark energy parameters. Our first analysis considers constraints from “geometric” data: CMB, Type Ia SN luminosity distances, and BAO data. We subsequently include datasets that probe the growth of cosmic structures, incorporating weak lensing, as well as integrated Sachs-Wolfe measurements through cross-correlations between CMB and galaxy survey data. We include the latter datasets separately, since our understanding of the cosmic clustering in dark energy models still suffers from several limitations. These LSS uncertainties are mainly related to our poor understanding of both the bias between galaxies and matter fluctuations (with a possible scale dependence of the bias itself, see [38–40]) and non-linearities at small redshifts (see [36, 41]). For the CMB, we use data and likelihood code from the WMAP team’s 5-year release [36] (both temperature TT and polarization TE; we will refer to this analysis as WMAP5). In this respect, our approach is more extensive than that in [8] and other recent studies, since we fully consider the CMB dataset instead of simply using the constraint on the $\theta$ parameter from the analysis of [36]. This constraint is model dependent (see, e.g., [42]), and changes with dark energy parameterizations.

Supernova data come from the Union data set (UNION) produced by the Supernova Cosmology Project [21]; however, to check the consistency of our results, we also used the recently released Constitution dataset (Constitution) [7] which, with 397 Type Ia supernovae, is the largest sample to date. We also used the latest SDSS release (DR7) BAO distance scale [22, 23]: at $z = 0.275$ we have $r_s(z_d)/D_V(0.275) = 0.1390 ± 0.0037$ (where $r_s(z_d)$ is the comoving sound horizon at the baryon drag epoch, $D_V \equiv [(1+z)^2D_A^2z/H(z)]^{1/2}$, $D_A(z)$ is the angular diameter distance and $H(z)$ is the Hubble parameter) and the ratio of distances $D_V(0.35)/D_V(0.20) = 1.736 ± 0.065$. Weak lensing (WL) data are taken from CFHTLS [27] and we use the weak lensing module provided in [24, 25], with some modifications to assess the likelihood in terms of the variance of the aperture mass (Eq. 5 of [27]) with the full covariance matrix [26]. The cross-correlation between CMB and galaxy survey data is employed using the public code at [28]. We modify it to take into account the temporal evolution of the dark energy equation of state, since the code only considers $w$CDM cosmologies. We refer to [29, 30] for a description of both the methodology and the datasets used. Finally, we use the recent value of the Hubble constant from the SHOES (Supernovae and $H_0$ for the Equation of State) program, $H_0 = 74.2 ± 3.6$ km s$^{-1}$ Mpc$^{-1}$ (1σ) [32], which updates the value obtained from the Hubble Key Project [31]. We also incorporate baryon density information from Big Bang Nucleosynthesis $\Omega_b h^2 = 0.022 ± 0.002$ (1σ) [33], as well as a top-hat prior on the age of the Universe, 10 Gyr < $t_0 < 20$ Gyr.
To reinforce our conclusions, we also created several mock datasets for upcoming and future SN, BAO, and CMB experiments. The quality of future datasets allows us to constrain the dark energy evolution beyond redshift $z = 1$. We thus consider an additional bin at $z = 1.7$, with a similar constraint: $w(z > 1.7) = w(z = 1.7)$. We consider a mock catalog of 2,298 SNe, with 300 SNe uniformly distributed out to $z = 0.1$, as expected from ground-based low redshift samples, and an additional 1998 SNe binned in 32 redshift bins in the range $0.1 < z < 1.7$, as expected from JDEM or similar future surveys [44]. The error in the distance modulus for each SN is given by the intrinsic error, $\sigma_{\text{int}} = 0.1$ mag. In generating the SN catalog, we do not include the effect of gravitational lensing, as these are expected to be small [45]. In addition, we use a mock catalog of 13 BAO estimates, including 2 BAO estimates at $z = 0.2$ and $z = 0.35$, with 6% and 4.7% uncertainties in $D_V$ respectively, 4 BAO constraints at $z = [0.6, 0.8, 1.0, 1.2]$ with corresponding fiducial survey precisions in $D_V$ of [1.9, 1.5, 1.0, 0.9]% (V5N5 from [46]), and 7 BAO estimates with precision $[0.36, 0.33, 0.34, 0.33, 0.31, 0.33, 0.32]$% from $z = 1.05$ to $z = 1.65$ in steps of 0.1 [47].

We simulate Planck data using a fiducial $\Lambda$CDM model, with the best fit parameters from WMAP5, and noise properties consistent with a combination of the Planck 100–143–217 GHz channels of the HFI [48], and fitting for temperature and polarization using the full-sky likelihood function given in [49]. In addition, we use the same priors on the Hubble parameter and on the baryon density as considered above. As can be seen from Table 1 and Figure 3, future data will reduce the uncertainties in $w_i$ by a factor of at least 2, with the relative uncertainty below 10% in all but the last bin (at $z = 1.7$).

IV. CONCLUSIONS

One of the main tasks for present and future dark energy surveys is to determine whether or not the dark energy density is evolving with time. We have performed a global analysis of the latest cosmological datasets, and have constrained the dark energy equation of state using a very flexible and almost model independent parameterization. We determine the equation of state $w(z)$ in five independent redshift bins, incorporating the effects of dark energy perturbations. We find no evidence for a temporal evolution of dark energy—the data is completely consistent with a cosmological constant. This agrees with most previous results, but significantly improves the overall constraints [13, 14, 19, 20].

Bayesian evidence models strongly suggest that the dark energy is a cosmological constant, given that the cosmological constant remains a very good fit to the data as the number of dark energy parameters increases (see e.g. [50] and references therein). We show
that future experiments, such as Planck or JDEM, will be able to reduce the uncertainty on $w(z)$ to less than 10% in multiple redshift bins, thereby mapping any temporal evolution of dark energy with high precision. With this data it will be possible to measure the temporal derivative of the equation of state $p_{\text{DE}}/\rho_{\text{DE}}$, useful in discriminating between two broad classes of “thawing” and “freezing” models [5].

Note: As we were completing this paper we became aware of the work reported in [51], which considers a similar analysis of cosmological data to constrain $w(z)$. While those authors find weak evidence for evolution of the EOS, we find no such evidence. The two analyses differ in the way $w(z)$ is interpolated (we use a spline, while they employ a tanh function), as well as different calculations of the effects of DE perturbations. Furthermore, we analyze different datasets; in this paper we have utilized both the latest BAO measurements [22, 23], and the latest value of the Hubble constant from the SHOES program [32].

PS acknowledges Alexandre Amblard for useful discussions and Shirley Ho for help with the ISW likelihood code. This research was funded by NSF CAREER AST-0605427 and by LANL IGPP-08-505.

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