

Constraints on the dark energy with barotropic equation of state: assessing the importance of different observations

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For dynamical dark energy with the barotropic equation of state we determine the mean values of parameters and their confidence ranges together with other cosmological parameters on the basis of different combined datasets. The used observations include Planck data on CMB temperature anisotropy, E-mode polarisation and lensing, BICEP2/Keck Array data on B-mode polarisation, BAO from SDSS and 6dFGS, power spectrum of galaxies from WiggleZ, weak lensing from CFHTLenS and SNIa data from the JLA compilation. We find that all but one mean models are phantom, mean values of the equation of state parameter at current epoch are close to -1 and constraints on the adiabatic sound speed of dark energy are weak. We investigate the effect of CMB polarisation data on the dark energy parameters estimation. We discuss also which type of data on the large scale structure of the Universe allows to determine the dark energy parameters most precisely.

Key words: cosmology: dark energy, cosmological parameters, cosmic background radiation, large-scale structure of Universe

INTRODUCTION

The final analysis of data obtained by the Planck satellite [3] shows that the dark energy at current epoch is close to the cosmological constant: $w_0 = -1.028 \pm 0.032$. However, the Λ term faces the interpretational problems (for a recent review see [13]).

One of the simplest alternatives to Λ is the dynamical dark energy in form of the minimally coupled classical scalar field. In previous papers (e. g. [14–16]) we have introduced and studied in detail such field with the barotropic equation of state. This model involves both quintessential and phantom subclasses, its equation of state parameter and energy density have the analytical form applicable at any time during the past history of the Universe.

The goal of this paper is to obtain new constraints on parameters of the dynamical dark energy with barotropic equation of state from more recent data than used in [16] and to investigate which data are most useful for tightening the constraints on dark energy parameters.

COSMOLOGICAL MODEL

We suppose that the Universe is spatially flat, homogeneous and isotropic with Friedmann-

Robertson-Walker (FRW) metric of 4-space

$$ds^2 = g_{ij}dx^i dx^j = a^2(\eta)(d\eta^2 - \delta_{\alpha\beta}dx^\alpha dx^\beta)$$

where $i, j = 0, 1, 2, 3$, $\alpha, \beta = 1, 2, 3$, a is the scale factor, η is the conformal time and $c = 1$. It is filled with photons, neutrinos, baryons, cold dark matter and dark energy. For neutrinos we apply the minimal-mass normal hierarchy of masses: a single massive eigenstate with $m_\nu = 0.06$ eV (such a model is used by the Planck Collaboration in [3], it is consistent with the global fits to data including oscillations).

The dark energy is assumed to be the minimally coupled classical scalar field with barotropic equation of state, which is described in detail in [16]. It has the equation of state (EoS) parameter:

$$w_{de} = \frac{p_{de}}{\rho_{de}} = \frac{(1 + c_a^2)(1 + w_0)}{1 + w_0 - (w_0 - c_a^2)a^{3(1+c_a^2)}} - 1$$

where 0 denotes the values at current time and $c_a^2 = \text{const}$ is the adiabatic sound speed of dark energy, which has the meaning of EoS parameter at the Big Bang if $c_a^2 > -1$ and at the infinite time if $c_a^2 < -1$, the asymptotic values in the opposite time directions are -1 , the case $c_a^2 = -1$ corresponds to

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the cosmological constant, energy density:

$$\rho_{de} = \rho_{de}^{(0)} \frac{(1 + w_0)a^{-3(1+c_a^2)} + c_a^2 - w_0}{1 + c_a^2}$$

and effective sound speed $c_s^2 = 1$.

We exclude from consideration the models with $w_0 < -1$ and $c_a^2 > w_0$, because for such values in the past the EoS parameter had discontinuity of the second kind and ρ_{de} changed the sign.

In the case of flat 3-space the dark energy model has 2 free parameters: w_0 and c_a^2 (the third one, $\Omega_{de} = \rho_{de}^{(0)}/\rho_{cr}^{(0)}$, where ρ_{cr} is the critical density, is determined as $\Omega_{de} = 1 - \Omega_b - \Omega_{cdm}$, where $\Omega_b = \rho_b^{(0)}/\rho_{cr}^{(0)}$ and $\Omega_{cdm} = \rho_{cdm}^{(0)}/\rho_{cr}^{(0)}$).

We also assume the slow-roll inflation driven by a single scalar field with a canonical kinetic term, so that the tensor-to-scalar ratio r and tensor spectral index n_t satisfy the consistency relation $n_t = -r/8$ (used in [5]).

METHOD AND DATA

We determine the dark energy parameters w_0 and c_a^2 jointly with other cosmological ones: $\Omega_b h^2$, $\Omega_{cdm} h^2$, $h \equiv H_0/100 \text{ km}/(\text{s} \cdot \text{Mpc})$ (here H_0 is the Hubble constant, the amplitude of primordial power spectrum A_s , the scalar spectral index n_s , the optical depth to reionization τ_{rei} and the tensor-to-scalar ratio $r \equiv A_t/A_s$).

To estimate these parameters we use the Monte Carlo Markov chain (MCMC) method implemented in the *CosmoMC* code¹ [11]. The *CAMB* code² is used to compute the theory predictions [12]. The dark energy perturbations are treated within the parametrized post-Friedmann (PPF) framework [9]. When necessary we use the nonlinear corrections by HALOFIT adopted for the studied type of dark energy.

Combined datasets include the following CMB observations:

- Planck: data on the TT, TE, EE spectra and lensing [4] (the usefulness of EE spectra to distinguish between different subclasses of the dark energy models with barotropic EoS was forecasted in [14, 15]);
- BICEP2/Keck Array+Planck: data on the B-mode polarisation in 1 frequency band 150 GHz [1] (hereafter BKP);
- BICEP2/Keck Array: data on the B-mode polarisation in 2 frequency bands 150 GHz and 95 GHz [2] (hereafter BK).

We use 3 types of the data on large scale structure of the Universe (LSS):

- BAO 6dFGS [7] and SDSS MGS [19] (hereafter BAO),
- power spectrum of galaxies from WiggleZ [17] or
- weak lensing from CFHTLenS [10].

The Supernovae Ia luminosity distances and redshifts are taken from the JLA compilation [6].

We do not discuss the tension between values of H_0 inferred from CMB [3] and obtained from direct measurements (e.g. [18]). We take into account the prior on H_0 from the reanalysis [8] which is in better agreement with CMB.

We use 12 different combined datasets in total.

For the dark energy parameters w_0 and c_a^2 we apply flat priors with the ranges of values $[-2, -0.33]$ and $[-2, 0]$ correspondingly.

Each MCMC run has 8 chains converged to $R < 0.01$.

RESULTS AND DISCUSSION

The results are presented in Figures 1–4 and Tables 1–3.

The mean values of w_0 from Tables 1–3 are much closer to -1 than in [16, 22] (where the 2013 year data from Planck were used) for all combined datasets, making the constraints on c_a^2 significantly weaker (indeed, as it can be seen in Fig. 1–3, the posteriors for c_a^2 are cut from below by the prior). Among the mean values of w_0 only the one obtained from Planck TT+BAO+JLA is larger than -1 so the mean model is quintessential. All other mean models are phantom. In all cases the mean value of c_a^2 is smaller than -1 meaning that in the past the EoS parameter evolved from -1 to the current value w_0 . The models with parameters on upper 1σ and 2σ confidence limits are quintessential, those with parameters on lower 1σ and 2σ confidence limits are phantom. This is in agreement with results obtained in [20] for the cosmological model with free tensor spectral index n_t .

As we see in Fig. 1–3, the inclusion of data on CMB polarisation (either only E or both E and B modes) allows to narrow somewhat the confidence contours for dark energy parameters w_0 and c_a^2 (this effect is most visible for the datasets including CFHTLenS) and to narrow sufficiently the confidence contours for Ω_{de} .

While the inclusion of E-mode polarisation has small effect on the upper limits of tensor-to-scalar ratio r (Fig. 1–3), the use of BKP and BK data on B-mode polarisation reduces them significantly. The upper 2σ limit for r decreases from 0.12 to 0.073 when the BAO data are used, from 0.12 to 0.072 in

¹<http://cosmologist.info/cosmomc>

²<http://camb.info/>

case of the WiggleZ data and from 0.12 to 0.072 for CFHTLenS.

In Fig. 4 we see that there is some tension between the constraints obtained from datasets including different types of the LSS data, especially for Ω_{de} , but all determinations are within 1σ limits. BAO data allow the most precise determination for Ω_{de} (from Table 1 the width of 2σ confidence range is 0.038), WiggleZ for w_0 (from Table 2 the width of 2σ confidence range is 0.245) and CFHTLenS for c_a^2 (from Table 3 the width of 2σ confidence range is 1.179).

CONCLUSIONS

For 12 combined datasets we determine the mean values of cosmological parameters and their confidence ranges for model with the dark energy with barotropic equation of state. For the mean model all but one combined datasets prefer phantom over quintessence. Evolution of the mean EoS parameter from -1 in the early Universe to w_0 at current epoch is slow (both values are close) and the constraints on c_a^2 are weak. Already at 1σ level the dark energy models with parameters at the lower confidence limits are phantom and those with parameters at the upper confidence limits are quintessence. Both E and B modes of CMB polarisation allow to narrow confidence ranges for the values of dark energy parameters comparing to only CMB TT spectrum and therefore should be included into combined datasets. No type of the LSS data can be preferable since the most precise determination for Ω_{de} is obtained from the combined datasets including BAO, for w_0 from the combined datasets including WiggleZ and for c_a^2 from the combined datasets including CFHTLenS.

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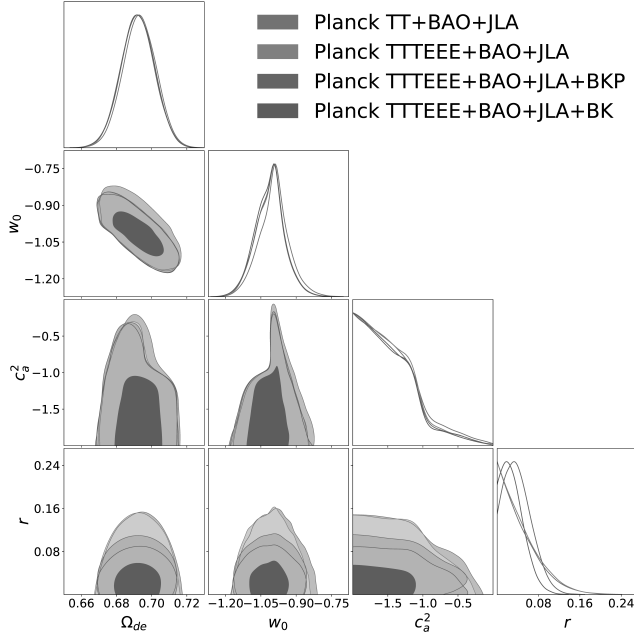


Fig. 1: 1D marginalized posteriors for Ω_{de} , w_0 , c_a^2 , r and 1σ , 2σ confidence contours from the 2D marginalized posterior distributions for the combined datasets including BAO.

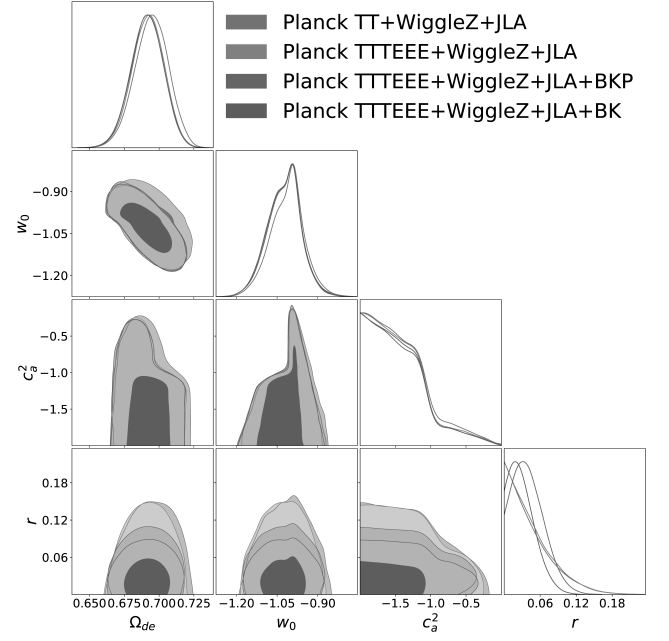


Fig. 2: 1D marginalized posteriors for Ω_{de} , w_0 , c_a^2 , r and 1σ , 2σ confidence contours from the 2D marginalized posterior distributions for the combined datasets including the power spectrum of galaxies.

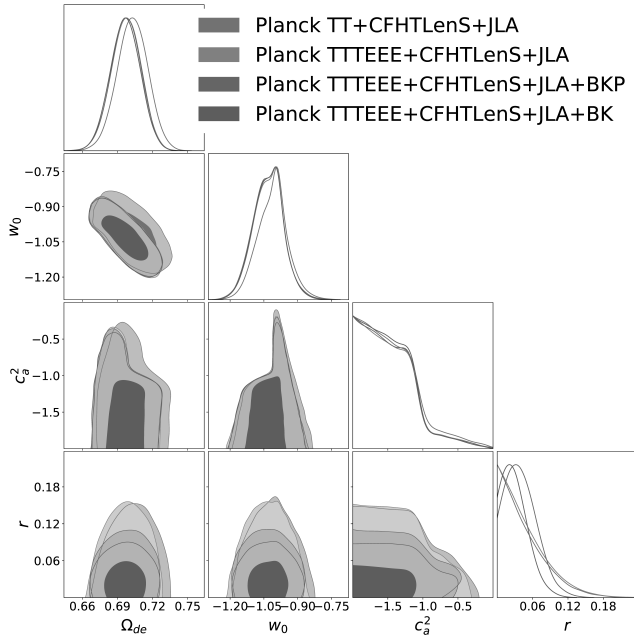


Fig. 3: 1D marginalized posteriors for Ω_{de} , w_0 , c_a^2 , r and 1σ , 2σ confidence contours from the 2D marginalized posterior distributions for the combined datasets including weak lensing.

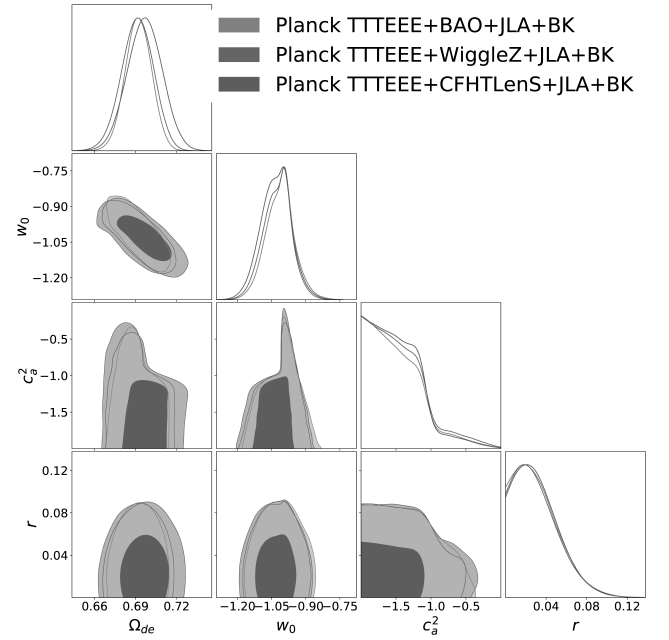


Fig. 4: 1D marginalized posteriors for Ω_{de} , w_0 , c_a^2 , r and 1σ , 2σ confidence contours from the 2D marginalized posterior distributions for the combined datasets including different types of the LSS data.

Table 1: The mean values, 1σ and 2σ confidence limits for cosmological parameters obtained from the observational datasets including CMB, BAO and JLA.

Parameters	Planck TT mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BKP mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BK mean $\pm 1\sigma \pm 2\sigma$
Ω_{de}	$0.693^{+0.010}_{-0.009} \quad +0.018_{-0.019}$	$0.692^{+0.009}_{-0.009} \quad +0.019_{-0.019}$	$0.692^{+0.010}_{-0.010} \quad +0.019_{-0.019}$	$0.692^{+0.010}_{-0.010} \quad +0.019_{-0.019}$
w_0	$-0.994^{+0.060}_{-0.064} \quad +0.139_{-0.133}$	$-1.010^{+0.057}_{-0.062} \quad +0.128_{-0.125}$	$-1.010^{+0.058}_{-0.062} \quad +0.130_{-0.129}$	$-1.013^{+0.058}_{-0.062} \quad +0.130_{-0.127}$
c_a^2	$-1.448^{+0.143}_{-0.552} \quad +0.808_{-0.552}$	$-1.467^{+0.147}_{-0.533} \quad +0.739_{-0.533}$	$-1.474^{+0.148}_{-0.526} \quad +0.755_{-0.526}$	$-1.485^{+0.143}_{-0.515} \quad +0.731_{-0.515}$
r	$0.045^{+0.010}_{-0.045} \quad +0.075_{-0.045}$	$0.046^{+0.010}_{-0.046} \quad +0.074_{-0.046}$	$0.042^{+0.015}_{-0.036} \quad +0.048_{-0.042}$	$0.032^{+0.008}_{-0.032} \quad +0.041_{-0.032}$
$10\Omega_b h^2$	$0.223^{+0.002}_{-0.002} \quad +0.004_{-0.004}$	$0.223^{+0.001}_{-0.001} \quad +0.003_{-0.003}$	$0.223^{+0.001}_{-0.001} \quad +0.003_{-0.003}$	$0.223^{+0.001}_{-0.001} \quad +0.003_{-0.003}$
$\Omega_{cdm} h^2$	$0.118^{+0.001}_{-0.001} \quad +0.003_{-0.003}$	$0.119^{+0.001}_{-0.001} \quad +0.002_{-0.002}$	$0.119^{+0.001}_{-0.001} \quad +0.002_{-0.002}$	$0.119^{+0.001}_{-0.001} \quad +0.002_{-0.002}$
h	$0.678^{+0.010}_{-0.011} \quad +0.021_{-0.020}$	$0.679^{+0.010}_{-0.011} \quad +0.021_{-0.020}$	$0.679^{+0.010}_{-0.011} \quad +0.021_{-0.020}$	$0.679^{+0.010}_{-0.011} \quad +0.021_{-0.020}$
n_s	$0.969^{+0.005}_{-0.005} \quad +0.010_{-0.010}$	$0.967^{+0.004}_{-0.004} \quad +0.009_{-0.008}$	$0.967^{+0.004}_{-0.004} \quad +0.008_{-0.008}$	$0.967^{+0.004}_{-0.004} \quad +0.008_{-0.008}$
$\log(10^{10} A_s)$	$3.066^{+0.026}_{-0.026} \quad +0.052_{-0.052}$	$3.061^{+0.024}_{-0.024} \quad +0.048_{-0.048}$	$3.063^{+0.024}_{-0.024} \quad +0.048_{-0.047}$	$3.064^{+0.024}_{-0.024} \quad +0.047_{-0.047}$
τ_{rei}	$0.068^{+0.014}_{-0.014} \quad +0.029_{-0.028}$	$0.065^{+0.013}_{-0.013} \quad +0.026_{-0.026}$	$0.065^{+0.013}_{-0.013} \quad +0.026_{-0.025}$	$0.066^{+0.013}_{-0.013} \quad +0.025_{-0.025}$

Table 2: The mean values, 1σ and 2σ confidence limits for cosmological parameters obtained from the observational datasets including CMB, WiggleZ and JLA.

Parameters	Planck TT mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BKP mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BK [21] mean $\pm 1\sigma \pm 2\sigma$
Ω_{de}	$0.694^{+0.013}_{-0.011} \quad +0.023_{-0.025}$	$0.692^{+0.012}_{-0.011} \quad +0.022_{-0.024}$	$0.691^{+0.012}_{-0.012} \quad +0.022_{-0.023}$	$0.691^{+0.012}_{-0.012} \quad +0.022_{-0.024}$
w_0	$-1.012^{+0.060}_{-0.060} \quad +0.125_{-0.130}$	$-1.025^{+0.062}_{-0.058} \quad +0.119_{-0.126}$	$-1.022^{+0.061}_{-0.058} \quad +0.123_{-0.127}$	$-1.024^{+0.062}_{-0.058} \quad +0.120_{-0.125}$
c_a^2	$-1.438^{+0.150}_{-0.562} \quad +0.815_{-0.562}$	$-1.456^{+0.146}_{-0.544} \quad +0.791_{-0.544}$	$-1.463^{+0.147}_{-0.537} \quad +0.778_{-0.537}$	$-1.460^{+0.145}_{-0.540} \quad +0.781_{-0.540}$
r	$0.045^{+0.010}_{-0.045} \quad +0.075_{-0.045}$	$0.045^{+0.010}_{-0.045} \quad +0.073_{-0.045}$	$0.042^{+0.016}_{-0.035} \quad +0.048_{-0.042}$	$0.031^{+0.008}_{-0.031} \quad +0.041_{-0.031}$
$10\Omega_b h^2$	$0.223^{+0.002}_{-0.002} \quad +0.004_{-0.004}$	$0.223^{+0.002}_{-0.002} \quad +0.003_{-0.003}$	$0.222^{+0.002}_{-0.002} \quad +0.003_{-0.003}$	$0.222^{+0.002}_{-0.002} \quad +0.003_{-0.003}$
$\Omega_{cdm} h^2$	$0.118^{+0.002}_{-0.002} \quad +0.004_{-0.004}$	$0.119^{+0.001}_{-0.001} \quad +0.003_{-0.003}$	$0.119^{+0.001}_{-0.001} \quad +0.003_{-0.003}$	$0.119^{+0.001}_{-0.001} \quad +0.003_{-0.003}$
h	$0.681^{+0.012}_{-0.012} \quad +0.024_{-0.023}$	$0.680^{+0.012}_{-0.012} \quad +0.024_{-0.023}$	$0.679^{+0.012}_{-0.012} \quad +0.024_{-0.023}$	$0.679^{+0.012}_{-0.012} \quad +0.024_{-0.023}$
n_s	$0.969^{+0.006}_{-0.006} \quad +0.011_{-0.011}$	$0.966^{+0.005}_{-0.005} \quad +0.009_{-0.009}$	$0.966^{+0.005}_{-0.005} \quad +0.009_{-0.009}$	$0.966^{+0.005}_{-0.005} \quad +0.009_{-0.009}$
$\log(10^{10} A_s)$	$3.062^{+0.029}_{-0.028} \quad +0.057_{-0.057}$	$3.056^{+0.025}_{-0.025} \quad +0.051_{-0.050}$	$3.057^{+0.025}_{-0.025} \quad +0.050_{-0.049}$	$3.059^{+0.025}_{-0.025} \quad +0.049_{-0.049}$
τ_{rei}	$0.066^{+0.016}_{-0.016} \quad +0.031_{-0.031}$	$0.062^{+0.014}_{-0.014} \quad +0.028_{-0.027}$	$0.062^{+0.014}_{-0.014} \quad +0.027_{-0.027}$	$0.063^{+0.014}_{-0.013} \quad +0.027_{-0.027}$

Table 3: The mean values, 1σ and 2σ confidence limits for cosmological parameters obtained from the observational datasets including CMB, CFHTLenS and JLA.

Parameters	Planck TT mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BKP mean $\pm 1\sigma \pm 2\sigma$	Planck TTTEEE+BK mean $\pm 1\sigma \pm 2\sigma$
Ω_{de}	$0.703^{+0.013}_{-0.013} \quad ^{+0.026}_{-0.027}$	$0.697^{+0.013}_{-0.013} \quad ^{+0.025}_{-0.026}$	$0.697^{+0.013}_{-0.013} \quad ^{+0.024}_{-0.026}$	$0.697^{+0.013}_{-0.013} \quad ^{+0.025}_{-0.025}$
w_0	$-1.011^{+0.062}_{-0.068} \quad ^{+0.140}_{-0.136}$	$-1.030^{+0.066}_{-0.064} \quad ^{+0.134}_{-0.136}$	$-1.031^{+0.067}_{-0.065} \quad ^{+0.137}_{-0.133}$	$-1.030^{+0.066}_{-0.064} \quad ^{+0.131}_{-0.132}$
c_a^2	$-1.456^{+0.151}_{-0.544} \quad ^{+0.768}_{-0.544}$	$-1.478^{+0.150}_{-0.522} \quad ^{+0.709}_{-0.522}$	$-1.482^{+0.151}_{-0.518} \quad ^{+0.687}_{-0.518}$	$-1.482^{+0.151}_{-0.518} \quad ^{+0.661}_{-0.518}$
r	$0.046^{+0.010}_{-0.046} \quad ^{+0.074}_{-0.046}$	$0.047^{+0.011}_{-0.047} \quad ^{+0.076}_{-0.047}$	$0.042^{+0.016}_{-0.036} \quad ^{+0.048}_{-0.042}$	$0.032^{+0.008}_{-0.032} \quad ^{+0.040}_{-0.032}$
$10\Omega_b h^2$	$0.224^{+0.002}_{-0.002} \quad ^{+0.004}_{-0.004}$	$0.223^{+0.002}_{-0.002} \quad ^{+0.003}_{-0.003}$	$0.223^{+0.002}_{-0.002} \quad ^{+0.003}_{-0.003}$	$0.223^{+0.002}_{-0.002} \quad ^{+0.003}_{-0.003}$
$\Omega_{cdm} h^2$	$0.117^{+0.002}_{-0.002} \quad ^{+0.004}_{-0.004}$	$0.119^{+0.001}_{-0.001} \quad ^{+0.003}_{-0.003}$	$0.119^{+0.001}_{-0.001} \quad ^{+0.003}_{-0.003}$	$0.119^{+0.001}_{-0.001} \quad ^{+0.003}_{-0.003}$
h	$0.687^{+0.013}_{-0.014} \quad ^{+0.028}_{-0.026}$	$0.684^{+0.013}_{-0.014} \quad ^{+0.028}_{-0.026}$	$0.684^{+0.014}_{-0.013} \quad ^{+0.027}_{-0.026}$	$0.684^{+0.013}_{-0.014} \quad ^{+0.028}_{-0.025}$
n_s	$0.972^{+0.006}_{-0.006} \quad ^{+0.012}_{-0.011}$	$0.968^{+0.005}_{-0.005} \quad ^{+0.009}_{-0.009}$	$0.968^{+0.005}_{-0.005} \quad ^{+0.009}_{-0.009}$	$0.967^{+0.005}_{-0.005} \quad ^{+0.009}_{-0.009}$
$\log(10^{10} A_s)$	$3.072^{+0.030}_{-0.030} \quad ^{+0.060}_{-0.058}$	$3.058^{+0.025}_{-0.025} \quad ^{+0.050}_{-0.050}$	$3.060^{+0.025}_{-0.025} \quad ^{+0.050}_{-0.050}$	$3.061^{+0.025}_{-0.025} \quad ^{+0.049}_{-0.049}$
τ_{rei}	$0.072^{+0.016}_{-0.016} \quad ^{+0.033}_{-0.032}$	$0.064^{+0.014}_{-0.014} \quad ^{+0.027}_{-0.027}$	$0.064^{+0.014}_{-0.014} \quad ^{+0.027}_{-0.027}$	$0.065^{+0.013}_{-0.014} \quad ^{+0.027}_{-0.027}$