Current constraints on early and stressed dark energy models and future 21 cm perspectives

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Despite the great progress of current cosmological measurements, the nature of the dominant component of the Universe, coined dark energy, is still an open question. Early dark energy is a possible candidate which may also alleviate some fine-tuning issues of the standard paradigm. Using the latest available cosmological data, we find that the 95% C.L. upper bound on the early dark energy density parameter is $\Omega_{\text{eDE}} < 0.009$. On the other hand, the dark energy component may be a stressed and inhomogeneous fluid. If this is the case, the effective sound speed and the viscosity parameters are unconstrained by current data. Future omniscopelike 21 cm surveys, combined with present cosmic microwave background data, could be able to distinguish between standard quintessence scenarios from other possible models with 2σ significance, assuming a non-negligible early dark energy contribution. The precision achieved on the Ω_{eDE} parameter from these 21 cm probes could be below $\mathcal{O}(10\%)$.

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I. INTRODUCTION

The nature of the mysterious dark energy component that currently dominates the energy content of the Universe reveals new physics missing from our Universe's picture, and constitutes the fundamental key to understand the fate of the Universe. The most economical explanation of the dark energy component attributes this energy density to the one of the vacuum, i.e., a cosmological constant scenario. Together with cold dark matter (CDM), the so-called Λ CDM scenario can account for present data with a flat universe made up of roughly 30% dark matter and 70% dark energy. In this minimal model, the dark energy equation of state, w , which corresponds to the ratio of the dark energy pressure to the dark energy density, is constant and equal to -1 . However, this simple picture suffers from severe fine-tuning theoretical issues (see Ref. [1] and references therein) as well as from problems with observations related to the matter power spectrum on scales of a few Mpc and below [2–7]. Possible alternatives to alleviate them have been extensively explored. Perfect dark energy fluids, characterized either by a constant ($w \neq -1$) or by a time varying dark energy equation of state $w(a(t))$, or scalar field models, are the most popular options considered in the cosmological data analyses, as their parametrizations require few extra parameters (two at most) to be added to the usual Λ CDM scenario.

There exists also alternative scenarios, in which the gravitational sector is modified, leading to a modification of Einstein's equations of gravity on large scales. Modifications of gravity (see e.g., [8] and references therein) incorporate models with extra spatial dimensions or an action which is nonlinear in the Ricci scalar. There are

also nonperfect fluid models, such as Chaplygin gas cosmologies [9], which involve more parameters than just one equation of state w . Of particular interest here is the early dark energy (hereafter EDE) case, as it arises as a natural hypothesis of dark energy [10–13]. EDE differs from the cosmological constant because it is not negligible in the early Universe and the contribution depends on the initial density parameter Ω_{eDE} . Furthermore, the EDE model considered here is based on a generic dark energy fluid which is inhomogeneous. Density and pressure are time varying; therefore the equation of state is not constant in time. The phenomenological analyses of these inhomogeneous dark energy models usually require additional dark energy clustering parameters, i.e., the dark energy effective sound speed and the dark energy anisotropic stress. The sound speed c_{eff}^2 [14–16] is defined as the ratio between the dark energy pressure perturbation and the dark energy density contrast in the rest frame of the fluid, $c_{\text{eff}}^2 \equiv (\delta P / \delta \rho)_{\text{rest}}$. In the simplest quintessence models, $c_{\text{eff}}^2 = 1$, while the anisotropic stress is zero. The effective sound speed determines the clustering properties of dark energy and consequently it affects the growth of matter density fluctuations. Therefore, in principle, its presence could be revealed in large scale structure observations. The growth of perturbations can also be affected by the anisotropic stress contributions [14,15,17] which lead to a damping in the velocity perturbations. In the parametrization used here, the damping effect is driven by the viscosity parameter c_{vis}^2 which links the anisotropic stress to the velocity perturbation and the metric shear.

Despite the precision achieved by the combination of cosmic microwave background (CMB) measurements from

the Planck satellite [18], baryon acoustic oscillation data from a number of galaxy surveys [19–23] and supernovae Ia luminosity distance measurements [24] in the extraction of the dark energy equation of state parameter, $w = -1.06 \pm 0.06$ at 68% C.L. [19], the nature of the dark energy component remains unknown. Therefore, it is mandatory to carefully study other possibilities including the one of an EDE component, as well as the clustering properties of the dark energy fluid. In this paper we shall address both issues, relaxing the perfect fluid assumption and considering current cosmological data, in addition to the recent BICEP2 measurements of the B-modes power spectrum [25].

We also explore the possibility of constraining an EDE component and/or a stressed dark energy fluid with future 21 cm surveys. The next generation of radio experiments, which will image the neutral intergalactic medium in 21 cm emission/absorption, will provide a unique probe of the Universe at higher redshifts ($z > 6$) which lie out of the reach of galaxy surveys and CMB experiments. The 21 cm line signal presents several advantages compared to traditional cosmic and astrophysical probes, see e.g., [26], and it could be used to test the nature of dark energy [27]. The future generation of radio interferometers testing the 21 cm signal, including the squared kilometer array [28] and omniscopes [29,30], may provide extra constraints on the cosmological parameters probing the epoch of reionization (EoR) or the high redshift window; see e.g., [31,32]. In addition, the 21 cm signal can also be used at low redshifts ($z < 5$), offering a competitive cosmological probe for unraveling the nature of the component responsible for the present Universe's accelerated expansion [33,34].

The structure of the paper is as follows. Sections II and III describe the early and stressed dark energy models' evolution in terms of the background and perturbation variables. In Sec. IV we present the method and data followed in the numerical analyses presented in Sec. V. Section VI addresses the future perspective and constraints from 21 cm surveys by means of a Fisher matrix forecast analysis. Finally, we draw our conclusions in Sec. VII.

II. EARLY DARK ENERGY MODELS

The concept of EDE cosmology was introduced in [10] and studied in several subsequent works following different possible effective parametrizations of the evolution of the dark energy fluid; see e.g., [11,13,18,35]. Here we follow Ref. [11] to describe the evolution of the background dark energy density from the high redshift, constant value Ω_{EDE}^0 until its present-day value Ω_{DE}^0 (assuming a flat universe with $\Omega_{\text{DE}}^0 + \Omega_{\text{m}}^0 = 1$):

$$\Omega_{\text{DE}}(a) = \frac{\Omega_{\text{DE}}^0 - \Omega_{\text{EDE}}(1 - a^{-3w_0})}{\Omega_{\text{DE}}^0 + \Omega_{\text{m}}^0 a^{3w_0}} + \Omega_{\text{EDE}}(1 - a^{-3w_0}), \quad (1)$$

where w_0 is the current value of the dark energy equation of state, i.e., $w(a=1)$. The evolution of $w(a)$ in this EDE parametrization reads

$$w(a) = -\frac{1}{3[1 - \Omega_{\text{DE}}(a)]} \frac{d \ln \Omega_{\text{DE}}(a)}{d \ln a} + \frac{a_{\text{eq}}}{3(a + a_{\text{eq}})}, \quad (2)$$

where a_{eq} is the scale factor at matter-radiation equality era. The time dependent equation of state $w(a)$ typically traces the dominant component of the Universe at each epoch: first $w \approx 1/3$ during the radiation dominated period, then $w \approx 0$ during the matter dominated era and finally $w \rightarrow w_0$ in the present epoch. The current value of the equation of state parameter w_0 might be different¹ from -1 .

III. STRESSED DARK ENERGY MODELS

Using the notation of Ref. [37] and assuming the synchronous gauge, we follow [13] to describe the dark energy scalar perturbation evolution equations in Fourier space for the density contrast (δ), the velocity divergence (θ) and the anisotropic stress perturbation (σ):

$$\frac{\dot{\delta}}{1+w} = -\left[k^2 + 9\left(\frac{\dot{a}}{a}\right)^2 \left(c_{\text{eff}}^2 - w + \frac{\dot{w}}{3(1+w)(\dot{a}/a)} \right) \right] \frac{\theta}{k^2} - \frac{\dot{h}}{2} - 3\frac{\dot{a}}{a}(c_{\text{eff}}^2 - w) \frac{\delta}{1+w}; \quad (3)$$

$$\dot{\theta} = -\frac{\dot{a}}{a}(1 - 3c_{\text{eff}}^2)\theta + \frac{\delta}{1+w}c_{\text{eff}}^2k^2 - k^2\sigma; \quad (4)$$

$$\dot{\sigma} = -3\frac{\dot{a}}{a} \left[1 - \frac{\dot{w}}{3w(1+w)(\dot{a}/a)} \right] \sigma + \frac{8c_{\text{vis}}^2}{3(1+w)} \left[\theta + \frac{\dot{h}}{2} + 3\dot{\eta} \right], \quad (5)$$

where c_{eff}^2 denotes the effective sound speed, the dot refers to derivative with respect to conformal time, and h and η are the usual synchronous gauge perturbation variables. In the last equation, the velocity and the metric shear [sometimes referred to as $H_T = -(h/2 + 3\eta)$] are related to the dark energy shear stress through the viscosity parameter c_{vis}^2 . The latter relation was first introduced in Ref. [15]² and relates directly the anisotropic stress with the damping of velocity fluctuations on shear-free frames ($H_T = 0$), if $c_{\text{vis}}^2 > 0$. We have also addressed the contribution of the dark energy shear stress to the evolution equations for the tensor perturbations.

¹Notice that the clustering properties of a universe with $-1 < w < -1/3$ deviate from those of a Λ CDM universe with $w = -1$ and therefore it can be inconsistent with observations [36].

²Note that σ here is related to the variable π in [14] through the relation $\sigma = (2/3)\pi/(1+w)$.

The differential equations above govern the clustering properties of the dark energy fluid, and we shall solve them and compare the results to current and future observations using the methods detailed in the following sections.

IV. METHOD AND DATA FOR CURRENT CONSTRAINTS

We have modified the latest version of the Boltzmann equations solver CAMB [38] in order to account for Eqs. (1)–(5).

The parameter space contains the six standard parameters of the Λ CDM model,

$$\{\Omega_b h^2, \Omega_c h^2, \theta, \tau, n_s, \ln(10^{10} A_s)\}, \quad (6)$$

where $\Omega_b h^2 = \omega_b$ is the present physical energy density in baryons, $\Omega_c h^2 = \omega_c$ is the present physical cold dark matter energy density, θ is the angular scale of the sound horizon, τ is optical depth to reionization and n_s and A_s are the spectral index and the amplitude of primordial scalar perturbations at a pivot scale $k = 0.05 \text{ Mpc}^{-1}$, respectively.

Since we include tensor perturbations, we have also considered the tensor-to-scalar ratio r parameter, defined relatively to the same pivot scale of the scalar perturbations, $k = 0.05 \text{ Mpc}^{-1}$. Finally, we include all the parameters describing the EDE model evolution (see Secs. II and III):

$$\{\Omega_{\text{eDE}}, w_0, c_{\text{vis}}^2, c_{\text{eff}}^2\}. \quad (7)$$

We assume flat priors on the parameters as listed in Table I. The sampling of the parameter space is performed through the Monte Carlo Markov chain (MCMC) public package CosmoMC [39].

The Bayesian inference is based on the CMB temperature anisotropy power spectrum of the Planck experiment, implemented following the prescriptions of Ref. [40]. We have also considered the CMB polarization measurements from the nine-year data release of the WMAP satellite [41]. In the following, we shall refer to the former data as WP. The maximum multipole number of the Planck temperature power spectra is $\ell_{\text{max}} = 2500$. The WP measurements reach a maximum multipole $\ell = 23$; see Ref. [41]. In order to directly constrain the tensor-to-scalar ratio r , the nine-bins measurements of the B-modes polarization power spectrum from the BICEP2 collaboration [25] are included.

V. CURRENT COSMOLOGICAL CONSTRAINTS

In this section we apply the data sets described above, using the MCMC method, to four possible scenarios:

- (i) Case 1: In this scenario, both the early dark energy component Ω_{eDE} and the dark energy perturbation parameters c_{eff}^2 and c_{vis}^2 are free parameters, with the priors specified in Table I. We also consider in this

TABLE I. Range of the flat priors for the cosmological parameters considered here.

Parameter	Prior
$\Omega_b h^2$	$0.005 \rightarrow 0.1$
$\Omega_c h^2$	$0.01 \rightarrow 0.99$
θ	$0.5 \rightarrow 10$
τ	$0.01 \rightarrow 0.8$
n_s	$0.5 \rightarrow 1.5$
$\ln(10^{10} A_s)$	$2.7 \rightarrow 4$
r	$0 \rightarrow 1$
Ω_{eDE}	$0 \rightarrow 0.1$
w_0	$-1 \rightarrow 0$
c_{eff}^2	$0 \rightarrow 1$
c_{vis}^2	$0 \rightarrow 1$

case the current value of the dark energy equation of state, w_0 , see Eq. (1), as a free parameter.

- (ii) Case 2: The early dark energy component Ω_{eDE} and w_0 are free parameters, but the dark energy perturbations are fixed to their standard values: $c_{\text{eff}}^2 = 1$ and $c_{\text{vis}}^2 = 0$ (i.e., no anisotropic stress contribution is considered in this case).
- (iii) Case 3: We consider no early dark energy component ($\Omega_{\text{eDE}} = 0$) but the dark energy perturbations c_{eff}^2 and c_{vis}^2 are both free parameters, varying with a flat prior in the range $[0, 1]$, as well as a constant dark energy equation of state w , which varies with a prior in the range $[-1, 0]$.
- (iv) Case 4: We consider a simple w CDM cosmology, i.e., a cosmological scenario with a constant dark energy equation of state, which is allowed to freely vary in the range $[-1, 0]$.

Table II shows the mean values with 1σ errors and the 2σ upper bounds for the EDE parameters following the case order listed above. Notice first that the dark energy perturbation parameters (c_{eff}^2 and c_{vis}^2) are poorly constrained: only in Case 1 present data are able to provide mild constraints on c_{eff}^2 , while c_{vis}^2 is unconstrained in both Cases 1 and 3. Figure 1 shows the marginalized one-dimension posteriors obtained for the perturbation parameters in Case 1: current CMB data do not show any significant preference for a particular region in the allowed parameter space. These results are consistent with previous works based on mock Planck data (see e.g., Ref. [42]).

Second, when setting $c_{\text{eff}}^2 = 1$ and $c_{\text{vis}}^2 = 0$ (see Case 2 above), we find an upper limit on the early dark energy parameter $\Omega_{\text{eDE}} < 0.012$ at 95% C.L. The former bound is looser than the one reported by the Planck collaboration, $\Omega_{\text{eDE}} < 0.010$ at 95% C.L. with the same data sets (Planck temperature and WP data). The larger value that we get on Ω_{eDE} is related to the degeneracy between this parameter and the tensor-to-scalar ratio r , as we shall explain below. The addition of the BICEP2 data makes our 95% C.L. upper limit on Ω_{eDE} tighter ($\Omega_{\text{eDE}} < 0.009$ at 95% C.L.).

TABLE II. Mean values with 1σ errors and 2σ upper bounds for the Ω_{eDE} parameter as well as for the most correlated cosmological parameters for the different possible cases described in Sec. V.

	Planck + WP	Planck + WP + BICEP2
Case 1		
Ω_{eDE}	< 0.014	< 0.010
w_0	< -0.663	< -0.722
r	< 0.12	0.15 ± 0.04
n_s	0.960 ± 0.007	0.963 ± 0.007
c_{eff}^2	0.465 ± 0.289	< 0.617 (95% c.l.)
c_{vis}^2	Unconstrained	Unconstrained
Case 2		
$\Omega_{\text{eDE}}(c_{\text{eff}}^2 = 1, c_{\text{vis}}^2 = 0)$	< 0.012	< 0.009
$w_0(c_{\text{eff}}^2 = 1, c_{\text{vis}}^2 = 0)$	< -0.659	< -0.722
r	< 0.10	0.15 ± 0.04
n_s	0.960 ± 0.007	0.963 ± 0.008
Case 3		
Ω_{eDE}	0	0
w	< -0.647	< -0.709
r	< 0.11	0.16 ± 0.04
n_s	0.960 ± 0.007	0.964 ± 0.007
c_{eff}^2	Unconstrained	Unconstrained
c_{vis}^2	Unconstrained	Unconstrained
Case 4		
$\Omega_{\text{eDE}}(c_{\text{eff}}^2 = 1, c_{\text{vis}}^2 = 0)$	0	0
$w(c_{\text{eff}}^2 = 1, c_{\text{vis}}^2 = 0)$	< -0.655	< -0.705
r	< 0.11	0.16 ± 0.04
n_s	0.960 ± 0.008	0.964 ± 0.007

When allowing the dark energy perturbations c_{eff}^2 and c_{vis}^2 to be free parameters (Case 1 above), the 95% C.L. upper bound Ω_{eDE} degrades but not significantly: we find $\Omega_{\text{eDE}} < 0.015$ ($\Omega_{\text{eDE}} < 0.010$) at 95% C.L. before (after) combining Planck and WP measurements with BICEP2 data.

In general, the results for the standard Λ CDM cosmological parameters do not deviate significantly from their expected mean values and errors. This can be noticed by comparing the first three cases depicted in Table II with the last rows, which show the expectations within the w CDM cosmological scenario. Indeed, the current value of the dark energy equation of state w_0 does not show a very strong dependence on the dark energy perturbation parameters, as its 95% C.L. upper bound remains unaffected when c_{eff}^2 and c_{vis}^2 are both freely varying. Concerning the value of n_s , its mean value is strongly affected when including BICEP2 data in our numerical analyses, regardless of the dark energy scenario.

Figure 2 shows the marginalized two-dimensional plots and the posteriors involving the most relevant cosmological parameters here in the case in which both the early dark energy component Ω_{eDE} and the perturbation parameters c_{eff}^2 and c_{vis}^2 are allowed to vary freely (see Case 1 above). The red contours refer to the results arising from the analysis

FIG. 1 (color online). Red (Blue) contours show the c_{eff}^2 (top panel) and c_{vis}^2 (bottom panel) marginalized one-dimensional posteriors obtained with Planck + WP (Planck + WP + BICEP2).

of Planck + WP data, while the blue contours include BICEP2 as well. The marginalized two-dimensional plot in the bottom left corner, in the (Ω_{eDE}, r) plane, shows the degeneracy between the EDE component and the tensor-to-scalar ratio r . There exists a mild anticorrelation between these two parameters, which can be easily understood: both parameters show an effect at very large scales, increasing the power at very low multipoles. As the BICEP2 data constrain r to be different from zero, the 2σ upper bound on Ω_{eDE} is tighter, in order to compensate the contribution from the tensor modes at large scales. A similar effect can also be noticed in the two-dimensional marginalized plot in the (w_0, r) plane: given the anticorrelation between w_0 and r , the BICEP2 measurements of r reduce the upper bound on w_0 . There also exists a degeneracy between the Ω_{eDE} and w_0 parameters, as can be noticed from the right lower panel of Fig. 2: larger (smaller) values of the present dark energy equation of state, w_0 , allow for smaller (larger) values of the

FIG. 2 (color online). Two-dimensional plots: Red (Blue) contours show the 68% and 95% C.L. allowed regions from Planck + WP (Planck + WP + BICEP2). One-dimensional plots: Red (Blue) lines depict the marginalized one-dimensional posteriors from Planck + WP (Planck + WP + BICEP2) measurements. In this case, both the dark energy perturbation parameters and the EDE component are free parameters (see Case 1 of Table II). BICEP2 measurements point towards a nonzero value of r . As a consequence, since Ω_{eDE} and r are anticorrelated, the constraints on Ω_{eDE} are tighter when considering BICEP2 data in the numerical analyses (see the results depicted in Table II).

EDE parameter, Ω_{eDE} . Therefore, these two parameters are anticorrelated, as can be learned from Eq. (1): for a given value of the Ω_{eDE} parameter and the scale factor a , the quantity Ω_{DE} grows as the value of w_0 does.

VI. 21 CM FORECASTS

In this section, we follow the description of Ref. [32] for the 21 cm brightness background temperature $T_b(z)$, for the evolution equations of the linear perturbation $\delta T_b(z)$ as well as for the reionization model implementation.

The study of the 21 cm signal requires us to deal with the angular location on the sky plane θ , and with the frequency difference Δf of the signal to a central 21 cm line of redshift z . The dual coordinates of this system are denoted by $\mathbf{u}_\perp$ and $u_\parallel$, and they are related to the standard comoving wave vector $\mathbf{k}$ components as follows:

$$\mathbf{u}_\perp = D_A(z)\mathbf{k}_\perp, \quad u_\parallel = y(z)k_\parallel, \quad (8)$$

where $D_A(z)$ is the angular comoving distance and

$$y(z) = \frac{\lambda_{21}(1+z)^2}{H(z)}, \quad (9)$$

where λ_{21} is the 21 cm wavelength (in the rest frame) and $H(z)$ is the Hubble rate. The 21 cm brightness temperature power spectrum relevant for our analyses, $P_{\delta T_b}(\mathbf{u})$, is related to $P_{\delta T_b}(\mathbf{k})$ as follows:

$$P_{\delta T_b}(\mathbf{u}) = \frac{P_{\delta T_b}(\mathbf{k})}{D_A(z)^2 y(z)}. \quad (10)$$

For the Fisher matrix analysis, we have adopted the formalism of Refs. [31,32]. Assuming that $P_{\delta T_b}(\mathbf{u})$ is Gaussian distributed, we can approximate the Fisher matrix by

$$F_{ab} = \frac{1}{2} \sum_{u_{\parallel}, u_{\perp}} \frac{N_c}{[P_{\delta T_b}(\mathbf{u}) + P_{\text{noise}}]^2} \frac{\partial P_{\delta T_b}(\mathbf{u})}{\partial \lambda_a} \frac{\partial P_{\delta T_b}(\mathbf{u})}{\partial \lambda_b}, \quad (11)$$

where $\lambda_{a,b}$ are the cosmological parameters involved in the Fisher forecast analysis, and

$$N_c = \frac{4\pi f_{\text{sky}}}{\Theta^2} 2\pi k_{\perp} \delta k_{\perp} \delta k_{\parallel} \frac{V}{(2\pi)^3} \quad (12)$$

is the number of independent cells probed for a given value of $\mathbf{u}$ (or $\mathbf{k}$), V is the comoving volume covered and Θ is the angular patch in the sky.³ In Eq. (11), P_{noise} is given by [32,43]

$$P_{\text{noise}}(\mathbf{u}) \simeq \frac{4\pi f_{\text{sky}}}{\Omega_{\text{fov}}} \frac{\lambda^2}{D^2 f_{\text{cover}}^2} \frac{T_{\text{sys}}^2}{B_W t_{\text{obs}}}, \quad (13)$$

with f_{sky} being the fraction of the sky covered by the survey, Ω_{fov} the field of view, λ the redshifted wavelength of the signal, T_{sys} the system temperature, D the size of the array, B_W the experiment's bandwidth and f_{cover} the covering factor of the array. Beam effects at small scales can be incorporated by multiplying Eq. (13) by the factor $\exp[\mathbf{u}_{\perp}^2 / (4\sqrt{\ln 2} \theta_{fw})^2]$, with $\theta_{fw} = 0.89\lambda/D$; see Ref. [32].

In what follows, we consider two possible 21 cm experiment configurations. The first one is a CHIME-like [44] experiment, covering a low redshift range $0.8 < z < 2.5$. In our analyses we use a setup similar to the one considered in [34]. The second one is an omniscopelike instrument sensitive to the EoR. In the latter case, we follow the setup of Ref. [32]. In our treatment of the Fisher matrix, we use a convolution of the signal with the frequency window function associated with the mean redshift of observation. This method helps in reducing the degeneracy between the cosmological parameters τ and $\ln(A_S)$ when considering one single redshift slice for an omniscopelike experiment [32]. Notice that, in what follows, we shall assume that most of the foregrounds can be eliminated, an assumption which is still under active research (see e.g., [45]). We also neglect the fact that ionizing sources could affect the 21 cm perturbations, providing extra contributions to the power spectrum [31,32]. Therefore the analysis presented here should be regarded as an optimistic appraisal of the 21 cm signal potential to constrain both an EDE component and its clustering properties.

We shall also analyze the joint constraints arising from the combination of future 21 cm probes and current CMB data. For doing such a combination, we add to the 21 cm Fisher matrix the Planck (or Planck + BICEP2) inverse covariance matrices obtained from our MCMC analyses

³ Θ is taken to be lower than 1 rad to be in agreement with the flat-sky approximation.

FIG. 3 (color online). Evolution of the background quantities for the fiducial models of Tables IV and VII. The redshift ranges tested by the 21 cm experiments considered here are shown by the grey rectangular areas.

described in the previous version. We believe this approach is correct because even if the values that nature has chosen for the parameters involved here in the analyses (see e.g., Table I) are unknown, the fiducial parameter values in the 21 cm forecasts are very close to the mean values found by the Planck collaboration [18], except for the dark energy perturbation parameters c_{eff}^2 and c_{vis}^2 , which are unconstrained by current data. However, even if present CMB measurements poorly determine these two parameters, the errors on both c_{eff}^2 and c_{vis}^2 are in general largely increased when neglecting their constraints from Planck, as we shall also illustrate.

We present results for two fiducial cosmological models: the fiducial model 1 (2) with $\Omega_{\text{eDE}} = 0.01$ (0.03), $c_{\text{vis}}^2 = 0$ (0.33) and $c_{\text{eff}}^2 = 1$ (0.33), both of them assuming the same value for the dark energy equation of state at present, $w_0 = -0.9$. Figure 3 shows the evolution of the background quantities $\Omega_{\text{DE}}(z)$ and $w(z)$, see Eqs. (1)–(2), as a function of the redshift, for these two possible fiducial cosmologies. The redshift ranges tested by the two possible 21 cm future experiments considered here are depicted by the grey rectangular zones. Notice that both experiments are located where the difference among the expansion histories for these two fiducial models is non-negligible. Therefore, one would expect to have sensitivity to distinguish between different cosmological backgrounds when exploring the 21 cm power spectrum in the two redshift ranges depicted in Fig. 3.

A. CHIME $0.8 < z < 2.5$

In Table III, we provide the value of the parameters specifying the CHIME experiment considered in our analyses, which are similar to those considered in Ref. [34]. For the system temperature, we have taken $T_{\text{sys}} = [40 + 5(\nu/710 \text{ Mhz})^{-2.6}] \text{ K}$, where ν is the

TABLE III. Specifications of the CHIME-like experiment; see also Ref. [34].

Redshift slices	B_W	D	f_{cover}	t_{obs}	f_{sky}
0.8/1/2/2.5	2 Mhz	100 m	1	1 yr	0.5

redshifted frequency of the 21 cm signal. We have also considered a comoving number density of sources of $0.03h^3 \text{ Mpc}^{-3}$, contributing to shot noise.

The results for the two possible fiducial models described in the previous section are presented in Table IV, using $u_{\perp}^{\text{min}} = 2\pi/\theta_{\text{res}}(z)$ with $\theta_{\text{res}} = \lambda_{21}(1+z)/D$. Notice that the CHIME configuration can provide a high precision measurement of w_0 . However, the precision in the extraction of the EDE background parameter Ω_{EDE} , as well as in the measurements of the dark energy clustering parameters c_{vis}^2 and c_{eff}^2 , is quite poor. Concerning the standard cosmological parameters, the constraints on both $\ln A_s$ and $\Omega_b h^2$ are worse than those obtained with current CMB data. Indeed, these two parameters affect the overall amplitude of the 21 cm signal, while the CMB amplitude signal is mainly driven by the $\ln A_s$ parameter, with $\Omega_b h^2$ controlling the CMB even-odd peak ratio. However, the constraints on both τ and n_s are tighter for the 21 cm experiment. Let us emphasize that the addition of BICEP2 data does not change the results presented here. If we neglect the information arising from current CMB measurements on c_{vis}^2 and c_{eff}^2 , the errors on these two parameters are notably degraded, as can be noticed from the results depicted in Table V. Therefore, even if current CMB measurements poorly constrain the dark energy perturbation parameters, they still provide some useful information concerning their effect and their degeneracies with the remaining cosmological parameters.

B. Omniscope $z > 7$

We provide in Table VI the specifications of the future omniscopelike experiment explored here. Table VII shows

TABLE IV. 1σ errors on the parameters describing the two fiducial models here, which only differ in the values of the Ω_{EDE} and the dark energy clustering parameters.

	Fiducial ₁ (fiducial ₂)	CHIME	CHIME + Planck and WP
$\Omega_b h^2$	0.02258	$2.07(2.15) \times 10^{-3}$	$2.55(2.22) \times 10^{-4}$
h	0.71	$1.4(2.21) \times 10^{-2}$	$0.88(1.11) \times 10^{-2}$
$\Omega_c h^2$	0.1109	$7.07(9.57) \times 10^{-3}$	$1.54(1.66) \times 10^{-3}$
Ω_{EDE}	0.01(0.03)	$1.92(2.97) \times 10^{-2}$	$3.31(3.8) \times 10^{-3}$
c_{vis}^2	0.(0.33)	13.6(2.24)	$2.82(2.63) \times 10^{-1}$
w_0	-0.9	$5.35(7.78) \times 10^{-2}$	$2.65(3.23) \times 10^{-2}$
c_{eff}^2	1.(0.33)	21.4(1.41)	$2.89(2.72) \times 10^{-1}$
n_s	0.963	$1.9(3.63) \times 10^{-2}$	$5.26(5.32) \times 10^{-3}$
τ	0.088	$2.78(2.69) \times 10^{-3}$	$7.41(6.79) \times 10^{-4}$
$\ln[10^{10} A_s]$	3.09784	$7.32(8.26) \times 10^{-1}$	$2.44(2.44) \times 10^{-2}$

TABLE V. The same as in Table V but neglecting the current CMB information on c_{vis}^2 and c_{eff}^2 .

	Fiducial ₁ (fiducial ₂)	CHIME	CHIME + Planck and WP
$\Omega_b h^2$	0.02258	$2.07(2.15) \times 10^{-3}$	$2.55(2.22) \times 10^{-4}$
h	0.71	$1.4(2.21) \times 10^{-2}$	$0.90(1.11) \times 10^{-2}$
$\Omega_c h^2$	0.1109	$7.07(9.57) \times 10^{-3}$	$1.80(1.66) \times 10^{-3}$
Ω_{EDE}	0.01(0.03)	$1.92(2.97) \times 10^{-2}$	$3.54(4.0) \times 10^{-3}$
c_{vis}^2	0.(0.33)	13.6(2.24)	11.29(0.80)
w_0	-0.9	$5.35(7.78) \times 10^{-2}$	$2.76(3.23) \times 10^{-2}$
c_{eff}^2	1.(0.33)	21.4(1.41)	18.95(0.84)
n_s	0.963	$1.9(3.63) \times 10^{-2}$	$5.26(6.0) \times 10^{-3}$
τ	0.088	$2.78(2.69) \times 10^{-3}$	$7.41(6.86) \times 10^{-4}$
$\ln[10^{10} A_s]$	3.09784	$7.32(8.26) \times 10^{-1}$	$2.44(2.44) \times 10^{-2}$

TABLE VI. Specifications of the omniscopelike experiment for which we have considered 10^6 antennas; see also Ref. [32].

Redshift slices	B_W	D	f_{cover}	t_{obs}	f_{sky}
9/10/11/12	10 Mhz	10 km	0.1	1 yr	0.5

TABLE VII. The same as in Table IV but for the omniscopelike experiment considered here; see also Ref. [32].

	Fiducial ₁ (fiducial ₂)	Omniscope	Omniscope + Planck and WP
$\Omega_b h^2$	0.02258	$2.85(5.75) \times 10^{-5}$	$2.64(4.79) \times 10^{-5}$
h	0.71	$5.51(5.54) \times 10^{-3}$	$3.39(3.78) \times 10^{-3}$
$\Omega_c h^2$	0.1109	$2.51(5.73) \times 10^{-4}$	$2.44(4.65) \times 10^{-4}$
Ω_{EDE}	0.01(0.03)	$0.697(1.6) \times 10^{-3}$	$0.684(1.47) \times 10^{-3}$
c_{vis}^2	0.(0.33)	$1.93(1.4) \times 10^{-1}$	$1.59(1.21) \times 10^{-1}$
w_0	-0.9	$1.53(1.56) \times 10^{-2}$	$0.953(1.09) \times 10^{-2}$
c_{eff}^2	1.(0.33)	1.78(0.22)	$2.86(1.7) \times 10^{-1}$
n_s	0.963	$2.89(4.27) \times 10^{-4}$	$2.65(3.96) \times 10^{-4}$
τ	0.088	$3.11(3.09) \times 10^{-5}$	$3.1(3.08) \times 10^{-5}$
$\log[10^{10} A_s]$	3.09784	$3.34(3.18) \times 10^{-2}$	$1.98(1.94) \times 10^{-2}$
Δ_z	1.5	$8.39(8.8) \times 10^{-4}$	$8.38(8.79) \times 10^{-4}$

the 1σ errors for the two fiducial models previously illustrated for the CHIME-like experiment.⁴ While the $\Omega_b h^2$ parameter can be measured with a precision similar to the one achieved with current CMB data, the $\ln A_s$ parameter is still better constrained by the latter measurements. For the setup and the fiducial model considered here, the errors on τ and n_s are significantly better than for CMB experiments; see also the discussion in Ref. [32]. The addition of Planck and/or BICEP2 priors does not

⁴In this case, we have also marginalized over the parameter Δ_z specifying the duration of the reionization process; see [32] for more details on the background reionization model.

TABLE VIII. The same as in Table V but for the omniscopelike experiment considered here.

	Fiducial ₁ (fiducial ₂)	Omniscope	Omniscope + Planck and WP
$\Omega_b h^2$	0.02258	$2.85(5.75) \times 10^{-5}$	$2.64(5.37) \times 10^{-5}$
h	0.71	$5.51(5.54) \times 10^{-3}$	$3.40(3.94) \times 10^{-3}$
$\Omega_c h^2$	0.1109	$2.51(5.73) \times 10^{-4}$	$2.49(5.44) \times 10^{-4}$
Ω_{eDE}	0.01(0.03)	$0.697(1.6) \times 10^{-3}$	$0.684(1.49) \times 10^{-3}$
c_{vis}^2	0(0.33)	$1.93(1.4 \times 10^{-1})$	$1.93(1.38 \times 10^{-1})$
w_0	-0.9	$1.53(1.56) \times 10^{-2}$	$0.954(1.14) \times 10^{-2}$
c_{eff}^2	1(0.33)	1.78(0.22)	1.78(0.21)
n_s	0.963	$2.89(4.27) \times 10^{-4}$	$2.85(4.18) \times 10^{-4}$
τ	0.088	$3.11(3.09) \times 10^{-5}$	$3.1(3.08) \times 10^{-5}$
$\log[10^{10} A_s]$	3.09784	$3.34(3.18) \times 10^{-2}$	$1.98(1.94) \times 10^{-2}$
Δ_z	1.5	$8.39(8.8) \times 10^{-4}$	$8.39(8.79) \times 10^{-4}$

change much the overall picture for the marginalized errors depicted in Table VI. Let us emphasize that we did not take into account extra ionizing sources that can severely damage the variances of the reionization model parameters; see e.g., [31,32].

Concerning the dark energy parameters, the constraints on the background parameters w_0 and Ω_{eDE} reach high

precision levels, with 2% and 7% (6%) errors, respectively, for $\Omega_{\text{eDE}} = 0.01(0.03)$. A similar precision on the measurement of the dark energy clustering parameters c_{eff}^2 and c_{vis}^2 is obtained with future 21 cm measurements, except for the case in which $c_{\text{vis}}^2 = 0$ and $c_{\text{eff}}^2 = 1.0$. For this particular scenario, the constraint on c_{eff}^2 is very poor.

Table VIII shows the analogue to Table VII but for the case in which the current CMB errors on the dark energy equation parameters are neglected. Note that, as in the CHIME experiment case, the errors on both c_{eff}^2 and c_{vis}^2 are increased, especially for the case of the fiducial model 1 explored here. Consequently, present CMB data can help, although very mildly, in improving the precision in the measurements of the dark energy properties.

Figure 4 shows the two-dimensional 1 and 2 σ allowed regions in a reduced number of parameters for the fiducial scenario with $\Omega_{\text{eDE}} = 0.01$, $c_{\text{vis}}^2 = 0$ and $c_{\text{eff}}^2 = 1.0$. The top panel of Fig. 4 illustrates the expected correlation in the (w, n_s) plane. As in the case of the analysis of Sec. V, Ω_{eDE} and w_0 are anticorrelated, and therefore there exists a mild anticorrelation between Ω_{eDE} and n_s , as depicted in the bottom panel of Fig. 4. We also depict in red solid lines the resulting contours after adding the Planck measurements.

VII. SUMMARY AND CONCLUSIONS

In the last few years CMB measurements have reached an extremely high sensitivity, allowing for high precision cosmology and providing, therefore, very tight constraints on the basic parameters governing the standard Λ CDM model. The recent claimed detection of primordial B modes from the BICEP2 experiment has also offered new insights in cosmology. Here we have exploited the former signal, together with the latest CMB measurements, to update the constraints on an early dark energy component. We find $\Omega_{\text{eDE}} < 0.009$ at 95% C.L. when Planck, WMAP polarization and BICEP2 data are considered, assuming that the early dark energy component can be described by a perfect fluid. If the former assumption is relaxed, and the dark energy perturbation parameters c_{eff}^2 and c_{vis}^2 are allowed to vary freely, Ω_{eDE} turns out to be less well constrained. Furthermore we find that current CMB measurements are unable to constrain c_{eff}^2 and c_{vis}^2 .

In this case, future cosmological measurements of the 21 cm line can be crucial. In the optimistic approach followed here (i.e., in the absence of foregrounds or extra ionizing sources), our Fisher matrix analyses of future data from an omniscopelike experiment show that the combination of these 21 cm cosmological probes and current CMB measurements will be able to distinguish between the canonical quintessence scenario (characterized by $c_{\text{eff}}^2 = 1$ and $c_{\text{vis}}^2 = 0$) and other possible models (with nonstandard clustering parameters, as, for instance, with $c_{\text{eff}}^2 = 0.33$ and $c_{\text{vis}}^2 = 0.33$) with 2 σ significance, in the presence of a non-negligible early dark energy

FIG. 4 (color online). 1 and 2 σ allowed regions from the Fisher analysis with an omniscopelike experiment with four redshift slices $z = 9, 10, 11, 12$ for the fiducial model 1. The addition of the Planck measurements results in the continuous red contours.

component Ω_{eDE} . The errors on the energy density of the former parameter from the joint analysis of future 21 cm data and current CMB measurements, assuming $\Omega_{\text{eDE}} = 0.01(0.03)$, are $0.684(1.47) \times 10^{-3}$. Future 21 cm probes can therefore achieve a precision below 10% in the measurement of an early, nonhomogeneous dark energy component.

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