A novel early dark energy model

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ABSTRACT

We present a theoretical study of an early dark energy (EDE) model. The equation of state $\omega(z)$ evolves during the thermal history in a framework of a Friedmann-Lemaitre-Robertson-Walker Universe, following an effective parametrization that is a function of redshift z. We explore the evolution of the system from the radiation domination era to the late times, allowing the EDE model to have a non-negligible contribution at high redshift (as opposed to the cosmological constant that only plays a role once the structure is formed) with a very little input to the Big Bang Nucleosynthesis, and to do so, the equation of state mimics the radiation behaviour, but being subdominant in terms of its energy density. At late times, the equation of state of the dark energy model asymptotically tends to the fiducial value of the De Sitter domination epoch, providing an explanation for the accelerated expansion of the Universe at late times, emulating the effect of the cosmological constant. The proposed model has three free parameters, that we constrain using SNIa luminosity distances, along with the CMB shift parameter and the deceleration parameter calculated at the time of dark energy - matter equality. With full knowledge of the best fit for our model, we calculate different observables and compare these predictions with the standardΛCDM model. Besides the general consent of the community with the cosmological constant, there is no fundamental reason to choose that particular candidate as dark energy. Here, we open the opportunity to consider a more dynamical model, that also accounts for the late accelerated expansion of the Universe.

1. Introduction

Observations of the luminosity distances of the Supernova type Ia (Riess et al., 2000, SNIa;) revealed that the expansion of the Universe is speeding up at late times. Within the cosmological standard model, there is an unknown matter–energy component that contributes by about 70% of the critical density, and this fluid is described as a smooth component with negative pressure. Although astronomers know the effect of this fluid, there is not a clear idea of how to detect it, mainly because it is a smooth component, dilute throughout all the Universe and the parameter of the equation of state today is most likely $\omega_0 = -1$, even if $\omega = \omega(t)$ in the past.

Different models have been proposed in the past years to explain the nature of this component: the cosmological constant Λ that accounts for the quantum vacuum energy (Carroll, 2001; Peebles and Ratra, 2003), scalar fields with different $\omega(t)$: Quintessence fields (Ratra and Peebles, 1988; Caldwell et al., 1998; Sami and Padmanabhan, 2003) (with the state equation $\omega = \frac{p_Q}{\rho_Q}$ = constant), K–essence (Armendáriz-Picón et al., 1999; Chiba et al., 2000; Armendariz-Picon et al., 2001; Chiba, 2002),

Taquionic fields Sen (2002a,b); Gibbons (2002), phantom fields (Caldwell, 2002; Cline et al., 2004), frustrated topological defects, extra–dimensions, massive (or massless) fermionic fields, galileons, effective parametrizations of the state equation, primordial magnetic fields, Chaplygin gas (Kamenshchik et al., 2000; Bento et al., 2004), holographic models (Hořava and Minic, 2000), Horndeski's theory (Clifton et al., 2012), and, early dark energy models (Wetterich, 2004; Doran and Robbers, 2006; Khoraminezhad et al., 2020), among others. All these models can be predicted by the Friedmann equations in the framework of General Relativity. Instead, modified gravity models impose the accelerated expansion through a geometrical contribution, rather than an energy density (Faraoni and Capozziello, 2011; De Felice and Tsujikawa, 2010).

The current paradigm in the standard model is the ΛCDM model, that has only a few free parameters, well-constrained with present observations. Nonetheless, the nature of the cosmological constant Λ is still unexplained. One can wonder if it is not more natural that the accelerated expansion could have been produced by a different smooth field, that evolves with redshift z, having a non-null contribution in the

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early Universe and emulating the action of the cosmological constant Λ at late times.

During the radiation domination epoch, the abundances of light nuclei predicted by the Big Bang Nucleosynthesis (Alpher et al., 1948; Gamow, 1946, BBN), in particular Y_{He}, can be used to quantify the degrees of freedom of the radiation components in the early Universe (García et al., 2011). At the matter domination era, when matter components are predominant and structure was formed, baryonic acoustic oscillations (BAO) and the anisotropies in temperature of the Cosmic Microwave Background also allow astronomers to constrain their dark energy (DE) models, although DE is not the main contributor of the matter-energy density in that stage.

Additional tests, such as the calculation of the age of the Universe or the *Statefinder* parameters can tell us the deviation from a given DE model from the ΛCDM predictions, and how feasible a DE candidate is in the observed Universe. With the aim to give a plausible explanation of the accelerated expansion of the universe, we have proposed a model of dark energy which has a non–null contribution at early times to increase the Hubble radius during radiation domination era and influence the Boltzmann equations that determine the evolution of the light abundances. All the conditions that allow us to describe the early dark energy are achieved with the effective parametrization, which is characterized by its equation of state that mimics the dominating component.

Throughout the paper, we use the cosmological parameters from the Planck Collaboration (Planck Collaboration et al., 2018) with $\Omega_{0m}=$ 0.3111 $\pm$ 0.0056, $\Omega_{\Lambda}=$ 0.6889 $\pm$ 0.0056 and $H_0=$ 67.66 $\pm$ 042 km s^{-1}Mpc^{-1} (or $h=$ 0.6766), and a spatially–flat model of the Universe with cold dark matter.

The paper is presented as follows: in Section 2, we describe an alternative DE candidate with a non-negligible contribution in the early Universe and that mimics the cosmological constant Λ effect at late times. Section 3 shows the method employed to find the best fitting parameters of the model proposed as a different option to dark en al. In Section 4, we explore the evolution with redshift of the dark energy density fraction and compare the observables predicted by our model with current cosmological observations. Section 5 discusses proxies that the model is submitted to constrain it and compare it with the current paradigm, Λ, in the standard model. Finally, Section 6 summarizes the findings of this study and proposes perspectives for DE candidates, which evolution with redshift is not well constrained with observations yet.

2. Effective parametrization of ω_ϕ

The goal of this work is to study a theoretical prescription that describes dark energy. In order to do so, we make no assumption on the nature of the dark energy component in our model, hence, it can be described as a non-interacting perfect fluid that evolves with other components of the plasma in the Universe, and therefore, it could be supposed as scalar field ϕ. We do not discuss further the nature of the DE model but leave open the possibility to link it with a particular scalar field in the literature.

The prospective model takes into account that the Universe is experiencing an accelerated expansion at late times, following a De Sitter attractor, hence $-1 < \omega_{de} < -\frac{1}{3}$. As a consequence, it should be compared with the cosmological constant Λ. Ultimately, the motivation of this work is to find the physical insight of the current expansion of the Universe, but also to give an alternative to ΛCDM model, since there is a significantly large difference with the energy of vacuum fluctuations.

In addition, we are interested to establish a realization that has a non-negligible contribution during the radiation domination epoch, being subdominant with respect to the radiation energy fraction. Therefore, our model could have an input to BBN, through effective degrees of freedom introduced in the Hubble parameter $H(z)$, as long as this action does not overcome the observational upper limits.

A contribution at high redshift ($z \sim 10^{11}$) can be achieved by imposing $\omega_\phi =1/3|_{v_{rad}}$, and the following condition for our DE' energy density:

$$\rho_{de}|_{rad} = b \cdot \rho_{rad} \qquad 0 \leq b < 1. \tag{1}$$

with ρ_{rad} the radiation energy density. The equation (1) can be described through the assumption $\rho_{de}|_{rad} \propto a^{-4}$. As a result, the early dark energy model would be characterized by an effective parametrization, that evolves in time, without impacting the hierarchy and chronology of the events in the cosmic history. The parametrization of the equation of state ω_{de} should converge to the limits mentioned above.

Different parametrizations have been proposed to describe the evolution of DE and/or a unified dark matter and dark energy model Davari et al. (2018) or constraints at high redshift Lorenz et al. (2017). In order to achieve a general solution of the dynamical system established in previous section, we propose an effective parametrization of the state equation valid up to very high redshift, towards to the Planck time:

$$\omega_\phi(z) = \frac{4/3}{\left(\frac{1+z_*}{1+z}\right)^m + 1} - 1. \tag{2}$$

Here, m is a factor that modules the transitions between the attractors, z_* is a redshift in matter domination epoch defined by:

$$z_* = \frac{z_{eq} + z_{de}}{2} \tag{3}$$

with z_{eq}, the matter–radiation equality and the z_{de}, the redshift when the De-Sitter domination (i.e. the accelerated expansion of the Universe stage) begins.

The parametrization (2) respects all the conditions previously mentioned, thus, explores an alternative to the ΛCDM current paradigm.

The energy density of the dark energy component ρ_ϕ is given by:

$$\int_\rho^{\rho_0} \frac{d\rho'}{\rho'} = -3 \int_a^1 \frac{(1 + \omega_\phi(a'))}{a'} da', \tag{4}$$

integrating (4), it is obtained:

$$\rho = \rho_0 \cdot (1 + z)^4 \left[\frac{\left(\frac{1+z_*}{1+z}\right)^m + 1}{(1 + z_*)^m + 1} \right]^{4/m} = \rho_0 \cdot f(z). \tag{5}$$

with:

$$f(z) = (1 + z)^4 \left[\frac{\left(\frac{1+z_*}{1+z}\right)^m + 1}{(1 + z_*)^m + 1} \right]^{4/m}. \tag{6}$$

Moreover, the fraction of the dark energy density $\Omega_\phi = 1 - F = \frac{\rho_\phi}{\rho_{cr}}$:

$$\Omega_\phi(z) = \frac{\rho_0}{\rho_{cr}} = \frac{\Omega_{\phi0} \cdot f(z)}{\Omega_{\phi0} \cdot f(z) + \Omega_{m0} \cdot (1 + z)^3}. \tag{7}$$

We remind the reader that we assume a spatially–flat Universe and a Concordance model, hence, $\Omega_{\phi0} + \Omega_{m0} + \Omega_{rad0} = 1$ and $\Omega_{rad0} \to 0$ at late times.

3. Best fitting parameters of the model

The formal solution of the parametrization (2) requires the estimation of the free parameters of the model $\{\Omega_{\phi_0}, m, z_{de}\}$, the fraction of the dark energy density, the module that regulates the transition between the radiation to the De-Sitter domination eras, and the dark energy domination redshift, respectively. A preliminary inspection of the parameter-space shows a large degeneracy between m and z_{de}.

We use observations of the luminosity distances of SNIa from the survey SUPERNOVA COSMOLOGY PROJECT UNION2.1 (Rubin et al., 2014,

SCP2.1)[2], along with the CMB shift parameter R_{CMB} and, the condition of the deceleration parameter equals to zero at $z = z_{de}$. Adopting R_{CMB} in this work, allow us to constrain the free parameters of the model at high redshift, during the matter domination era.

We build an MCMC module to find the set of best-fitting parameters to the model. The priors of the model proposed can be summarized as:

- Ω_{ϕ_0} should be strictly positive, [0,1] in the Concordance model.
- Negative values of m lead to an inverted transition between the radiation and the De-Sitter attractors (the latter occurring first than the former), which is not consequent with the thermal history of the Universe. On the other hand, $m = 0$ produces no transition whatsoever, then, m is strictly positive in the framework of the Standard Model. Furthermore, visual inspection of the evolution of this parameter shows that $m > 90$ leads to a quick transition (for very large values of m to an instantaneous transition) between the attractors. We discard these values of m because they are unlikely from the observational point of view. In fact, the structure was formed during the matter domination epoch, which would not happen if there would not have existed an extended transition between the radiation and De-Sitter domination eras.
- The redshift of matter – dark energy equality, z_{de} has already occurred since the Universe is experiencing an accelerated expansion $\Rightarrow 0 < z_{de} \gtrsim 1.5$. The upper limit takes into account that cosmic structure was formed during the matter domination epoch, and that has been observed through different with different surveys to-date 2DFGRS[3], 6DFGS[4], WIGGLEZ[5] and the Sloan Digital Sky Survey SDSS[6].

We must break the large degeneracy between m and z_{de}. To do such, as well as to find the best fitting values for $\{\Omega_{\phi_0}, m, z_{de}\}$ set, we use the luminosity distance $d_L(z)$ -equation (8) - and the distance modulus μ -equation (9)- are built for our model to compare these functions with the observational SNIa distance modulus from SCP2.1, with z up to 1.4.

$$d_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{B(z')}, \tag{8}$$

$$B(z') = (\Omega_{\phi_0} f(z'; m, z_*) + (1 - \Omega_{\phi_0})(1 + z')^3)^{1/2},$$

$$\mu = m - M = 5(\log_{10} d_L(z) - 1). \tag{9}$$

As mentioned above, the CMB shift parameter R_{CMB} is also imposed as condition to constrain the set of free parameters of the model. The function R_{CMB} measures the shifting of the acoustic peaks from from the BAO (Bond et al., 1997; Efstathiou and Bond, 1999) and it is defined as the comoving distance between the last scattering surface and today:

$$R = (\Omega_m H_0^2)^{1/2} \int_0^{1089} \frac{dz}{H(z)}, \tag{10}$$

Neither Planck Collaboration et al. (2015) or Planck Collaboration et al. (2018) calculate directly the value of this parameter, different than the WMAP-7 that inferred the value of the CMB shift parameter as $R = 1.719 \pm 0.019$ (Panotopoulos, 2011). Nonetheless, Huang et al. (2015) use cosmological parameters from Planck Collaboration et al. (2015) to compute an updated value of $R = 1.7496 \pm 0.005$. It is worth noticing that this is the only observable that we constrain with Planck Collaboration et al. (2015), and not with Planck Collaboration et al. (2018) cosmological parameters, as stated in the introduction.

The third condition assumed to calculate the three free parameters of the model is the deceleration parameter condition $q(z_{de}) = 0$, i.e. the

Universe starts it accelerated expansion at the time that the dark energy density overcomes other matter-energy contributions. Although the deceleration parameter is no longer used in the framework of the Concordance model, its definition and solution are quite handy to narrow down the degeneracy between m and z_{de}.

$$q(z_{de}) = 0 \quad \text{with} \quad q(z) = (1 + z)\frac{\partial H}{\partial z} - 1. \tag{11}$$

The best-fitting parameters are obtained with an MCMC module that takes into account the three conditions previously described. Fig. 1 shows the posteriors of Ω_{ϕ_0}, m, and z_{de}, and it has been calculated with 3 walkers in the MCMC routine built in python. It converges after 100000 steps around the parameter–space. The R_{CMB} constrain at high redshift is determinant to break the degeneracy occurring in two of the three free parameters. The corner plot 1 shows the best fits to the early dark energy model in blue and then, the 68% interval regions allow us to determine the errors of the model.

The best estimates for the free parameters of the model and their errors are displayed in Table 1, as well as some derived parameters relevant to cosmology. We compare these best-fitting values with the ones from the ΛCDM model from Planck Collaboration et al. (2018).

Numerical calculations made with our background model, allow us to report the CMB shift parameter associated $R_{cal} = 1.85 \, ^{+0.12}_{-0.13}$. The value is slightly larger than the one calculated by Huang et al. (2015), but as claimed before, our model differs from ΛCDM result, as expected. Besides, R depends strongly on the factor $H(z)$, that changes with the model considered. In addition, we remind the reader that we adopt the Planck Collaboration et al. (2015) cosmological parameters for this particular observable, rather than Planck Collaboration et al. (2018), since the value has not been reported yet in the literature with the latter cosmological parameters.

4. Evolution of the observables associated to the DE model

Once the set of free parameters has been constrained with the MCMC method, the evolution of the dark energy model is complete and can be studied in the different cosmological eras.

Fig. 2 shows the evolution of the equation of state ω as function of z. The early DE model emulates radiation during this epoch and then, it evolves to the De-Sitter era. At late times, our theoretical description emulates the cosmological constant. In fact, dark energy relaxes to the asymptotic ΛCDM model during De-Sitter epoch. The blue curve shows the equation of state for our model, and the dashed lines represent the upper and lower limits imposed by the errors of the set of parameters $\{\Omega_{\phi_0}, m, z_{de}\}$ and the shaded cyan region display the possible range where $\omega(z)$ can evolve inside the error bars.

On the other hand, Fig. 3 presents the behaviour of $f(z)$. This function characterizes the evolution of the dark energy density in our model. During radiation domination epoch, the field scales as radiation $\rho \propto (1 + z)^4$ until z_{eq}. After that, ρ has a complex behaviour which guarantees the late convergence to accelerated expansion. At this point, the model evolves asymptotically to -1 (as the cosmological constant). At $z = 0$, the function $f(z = 0) = 1$, by construction, indicating that the dark energy density of the field is dominant over matter and the dark energy candidate satisfies the current observations and is in agreement with the predictions from the Concordance model.

The evolution of the dark energy density fraction is shown in Fig. 4. In the plot, it is possible to distinguish that $\Omega_{\phi 0} = 0.631$, the value of the dark energy density fraction today. When times evolves back (i.e. increasing z), the energy density of the field decreases, being subdominant during matter and radiation epoch, as imposed by construction with the parametrization of the equation of state. Nonetheless, the value of the energy density fraction of the model has a non-negligible contribution of the field energy density.

Moreover, we analyse the luminosity distance in our model with the best fitting parameters found in the previous section. Fig. 5 displays the

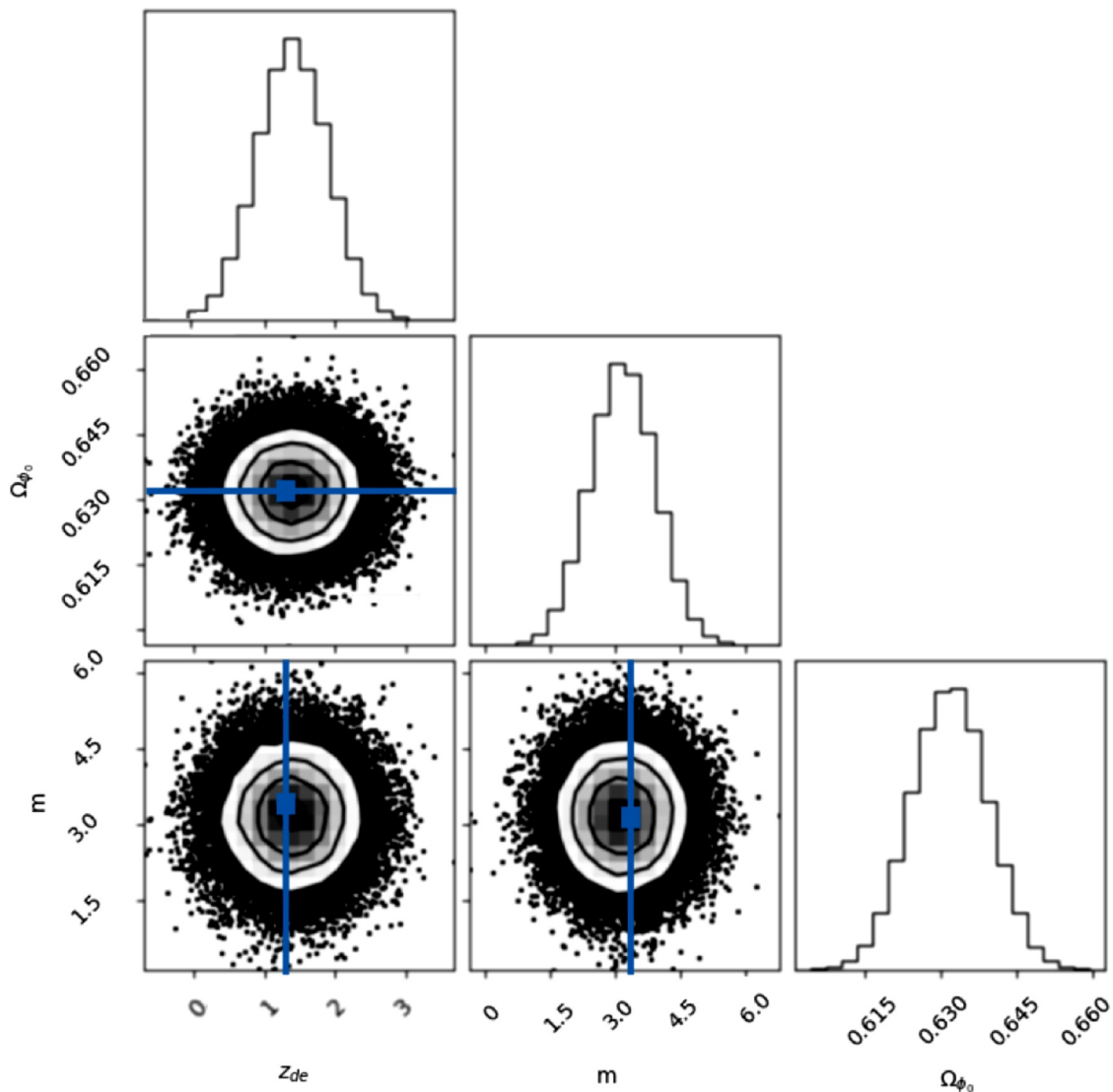[2] http://www-supernova.lbl.gov/

[3] http://www.2dfgrs.net/

[4] http://www.6dfgs.net/

[5] http://wigglez.swin.edu.au/

[6] https://www.sdss.org/

Fig. 1. Posteriors of our free parameters Ω_{ϕ_0}, m and z_{de}, with shaded 68% intervals, fitting to SNIa luminosity distances data from SCP2.1, on top of the simultaneous constraints given by the CMB shift parameter R_{CMB} and the deceleration parameter $q(z_{de}) = 0$. The best values estimated with the MCMC method lay within the prior conditions. With our analysis, we are able to recover the best values of the free parameters: Ω_{ϕ_0}=0.63 $\pm$ 0.05, m= 3.2 $\pm$ 0.9, and z_{de}= 1.2 $\pm$ 0.3. The latter parameters maximize the likelihood function, and break the tight degeneracy existent between m and z_{de}.

Table 1

Summary of the best values of the free parameters of the DE model and comparison with the ΛCDM. Column 1: parameter name. Column 2: estimates for our model. Column 3: ΛCDM comparison (Planck Collaboration et al., 2018).

Parameter	Our model	ΛCDM model
Ω_{ϕ_0}	0.631 $\pm$ 0.005	0.6889 $\pm$ 0.0056
m	3.2 $\pm$ 0.9	–
z_{de}	1.2 $\pm$ 0.3	–
Ω_{m0}	0.369 $\pm$ 0.005	0.3111 $\pm$ 0.0056
ω_0	-0.976 $\pm$ 0.358	-1

distance modulus in our model in a blue line (with the boundaries inside the parameter-space in blue dashed lines), the prediction with the ΛCDM model in magenta. To complement the study, we plot the observations of SNIa from SCP2.1 in black points with their corresponding errors.

The predictions for the distance modulus of ΛCDM and the EDE models lay quite close, especially at high redshift, and both are below the observations from $z \sim$ 1. Interestingly, both models fit very well at low redshift, when the luminosity distance grows linearly with redshift, independently of the model chosen.

It is worth mentioning that the ΛCDM standard model was originally fitted to the data with WMAP-7 cosmological parameters, but with current cosmology, and particularly, the value for H_0, there is a slight discrepancy with SCP2.1 data at redshifts higher than 1.

Additional analysis is carried out with measurements of $H(z)/(1 + z)$ vs. z and our model prediction. Fig. 6 draws a comparison among our model (blue solid line) with BAO observations from BOSS DR12 from Alam et al. (2017) in yellow diamonds, from BOSS DR14 quasars by Zarrouk et al. (2018) in the pink inverted triangle, BOSS DR14 Lyα autocorrelation at z= 2.34 with the grey circle, and BOSS DR14 joint constraint from the Lyα auto-correlation and cross-correlation with quasars from Blomqvist et al. (2019) in the dark red square. All the previous observations have computed with Planck Collaboration et al. (2018) cosmological parameters. Finally, the inferred Hubble measurement today from Riess et al. (2019) is shown with the cyan right tilted triangle. ΛCDM is plotted as a reference in a magenta line.
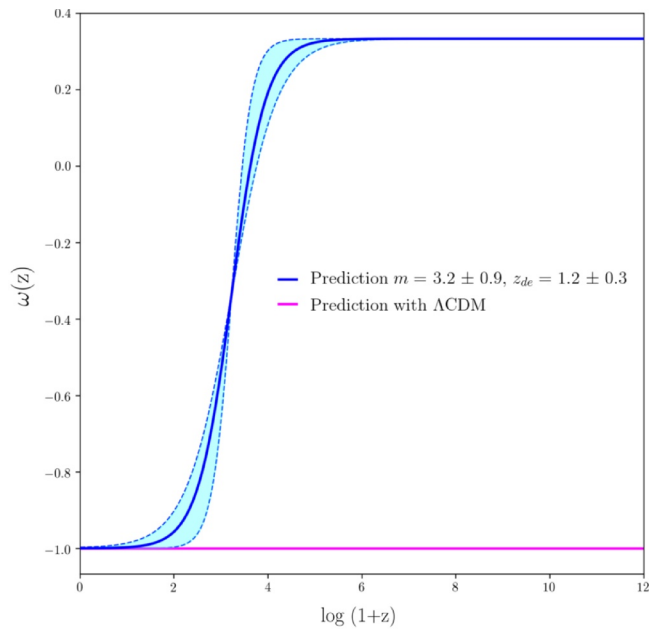
Fig. 2. Equation of state $\omega(z)$ as a function of redshift z. The parameterization is valid up to the Planck time. The blue line represents the equation of state of the field, the dashed lines show the upper and lower limits of $\omega(z)$, whereas the cyan region displays all the possible values that the equation of state could take inside the parameter-space allowed within the error bars. The purple line shows a comparison of the evolution of the equation of state in the case of the ΛCDM model.

Fig. 4. Dark energy density fraction Ω_ϕ with redshift z. The blue line presents the evolution of the energy density of the field. The dashed lines show the upper and lower limits of the dark energy density inside the error bars of the parameters. Within these boundaries, in the cyan shaded region, the possible values of Ω_ϕ within the parameter-space. It is worth noticing that at $z \sim 10^{10}$, Ω_ϕ raises from a value close to zero, indicating that our model is an EDE and it energy density fraction could contribute with some effective degrees of freedom in the Hubble parameter at radiation domination era.
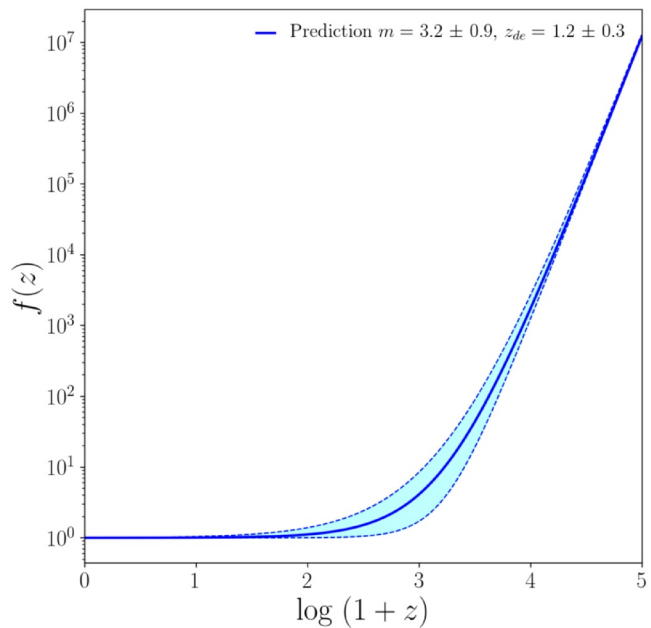

Fig. 3. Dark energy density factor $f(z)$ as a function of redshift z. The factor grows with redshift, differently from the evolution of the dark energy density Ω_ϕ. The blue continuous line shows the evolution of $f(z)$, whereas the dashed lines the upper and lower limits of the function inside the error bars of the parameters. The cyan shaded region, all the possible values of $f(z)$ within the parameter-space.

Fig. 5. Distance modulus vs. redshift z computed with our model and ΛCDM. We compare the theoretical predictions with observational data of SNIa from SCP2.1. We present our model, ΛCDM and SNIa from SCP release in the blue line, magenta line and black points, respectively.

5. Standard cosmological probes

Age of the Universe with this model

The age of the Universe for a given model in a standard cosmology is given by the expression:
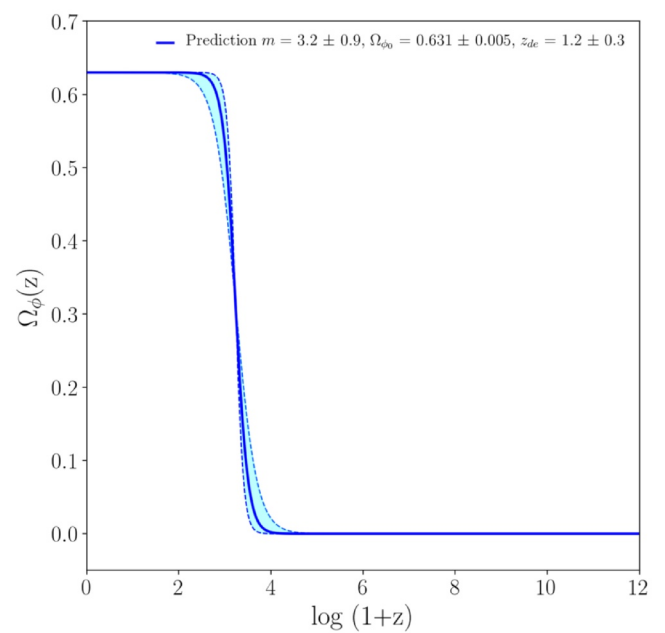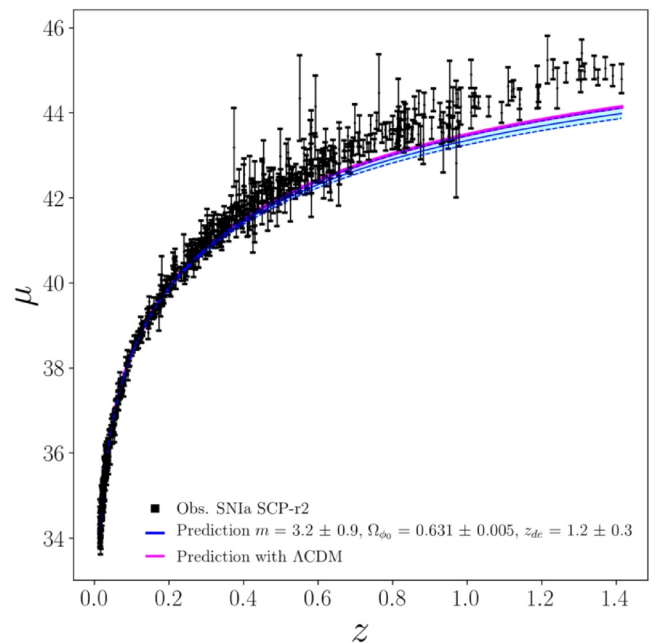
$$t_0 = \frac{1}{H_0} \int_0^\infty \frac{dz'}{(1+z')\sqrt{\Omega_{\phi 0} \cdot f(z) + \Omega_{m0} \cdot (1+z)^3}},$$

(12)

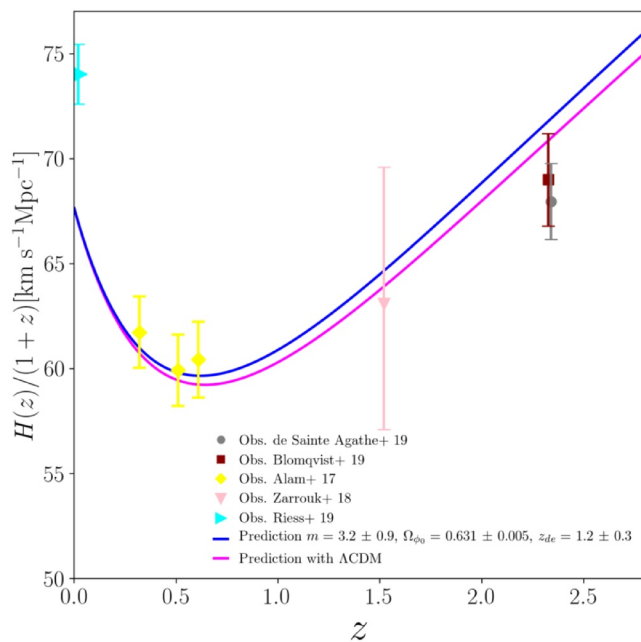In our model, with the parameters in Table 1, the calculated age of

Fig. 6. Prediction for $H(z)/(1 + z)$ as a function of z. We compare our model (blue solid line) with ΛCDM model (magenta solid line) and BAO observations derived with BOSS DR12 from Alam et al. (2017) in yellow diamonds, from BOSS DR14 quasars by Zarrouk et al. (2018) in the pink inverted triangle, BOSS DR14 Lyα autocorrelation at $z= 2.34$ with the grey circle, and BOSS DR14 joint constraint from the Lyaα auto-correlation and cross-correlation with quasars from Blomqvist et al. (2019) in the dark red square. All the previous observations have computed with Planck Collaboration et al. (2018) cosmological parameters. The inferred Hubble measurement at $z= 0$ derived independently by Riess et al. (2019) is shown with the cyan right tilted triangle.

the Universe is:

$$t_0 = 13.441 \pm 0.004 \ \text{Gyr.} \tag{13}$$

As an important remark, (13) is only an approximation of the age of the Universe today, since the parametrization (2) needs further constraints with high redshift observables. However, the result is quite outstanding, taking into account that our model differs significantly at high redshift from the standard one.

One way that the result can be interpreted is that the existence of early dark energy makes the Universe evolve faster than in the standard model. In this picture, the more negative ω is, the more accelerated is the expansion. Also, the Universe is "younger" if the dark energy component is precisely the one here proposed, given a value of H_0.

Statefinder parameters

In order to distinguish between a dark energy model and ΛCDM, Gao and Yang (2010) proposes a test using the *Statefinder* parameters, defined as:

$$r = 1 + \frac{9}{2}\Omega_\phi \omega_\phi (1 + \omega_\phi) - \frac{3}{2}\Omega_\phi \frac{\dot{\omega}_\phi}{H}, \tag{14}$$

$$s = 1 + \omega_\phi - \frac{1}{3}\frac{\dot{\omega}_\phi}{H\omega_\phi}, \tag{15}$$

The values of these parameters with the Standard model are $\{r, s\} = \{1, -1\}$ today (i.e. at $z= 0$). Any DE model-parameters will differ from the ΛCDM, and the departure of the former and the latter models in the space parameter at $z= 0$ determines how extreme a DE model is compared with the behaviour of the cosmological constant.

Fig. 7 shows the *Statefinder* space. The purple square and the golden star represent the ΛCDM and our DE model today, respectively. The
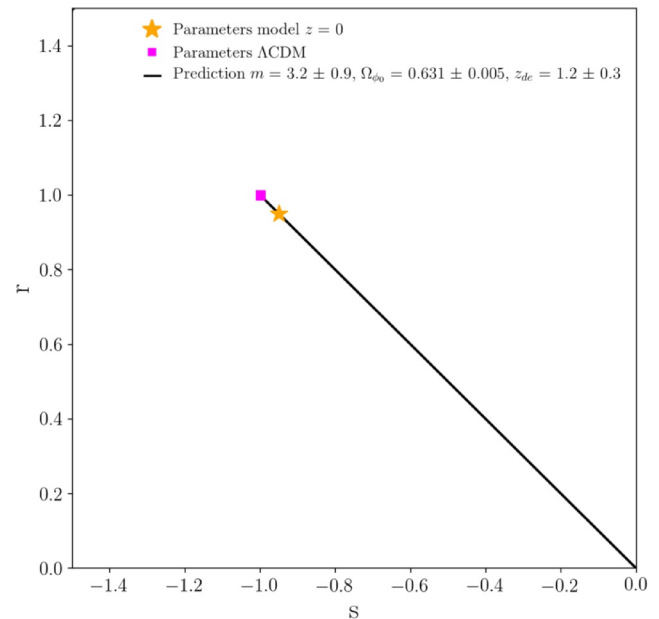

Fig. 7. *Statefinder* parameters space. The set of parameters today for ΛCDM is presented with a purple square $\{r, s\} = \{1, -1\}$, while the values for our DE model are shown with the golden star. The black line exhibits the evolution with redshift of the *Statefinder* parameters given our model. The effective parametrization evolves from high redshift (early times) in the right lower side to the future in the left upper corner.

black line shows the evolution of our model from the past ($\{r, s\} = \{0, 0\}$) to the future ($r > 0$ and $s < 0$). Interestingly, the line evolves towards the prediction of the standard model at $z= 0$, however, the equation of state has not reached the value $\omega_\phi = -1$ yet, therefore, there is still a gap between the refereed points in Fig. 7. In other words, our model is slightly off from the ΛCDM, because the prediction of the values Ω_{m0}, $\Omega_{\phi0}$ and z_* slightly differ from the standard model. Nevertheless, as discussed along this section, the equation of state relaxes and tends to ΛCDM model, once the field reaches the de-Sitter era.

6. Conclusions and perspectives

We have proposed a model of dark energy that causes an accelerated expansion of the Universe at late times, but also, has a non-negligible contribution during the radiation domination epoch. This dark energy candidate evolves from a radiation domination era to the De-Sitter time and emulates the behaviour of the cosmological constant. The properties of the dark energy component and it evolution in time (or redshift) have been extensively discussed, using an effective parametrization of the equation of state of the perfect fluid that could describe a scalar field.

Using distance modulus of SNIa up to $z \sim 1.4$ from the Supernova Cosmology Project 2.1 data sample, along with the CMB shift parameter R_{CMB} and, the condition of the deceleration parameter equals to zero at $z = z_{de}$, we constrained the free parameters of our model: Ω_{ϕ_0}, the dark energy density of the field today, m, a factor that modules the transition between the radiation to the dark energy domination era, and, z_{de}, the redshift when the Universe reaches the De-Sitter era and its energy density overtakes the matter density (ending up the matter domination era).

The complete solution of the parametrization allows us to study the dynamical evolution of the equation of state and the associated energy density fraction of the EDE candidate. Also, with the proposed method, we break the inner degeneracies among the free parameters.

Ongoing work will impose additional constraints on the model by computing the energy density of the field during radiation, when the

Universe is about a few minutes old, to study Big Bang Nucleosynthesis (BBN) and inferred parameters at this time. BBN is a well defined cosmological probe that can be used to rule out alternative models of dark matter and energy. Our model would not struggle in this cosmological regime since its energy contribution during radiation domination era is quite a subdominant, but non-negligible, therefore, it can play an important role as an effective degree of freedom of energy in the Hubble factor.

Future efforts will be also focused on the most general family of solutions for the equation of state $\omega(z)$, using Heaviside step functions, that move between the cosmological domination epochs, and in the case of study, from the radiation to the De-Sitter era, satisfying different observational proxies. One of the crucial questions that arise with the introduction of these kind of equations for ω_ϕ is the nature of dark energy and the interpretation of the energy density associated with the field $\rho_{de}(z) = \rho_{de0}\exp\left[\int_0^z \frac{3}{1+z'}(1 + \omega(z'))dz'\right]$.

Finally, our goal is to fully understand if these alternative models for dark energy are competitive candidates to explain the accelerated expansion of the Universe at late times, avoiding the discrepancies that appear with the cosmological constant Λ, the fine-tuning after inflation and an unnecessary number of free parameters that have no physical interpretation. Our model has shown to provide compelling results as an early dark energy model. Ultimately, it seems about natural to have an evolving equation of state in the cosmological context, hence this study makes progress in this direction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.newast.2020.101503.

References

Alam, S., Ata, M., Bailey Stephen, e.a., 2017. The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample 470 (3), 2617–2652. https://doi.org/10.1093/mnras/stx721.

Alpher, R.A., Bethe, H., Gamow, G., 1948. The Origin of Chemical Elements. Physical Review 73, 803–804.

Armendáriz-Picón, C., Damour, T., Mukhanov, V., 1999. k-Inflation. Physics Letters B 458, 209–218. arXiv:hep-th/9904075

Armendariz-Picon, C., Mukhanov, V., Steinhardt, P.J., 2001. Essentials of k-essence 63 (10), 103510. arXiv:astro-ph/0006373

Bento, M.C., Bertolami, O., Sen, A.A., 2004. Revival of the unified dark energy dark matter model? 70 (8), 083519. arXiv:astro-ph/0407239

Blomqvist, M., du Mas des Bourboux, H., Busca Nicolás, G.e.a., 2019. Baryon acoustic oscillations from the cross-correlation of Lyα absorption and quasars in eBOSS DR14 629, A86. https://doi.org/10.1051/0004-6361/201935641. arXiv:1904.03430

Bond, J.R., Efstathiou, G., Tegmark, M., 1997. Forecasting cosmic parameter errors from microwave background anisotropy experiments 291, L33–L41. arXiv:astro-ph/9702100

Caldwell, R.R., 2002. A phantom menace? Cosmological consequences of a dark energy component with super-negative equation of state. Physics Letters B 545, 23–29. arXiv:astro-ph/9908168

Caldwell, R.R., Dave, R., Steinhardt, P.J., 1998. Quintessential Cosmology Novel Models of Cosmological Structure Formation 261, 303–310.

Carroll, S.M., 2001. The Cosmological Constant. Living Reviews in Relativity 4, 1. arXiv:astro-ph/0004075

Chiba, T., 2002. Tracking k-essence 66 (6), 063514. arXiv:astro-ph/0206298

Chiba, T., Okabe, T., Yamaguchi, M., 2000. Kinetically driven quintessence 62 (2), 023511.

Clifton, T., Ferreira, P.G., Padilla, A., Skordis, C., 2012. Modified gravity and cosmology 513 (1), 1–189. https://doi.org/10.1016/j.physrep.2012.01.001. arXiv:1106.2476

Cline, J.M., Jeon, S., Moore, G.D., 2004. The phantom menaced: Constraints on low-energy effective ghosts 70 (4), 043543. arXiv:hep-ph/0311312

Davari, Z., Malekjani, M., Artymowski, M., 2018. New parametrization for unified dark matter and dark energy 97 (12), 123525.

De Felice, A., Tsujikawa, S., 2010. f(R) Theories. Living Reviews in Relativity 13, 3. arXiv:1002.4928

Doran, M., Robbers, G., 2006. Early dark energy cosmologies 2006 (6), 026.

Efstathiou, G., Bond, J.R., 1999. Cosmic confusion: degeneracies among cosmological parameters derived from measurements of microwave background anisotropies 304, 75–97. arXiv:astro-ph/9807103

Faraoni, V., Capozziello, S., 2011. Beyond Einstein Gravity. 170 Springer, Dordrecht. https://doi.org/10.1007/978-94-007-0165-6.

Gamow, G., 1946. Expanding Universe and the Origin of Elements. Physical Review 70, 572–573.

Gao, X.-T., Yang, R.-J., 2010. Geometrical diagnostic for purely kinetic k-essence dark energy. Physics Letters B 687, 99–102. arXiv:1003.2786

García, L., Tejeiro, J., Castañeda, L., 2011. Primordial nucleosynthesis in the presence of sterile neutrinos. Proceedings of the International School of Physics Enrico Fermi 178, 309–316.

Gibbons, G.W., 2002. Cosmological evolution of the rolling tachyon. Physics Letters B 537, 1–4. arXiv:hep-th/0204008

Hořava, P., Minic, D., 2000. Probable Values of the Cosmological Constant in a Holographic Theory. Physical Review Letters 85, 1610–1613. arXiv:hep-th/0001145

Huang, Q.-G., Wang, K., Wang, S., 2015. Distance priors from Planck 2015 data 12, 022. arXiv:1509.00969

Kamenshchik, A., Moschella, U., Pasquier, V., 2000. Chaplygin-like gas and branes in black hole bulks. Physics Letters B 487, 7–13. arXiv:gr-qc/0005011

Khoraminezhad, H., Viel, M., Baccigalupi, C., Archidiacono, M., 2020. Constraints on the Spacetime Dynamics of an Early Dark Energy Component. arXiv e-prints 2001.10252.

Lorenz, C.S., Calabrese, E., Alonso, D., 2017. Distinguishing between neutrinos and time-varying dark energy through cosmic time 96 (4), 043510. arXiv:1706.00730

Panotopoulos, G., 2011. A dynamical dark energy model with a given luminosity distance. General Relativity and Gravitation 43, 3191–3199. arXiv:1107.4475

Peebles, P.J., Ratra, B., 2003. The cosmological constant and dark energy. Reviews of Modern Physics 75, 559–606. arXiv:astro-ph/0207347

Planck Collaboration, Ade, P. A. R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Banday, A. J., Barreiro, R. B., Bartlett, J. G., et al. 2015. Planck 2015 results. XIII. Cosmological parameters. ArXiv e-prints 1502.01589.

Planck Collaboration, Aghanim, N., Akrami Y., e. a., 2018. Planck 2018 results. VI. Cosmological parameters. arXiv e-prints, pagesarXiv:1807.06209.

Ratra, B., Peebles, P.J.E., 1988. Cosmological consequences of a rolling homogeneous scalar field 37, 3406–3427.

Riess, A.G., Casertano, S., Yuan, W., Macri, L.M., Scolnic, D., 2019. Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond ΛCDM 876 (1), 85. https://doi.org/10.3847/1538-4357/ab1422. arXiv:1903.07603

Riess, A.G., Filippenko, A.V., et al., 2000. Tests of the Accelerating Universe with Near-Infrared Observations of a High-Redshift Type IA Supernova 536, 62–67. arXiv:astro-ph/0001384

Rubin, D., Aldering, G.S., et al., 2014. Updates to the Union SNe Ia Compilation. American Astronomical Society Meeting Abstracts #223. Vol. 223 of American Astronomical Society Meeting Abstracts. pp. 245.09.

Sami, M., Padmanabhan, T., 2003. Viable cosmology with a scalar field coupled to the trace of the stress tensor 67 (8), 083509. arXiv:hep-th/0212317

Sen, A., 2002. Rolling Tachyon. Journal of High Energy Physics 4, 048. arXiv:hep-th/0203211

Sen, A., 2002. Tachyon Matter. Journal of High Energy Physics 7, 065. arXiv:hep-th/0203265

Wetterich, C., 2004. Phenomenological parameterization of quintessence. Physics Letters B 594 (1-2), 17–22.

Zarrouk, P., Burtin, E., Gil-Marín Héctor, e.a., 2018. The clustering of the SDSS-IV extended Baryon Oscillation Spectroscopic Survey DR14 quasar sample: measurement of the growth rate of structure from the anisotropic correlation function between redshift 0.8 and 2.2 477 (2), 1639–1663. https://doi.org/10.1093/mnras/sty506. arXiv:1801.03062