A novel early Dark Energy model

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\textbf{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-Lemaître-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 standard $\Lambda$CDM 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 (SNIa; Riess et al., 2000) 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 $\Lambda$ 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 $\omega = \omega_R (\equiv \text{constant})$, 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; Khoramizhad 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 $\Lambda$CDM model, that has only a few free parameters, well-constrained with present observations. Nonetheless, the nature of the cosmological constant $\Lambda$ 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 early Universe and emulating the action of the cosmological constant $\Lambda$ at late times.

During the radiation domination epoch, the abundances of light nuclei predicted by the Big Bang Nucleosynthesis (BBN Alpher et al., 1948; Gamow, 1946), in particular $Y_{\text{He}}$, 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
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University 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 $\Omega_{\text{m}}^0 = 0.3111 \pm 0.0056$, $\Omega_{\Lambda}^0 = 0.6889 \pm 0.0056$ and $H_0 = 67.66 \pm 0.042$ 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 $\Lambda$ 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 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:

$$\omega_\phi(z) = \frac{4/3}{(1+z_s)^m} - 1. \quad (2)$$

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

$$z_s = \frac{z_{eq} + z_{de}}{2} \quad (3)$$

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 $\rho_\phi$ is given by:

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

integrating (4), it is obtained:

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

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:

$$\omega_\phi(z) = \frac{4/3}{(1+z_s)^m} - 1. \quad (2)$$

with $\rho_{\text{rad}}$ the radiation energy density. The equation (1) can be described through the assumption $\rho_{\text{de}} |_{\text{rad}} \propto a^{-4}$. 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 $\omega_{\text{de}}$ should converge to the limits mentioned above.

$$\rho_{\text{de}} |_{\text{rad}} = b \cdot \rho_{\text{rad}} \quad 0 \leq b < 1. \quad (1)$$
with:

\[
f(z) = (1 + z)^{\frac{1}{3} \left[ \frac{1 + z_e}{1 + z} \right]^m + 1} \left[ \frac{1 + z_e}{1 + z} \right]^m + 1 \right]^{4/m}.
\]  

(6)

Moreover, the fraction of the dark energy density \( \Omega_\phi = 1 - \frac{\rho_\phi}{\rho_{cr}} \) allows us to constrain the free parameters of the model at high redshift, during the matter domination era. A preliminary inspection of the parameter-space shows a large degeneracy between \( m \) and \( z_{de} \).

\[
\Omega_\phi(z) = \frac{\rho_\phi(z)}{\rho_{cr}} = \frac{\Omega_\phi(0) \cdot f(z)}{\Omega_\phi(0) \cdot f(0) + \Omega_m(0) \cdot (1 + z)^3}. \tag{7}
\]

We remind the reader that we assume a spatially-flat Universe and a Concordance model, hence, \( \Omega_\phi(0) + \Omega_m(0) + \Omega_{rad0} = 1 \) and \( \Omega_{rad0} \rightarrow 0 \) 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 and 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 (SCP2.1 Rubin et al., 2014)\(^1\), 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:

- \( \Omega_\phi(0) \) 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 consistent 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 \( \Rightarrow 0 < z_{de} \geq 1.5 \). 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 \(^2\), 6dFGS \(^3\), WiggleZ \(^4\) and the Sloan Digital Sky Survey SDSS \(^5\).

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 \( \mu \)-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.

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

\[
B(z') = (\Omega_\phi(0)f(z'; m, z_{de}) + (1 - \Omega_\phi(0))(1 + z')^3)^{1/2},
\]

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

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:

\[
R = \left( \Omega_mH_0^2 \right)^{1/2} \int_0^{1089} \frac{dz}{H(z)}. \tag{10}
\]

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 withPlanck 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 overcome 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

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\(^1\) http://www-supernova.lbl.gov/

\(^2\) http://www.2dfgrs.net/

\(^3\) http://www.6dfgs.net/

\(^4\) http://wigglez.swin.edu.au/

\(^5\) http://www.sdss.org/
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Figure 1: Posteriors of our free parameters $\Omega_0$, $m$, 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: $\Omega_0 = 0.63 \pm 0.05$, $m = 3.2 \pm 0.9$, and $z_{de} = 1.2 \pm 0.3$. The latter parameters maximize the likelihood function, and break the tight degeneracy existent between $m$ and $z_{de}$.

The best-fitting parameters are obtained with an MCMC module that takes into account the three conditions previously described. Figure 1 shows the posteriors of $\Omega_0$, $m$, 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 $\Lambda$CDM 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 $\Lambda$CDM 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 parame-
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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 |
|-----------|-----------|------------|
| Ωm0       | 0.631 ± 0.005 | 0.6889 ± 0.0056 |
| m         | 3.2 ± 0.9  | –          |
| zde       | 1.2 ± 0.3  | –          |
| Ωm0       | 0.369 ± 0.005 | 0.3111 ± 0.0056 |
| aH0       | -0.976 ± 0.358 | -1          |

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.

Figure 2 shows the evolution of the equation of state ω as a 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 \{Ω_m0, m, z_de\} and the shaded cyan region display the possible range where ω(z) can evolve inside the error bars.

On the other hand, Figure 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 ρ ∝ (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 Figure 4. In the plot, it is possible to distinguish that Ω_m0 = 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. Figure 5 displays the 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 ~ 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. Figure 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 auto-correlation at z = 2.34 with the grey circle, and BOSS DR14 joint constraint from the Lyα auto-correlation and cross-

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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.

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:

\[
t_0 = \frac{1}{H_0} \int_0^\infty \frac{dz'}{(1 + z') \sqrt{\Omega_{\phi_0} \cdot f(z) + \Omega_{m_0} \cdot (1 + z)^3}},
\]

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

\[
t_0 = 13.441 \pm 0.004 \text{ Gyr}.
\]

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 \( \omega \) 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:

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

\[
s = 1 + \omega_{\phi} - \frac{1}{3} \frac{\dot{\omega}_{\phi}}{H \omega_{\phi}},
\]

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. Figure 7 shows the Statefinder space. The purple square and the golden star represent the ΛCDM and our DE model today, respectively. The black line shows the evolution of our model from the past (\( \{r, s\} = \{0, 0\} \)) to the future (\( r > 0 \) and...
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Figure 5: Distance modulus vs. redshift $z$ computed with our model and $\Lambda$CDM. We compare the theoretical predictions with observational data of SNIa from SCP2.1. We present our model, $\Lambda$CDM and SNIa from SCP release in the blue line, magenta line and black points, respectively.

$s < 0)$. Interestingly, the line evolves towards the prediction of the standard model at $z = 0$, however, the equation of state has not reached the value $w_0 = -1$ yet, therefore, there is still a gap between the refereed points in Figure 7. In other words, our model is slightly off from the $\Lambda$CDM, because the prediction of the values $\Omega_{m0}$, $\Omega_{\Lambda 0}$ and $z_{de}$ slightly differ from the standard model. Nevertheless, as discussed along this section, the equation of state relaxes and tends to $\Lambda$CDM 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 $R_{\text{CMB}}$ and, the condition of the deceleration parameter equals to zero at $z = z_{de}$, we constrained the free parameters of our model: $\Omega_{\phi 0}$, the dark energy density of the field today, $m$, a factor that modulates 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 Heav-
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Figure 7: Statefinder parameters space. The set of parameters today for \( \Lambda \)CDM 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 lower right side to the future in the left upper corner.

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 \( \Lambda \), 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.

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