Reconciling $H_0$ tension in a six parameter space?

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Consistent observations indicate that some of the important cosmological parameters measured through the local observations are in huge tension with their measurements from the global observations (within the minimal ΛCDM cosmology). The tensions in those cosmological parameters have been found to be either weakened or reconciled with the introduction of new degrees of freedom that effectively increases the underlying parameter space compared to the minimal ΛCDM cosmology. It might be interesting to investigate the above tensions within the context of an emergent dark energy scenario proposed recently by Li and Shafieloo [1]. We find that the tension on $H_0$ is clearly alleviated within 68% confidence level with an improvement of the $\chi^2$ for CMB, for the above emergent dark energy model having only six free parameters similar to the spatially flat ΛCDM model.

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I. INTRODUCTION

According to a series of distinct observational data, Λ-cold-dark-matter (ΛCDM) cosmology is one of the best cosmological descriptions for the currently accelerated expansion of the universe, but on the other hand, it has been diagnosed with a number of severe problems. Apart from its inherent cosmological constant problem, the estimations of some important cosmological parameters in ΛCDM based cosmological framework exhibit huge tensions with respect to their estimations by other measurements. For instance, the estimation of the Hubble constant $H_0$ from ΛCDM based Planck’s mission [2] is more than 4σ apart from its estimation by the SH0ES collaboration [3], more than 5σ if combined with the H0LiCOW collaboration result [4], and around $4.7\sigma$ for its cosmology independent local determination [5]. Additionally, the estimation of the $S_8 (= \sigma_8 \sqrt{\Omega_m/0.3}$) parameter from Planck in a ΛCDM scenario is in tension with the cosmic shear measurements by different missions, for instance, KiDS-450 [6, 7, 8], DES [9, 10], and CFHTLenS [11, 12, 13]. Whether such tensions call for a new physics [14, 15] or they are arising due to the systematics [16] are not clearly understood at this stage. However, undoubtedly, the $H_0$ and $S_8$ tensions are two primary issues for modern cosmology and should be carefully investigated.

Since ΛCDM is unable to explain these issues, an usual approach is to consider the cosmological models beyond ΛCDM. Following this motivation, several extensions of the ΛCDM cosmology have been introduced with a possible solution to the $H_0$ tension [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55]. The tension on $H_0$ is alleviated within 68% confidence level with an improvement of the $\chi^2$ for CMB, for the above emergent dark energy model having only six free parameters similar to the spatially flat ΛCDM model. However, extended cosmological models naturally include extra free parameters compared to the six parameter ΛCDM scenario, and are therefore disfavoured with respect to it. It has thus been a natural search for some alternative cosmological model having same number of free parameters as in ΛCDM but having the ability to solve or reconcile the tension on of the two important parameters, namely, $H_0$ and $S_8$.

In the present article we work with a dynamical emergent dark energy model, recently introduced in [1], that has exactly same number of free parameters as in ΛCDM model. We investigate the model considering its evolution at the level of background and perturbations and constrain it using the presently available cosmological datasets including Planck 2015 cosmic microwave background (CMB) radiation, Pantheon sample of the Supernovae Type Ia, Baryon acoustic oscillations distance measurements, and the recently released local estimation of the Hubble constant by Riess et al. [3]. Our analyses clearly show that the tension on $H_0$ is reconciled within 68% confidence-level for this model [1]. This is one of the key results of this paper because so far we are aware of the literature, probably this is the first time we are reporting the reconciliation of $H_0$ tension in a six parameter space, improving the $\chi^2$ for CMB.

The work has been organized in the following way. In section [1] we briefly discuss the basic governing equations for the introduced dynamical dark energy model in a spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) universe. In section [2] we present the observa-
tional data and the methodology for this paper. After that in section IX we discuss the main results extracted from this model. Finally, we close the work in section V with a short summary of entire results.

II. PHENOMENOLOGICALLY EMERGENT DARK ENERGY

We consider a spatially flat Friedmann-Lemaître-Robertson-Walker (FLRW) metric to describe the geometrical configuration of the universe. We also consider that the gravitational sector of the universe is well described by the Einstein gravity where matter is minimally coupled to it. Additionally, we further assume that none of the fluids are interacting with each other, at least non-gravitationally. So, if the content of the universe is comprised of radiation, pressureless matter sector (baryons+cold dark matter) and a dark energy fluid \( \rho_{DE} \), then in the background of a spatially flat FLRW universe, one can write down the Hubble equation as

\[
H^2 = H_0^2 \left[ \Omega_m(1+z)^4 + \Omega_m0(1+z)^3 + \Omega_{DE}(z) \right]
\]

where \( H \) is the Hubble parameter of the FLRW universe, \( \Omega_m \) is the density parameter for radiation, \( \Omega_m0 \) is the density parameter for matter (baryons+cold dark matter) and \( \Omega_{DE}(z) \) is the dark energy density parameter. The dark energy density parameter can be solved as

\[
\Omega_{DE}(z) = \Omega_{DE,0} \exp \left[ 3 \int_0^z \frac{1 + w(z')}{1 + z'} dz' \right]
\]

where \( \Omega_{DE,0} \) is the current value of \( \Omega_{DE} \); \( w_{DE}(z) = p_{DE}(z)/\rho_{DE}(z) \), is the equation-of-state of the dark energy fluid. There are various ways to depict the evolution of the universe — either by prescribing the equation-of-state of the dark energy, or by providing the density parameter for dark energy. In this work we shall consider the second approach recently proposed in [1]:

\[
\Omega_{DE}(z) = \Omega_{DE,0} \left[ 1 - \tanh(\log_{10}(1+z)) \right]
\]

where \( \Omega_{DE,0} = 1 - \Omega_m0 - \Omega_m \) and \( 1 + z = a_0a^{-1} = a^{-1} \) (without any loss of generality we set \( a_0 \), the current value of the scale factor to be unity, i.e., \( a_0 = 1 \)). As already argued in [1] this model is similar to the \( \Lambda \)CDM one in the sense that both the models have six free parameters. So, from the statistical ground the models are same. Certainly, it will be interesting to investigate such phenomenological model having same number of free parameters in light of the latest observations. In Ref. [1], the authors present its observational constraints at the level of background. In the current work we want to extend this study by analysing its behaviour at the level of perturbations as well.

Since there is no interaction between any two fluids under consideration, hence, using the conservation equation for dark energy, namely,

\[
\dot{\rho}_{DE}(z) + 3H(1+w_{DE}(z))\rho_{DE}(z) = 0,
\]

one can derive the dark energy equation-of-state as

\[
w_{DE}(z) = -1 + \frac{1}{1+z} \times \frac{d \ln \Omega_{DE}(z)}{dz},
\]

which for the present model in (3) takes the form

\[
w_{DE}(z) = -1 - \frac{1}{3 \ln 10} \times \left[ 1 + \tanh(\log_{10}(1+z)) \right]
\]

Thus, for any prescribed \( \Omega_{DE}(z) \) one can derive the dark energy equation-of-state. As explained in [1], the equation-of-state (4) has an interesting symmetrical feature. From (4) one can see that at early time, i.e. for \( z \to \infty \), \( w_{DE} \to -1 \rightleftharpoons \Lambda \)CDM and for \( z \to 1 \) (far future), \( w_{DE} \to -1 \). And at preset time (i.e. \( z = 0 \)), we see \( w_{DE} = -1 - \frac{1}{\pi \ln 10} \) that means a phantom dark energy equation of state. Note that as described briefly in [1], the pivot point of transition in this model can be considered to be the redshift of matter-dark energy densities equality. For the present model in (3), dark energy has no effective presence in the past as shown in Fig. 1 of [1], while it emerges at present time, therefore, by the authors of [1], this model has been named as Phenomenologically Emergent Dark Energy (PEDE) model and we use the same name throughout this article.

III. OBSERVATIONAL DATA

In this section we describe the main observational data that are used to constrain the proposed dark energy model.

1. Cosmic Microwave Background (CMB): The Cosmic Microwave Background measurements are one of the potential data to unveil the nature of the dark universe. Here we make use of the Planck 2015 data [67,68] that include both high-\( \ell \) (30 \( \leq \ell \leq 2508 \)) TT and low-\( \ell \) (2 \( \leq \ell \leq 29 \)) TT likelihoods. We also consider the Planck polarization likelihood in the low-\( \ell \) multipole regime (2 \( \leq \ell \leq 29 \)) as well as the high-multipole (30 \( \leq \ell \leq 1996 \)) EE and TE likelihoods.

2. Baryon acoustic oscillation (BAO) distance measurements: We use 6dFGS [69], SDSS-MGS [70], and BOSS DR12 [71] surveys, as considered by the Planck collaboration [66].

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1 Let us note that here we fix the total neutrino mass to \( M_{\nu} = 0.06 \text{ eV} \) according to the Planck mission. This is certainly justified through the tight upper limits available on \( M_{\nu} \) [62, 63, 64, 65, 66].
Prior analysis.
posed on various free parameters during the statistical spectrum. In Table I we display the priors that are im-
and reionization optical depth, horizon to the angular diameter distance,
parameter space \( \Lambda \) that we will consider has six parameters similarly to the portforPlanck2015likelihood [68]. The parameterspace man and Rubin. This which is equipped with a convergence statistics by Gel-
To perform the numerical analysis we use the markov Chain Monte Carlo (MCMC) package CosmoMC [75] [76] which is equipped with a convergence statistics by Gel-
5. Dark energy survey (DES): We consider the first-year of the Dark Energy Survey measurements [9] [10] [73], as adopted by the Planck collaboration in [66].
6. Lensing: We use the lensing reconstruction power spectrum obtained from the CMB trispectrum analysis [74].

| Parameter          | Prior             |
|--------------------|-------------------|
| \( \Omega_b h^2 \) | [0.005, 0.1]      |
| \( \Omega_c h^2 \) | [0.01, 0.99]      |
| \( \tau \)         | [0.01, 0.8]       |
| \( n_s \)          | [0.5, 1.5]        |
| \( \log[10^{10} A_s] \) | [2.4, 4]       |
| \( 100 \theta_{MC} \) | [0.5, 10] |

TABLE I. Priors imposed on various free parameters of the PEDE and \( \Lambda \)CDM cosmological models. Recall that this model has same number of parameters as in flat \( \Lambda \)CDM model.

3. Supernovae Type Ia (Pantheon): The Supernovae Type Ia (SNIa) were the first standard candles that signaled for an accelerating universe. In this work we make use of the Pantheon sample, the latest compilation of SNIa, comprising 1048 data points in the redshift region \( z \in [0.01, 2.3] \) [72].

4. Hubble constant (R19): We include the recent estimation of the Hubble constant, \( H_0 = 74.03 \pm 1.42 \text{ km/s/Mpc at 68\% CL} \) [3], which is in tension (4.4\( \sigma \)) with CMB estimation within the minimal cosmological model \( \Lambda \)CDM.

5. Dark energy survey (DES): We consider the first-year of the Dark Energy Survey measurements [9] [10] [73], as adopted by the Planck collaboration in [66].

IV. RESULTS

The current PEDE model has the same number of free parameters as in spatially flat \( \Lambda \)CDM model. So, statistically within the spatially flat FLRW background, the PEDE and \( \Lambda \)CDM are on the same ground. We have con-
strained both the models using the same observational data (see section [11]) in order to perform a statistical comparison between them with the aim to focus on the tensions on both \( H_0 \) and \( S_8 = \sigma_8 \sqrt{\Omega_m/3} \). In Table [11] we show the observational constraints on the PEDE model using a number of cosmological datasets such as CMB, CMB+BAO, CMB+Pantheon, CMB+R19, CMB+DES and CMB+Lensing. Fig. [1] shows the 1D posterior distributions of all parameters of this model together with 2D joint contours consider-
ing several combinations of the parameters at 68\% and 95\% CL. At the same time in order to make a compar-
ison of the PEDE model with the \( \Lambda \)CDM cosmology, in Table [11] we show the constraints on the \( \Lambda \)CDM scenario using the same combination of data of the PEDE model. Our analyses clearly show that for the PEDE model, the Hubble constant \( H_0 \), takes very high values compared to the values of \( H_0 \) obtained from \( \Lambda \)CDM model. For the PEDE model one can see that CMB dataset alone esti-
mate \( H_0 = 72.58^{+0.79}_{-0.80} \text{ km/s/Mpc (68\% CL) while for the same dataset \( \Lambda \)CDM model returns, } H_0 = 67.47^{+0.66}_{-0.65} \text{ km/s/Mpc (68\% CL). One can notice that the difference in the error bars on } H_0 \text{ for both the models are not much significant, but the values of } H_0 \text{ for the PEDE model is perfectly in agreement with the Hubble constant esti-
mate from R19: } H_0 = 74.03^{+0.42}_{-0.43} \text{ km/s/Mpc (68\% CL). Moreover, there is an improvement of the } \chi^2 \text{ of about 1.5 for the PEDE model with respect to the } \Lambda \text{CDM one for the same number of degrees of freedom. When external datasets, such as BAO, Pantheon, etc., are added to CMB dataset, the estimations of } H_0 \text{ for all the observa-
tional combinations in the PEDE model (see Table [11]), take significantly higher values compared to the } H_0 \text{ esti-
mates for } \Lambda \text{CDM one (see Table [11]). Moreover, also the error bars on } H_0 \text{ for PEDE model are really stable for all the observational datasets, therefore the } H_0 \text{ tension reconciled within 68\% CL, for this PEDE model, is not due to a volume effect. This is a very interesting result because without using any additional degrees of freedom, only dynamical character of the dark energy density (equivalently, dark energy equation of state) can reconcile the } H_0 \text{ tension in a remarkable way. One should note the symmetrical form of dark energy density in this model where the pivot of transition is simply the epoch of matter-dark energy density equality. Additionally, when R19 and DES are added to the CMB dataset, we see a large improvement of the } \chi^2 \text{ for PEDE model compared to the } \Lambda \text{CDM, for instance, } \Delta \chi^2 \sim 17^2 \text{ for CMB+R19} \text{(PEDE)} \text{.}

2 Let us note that we define \( \Delta \chi^2 \) as: \( \chi^2 (\text{PEDE}) - \chi^2 (\text{ACDM}) \).
TABLE II. We report the 68% and 95% CL constraints on the free and derived parameters of the cosmic scenario driven by the Phenomenologically Emergent Dark Energy model [3] using various observational datasets. In the last row of the table we also display the best-fit values of $\chi^2$ for all the observational datasets.
We report the 68% and 95% CL constraints on the free and derived parameters of the ΛCDM model using various observational datasets. In the last row of the table we also display the best-fit values of $\chi^2$ for all the observational datasets.

### Table III

| Parameter | CMB | CMB+BAO | CMB + Planck | CMB+R19 | CMB+DES | CMB + Lensing |
|-----------|-----|---------|-------------|---------|---------|---------------|
| $\Omega_b h^2$ | $0.0119^{+0.0065}_{-0.0027}$ | $0.0118^{+0.0069}_{-0.0026}$ | $0.0119^{+0.0064}_{-0.0027}$ | $0.1170^{+0.0019}_{-0.0021}$ | $0.1170^{+0.0019}_{-0.0021}$ | $0.1188^{+0.0019}_{-0.0021}$ |
| $\Omega_c h^2$ | $0.2225^{+0.0015}_{-0.0007}$ | $0.2229^{+0.0014}_{-0.0007}$ | $0.2227^{+0.0015}_{-0.0007}$ | $0.2242^{+0.0015}_{-0.0009}$ | $0.2243^{+0.0016}_{-0.0007}$ | $0.2225^{+0.0015}_{-0.0009}$ |
| $100\theta_{MC}$ | $1.0407^{+0.0033}_{-0.001}
| $\tau$ | $0.087^{+0.017}_{-0.014}$ | $0.087^{+0.017}_{-0.014}$ | $0.087^{+0.017}_{-0.014}$ | $0.092^{+0.017}_{-0.015}$ | $0.092^{+0.017}_{-0.015}$ | $0.092^{+0.017}_{-0.015}$ |
| $\Omega_{m0}$ | $0.299^{+0.021}_{-0.019}$ | $0.299^{+0.021}_{-0.019}$ | $0.299^{+0.021}_{-0.019}$ | $0.310^{+0.021}_{-0.019}$ | $0.310^{+0.021}_{-0.019}$ | $0.310^{+0.021}_{-0.019}$ |
| $\sigma_8$ | $0.827^{+0.017}_{-0.014}$ | $0.827^{+0.017}_{-0.014}$ | $0.827^{+0.017}_{-0.014}$ | $0.847^{+0.018}_{-0.015}$ | $0.847^{+0.018}_{-0.015}$ | $0.847^{+0.018}_{-0.015}$ |
| $H_0$ | $67.4^{+1.6}_{-1.4}$ | $67.4^{+1.6}_{-1.4}$ | $67.4^{+1.6}_{-1.4}$ | $68.5^{+1.7}_{-1.5}$ | $68.5^{+1.7}_{-1.5}$ | $68.5^{+1.7}_{-1.5}$ |
| $\chi^2$ | 12964.062 | 12969.178 | 13998.916 | 12980.828 | 13492.378 | 12974.924 |

### Diagram

**FIG. 2.** We compare the observational constraints on PEDE and ΛCDM models obtained from the CMB data alone.
and $\Delta \chi^2 \sim 7$ for CMB+DES. This large improvement we see is due to the fact that for these cases the CMB data are more in agreement with the additional data in the PEDE model with respect to the $\Lambda$CDM scenario. For all the other combinations of data (such as CMB+BAO, CMB+Pantheon and CMB+Lensing) the $\chi^2$ for PEDE slightly gets worse compared to $\chi^2$ for $\Lambda$CDM.

We present the comparisons between the CMB constraints of PEDE and $\Lambda$CDM model in Fig. 2. We do not show other combinations because qualitatively they look similar. Here we can observe that all the cosmological parameters, with the exception of $H_0$, $\sigma_8$ and $\Omega_m$, perfectly coincide in the PEDE and $\Lambda$CDM models. Instead, the Hubble constant $H_0$ and the clustering parameter $\sigma_8$ shift towards higher values, while $\Omega_m$ towards a smaller one. If we now compute the $S_8$ parameter, the PEDE model seems to be able to alleviate also this tension, shifting $S_8$ more in agreement with the cosmic shear data. In fact, we found that in PEDE model the DES alone estimates, $S_8 = 0.848^{+0.023}_{-0.033}$ at 68% CL, in agreement within 1σ with the CMB. However, the tension between these two datasets in the PEDE model is not completely solved, because $\sigma_8$ is much higher for the CMB only than for DES only (for which $\sigma_8 = 0.665^{+0.036}_{-0.054}$ at 68% CL), and $\Omega_m$ is much lower compared to its estimation from DES only: $\Omega_m = 0.491^{+0.045}_{-0.035}$.

We now discuss the behaviour of this emergent DE model in the large scales through Fig. 3 where we explicitly compare the PEDE and $\Lambda$CDM models considering the CMB temperature anisotropy spectra and matter power spectra. The left and right graph of Fig. 3 respectively describe the CMB temperature anisotropy spectra and matter power spectra. From the left graph of Fig. 3 we notice that at the lower multipoles (around $l \leq 10^3$), the PEDE has a slight deviation from the $\Lambda$CDM but such deviation is very mild and completely hidden by the cosmic variance. However, one can note that (see Fig. 3) the amplitude of the first acoustic peak in the CMB power-spectrum for both the models does not change at all. Similar observation can be found from the matter power spectra shown in the right side of Fig. 3. So, PEDE has a mild deviation from the $\Lambda$CDM and this is only detected from the CMB and matter power spectra.

$$\ln B_{ij}$$

| Strength of evidence for model $M_i$ | $\ln B_{ij}$ |
|-------------------------------------|-------------|
| Weak                               | $0 \leq \ln B_{ij} < 1$ |
| Definite/Positive                  | $1 \leq \ln B_{ij} < 3$ |
| Strong                             | $3 \leq \ln B_{ij} < 5$ |
| Very strong                        | $\ln B_{ij} \geq 5$ |

TABLE IV. The table shows the revised Jeffreys scale [81] which is used to compare the underlying cosmological models.

Finally, we analyze the performance of the current PEDE model with respect to the standard $\Lambda$CDM model. It is a very natural question to ask how efficient a new cosmological model is, since from the theoretical ground, the introduction of a new dark energy model is very easy. So, we close this section with the Bayesian evidences computed for the PEDE model with respect to $\Lambda$CDM as the reference model. To calculate the Bayesian evidence for all the observational data we use a cosmological code MCEvidence originally developed by the authors of [77, 78]. Let us note that the use of MCEvidence for computing the Bayesian evidences needs only the MCMC chains that are used to extract the cosmological parameters using the observational datasets (we also refer to [79, 80] for the same discussions). The performance of a cosmological model (say $M_i$) with respect to some reference cosmological model (here $\Lambda$CDM) is quantified through the Bayes factor $B_{ij}$ of the model $M_i$ with respect to the reference model $M_j$ (or, the logarithm of the Bayes factor, namely, $\ln B_{ij}$). In Table IV we display the revised Jeffreys scale that quantifies the observational support of the underlying cosmological model and in Table IV we summarize the values of $\ln B_{ij}$ computed for the PEDE model, for all the ob-
sitional datasets. From the analysis, we clearly see that except from CMB+R19 combination, all other observational datasets favour ΛCDM over the PEDE. The interesting observation is the case with CMB+R19 where we see that PEDE is favored over ΛCDM with a positive evidence. This is in agreement with the observations because for CMB+R19, the $\chi^2$ for PEDE is much improved of about 17 compared to the $\chi^2$ for ΛCDM. This is also in agreement with the analyses of [1] where the authors claim that the PEDE model can be favored compared to ΛCDM when some hard cut priors on $H_0$ is implemented.

| Dataset          | $\ln B_{ij}$ | Strength of evidence |
|------------------|---------------|----------------------|
| CMB              | -0.2          | Weak                 |
| CMB+BAO          | -3.1          | Strong               |
| CMB+Pantheon     | -5.8          | Strong               |
| CMB+R19          | 2.7           | Definite/Positive    |
| CMB+DES          | -1.6          | Definite/Positive    |
| CMB+Lensing      | -0.6          | Weak                 |

TABLE V. Summary of $\ln B_{ij}$ values, where $j$ refers to the reference model ΛCDM and $i$ refers to the PEDE model. The negative sign actually indicates that the reference model is favored over the PEDE model and the positive sign is for the reverse conclusion.

V. CONCLUDING REMARKS

Despite of having tremendous success to frame the presently ongoing accelerated expansion of the universe, the Λ-cosmology is equally challenged for several unexplained issues associated with it. The cosmological constant problem is undoubtedly one of the biggest challenges to explain. Apart from that the tensions in some parameters have been another remarkable issue at current time. The measurements of $H_0$ and $S_8$ in ΛCDM based framework do not agree with their measurements by other experimental missions – known as tensions in the cosmological parameters. The parameter $H_0$ is in more than 4σ tension between (ΛCDM-based) Planck and local observations by the SH0ES collaboration [3]. On the other hand, $S_8$ parameter is in tension between Planck and other observations, such as KiDS-450 [6, 7, 8], DES [9, 10] and CFHTLens [11, 12, 13]. Some recent literature investigating along this line found that an extended parameter space compared to ΛCDM is able to ease such tensions, however, due to extra free parameters, from Bayesian point of view, ΛCDM remains favored compared to the extended cosmological models. A natural inquiry, that forced us to look for an alternative cosmological model, having same number of parameters as in ΛCDM but with the potentiality to address some of the above problems. Our search became easy with the finding of a new dark energy model recently proposed in [1]. We investigated the model using the background and perturbations data in order to explore how the model is able to reconcile the $H_0$ and $S_8$ tensions.

In Table III we show the observational constraints on the PEDE model using various cosmological datasets. From Table III it is quite clear that $H_0$ takes considerably higher values compared to the estimations of $H_0$ for the ΛCDM model (see Table III). For CMB alone dataset, we see that at 68% CL, $H_0 = 72.58^{+0.72}_{-0.80}$ for the PEDE model which is pretty close to its local estimations by Riess et al. [3] and the estimations for other datasets remain almost same with stable error bars on $H_0$. This clearly shows us that within 68% CL, the tension on $H_0$ is perfectly reconciled, with an improvement of the $\chi^2$. This is one of the very interesting findings because the PEDE model has exactly six parameters as in ΛCDM model. Now concerning the $S_8$ parameter, we find that its value using DES alone is in agreement with the estimations from CMB for PEDE model, so it is able to reconcile this tension as well. However, the tension between these two datasets (i.e. DES and CMB from Planck) in the PEDE model is not completely solved because we find that $S_8$ is much higher for the CMB data alone compared to its estimation from DES alone, and additionally, $\Omega_m0$ is much lower for CMB alone compared to its estimation from DES only.

In summary, it is evident that the current PEDE model is a new appealing addition in the literature of dark energy models which, based on its present observational features, should be considered as a potential candidate for further investigations. In a forthcoming work we plan to include the interaction into this context and study the $H_0$ and $S_8$ tensions in order to examine whether first of all the alleviation of $H_0$ tension is independent of the interaction and secondly, if the tension on $S_8$ is much relaxed compared to the present case study.

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