Exploring Early Dark Energy solution to the Hubble tension with Planck and SPTPol data

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A promising idea to resolve the long standing Hubble tension is to postulate a new subdominant dark-energy-like component in the pre-recombination Universe which is traditionally termed as the Early Dark Energy (EDE). However, as shown in Refs. \[6,2\] the cosmic microwave background (CMB) and large-scale structure (LSS) data impose tight constraints on this proposal. Here, we revisit these strong bounds considering the Planck CMB temperature anisotropy data at large angular scales and the SPTPol polarization and lensing measurements. As advocated in Ref. \[3\], this combined data approach predicts the CMB lensing effect consistent with the $\Lambda$CDM expectation and allows one to efficiently probe both large and small angular scales. Combining Planck and SPTPol CMB data with the full-shape BOSS likelihood and information from photometric LSS surveys in the EDE analysis we found for the Hubble constant $H_0 = 69.79 \pm 0.99 \text{ km s}^{-1}\text{Mpc}^{-1}$ and for the EDE fraction $f_{\text{EDE}} < 0.094 (2\sigma)$. These bounds obtained without including a local distance ladder measurement of $H_0$ (SH0ES) alleviate the Hubble tension to a $2.5\sigma$ level. Including further the SH0ES data we obtain $H_0 = 71.81 \pm 1.19 \text{ km s}^{-1}\text{Mpc}^{-1}$ and $f_{\text{EDE}} = 0.088 \pm 0.034$ in full accordance with SH0ES. We also found that a higher value of $H_0$ does not significantly deteriorate the fit to the LSS data. Overall, the EDE scenario is (though weakly) favoured over $\Lambda$CDM even after accounting for unconstrained directions in the cosmological parameter space. We conclude that the large-scale Planck temperature and SPTPol polarization measurements along with LSS data do not rule out the EDE model as a resolution of the Hubble tension. This paper underlines the importance of the CMB lensing effect for robust constraints on the EDE scenario.

I. INTRODUCTION

The precise determination of the present-day expansion rate of the Universe, expressed by the Hubble constant $H_0$, is one of the most challenging tasks of modern cosmology. Indeed, the value of $H_0$ inferred from different observations appears to be in persistent discrepancy which is conventionally treated as a tension between the direct (local) and indirect (global) measurements of the Hubble constant. Namely, the Planck measurement of $H_0$ coming from the cosmic microwave background (CMB) \[4\] disagrees with the SH0ES result \[5\], based on traditional distance ladder approach utilizing Type Ia supernova, at $4.4\sigma$ level. The significance of this tension makes it unlikely to be a statistical fluctuation and hence requires an explanation.

Numerous local or late-time observations can provide an independent cross-check on the Cepheid-based $H_0$ measurements. In particular, the SN luminosity distances can be calibrated by Miras, $H_0 = 73.3 \pm 3.9 \text{ km s}^{-1}\text{Mpc}^{-1}$ \[6\] and the Tip of the Red Giant Branch (TRGB) in the Hertzsprung-Russell diagram, $H_0 = 69.6 \pm 1.9 \text{ km s}^{-1}\text{Mpc}^{-1}$ \[7\]. Alternatively, local measurements can be performed without relying on any distance ladder indicator through very-long-base interferometry observations of water megamasers $H_0 = 73.9 \pm 3.9 \text{ km s}^{-1}\text{Mpc}^{-1}$ \[8\], using strongly-lensed quasar systems $H_0 = 73.3^{+1.7}_{-1.8} \text{ km s}^{-1}\text{Mpc}^{-1}$ \[9\] and gravitational wave signal from merging binary neutron stars \[13, 14\]. All these measurements affected by completely different possible systematics agree with each other and give persistently higher values of $H_0$ being in conflict with the Planck prediction \[15\].

The Hubble tension can be explained by the impact of possible systematics in the Planck data. Indeed, it has been found that the Planck data suffer from multiple internal inconsistencies that can potentially obscure the cosmological inference \[4, 16, 17\]. The most significant feature refers to an interesting oscillatory shape in $H_0$ being in conflict with the Planck prediction \[15\].

\textsuperscript{1} Recently, the modeling error in time delay cosmography under the assumptions on the form of the mass density profile has been questioned \[10, 11\]. The thing is that there is a significant mass-sheet degeneracy that leaves the lensing observables unchanged while rescaling the absolute time delay, and thus alters the inferred $H_0$. The common strategy to deal with that is to make assumptions on the mass density profile motivated by local observations as done by H0LiCOW \[9\]. An alternative approach is to partially constrain this inherent degeneracy exclusively by the kinematic information of the deflector galaxy that brings much looser constraints, $H_0 = 74.5^{+5.9}_{-5.1} \text{ km s}^{-1}\text{Mpc}^{-1}$ for a sample of 7 lenses (6 from H0LiCOW) and $H_0 = 67.4^{+4.1}_{-3.9} \text{ km s}^{-1}\text{Mpc}^{-1}$ when a set of 33 strong gravitational lenses from the SLACS sample is used \[12\]. This hierarchical analysis fully accounts for the mass-sheet degeneracy in the error budget that statistically validates the mass profile assumptions made by H0LiCOW \[12\].
the TT power spectrum that resembles an extra lensing smoothing of the CMB peaks compared to the $\Lambda$CDM expectation. The significance of this "lensing anomaly" is rather high, $2.8\sigma$, while no systematics in the Planck data has been identified so far $[4,19]$. Such inconsistencies force one to consider independent measurements of the CMB anisotropies, especially on small scales. Ground based observations provided by the South Pole Telescope (SPT) $[22,23]$ and the Atacama Cosmology Telescope (ACT) $[22,23]$ perfectly suit for this purpose since they probe exclusively small angular scales. These observations indicate internally consistent gravitational lensing of CMB, i.e. the lensing information deduced from the smoothing of acoustic peaks at high-$\ell$ agrees well with the predictions of 'unlensed' CMB temperature and polarization power spectra $[21,24]$.

A more beneficial approach is to combine ground based observations with the full sky surveys. Indeed, ground-based telescopes are sensitive to much smaller angular scales unattainable in full sky surveys that can bring a noticeable cosmological gain. Recently, combined data analysis based on the Planck temperature and SPTPol polarization and lensing measurements found a substantially higher value $H_0 = 69.68 \pm 1.00 \text{ km s}^{-1}\text{Mpc}^{-1}$ $[8]$ that alleviates the Hubble tension to $2.5\sigma$ statistical significance within the $\Lambda$CDM cosmology. It also completely mitigates the so-called $S_8$ tension between different probes of Large Scale Structure (LSS) statistics and the Planck measurements $[25]$. It implies that the mild tension between the LSS and CMB data is solely driven by an excess of the lensing-induced smoothing of acoustic peaks observed in the Planck temperature power spectrum at high-$\ell$ $[3,17,19]$.

Besides that, the information about the present-day expansion rate of the Universe can be extracted from different measurements at low redshifts calibrated by any early-universe data independently of any CMB data. This is done by combining LSS observations with primordial deuterium abundance measurements. First such measurement comes from the baryon acoustic oscillation (BAO) experiments. Utilizing the BAO data from the Baryon Oscillation Spectroscopic Survey (BOSS) $[26]$, the prior on $\omega_b$ inferred from the Big Bang Nucleosynthesis (BBN) $[27]$ and late-time probe of the matter density from the Dark Energy Survey (DES) $[28]$ yields $H_0 = 67.4^{+1.3}_{-1.2} \text{ km s}^{-1}\text{Mpc}^{-1}$ $[29]$. Measurements of BAO scales for galaxies and the Ly$\alpha$ forest $[30]$ augmented with the BBN prior bring similar estimate $H_0 = 67.6 \pm 1.1 \text{ km s}^{-1}\text{Mpc}^{-1}$ $[31,33]$. Second, the Hubble constant measurement can be accomplished with galaxy clustering alone using the full-shape (FS) information of the galaxy power spectrum $[34-36]$. In particular, the joint FS+BAO analysis brings $H_0 = 68.6 \pm 1.1 \text{ km s}^{-1}\text{Mpc}^{-1}$ $[36]$. Importantly, all these measurements assume the standard evolution of the Universe prior to recombination. It sticks the sound horizon $r_s$ to the $\Lambda$CDM function of cosmological parameters. However, any sizable shift in $H_0$ value that needed to solve the Hubble tension must be accompanied by corresponding modification of $r_s$ to preserve the fit to CMB data that measure the angular scale of the sound horizon $\theta_s$ with a very high accuracy. This modification can be accomplished by introducing a new component which increases $H(z)$ in the decade of scale factor evolution prior to recombination. Such early-universe scenarios have been advocated as the most likely solution of the Hubble tension in Ref. $[37]$. The broad subclass of these models has been termed Early Dark Energy (EDE). Many EDE-like scenarios have been proposed from a phenomenological point of view $[33-35]$, whilst others present concrete realizations of particle-physics models $[14,47]$. It is pertinent to highlight two interesting realizations $[48,49]$ in which the EDE field becomes dynamical precisely around matter-radiation equality that ameliorates the coincidence problem inherent to most EDE implementations.

We examine one popular EDE implementation which postulates a dynamical scalar field which behaves like dark energy in early times and then rapidly decays in a relatively narrow time interval near matter-radiation equality. The increased energy density of the Universe prior to recombination shrinks the comoving sound horizon $r_s$ which lifts up $H_0$ while keeping the angular scale $\theta_s$ intact. This extension of the $\Lambda$CDM model can be parameterized by 3 parameters: the maximal injected EDE fraction $f_{\text{EDE}}$, the critical redshift $z_s$ at which this maximum is reached and an initial scalar field value denoted by dimensional quantity $\theta_i$ (in analogy to the axion misalignment angle $[50,52]$). It has been previously established that this prescription allows for values of $H_0$ consistent with SH0ES whilst preserving the fit to the CMB data $[10,11]$.

The situation becomes more intricate when LSS data are taken into account. The thing is that the EDE scenario matches the CMB data at the cost of shifting several cosmological parameters that is not compatible with LSS data. In particular, it substantially increases the physical density of cold dark matter $\omega_c$ and to a lesser extent the spectral index $n_s$ that raise up the late-time parameter $S_8 = \sigma_8\sqrt{\Omega_m}/0.5$. This change exacerbates the $S_8$ tension between LSS observables and the Planck data and imposes tight constraints on the EDE scenario as a possible solution to the Hubble tension $[1]$. Namely, when considering all LSS data with the Planck, SNIA, BAO and RSD measurements one finds $f_{\text{EDE}} < 0.06(2\sigma)$ $[11]$ which is well below the value needed to resolve the Hubble tension, $f_{\text{EDE}} \sim 0.1$. The main driver of this strong constraint is the overly enhanced lensing-induced smoothing effect that affects the Planck temperature power spectrum at high-$\ell$ and pulls the late-time amplitude to a higher value $[17,19]$ being in conflict with the LSS data. It has been shown that the tension between the Planck and various LSS probes can be reconciled if one combines the large-angular scale Planck temperature mea-
measurements with the ground-based observations of the SPTPol survey as argued in Ref. [3]. Thus, one expects that the tight LSS constraints on EDE can be alleviated if one replaces the Planck CMB data at high multipoles \( \ell \) with the SPTPol measurements. Revising the constraining power of LSS in the EDE model using the different CMB setup that predicts the consistent CMB lensing effect is one of the main goals of this paper.

Another important ingredient of our study is the full-shape analysis of galaxy power spectrum. This treatment is based on complete cosmological perturbation theory with a major input from the Effective Field Theory (EFT) of LSS. This approach includes all necessary ingredients (UV counterterms and IR resummation) needed to reliably describe galaxy clustering on mildly nonlinear scales. The full-shape template of the galaxy power spectrum contains a large amount of cosmological information that can effectively constrain various extensions of the \( \Lambda \)CDM model. In particular, it has been shown that the full-shape BOSS likelihood yields a \( \approx \) 20\% improvement on the EDE constraint from the CMB data alone [2]. Crucially, the standard BOSS likelihood does not appreciably shrink the Planck limits due to the lack of full-shape information therein [2]. In order to obtain more refined constraints on EDE, we employ the full-shape BOSS likelihood in our analysis.

In this paper, we examine the EDE scenario using the Planck and SPTPol measurements of the CMB anisotropy. Namely, we follow the combined data approach validated in Ref. [3] and combine the Planck temperature power spectrum at large angular scales with polarization and lensing measurements from the SPTPol survey [21]. This approach ensures the internally consistent CMB lensing effect and allows one to gain cosmological information from both large and small angular scales.

We improve our previous analysis [2] in several directions. First, we solve the evolution of the scalar field perturbations directly using the Klein-Gordon equation which does not rely on the effective fluid description. Second, we consider a more realistic EDE setup which generalizes a pure power-law potential considered in Ref. [3]. Third, we use the full BOSS galaxy power spectrum likelihood that yields much stronger constraints on EDE compared to the standard BOSS likelihood [2]. Finally, we exploit the more recent LSS data coming from the DES-Y1 [25], Kilo-Degree Survey (KiDS) [54] and Subaru Hyper Suprime-Cam (HSC) [55] measurements that allow us to reduce by half the error bars on \( S_8 \) compared to that examined in Ref. [3].

The outline of this paper is as follows. In Sec. II, we review the physics of the EDE scenario. In Sec. III we present the combined data approach, data sets and main results. Finishing in Sec. IV we highlight the differences between our approach and previous EDE analyses, interpret our outcomes and discuss the prospects.

### II. THE EARLY DARK ENERGY MODEL

The main goal of EDE proposal is to decrease the comoving sound horizon of the last scattering epoch,

\[
 r_s(z_s) = \int_{z_s}^{\infty} \frac{dz}{H(z)} c_s(z),
\]

where \( z_s \) denotes the redshift of the last scattering in such a way that the higher value of \( H_0 \) encoded in the comoving angular diameter distance

\[
 D_A(z_s) = \int_0^{z_s} \frac{dz}{H(z)},
\]

can be accommodated without changing the angular scale of the sound horizon,

\[
 \theta_s = \frac{r_s(z_s)}{D_A(z_s)}.
\]

Necessary adjustments of the early-universe dynamics can be readily understood. The angular diameter distance defined by (2) is driven by the low-redshift cosmic evolution and, hence, directly relies on \( H_0 \). Eq. (3) implies that the upward shift in \( H_0 \) must be accompanied by the downward shift of \( r_s \), since \( \theta_s \) is measured to 0.03\% precision by Planck. However, the sound horizon given by (1) is saturated near the lower bound of the integral that requires the increased expansion rate of the Universe at times shortly before recombination. In EDE scenarios such increase is provided by an additional contribution to the total energy density of the Universe which acts as dark energy at early times. The magnitude of the Hubble tension dictates the energy scale of the early-time contribution to be of order \( \sim \) eV. Crucially, this extra energy density initially stored in EDE must rapidly decay and practically disappear before the last scattering so as not to affect the CMB anisotropy on small scales.

The simplest model where the requisite dynamics can be realized is that of the scalar field. Indeed, in this scenario at high redshifts the scalar field is frozen and acts as EDE whereas afterwards it begins to oscillate and its energy density redshifts like matter density, \( \rho \propto a^{-3} \). In the context of particle physics, the candidate for this scalar field can be the axion [50, 58] with a periodic potential \( V \propto m^2 f^2 \cos \phi / f \) generated by non-perturbative effects. However, the EDE field must decay as radiation or faster to keep the late-time evolution intact, while in the simplest example of axion-like model the EDE energy density redshifts as matter. This obstacle can be alleviated by introducing multiple axion-like fields [58] or super-Planckian field excursions [59].
We follow the proposal made in Ref. [40] which considers a single scalar field with potential

\[ V = V_0 \left(1 - \cos(\phi/f)\right)^n, \quad V_0 = m^2 f^2. \tag{4} \]

where the parameter \( n \) controls the decay rate of the scale field. \( n = 2 \) affords the dilution of the energy density initially stored in EDE as radiation \((x a^{-4})\), and for \( n \to \infty \) it redshifts as kinetic energy \((x a^{-6})\) thereby reproducing the Acoustic Dark Energy scenario [43]. Recent investigations of the EDE dynamics with potential \([4] \) in the context of the Hubble tension reveal that the case \( n = 3 \) provides a somewhat better fit to the overall cosmological data \([3, 41, 42] \).

Overall, the cosmological dynamics of EDE field with potential \([4] \) can be succinctly described by the following effective parameters: the maximal EDE fraction in the total energy density of the Universe, \( f_{\text{EDE}} \), and the critical redshift, \( z_c \), when it is reached. Along with the initial condition for the scalar field, \( \theta_i \equiv \phi_i / f \) and the exponent \( n \) these parameters entirely describe the EDE evolution in the expanding Universe.

### III. CONSTRAINTS ON THE EDE SCENARIO

Parameter estimates presented in this paper are obtained with the combined Einstein-Boltzmann code comprised of \textsc{CLASS-EDE} [11] and \textsc{CLASS-PT} [60] (both extensions of \textsc{CLASS} \([61,62] \)) interfaced with the \textsc{Montepython} Monte Carlo sampler \([62, 63] \). We perform the Markov Chain Monte Carlo approach to sample the posterior distribution adopting a Gelman-Rubin \([64] \) convergence criterion \( R - 1 < 0.15 \). The plots with posterior densities and marginalized limits are generated with the latest version of the \textsc{getdist} package \([65] \).

Following previous EDE analysis \([1, 2] \) we impose uniform priors on the EDE parameters: \( f_{\text{EDE}} = [0.001, 0.5] \), \( \log_{10}(z_c) = [3, 4.3] \) and \( \theta_i = [0.1, 3.1] \). We fix \( n = 3 \) as the cosmological data only weakly constrain this parameter \([11] \). We also vary 6 standard \( \Lambda \)CDM parameters within broad uniform priors: \( \Omega_c h^2, \omega_b = \Omega_b h^2, H_0, \ln(10^{10} A_s), n_s \) and \( \tau \). We assume the normal neutrino hierarchy with the total active neutrino mass \( \sum m_\nu = 0.06 \text{eV} \). When the full-shape BOSS likelihood is included, all matter transfer functions are calculated along the lines of the standard cosmological perturbation theory that consistently predict galaxy/matter clustering on mildly nonlinear scales. Otherwise, we use the Halofit module to compute nonlinear matter power spectrum which allows us to reliably predict the lensed CMB power spectra and lensing potential power spectrum at high multipoles.

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3 The code that combines both \textsc{CLASS-EDE} and \textsc{CLASS-PT} extensions is available on the web-page [https://github.com/Michalychforever/EDE_class_pl](https://github.com/Michalychforever/EDE_class_pl).

4 [https://getdist.readthedocs.io/en/latest/](https://getdist.readthedocs.io/en/latest/)

A. Methodology

The cornerstone of our analysis is the combined data approach that allows one to extract reliable cosmological information from multiple CMB experiments in a wide range of angular scales, see \([3] \). We examine the \( \Lambda \)CDM and EDE predictions utilizing the Planck large-angular scale measurements along with the ground-based observations of the 500 deg\(^2 \) SPTPol survey. Before going to the data sets we assert our CMB setup.

We combine the Planck TT power spectrum at \( \ell < 1000 \) with the SPTPol measurements of TE, EE spectra following the CMB specification adopted in Ref. \([3] \). We do not include the Planck polarisation measurements at intermediate angular scales because the Planck TE and EE spectra have residuals at \( \ell \sim 30 – 1000 \) relative to the \( \Lambda \)CDM prediction. Given this range of multipoles roughly corresponds to the modes that enter the horizon while the EDE density is important, the Planck polarization measurements strongly disfavour the EDE solution as shown in Ref. \([66] \). Interestingly, the ACT observations do not detect any features in the TE and EE measurements in this multipole region. This data discrepancy motivates us to take the TE and EE power spectra entirely from the SPTPol survey which do not manifest any significant residuals relative to \( \Lambda \)CDM \([21] \).

We further include the SPTPol measurement of the lensing potential power spectrum \( C_{\phi\phi} \). Despite a somewhat higher constraining power of the Planck lensing measurements, we do not include it for the following reasons. First, it allows us to investigate the lensing information entirely encoded in SPTPol maps. Second, despite the fact that the Planck lensing amplitude extracted from quadratic estimators of T-, E-, B-fields is in excellent agreement with that from the Planck power spectra, the former is in a mild tension with the large-angular scale Planck TT and SPTPol data which prefer substantially lower values of fluctuation amplitudes \([19, 21] \). To provide a self-consistent cosmological inference we employ the direct measurement of \( C_{\phi\phi} \) from the SPTPol survey that agrees well with SPTPol measurements of TE and EE spectra \([67] \).

B. Data sets

We employ the Planck temperature \textsc{Plik} likelihood for multipoles \( 30 \leq \ell < 1000 \) in the concert with low-\( \ell \) \textsc{Commander} TT likelihood, and the low-\( \ell \) \textsc{SimAll} EE likelihood \([4] \). We vary over all nuisance parameters required to account for observational and instrumental uncertainties. We refer to these measurements as Planck-low\( \ell \).

We utilize CMB polarization measurements from the 500 deg\(^2 \) SPTPol survey which includes TE and EE spectra in the multipole range \( 50 \leq \ell \leq 8000 \) \([21] \). We vary all necessary nuisance parameters which account for foreground, calibration and beam uncertainties and impose reasonable priors on them. We transform theoretical
spectra from unbinned to binned bandpower space using appropriate window functions. We supplement these polarization measurements with the observation of the lensing potential power spectrum $C_{\ell}^{\phi\phi}$ in the multipole range $100 < \ell < 2000$ from the same 500 deg$^2$ SPTPol survey [55]. The lensing potential is reconstructed from a minimum-variance quadratic estimator that combines both the temperature and polarization CMB fields. To take into account the effects of the survey geometry we convolve the theoretical prediction for the lensing potential power spectrum with appropriate window functions at each point in the parameter space. We also perturbatively correct $C_{\ell}^{\phi\phi}$ to address the difference between the recovered lensing spectrum from simulation and the input spectrum along the lines of Ref. [67]. We denote these SPTPol polarization and lensing measurements\(^5\) as SPT in what follows.

We use the data from the final BOSS release DR12 [20], implemented as a joint FS+BAO likelihood, as in Ref. [36]. We refer the reader to [34, 69] for details of the pre-reconstruction full-shape power spectrum analysis and to Ref. [36] for the strategy of the BAO measurements performed with the post-reconstruction power spectra. Our likelihood includes both pre- and post-reconstruction galaxy power spectrum multipoles $\ell = 0, 2$ across two different non-overlapping redshift bins with $z_{\text{eff}} = 0.38$ and $z_{\text{eff}} = 0.61$ observed in the North and South Galactic Caps (NGC and SGC, respectively). It results in the four different data chunks with the total comoving volume $\approx 6 (h^{-1} \text{Gpc})^3$. We create separate sets of nuisance parameters for each data chunk and vary all of them independently. We impose the conservative priors on the nuisance parameters following Ref. [34]. We employ the wavenumber range $[0.01, 0.25] h\text{Mpc}^{-1}$ for the pre-reconstruction power spectra and $[0.01, 0.3] h\text{Mpc}^{-1}$ for the BAO measurements based on the post-reconstruction power spectra. We recall this full-shape likelihood as BOSS.

We adopt the SH0ES measurement of the Hubble constant $H_0 = 74.03 \pm 1.42\,\text{km\,s}^{-1}\text{Mpc}^{-1}$ [5]. We impose the Gaussian prior on $H_0$ and call this local measurement as SH0ES.

Finally, we utilize the additional LSS information from multiple photometric surveys. In particular, we consider the DES-Y1 galaxy clustering, galaxy-galaxy lensing and cosmic shear observations [28] along with the weak gravitational lensing measurements from KiDS-100 [54] and HSC [55]. As demonstrated in [1], the DES-Y1 "3x2pt" likelihood can be well approximated in the EDE analysis by a Gaussian prior on $S_8$. Driven by this observation, we include the DES-Y1, KiDS-100 and HSC measurements via appropriate priors on $S_8$. Namely, for the DES-Y1 combined data analysis we use $S_8 = 0.773^{+0.026}_{-0.020}$ [28]; for the KiDS-100 cosmic shear measurements we adopt $S_8 = 0.759^{+0.024}_{-0.021}$ [54]; for HSC observations we utilize $S_8 = 0.780^{+0.030}_{-0.032}$ [55]. Finally, we weight each mean with its inverse-variance and obtain the resultant constraint $S_8 = 0.769 \pm 0.015$. We include this combined measurement as a Gaussian prior and refer to this simply as $S_8$ in our analysis.

## C. Results

We report our main results obtained from analyses of different cosmological data sets.

### 1. Planck-low$\ell$+SPT

We firstly examine the cosmological inference from the primary CMB data alone following [3]. The resulting parameter constraints in the $\Lambda$CDM and EDE models inferred from the Planck-low$\ell$+SPT data are given in Tab. 1. The limits for the $\Lambda$CDM scenario are taken from Ref. [3] (data set Base therein). The 2d posterior distributions for the EDE model are shown in Fig. 1.

We find no evidence for non-zero $f_{\text{EDE}}$ in the CMB data only analysis. We report an upper bound $f_{\text{EDE}} < 0.104 (2\sigma)$ which is compatible with the amount of EDE required to alleviate the Hubble tension. Thus, the EDE model yields substantially higher values of the Hubble parameter, $H_0 = 70.79 \pm 1.41\,\text{km\,s}^{-1}\text{Mpc}^{-1}$, being in $1.6\sigma$ agreement with the SH0ES measurements. We emphasize that the Planck-low$\ell$+SPT data allow for somewhat larger values of $f_{\text{EDE}}$ as compared to that from the full Planck likelihood, namely $f_{\text{EDE}} < 0.087 (2\sigma)$ [1]. At the same time, the EDE scenario supplies substantially low values of the late-time amplitude, $S_8 = 0.766 \pm 0.024$, being in perfect agreement with the multiple probes of LSS. This effect is attributed to the fact that the large-angular scale Planck temperature power spectrum and SPTPol data both accommodate a low $S_8$ [1]. On the contrary, the full Planck likelihood favours substantially higher values of $\sigma_8$ and $S_8$ which are primarily driven by overly enhanced lensing smoothing of the CMB peaks in the Planck temperature spectrum. The upward shift of these parameters makes the EDE prediction incompatible with the current LSS data as reported in Ref. [1]. The Planck-low$\ell$+SPT data allows one to alleviate this issue making the region of appreciably high $f_{\text{EDE}} \sim 0.1$ compatible with cosmological data.

The epoch of EDE is constrained to $\log_{10}(z_e) < 55 \pm 0.15$. It reliably supports only a lower bound on $z_e$, whereas the upper tail of $\log_{10}(z_e)$ remains largely unconstrained. The posterior distribution for $\log_{10}(z_e)$ clearly indicates one single maximum, whereas the previous EDE studies hint at a weakly bimodal distribution.

\(^5\) The complete SPTPol likelihoods for the Montepython environment are publicly available at [https://github.com/ksardase/SPTPol-montepython]

\(^6\) We do not include the cross-correlation between these measurements because the sky overlap between these surveys is small, see [1].
for that \cite{1,2,41}. As discussed in Ref. \cite{41}, this ambiguous behaviour is driven by the Planck polarization measurements at high-$\ell$ and could simply be a noise fluctuation. We also find a much flatter distribution for the initial field displacement, namely $\theta_i = 1.60^{+1.13}_{-0.88}$. The previous EDE analyses which adopted the full Planck likelihood \cite{1,2,41} reveal, on the contrary, a strong preference for a large initial field displacement. This large $\theta_i$ preference comes from a oscillatory pattern in the residuals of the TE and EE Planck spectra in the multipole range $\ell \sim 30 - 500$ \cite{41} which is disfavored by the Planck-low$\ell$+SPT data.\footnote{The ACT observations also do not detect any oscillatory feature in TE and EE measurements at intermediate scales \cite{22} thus supporting our inference. This implies that the residuals observed in Planck polarization measurements are, most likely, merely caused by systematic effects \cite{66}.} Thus, our result validates the monomial expansion of the field potential when one employs the optimally constructed Planck-low$\ell$+SPT likelihood.

\subsection{Planck-low$\ell$+SPT+BOSS}

We perform a joint analysis of the Planck-low$\ell$+SPT data and the BOSS DR12 FS+BAO likelihood. The parameter constraints for the ΛCDM and EDE scenarios are presented in Tab. \cite{1} The corresponding 2d posterior distributions are shown in Fig. \cite{1}

We found an appreciably weaker constraint on EDE, $f_{\text{EDE}} < 0.118$ (2$\sigma$), compared to that in the analysis with CMB alone in the previous subsection. The 14% alleviation of the upper bound is primarily driven by the upward shift in the mean value of $\omega_c$ needed to maintain the fit to the BOSS data. We emphasize that our analysis provides with substantially larger values of $f_{\text{EDE}}$ compared to that from the full Planck and BOSS data, $f_{\text{EDE}} < 0.072$ (2$\sigma$) \cite{2}. Despite the weaker constraint on $f_{\text{EDE}}$, the mean value of $H_0$ significantly decreases and its error bar is considerably shrunk, namely $H_0 = 68.52 \pm 0.58$ km s$^{-1}$Mpc$^{-1}$ and $H_0 = 69.89 \pm 1.28$ km s$^{-1}$Mpc$^{-1}$ in the ΛCDM and EDE scenarios. It becomes possible due to the more precise BAO measurements which being combined with the FS information impose a tight constraint on $H_0$. Nevertheless, within the EDE scenario the Hubble tension with the SH0ES measurement is below 2.2$\sigma$ statistical significance. Besides that, we found appreciably larger values of $S_8$, namely $S_8 = 0.785 \pm 0.014$ and $S_8 = 0.792 \pm 0.016$ in the ΛCDM and EDE models. We emphasize that these constraints are fully compatible with the galaxy clustering and weak gravitational lensing measurements that justifies further including of DES-Y1, KiDS-1000 and HSC data. Overall, the BAO+FS BOSS likelihood yields unprecedented gain of cosmological information: it provides with the two-fold improvement for the $\omega_c$ and $H_0$ measurements over those from the CMB alone.

Regarding the other EDE parameters, we found a slightly more precise measurement of the EDE epoch, $\log_{10}(z_c) = 3.69^{+0.03}_{-0.14}$. As a result, the maximum of the posterior distribution for this parameter is better visualized as can be appreciated from Fig. \cite{1} We do not find any improvement for the initial field displacement, $\theta_i = 1.61^{+1.13}_{-0.83}$ which still supports the substantially flat distribution. It also corroborates our CMB only analysis which does not find any evidence for subdominant peaks in the $\log_{10}(z_c)$ distribution. This indicates that the bimodality behaviour previously claimed in the EDE analyses \cite{1,2,41} indeed comes from the Planck measurements at high-$\ell$ in full accord with the claim made in Ref. \cite{41}.

| Parameter          | ΛCDM    | EDE     |
|-------------------|---------|---------|
| $\ln(10^{10}A_s)$ | 3.021 ± 0.017 | 3.024 ± 0.018 |
| $n_s$             | 0.9785 ± 0.0074 | 0.9816 ± 0.0094 |
| $H_0$ [km/s/Mpc]  | 69.68 ± 1.00  | 70.79 ± 1.41  |
| $\Omega_b h^2$    | 0.02269 ± 0.00025 | 0.02291 ± 0.00036 |
| $\Omega_{\text{cdm}} h^2$ | 0.1143 ± 0.0020  | 0.1178 ± 0.0039 |
| $\tau_{\text{reio}}$ | 0.0510 ± 0.0086  | 0.0511 ± 0.0085 |
| $\log_{10}(z_c)$  | $-\infty$    | 3.75$^{+0.52}_{-0.17}$ |
| $f_{\text{EDE}}$  | $-\infty$    | $< 0.104$    |
| $\theta_i$        | $-\infty$    | 1.60$^{+1.13}_{-0.83}$ |
| $\Omega_m$        | 0.2838 ± 0.0118 | 0.2822 ± 0.0120 |
| $\sigma_8$        | 0.7842 ± 0.0087 | 0.7894 ± 0.0131 |
| $S_8$             | 0.763 ± 0.022  | 0.766 ± 0.024  |
| $r_s$             | 145.76 ± 0.46  | 143.71 ± 1.84  |

TABLE I. Marginalized constraints on the cosmological parameters in ΛCDM and in the EDE scenario with $n = 3$, as inferred from the Planck-low$\ell$+SPT data. The upper limit on $f_{\text{EDE}}$ is quoted at 95% CL.
On the next step, we include the $S_8$ information from DES-Y1, KiDS-1000 and HSC measurements by adopting the Gaussian prior $S_8 = 0.769\pm0.015$. The parameter constraints in the $\Lambda$CDM and EDE scenarios are reported in Tab. III (second and third columns). The corresponding 2d posterior distributions are shown in Fig. 2.

We found a more stringent limit on EDE, $f_{EDE} < 0.094$ (2$\sigma$), which represents a 20% improvement over that from the analysis without $S_8$ information in the previous subsection. This gain is explained by a $0.5\sigma$ downward shift in $\omega_c$ which strongly correlates with $f_{EDE}$. A lower value of $\omega_c$, in turn, reduces the growth rate of perturbations at late times that allows one to accommodate a substantially lower value of $S_8$ in accord with the $S_8$ data. In particular, the combined Planck-$\ell$+SPT+BOSS+S8 data bring $S_8 = 0.776 \pm 0.011$ and $S_8 = 0.780 \pm 0.011$ in the $\Lambda$CDM and EDE scenarios which represent 20% and 30% improvements over that in the Planck-$\ell$+SPT+BOSS analysis (without $S_8$). More precise determination of $S_8$ improves the $H_0$ constraints to the same extent, namely $H_0 = 68.84\pm0.50$ km s$^{-1}$Mpc$^{-1}$ and $H_0 = 69.79 \pm 0.99$ km s$^{-1}$Mpc$^{-1}$ in the $\Lambda$CDM and EDE scenarios. We emphasize that the mean values of $H_0$ upon including the $S_8$ information remain essentially unchanged that demonstrates a high level of compatibility between the Planck-$\ell$+SPT+BOSS and $S_8$ data. It is worth nothing that the $H_0$ constraint inferred in the $\Lambda$CDM scenario is in a substantial $3.5\sigma$ tension with the Cepheid calibrated local measurement of $H_0$. In the EDE model this tension is alleviated to an allowable level of $2.5\sigma$ that makes the Planck-$\ell$+SPT+BOSS+S8 and SH0ES data statistically compatible within the EDE framework.

Upon including the $S_8$ information we do not find a substantial improvement in the $\log_{10}(z_c)$ and $\theta_4$ measurements. We found $\log_{10}(z_c) = 3.74_{-0.15}^{+0.56}$ and $\theta_4 = 1.57_{-0.56}^{+1.05}$ which are consistent with the results of the previous analysis without the $S_8$ data. The virtually intact constraints on these parameters can be readily understood. Unlike $f_{EDE}$, the $\log_{10}(z_c)$ and $\theta_4$ very weakly correlate with the other $\Lambda$CDM parameters as demonstrated in Fig. 1. It implies that a more precise measurements of $S_8$ without a significant shift in its mean value can not substantially alter the posterior distributions of $\log_{10}(z_c)$ and $\theta_4$ parameters.

We finally address the Cepheid-based local measurements of $H_0$. Since the SH0ES measurement and Planck-$\ell$+SPT+BOSS+S8 inference of $H_0$ are in the significant tension in the framework of $\Lambda$CDM cosmology, we do not combine them in one data set under the $\Lambda$CDM assumption. The parameter constraints for the EDE scenario are presented in Tab. III (fourth column). The corresponding 2d posterior distributions are shown in Fig. 2.

We found $f_{EDE} = 0.088 \pm 0.034$, which indicates a $2.6\sigma$ preference for nonzero EDE. This result is driven by the SH0ES measurement which favours a substantially higher value of $H_0$. Namely, we found $H_0 = 71.81 \pm 1.19$ km s$^{-1}$Mpc$^{-1}$ which is now in $1.2\sigma$ agreement with the SH0ES data. We emphasize that the error bar on $H_0$ increases quite moderately, by 20% over that from the analysis without SH0ES. It indicates that a better agreement with the SH0ES measurement comes from a released freedom in the EDE model rather than to be a result of the worse description of other data sets. Indeed, the constraint on $S_8$ remains virtually unchanged compared to the analysis without SH0ES, namely $S_8 = 0.783 \pm 0.012$. It implies that a higher $H_0$ does not significantly degrade the fit to the LSS data. Thus, our approach based on the Planck-$\ell$+SPT

| Parameter                  | $\Lambda$CDM | EDE       |
|----------------------------|--------------|-----------|
| $\ln(10^{10}A_s)$         | 3.014 ± 0.017| 3.019 ± 0.018|
| $\eta_s$                  | 0.9716 ± 0.0056| 0.9766 ± 0.0090|
| $H_0$ [km/s/Mpc]           | 68.50 ± 0.57 | 69.89 ± 1.28 |
| $\Omega_{\text{cdm}}h^2$  | 0.0225 ± 0.00021| 0.02279 ± 0.00039|
| $\tau_{\text{reio}}$      | 0.1166 ± 0.0012 | 0.1213 ± 0.0042 |
| $\log_{10}(z_c)$          | 0.0456 ± 0.0082 | 0.0457 ± 0.0085 |
| $f_{EDE}$                 | -            | 3.69\pm0.14 |
| $\theta_4$                | -            | < 0.118 |
| $\Omega_m$                | 0.2978 ± 0.0071 | 0.2963 ± 0.0070 |
| $\sigma_8$                | 0.7880 ± 0.0074 | 0.7966 ± 0.0129 |
| $S_8$                      | 0.785 ± 0.014  | 0.792 ± 0.016  |
| $r_s$                      | 145.31 ± 0.31  | 142.67 ± 2.14  |

### TABLE II. Marginalized constraints (68% CL) on the cosmological parameters in $\Lambda$CDM and in the EDE scenario with $n = 3$, as inferred from the Planck-$\ell$+SPT+BOSS data. The upper limit on $f_{EDE}$ is quoted at 95% CL.
CMB data alleviates the conflict between the SH0ES-tension-resolving EDE cosmologies and LSS data previously claimed in Ref. [1, 2].

Addressing the local $H_0$ measurements significantly alters the posterior distribution for $\log_{10}(z_c)$ and $\theta_i$ parameters. We found a more stringent constraint on the EDE epoch, $\log_{10}(z_c) = 3.64^{+0.13}_{-0.18}$, as opposed to the more flattened distribution observed in the previous analyses without SH0ES. This result distinctively indicates a narrow redshift interval prior to recombination at which EDE efficiently decays in full accord with the EDE proposal. We also find a strong preference for large initial field displacement, $\theta_i = 1.79^{+1.02}_{-0.42}$, consistent with the findings of [1, 11]. Our results reflect how the SH0ES measure-
TABLE III. Marginalized constraints (68% CL) on the cosmological parameters in ΛCDM and in the EDE scenario with \( n = 3 \), as inferred from the Planck-lowℓ + SPT + BOSS + \( S_8 \) (second and third columns) and Planck-lowℓ + SPT + BOSS + \( S_8 \) + SH0ES (fourth column) data sets. The upper limit on \( f_{\text{EDE}} \) is quoted at 95% CL.

| Parameter | ΛCDM | EDE | EDE + SH0ES |
|-----------|------|-----|-------------|
| \( \ln(10^9 A_s) \) | 3.008 ± 0.107 | 3.013 ± 0.107 | 3.021 ± 0.107 |
| \( n_s \) | 0.9735 ± 0.0054 | 0.9753 ± 0.0076 | 0.9870 ± 0.0089 |
| \( H_0 \) [km/s/Mpc] | 68.82 ± 0.50 | 69.79 ± 0.99 | 71.81 ± 1.19 |
| \( \Omega_{b0} h^2 \) | 0.02255 ± 0.00020 | 0.02276 ± 0.00036 | 0.02318 ± 0.00042 |
| \( \Omega_{c0} h^2 \) | 0.1159 ± 0.0010 | 0.1193 ± 0.0028 | 0.1241 ± 0.0039 |
| \( \tau_{\text{reio}} \) | 0.0437 ± 0.0087 | 0.0446 ± 0.0086 | 0.0448 ± 0.0089 |
| \( \log_{10}(z_c) \) | 3.74 ± 0.56 | 3.64 ± 0.18 | 3.64 ± 0.18 |
| \( f_{\text{EDE}} \) | < 0.094 | 0.088 ± 0.034 | 0.088 ± 0.034 |
| \( \theta_1 \) | 1.57 ± 1.05 | 1.79 ± 0.02 | 1.79 ± 0.02 |
| \( \Omega_m \) | 0.2938 ± 0.0059 | 0.2930 ± 0.0059 | 0.2870 ± 0.0055 |
| \( \sigma_s \) | 0.7839 ± 0.0069 | 0.7889 ± 0.0089 | 0.8005 ± 0.0111 |
| \( S_8 \) | 0.7766 ± 0.010 | 0.780 ± 0.011 | 0.783 ± 0.012 |
| \( r_s \) | 145.45 ± 0.28 | 143.51 ± 1.50 | 140.61 ± 2.01 |

TABLE IV. \( \chi^2 \) values for the best-fit EDE model optimized to the Planck-lowℓ + SPT + BOSS + \( S_8 \) (second column) and Planck-lowℓ + SPT + BOSS + \( S_8 \) + SH0ES (third column) data.

| Data set | w/o SH0ES | w SH0ES |
|----------|------------|---------|
| Planck-lowℓ | 825.43 | 825.45 |
| SPT | 148.82 | 145.83 |
| BOSS | 476.55 | 478.80 |
| \( S_8 \) | < 0.01 | 1.03 |
| SH0ES | 10.23 | 1.13 |
| \( \sum \chi^2_{\text{SH0ES}} \) | 1450.79 | 1451.10 |
| \( \sum \chi^2 \) | 1461.02 | 1452.23 |

To scrutinize the impact of the SH0ES measurements, we examine the goodness-of-fit for each individual likelihood. For that, we provide the best-fit \( \chi^2 \) values for each data set optimized to the data with and without SH0ES measurements in Tab. [IV] We found that the total \( \chi^2 \)-statistics optimized to the data without SH0ES changes insignificantly, \( \Delta \chi^2_{\text{SH0ES}} = 0.31 \). It implies that adding SH0ES does not considerably spoil the fit to the other data. In particular, including SH0ES does not affect the fit to the Planck-lowℓ likelihood. In turn, it moderately degrades the fit to the BOSS data by \( \Delta \chi^2_{\text{BOSS}} = 2.25 \). This effect can be readily understood. A higher value of \( H_0 \) driven by SH0ES is accommodated by higher \( f_{\text{EDE}} \) which, in turn, strongly correlates with \( \omega_c \) and \( \sigma_s \) as shown in Fig. [2]. However, higher values of these parameters break at odds with the BOSS likelihood that favours moderately lower values of \( \omega_c \) and \( \sigma_s \). The worsening of the BOSS fit is entirely compensated by the improved fit to the SPT data. Namely, we found \( \Delta \chi^2_{\text{Pol}} = -2.24 \) and \( \Delta \chi^2_{\text{Lens}} = -0.75 \) for polarization and gravitational lensing measurements, respectively. These improvements can be attributed to considerably higher values of \( H_0 \) inferred from the SPTPol survey [21, 67]. Finally, the fit to the \( S_8 \) data degrades quite marginally, \( \Delta \chi^2_{S_8} = 1.03 \). It demonstrates that the EDE scenario can accommodate a higher value of \( H_0 \) while not significantly deteriorating the fit to the galaxy clustering and weak lensing measurements.

To reliably predict the preference of the EDE scenario over ΛCDM we resort to several statistical tools. First, we employ an essentially frequentist Akaike Information Criteria (AIC) [70] that sets the penalty for extra free parameters in more complex models. For that, we build up the absolute difference in logarithmic likelihoods \( \log L \) calculated for EDE and ΛCDM models at their respective best-fit points optimized to the Planck-lowℓ + SPT + BOSS + \( S_8 \) + SH0ES likelihood. The AIC states that the quantity \( 2\Delta \log L \) defined in this way is distributed as \( \chi^2_n \) with \( n \) degrees of freedom equal to the difference of fitting parameters in ΛCDM and EDE models. As the EDE model has three extra parameters, we put \( n = 3 \). We found \( 2\Delta \log L = 9.3 \) that indicates a quite moderate 2.2σ preference for the EDE scenario over ΛCDM. Second, we apply a more sophisticated Bayesian evidence analysis which is ought to be preferred in model comparison since it addresses the prior volume effects that allows one to directly control the lack of predictivity of more complicated models [71]. The AIC does not account for the prior information which is highly relevant for model comparison questions and omitting it would result in seriously wrong inferences [72]. To avoid this, we employ the MCEvidence code [73] to estimate the Bayesian evidence for EDE and ΛCDM models. Using the Planck-lowℓ + SPT + BOSS + \( S_8 \) + SH0ES data set we found a Bayes factor (the ratio of EDE and ΛCDM evidences) \( B_{01} = 1.8 \) that supports the EDE preference over ΛCDM. This preference is rather weak according to Jeffrey’s scale [71] due to a significantly larger parameter space volume in the EDE model compared to that in
FIG. 2. Posterior distributions of the cosmological parameters of the EDE model for different data sets. The gray and yellow bands represent the constraints (1σ and 2σ confidence regions) on $H_0$ and $S_8$ coming from SH0ES and $S_8$ data, respectively.

IV. CONCLUSIONS

The EDE scenario is a compelling early-time resolution of the persistent and increasingly significant tension between local and global measurements of the Hubble constant. The EDE model successfully decreases the sound horizon enabling a higher value of $H_0$ in concordance with the SH0ES measurement. Accompanying shifts in $\omega_c$.
\( \omega_c \) and \( n_s \) parameters produce the CMB power spectra nearly indistinguishable from that in the \( \Lambda \)CDM scenario, hence providing a good fit to both the primary CMB and distance-ladder \( H_0 \) data. However, as demonstrated in Ref. [1], the shifts in the standard \( \Lambda \)CDM parameters are in tension with the various LSS data, in particular measurements of galaxy clustering and weak gravitational lensing. The region of parameter space capable of addressing the Hubble tension is further constrained when the full BOSS galaxy power spectrum likelihood is included [2]. In this paper, we revisit these stringent limits on EDE using a different CMB setup.

In fact, past claims of tight constraints on the EDE scenario [1, 2] essentially rely on the full Planck data. However, the Planck’s residuals of the CMB temperature power spectrum present a curious oscillatory feature conventionally attributed to the extra smoothing effect of gravitational lensing that pulls the late-time amplitude to a higher value [1, 17]. Although the lensing-like anomaly does not significantly alter the \( \Lambda \)CDM predictions [1, 19], its effect may be crucial for the various extensions of the \( \Lambda \)CDM model which open up a new degeneracy direction with \( \sigma_8 \). This is indeed the case for the EDE scenario which dictates a higher value of \( \sigma_8 \) for the SH0ES tension-resolving cosmology due to the tight correlation between \( \sigma_8 \), \( f_{\text{EDE}} \) and \( H_0 \) parameters. The overly enhanced smoothing of CMB peaks in the Planck temperature power spectrum increases \( \sigma_8 \) even further that exacerbates the discrepancy between the Planck and LSS data in the EDE framework. As demonstrated in Ref. [7], the full Planck likelihood indeed provides the more stringent constraints on EDE compared to the ‘unlensed’ CMB power spectra. Since we do not know what is behind the Planck lensing anomaly, the more conservative approach would be to analyse the CMB data without this feature. The one way is to marginalize over the lensing information in the Planck CMB power spectra as done in Ref. [7]. The second approach refers to the usage of alternative CMB measurements. In our analysis we employ the second treatment and combine the Planck and SPTPol measurements following the strategy of Ref. [3].

In this work, we reanalyse the EDE scenario using the Planck and SPTPol measurements of the CMB anisotropy, the full BOSS likelihood and photometric galaxy clustering and weak lensing data. As the primary CMB data we consider the Planck TT power spectrum at \( \ell < 1000 \) and the SPTPol measurements of TE, EE and lensing potential power spectra. It has been shown in Ref. [3] that this CMB setup predicts the consistent CMB lensing effect in the \( \Lambda \)CDM cosmology which modelling is important for resulting EDE constraints [7]. In this paper, we extend the previous EDE analysis [3] assuming a more motivated power-law cosine potential [1] and implementing a full perturbative dynamics of the EDE field.

We find no evidence for EDE in the primary CMB data alone: the fit to Planck-low-\( \ell \)-SPT brings \( f_{\text{EDE}} < 0.104 \) (2\( \sigma \)). Our CMB analysis yields considerably higher values of the Hubble parameter, \( H_0 = 70.79 \pm 1.41 \), albeit with a 40% larger error bar compared to that from the full Planck data [1]. Upon including the full BOSS galaxy power spectrum likelihood we found a somewhat looser constraint on EDE, \( f_{\text{EDE}} < 0.118 \) (2\( \sigma \)). The mean value of the Hubble constant is shifted considerably downwards, \( H_0 = 69.89 \pm 1.28 \) km s\(^{-1}\) Mpc\(^{-1}\). Supplemented with additional LSS data in the form of a Gaussian prior on \( S_8 \) from DES-Y1 [28], KiDS [54] and HSC [55] photometric measurements (a procedure was validated for the EDE model in [1]), we obtain a considerably tighter constraint on EDE, \( f_{\text{EDE}} < 0.094 \) (2\( \sigma \)) and \( H_0 = 69.79 \pm 0.99 \) km s\(^{-1}\) Mpc\(^{-1}\). We emphasize that even after taking into account the data from photometric surveys the available \( f_{\text{EDE}} \) values are still capable of addressing the Hubble tension in contrast to the past EDE analyses which fail to simultaneously resolve the Hubble tension and maintain a good fit to both CMB and LSS data [1, 2]. The main culprit of the past strong constraints on EDE is the overly enhanced smoothing effect of acoustic peaks that mainly affects the Planck temperature spectrum at high-\( \ell \) and pulls \( \sigma_8 \) to a higher value thereby conflicting with the LSS constraints. We also found that the \( H_0 \)-tension with the SH0ES measurements is alleviated to an acceptable 2.5\( \sigma \) level that enables one to include the SH0ES data in the fit.

Finally, we fit the EDE model to the combined data set with SH0ES. We found a 2.6\( \sigma \) evidence for non-zero EDE, \( f_{\text{EDE}} = 0.088 \pm 0.034 \). Our measurements reconcile the tension with the SH0ES-only constraint leading to \( H_0 = 71.81 \pm 1.19 \) km s\(^{-1}\) Mpc\(^{-1}\). We emphasize that our inference of the Hubble constant yields a considerably higher mean value with only modestly larger error bar compared to the results of past EDE studies that utilize a similar combination of data sets (with the high-\( \ell \) Planck data) [1, 40, 41]. We scrutinize the impact of the SH0ES data on the goodness-of-fit of each individual measurement. We found that the inclusion of SH0ES moderately degrades the fit to the BOSS likelihood but this effect is entirely compensated by the improved fit to the SPTPol data. At the same time, the goodness-of-fit of the photometric LSS data is only marginally deteriorated upon including SH0ES in the analysis. It reconciles the conflict between the SH0ES-tension-resolving EDE cosmologies and LSS data previously claimed in Ref. [1, 2]. The AIC criteria indicates a mild preference for the EDE scenario over \( \Lambda \)CDM at a 2.2\( \sigma \) level. The statistical analysis based on the Bayesian evidence reveals an even weaker evidence for the EDE scenario. It is caused by a significantly larger volume of parameter space available in the EDE model.

Overall, our results indicate that the combined analysis of Planck and SPTPol data can address a higher \( H_0 \) value in full concordance with the SH0ES measurement whilst not substantially worsening the fit to the galaxy clustering and weak lensing measurements. This inference is mainly driven by two causes. First, our primary CMB data perfectly agree with the various LSS data within
the ΛCDM cosmology [3] that opens up a new region of higher σ8 values which can accommodate a higher H0 in the EDE scenario. Second, the combined data approach provides considerably larger error bars as compared to those in the baseline Planck analysis [4] that facilitates a resolution of the Hubble tension. In particular, the fit to Planck-lowℓ + SPT yields the H0 measurement with twice the error bar and a 40% looser constraint on σ8 [3] as compared to that in the full Planck data analysisassuming the ΛCDM cosmology. All this makes the LSS constraints on EDE rather harmless. The constraints obtained in this work are similar to those from Ref. [74] that examines the lensing-marginalized Planck power spectra. Likewise, this paper underlines the extreme importance of CMB lensing effect for obtaining solid constraints on EDE. Future high-resolution Simons Observatory’s Large Telescope Aperture (CMB-S4) [74] will probe the CMB anisotropy with pinpoint accuracy thus providing the robust measurement of the CMB lensing effect down to very small scales. Upgrading the ongoing ground-based experiments such as SPT-3G (http://hlit.jinr.ru).

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