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Early Dark Energy in Precision Cosmology

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Early Dark Energy in light of precise cosmological observations

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Abstract. The flat ΛCDM model of the Universe has started to falter due to recent and precise observations. A prominent example is the Hubble tension; the Hubble constant, the rate at which the universe is currently expanding, is different depending on the method used to measure it. One of the most promising models to resolve the tension is the axion-like Early Dark Energy (EDE) model. However, all the previous work on EDE models assumed a flat Universe. Since the detection of such a component has a significant impact on our understanding of fundamental physics, we must revisit the assumptions in the flat ΛCDM model. In this paper, we will systematically study the impact of the shape of the Universe on the EDE model in light of state-of-the-art cosmological observations. Our goal is to clarify how the EDE model and the shape of the Universe are simultaneously constrained with these recent datasets.

Contents

1 Introduction

Cosmic acceleration is one of the biggest mysteries in fundamental physics, as its discovery was featured in Nobel Prize Physics in 2011. A flat ΛCDM model has been able to explain a whole series of cosmological observations, and is established as a concordance cosmological model. The flat ΛCDM describes a model whose current energy component consists of 4% of us (i.e., atoms or baryons), 27% of cold dark matter (CDM), 69% of the cosmological constant, so-called Λ, and zero curvature (i.e., flatness) of the Universe.

However, recent precise observations have shown a surprise in the ΛCDM model, and the 'Hubble tension' is the most prominent example. The Hubble constant, the rate at which the universe is currently expanding, is measured as $73 \pm 1.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ by a local distance-ladder measurement [1], while it is indirectly measured as $67 \pm 0.60\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ from Cosmic Microwave Background [2]. This tension arises under an assumption of a ΛCDM model. Therefore, if it is not accounted for by an unknown systematics, it could imply new physics. Many solutions have been proposed to resolve the Hubble tension including various dark energy models, modified gravity, inflationary models, and modified recombination history to name a few [3].

In this paper, we will be focusing on a dark energy model that is currently rising in popularity, the axion-like Early Dark Energy (EDE) model. This model introduces a new energy component in the ΛCDM model, which alters the expansion history in early times. A few hints have been found of observational data preferring EDE over ΛCDM [4, 5]. However, all the previous work on EDE models assumed spacial flatness of the Universe. Given the fundamental importance of such a claim, it is important to reassess an EDE model by relaxing basic assumptions of the flatness. It is not trivial to estimate the impact of the spatial curvature on the EDE preference, because there are known degeneracies between the curvature and other parameters. The current constraints (using Cosmic Chronometers and SNe 1a data) of the curvature density parameter, Ω_{K}, report a value very close to zero, $\Omega_{\mathrm{K}} = -0.03 \pm 0.26$ [6], consistent with a flat universe. We will systematically study the impact of the spatial curvature on the EDE model using various data sets in combination with codes using MCMC and Bayesian statistics.

The structure of this paper is as follows. In Sec. 2, we outline a more technical theoretical background of the physics involved in this research. It is followed by Sec. 3 which describes the method to conduct this experiment as well as the various data sets used. In Secs. 4 and 5, we report our results and give a discussion of their implications, including plans on how to continue this research in the future. The main body of this paper is nine-page long from Sec. 2 through Sec. 5.

2 Theoretical Background

We can measure the cosmic expansion history to infer a cosmological model, because there are 'standard rulers' for which we know or can compute the absolute size of an object on the basis of simple physics. One of the key standard rulers is the sound horizon scale at the time of the last scattering surface of the CMB, $r_s(z_*)$ where $z_* \sim 1090$. The sound horizon is the comoving distance that a sound wave of the primordial plasma can travel from the beginning of the universe to the point of the last scattering surface, defined by

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{dz}{H(z)} c_s(z), \tag{2.1}$$

where $z = 1/a - 1$ is the cosmological redshift, a is the scale factor of the universe, and z_* is the redshift of the CMB last scattering. The sound speed, $c_s(z)$, is given by $c_s(z)^2 = c^2/3\{1 + R(z)\}$ where c is the speed of light and $R(z) = 3\rho_\mathrm{b}/(4\rho_\gamma)$ is the baryon-to-photon ratio. The wave propagation is affected by cosmic expansion through the factor of the Hubble expansion rate, $H(z) \equiv \dot{a}/a$, which is given by the Friedmann equation in a ΛCDM model:

$$H(z)^2 = H_0^2 \left\{ \Omega_\mathrm{m}(1+z)^3 + \Omega_\Lambda + \Omega_\mathrm{K}(1+z)^2 + \Omega_\gamma(1+z)^4 \right\}, \tag{2.2}$$

where Ω_X (X = m, Λ, K, γ) is the present dimensionless density parameter for matter, the cosmological constant Λ, the curvature K, and the radiation, respectively. The Hubble constant $H_0 = 100h$ km/s/Mpc is the current expansion rate of the universe, and h is a corresponding dimensionless Hubble constant. Since the integral in Eq. (2.1) is dominated by the radiation-dominated era and $H_0^2\Omega_\gamma$ is determined only by the temperature of the CMB monopole, the sound horizon scale is not explicitly dependent on H_0 but on the baryon density parameter, $\Omega_\mathrm{b}H_0^2$. The CMB temperature and polarization anisotropies allow us to infer the angular size of the sound horizon scale, i.e.

$$\theta_s \equiv \frac{r_s(z_*)}{D_A(z_*)}. \tag{2.3}$$

$D_A(z_*)$ is the angular diameter distance at $z = z_*$, given by

$$D_A(z) = \frac{1}{1+z} S_K \left[\int_0^z \frac{c\,dz'}{H(z')} \right], \tag{2.4}$$

where the comoving distance $S_K(x)$ is obtained as $\sinh(\sqrt{-K}x)/\sqrt{-K}$ for $K < 0$, x for $K = 0$, or $\sin(\sqrt{K}x)/\sqrt{K}$ for $K > 0$ where $\Omega_\mathrm{K} = -c^2K/H_0^2$. Notice that $D_A(z) \propto H_0^{-1}$. A flat ΛCDM universe provides an excellent fit with the Planck CMB data with $100\theta_s = 1.04110 \pm 0.00031$ rad and $r_s(z_*) = 144.43 \pm 0.26$ Mpc. This leads to $H_0 = 67.36 \pm 0.54$ km/s/Mpc with $\Omega_\mathrm{m} = 0.3153$ [2] which is inconsistent with the local measurement of the Hubble constant, $H_0 = 73.0 \pm 1.4$ km/s/Mpc [1]. This is the quantitative statement of the Hubble tension.

The sound wave of the primordial plasma imprints another standard ruler on the large-scale structure of the universe. Since the baryon interacts with CDM via gravity after the baryon's dragging epoch at $z_{\rm drag} \sim 1060$, the acoustic oscillation in the primordial baryon-photon fluid also appears in the matter distribution at late times. Galaxies trace the underlying matter density field at large scales, and hence the Baryon Acoustic Oscillations (BAOs) can be precisely measured with a galaxy survey as a standard ruler to measure the cosmic expansion at low redshift, $z \lesssim 3$. Since we measure the BAO scale from a three-dimensional galaxy map, a BAO survey allows us to simultaneously measure

$$\theta_{\rm BAO} = \frac{r_s(z_{\rm drag})}{D_A(z)} \quad \text{and} \quad c\Delta z_{\rm BAO} = r_s(z_{\rm drag})H(z), \tag{2.5}$$

where z is the typical redshift of a galaxy map. The Planck CMB data provides $r_s(z_{\rm drag}) = 147.09 \pm 0.26$ in a flat ΛCDM model. The BAO distance measurements mainly from Sloan Digital Sky Survey (SDSS) are in excellent agreement with a flat ΛCDM model in Planck with $H_0 \sim 68\,\mathrm{km/s/Mpc}$ [2, 7, 8]. Thus the combination of Planck CMB and BAO do not help us resolve the Hubble tension.

Since θ_s or $\theta_{\rm BAO}$ is precisely measured with CMB or BAO and is proportional to $r_s(z_*)H_0$ or $r_s(z_{\rm drag})H_0$, one way to alleviate the Hubble tension is to reduce the sound horizon scale by introducing new physics prior to the CMB last scattering surface. A novel Early Dark Energy model exactly achieves this, motivated by an extremely light axion-like scalar field ϕ [9]. In general, such a scalar field is modeled with a potential

$$V(\phi) = m^2\phi^2 \left\{1 - \cos\left(\frac{\phi}{f}\right)\right\}^n \tag{2.6}$$

where f is the decay constant of the scalar field. For the scalar field to be effective before the CMB epoch, the mass m should be smaller than the mass scale corresponding to the Hubble horizon scale at CMB, $m \lesssim 10^{-27}\,\mathrm{eV}/c^2$, so that the field begins to oscillate around the potential minimum. Since the potential minimum is locally $V \sim \phi^{2n}$ where the equation of state of the field is given by $w_\phi = (n-1)/(n+1)$, we consider $n = 3$ such that the cosmic expansion is decelerated with $w_\phi < 1/3$ (or $n > 2$) and hence the sound horizon is reduced. The phenomenology of this scalar field can be parameterized by the following effective parameters: z_c, critical redshift, which is the redshift at which the EDE contributes to its maximal fraction, $\theta_i \equiv \phi/f$, where θ_i shows the initial displacement of the scalar field. The third parameter is $f_{\rm EDE} \equiv \max(\rho_{\rm EDE}(z)/\rho_{\rm tot}(z))$ which indicates the maximal fractional contribution to the total energy density of the universe. The evolution of the EDE energy fraction is shown in Fig. 1. Since θ_s is precisely measured by the frequency of the angular power spectra of the CMB temperature and polarization anisotropies, the EDE parameters are constrained by other physical effects on the CMB spectra. The most prominent difference from the ΛCDM case is the reduction of the diffusion damping scale, which increases the relative power of the CMB spectra at high ℓ [10].

Previous studies (except [11]) assume the spatial flateness, i.e., $\Omega_{\rm K} = 0$ in constraining the EDE model. Even though a flat ΛCDM model is in an excellent agreement with the CMB and other cosmological probes, the flatness is not guaranteed to provide the best-fit model particularly when the EDE component is favored by the data. In other words, the assumption of $\Omega_{\rm K} = 0$ could lead to a biased inference of the parameters of the EDE model. In Planck,

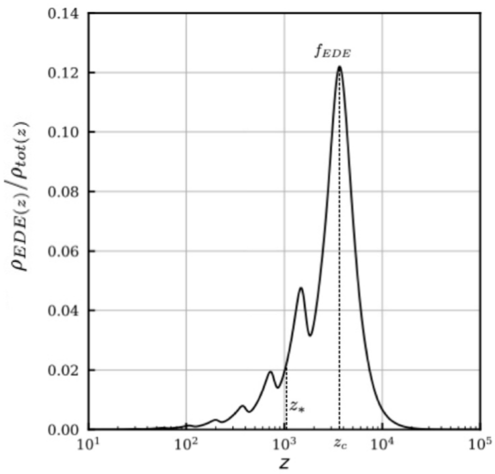

Figure 1. Fraction of the EDE energy density as a function of redshift, taken from [5]. The full list of assumed parameters in this example includes $H_0 = 100h = 72.9$km/s/Mpc, $\Omega_b h^2 = 0.002253$, $\Omega_m h^2 = 0.1306$, $f_{\rm EDE} = 0.122$, $\log_{10}(z_c) = 3.562$, and $\theta_i = 2.83$.

Parameters	Prior
$100\theta_s$	[0.5,10]
$\ln 10^{10}{\rm A_s}$	[1.61,3.96]
n_s	[0.8,1.2]
$\tau_{\rm reio}$	[0.02,None]
$\Omega_{\rm K}$	[-0.5,0.5]
A_L	[0.1,2.1]
$\log_{10} z_c$	[3.1,4.3]
θ_i	[0.1,3.1]
$f_{\rm EDE}$	[0.001,0.5]

Table 1. The assumed ranges of uniform priors.

the flatness was favored by the smooth temperature spectra at $\ell \gtrsim 1000$ which completely degenerates with the lensing effect [12]. The primary CMB temperature and polarization fields are gravitaionally distorted by large-scale structures between the last scattering surface and the observer (see [13] for a review). Given the existing discrepancies of the CMB lensing signal among various measurements, we conservatively vary the amplitude of the CMB lensing with a parameter, A_L. This approach allows us to extract information on an EDE model without relying too much on the lensing information.

3 Method and Data Sets

We fit the ΛCDM and EDE models to a series of cosmological data to find the best fit model parameters and quantify the statistical uncertainties. Since direct sampling of likelihood functions in a high-dimensional parameter space is computationally infeasible, we adopt the Markov chain Monte Carlo (MCMC) method. MCMC is based on Bayesian statistics, since there is only one universe to observe and take data. More specifically, we use the Metropolis-Hastings algorithm to efficiently sample the posterior distribution of the model parameters.

A key ingredient in the Bayes theorem is a prior on the model parameters. A choice of the prior could have a quantitative impact on statistical inference and model selection. Such an impact is negligible, however, if a uniform prior range is sufficiently wider than a sampled distribution. In this paper, we show our main results with the publicly available MCMC code `Montepython`[1] [14]. `Montepython` is integrated with `CLASS_EDE`[2] which is a modified version of the `CLASS` code [15] that accounts for the EDE model. For verification, we also use `cobaya`[3] [16] which includes interfaces to Boltzmann equation solvers, `CAMB` [17] and `CLASS`.

In the flat ΛCDM model, the main cosmological parameters include $\{\Omega_b h^2, \Omega_{cdm}h^2, \theta_s, \ln[10^{10}A_s], n_s, \tau_{reio}\}$. A_s and n_s denote normalization and spectral index of the primordial power spectrum for the curvature perturbation, respectively. The reionizatoin optical depth τ_{reio} represents a probability that CMB photons are scattered due to cosmic reionization. When we consider a non-flat cosmology, we include two more parameters, $\{\Omega_K, A_L\}$. The reason why we add the lensing parameter A_L is that there exists a degeneracy between Ω_K and A_L in the Planck temperature data [12], and this helps isolate the lensing information from the data set we consider. Regarding an EDE model, we add three more parameters, $\{f_{EDE}, \log_{10} z_c, \theta_i\}$. The prior choice on these parameters is given in Table. 1. Moreover, depending on the choice of the dataset we use, we have additional nuisance parameters. For instance for the case of the full Planck 2018 likelihood (temperature and polarization CMB power spectra from low and high multipoles) we have 47 nuisance parameters that would be added to our multidimensional parameter space. For the case of SPTPol likelihood (temperature, polarization and lensing), we have 12 nuisance parameters. To analyze the chains and produce our plots, we use the `GetDist`[4] Python package [18]. We consider chains to be sufficiently converged, checking the Gelman-Rubin criterion $|R - 1|$.

Regarding the datasets we use in this paper, the most precise observations of the CMB anisotropies over the full sky has been done by the Planck satellite [2] which comes up with the cosmological parameters measurements at the percent level accuracy. Sensitive measurements of the CMB temperature and anisotropy have been done using the ground-based telescopes such as South Pole Telescope (SPT [19]), Atacama Cosmology Telescope(ACT [20]) and POLARBEAR [21] that are very sensitive to the small angular scales which are not reachable in full sky surveys and they would be complementary to Planck in terms of frequency bands, angular resolution, and instrumental sensitivity. One of the most sensitive measurements of the small angular scales has been done by the SPT observation of 2540 $\deg^2$ SPT-SZ survey [22]. Since the measurements of the E-mode of the CMB polarization anisotropies are less contaminated by the foregrounds in comparison with the temperature measurements, the E-mode auto power spectrum (`EE`) and the temperature-E-mode cross spectra (`TE`), have more potential to study the small angular scales. Other than that, the lensing potential from the SPT dataset which has been directly extracted from estimators of T-, E- or B-fields, can give us independent measurements of the lensing potential.

Overall, the CMB data sets used in this research is a combination of Planck 2018[5] [2] and

[1] https://github.com/PoulinV/montepython_public_v3
[2] https://github.com/mwt5345/class_ede
[3] https://github.com/CobayaSampler/cobaya
[4] https://getdist.readthedocs.io/
[5] http://pla.esac.esa.int/pla/cosmology

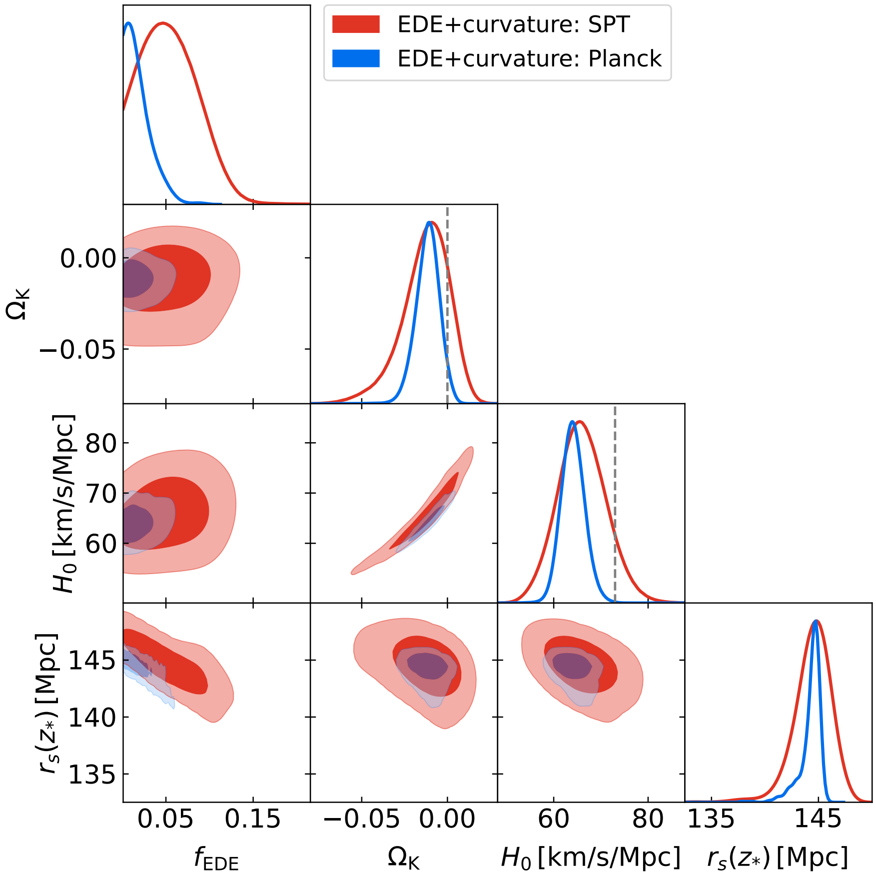

Figure 2. 1D and 2D posterior distributions (68% and 95% C.L.) of various cosmological parameters when using Planck and SPT datasets.

SPTPol[6] [19] likelihoods. The first dataset we use includes the high-l ($l \geq 30$) `TTTEEE` (from `Plik` likelihood), low-l ($l \leq 30$) `TT` (from `Commander` likelihood) and low-E `EE` (from `SimAll` likelihood) and the Planck-*lensing*. We refer to this combination of dataset as "Planck" hereafter. The second dataset consists of the high-l ($30 \leq l \leq 165$) `TT` (from `Plik` likelihood), low-l ($l \leq 30$) `TT` (from `Commander` likelihood), low-E `EE` (from `SimAll` likelihood) and SPTPol ($50 \leq l \leq 8000$) [23] and SPTLens ($100 \leq l \leq 2000$) [24]. We refer to the second combination as "SPT". Alongside with the CMB measurements, in some cases we added the BAO datasets from SDSS DR12 [25] to break the degeneracies between some parameters like Ω_K and H_0.

4 Results

We first compare the two datasets, Planck (blue) and SPT (red), in light of an EDE model with Ω_K varied in Fig. 2. In a two-dimensional contour plot, we show 68% and 95% Confidence Limit (C.L., hereafter). In a one-dimensional plot, we show the posterior distribution marginalized over all other parameters; the peak basically corresponds to the most favorable parameter given the data and model. Our f_{EDE} constraints are broadly in good

[6] https://github.com/ksardase/SPTPol-montepython

Constraints on EDE		
Dataset & Model	SPT	SPT varying Ω_K
$\mathbf{f}_{\rm EDE}$	$0.0607^{+0.025}_{-0.043}$	$0.0560^{+0.027}_{-0.036}$
$\theta_{\mathbf{i}}$	$0.5212^{+0.109}_{-0.386}$	$0.6269^{+0.284}_{-0.290}$
$\mathbf{log_{10}(z_c)}$	$3.8431^{+0.378}_{-0.246}$	$4.002^{+0.223}_{-1.134}$
H_0 [km s^{-1} Mpc^{-1}]	$71.591^{+0.999}_{-2.065}$	$66.045^{+4.858}_{-5.266}$
Ω_K	—	$-0.0125^{+0.016}_{-0.010}$
$r_s(z_*)$ [Mpc]	$143.308^{+2.693}_{-1.120}$	$144.470^{+1.873}_{-1.358}$

Table 2. The mean and 68% C.L. (as per convention shown in previous work) for cosmological parameters in an EDE model including Planck 2018 and SPT data with and without varying curvature parameter Ω_K.

agreement with previous work. For Planck, [5] gives $f_{\rm EDE} < 0.087$, and for SPT, [4] gives $f_{\rm EDE} = 0.123 \pm 0.062$. This fact suggests that the impact of varying Ω_K has little impact on the determination of $f_{\rm EDE}$, supported by a Pearson correlation coefficient, this indicates how strongly two variables are linearly related, between Ω_K and $f_{\rm EDE}$, but this correlation is ignorable. In both Planck and SPT, there is a sign of a closed universe ($\Omega_K < 0$), although $\Omega_K = 0$ lies still within the 68% C.L.

Even in the case of SPT where non-zero $f_{\rm EDE}$ is preferred, the bestfit H_0 is not fully consistent with the local measurement of $H_0 = 73\,{\rm km/s/Mpc}$ (dashed vertical line in the one-dimensional posterior on H_0). To understand the reason behind this result, we compare the three models in the SPT case in Fig. 3; a flat ΛCDM (gray), a flat EDE (cyan), and an EDE model with varying Ω_K (blue, the same result in Fig. 2). As expected, non-zero $f_{\rm EDE}$ results in reduction of the sound horizon scale $r_s(z_*)$, $r_s(z_*) = 146.73 \pm 0.861$ for ΛCDM and $r_s(z_*) = 144.47 \pm 1.949$ for the EDE model. However, the reduction is not compensated for by the increase in H_0 unlike the flat ΛCDM model, due to the strong degeneracy between H_0 and Ω_K. This is not surprising because both H_0 and Ω_K change the distance up to the last scattering surface of the CMB (see the denominator in Eq. (2.1)). In Fig. 4, we compare the bestfit models of the CMB temperature power spectrum with the Planck (cyan) and SPT (red) data points. The three bestfit curves give similar goodness of fit (or χ^2), and hence they are not distinguishable with the Planck or SPT data.

An additional constraint from low-redshift probes sheds some light on the degeneracies among the model parameters. In Fig. 5, we show the result when we add the BAO data to the Planck, and SPT combination. An interesting result comes from adding the BAO data breaking the degeneracy between Ω_K and H_0. We obtain values of $\Omega_K = -0.004 \pm 0.003$, $H_0 = 69.170 \pm 1.40$, and $r_s(z_*) = 144.71 \pm 1.75$. Interestingly, we see that the preferred value of $f_{\rm EDE}$ is $f_{\rm EDE} = 0.064762 \pm 0.0230$ which is higher than both Planck and SPT cases (see Table 4).

5 Summary and discussion

During this research, we have probed the EDE model of the universe, specifically what happens to the Hubble constant when a varying Ω_K parameter is introduced. We used various data sets (Planck2018, SPT, BAO) and publicly available codes combined with MCMC

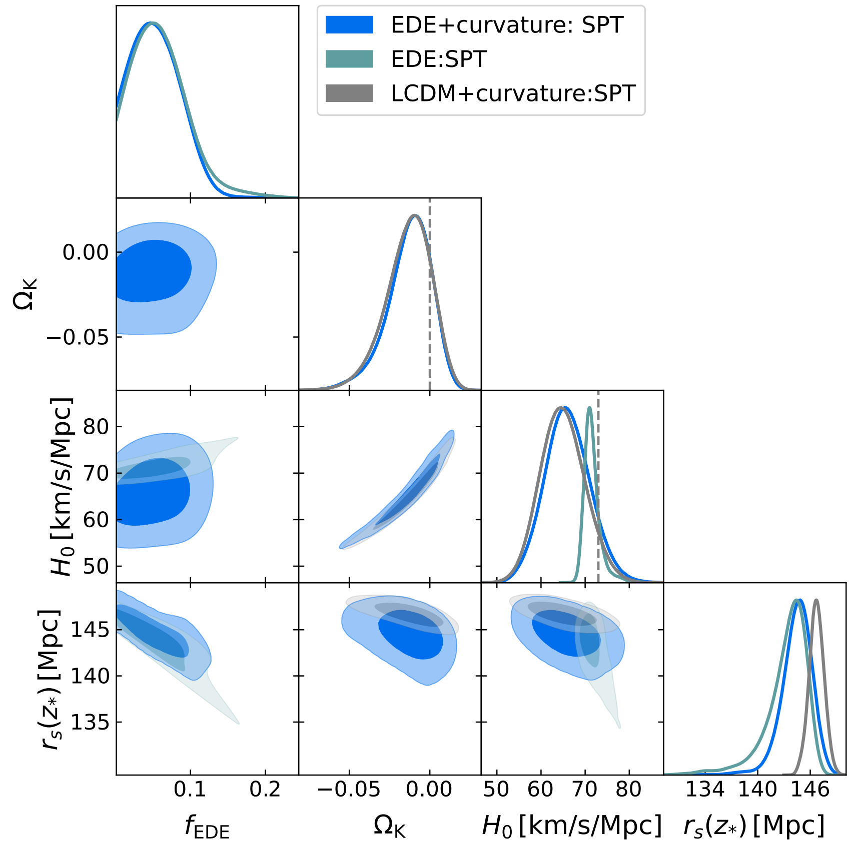

Figure 3. 1D and 2D posterior distributions (68% and 95% CL) of various cosmological parameters when varying model, and curvature parameter (in case of EDE)

Bayesian statistics to evaluate this model as well. By doing this, we found that when looking at the early dark energy parameter using just the Planck dataset compared to a Planck+SPT dataset, a lower value of $f_{\rm EDE}$ and H_0 is preferred ($f_{\rm EDE} = 0.0202 \pm 0.0152$ and $H_0 = 64.081 \pm 2.510$). We also looked at EDE:SPT models with a zero and nonzero $\Omega_{\rm K}$ and we found the $f_{\rm EDE}$ parameter is changed only very marginally when $\Omega_{\rm K}$ is varied from 0. As stated in Sec. 2, a smaller sound horizon scale would result in a larger H_0, thus making a step towards alleviating the Hubble Tension. Fig. 3 confirms this as the EDE model that does not include a varied value of $\Omega_{\rm K}$ results in both the smallest sound horizon scale, $r_* = 143.308 \pm 2.524$, and the largest Hubble constant $H_0 = 71.591 \pm 1.998$. Adding BAO, we saw an $\Omega_{\rm K}$ that was closer to zero, $\Omega_{\rm K} = -0.004 \pm 0.003$, and a slightly larger H_0 value, $H_0 = 69.170 \pm 1.40$. $r_s(z_*)$ changes negligibly when BAO data is added, $r_s(z_*) = 144.71 \pm 1.75$. We also notice that adding the BAO data breaks the degeneracy between $\Omega_{\rm K}$ and H_0. Another interesting result of the BAO dataset is that it shows to prefer a higher $f_{\rm EDE}$ than the other two data combinations.

Our results in this report compare generally well with those in similar literature. Hill et. al [5] reported values of $f_{\rm EDE} < 0.087$ and $H_0 = 68.29 \pm 1.02$ when they evaluated an EDE model using the Planck2018 TTTEEE data set only. When we looked into this data

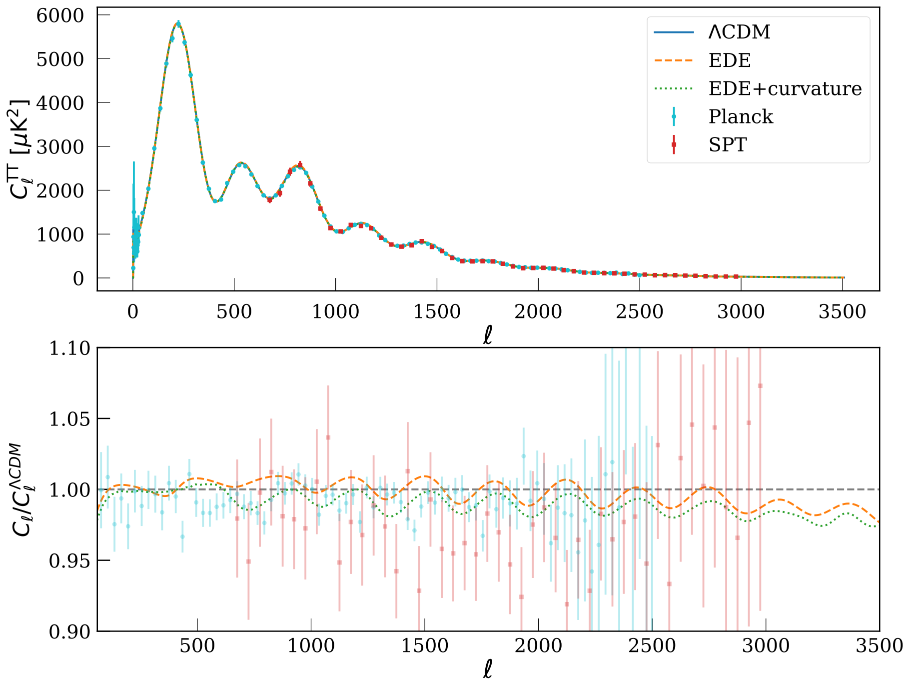

Figure 4. (Upper panel) The CMB temperature power spectrum, $C_\ell^{\rm TT}$. The data points with errors show the Planck (cyan) and SPT (red) measurements. We show the three bestfit models, a flat ΛCDM (solid blue), a flat EDE (dashed orange), and an EDE model with varying $\Omega_{\rm K}$ (green dotted). (Lower panel) The differences in the upper panel are highlighted, divided by the bestfit flat ΛCDM model.

set we found $f_{\rm EDE} = 0.0202 \pm 0.0152$ and $H_0 = 64.081 \pm 2.510$. After adding the SPT data set to Planck, we found our results to be in good agreement with Smith et. al [4] who preformed the same measurement but assumed a flat universe. The values reported in their paper, $f_{\rm EDE} = 0.123 \pm 0.062$ and $H_0 = 72.58 \pm 2.3$, look similar to what we obtained from Planck2018+SPT, $f_{\rm EDE} = 0.0607 \pm 0.0367$ and $H_0 = 71.591 \pm 1.998$. As is seen, these results compare well to those of an assumed flat universe.

Going forward, the next step would be to repeat this analysis using data from ACT and compare the results to those done in an assumed flat universe. In the near future, we will have better CMB polarization and lensing data from the experiments such as LiteBird, CMB-S4, and the Simons Array (see e.g., [26] for a recent review). Not only could better CMB data be used, but also better galaxy BAO data from many current and upcoming projects such as HETDEX [27], DESI [28], PFS [29], and Roman Space Telescope [30]. These new data sets could lead to different results and shed light on new information.

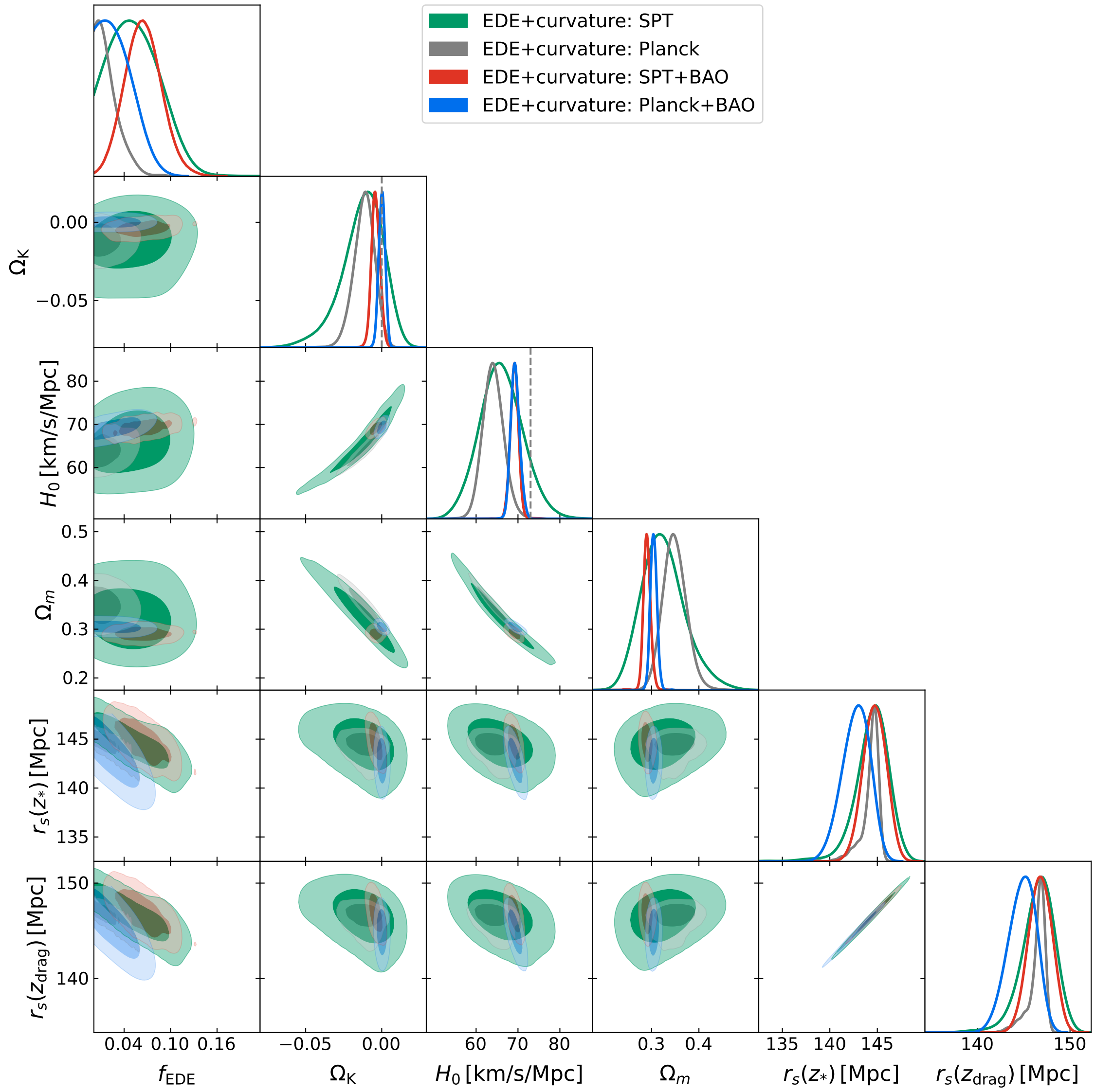

Figure 5. 1D and 2D posterior distributions (68% and 95% C.L.) of various cosmological parameters when using Planck, Planck+SPT, and Planck+SPT+BAO datasets.

6 Nomenclature

- CMB: Cosmic Microwave Background, faint cosmic background radiation left over from the Big Bang.
- EDE: Early Dark Energy; proposed model of the universe.
- ΛCDM: Λ-cosmological constant, CDM- cold dark matter; current/most accepted model of the universe.
- SPT: South Pole Telescope dataset
- ACT: Atacama Cosmology Telescope dataset
- Planck: Planck Telescope dataset
- Ω_{K}: Curvature density Parameter
- $r_s(z_*)$: Sound horizon scale at the time of the last scattering surface.
- H_0: Hubble constant; current expansion rate of the universe.
- BAO: Baryon Acoustic Oscillations
- Redshift: Corresponds to distance; displacement of the spectrum of an astronomical object toward longer (red) wavelengths.
- Prior: What is known about a parameter before empirical evidence is taken into account.
- Anisotropies: Properties that have different values when measured along axes in different directions.
- f_{EDE}: The maximal fractional contribution to the total energy density of the universe.
- Last Scattering: Where the CMB photons were scattered for the last time before arriving at our detectors.

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References

[1] A.G. Riess, S. Casertano, W. Yuan, J.B. Bowers, L. Macri, J.C. Zinn et al., *Cosmic distances calibrated to 1and hubble space telescope photometry of 75 milky way cepheids confirm tension with cdm*, *The Astrophysical Journal Letters* **908** (2021) L6.

[2] N. Aghanim, Y. Akrami, M. Ashdown, J. Aumont, C. Baccigalupi, M. Ballardini et al., *Planck 2018 results*, *Astronomy Astrophysics* **641** (2020) A6.

[3] E.D. Valentino, O. Mena, S. Pan, L. Visinelli, W. Yang, A. Melchiorri et al., *In the realm of the hubble tension—a review of solutions*, *Classical and Quantum Gravity* **38** (2021) 153001.

[4] T.L. Smith, M. Lucca, V. Poulin, G. Abellán, L. Balkenhol, K. Benabed et al., *Hints of early dark energy in planck, spt, and act data: new physics or systematics?*, 2022.

[5] J.C. Hill, E. McDonough, M.W. Toomey and S. Alexander, *Early dark energy does not restore cosmological concordance*, *Physical Review D* **102** (2020) .

[6] S. Dhawan, J. Alsing and S. Vagnozzi, *Non-parametric spatial curvature inference using late-universe cosmological probes*, *Monthly Notices of the Royal Astronomical Society: Letters* **506** (2021) L1.

[7] S. Alam, M. Ata, S. Bailey, F. Beutler, D. Bizyaev, J.A. Blazek et al., *The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: cosmological analysis of the DR12 galaxy sample*, MNRAS **470** (2017) 2617 [1607.03155].

[8] S. Alam, M. Aubert, S. Avila, C. Balland, J.E. Bautista, M.A. Bershady et al., *Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory*, Phys. Rev. D **103** (2021) 083533 [2007.08991].

[9] V. Poulin, T.L. Smith, T. Karwal and M. Kamionkowski, *Early dark energy can resolve the hubble tension*, *Phys. Rev. Lett.* **122** (2019) 221301.

[10] V. Poulin, T.L. Smith, D. Grin, T. Karwal and M. Kamionkowski, *Cosmological implications of ultralight axionlike fields*, Phys. Rev. D **98** (2018) 083525 [1806.10608].

[11] E. Fondi, A. Melchiorri and L. Pagano, *No evidence for EDE from Planck data in extended scenarios*, *arXiv e-prints* (2022) arXiv:2203.12930 [2203.12930].

[12] E.D. Valentino, A. Melchiorri and J. Silk, *Planck evidence for a closed universe and a possible crisis for cosmology*, *Nature Astronomy* **4** (2019) 196.

[13] A. Lewis and A. Challinor, *Weak gravitational lensing of the CMB*, Phys. Rep. **429** (2006) 1 [astro-ph/0601594].

[14] B. Audren, J. Lesgourgues, K. Benabed and S. Prunet, *Conservative Constraints on Early Cosmology: an illustration of the Monte Python cosmological parameter inference code*, *JCAP* **1302** (2013) 001 [1210.7183].

[15] D. Blas, J. Lesgourgues and T. Tram, *The cosmic linear anisotropy solving system (class). part ii: Approximation schemes*, *Journal of Cosmology and Astroparticle Physics* **2011** (2011) 034–034.

[16] J. Torrado and A. Lewis, *Cobaya: code for bayesian analysis of hierarchical physical models*, *Journal of Cosmology and Astroparticle Physics* **2021** (2021) 057.

[17] A. Lewis, A. Challinor and A. Lasenby, *Efficient computation of CMB anisotropies in closed FRW models*, ApJ **538** (2000) 473 [astro-ph/9911177].

[18] A. Lewis, *GetDist: a Python package for analysing Monte Carlo samples*, 1910.13970.

[19] A. Chudaykin, D. Gorbunov and N. Nedelko, *Combined analysis of planck and sptpol data favors the early dark energy models*, *Journal of Cosmology and Astroparticle Physics* **2020** (2020) 013–013.

[20] S.K. Choi, M. Hasselfield, S.-P.P. Ho, B. Koopman, M. Lungu, M.H. Abitbol et al., *The atacama cosmology telescope: a measurement of the cosmic microwave background power spectra at 98 and 150 ghz*, *Journal of Cosmology and Astroparticle Physics* **2020** (2020) 045–045.

[21] POLARBEAR collaboration, *A Measurement of the CMB E-mode Angular Power Spectrum at Subdegree Scales from670 Square Degrees of POLARBEAR Data*, *Astrophys. J.* **904** (2020) 65 [2005.06168].

[22] K.T. Story, C.L. Reichardt, Z. Hou, R. Keisler, K.A. Aird, B.A. Benson et al., *A measurement of the cosmic microwave background damping tail from the 2500-square-degree spt-sz survey*, *The Astrophysical Journal* **779** (2013) 86.

[23] SPT collaboration, *Measurements of the Temperature and E-Mode Polarization of the CMB from 500 Square Degrees of SPTpol Data*, *Astrophys. J.* **852** (2018) 97 [1707.09353].

[24] SPT collaboration, *Constraints on Cosmological Parameters from the 500 deg^2 SPTpol Lensing Power Spectrum*, *Astrophys. J.* **888** (2020) 119 [1910.07157].

[25] S. Alam, M. Ata, S. Bailey, F. Beutler, D. Bizyaev, J.A. Blazek et al., *The clustering of galaxies in the completed sdss-iii baryon oscillation spectroscopic survey: cosmological analysis of the dr12 galaxy sample*, *Monthly Notices of the Royal Astronomical Society* **470** (2017) 2617–2652.

[26] C.L. Chang, K.M. Huffenberger, B.A. Benson, F. Bianchini, J. Chluba, J. Delabrouille et al., *Snowmass2021 Cosmic Frontier: Cosmic Microwave Background Measurements White Paper*, *arXiv e-prints* (2022) arXiv:2203.07638 [2203.07638].

[27] K. Gebhardt, E. Mentuch Cooper, R. Ciardullo, V. Acquaviva, R. Bender, W.P. Bowman et al., *The Hobby-Eberly Telescope Dark Energy Experiment (HETDEX) Survey Design, Reductions, and Detections*, ApJ **923** (2021) 217 [2110.04298].

[28] DESI Collaboration, A. Aghamousa, J. Aguilar, S. Ahlen, S. Alam, L.E. Allen et al., *The DESI Experiment Part I: Science,Targeting, and Survey Design*, *arXiv e-prints* (2016) arXiv:1611.00036 [1611.00036].

[29] M. Takada, R.S. Ellis, M. Chiba, J.E. Greene, H. Aihara, N. Arimoto et al., *Extragalactic science, cosmology, and Galactic archaeology with the Subaru Prime Focus Spectrograph*, PASJ **66** (2014) R1 [1206.0737].

[30] Y. Wang, Z. Zhai, A. Alavi, E. Massara, A. Pisani, A. Benson et al., *The High Latitude Spectroscopic Survey on the Nancy Grace Roman Space Telescope*, ApJ **928** (2022) 1 [2110.01829].