Towards early dark energy and $n_s=1$ with Planck, ACT and SPT

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ABSTRACT: We investigate the constraints on early dark energy (EDE) by combining the most recent CMB observations available, ACT DR4, SPT-3G, and Planck2018 ($\ell_{TT,\text{max}} = 1000$) data. This combined CMB dataset favors non-zero EDE fractions and large Hubble constants. The inclusion of BAO+Pantheon data has little effect on the results, leads to $H_0 = 71.6(72.9)^{+2.0}_{-1.3}$ and $73.17(72.74)^{+0.55}_{-0.77}$ km/s/Mpc for axion-like EDE and AdS-EDE, respectively. The axion-like EDE can fit the data significantly better ($\Delta\chi^2 \lesssim -10$) than ΛCDM, which is mainly driven by the ACT data. It is found again that if the current $H_0$ measured locally is correct, complete resolution of the Hubble tension seems to be pointing towards a scale invariant Harrison-Zeldovich spectrum of primordial scalar perturbation, i.e. $n_s = 1$ for $H_0 \sim 73$ km/s/Mpc.
1 Introduction

As the precision of cosmological observations increases, the standard ΛCDM model is facing challenges. One of the critical problems is the $4 \sim 6\sigma$ tension between the Hubble constant based on the early universe with the ΛCDM model and that measured by direct observations of the local universe without assuming the ΛCDM model [1, 2] (see e.g. [3–5] for recent reviews), dubbed as the Hubble tension. The systematic errors are unable to explain it entirely, so modifications to the cosmological model are required [6–10].

Pre-recombination early dark energy (EDE) [11, 12] is one of the most promising route to resolve the Hubble tension. In corresponding scenario, energy injection before recombination led to faster expansion of the Universe, which so reduced the sound horizon. As $\theta^*_s = r^*_s / D^*_A$ is measured precisely by CMB observations, we can obtain a higher $H_0$ while keeping late-time physics unchanged. There are various kinds of phenomenological models [12–25] for this early energy injection with effective fluids or scalar fields, see also [26–28]. Decay of EDE must be rapid so as not to spoil other observations, which can be achieved by an oscillatory potential in axion-like EDE, e.g.Refs.[12, 16], or by an anti-de Sitter (AdS) phase in AdS-EDE [19]. Both showed a better fit to the CMB, baryon acoustic oscillation (BAO) and local $H_0$ data.

Planck data, the most precise large-scale CMB observation currently available, alone seems not favor axion-like EDE model (see Ref.[29]). However, the Planck data itself is debatable, especially its small scale part of TT power spectrum. The inconsistency between the $\ell < 1000$ and $\ell > 1000$ part of Planck’s TT power spectrum has been pointed out in Refs.[30, 31]. Moreover, the smoothing effect of gravitational lensing on acoustic peaks
of the CMB power spectrum exceeds that expected in ΛCDM model [30, 32]. However, ground-based CMB observations, such as ACT and SPT, providing precise measurements on small scale power spectrum have not found this over-smoothing effect [33–35].

It has been found that, without the small scale part of Planck TT power spectrum, a large fraction of EDE and a large Hubble constant are possible. Recently, combined analysis of Planck data (ℓTT ≲ 1000) with ACT or SPT data have been performed for EDE models, such as Planck + SPTpol for power-law potential EDE [36], axion-like EDE [37], AdS-EDE [38] and Planck + ACT DR4 for axion-like EDE [39, 40] and NEDE [40]. And also Planck + ACT DR4 + SPT-3G Y1 for axion-like EDE [41].

In this work, in view of the important role of ground-based CMB observations, we investigate the constraints on axion-like EDE and AdS-EDE models using the combination of Planck18 data (we exclude ℓ > 1000 part of Planck TT power spectrum) with the recent SPT-3G Y1 and ACT DR4 data, with and without BAO and Pantheon data. We find that this combined CMB dataset favors a non-zero EDE fraction and a large Hubble constant for both models. In Ref.[42], it has been found that with fullPlanck+BAO+Pantheon dataset the pre-recombination solutions of the Hubble tension implies a scale-invariant Harrison-Zeldovich spectrum of primordial scalar perturbation, i.e. \( n_s = 1 \) for \( H_0 \approx 73 \text{ km/s/Mpc} \). It is also interesting to recheck this conclusion with our combined CMB dataset.

The paper is outlined as follows. We explain our data, models and methodology in section 2. Results are presented in section 3. Then we analyse and discuss it in section 4. Finally, we conclude in section 5.

2 Model, Data and Methodology

The first EDE model is: axion-like EDE, where the energy injection before recombination is achieved by a scale field with axion-like potential [12]:

\[
V(\phi) = m^2 f^2 (1 - \cos \theta)^n, \quad \text{where} \quad \theta = \phi / f \in [-\pi, \pi]
\]  

(2.1)

It describes the axion for \( n = 1 \), which naturally arises in high energy theory. Initially, the field sit in the upper region of its potential due to the Hubble fiction, resulted in \( w \approx -1 \), i.e. an dark energy injection. Afterwards it will roll to the bottom of the potential and oscillate with \( w \approx (n - 1) / (n + 1) \). Therefore, the energy will redshift faster than matter if \( n > 1 \), avoid degrading other measurements (e.g. matter density and CMB). Here, we fixed \( n = 3 \), which is a suitable value for the current data [16].

Another model we consider is AdS-EDE, with phenomenological potential [19, 38]:

\[
V(\phi) = \begin{cases} 
V_0 \left( \frac{\phi}{M_{\text{Pl}}} \right)^4 - V_{\text{AdS}}, & \frac{\phi}{M_{\text{Pl}}} < \left( \frac{V_{\text{AdS}}}{V_0} \right)^{1/4} \\
0, & \frac{\phi}{M_{\text{Pl}}} > \left( \frac{V_{\text{AdS}}}{V_0} \right)^{1/4}
\end{cases}
\]  

(2.2)

where \( M_{\text{Pl}} \) is the reduced Planck mass. \( V_{\text{AdS}} \) is the depth of AdS phase. The significant difference from axion-like EDE is that the energy redshifts in an AdS phase. In an AdS

\[^1\]Other potentials are also possible [43].
phase with $w > 1$ the energy of EDE can redshift faster than that in oscillation phase, thus results less destruction to other measurement. It is well-known that AdS vacua is ubiquitous in high energy theories, so the AdS-EDE model can be well-motivated, see also the applications of AdS vacua to late Universe [44–50].

We consider the following CMB data sets at first:

- **Planck 2018**: We use the low-$\ell$ TT,EE Commander likelihoods and high-$\ell$ TT,TE,EE Plik likelihoods, with also the reconstructed lensing power spectrum [51].

- **SPT-3G Y1**: We use the public SPT-3G likelihood, which includes TE and EE power spectrum within multipoles $300 < \ell < 3000$ [35].

- **ACT DR4**: We use the marginalized likelihood from ACT Data Release 4, which includes TE and EE power spectrum within multipoles $326 < \ell < 4325$ and TT power spectrum within multipoles $576 < \ell < 4325$ [52].

This data set combination is confirmed in Ref.[53], which showed $H_0 = 67.49 \pm 0.53$ km/s/Mpc for ΛCDM model. As mentioned, it might be better to discard the small scale part of Planck’s TT, so when combine Planck measurement with ACT and SPT data, we cut the Planck’s high-$\ell$ TT power spectrum to $\ell_{\text{TT,max}} = 1000$. Then, we use galaxy BAO measurements from 6DF [54], SDSS DR7 MGS [55] in low-$z$ and BOSS DR12 [56] in high-$z$. Type Ia supernovae from Pantheon [57] is also used.

We perform MCMC sampling with Cobaya [58]. The models are calculated using the modified CLASS [59], where we improved the accuracy for the calculation of the lensing effect since it has non-negligible effects on the small-scale CMB power spectrum. The Gelman-Rubin criterion for all chains is converged to $R - 1 < 0.1$.

Here, we adopt same parameters and priors as Refs.[40] and [38], for axion-like EDE model: $\log_{10}(z_c) \in [2, 4.5]$, $f_{\text{EDE}} \in [0, 0.3]$, where $z_c$ is the redshift at which the field starts rolling and $f_{\text{EDE}}$ is the energy fraction of EDE at $z_c$, the initial position of EDE field $\Theta_{\text{ini}} \in [0, 3.1]$, while for AdS-EDE model: $\ln(1 + z_c) \in [7.5, 9]$, $f_{\text{EDE}} \in [0, 0.3]$. In order to have a significant AdS phase while make the field able to climb out of the AdS well, we fixed $\alpha_{\text{AdS}} \equiv (\rho_m(z_c) + \rho_r(z_c)) / V_{\text{AdS}} = 3.79 \times 10^{-4}$ as [19]. The neutrino assumption is the same as Planck [51]. The posterior distribution is plotted using GetDist [60]. The bestfit points are obtained through BOBYQA [61–63].
Figure 1. Posterior distributions of relevant parameters in axion-like EDE model (68% and 95% confidence range). Grey bands represent the 1σ and 2σ regions of the SH0ES measurement [64] and model-independent constraint on $\beta_{BAO}$ from BAO and SN, respectively.

3 Results

3.1 axion-like EDE

We show the posterior distribution in Figure 1 and the mean (best-fit) values of cosmological parameters in Table 1. The result is similar to Refs. [65] with $\ell_{TT,\text{max}} = 650$, where BAO and SN data were not included. We see that Planck($\ell_{TT,\text{max}} = 1000$)+ACT DR4+SPT-3G

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2 The difference between the power-law and cosine potentials in the axion EDE is also important [16].
3 https://github.com/SouthPoleTelescope/spt3g_y1_dist
4 https://github.com/ACTCollaboration/pyactlike
5 This choice of $\ell_{TT,\text{max}}$ is the same as Refs. [36–38] and close to Refs. [40] (where $\ell_{TT,\text{max}} = 1060$) and [39, 41] (where $\ell_{TT,\text{max}} = 650$).
6 The codes are available at https://github.com/PoulinV/AxiCLASS for axion-like EDE and https://github.com/genye00/class_multiscf for AdS-EDE.
The inclusion of BAO+Pantheon does not alter the result too much. This can be confirmed by checking $β_{\text{BAO}} = c/\left( Hr_s^{\text{darg}} \right)$, which BAO+Pantheon mainly constrain. We can find in Figure 1 that the $β_{\text{BAO}}$ obtained from CMB data alone is consistent with that constrained by BAO+SN observations. 7 Besides, the preference for large $Θ_{\text{ini}}$ due to the inclusion of Planck’s high-$\ell$ TE,EE power spectrum, is in agreement with the analysis in [16]. Unlike Ref.[39], we find $\log_{10}(z_c) ≈ 3.5$, close to the matter-radiation equality, even with lensing and BAO data included. This is because a larger $Θ_{\text{ini}}$ prefers the parameter region with smaller $z_c$, which can also be found in the Appendix B of Ref.[40].

We present the $χ^2$ for the bestfit points in Table 3 and Table 4. We found significant improvements $Δχ^2 ≈ −11$ without and with BAO+Pantheon for axion-like EDE model compared to $Λ$CDM in fitting CMB data. The main improvement is come from CMB data, especially ACT DR4 and Planck high-$\ell$ part.

### 3.2 AdS-EDE

The combined CMB dataset still favor a non-zero fraction of AdS-EDE $f_{\text{EDE}} = 0.1257(0.1199)_{−0.014}^{+0.050}$ and a large Hubble constant $H_0 = 73.31(72.48)_{−0.93}^{+0.68}$, see the posterior distribution in Figure 2 and the mean (best-fit) values in Table 2, and the inclusion of BAO+Pantheon does not change the results. However, different from that for axion-like EDE, the fullPlanck+BAO+Pantheon dataset still favor a large $H_0 = 72.52(72.46) ± 0.51$ for AdS-EDE. A distinct non-Gaussian distribution is shown in $f_{\text{EDE}}$-$\ln(z_c)$ plane. This is a reflection of AdS bound, or else the

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Table 1. The mean (best-fit) $±1σ$ errors of parameters in axion-like EDE model for each dataset combination. The result with fullPlanck+BAO+Pantheon is from Ref.[40].

| parameters | Planck($ℓ_{TT, \text{max}} = 1000$) +ACT DR4+SPT-3G Y1 | Planck($ℓ_{TT, \text{max}} = 1000$) +ACT DR4+SPT-3G Y1 +BAO+Pantheon | Planck +BAO+Pantheon |
|------------|------------------------------------------------------|-------------------------------------------------------------------|---------------------|
| $f_{\text{EDE}}$ | 0.127(0.150)_{−0.034}^{+0.058} | 0.112(0.148)_{−0.038}^{+0.064} | $< 0.084(0.09)$ |
| $\log_{10}(z_c)$ | 3.507(3.514)_{−0.024}^{+0.046} | 2.53(2.75)_{−0.11}^{+0.35} | unconstrained (3.569) |
| $Θ_{\text{ini}}$ | 2.66(2.80)_{−0.20}^{+0.21} | 2.68(2.75)_{−1.5}^{+2.0} | 1.933(2.773)_{−0.44}^{+1.2} |
| $H_0$ | 72.4(73.4)_{−1.7}^{+2.2} | 71.6(72.9)_{−1.5}^{+2.0} | 68.6(70.88)_{−1.1}^{+0.55} |
| 100$ω_b$ | 2.263(2.262)_{−0.019}^{+0.017} | 2.260(2.267)_{−1}^{+0.017} | 2.257(2.270)_{−0.02}^{+0.017} |
| $ω_{\text{cdm}}$ | 0.13(0.134)_{−0.065}^{+0.062} | 0.1307(0.1348)_{−0.0653}^{+0.0067} | 0.1219(0.1278)_{−0.0034}^{+0.0031} |
| $10^9A_s$ | 2.139(2.141)_{−0.035}^{+0.035} | 2.126(2.140)_{−0.035}^{+0.035} | 2.118(2.159)_{−0.034}^{+0.034} |
| $n_s$ | 0.9933(0.9962)_{−0.0098}^{+0.0098} | 0.9885(0.9933)_{−0.0078}^{+0.0094} | 0.9719(0.9850)_{−0.0076}^{+0.0048} |
| $τ_{\text{reio}}$ | 0.5310(0.526)_{−0.0073}^{+0.0073} | 0.5090(0.516)_{−0.0070}^{+0.0078} | 0.0569(0.0671)_{−0.0078}^{+0.0071} |
| $S_8$ | 0.832(0.830)_{−0.014}^{+0.014} | 0.833(0.839)_{−0.014}^{+0.014} | 0.828(0.836)_{−0.013}^{+0.013} |
| $Ω_m$ | 0.2964(0.2921)_{−0.0085}^{+0.0085} | 0.3000(0.2975)_{−0.0058}^{+0.0058} | 0.3085(0.3008)_{−0.0059}^{+0.0059} |

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7BAO+Pantheon constraints on $β_{\text{BAO}}$ are calculated in [38] based on the model-independent approach described in [66, 67].
EDE field will be unable to climb out of AdS well. These results are consistent with out previous results [38], where Planck (ℓ_{TT, max} = 1000) and SPTpol were included as CMB datasets. Furthermore, we now have smaller error bars, as SPT-3G Y1 data has stronger constraining power than SPTpol, and ACT DR4 has comparable constraining power.

We present the χ² for the bestfit points in Table 3 and Table 4. We find that AdS-EDE shows about Δχ² ≈ +2 worse fit to the corresponding dataset than ΛCDM, mainly comes from Planck lensing. This difference is statistically insignificant. However, similar to ΛCDM, AdS-EDE does not fit better to Planck high-ℓ part and ACT data, compared with axion-like EDE. Here, we only have investigated the simplest AdS-EDE model, actually other AdS potentials are also possible. Note that the bestfit point is so close to AdS bound that the “real” bestfit point might be covered by it. The AdS bound is controlled by α_{AdS}, thus a smaller α_{AdS} can bring a better fit.
Table 2. The mean (best-fit) ±1σ errors of parameters in AdS-EDE model for each dataset combination. The result with full Planck+BAO+Pantheon is from Ref. [38].

| parameters | Planck(ℓTT, max = 1000) + ACT DR4+SPT-3G Y1 | Planck(ℓTT, max = 1000) + ACT DR4+SPT-3G Y1 + BAO+Pantheon | Planck + BAO+Pantheon |
|------------|---------------------------------------------|-------------------------------------------------------------|-----------------------|
| ∫EDE       | 0.1257(0.1199)±0.014                        | 0.1253(0.1163)±0.013                                        | 0.1124(0.1084)±0.0070 |
| ln(1 + zc) | 8.009(8.007)±0.060                          | 8.011(7.968)±0.065                                          | 8.153(8.147)±0.075    |
| H0         | 73.31(72.98)±0.68                            | 73.17(72.74)±0.55                                          | 72.52(72.46)±0.51     |
| 100ωb      | 2.309(2.311) ± 0.021                         | 2.308(2.299) ± 0.020                                        | 2.341(2.331)±0.018    |
| ωcdm       | 0.1367(0.1361)±0.0021                        | 0.1370(0.1358)±0.0016                                        | 0.1346(0.1336)±0.0016 |
| 10^9As     | 2.134(2.138)±0.040                          | 2.135(2.120)±0.035                                          | 2.175(2.159)±0.033    |
| ns         | 1.0014±0.0021                                 | 1.0013(0.9989)±0.0059                                        | 0.9964(0.9949)±0.0047 |
| τreio      | 0.454(0.448)±0.010                           | 0.449(0.443)±0.0098                                         | 0.0545(0.0523)±0.0071 |
| S8         | 0.857(0.860) ± 0.017                         | 0.860(0.858) ± 0.012                                         | 0.863(0.856)±0.011    |
| Ωm         | 0.2987(0.3001) ± 0.0087                      | 0.3002(0.3014) ± 0.0060                                      | 0.3016(0.3002) ± 0.0051 |

|          | ACeDM | axion-like EDE | AdS-EDE |
|----------|-------|----------------|---------|
| Planck low-ℓ TT | 21.74 | 20.63 | 20.32 |
| Planck low-ℓ EE  | 395.72 | 395.83 | 396.21 |
| Planck high-ℓ TTTEE (ℓTT, max = 1000) | 1985.91 | 1983.32 | 1982.90 |
| Planck lensing | 9.16 | 10.73 | 11.32 |
| ACT DR4    | 297.48 | 289.17 | 300.03 |
| SPT-3G Y1  | 1117.31 | 1116.94 | 1118.93 |
| Total χ²   | 3827.32 | 3816.61 | 3829.72 |
| χ²model–ACeDM | −10.71 | +2.40 |

Table 3. χ² values for best-fit models to Planck (ℓTT, max = 1000) + ACT DR4 + SPT-3G Y1 dataset.

4 Discussion

4.1 Where do the differences in model fit come from?

As the main improvements come from the ACT and Planck high-ℓ part, we display the cumulative ∆χ² of them in Figure 3 to clarify the origin of the data in favor of the axion-like EDE model. It is clear that the preference for the axion-like EDE arises mainly from the narrow ℓ ≈ 1300 part of the ACT TE spectrum and the wide 1400 ≤ ℓ ≤ 2000 part of the ACT TT spectrum, where the latter is also valid for AdS-EDE. The lowest several bins of the ACT EE spectrum also contribute to the improvement for both model (similar to the analysis in [39]). However, the next few bins could not be fitted well, resulting in no significant preference in the ACT EE spectrum.

The exact reasons can be found in the residual plots (Figure 4). ACT data in the ℓ ≈ 1300 part of the TE spectrum seems to favor smaller values, and the axion-like EDE
### Table 4.

|                          | ΛCDM | axion-like EDE | AdS-EDE |
|--------------------------|------|----------------|---------|
| Planck low-ℓ TT         | 21.54| 20.81          | 20.45   |
| Planck low-ℓ EE         | 396.11| 395.84         | 395.85  |
| Planck high-ℓ TT EEEE, (ℓ_{TT, max} = 1000) | 1986.18| 1981.81        | 1984.92 |
| Planck lensing          | 9.27 | 10.41          | 11.20   |
| ACT DR4                 | 297.60| 290.54         | 297.92  |
| SPT-3G Y1               | 1117.60| 1117.01        | 1118.44 |
| BAO low-ν               | 1.67 | 2.25           | 1.86    |
| BOSS DR12 BAO           | 3.57 | 3.50           | 3.50    |
| Pantheon                | 1034.81| 1034.74        | 1034.75 |
| total $\chi^2$          | 4868.34| 4856.90        | 4869.91 |
| $\chi^2_{\text{model-ΛCDM}}$ | -11.44| +1.57          |         |

The cumulative $\chi^2_{\text{model-ΛCDM}}$ of each part of data in the best-fit points to Planck ($\ell_{\text{TT, max}} = 1000$) + ACT DR4 + SPT-3G Y1 + BAO + Pantheon dataset.

**Figure 3.** The cumulative $\chi^2_{\text{model-ΛCDM}}$ of each part of data in the best-fit points to Planck ($\ell_{\text{TT, max}} = 1000$) + ACT DR4 + SPT-3G Y1 + BAO + Pantheon.

captures this point. Besides, in the axion-like EDE model, there seems to be a shift to larger $\ell$ since the 5th acoustic peak of the TT spectrum. This shift is more visible in the
Figure 4. The residuals of the best-fit points for each model relative to ΛCDM model in Planck ($\ell_{TT, \text{max}} = 1000$) + ACT DR4 + SPT-3G Y1 + BAO + Pantheon and the constraints of different CMB data. The light colored part of the Planck TT spectrum is the unused data.

Figure 5. The relation between $A_L$ and $f_{EDE}$ in axion-like EDE model with fullPlanck + BAO + Pantheon dataset.

In addition, the axion-like EDE model also provides a better fit to the $\ell \lesssim 900$ part of Planck TE,EE spectrum. Some of them come from the previously mentioned shift toward high $\ell$. 
4.2 Why does the high-$\ell$ part of Planck TT not favor the EDE model?

There are some oscillatory residuals in the Planck TT high-$\ell$ part, and such oscillatory residuals might be related to the lensing anomaly [30, 32] and parameter differences between different scales of the Planck TT spectrum [30, 31]. Although oscillatory residuals also appear in our bestfit EDE model, it is in a different phase than the oscillatory residuals of the high-$\ell$ part of Planck TT spectrum, see Figure 4.

Nevertheless, we considered the simplest possibility: whether the possible solution to the lensing anomaly is related to that the high-$\ell$ part of Planck TT spectrum disfavors the EDE models? We performed the MCMC analysis by varying the rescaling factor $A_L$ (see [68] for standard definition) of the lensing potential with the fullPlanck+BAO+Pantheon dataset. The results are presented in Figure 5, where we do not find any significant degeneracy between $A_L$ and EDE parameters, which suggests that the lensing anomaly alone cannot explain this disfavor to EDE models. See Fig.6 in [69] for an attempt to modify late dark energy.

However, it is important to note that the lensing anomaly is only a naive reflection of the oscillation pattern on this Planck TT spectrum. In fact, lensing anomaly also cannot explain the inconsistency between different scales of the Planck TT spectrum [31]. And this oscillation pattern was not found in ground-based CMB observations (see also [22]), which can already be better than Planck constraints in $\ell \gtrsim 2000$, so further observations of the TT spectrum in the $1000 \lesssim \ell \lesssim 2000$ part are necessary.

4.3 $n_s = 1$?

In EDE models, some other cosmological parameters must be shifted to compensate the raising of $H_0$. We show clear shifts of relevant parameters in Figure 6. As these parameters are shifted, the CMB power spectrum barely changes over the range of scales we are interested in, as showed by the black line in the Figure 7. This indicates that our CMB dataset is well constrained to the power spectrum. \footnote{Note that some of the parameters are shifted differently than in Ref.[38]. This is partly because the $\theta_s$ measurement is not as precise in Ref.[38] as it is here.}

In addition to altering $r^*_s$, pre-recombination EDE also affects the amplitude of power spectrum. Here, the Weyl potential will accelerated decay (eventually to a smaller level),
Figure 7. Relative changes in CMB power spectrum with respect to our bestfit ΛCDM model when changing certain parameters from ΛCDM to axion-like EDE bestfit values. $\theta_s^*$ is fixed by adjusting $H_0$ when changing $\omega_m$ and relevant EDE parameters.

as shown in Figure 8, see also [15, 70] for other EDE models. The faster decay of the Weyl potential results in the enhancement of CMB power spectrum of $\ell \lesssim 700$, which further leads to the enhancement of early ISW effect. In order to balance the enhancement of the early ISW effect, which is measured to be self-consistent in the ΛCDM model [71], $\omega_{\text{cdm}}$ is shifted to a larger value. The direction of shift is consistent with the constraint of BAO+Pantheon. The remaining power spectrum amplitude changes, especially around the pivot, is complemented by the overall amplitude $A_s e^{-2\tau}$.

The high $\ell$ part of power spectrum is mainly controlled by diffusion damping. The energy injection before recombination will amplify the ratio $r_\Delta/r_s^*$, thus enhancing the damping as $\theta_s$ is well fixed. This can not be complemented fully by the rise of $A_s e^{-2\tau}$, leads to the rise of $n_s$, as shown in Figure 6.\footnote{The rises of $n_s$ and $\omega_m$ result in a larger $S_8$, which, however, can be lowered by new physics beyond cold dark matter [72–76], see also [77–79].}

Actually, we have

$$\delta n_s \approx 0.3 \frac{\delta H_0}{H_0}$$

(4.1)
for our combined CMB dataset, which is slightly different for other dataset, e.g. $\delta n_s \approx 0.4 \frac{\delta H_0}{H_0}$ for fullPlanck+BAO+Pantheon dataset [42], see also recent [80]. This is due to the different constraining power of the CMB datasets, especially in the region of diffusion damping. However, they all suggest $n_s = 1$, i.e. a scale invariant spectrum. See also Refs.[81–83] for studies with $N_{\text{eff}}$. This hints that the primordial Universe model might need to be reconsidered, e.g. a inflation potential $V \sim \phi^p$ with a small $p$ [84], the curvaton scenario with a sub-Planckian field excursion [85], multi-natural inflation [86–89], ALP or QCD axion inflation [90–94], see also [95].

5 Conclusion

We investigated the constraints on EDE by combining the most precise CMB data available, i.e. Planck, SPT and ACT data. However, since the small scale part of Planck TT spectrum suffers from some anomalies, we exclude $\ell > 1000$ part of Planck TT power spectrum. Our main conclusions are as follows:

- The combined CMB dataset favors non-zero EDE fractions and large Hubble constants for both axion-like EDE and AdS-EDE models, i.e. $H_0 = 72.4(73.4)^{+2.2}_{-1.7}$ km/s/Mpc and 73.31(72.98)$^{+0.68}_{-0.93}$ km/s/Mpc, respectively. The inclusion of BAO+Pantheon data does not change the results, i.e. $H_0 = 71.6(72.9)^{+2.0}_{-1.3}$ and 73.17(72.74)$^{+0.55}_{-0.77}$ km/s/Mpc, respectively. In addition, it is also noted that the fullPlanck+BAO+Pantheon dataset still favors a large $H_0 = 72.52(72.46) \pm 0.51$ km/s/Mpc for AdS-EDE.

- The axion-like EDE model can fit the data significantly better than $\Lambda$CDM, which is mainly driven by the ACT part.
• The reason for the disfavor of the high-\(\ell\) part of Planck TT to EDE is that the oscillatory pattern of high-\(\ell\) TT spectrum in EDE do not match the oscillatory residual of Planck. The lensing anomaly can not explain it.

• The scale relationship between \(n_s\) and \(H_0\) reappears, see (Equation 4.1), which implies \(n_s = 1\) for \(H_0 \sim 73\) km/s/Mpc.

However, it should be noted that the ACT data seem to have some slight discrepancies with Planck and SPT results [34, 96], at least under the \(\Lambda\)CDM model. Therefore further observations and analyses on CMB are needed. In fact, the first year result of SPT-3G only made use of half of a observing season and part of detectors [35], and also the results of ACT DR5 is being released [97]. Ground-based CMB observations will have even better constraints, which will help to reveal whether and how the CMB observations really favor the EDE models.

Note added: When this project will be completed, Ref.[98] is present, which has investigated the constraints on (axion-like) EDE using ACT DR4, SPT-3G, and Planck2018 (\(\ell_{\text{TT}} < 650\)) data, with and without BAO+Pantheon data.

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