



Letter

Impact of the Hubble tension on the $r - n_s$ contourJun-Qian Jiang^{a,b,*}, Gen Ye^c, Yun-Song Piao^{a,b,d,e}^a School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China^b School of Physics, University of Chinese Academy of Sciences, Beijing 100049, China^c Leiden University, Instituut-Lorentz for Theoretical Physics, 2333CA, Leiden, Netherlands^d International Center for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China^e Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, China

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ABSTRACT

The injection of early dark energy (EDE) before the recombination, a possible resolution of the Hubble tension, will not only shift the scalar spectral index n_s towards $n_s = 1$, but also be likely to tighten the current upper limit on tensor-to-scalar ratio r . In this work, with the latest CMB datasets (Planck PR4, ACT, SPT and BICEP/Keck), as well as BAO and SN, we confirm this result, and discuss its implication on inflation. We also show that if we happen to live with EDE, how the different inflation models currently allowed would be distinguished by planned CMB observations, such as CMB-S4 and LiteBIRD.

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1. Introduction

Inflation is a current paradigm of the very early universe, predicting a nearly scale-invariant primordial scalar perturbation and primordial gravitational wave (GW). A combined analysis of the CMB observations by Planck with other datasets showed the scalar spectral index $n_s = 0.965 \pm 0.004$ (68% CL) [1], while its combination with the recent BICEP/Keck dataset showed tensor-to-scalar ratio $r < 0.036$ (95% CL)

[2]. However, both results are based on the Λ CDM model, and cosmological model-dependent.

Recently, some inconsistencies in cosmological observations have been suggested, see e.g. Refs. [3,4] for recent reviews. The most well-known is the Hubble tension, which have inspired the exploring beyond Λ CDM model, e.g. [5–12]. In the early dark energy (EDE) resolution [13,14] of the Hubble tension, a unknown EDE component before the recombination lowered the sound horizon $r_s = \int \frac{c_s}{H(z)} dz$, where c_s and

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$H(z)$ is the sound speed and Hubble parameter before the recombination respectively, so that H_0 is lifted, which, however, also brings an unforeseen effect on our understanding on inflation.

It has been found that the injection of EDE¹ will alter the results of n_s [15–19], specially if $H_0 \gtrsim 72$ km/s/Mpc, n_s will be shifted to $n_s = 1$ ($|n_s - 1| \sim \mathcal{O}(0.001)$) [20], and the current limit on tensor-to-scalar ratio r [21], see also [22–24] for studies on the possibilities of $n_s = 1$. Thus some inflation models that had been considered possible in the Λ CDM model might be excluded, while some inflation models which had been excluded might be reconsidered as possible. However, it is interesting to ask whether the result on $r - n_s$ is still credible with the Planck PR4 [25], as well as latest ACT [26], SPT-3G [27,28] dataset. In this work, we will investigate this issue.

It is expected that cosmological observations would have the ability to discriminate between different inflation models if their precision becomes high enough. In upcoming decade, the Simons Observatory [29], CMB-S4 [30], as well as the LiteBIRD satellite [31], will play significant roles in improving the constraint on $r - n_s$. The combination of CMB-S4 and LiteBIRD will be able to reach $\sigma(n_s) \sim 0.005$ and $\sigma(r) < 10^{-3}$. This forecast is obtained assuming AdS-EDE, in which the potential is ϕ^4 -like but with an anti-de Sitter (AdS) phase [20], but we expect this should be similar for other EDE models. Here, we also will show how different inflation models allowed by the present observations can be distinguished by upcoming CMB-S4 and LiteBIRD experiments.

The outline of paper is as follows. We show in section 2 the impact of EDE on the current constraint on $r - n_s$ and its implication for inflation. The abilities of CMB-S4 and LiteBIRD with EDE are forecasted in section 3. We conclude in section 4. The priors for all cosmological parameters employed in our analysis are shown in Appendix A. In Appendix B, we present the results with the tensor spectral index n_t and running of scalar spectral index α_s . The details on noise power spectrum and delensing used in our forecast are shown in Appendix C and posterior distributions for all cosmological parameters are shown in Appendix D.

2. Results with current data

2.1. Datasets and models

Datasets are as follows:

- **PR4**: The latest release of Planck maps (PR4), with the NPIPE code [25]. We take use of the `hillipop` likelihood [32] for high- ℓ part and `lollipop` [33] as low- ℓ polarization likelihood. As for the low- ℓ TT power spectrum, we take use of the public `commander` likelihood [34]. Planck PR4 lensing likelihood [35] is included.
- **ACT**: The ACTPol Data Release 4 (DR4) [26] likelihood for all TT, TE, EE power spectrum, which has already been marginalized over SZ and foreground emission.
- **SPT**: The SPT-3G Y1 data [27] of the TE, EE power spectrum and the recent TT power spectrum data [28]. We take use of the likelihoods adapted for `cobaya`.²
- **BK18**: The latest BICEP/Keck likelihood on the BB power spectrum [2].
- **BAO**: The 6dF Galaxy Survey [36] and SDSS DR7 main Galaxy sample [37] for the low- z part. The eBOSS DR16 data [38], which include LRG, ELG, Quasar, Ly α auto-correlation and Ly α -Quasar cross-correlation, for the high- z part.³ We use a combined likelihood with the BOSS DR12 BAO data [41].

¹ Actually, “EDE” corresponds to EDE+ Λ CDM, which is only a pre-recombination modification to Λ CDM, and the evolution after the recombination must still be Λ CDM-like.

² https://github.com/xgarrido/spt_likelihoods.

³ Although it has been argued that there may be some inconsistency with the Lyman- α BAO data (see e.g. Ref. [39]), the joint constraint does not depend on

- **SN**: The uncalibrated measurement of Pantheon+ on the Type Ia supernovae (SNe Ia) ranging in redshift from $z = 0.001$ to 2.26 [42].

In this work, for the CMB observations, we consider the combination of Planck and BICEP/Keck, and also the combination of Planck, ACT, SPT and BICEP/Keck. When the small scales of CMB spectrum can be complemented by ground-based CMB observations focused on small scales, we cut the PR4 TT spectrum to $\ell < 1000$ as there are some doubts about the Planck TT high- ℓ part (e.g. [43–45]). Meanwhile, it has been shown that EDE seems to resolve Hubble tension in this scenario. As we are investigating the impact of Hubble tension, we only focus on the scenario where Hubble tension can be resolved. Besides, we cut the `hillipop` EE likelihood to $\ell > 150$ in order to avoid the correlations with the `lollipop` likelihood. BAO and SN, which do not conflict with the CMB observations, are included in all datasets.

In canonical scalar field models of EDE, the EDE field is frozen initially due to the Hubble friction, and thus contributes extra energy before recombination, resulting in a lower sound horizon r_s^* , so a higher H_0 , as $\theta_s = r_s/D_A \sim r_s H_0$ is set precisely by CMB observations. As the expansion of the Universe slows down, the EDE begins to roll down and lose its energy. The requirement that EDE must decay fast enough to avoid disruption of the CMB fit has motivated different EDE models. Here, we consider the axion-like EDE [14], which is achieved by a scalar field with axion-like potential (see recent [46,47] for models in string theory), and the AdS-EDE [20,48,49]. In the axion-like EDE model, the fast decay is achieved through an oscillation phase, which has an equation-of-state parameter $w = 1/2$ (here we consider the case $n = 3$ for the axion-like EDE potential). While in the AdS-EDE model, it is achieved through an AdS phase, which has an equation-of-state parameter $w > 1$. Here we consider an AdS-EDE with a ϕ^4 -like potential. In both cases, EDE can decay faster than the radiation. In our analysis, we use the phenomenological parameter z_c , which means the redshift when the field starts rolling, and f_{EDE} , which means the energy fraction of EDE at z_c , instead of the theoretical parameters.

The MCMC sampling is performed using `Cobaya` [50], while we use the modified `CLASS` [51]⁴ to calculate models. The cosmological parameters include the six standard Λ CDM parameters $\{H_0, n_s, \omega_b, \omega_{\text{cdm}}, \tau_{\text{reio}}, A_s\}$, where H_0 is Hubble constant, n_s is scalar spectral index, $\omega_b = \Omega_b h^2$ ($h = H_0/100$) is baryon density today, $\omega_{\text{cdm}} = \Omega_{\text{cdm}} h^2$ is dark matter density today, τ_{reio} is optical depth, A_s is the primordial curvature perturbations. In addition to these, we also sample on the tensor/scalar ratio $r = \frac{A_t}{A_s}$ at the pivot scale 0.05 Mpc^{-1} and the parameters of EDE models z_c and f_{EDE} . For axion-like EDE, we also sample the initial phase Θ_{ini} .

2.2. Results

Our results are shown in Fig. 1 and Table 1. Since we are exploring the impact on the $r - n_s$ contour of EDE models in light of the Hubble tension, we choose the models and corresponding data set that allow enough EDE to resolve the tension, even it cannot degenerate to Λ CDM. In such EDE-like models,⁵ we have $H_0 \gtrsim 72$ km/s/Mpc, compatible with the recent local H_0 measurement [52] (hereafter R21), see also

whether the Lyman- α BAO data is included or not in the new data [40]. And we have checked that our conclusion does not depend on the selection of BAO data.

⁴ The codes are available at <https://github.com/PoulinV/AxiCLASS> for axion-like EDE and https://github.com/genye00/class_multiscf for AdS-EDE.

⁵ In the AdS-EDE model, with only PR4+BAO+SN(+BK18) dataset, $H_0 \gtrsim 72$ km/s/Mpc is acquired due to the existence of the AdS bound, where the field failed to climb out of the AdS potential for small f_{EDE} . Therefore, the posterior will not be connected to the Λ CDM even if the parameter prior range allows it. However, Λ CDM is allowed in some AdS-EDE models in which the depth of AdS vacuum is varied and regarded as a MCMC parameter, while AdS-

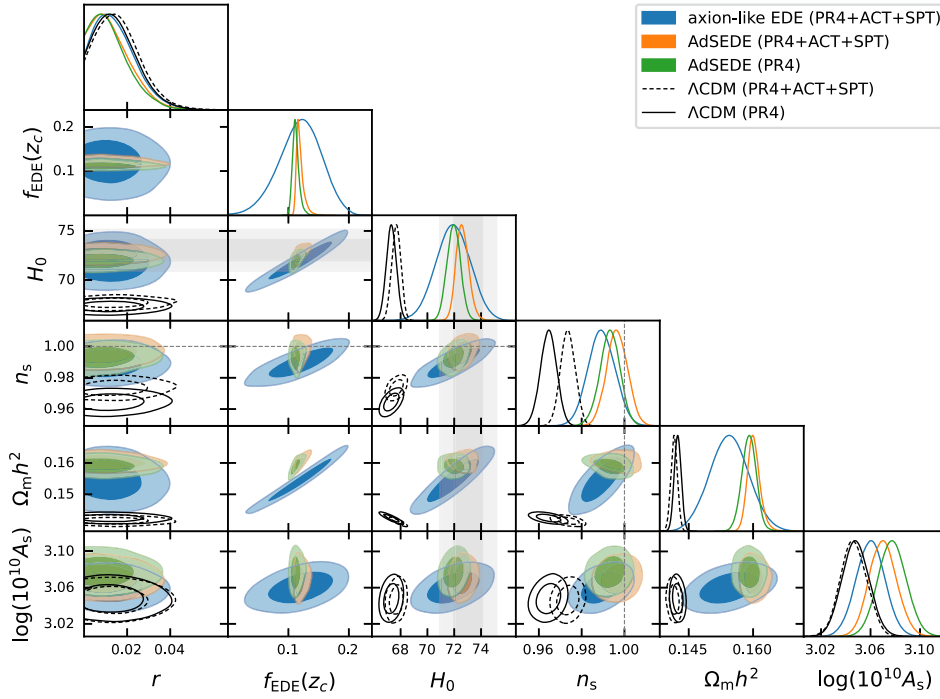


Fig. 1. Marginalized posterior distributions (68% and 95% confidence intervals) for relevant parameters in different models with different datasets. See Appendix D for all parameters. BK18 is included in all datasets. Constraint of R21 [52] on H_0 is shown as a gray band.

Table 1

68% confidence intervals for the parameters in different EDE models with different datasets, the best-fit values are shown in parentheses. And for the one-tailed distribution we show 95% confidence intervals. BK18 is included in all datasets.

Parameters	AdSEDE (PR4+ACT+SPT)	Axion-like EDE (PR4+ACT+SPT)	AdSEDE (PR4)
$\log_{10}(z_c)$	$3.470(3.4647)^{+0.022}_{-0.027}$	$3.514(3.5022) \pm 0.044$	$3.540(3.4536)^{+0.035}_{-0.041}$
f_{EDE}	$0.1193(0.11326)^{+0.0028}_{-0.0070}$	$0.119(0.0967)^{+0.038}_{-0.032}$	$0.1123(0.1225)^{+0.0040}_{-0.0062}$
Θ_{ini}		$2.737(2.752) \pm 0.087$	
r	< 0.0303	< 0.0324	< 0.0284
$\log(10^{10} A_s)$	$3.070(3.0663) \pm 0.011$	$3.060(3.0613) \pm 0.012$	$3.078(3.0706) \pm 0.011$
n_s	$0.9966(0.99438) \pm 0.0049$	$0.9893(0.9857) \pm 0.0063$	$0.9932(0.9903)^{+0.0049}_{-0.0044}$
H_0	$72.62(72.255)^{+0.42}_{-0.51}$	$71.9(71.12) \pm 1.3$	$71.96(71.58) \pm 0.50$
$\Omega_b h^2$	$0.02300(0.022928) \pm 0.00016$	$0.02251(0.022424)^{+0.00015}_{-0.00017}$	$0.02321(0.023108)^{+0.00018}_{-0.00016}$
$\Omega_c h^2$	$0.1365(0.13588)^{+0.0013}_{-0.0016}$	$0.1319(0.12895) \pm 0.0045$	$0.1352(0.13622) \pm 0.0018$
τ_{reio}	$0.0521(0.0505) \pm 0.0060$	$0.0542(0.0561) \pm 0.0056$	$0.0591(0.0580) \pm 0.0063$
Ω_m	$0.3038(0.30541) \pm 0.0050$	$0.2987(0.29929) \pm 0.0050$	$0.3072(0.3122) \pm 0.0053$
S_8	$0.868(0.8676) \pm 0.010$	$0.848(0.8448) \pm 0.012$	$0.871(0.8751) \pm 0.011$
$\chi^2 - \chi^2_{\Lambda\text{CDM}}$	-6.0	-11.2	2.0

Refs. [16,17,53] with Planck PR3, and Appendix B for the results with n_t and the running α_s of n_s .

Apart from the uplift of H_0 , another dramatic change is the shift of the n_s - r contour, which is shown in Fig. 2, specially n_s is shifted close to $n_s = 1$.⁶ The shift of n_s is a common result of any pre-recombination resolution (without modifying the recombination physics) for the Hubble tension [15]. The shift of n_s with respect to H_0 can be approximated as [15,16]:

$$\delta n_s \approx 0.4 \frac{\delta H_0}{H_0}. \quad (2.1)$$

EDE and higher H_0 are still preferred, see e.g. [48]. Here we take AdS-EDE with ϕ^4 -like potential for simplicity.

⁶ It has even been found that if the Hubble tension is fully resolved in such EDE models, it may suggest a Harrison-Zeldovich spectrum (i.e. $n_s = 1$) [18].

The upper limit of r (e.g. $r < 0.028$ in AdS-EDE) has been slightly lower than that under the ΛCDM model $r < 0.330$ (PR4)⁷ and $r < 0.0352$ (PR4+ACT+SPT). This is mainly because the slight uplifts of ω_m and A_s in EDE models, compared with ΛCDM , enhance the lensing spectrum between $200 < \ell < 800$. The constraint on r mainly comes from the observation of the CMB BB spectrum, where the effect of lensing is the main contributor in the present observational range. A larger lensing spectrum means a higher contribution, which in other words is smaller r after subtracting this contribution [21].

In well-known single field slow-roll inflation models, n_s follows [59–62]

$$n_s - 1 = -\frac{\mathcal{O}(1)}{N_*} \quad (2.2)$$

⁷ See Table 4 for detailed values. Our results differ slightly from Ref. [54] due to the different CMB data combinations selected and the BAO+SN dataset.

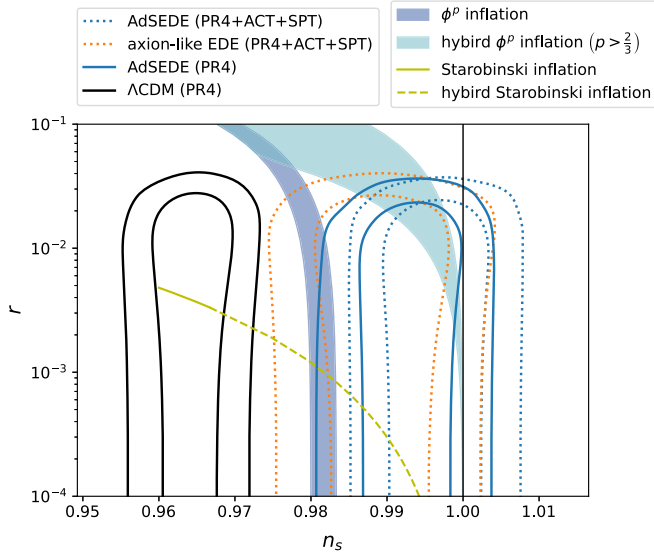


Fig. 2. The r - n_s contour for different models and different combinations of datasets. We also plot the predictions of some inflation models on n_s and r . The yellow line and the blue band represent Starobinski inflation [55] and ϕ^p inflation, respectively, with $50 \leq N_* \leq 60$. The dashed yellow line and the cyan band correspond to their hybrid variants where the inflation ended in a deep slow-roll region so that $N_* \gg 60$. The left bound ($p = 2/3$) of the cyan band is associated with the monodromy inflation [56,57] and the right bound ($p \rightarrow \infty$) is associated with the power-law inflation [58].

in large N_* limit, where N_* is the e-folding number spent during inflation ($M_p = 1$)

$$N_* \approx \Delta N + \int_{\phi_e}^{\phi_c} \frac{d\phi}{\sqrt{2\epsilon}} = \left(\int_{\phi_c}^{\phi_*} + \int_{\phi_e}^{\phi_c} \right) \frac{d\phi}{\sqrt{2\epsilon}} \approx N(\phi_*), \quad (2.3)$$

where $\epsilon = -\dot{H}/H^2$ is the slow-roll parameter and ϕ_* is the value of the field at which the perturbation mode with $k = k_*$ exits horizon, which sets N_* . Here ϕ_c is the value of the field when $\Delta N \approx 60$ was reached and ϕ_e is the value of the field when inflation ended in these models. Thus both n_s and r are related to N_* rather than ΔN . It is usually thought that inflation ended at ϕ_e when the slow-roll condition breaks down, we have $N_* = \Delta N \approx 60$ (inflation ends around $\sim 10^{15}$ GeV). However, if inflation ended prematurely at ϕ_c during the slow-roll regime when $\epsilon \ll 1$, we will have $N_* \gg 60$ but still $\Delta N \approx 60$ [63,64].

It is interestingly found that some inflation models, such as the power-law inflation [58] and the ϕ^p inflation [56,57,65,66], which were disfavored in the Λ CDM model, are now compatible with the EDE, see Fig. 2. In such inflation models, the inflation might end up by a waterfall instability, which is similar to the hybrid inflation [67,68], at a deep slow-roll region $\epsilon \ll 1$, so that $N_* \gg 60$. The perturbation modes near N_* can be just at CMB band, so we have $|n_s - 1| \ll \mathcal{O}(0.01)$. See also e.g. [69–72] for recent significant endeavors in inflation model with $n_s = 1$.

3. Forecast with CMB-S4 and LiteBIRD

It is also significant to investigate the impact of EDE on the constraining power of CMB-S4 and LiteBIRD. The CMB-S4 [73] will cover the sky area of $f_{\text{sky}} = 0.4$, so $20 < \ell < 5000$ for CMB, while the LiteBIRD [31] is a satellite covering a larger sky area. Here, we assume $f_{\text{sky}} = 0.9$ (so $2 < \ell < 200$) for LiteBIRD, and also set $\ell_{\text{min}} = 200$ for CMB-S4 to avoid the correlation between them. And relevant noise power spectrum and delensing are presented in Appendix C.

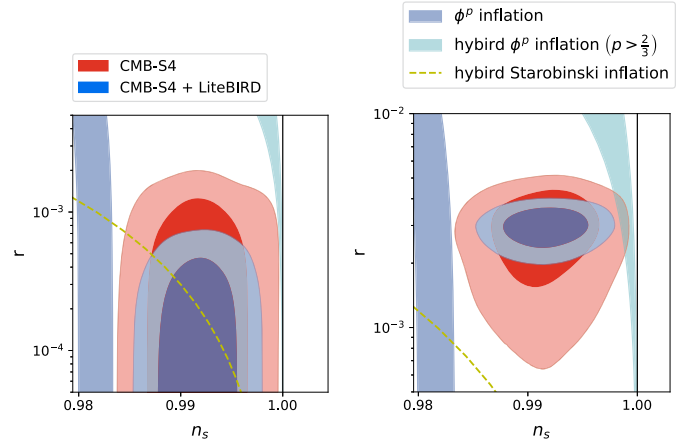


Fig. 3. The forecasted r - n_s contours with CMB-S4 and CMB S4+LiteBIRD in AdSEDE. Based on the bestfit results of AdSEDE for PR4+BK18, we fix r to 0 (left) and 0.003 (right). We also plot the predictions of some inflation models on n_s and r , the same as Fig. 2.

Table 2

The fiducial values for the cosmological parameters used to create the forecast.

Parameters	Values
$\log_{10}(z_c)$	3.512
f_{EDE}	0.112
$\log(10^{10} A_s)$	3.076
n_s	0.9916
H_0	71.92
$\Omega_b h^2$	0.02317
$\Omega_c h^2$	0.1362
τ_{reio}	0.0578

We use the Fisher matrix to make predictions. The Fisher matrix is the expectation of the Hessian of the log-likelihood [74]:

$$F_{ij} = \langle H_{ij} \rangle = \left\langle \frac{\partial^2 \ln \mathcal{L}}{\partial \theta_i \partial \theta_j} \right\rangle = \sum_{\ell} \text{Tr} \left\{ \frac{\partial C_{\ell}}{\partial \theta_i} C_{\ell}^{-1} \frac{\partial C_{\ell}}{\partial \theta_j} C_{\ell}^{-1} \right\} \quad (3.1)$$

where $C_{\ell}^{XY} \equiv \left(\frac{2\ell+1}{2} f_{\text{sky}} \right)^{-1/2} \left(C_{\ell}^{XY} + N_{\ell} \delta^{XY} \right)$ is the covariance matrix. X, Y represent T, E, B respectively, f_{sky} is the fraction of the sky, and C_{ℓ} , N_{ℓ} is the power spectrum and noise curve (defined in Appendix C) respectively. Thus we can estimate the parameter probability covariance matrix: $\mathbf{C} = [\mathbf{F}]^{-1}$.

Here, we assume AdS-EDE as the fiducial cosmological model. And set the cosmological parameters to the best-fit values⁸ based on the PR4+BK18 dataset. The detailed values are shown in Table 2. We then considered different r as the fiducial values. The results are shown in Fig. 3, where we set $r = 0$ (left) and $r = 0.003$ (right) respectively. The ϕ^p inflation ($p > 2/3$) and the power-law inflation with a hybrid end will be ruled out at 2σ level, if r is still undetected, while the Starobinski inflation with $N_* \approx 300$ is consistent, since

$$r = \frac{12}{N_*^2} \sim \mathcal{O}(1/10^4). \quad (3.2)$$

However, if $r = 0.003$, which would be detected by CMB-S4 and LiteBIRD, the ϕ^p inflation ($p > 2/3$), power-law inflation and Starobinski inflation all will be ruled out at 2σ level, only the ϕ^p inflation with $p < 2/3$ with a hybrid end might survive.

⁸ When searching for the best-fit values, we fixed $r = 0$ as we expect that $r \lesssim 0.003$ will not have a significant impact on the other parameters.

4. Conclusion

It has been widely thought that the conflicts in cosmological observations imply modifications beyond Λ CDM model. However, such modifications, specially the injection of EDE before the recombination, might be bringing a unforeseen impact on searching for primordial GW and setting the value of n_s , so our perspective on inflation.

Here, with the latest CMB datasets, we found for EDE that $|n_s - 1| \lesssim \mathcal{O}(0.01)$, while the upper limit of r is also slightly tighten, $r < 0.028$ with Planck PR4+BK18 and $r < 0.030$ with Planck PR4+ACT+SPT+BK18 dataset, which is consistent with the results with Planck PR3+BK18 [21]. In light of our constraint on $r - n_s$, the inflation models allowed by the results in the Λ CDM model, such as Starobinski inflation, will be excluded. However, in corresponding models satisfying (2.2), if inflation ends by a waterfall instability when inflaton is still at a deep slow-roll region, n_s can be lifted close to $n_s = 1$, so that the inflation models which have been ruled out, such as the ϕ^p inflation, and also the Starobinski model become possible again with their hybrid variants. It is also interesting to explore other models with $|n_s - 1| \lesssim \mathcal{O}(0.01)$.

In upcoming decade, the combination of the CMB-S4 [30] and the LiteBIRD satellite [31] will be able to reach $\sigma(n_s) \sim 0.005$ and $\sigma(r) < 10^{-3}$. Here, we also show that the different inflation models allowed by the present observations (if we happen to live with EDE) would be distinguished by both experiments.

Here, we only force the Hubble tension in our analysis. However, it is important to note that there are also many inconsistencies in other cosmological observations, such as S_8 tension. Some of them call for the modification to the Λ CDM model (see e.g. [3,4] for reviews), and may also affect the $r - n_s$ contour in Fig. 2, which will impact our perspective on the inflation models. Therefore, it is worth questioning the relevant issues beyond just the Hubble tension.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Priors for cosmological parameters (Table 3)

Table 3
Priors for cosmological parameters used in this work. All of them are flat priors for corresponding parameters. $\log_{10}(1 + z_c)$ and f_{EDE} are only used for EDE models. Θ_i are only used for the axion-like EDE model. n_s and α_s are only used in Appendix B.

Parameters	Priors
r	[0, 0.5]
$\ln(10^{10} A_s)$	[1.61, 3.91]
n_s	[0.8, 1.2]
H_0	[20, 100]
ω_b	[0.005, 0.1]
ω_{cdm}	[0.05, 0.99]
τ_{reio}	[0.01, 0.8]

Table 3 (continued)

Parameters	Priors
$\log_{10}(1 + z_c)$	[2, 4.5]
f_{EDE}	[0, 0.3]
Θ_i	[0, 3.1]
n_t	[-10, 10]
α_s	[-0.1, 0.1]

Appendix B. Results for n_t and α_s

In Fig. 4, we present the result for the spectral tilt n_t of primordial GW and the running of scalar spectral index $\alpha_s = dn_s/dk$. We imposed the flat priors on both n_t and α_s . We did not find the significant effects of EDE on the observations of n_t and α_s . The main difference on α_s is attributed to the different combination of CMB datasets.

However, when we switch from (r_{pivot}, n_t) to (r_{k_1}, r_{k_2}) through

$$r_k = r_{\text{pivot}} \left(\frac{k}{k_{\text{pivot}}} \right)^{n_t - n_s + 1} \quad (\text{B.1})$$

with $k_1 = 0.002 \text{ Mpc}^{-1}$ and $k_2 = 0.02 \text{ Mpc}^{-1}$, in light of Planck18 [75]. We find their discrepancy on r_2 , as shown in Fig. 5, which is constrained to $r_2 < 0.0457$ and $r_2 < 0.0566$ (95% CL) for AdSEDE and axion-like EDE, respectively, with the PR4+ACT+SPT CMB dataset while $r_2 < 0.0424$ (95% CL) for AdSEDE with the PR4 CMB dataset. Their values are lower than $r_2 < 0.0653$ (95% CL) for Λ CDM with the PR4 CMB dataset and $r_2 < 0.0656$ (95% CL) with the PR4+ACT+SPT CMB dataset. These discrepancies are more significant than that of r_{pivot} . The main reason is that in EDE the lensing spectrum at this scale ($\ell \sim 250$) is larger [21].

Appendix C. On noise power spectrum and delensing

In section 3 we investigate the impact of EDE on the constraining power of CMB-S4 and LiteBIRD. The noise power spectrum N_ℓ for CMB-S4 is taken from the wiki of CMB-S4.⁹ And for LiteBIRD, we consider a noise curve of

$$N_\ell^{XY} = s^2 \exp \left(\ell(\ell + 1) \frac{\theta_{\text{FWHM}}^2}{8 \log 2} \right), \quad (\text{C.1})$$

where the temperature noise is $s = 2 \mu\text{K-arcmin}$, $\theta_{\text{FWHM}} = 30 \text{ arcmin}$ for the full-width half-maximum beam size [76], and the polarization noise has additional factor $\sqrt{2}$.

Delensing on the CMB maps can help improve constraints on r as well as reduce the effects of the cosmological models on the lensing, specially the EDE model. We simply model it as

$$C_\ell = A_L C_\ell^{\text{lensed}} + (1 - A_L) C_\ell^{\text{unlensed}} \quad (\text{C.2})$$

for the C_ℓ in Equation (3.1). The delensing efficiency factor $A_L = 0.27$ is considered for CMB-S4¹⁰ and $A_L = 0.57$ for LiteBIRD [76]. In addition, we model the effects of thermal dust [77] and synchrotron [78] for those polarization noise power spectrums which have not yet taken the foreground into account as

$$A_{\text{dust}} \ell^{-2.42}, \quad A_{\text{synch}} \ell^{-2.3}, \quad (\text{C.3})$$

respectively, where A_{dust} and A_{synch} will be regarded as the nuisance parameters and be marginalized away.

⁹ https://cmb-s4.uchicago.edu/wiki/index.php/Survey_Performance_Expectations.

¹⁰ https://cmb-s4.uchicago.edu/wiki/index.php/Estimates_of_delensing_efficiency.

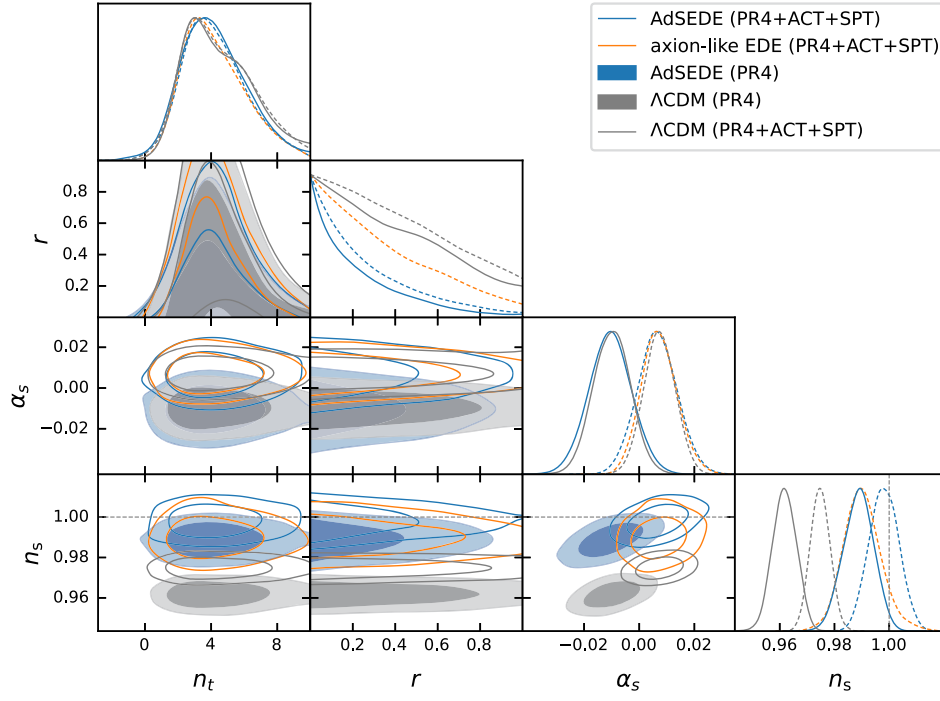


Fig. 4. Marginalized posterior distributions (68% and 95% confidence intervals) for relevant parameters under different models and datasets. BK18 is included in all the dataset.

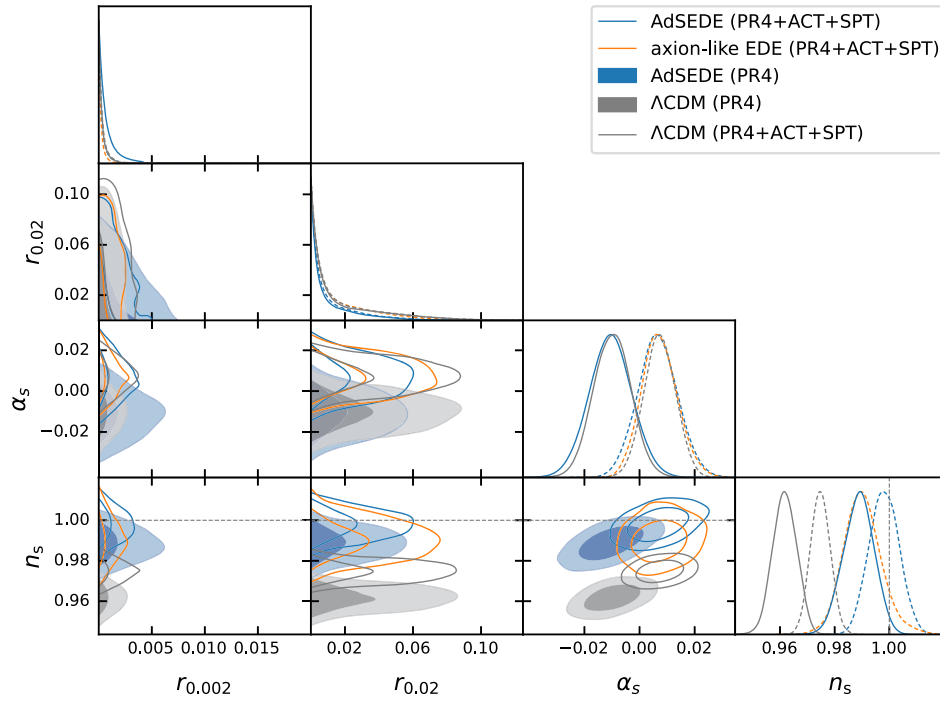


Fig. 5. Marginalized posterior distributions (68% and 95% confidence intervals) for relevant parameters under different models and datasets. BK18 is included from all the dataset.

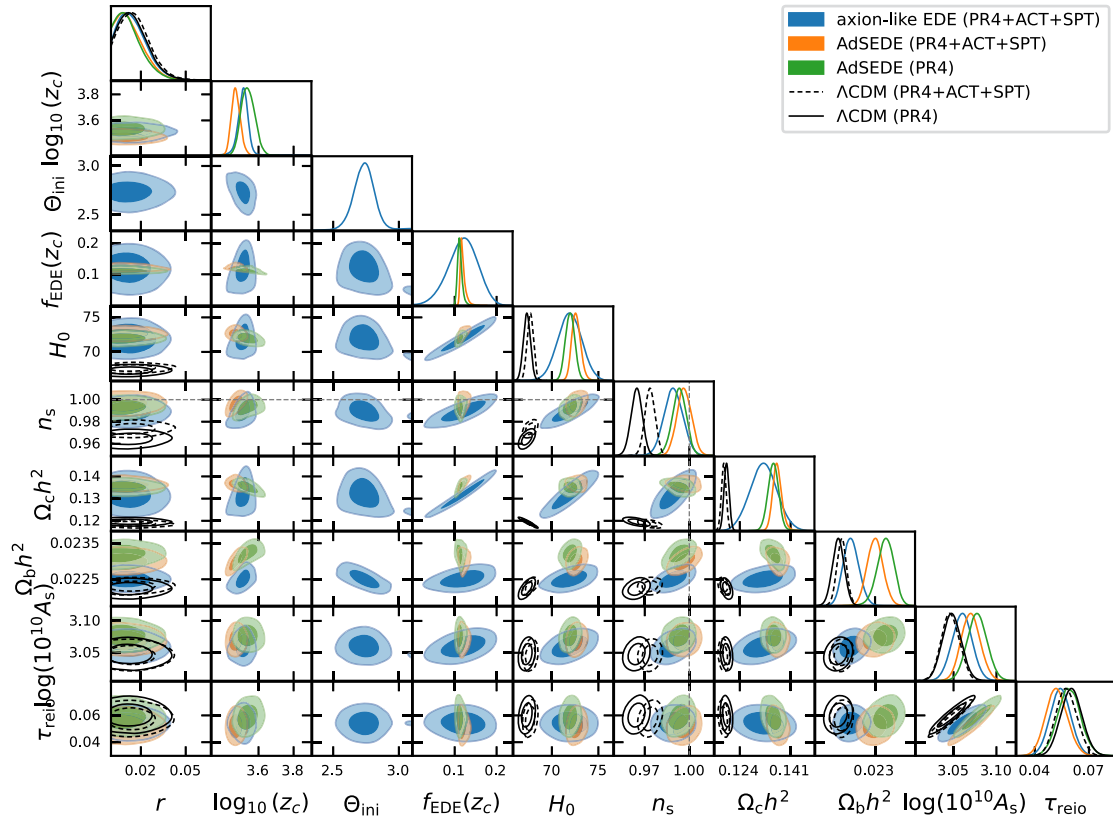


Fig. 6. Marginalized posterior distributions (68% and 95% confidence intervals) for all cosmological parameters in different models with different datasets. BK18 is included in all datasets. Constraint of R21 [52] on H_0 is shown as a gray band.

Appendix D. Marginalized posterior distributions for all cosmological parameters (Fig. 6)

Table 4

68% confidence intervals for the parameters in Λ CDM model with different datasets, the best-fit values are shown in parentheses. And for the one-tailed distribution we show 95% confidence intervals. BK18 is included in all datasets.

Parameters	Λ CDM (PR4+ACT+SPT)	Λ CDM (PR4)
r	< 0.0352	$r < 0.0330$
$\log(10^{10} A_s)$	$3.046(3.0376) \pm 0.011$	$3.048(3.0424) \pm 0.011$
n_s	$0.9736(0.97236) \pm 0.0034$	$0.9645(0.96627) \pm 0.0038$
H_0	$67.68(67.546) \pm 0.34$	$67.31(67.395) \pm 0.38$
$\Omega_b h^2$	$0.02231(0.022304) \pm 0.00010$	$0.02224(0.022257) \pm 0.00012$
$\Omega_c h^2$	$0.11865(0.11887) \pm 0.00079$	$0.11956(0.11928) \pm 0.00084$
τ_{reio}	$0.0575(0.0515) \pm 0.0057$	$0.0603(0.0575) \pm 0.0059$
Ω_m	$0.3092(0.31084) \pm 0.0047$	$0.3144(0.3130) \pm 0.0051$
S_8	$0.8220(0.8209) \pm 0.0090$	$0.8302(0.8256) \pm 0.0095$

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