

Topological defects as effective dynamical dark energy

Haipeng An^{1,2,*} Chengcheng Han^{3,4,†} and Borui Zhang^{1,‡}

¹*Department of Physics, Tsinghua University, Beijing 100084, China*

²*Center for High Energy Physics, Tsinghua University, Beijing 100084, China*

³*School of Physics, Sun Yat-Sen University, Guangzhou 510275, People's Republic of China*

⁴*Asia Pacific Center for Theoretical Physics, Pohang 37673, Korea*



(Received 12 September 2025; accepted 30 January 2026; published 24 February 2026)

In this work, we consider the possibility that the dynamical dark energy hinted at by recent Dark Energy Spectroscopic Instrument data may be mimicked by the effects of additional components in the universe, potentially arising from topological defects. We find that the data does not show a particular preference for the existence of cosmic strings. However, a domain wall contribution at the percent level can improve the fit, yielding a $\Delta\chi^2 = -1.72$ and $\Delta\text{DIC} = -0.94$ compared to the Λ CDM model (Λ CDM). The improvement indicates that topological defects remain a viable and interesting extension to Λ CDM, meriting further investigation with future cosmological data.

DOI: [10.1103/2m4c-1zl5](https://doi.org/10.1103/2m4c-1zl5)

I. INTRODUCTION

The driver of the accelerating expansion of our Universe is the most mystery in fundamental physics. In the standard model of cosmology, it is provided by the cosmological constant, which is equivalent to the vacuum energy of quantum fields and therefore is also known as the dark energy (DE). In this case, the equation of state parameter for dark energy, $w_{\text{DE}} = -1$. The equation of state parameter, w_{DE} can be extracted from the measurement of the evolution of the baryon acoustic oscillation (BAO) using large scale structure surveys. Recent results from the Dark Energy Spectroscopic Instrument (DESI) found significant deviation of the Hubble expansion rate from what is predicted by the standard Λ CDM model in their second data release (DR2) [1–3]. As shown in Fig. 1, we can see that the measured Hubble expansion rate is larger than what is predicted by the Λ CDM model (shown by the red curve) at the redshift $z \sim 0.5$ – 0.8 . If this deviation is physical, it indicates that energy density in addition to the Λ CDM model is injected into our Universe in this redshift region. This deviation can be explained by introducing evolving DE with intriguing dynamics [4–32], noncold dark matter [33,34], dynamical dark matter [35,36], dark matter-DE interactions [17,37–48],

nonvanishing cosmic curvature contribution [49], modified theories of gravity from various UV considerations [46,50–57], assuming existence of nontrivial local structures [58,59], and modifying the recombination history of the Universe [60].

The data suggests an evolving dark energy model with a phantomlike equation of state transitioning from $w < -1$ to $w > -1$ in recent times. In this work, instead of invoking an evolving dark energy component, we propose that there may be a missing part in the composition of our universe. In particular, the inclusion of topological defects can mimic the evolving dark energy.

Topological defects, such as cosmic strings and domain walls, evolve differently from dark energy and dark matter. For the frustrated domain walls [61,62] or cosmic strings [63,64], the equations of state satisfy,

$$w_{\text{td}} = \begin{cases} -\frac{2}{3}, & \text{domain wall} \\ -\frac{1}{3}, & \text{cosmic string} \end{cases}. \quad (1)$$

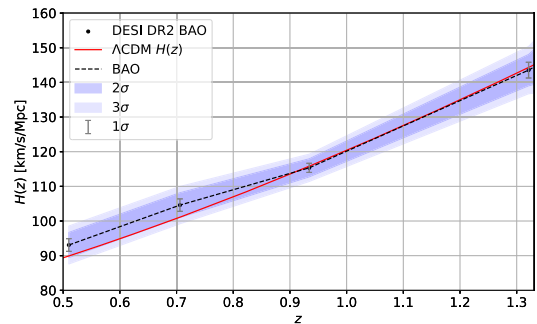


FIG. 1. Hubble expansion rate measured by the DESI-2 from $z = 0.5$ to $z = 1.35$.

* Contact author: anhp@mail.tsinghua.edu.cn

† Contact author: hanchch@mail.sysu.edu.cn

‡ Contact author: zhangbr22@mails.tsinghua.edu.cn

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

To fit the observed data, we consider the possibility that a non-negligible fraction of the present-day energy density of the Universe is attributed to topological defects. A substantial population of domain walls or cosmic strings is strongly constrained by current measurements of cosmic microwave background (CMB) anisotropies. These constraints typically require the cosmic string tension to satisfy $G\mu < \mathcal{O}(10^{-7})$ [65], and the phase transition associated with domain wall formation to occur at $\eta < \mathcal{O}(1)$ MeV [66,67]. These conditions translate into upper bounds on the fractional energy densities $\Omega_{\text{cs}} < \mathcal{O}(10^{-7})$ for cosmic strings and $\Omega_{\text{dw}} < \mathcal{O}(10^{-4})$ for domain walls.

However, such limits are generally derived under the assumption that the topological defects remain in the scaling regime, where their energy density redshifts efficiently with cosmic expansion. In contrast, frustrated domain walls or cosmic strings redshift more slowly—their energy density dilutes less rapidly than in the scaling case. For a fixed present-day fraction, frustrated defects would have contributed less to the total energy density at earlier times, resulting in weaker constraints from the CMB. Moreover, frustrated topological defects do not cluster or form large-scale structures, which suppresses their impact on CMB anisotropies. The constraints can be further relaxed if the defects enter the horizon only at late times in cosmic history. This requires the defects to have a sufficiently large correlation length. Taking these effects into account, it remains plausible that topological defects could contribute up to a percent-level fraction of the current energy density of the Universe. In this work, we investigate this possibility and quantify its implications.

II. THE EVOLUTION OF $H(z)$

In our setup, we assume a flat universe with $\Omega_k = 0$. Then the expansion rate of the universe can be written as

$$\frac{H^2(z)}{H_0^2} = \Omega_{\text{bc}}(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_\nu \frac{\rho_\nu(z)}{\rho_{\nu 0}} + \Omega_{\text{td}}(1+z)^{3(1+w_{\text{td}})} + \Omega_\Lambda, \quad (2)$$

where H_0 is the Hubble parameter today, $\Omega_{\text{bc}} = \Omega_b + \Omega_c$ denotes the current fractional density of baryons and cold

dark matter. Ω_γ and Ω_ν represent the current fractional densities of radiation and neutrinos, respectively. The total matter density is defined as $\Omega_{\text{m}0} = \Omega_{\text{bc}} + \Omega_\nu$ when neutrinos are nonrelativistic. We adopt the dark energy as the cosmological constant with fraction $\Omega_\Lambda = 1 - \Omega_{\text{m}0} - \Omega_{\text{td}} - \Omega_\gamma$.

We plot the ratio of the Hubble parameter of the topological-defect models to that of the Λ CDM model, with H_0 and $\omega_{b(c)} \equiv \Omega_{b(c)} h^2$ held fixed, as shown in Fig. 2. From the plot, a bump appears whose peak is near the scale factor $a \simeq 0.55 - 0.7$, corresponding to redshift $z \simeq 0.4 - 0.8$, consistent with the Hubble parameter increase measured by DESI DR2, as shown in Fig. 1.

In our model, the sole free parameter is the present-day fractional density of topological defects. By varying this parameter, we find that the amplitude of the bump increases with increasing defect fraction. This behavior is expected: topological defects redshift faster than the cosmological constant but slower than matter, so they are negligible at early times. However, since their present-day fraction is fixed, their fractional contribution exceeds that of the cosmological constant across a wide range of redshifts, thereby mitigating the decline of the Hubble parameter compared to a model with only matter and a cosmological constant. For comparison, in Fig. 1 we also show the Hubble rate for the Chevallier-Polarski-Linder parametrization (CPL) model, a similar bump appears when $a \simeq 0.7$ while a valley shows up when $a \simeq 0.4$.

To sample posteriors in parameter space, we employ the Metropolis-Hastings Markov chain Monte Carlo (MCMC) algorithm, using the cosmological inference framework Cobaya [68], which implements adaptive fast-slow-optimized MCMC samplers for Bayesian analysis. The theoretical predictions are based on a modified version of CAMB [69], which is integrated within Cobaya. To constrain the model parameters, we utilize measurements from both BAO and Type Ia supernovae (SNe). BAO data are taken from DESI DR2, while SNe measurements are drawn from three recent datasets: Pantheon+ [70,71], Union3 [72], and DESY5 [73]. All these datasets are incorporated into Cobaya as likelihoods.

We adopt the CMB-inferred values of $(\theta_*, \omega_b, \omega_{\text{bc}})_{\text{CMB}}$ as a correlated Gaussian distribution [1]. Correlated

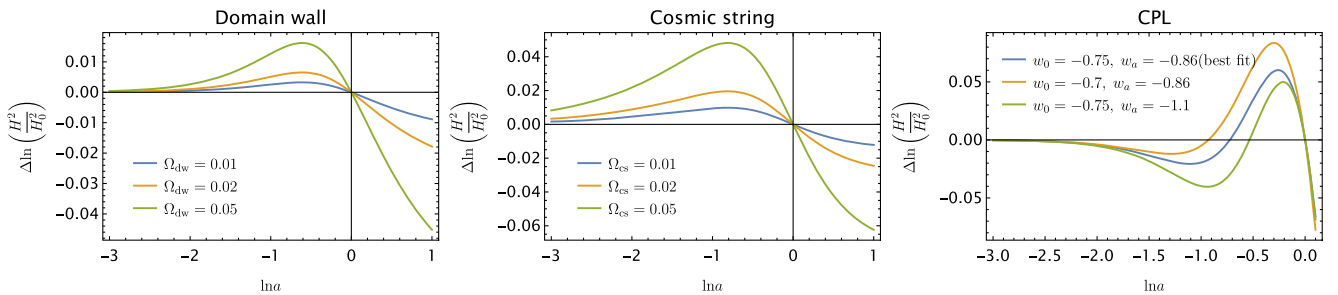


FIG. 2. Figure illustrating the difference of $\log(H^2/H_0^2)$ between topological defects and Λ CDM.

TABLE I. Parameter priors used in various dark energy parametrizations.

Model	Parameter	Prior
<i>Baseline</i>	ω_c	$\mathcal{U}[0.11, 0.13]$
	ω_b	$\mathcal{U}[0.021, 0.024]$
	$100\theta_{MC}$	$\mathcal{U}[1.03, 1.05]$
<i>Topological defects</i> + Λ CDM		
<i>Domain wall</i>	ω_{dw}	$\mathcal{U}[0, 0.05]$
<i>Cosmic string</i>	ω_{cs}	$\mathcal{U}[0, 0.05]$
$\Omega_k + \Lambda$ CDM	Ω_k	$\mathcal{U}[0, 0.05]$

Gaussian posteriors on the parameters $(\theta_*, \omega_b, \omega_{bc})$, obtained by marginalizing over the ISW and lensing contributions and other possible late-time effects, are used in our analysis. We incorporate this information in the form of a correlated Gaussian distribution, as a more model-independent and computationally efficient alternative to the full CMB likelihood, which we refer to in the following as $(\theta_*, \omega_b, \omega_{bc})_{CMB}$. We use the result performed by [1,74] based on the CamSpec CMB likelihood, which defines a compressed likelihood that can be achieved by the Gaussian mixture likelihood sector implemented in Cobaya with mean

$$\mu(\theta_*, \omega_b, \omega_{bc}) = \begin{pmatrix} 0.01041 \\ 0.02223 \\ 0.14208 \end{pmatrix}, \quad (3)$$

and the covariance matrix yields

$$\mathbf{C} = 10^{-9} \times \begin{pmatrix} 0.006621 & 0.12444 & -1.1929 \\ 0.12444 & 21.344 & -94.001 \\ -1.1929 & -94.001 & 1488.4 \end{pmatrix}. \quad (4)$$

Also, We adopt the Gelman–Rubin convergence diagnostic $R - 1 < 0.01$ [75] as the stopping criterion for all MCMC chains. After convergence is achieved, the first 30% of the samples are discarded as burn-in. The fitting result is shown in Table II.

The parameter priors adopted in this work are listed in Table I. Since the measurements of the parameters θ_* , ω_b , and ω_c are highly precise [76] (in the sampling, ω_{bc} acts as a derived quantity), and the MCMC sampling results (in terms of χ^2) are not sensitive to the choice of priors, we adopt narrower prior ranges for these three parameters compared to those used in [2]. This choice improves sampling efficiency while still ensuring that the prior ranges are sufficiently broad to encompass the Planck measurement uncertainties [76]—specifically, the prior range exceeds the central value by more than $\pm 5\sigma$ —and the variance of the likelihood in Eq. (4).

We also present the triangle plot of the posterior distributions of the parameters for different models (see Figs. 3 and 4). The data are analyzed and the plots are generated using GetDist [77].

 TABLE II. Fitting result for different models comparing with Λ CDM.

	+PantheonPlus	+Union3	+DES Y5
DESI DR2 BAO + $(\theta_*, \omega_b, \omega_{bc})_{CMB}$			
Domain wall + Λ CDM			
$\Delta\chi^2_{MAP}$	-0.064	-0.014	-1.72
$-2\Delta \log \mathcal{P}$	-6.05	-6.01	-7.71
Δ DIC	0.62	0.73	-0.94
$\ln B$	-0.69 ± 0.34	-0.31 ± 0.33	0.32 ± 0.32
Cosmic string + Λ CDM			
$\Delta\chi^2_{MAP}$	0.19	0.21	0.037
$-2\Delta \log \mathcal{P}$	-5.82	-5.80	-5.97
Δ DIC	1.71	1.83	1.40
$\ln B$	-2.45 ± 0.35	-3.09 ± 0.36	-2.93 ± 0.35
$\Omega_k + \Lambda$ CDM			
$\Delta\chi^2_{MAP}$	-4.55	-4.49	-5.10
$-2\Delta \log \mathcal{P}$	-10.54	-10.49	-11.09
Δ DIC	-2.88	-2.77	-3.47
$\ln B$	0.10 ± 0.36	-0.13 ± 0.36	-0.25 ± 0.35
CPL			
$\Delta\chi^2_{MAP}$	-7.40	-13.55	-17.75
$-2\Delta \log \mathcal{P}$	-1.40	-7.56	-11.76
Δ DIC	-6.78	-10.06	-14.13
$\ln B$	-1.62 ± 0.37	1.97 ± 0.36	3.30 ± 0.36

To identify the best-fit parameters and their associated χ^2 , we perform a minimization with iminuit [78] initialized at the maximum *a posteriori* (MAP) point of each MCMC chain. We calculate $\Delta\chi^2_{MAP}$, which is the reduction in the best-fit χ^2 relative to the Λ CDM.

$$\Delta\chi^2_{MAP} = -2\Delta \ln \mathcal{L} = -2[\ln \mathcal{L}_{MAP} - \ln \mathcal{L}_{MAP}^{\Lambda CDM}]. \quad (5)$$

Here, $\Delta\chi^2_{MAP}$ is twice the difference in negative log-likelihood values evaluated at the respective MAP points, and a more negative $\Delta\chi^2_{MAP}$ indicates a better fit. Moreover, we also calculated the difference in the negative logarithms of the posterior probabilities between the corresponding model and the standard model, denoted as $-2\Delta \log \mathcal{P}$.

In addition, we examine the deviance information criterion (DIC) [2,79,80], which is defined as

$$DIC \equiv D(\bar{\theta}) + 2p_D, \quad (6)$$

where θ is the set of sampling parameters, $p_D \equiv \overline{D(\theta)} - D(\bar{\theta})$. The DIC, comparing with χ^2_{MAP} , accounts for model complexity; models with smaller DIC values are preferred. DIC penalizes models through two components: the posterior mean deviance, $\bar{D}$, which measures goodness of fit; and the effective number of parameters, p_D . Because $\bar{D}$ typically decreases when additional parameters are included, the p_D term compensates by penalizing

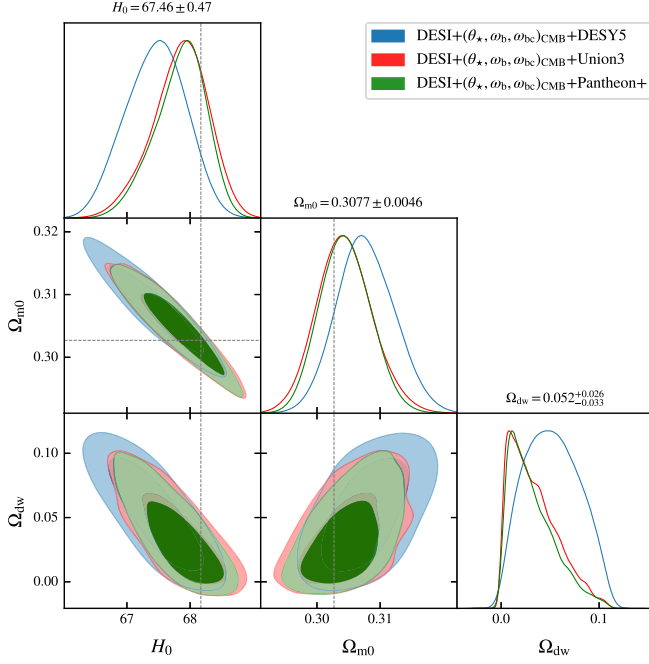


FIG. 3. Posterior distributions of parameters in the domain wall model combined with DESI, CMB, and supernovae. The model is with one sampling parameter Ω_{dw} . The blue contours indicate the constraint from DESY5, the red contours correspond to Union3 and the green contours are for the Pantheon+. The gray dashed lines correspond to the value of H_0 and $\Omega_{\text{m}0}$ of ΛCDM [1].

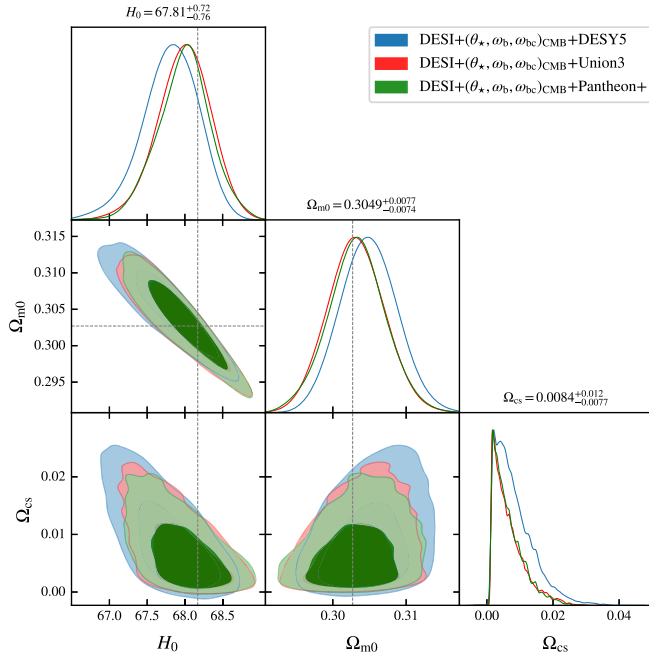


FIG. 4. Posterior distributions of parameters in the cosmic string model combined with DESI, CMB and supernovae. The model is with one sampling parameter Ω_{cs} . The blue contours indicate the constraint from DESY5, the red contours correspond to Union3, and the green contours are for the Pantheon+. The gray dashed lines correspond to the value of H_0 and $\Omega_{\text{m}0}$ of ΛCDM [1].

complexity, thereby favoring models with fewer effective parameters.

To compare the models, we compute the Bayes factors using the nested sampler PolyChord [81,82], which is integrated into Cobaya. The Bayesian evidence is then estimated using the ANESTHETIC package [83]. The Bayes factor of two models is defined as the ratio of their evidence $\mathcal{Z}$ under a given dataset: $B = \mathcal{Z}_1/\mathcal{Z}_2$, where the evidence (marginal likelihood) is evaluated as

$$\mathcal{Z} = \int \mathcal{L}(\theta)\pi(\theta)d\theta, \quad (7)$$

where $\mathcal{L}(\theta)$ is the likelihood and $\pi(\theta)$ is the prior. And we calculate the logarithm of the evidence, where $\ln B = \Delta \ln \mathcal{Z}$. for each model. Unlike the traditional $\Delta\chi^2$ criterion, which compares only the maximum-likelihood values and typically assumes nested models and Gaussian errors, $\Delta \ln \mathcal{Z}$ automatically incorporates the full parameter space volume, thus penalizing unnecessary complexity and implementing Occam's razor in a principled way. As a result, $\Delta \ln \mathcal{Z}$ remains valid even for non-nested models or non-Gaussian likelihoods, yielding a more robust and probabilistically consistent measure of model preference.

In summary, negative values of $\Delta\chi^2_{\text{MAP}}$ indicate that the model achieves a better best fit χ^2 than ΛCDM ; a negative ΔDIC indicates that the model is preferred according to the deviance information criterion; and $\ln B > 0$ constitutes Bayes evidence in favor of the model, whereas $\ln B < 0$ indicates evidence against it, according to the Jeffreys scale. Based on the values of these quantities in Table II, the corresponding results are discussed as follows:

For the domain-wall model ($w = -2/3$), we find that, when combined with the Pantheon + and Union3 supernova samples, it yields a slightly better fit than the ΛCDM model. When combined with the DESY5 dataset, even a domain-wall contribution at the few-percent level can improve the fit, giving $\Delta\chi^2 = -1.72$ compared to ΛCDM , suggesting a mild preference for the domain-wall model. Considering the DIC, the combination with Pantheon + and Union3 data yields $\Delta\text{DIC} \approx +0.6$ to $+0.7$, indicating that the data does not particularly favor the increased complexity of the model. In contrast, the combination with DESY5 gives $\Delta\text{DIC} = -0.94$, implying that, after penalizing model complexity, the domain-wall extension is actually favored. A similar trend is also observed in the logarithmic Bayes factor, $\ln B$.

This preference arises because a network of domain walls with equation of state $w = -2/3$ and present-day fractional density $\Omega_{\text{dw}} \simeq 5\%$ (see Fig. 3) behaves like an additional fluid that redshifts more slowly than matter but more rapidly than a cosmological constant. This enables a transient phase of cosmic acceleration, which can modestly improve the fit to supernova data. Overall, we find that a model including a few-percent domain-wall component can

achieve up to $\Delta\chi^2_{\text{MAP}} \simeq -1.72$ when combining BAO, CMB, and supernova datasets (DESY5), suggesting that such a modification to Λ CDM is mildly preferred by current data and merits consideration as a viable extension.

For the cosmic string model, we find $\Delta\chi^2_{\text{MAP}} = +0.19$, $+0.2$, and $+0.037$ when combined with the Pantheon+, Union3, and DESY5 supernova datasets, respectively. These results indicate that the data does not exhibit a significant preference for the presence of cosmic strings. This conclusion is also supported by Fig. 4, which shows a preference for a low or negligible cosmic string contribution to the energy budget of the universe. The situation worsens when model complexity is taken into account. The deviance information criterion yields $\Delta\text{DIC} \approx 1.7$, 1.8 , and 1.4 for the Pantheon+, Union3, and DESY5 datasets, respectively, suggesting that the added complexity of the cosmic string model is not justified by the data. A similar conclusion is drawn from the logarithmic Bayes factor $\ln B$.

A network of long cosmic strings behaves like a fluid with an equation of state $w = -1/3$, corresponding to an energy density that redshifts as $\rho_{\text{cs}} \propto a^{-2}$. Such a component would contribute a term to the Hubble parameter of the form $\Omega_{\text{cs}}(1+z)^2$. Although one might expect this additional contribution to improve the fit—particularly as suggested by Fig. 2—the data does not show a meaningful preference for the existence of cosmic strings in our universe. Note that our result is consistent with that of the recent work [84] which studies several case of cosmic strings.

For comparison, we also present results for an alternative extension of the Λ CDM model: the $\Omega_k + \Lambda$ CDM framework. Although both cosmic strings and spatial curvature Ω_k scale as a^{-2} , they are fundamentally different in nature. Spatial curvature is a geometric property that characterizes the overall flatness of spacetime and enters the Friedmann equation as a term evolving like a^{-2} . However, its influence goes beyond modifying the expansion rate: while cosmic strings affect only the Hubble parameter $H(z)$, spatial curvature also alters the functional form of distance-related observables, such as the transverse comoving distance.

This distinction is clearly reflected in our fitting results. Compared to the cosmic string model, the $\Omega_k + \Lambda$ CDM extension consistently yields $\Delta\chi^2_{\text{MAP}} \approx -4$ to -5 . It also results in $\Delta\text{DIC} \approx -3$, suggesting that, after accounting for model complexity, the curved-universe extension is statistically favored. However, the Bayes factor remains inconclusive, with $\ln B \approx 0 \pm 0.36$, providing strong support neither for nor against the inclusion of spatial curvature. In Bayesian terms, the data are compatible with a small, nonzero Ω_k , but do not compellingly require its presence.

For comparison, Table II also presents the fitting results for the CPL model. A noticeable improvement is obtained with the CPL parametrization. When combined with the DES Y5

dataset, it yields $\Delta\chi^2 = -17.75$ and $\Delta\text{DIC} = -14.13$ at the best-fit point relative to Λ CDM. Although the CPL model currently provides the best fit to the data, it is still premature to claim firm evidence for dynamical dark energy.

III. CONCLUSION

In this work, we studied the potential contribution of topological defects—specifically domain walls and cosmic strings—to the energy content of the universe as a means to explain the mild tension observed in the DESI DR2 BAO data. Instead of invoking a time-varying dark energy component, we proposed that these defects could mimic dynamical effects through their distinct redshift behavior.

Our analysis, based on a combination of DESI DR2, CMB compressed likelihoods, and various Type Ia supernova datasets, revealed no significant evidence for cosmic strings. In contrast, we found that including a domain wall component at the percent level modestly improves the fit to the data. When combined with the DESY5 supernova dataset, the domain wall model yields a best-fit improvement of $\Delta\chi^2 = -1.72$ over Λ CDM and shows a slight preference in terms of the DIC and Bayes factor.

This result suggests that domain walls, which redshift more slowly than matter but faster than a cosmological constant, can effectively mimic an evolving dark energy component in the relevant redshift range. While not conclusive, the improvement indicates that topological defects—particularly domain walls—remain a viable and interesting extension to Λ CDM, meriting further investigation with future cosmological data.

ACKNOWLEDGMENTS

The work of H. A. is supported in part by the National Key R&D Program of China under Grants No. 2021YFC2203100 and No. 2017YFA0402204, the NSFC under Grants No. 12475107 and No. 12525506, and the Tsinghua University Dushi Program. The work of C. H. is supported by the National Key R&D Program of China under Grant No. 2023YFA1606100 and by the National Natural Science Foundation of China under Grant No. 12435005. C. H. acknowledges supports from the Sun Yat-Sen University Science Foundation, the Fundamental Research Funds for the Central Universities at Sun Yat-sen University under Grant No. 24qnp117, and the Key Laboratory of Particle Astrophysics and Cosmology (MOE) of Shanghai Jiao Tong University.

DATA AVAILABILITY

The data that support the findings of this article are openly available [85], embargo periods may apply.

- [1] M. Abdul Karim *et al.* (DESI Collaboration), DESI DR2 results II: Measurements of baryon acoustic oscillations and cosmological constraints, *Phys. Rev. D* **112**, 083515 (2025).
- [2] K. Lodha *et al.* (DESI Collaboration), Extended dark energy analysis using DESI DR2 BAO measurements, *Phys. Rev. D* **112**, 083511 (2025).
- [3] G. Gu *et al.* (DESI Collaboration), Dynamical dark energy in light of the DESI DR2 baryonic acoustic oscillations measurements, *Nat. Astron.* **9**, 1879 (2025).
- [4] Z.-K. Guo, Y.-S. Piao, X.-M. Zhang, and Y.-Z. Zhang, Cosmological evolution of a quintom model of dark energy, *Phys. Lett. B* **608**, 177 (2005).
- [5] W. Hu, Crossing the phantom divide: Dark energy internal degrees of freedom, *Phys. Rev. D* **71**, 047301 (2005).
- [6] L. Huang, R.-G. Cai, and S.-J. Wang, The DESI DR1/DR2 evidence for dynamical dark energy is biased by low-redshift supernovae, *Sci. China Phys. Mech. Astron.* **68**, 100413 (2025).
- [7] D. Oriti and X. Pang, Late-time cosmic acceleration from quantum gravity, *Classical Quantum Gravity* **42**, 155003 (2025).
- [8] A. N. Ormondroyd, W. J. Handley, M. P. Hobson, and A. N. Lasenby, Comparison of dynamical dark energy with Λ CDM in light of DESI DR2, [arXiv:2503.17342](#).
- [9] H. N. Luu, Y.-C. Qiu, and S. H. H. Tye, Dynamical dark energy from an ultralight axion, *Phys. Rev. D* **112**, 023524 (2025).
- [10] J. Lee, K. Murai, F. Takahashi, and W. Yin, Isotropic cosmic birefringence from string axion domain walls without cosmic strings, and DESI results, *Phys. Rev. D* **112**, 043538 (2025).
- [11] S. Nakagawa, Y. Nakai, Y.-C. Qiu, and M. Yamada, Interpreting cosmic birefringence and DESI data with evolving axion in Λ CDM, *Phys. Lett. B* **868**, 139774 (2025).
- [12] L. A. Anchordoqui, I. Antoniadis, and D. Lust, S-dual quintessence, the swampland, and the DESI DR2 results, *Phys. Lett. B* **868**, 139632 (2025).
- [13] S. Hur, V. Jejjala, M. J. Kavcic, D. Minic, and T. Takeuchi, Dynamical dark energy, dual spacetime, and DESI, *J. Cosmol. Astropart. Phys.* **11** (2025) 054.
- [14] Y.-H. Pang, X. Zhang, and Q.-G. Huang, The impact of the Hubble tension on the evidence for dynamical dark energy, *Sci. China Phys. Mech. Astron.* **68**, 280410 (2025).
- [15] S. Nesseris, Y. Akrami, and G. D. Starkman, To CPL, or not to CPL? What we have not learned about the dark energy equation of state, [arXiv:2503.22529](#).
- [16] E. Chaussidon *et al.*, Early time solution as an alternative to the late time evolving dark energy with DESI DR2 BAO, *Phys. Rev. D* **112**, 063548 (2025).
- [17] C. You, D. Wang, and T. Yang, Dynamical dark energy implies a coupled dark sector: Insights from DESI DR2 via a data-driven approach, *Phys. Rev. D* **112**, 043503 (2025).
- [18] D. A. Kessler, L. A. Escamilla, S. Pan, and E. Di Valentino, One-parameter dynamical dark energy: Hints for oscillations, [arXiv:2504.00776](#).
- [19] Y. Akrami, G. Alestas, and S. Nesseris, Has DESI detected exponential quintessence?, [arXiv:2504.04226](#).
- [20] K. Murai and F. Takahashi, Why $w \neq -1$? anthropic selection in a Λ + axion dark energy model, *Phys. Rev. D* **112**, 103501 (2025).
- [21] R. de Souza, G. Rodrigues, and J. Alcaniz, Thawing quintessence and transient cosmic acceleration in light of DESI, *Phys. Rev. D* **112**, 083533 (2025).
- [22] B. R. Dinda and R. Maartens, Physical vs phantom dark energy after DESI: Thawing quintessence in a curved background, *Mon. Not. R. Astron. Soc.* **542**, L31 (2025).
- [23] E. M. Teixeira, W. Giarè, N. B. Hogg, T. Montandon, A. Poudou, and V. Poulin, Implications of distance duality violation for the H_0 tension and evolving dark energy, *Phys. Rev. D* **112**, 023515 (2025).
- [24] W. J. Wolf, C. García-García, T. Anton, and P. G. Ferreira, Assessing cosmological evidence for non-minimal coupling, *Phys. Rev. Lett.* **135**, 081001 (2025).
- [25] C. Li, J. Wang, D. Zhang, E. N. Saridakis, and Y.-F. Cai, Quantum gravity meets DESI: Dynamical dark energy in light of the trans-Planckian censorship conjecture, *J. Cosmol. Astropart. Phys.* **08** (2025) 041.
- [26] W. Lin, L. Visinelli, and T. T. Yanagida, Testing quintessence axion dark energy with recent cosmological results, *J. Cosmol. Astropart. Phys.* **10** (2025) 023.
- [27] A. Smith, P. Brax, C. van de Bruck, C. P. Burgess, and A.-C. Davis, Screened axio-dilaton cosmology: Novel forms of early dark energy, *Eur. Phys. J. C* **85**, 1062 (2025).
- [28] D. Wang, Quintessence dark matter, [arXiv:2505.08154](#).
- [29] L. Csillag and E. Jensko, Geometric formulation of k -essence and late-time acceleration, [arXiv:2505.15975](#).
- [30] Z. Bayat and M. P. Hertzberg, Examining quintessence models with DESI data, *J. Cosmol. Astropart. Phys.* **08** (2025) 065.
- [31] J. W. Moffat and E. J. Thompson, Dynamical dark energy at late time Λ CDM, [arXiv:2505.18900](#).
- [32] Y. Cai, X. Ren, T. Qiu, M. Li, and X. Zhang, The quintom theory of dark energy after DESI DR2, [arXiv:2505.24732](#).
- [33] U. Kumar, A. Ajith, and A. Verma, Evidence for non-cold dark matter from DESI DR2 measurements, [arXiv:2504.14419](#).
- [34] M. Abedin, L. A. Escamilla, S. Pan, E. Di Valentino, and W. Yang, When dark matter heats up: A model-independent search for non-cold behavior, *Phys. Rev. D* **112**, 123537 (2025).
- [35] D. Wang, Evidence for dynamical dark matter, [arXiv:2504.21481](#).
- [36] X. Chen and A. Loeb, Evolving dark energy or evolving dark matter?, *J. Cosmol. Astropart. Phys.* **07** (2025) 059.
- [37] G. Huey and B. D. Wandelt, Interacting quintessence. The coincidence problem and cosmic acceleration, *Phys. Rev. D* **74**, 023519 (2006).
- [38] S. Das, P. S. Corasaniti, and J. Khoury, Super-acceleration as signature of dark sector interaction, *Phys. Rev. D* **73**, 083509 (2006).
- [39] A. Aboubrahim and P. Nath, Upper limits on dark energy-dark matter interaction from DESI DR2 in a field-theoretic analysis, *J. Cosmol. Astropart. Phys.* **10** (2025) 081.
- [40] A. Chakraborty, P. K. Chanda, S. Das, and K. Dutta, DESI results: Hint towards coupled dark matter and dark energy, *J. Cosmol. Astropart. Phys.* **11** (2025) 047.
- [41] J. Khoury, M.-X. Lin, and M. Trodden, Apparent $w < -1$ and a lower S_8 from dark axion and dark baryons interactions, *Phys. Rev. Lett.* **135**, 181001 (2025).

- [42] R. Shah, P. Mukherjee, and S. Pal, Interacting dark sectors in light of DESI DR2, *Mon. Not. R. Astron. Soc.* **542**, 2936 (2025).
- [43] E. Silva, M. A. Sabogal, M. S. Souza, R. C. Nunes, E. Di Valentino, and S. Kumar, New constraints on interacting dark energy from DESI DR2 BAO observations, *Phys. Rev. D* **111**, 123511 (2025).
- [44] S. Pan, S. Paul, E. N. Saridakis, and W. Yang, Interacting dark energy after DESI DR2: A challenge for Λ CDM paradigm?, *Phys. Rev. D* **113**, 023515 (2026).
- [45] D. Shlivko, P. J. Steinhardt, and C. L. Steinhardt, Optimal parameterizations for observational constraints on thawing dark energy, *J. Cosmol. Astropart. Phys.* **06** (2025) 054.
- [46] Y. Yang, Q. Wang, X. Ren, E. N. Saridakis, and Y.-F. Cai, Modified gravity realizations of quintom dark energy after DESI DR2, *Astrophys. J.* **988**, 123 (2025).
- [47] N. Cruickshank, R. Crittenden, K. Koyama, and M. Bruni, Forecasts for interacting dark energy with time-dependent momentum exchange, *J. Cosmol. Astropart. Phys.* **10** (2025) 052.
- [48] M. van der Westhuizen, D. Figueruelo, R. Thubisi, S. Sahl, A. Abebe, and A. Paliathanasis, Compartmentalization in the dark sector of the universe after DESI DR2 BAO data, *Phys. Dark Universe* **50**, 102107 (2025).
- [49] B. R. Dinda, Cosmic curvature on large-scale structures with homogeneous dark energy, *Phys. Rev. D* **111**, 103533 (2025).
- [50] X. Zhu, R. Xu, and D. Xu, Bumblebee cosmology: Tests using distance- and time-redshift probes, *Phys. Dark Universe* **50**, 102127 (2025).
- [51] J. Pan and G. Ye, Non-minimally coupled gravity constraints from DESI DR2 data, [arXiv:2503.19898](https://arxiv.org/abs/2503.19898).
- [52] A. Paliathanasis, Dark energy within the generalized uncertainty principle in light of DESI DR2, *J. Cosmol. Astropart. Phys.* **09** (2025) 067.
- [53] F. Plaza and L. Kraiselburd, Testing $f(R)$ -gravity models with DESI DR2 2025-BAO and other cosmological data, *Phys. Rev. D* **112**, 023554 (2025).
- [54] A. Paliathanasis, Testing non-coincident $f(Q)$ -gravity with DESI DR2 BAO and GRBs, *Phys. Dark Universe* **49**, 101993 (2025).
- [55] M. Scherer, M. A. Sabogal, R. C. Nunes, and A. De Felice, Challenging Λ CDM: 5σ evidence for a dynamical dark energy late-time transition, *Phys. Rev. D* **112**, 043513 (2025).
- [56] J. Smirnov, Dynamical dark energy emerges from massive gravity, [arXiv:2505.03870](https://arxiv.org/abs/2505.03870).
- [57] M. Postolak, Non-minimally coupled scalar field dark sector of the universe: In-depth (Einstein frame) case study, [arXiv:2505.07456](https://arxiv.org/abs/2505.07456).
- [58] I. Banik and V. Kalaitzidis, Testing the local void hypothesis using baryon acoustic oscillation measurements over the last twenty years, *Mon. Not. R. Astron. Soc.* **540**, 545 (2025).
- [59] J. W. Moffat, Void and density walls inhomogeneous cosmic web and dark energy, [arXiv:2503.20912](https://arxiv.org/abs/2503.20912).
- [60] S. H. Mirpoorian, K. Jedamzik, and L. Pogosian, Is dynamical dark energy necessary? DESI BAO and modified recombination, *J. Cosmol. Astropart. Phys.* **12** (2025) 050.
- [61] R. A. Battye, M. Bucher, and D. Spergel, Domain wall dominated universes, [arXiv:astro-ph/9908047](https://arxiv.org/abs/astro-ph/9908047).
- [62] P. Pina Avelino, C. J. A. P. Martins, J. Menezes, R. Menezes, and J. C. R. E. Oliveira, Frustrated expectations: Defect networks and dark energy, *Phys. Rev. D* **73**, 123519 (2006).
- [63] T. Vachaspati and A. Vilenkin, Formation and evolution of cosmic strings, *Phys. Rev. D* **30**, 2036 (1984).
- [64] T. Vachaspati and A. Vilenkin, Evolution of cosmic networks, *Phys. Rev. D* **35**, 1131 (1987).
- [65] P. A. R. Ade *et al.* (Planck Collaboration), Planck 2013 results. XXV. Searches for cosmic strings and other topological defects, *Astron. Astrophys.* **571**, A25 (2014).
- [66] A. Lazanu, C. J. A. P. Martins, and E. P. S. Shellard, Contribution of domain wall networks to the CMB power spectrum, *Phys. Lett. B* **747**, 426 (2015).
- [67] L. Sousa and P. P. Avelino, Cosmic microwave background anisotropies generated by domain wall networks, *Phys. Rev. D* **92**, 083520 (2015).
- [68] J. Torrado and A. Lewis, Cobaya: Code for Bayesian analysis of hierarchical physical models, *J. Cosmol. Astropart. Phys.* **05** (2021) 057.
- [69] A. Lewis, A. Challinor, and A. Lasenby, Efficient computation of CMB anisotropies in closed FRW models, *Astrophys. J.* **538**, 473 (2000).
- [70] D. Scolnic *et al.*, The Pantheon + Analysis: The full data set and light-curve release, *Astrophys. J.* **938**, 113 (2022).
- [71] D. Brout *et al.*, The Pantheon + Analysis: Cosmological constraints, *Astrophys. J.* **938**, 110 (2022).
- [72] D. Rubin *et al.*, Union Through UNITY: Cosmology with 2,000 SNe using a unified Bayesian framework, *Astrophys. J.* **986**, 231 (2025).
- [73] T. M. C. Abbott *et al.* (DES Collaboration), The dark energy survey: Cosmology results with ~ 1500 new high-redshift Type Ia supernovae using the full 5 yr data set, *Astrophys. J. Lett.* **973**, L14 (2024).
- [74] P. Lemos and A. Lewis, CMB constraints on the early Universe independent of late-time cosmology, *Phys. Rev. D* **107**, 103505 (2023).
- [75] A. Gelman and D. B. Rubin, Inference from iterative simulation using multiple sequences, *Stat. Sci.* **7**, 457 (1992).
- [76] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); **652**, C4(E) (2021).
- [77] A. Lewis, GetDist: A Python package for analysing Monte Carlo samples, *J. Cosmol. Astropart. Phys.* **08** (2025) 025.
- [78] H. Dembinski *et al.*, [scikit-hep/iminuit](https://scikit-hep.org/iminuit), 10.5281/zenodo.3949207 (2025).
- [79] D. J. Spiegelhalter, N. G. Best, B. P. Carlin, and A. van der Linde, Bayesian measures of model complexity and fit, *J. R. Stat. Soc. Ser. B* **64**, 583 (2002).
- [80] A. R. Liddle, Information criteria for astrophysical model selection, *Mon. Not. R. Astron. Soc.: Lett.* **377**, L74 (2007).
- [81] W. J. Handley, M. P. Hobson, and A. N. Lasenby, PolyChord: Nested sampling for cosmology, *Mon. Not. R. Astron. Soc.* **450**, L61 (2015).

-
- [82] W. J. Handley, M. P. Hobson, and A. N. Lasenby, PolyChord: Next-generation nested sampling, *Mon. Not. R. Astron. Soc.* **453**, 4385 (2015).
- [83] W. Handley, ANESTHETIC: Nested sampling visualisation, *J. Open Source Software* **4**, 1414 (2019).
- [84] H. Cheng, E. Di Valentino, and L. Visinelli, Cosmic strings as dynamical dark energy: Novel constraints, [arXiv:2505.22066](#).
- [85] All raw data corresponding to the findings in this manuscript —10.1103/2m4c-1zl5. Embargo applies before 01Feb26.