Thermal friction as a solution to the Hubble tension

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A new component added to the standard model of cosmology that behaves like a cosmological constant at early times and then dilutes away as radiation or faster can resolve the Hubble tension. We show that a rolling axion coupled to a non-Abelian gauge group exhibits the behavior of such an extra component at the background level and can present a natural particle-physics model solution to the Hubble tension. We compare the contribution of this bottom-up model to the phenomenological fluid approximation and determine that CMB observables sensitive only to the background evolution of the Universe are expected to be similar in both cases, strengthening the case for this model to provide a viable solution to the Hubble tension.

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I. INTRODUCTION

The tremendously successful standard model of cosmology assumes a flat universe, cold dark matter (CDM) and cosmological-constant dark energy Λ. This ΛCDM model correctly describes numerous observables including the complex structure of the cosmic microwave background (CMB) spectra [1,2]. However, its predictions for the current rate H_0 of expansion of the Universe based on the CMB are discrepant with the most precise direct measurements in the local universe at $> 4\sigma$ [3–6]. With no obvious systematic cause in sight [7–17], this worsening tension has inspired many theorists to postulate new physics beyond the ΛCDM model [[4,18–21] for e.g., and references therein]. However, few solutions exist [19,22–26] that simultaneously resolve the Hubble tension while also providing a good fit to all observables.

One of the more successful solutions is the addition of an early dark energy (EDE) component [22–24,27], disjoint from the late-time dark energy. This component behaves like a cosmological constant at early times, then dilutes away as fast or faster than radiation at some critical redshift z_c, localizing its influence on cosmology around z_c. It increases the prerecombination expansion rate, decreasing the size r_s of the sound horizon. The CMB inference of H_0 is based on r_s and its angular size θ_* on the surface of last scatter. Precise observations of θ_* combined with a ΛCDM-based deduction of r_s determine H_0 as $\theta_* \sim r_s H_0$. Hence, a theory that predicts a smaller r_s also infers a greater H_0 to preserve the precisely measured θ_*, alleviating the Hubble tension. It was proposed as a phenomenological solution, the dynamics of which could emerge from various particle-physics models [23–25,28–30].

In this paper, we present a dynamical particle-physics model that could solve the Hubble tension, which at the background level, mimics the evolution of early dark energy. This model, the "dissipative axion" (DA), is presented in Sec. II. Although we leave the details of the perturbations of this model to future work, in Sec. III, we argue why the background dynamics of this model are promising and indicate that the DA can form an extra dark energy component that resolves the Hubble tension. We conclude in Sec. IV, where we discuss the broader implications of this model and the way forward.

II. MODEL

We add a pure dark non-Abelian gauge group [SU(2)] and an axion ϕ to the Standard Model particle content. The dark gauge bosons interact with ϕ via a CP-odd coupling,

$$\mathcal{L}_{\rm int} = \frac{\alpha}{16\pi}\frac{\phi}{f}\tilde{F}^{\mu\nu}_a F^a_{\mu\nu}, \tag{1}$$

where $F^a_{\mu\nu}$ ($\tilde{F}^a_{\mu\nu} = \epsilon^{\mu\nu\alpha\beta}F^a_{\alpha\beta}$) is the field strength of the dark gauge bosons and $\alpha = \frac{g^2}{4\pi}$, where g is the gauge coupling of the dark group. The dark sector is decoupled from the standard model. We give the axion, which is displaced from its minimum, a simple UV-potential,[1]

[1] The IR potential from the confining group is rapidly suppressed at temperatures above the confining scale, and we have checked that its contribution is subdominant for our parameters.

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$$V(\phi) = \frac{1}{2} m^2 \phi^2. \tag{2}$$

This potential intuitively illustrates the dynamics of our model, as the axion is essentially an overdamped harmonic oscillator. The interaction term $\mathcal{L}_{\rm int}$ adds an additional friction $\Upsilon(T_{\rm dr})$ to the equation of motion, dissipating energy through the production of dark radiation $\rho_{\rm dr}$ which is comprised of dark gauge bosons, where $T_{\rm dr}$ is the temperature of the dark radiation. In the small coupling limit ($\alpha \ll 1$), $m \ll \alpha^2 T_{\rm dr}$, and this friction can be inferred from the sphaleron rate for a pure non-Abelian gauge group [31–33] and scales as

$$\Upsilon(T_{\rm dr}) = \kappa \alpha^5 \frac{T_{\rm dr}^3}{f^2}, \tag{3}$$

where κ is an O(10) number[2] with weak dependence on α and $f > T_{\rm dr}$. The following equations of motion then describe the homogeneous evolution of the axion-radiation system:

$$\ddot{\phi} + (3H + \Upsilon(T_{\rm dr}))\dot{\phi} + m^2\phi = 0$$
$$\dot{\rho}_{\rm dr} + 4H\rho_{\rm dr} = \Upsilon(T_{\rm dr})\dot{\phi}^2, \tag{4}$$

where $\rho_{\rm dr} = \frac{\pi^2}{30} g_* T_{\rm dr}^4$ and $g_* = 7$ denotes the relativistic degrees of freedom in the new dark sector. [$g_* = 2(N^2 - 1) + 1$ for a general SU(N), where the factor of 2 accounts for two gauge boson polarizations per gauge boson ($N^2 - 1$) and the axion contributes 1 additional degree of freedom.]

In the original EDE work, an oscillating scalar field subject only to Hubble friction had been proposed, whose energy must dilute like radiation or faster after the field becomes dynamical in order to diminish the Hubble tension. This requirement places rigid demands on the scalar-field potential $V \propto (1 - \cos\frac{\phi}{f})^n$ considered by [25] (or $V \propto \phi^{2n}$ as in [23]) with $n \geq 2$. These potentials do not easily emerge from a UV-complete theory without extreme fine-tuning. Other proposed phenomenological EDE candidates [24] have similar fine-tuning issues.

In our DA model, the particle-production friction $\Upsilon \gg m, 3H$, overdamps the motion of the scalar field. Thus, because the field is not oscillating, its dynamics are not sensitive to the potential $V(\phi)$. Instead, the friction Υ extracts energy from the scalar field into the dark radiation, which automatically dilutes away as a^{-4}.

We approximate the solution to the equation of motion Eq. (4) as

$$\phi(z) \approx \phi_0 e^{-\frac{m^2}{H(z)\Upsilon(z)}}, \tag{5}$$

which is the solution to an overdamped oscillator where we approximated $t \simeq H(z)^{-1}$. Equation (5) illustrates that the DA begins to roll faster when $\frac{\Upsilon(z_d)}{m^2} \equiv H(z_d)$, where z_d denotes the redshift at which the axion field becomes dynamical. At high redshifts ($z \gg z_d$) the axion is slowly rolling, building up to a steady-state temperature on time scales of order Υ^{-1} in the dark sector,

$$T_{\rm dr}(z) \approx \left(\frac{m^4 f^2 \phi^2(z)}{2\frac{\pi^2}{30} g_* \kappa \alpha^5 H(z)} \right)^{\frac{1}{7}}, \tag{6}$$

by continuously extracting energy from the rolling field [34]. As the field begins to roll faster, the temperature $T_{\rm dr}$ in the dark sector rises steadily, and the field continuously dumps its energy into the dark radiation bath. However, due to the weak dependence of the temperature on the background quantities, this change is O(1). Therefore, approximating the friction $\Upsilon(z)$ as roughly constant does not change the qualitative behavior of our model at the background level, as we discuss in more detail in Sec. III. Eventually, as the axion energy depletes, the source term $\Upsilon\dot{\phi}^2$ becomes smaller than $4H\rho_{\rm dr}$, leading to a decrease in temperature $T_{\rm dr}$ until $\Upsilon\dot{\phi}^2$ becomes negligible, and the dark radiation dilutes away as a^{-4}.

The generation of a steady-state temperature is independent of the presence of an initial dark temperature, as even starting with temperature fluctuations of the order of Hubble is sufficient to rapidly build up to the temperature in Eq. (6) [34]. Indeed, the main features of the DA are universal in the presence of any large friction [$\Upsilon \gg H(z)$] for $\Upsilon \propto T^p$ with $p < 4$. The minimal model presented here has been explored in more detail [34] in the context of warm inflation [35–40].

III. BACKGROUND DYNAMICS

Having laid the groundwork for the background evolution of the DA, we turn to its ability to mimic EDE and draw comparisons with the best-fit parameters of Ref. [[22] hence forth labeled P18]. The particle setup in Sec. II results in a rolling scalar field that behaves like a cosmological constant at early times plus a dark radiation component. The total contribution $\rho_{\rm DA}$ to an EDE-like component is then given by their sum,

$$\rho_{\rm DA}(z) = \rho_\phi(z) + \rho_{\rm dr}(z), \tag{7}$$

where $\rho_\phi(z) \approx \frac{1}{2} m^2 \phi^2(z)$.[3] At very early times, the radiation component is subdominant, and ϕ is essentially frozen, acting like a cosmological constant giving

$$\rho_{\rm DA}(z \gg z_d) \approx \frac{1}{2} m^2 \phi_0^2, \tag{8}$$

[2]For a general SU(N) κ increases with N. For details see [32].

[3]The kinetic energy component of ϕ is negligible due to the large friction term.

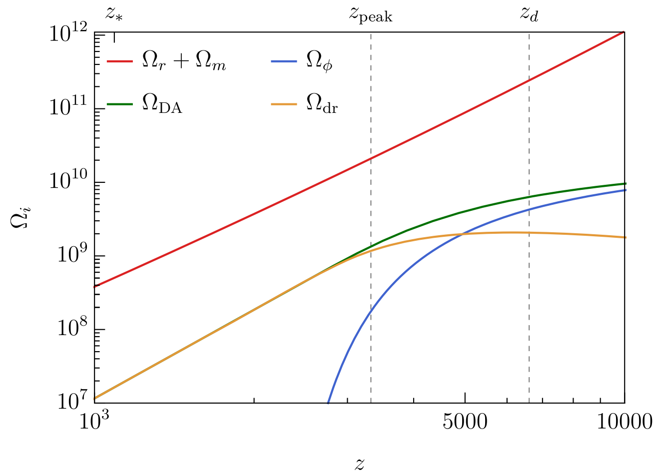

FIG. 1. The fractional energy densities $\Omega_i = \rho_i/\rho_{\rm crit}$ of the different components in the DA and those in a ΛCDM universe, where $\rho_{\rm crit}$ is the critical density today. The total DA contribution (green) is a sum of its subcomponents. At early times ($z \gg z_d$), the energy density Ω_ϕ in the scalar field (blue) is roughly constant and the dark radiation component $\Omega_{\rm dr}$ (yellow) is subdominant. At intermediate times ($z_{\rm peak} < z < z_d$), the dark radiation $\Omega_{\rm dr}$ transitions to become dominant as Ω_ϕ drops. Shortly after $T_{\rm dr}$ reaches a maximum, the total fractional DA energy density peaks at redshift $z_{\rm peak}$.

which is a function of only the axion potential and its initial conditions. Sometime after the axion thaws ($z < z_d$), the dark radiation becomes the dominant contributor to EDE as illustrated in Fig. 1. The DA constitutes a total fraction,

$$f_{\rm DA}(z) = \frac{\rho_{\rm DA}(z)}{\rho_m(z) + \rho_r(z) + \rho_{\rm DA}(z)} \tag{9}$$

of the energy density of the Universe, where ρ_m and ρ_r denote the matter and radiation densities. This fraction reaches a maximum at $z_{\rm peak}$. Relating this to the "critical redshift" z_c of the EDE as defined in P18, their best fit $z_c = 5345$[4] for the EDE that dilutes as radiation, which corresponds to $z_{\rm peak} = 3322$. Roughly at this time, the source term $\Upsilon\dot{\phi}^2$ in Eq. (4) becomes negligible, and the dark radiation dilutes away as a^{-4} as shown in Fig. 1.

By approximating the friction $\Upsilon(z_{\rm peak}) = \Upsilon_0$ as a constant, we illustrate how to estimate $z_{\rm peak}$ analytically. In this limit, the approximation for the temperature of the dark radiation simplifies to

$$T_{\rm dr}(z > z_{\rm peak}) \simeq \left(\frac{m^2\phi(z)}{2\sqrt{\frac{\pi^2}{30} g_* H(z)\Upsilon_0}} \right)^{\frac{1}{2}}, \tag{10}$$

which, using Eqs. (5) and (7), allows us to approximate $f_{\rm DA}$ as an analytical function in z,

$$f_{\rm DA}(z \geq z_{\rm peak}) \simeq \frac{e^{-\frac{2m^2}{H(z)\Upsilon_0}} \frac{1}{2} m^2\phi_0^2 (1 + \frac{m^2}{2H(z)\Upsilon_0})}{\rho_m(z) + \rho_r(z)}. \tag{11}$$

Solving $\frac{df_{\rm DA}}{dz}|_{z_{\rm peak}} = 0$, and assuming that the peak lies close to matter-radiation equality, we can approximate $z_{\rm peak}$ as

$$z_{\rm peak} \simeq \left(\frac{1}{2\sqrt{\Omega_m}} \frac{m^2}{H_0 \Upsilon_0} \right)^{\frac{2}{3}}, \tag{12}$$

where Ω_m is the fractional matter density today and $z_{\rm peak}$ is now dependent only on $\frac{\Upsilon_0}{m^2}$. Equations (10)–(12) demonstrate how the physical observables depend exclusively on $\frac{\Upsilon}{m^2}$, which sets the time scale at which the axion becomes dynamical, and $\frac{1}{2} m^2\phi_0^2$ which scales the total amount of early dark energy. Therefore, at the background level, we effectively introduce only two new parameters beyond ΛCDM, but expect the perturbations to depend on more than just these two parameters. Including the full temperature dependence of the friction at the background level requires solving the coupled differential Eq. (5) numerically by specifying an initial condition $\frac{\Upsilon(z_i)}{m^2}$ at some z_i, increasing the effective number of background parameters to three. While this does not have a significant impact on the qualitative behavior of the DA system, it does change $\frac{\Upsilon(z_i)}{m^2}$, and $\frac{1}{2} m^2\phi_0^2$ by O(1) when keeping $z_{\rm peak}$ and $f_{\rm DA}(z_{\rm peak})$ fixed.

For redshifts smaller than $z_{\rm peak}$, the early dark energy is dominated by the radiation component which dilutes as

$$\rho_{\rm DA}(z < z_{\rm peak}) \simeq \rho_{\rm dr}(z_{\rm peak}) \left(\frac{1+z}{1+z_{\rm peak}} \right)^4. \tag{13}$$

The fractional energy density $f_{\rm DA}$ is then peaked at $z_{\rm peak}$, as shown in Fig. 2. Our proposed model hence mimics the EDE proposed in P18 with $n = 2$, which resolves the Hubble tension.

The primary difference between the two models at the background level is a narrower peak for the DA (the effect being more pronounced for the constant friction approximation), as seen in Fig. 2. Based on this, we explore the expected differences between the background observables of the two models. In particular, we discuss the impact on CMB observables that capture the important features of the full CMB spectrum, but depend only on the background evolution of the Universe [20,22,41]. These are the size r_s of the sound horizon, the ratio $r_{\rm damp}/r_s$ of the damping scale to the sound horizon, the height of the first peak and the horizon size at matter-radiation equality.

[4]The posteriors for EDE parameters in P18 are non-Gaussian. The best-fit parameters quoted here therefore do not correspond to their mean values, and we hence do not include errors on these quotes.

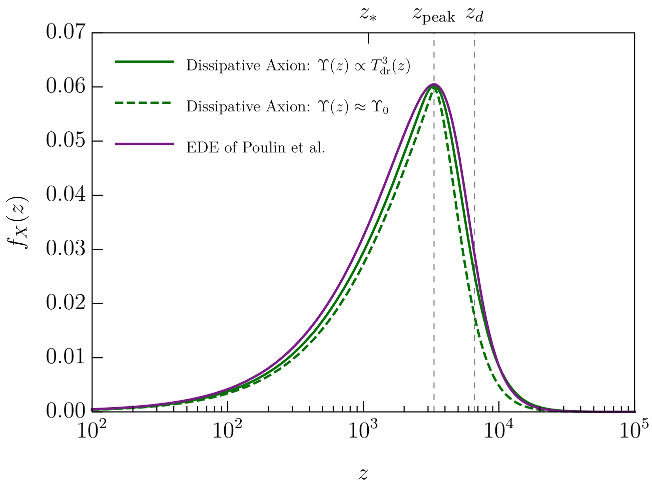

FIG. 2. We compare the fractional early dark energy density of the full temperature dependent DA model [$\Upsilon(z) \propto T_{\rm dr}^3$, solid green] with the semianalytical approximations in Eqs. (11) and (13), treating the friction as constant [$\Upsilon(z) \approx \Upsilon_0$ dashed green] and the EDE fluid approximation of an oscillating scalar field from Poulin *et al.* [22] (purple). This plot uses the $n = 2$ EDE best-fit parameters [$z_c = 5345$, $f_{\rm EDE}(z_c) = 0.044$ which corresponds to $z_{\rm peak} = 3322$, $f_{\rm EDE}(z_{\rm peak}) = 0.060$] and dissipative axion parameters $\frac{\Upsilon(z_{\rm peak})}{m^2} = 1.3 \times 10^{36}\ {\rm GeV}^{-1}$ ($\frac{\Upsilon_0}{m^2} = 5.7 \times 10^{36}\ {\rm GeV}^{-1}$), and $\frac{1}{2} m^2 \phi_0^2 = 0.55\ {\rm eV}^4$ ($\frac{1}{2} m^2 \phi_0^2 = 0.21\ {\rm eV}^4$) for the temperature dependent (independent) DA model.

As our model adds more radiation to the Universe, we naively expect the redshift of matter-radiation equality to shift. Quantifying this shift correctly requires a full Markov chain Monte Carlo (MCMC) to allow other cosmological parameters, in particular the physical density $\omega_{\rm cdm}$ of cold dark matter to compensate for some or all of the shift. We expect that the results of the MCMC will pull our posteriors in a direction that minimizes change to $z_{\rm eq}$. We hence leave further discussion of changes to $z_{\rm eq}$ for future work. We expect an increase in $\omega_{\rm cdm}$ to similarly compensate for a change to the height of the first CMB peak. Such an increase was observed by P18 for EDE—the best-fit $\omega_{\rm cdm}$ increases by ~9% in the $n = 2$ EDE cosmology relative to ΛCDM. To compare, their maximum $f_{\rm EDE} \leq 7\%$. Moreover, the dark radiation peaks during matter-domination, further minimizing the effect of adding dark radiation to the Universe. Consequently, in this paper, we limit our comparisons of the two models to investigating the effects of the sharper peak in $f_{\rm DA}$.

We first note that a slight narrowing of the peak of $f_{\rm DA}$ relative to $f_{\rm EDE}$ has minimal impact on the recombination redshift z_*. This was verified using a modified version of the equation of state parametrization of the EDE of P18, similar to Ref. [24], sharpening the peak in $f_{\rm EDE}$ and calculating z_* with the CLASS cosmology code [42,43]. As z_* is a background quantity, and $f_{\rm DA}$ is nearly identical to a narrower $f_{\rm EDE}$, we expect z_* for the DA to be similar to the EDE scenario. Then, the main change to r_s comes not from the limits of its integral, but the integrand, specifically, the expansion rate. Knowing how the expansion rate for the DA differs from EDE, we can calculate r_s by fixing the background cosmology to the best fit of the $n = 2$ EDE of P18, and the DA parameters such that the temperature dependent (independent) $z_{\rm peak}$ and $f_{\rm DA}(z_{\rm peak})$ match the best-fit EDE (values specified in the caption of Fig. 2), giving

$$r_s(z_*) = \int_{z_*}^{\infty} dz \frac{c_s(z)}{H(z)} = 140.0(140.1)\ {\rm Mpc}, \quad (14)$$

compared to $r_s = 139.8$ Mpc in P18. Here, $c_s(z)$ is the speed of sound in plasma, and the DA enters into the expansion rate $H(z)$. This is well within 1σ of the r_s in the best-fit EDE scenario of P18 for $n = 2$, for which the best-fit Hubble constant increases to $H_0 = 71.1$ km/s/Mpc. This along with a larger error on H_0 resolves the tension in the EDE case. As the CMB inferences of r_s and H_0 are degenerate, with a reduced r_s that matches P18 in the DA model, we similarly expect a high H_0 that will significantly ease the Hubble tension, if not resolve it.

For $r_{\rm damp}$, we expect a smaller change still, as the integral for $r_{\rm damp}$ is sharply peaked close to recombination and less sensitive to the expansion rate $\sim z_{\rm eq}$. While the change in r_s is absorbed by H_0, thereby diminishing the Hubble tension, changes to $r_{\rm damp}/r_s$ can be absorbed by the tilt n_s of the primordial power spectrum as noted by Refs. [20,22].

Another requirement of EDE models that succeed in resolving this discrepancy is an effective sound speed $c_s^2 < 1$ of perturbations in the new component [23–25]. This in part led to the success of Refs. [22,25]. The DA model consists of a scalar field ($c_s^2 = 1$) and dark radiation ($c_s^2 = 1/3$) [44]. Although the coupling between the two components complicates matters, as $\rho_\phi < 20\%$ at $z_{\rm peak}$, the rest of the energy density being made up of dark radiation, naively, we expect c_s^2 for the DA to be between $1/3 < c_s^2 < 1$. Here, we simply seek to motivate the relevance of this model as a particle theory solution to the Hubble tension and leave the exploration of perturbations to subsequent work. As the DA model produces a value for r_s extremely close to the EDE value, and little to no difference is expected in $r_{\rm damp}$ between the two models, these expectations coupled with the predicted increase in $\omega_{\rm cdm}$ make the DA a promising theoretical model to deliver the extra early dark energy component that can resolve the Hubble tension.

IV. DISCUSSION

In this paper, we propose the DA as a particle-model solution to the Hubble tension. The axion couples to a dark non-Abelian gauge group,[5] which adds an additional

[5]We have focused on SU(2). A generalization to SU(N) only changes numerical factors for g_* and κ without qualitative impact.

friction to the equation of motion of the axion and sources a dark radiation bath as the field rolls down its potential. This overdamped system has a well understood UV-completion and greatly alleviates the fine-tuning concerns present for the scalar-field EDE solutions. The injection time and total amount of added energy content is quantified fully by two linear combinations of parameters: $\frac{\Upsilon_0}{m^2}$ and $\frac{1}{2}m^2\phi_0^2$. The full theory has additional parameters, as the friction is determined by: $\Upsilon = \kappa\alpha^5\frac{T_{\rm dr}^3}{f^2}$. Here, κ is an O(10) number, $\alpha < 0.1$, $T_{\rm dr} < f$, and $m \ll \alpha^2 T_{\rm dr}$. For the sample values specified in the caption of Fig. 2, we find that these conditions are easily satisfied for many different combinations of viable parameters, for example: $m = 4\times10^{-25}$ eV, $T_{\rm dr}(z_{\rm peak}) = 0.4$ eV, $f = 0.3$ GeV, $\alpha = 0.1$, $\phi_0 = 10^{-3}M_{\rm Pl}$, where $M_{\rm Pl}$ is the reduced Planck scale. We expect the full perturbative analysis to lift some of the degeneracy in these parameters and also in the choice of potential for the DA.

We have solely investigated the overdamped DA regime. Particle-sourcing friction could also play a role in an underdamped regime. Moreover, the DA can be theorized to have a UV-completion that ties its friction to the dark matter abundance. The symmetry breaking scale f can, for example, be linked to the presence of heavy quarks charged under the dark SU(N). Thus, the dark matter abundance could be determined by f, which also controls the friction Υ, potentially allowing a dynamical explanation for why the DA begins to roll close to matter-radiation equality. We leave a detailed exploration of this to future work.

We note that $N_{\rm eff}$ constraints will not restrict this model. While the CMB was emitted at the redshift of recombination, the peaks of the CMB spectra in fact encode information from redshifts $z \lesssim 10^6$ [27,45]. The DA adds dark radiation to the Universe only after $\sim z_{\rm eq}$, unlike $N_{\rm eff}$ which adds radiation to the Universe at all times. Their imprints on the CMB peaks are hence different—the DA is expected to cause its largest change to the CMB close to the first peak in the TT spectrum based on Refs. [27,45], while $N_{\rm eff}$ is not only constrained by matter-radiation equality, but also through its effect on the higher peaks in the CMB TT spectrum [46]. These distinct effects on the CMB imply that the DA model cannot be quantified by $N_{\rm eff}$, nor be restricted by $N_{\rm eff}$ constraints.

Lastly, we have invoked the DA model here as an explanation of extra dark energy components that resolve the Hubble tension, but this model has applications far beyond this tension. It has already been shown to be a viable candidate for cosmic inflation [34] and could similarly drive the current cosmic acceleration (for example, [47]). A family of scalar fields have often been theorized to cause the two known eras of cosmic expansion [48,49]. We add the DA to this list.

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