

Assessing Cosmological Evidence for Nonminimal Coupling

William J. Wolf^{1,*}, Carlos García-García¹, Theodore Anton^{1,2} and Pedro G. Ferreira¹

¹*Astrophysics, University of Oxford, DWB, Keble Road, Oxford OX1 3RH, United Kingdom*

²*Astronomy Unit, School of Physical and Chemical Sciences, Queen Mary University of London, Mile End Road, London E1 4NS, United Kingdom*

 (Received 14 April 2025; revised 5 June 2025; accepted 28 July 2025; published 19 August 2025)

The recent observational evidence of deviations from the Lambda cold dark matter model points toward the presence of evolving dark energy. The simplest possibility consists of a cosmological scalar field φ , dubbed “quintessence,” driving the accelerated expansion. We assess the evidence for the existence of such a scalar field. We find that, if the accelerated expansion is driven by quintessence, the data favor a potential energy $V(\varphi)$ that is concave, i.e., $m^2 = d^2V/d\varphi^2 < 0$. Furthermore, and more significantly, the data strongly favor a scalar field that is nonminimally coupled to gravity [Bayes factor $\log(B) = 7.34 \pm 0.6$], leading to time variations in the gravitational constant on cosmological scales, and the existence of fifth forces on smaller scales. The fact that we do not observe such fifth forces implies that *either* new physics must come into play on noncosmological scales *or* that quintessence is an unlikely explanation for the observed cosmic acceleration.

DOI: [10.1103/jysf-k72m](https://doi.org/10.1103/jysf-k72m)

Introduction—A new generation of cosmological surveys has allowed us to place much tighter constraints on the history of the Hubble rate. Until now, a model in which late time acceleration is driven by a cosmological constant, Λ , has been adequate to describe observations. However, new data are providing intriguing, but tentative, evidence for evolving dark energy [1,2].

It is often useful to characterize dark energy (DE) in terms of its bulk properties. We can define an equation of state, $w \equiv P_{\text{DE}}/\rho_{\text{DE}}$, in terms of the pressure and energy density of the dark energy. Λ has an equation of state $w = -1$, but evolving dark energy has an equation of state $w(a)$, which is a function of the scale factor of the Universe and is often approximated in terms of two parameters, $w(a) \simeq w_0 + w_a(1 - a)$, known as the Chevallier-Polarski-Linder (CPL) parametrization [3,4]. Current observations of the cosmic microwave background (CMB), baryon acoustic oscillations (BAOs), and type Ia supernovae (SNe) seem to indicate that $w_a < 0$ [1,2,5–11], i.e., that the equation of state is “thawing,” or increasing, with time.

The simplest form of thawing dark energy—quintessence as a minimally coupled scalar field—is only marginally favored over a cosmological constant and is not statistically favored over parametric models of an evolving equation of state. In other words, while the data do seem to prefer a

dark energy that evolves in time, the type of evolution being uncovered is *not* well-described by standard quintessence [12,13]. Thus, if one is to assume that a scalar field is the source of late time acceleration, one needs to look more broadly.

We will show that current cosmological data favor quintessence that is nonminimally coupled to gravity through a term of the form $\xi\varphi^2 R$. While the presence of nonminimal coupling is not, in and of itself, striking, it does lead to some far-reaching consequences for physics on other scales. Hence, if the evidence for nonminimal coupling persists and strengthens, it will necessarily imply a reformulation of our understanding of dark energy in a wider physical context.

Scalar field dark energy—There has been much focus on phenomenological parametrizations of dark energy [14–22]. While these approaches can be informative, they do not shed light on the microphysics of dark energy [23]. In other words, they do not help in fighting the specter of underdetermination [24] and so will not lead us to the exact microphysical theory for dark energy. In this Letter we want to go further and try to glean information about the microphysics from cosmological data.

What we mean by “microphysical theory” is the action for the fundamental field that constitutes dark energy. A common assumption is that dark energy is in the form of a scalar field, which can generally be described by an action [25],

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} F(\varphi) R - \frac{1}{2} G(\varphi) X - V(\varphi) - J(\varphi) X^2 + \mathcal{L}_M(g_{\alpha\beta}, \psi_M) \right], \quad (1)$$

*Contact author: william.wolf@stx.ox.ac.uk

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

where $g_{\alpha\beta}$ is the metric, R the Ricci scalar, φ the scalar field, $X = \partial_\mu \varphi \partial^\mu \varphi$, and $\mathcal{L}_M$ is the action for matter.

Current data already constrain the terms in Eq. (1). Thawing quintessence ($F = G = 1$, $J = 0$) is not particularly favored [12,13]. Although it lies in the thawing regime ($w_a < 0$) and can yield a better χ^2 fit than Lambda cold dark matter (Λ CDM) [26–33], evidence-based comparisons are less optimistic. Depending on the SNe dataset, it is either disfavored relative to Λ CDM or outperformed by parametric (w_0, w_a) models [12,14,16,18,33–35]. If dark energy evolves, the trend appears inconsistent with simple thawing quintessence models and instead suggests rapid evolution (suggested by the large, negative w_a values favored by the data), and possibly even phantom behavior in the past ($w < -1$) [13,16,17,36–42].

For the case of $F \neq 1$ [13,14,38,43–48] we can consider a general subset of models by expanding F and V ,

$$\begin{aligned} F(\varphi) &\simeq 1 - \xi \frac{\varphi^2}{M_{\text{Pl}}^2}, \\ V(\varphi) &\simeq V_0 + \beta\varphi + \frac{1}{2}m^2\varphi^2, \end{aligned} \quad (2)$$

with $G(\varphi) = 1$ and $J(\varphi) = 0$ (see End Matter for more details on this expansion to quadratic order). Despite keeping ourselves ignorant about the specific quintessential action, we can at least try to answer two fundamental questions about the scalar field: “What is the mass of the scalar field?” and “Is it nonminimally coupled to gravity?”

Dark energy described by Eqs. (1) and (2) typically thaws, as current data suggests, but behaves differently for $\xi = 0$ versus $\xi \neq 0$. In the minimally coupled case, the field starts as potential-energy dominated, mimicking a cosmological constant, then evolves around $z \sim 0\text{--}2$ with $w_a < 0$, though not steeply enough to fully match observations [12,13]. With nonminimal coupling ($\xi \neq 0$), the field evolves like a minimally coupled field during radiation domination (given that $R \simeq 0$), yielding $w \simeq -1$. In the matter era, the effect of the nonminimal coupling is to push the field into the phantom regime ($w < -1$), then across the phantom divide as the field accelerates (see Fig. 5 in End Matter). We find that the combination of nonminimal coupling generating phantom behavior and $m^2 = d^2V/d\varphi^2 < 0$ generating rapid thawing leads to more rapid variation in w across the redshift range where most of the data is concentrated ($0.2 \lesssim z \lesssim 2$). This generates a more negative w_a , improving the agreement with data. One can see this in Fig. 1, where the minimal and nonminimally coupled theories have been projected onto the (w_0, w_a) plane following the procedure in [12–14,49,50], which determines a theory prior in the (w_0, w_a) parameters by directly using the errors associated with the observables.

Results—We investigate the cosmological evidence for dynamical dark energy using a collection of data comprising DESI DR2 BAO [51,52], Planck 2018 CMB

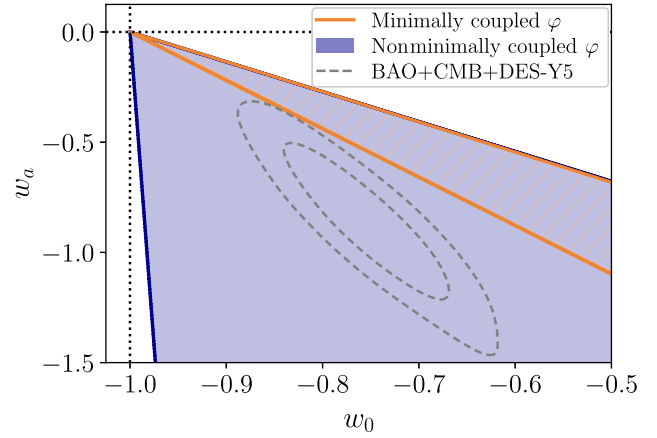


FIG. 1. Projected theory priors into the (w_0, w_a) plane for both minimally and nonminimally coupled dark energy by fitting (w_0, w_a) to the theory prediction of the observables used in the data constraints.

temperature and polarization [5,6], and ACT DR6 CMB lensing [7,8]. These make our baseline data combination (BAO + CMB), which we supplement with type IA SNe data from PANTHEON+ [9], Union3 [10], or DES-Y5 [11,53]. For all data, we use the official likelihoods, as implemented in COBAYA [54]. For Planck, we use Planck PR3 PLIK. We use the nested sampler POLYCHORD [55] to derive the parameter posterior distributions and to calculate the Bayesian evidence $\log \mathcal{Z} = \log \int \mathcal{L}(D|\theta, M) P(\theta|M) d\theta$, where $\mathcal{L}(D|\theta, M)$ is the likelihood, $P(\theta|M)$ is the prior, and θ the sampled parameters. In order to provide an additional assessment of these models, we also compute the deviance information criteria (DIC) defined as $\text{DIC} = D(\bar{\theta}) + 2p_D$, where $D(\theta) = -2 \log \mathcal{L}(\theta)$ and $p_D = \overline{D(\theta)} - D(\bar{\theta})$ is a term that penalizes additional complexity in the model. $\overline{D(\theta)}$ denotes the average deviance over the posterior and $D(\bar{\theta})$ denotes the deviance evaluated at the posterior mean.

For dark energy, we consider three models (see End Matter for a discussion of parameter priors): (i) nonminimally coupled quintessence, (ii) minimally coupled quintessence corresponding to the model studied in [12,23] where $V(\varphi) = V_0 + \frac{1}{2}m^2\varphi^2$, and (iii) the CPL parametrization. We quantify their fit to the data by reporting the best fit $\chi^2 = -2 \log \mathcal{L}$ and its difference with respect to Λ CDM, $\Delta\chi^2_{X\Lambda} = \chi^2_X - \chi^2_\Lambda$. In order to account for the extra degrees of freedom, we use both the $\Delta\text{DIC}_{X\Lambda}$ and the Bayes factor $\log B_{X\Lambda} = \log \mathcal{Z}_X - \log \mathcal{Z}_\Lambda$ to assess the supporting evidence in favor of a given model over Λ CDM. For both $\Delta\chi^2$ and ΔDIC , negative values indicate a preference for the model, whereas for $\log B$ positive values indicate a preference for the model. Note that on the Jeffrey’s scale $\log B_{X\Lambda} > 5$ indicates strong evidence for model X relative to Λ CDM [56,57]. The results can be found in Table I, where the $\log B_{X\Lambda}$ values all have an uncertainty of $\simeq 0.6$.

TABLE I. Statistical comparison for dynamical dark energy models relative to Λ CDM from the combination of BAO, CMB, and different SNe samples.

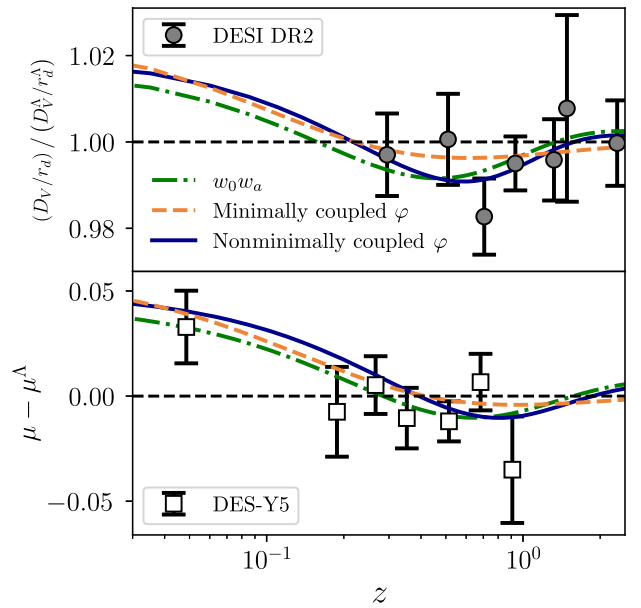
		PANTHEON+	Union3	DES Y5
$\log B$	Min. φ	-1.96	+1.53	+3.46
	$w_0 w_a$	-1.57	+4.02	+5.55
	Nonmin. φ	+3.14	+6.45	+7.34
$\Delta\chi^2$ (Δ DIC)	Min. φ	-2.9 (-0.32)	-7.4 (-3.41)	-14.1 (-9.96)
	$w_0 w_a$	-8.0 (-4.89)	-14.0 (-12.2)	-18.2 (-16.4)
	Nonmin. φ	-14.1 (-11.5)	-19.4 (-16.4)	-23.6 (-21.5)

For CPL, the $\Delta\chi^2_{w_0 w_a \Lambda}$, Δ DIC $_{w_0 w_a \Lambda}$, and $\log B_{w_0 w_a \Lambda}$ values are consistent with other works in the literature that have used similar datasets (e.g., [12,14–16,33]): in particular, $w_0 w_a$ significantly improves the fit to all datasets, but is evidentially disfavored with respect to Λ CDM when the PANTHEON+ data are used, while it is evidentially favored with Union3 and DES-Y5. For minimally coupled dark energy, while it can improve the fit to the data, it is the worst performing dynamical dark energy model. While it is evidentially disfavored with respect to the PANTHEON+ data (in agreement with [12,33]), we begin to see some moderate evidence for it emerge with the Union3 and DES-Y5 data. Given that these datasets significantly strengthen the preference for dynamical dark energy, we attribute this improvement in evidence to the fact that this dark energy model allows for more rapid evolution at low z than standard minimally coupled quintessence models (when $m^2 < 0$) [12,23,28,58]. Finally, the nonminimally coupled dark energy model provides the best fit to the data across the board. At first glance, this may not be surprising considering that it has more parameters than any of the other dark energy models considered, but the Bayesian evidence and DIC results indicate that the additional parameters justify their inclusion, with the model being strongly favored by its Bayes factor and only receiving a modest DIC penalty. The nonminimally coupled model is the only model that is evidentially favored over Λ CDM with respect to *all* dataset combinations.

Given that the BAO + CMB + DES-Y5 gives the strongest evidence for dynamical dark energy, we will dive a little further into this data combination. Figure 2 depicts both the DESI DR2 BAO data for the angle-averaged distance D_V and the DES-Y5 SNe data for the distance modulus μ against the best fits for all dynamical dark energy models, all normalized to the best-fit Λ CDM model. For visualization, the SNe data has been binned in redshift and we have calculated the weighted average distance moduli and errors using the covariance matrix to include both statistical and systematic errors. See Ref. [2] VII. B] for a similar plot. Clearly, all dynamical models offer a significant improvement in fitting these distance measurements. In fact, they all perform similarly well in terms of their ability to fit the BAO and SNe data

simultaneously, with $\Delta\chi^2_{\chi\Lambda} \simeq -15$ for every dynamical dark energy model. Where the CPL and nonminimally coupled dark energy separate themselves from minimally coupled dark energy is in their ability to simultaneously improve the fit to both the lower z data and the CMB data over Λ CDM, which makes up the rest of the $\Delta\chi^2$ difference between these models and Λ CDM ($\Delta\chi^2_{\chi\Lambda} \simeq -3$ for CPL and $\simeq -7$ for the nonminimally coupled model).

Figure 3 shows the constraints of the nonminimally coupled scalar field parameters. We find $\xi = 2.31^{+0.75}_{-0.34}$, $\beta = 2.85^{+0.53}_{-0.29}$, $m^2 = -1.8 \pm 1.2$, and $V_0 = 0.654^{+0.086}_{-0.13}$. Note that both minimally and nonminimally coupled dark energy models strongly favor $m^2 = d^2 V / d\varphi^2 < 0$, as concave potentials allow for more rapid variation in the scalar field [12,23,28,58]. Such potentials are unbounded from below, absent other corrections; however, this is not relevant for cosmological constraints as we find that the field excursion is $\Delta\varphi / M_{\text{Pl}} \simeq \mathcal{O}(0.1)$ and never enters a


 FIG. 2. Observables from the best-fit dark energy models compared with the angle-averaged distance D_V and the distance modulus μ , normalized to Λ CDM.

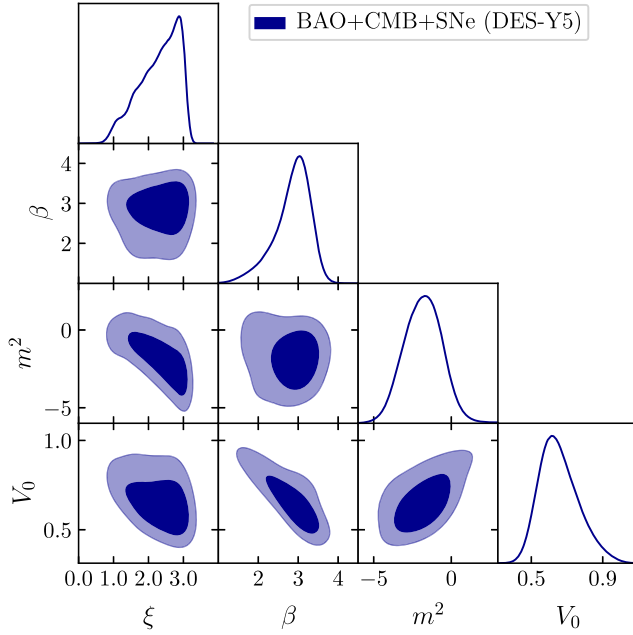


FIG. 3. 68% and 95% CL posterior distributions for the nonminimally coupled dark energy parameters.

pathological regime. Finally, the left-hand panel of Fig. 4 shows the constraints on $w(z)$. As anticipated, the posterior distribution of $w(z)$ is consistently below -1 by more than 2σ in the matter dominated era, crossing the phantom divide at about $z \sim 0.5$ and reaching $w(z=0) = -0.841^{+0.029}_{-0.028}$ today, 5.7σ away from $w = -1$. This quick transition over this range of redshifts is what allows this model to significantly improve the fit to both the early (CMB) and late time (BAO and SNe) data simultaneously, and resembles the evolution favored by the parametric dark energy models (e.g., [16] [Fig. 4]). Furthermore, we also see in the central panel that the nonminimal coupling has a significant impact on the strength of gravity, parametrized by $\mu(z)$, with $\mu(z=0) = 1.77^{+0.23}_{-0.18}$, 4.3σ away from the general relativity with $\mu = 1$. These cosmological results have profound implications for the nature of gravity.

Ancillary gravitational consequences—The nonminimal coupling of the scalar field to the metric brings with it a host of undesirable consequences and it would be remiss of us not to consider them. On the largest scales, we have that the effective gravitational constant, G_{eff} (as opposed to the bare gravitational constant that appears in the action, $8\pi G_0 = M_{\text{Pl}}^{-2}$) is time varying, $\dot{G}_{\text{eff}}/G_{\text{eff}} = 2\xi\dot{\varphi}/(1 - \xi\varphi^2)$. We find that, for parameters that can best fit the cosmological data, $\dot{G}_{\text{eff}}/G_{\text{eff}} \simeq 10^{-11}/\text{yr}$. Constraints on this quantity (which are independent of any assumptions about the cosmological model) should not be confused with the constraints that come from the Solar System or compact binaries on the Newton-Poisson G_{N} [66–68] (although they are around the same order of magnitude [69]).

As we go further down in scale, we have that the nonminimal coupling will affect the gravitational constant that enters in the Newtonian limit, in the Newton-Poisson equation. We then have that $\nabla^2\Phi = 4\pi G_0\mu(z)\bar{\rho}_M\delta_M$ where Φ is the Newtonian potential, $\bar{\rho}_M$ and δ_M are the background and fractional density perturbation of matter, and $\mu(z)$ captures the time evolution of Newton’s constant on the scales of gravitational clustering. We can see the impact of this time variation in two distinct ways. The central panel of Fig. 4 shows the inferred $\mu(z)$ from CMB + DESI + DESY5 data. For $z < 0.6$, $\mu(z)$ deviates from the general relativity value by over 2 standard deviations (4.3σ today), suggesting a preference for modifications to gravitational clustering in the Newtonian regime (see also [70] for a compatible model-agnostic reconstruction). The right-hand panel shows $f\sigma_8(z)$, where $f = d\ln\delta/d\ln\eta$ is the growth rate and σ_8 is the mass variance on scales of $8h^{-1}$ Mpc. The nonminimally coupled model is consistent with higher redshift measurements, although less so for the lowest redshift measurements. Note, however, that current data on structure growth are still too imprecise to tightly constrain departures from Λ CDM; furthermore, an accurate covariance matrix for how these measurements correlate with distance measurements is still lacking, hindering any attempts at a combined analysis.

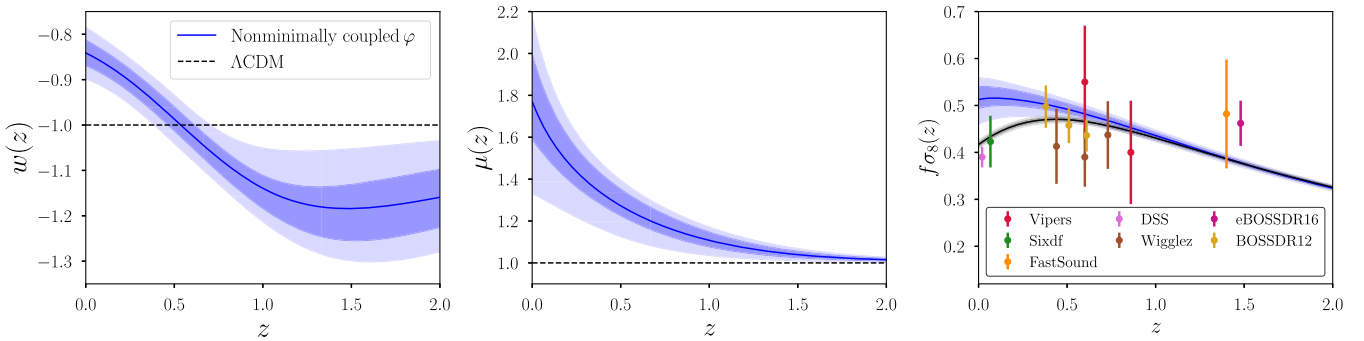


FIG. 4. Reconstruction of the equation of state $w(z)$, $\mu(z)$, and $f\sigma_8(z)$ obtained in Fig. 3. The $f\sigma_8$ measurements were not used in obtaining the constraints and are plotted for reference. One can see that this nonminimally coupled model is reasonably compatible with these $f\sigma_8$ data points [59–65].

Nonminimally coupled scalar fields are tightly constrained on small scales, with no evidence of fifth forces in astrophysical systems [71,72]. Specifically, parametrized post-Newtonian (PPN) parameters are strongly bounded: Cassini data [73] constrain the light-bending parameter to $\gamma_{\text{PPN}} - 1 = (2.1 \pm 2.3) \times 10^{-5}$, and MESSENGER [74,75] bounds the nonlinearity parameter to $\beta_{\text{PPN}} - 1 = (-2.7 \pm 3.9) \times 10^{-5}$. These imply $\xi(\varphi_0/M_{\text{Pl}})^2 \leq 6 \times 10^{-6}$ and $\xi \leq 1$, in tension with the cosmological requirement $\xi(\varphi_0/M_{\text{Pl}})^2 \sim 0.1$. In the Einstein frame, matter couples via $\tilde{g}_{\alpha\beta} \sim [1 - \xi(\psi/M_{\text{Pl}})^2]g_{\alpha\beta}$, leading to time- and space-varying constants that are observationally constrained.

Fifth forces can be suppressed on small scales, as seen from the action in Eq. (1). Adding the effective-field-theory-allowed term $(1/\Lambda^4) \int d^4x \sqrt{-g} X^2$ enables gravitational screening that protects small scales from large deviations [43,76–80]. This leads to Vainshtein screening [81], distinct from Galileon models, due to the explicit nonminimal coupling to the Einstein-Hilbert term. The fifth force becomes sensitive to the local scalar field and, in the screened regime, takes the form $F_5/F_N \propto (r/r_V)^{4/3}$ [82], where $r_V = [9M/(16\pi\Lambda^2 M_{\text{Pl}})]^{1/2}$, and $F_N \propto r^{-2}$. For comparison, cubic Galileons yield $F_5/F_N \propto (r/r_V)^{3/2}$ [83]. With $\Lambda \lesssim 10^{-2}$ eV, Solar System screening ($r_V \gtrsim 10^{-3}$ pc for $M \sim M_\odot$) is achievable without altering cosmic expansion. Another alternative is to break the universality of the nonminimal coupling and assume that the dark energy, in the Einstein frame, is *only* coupled to the dark matter. Such a scenario corresponds to an interacting dark matter or dark energy model [84–90] and might avoid some of the constraints on fifth forces. However, as with screening, it would be another (more contrived) version of nonminimal coupling.

The only way to avoid nonminimal coupling may be through a radical reformulation of the kinetic structure of the scalar field. A purely shift-symmetric theory, replacing the kinetic term by a more complicated function, $X \rightarrow K(X, \square\varphi)$, leads to $w < -1$ throughout and the resulting (w_0, w_a) does not overlap with the current constraints [50]. Breaking the shift symmetry by, for example, adding a potential, may make such theories more consistent with the data, but will in turn lead to other problems, such as superluminal motion and instabilities. We will explore these models in future work.

Discussion—In this Letter we have shown that *if we assume that the accelerated expansion is driven by a dynamical scalar field*, there is compelling statistical evidence (by any measure) that it must be nonminimally coupled to gravity and that its potential V satisfy $d^2V/d\varphi^2 < 0$. The nonminimal coupling will drive time variation of the effective gravitational constant, affect the growth rate of structure, and lead to fifth forces on much smaller scales. Such forces are tightly constrained through a range of different methods on laboratory and Solar System

scales. Given the *absence* of any evidence for fifth forces, this means that additional new physics must be invoked to screen the presence of a nonminimal coupling.

Such a nonminimal coupling will naturally arise in the effective action of a theory coupled to gravity [25,91–97]. Furthermore, theories with extra dimensions may lead to nonminimal couplings, with one caveat: given the substantial deviation of $w(a)$ from -1 , we inevitably have substantial field excursions. In this case we find that $\Delta\varphi/M_{\text{Pl}} \sim \mathcal{O}(0.1)$ which is manageable, yet far too large to be accommodated in some of the better motivated theories of dark energy. Furthermore, the screening scale Λ will be substantially larger than $(H_0 M_{\text{Pl}})^{1/2}$ and thus may lead to strong coupling problems.

The quintessence hypothesis clearly leads us down a path of ever increasing complexity, and the consequences are sufficiently jarring that it behooves us to step back and reconsider our assumptions. A key assumption is that the dark energy is in the form of a scalar field. One might want to consider the handful of proposals that do not reduce to a scalar field on large scales (or an effective description in terms of a scalar-tensor theory) [98]. Another possibility is that the details of the accelerated expansion we are inferring is a result of our mismodeling the cosmological space-time and, as a result, observables may be nontrivially affected by the inhomogeneous nature of the cosmos [99–103]. We should also revisit the assumptions that have gone into the analysis of the data—the presence or absence of a cosmic dipole, the role of the low redshift supernovae, the discrepancy between different supernovae and between different BAO samples, etc. [104–131]. We will watch with interest as the various analyses are independently scrutinized, and await the expected increase in the quality and quantity of the data from the new generation of surveys.

Acknowledgments—We thank D. Alonso, J. Conlon, E. Copeland, H. Desmond, D. Kaiser, K. Lodha, J. Noller, M. Vincenzi, and G. Ye for many valuable conversations. W. J. W. is supported by St. Cross College, University of Oxford. C. G. G. is supported by the Beecroft Trust. T. A. acknowledges support from a Balzan Fellowship. T. A. is grateful to the Astrophysics Department at Oxford and New College Oxford for their hospitality throughout his visit. P. G. F. is supported by STFC and the Beecroft Trust.

Data availability—The data that support the findings of this Letter are openly available [2,6,8,9,10,11].

-
- [1] A. G. Adame *et al.* (DESI Collaboration), DESI 2024 VI: Cosmological constraints from the measurements of baryon acoustic oscillations, *J. Cosmol. Astropart. Phys.* **02** (2025) 021.
 - [2] M. Abdul Karim *et al.* (DESI Collaboration), DESI DR2 results II: Measurements of baryon acoustic oscillations and cosmological constraints, [arXiv:2503.14738](https://arxiv.org/abs/2503.14738).

- [3] M. Chevallier and D. Polarski, Accelerating universes with scaling dark matter, *Int. J. Mod. Phys. D* **10**, 213 (2001).
- [4] E. V. Linder, Exploring the expansion history of the universe, *Phys. Rev. Lett.* **90**, 091301 (2003).
- [5] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. VI. Cosmological parameters, *Astron. Astrophys.* **641**, A6 (2020); *Astron. Astrophys.* **652**, C4(E) (2021).
- [6] N. Aghanim *et al.* (Planck Collaboration), Planck 2018 results. V. CMB power spectra and likelihoods, *Astron. Astrophys.* **641**, A5 (2020).
- [7] F. J. Qu *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: A measurement of the DR6 CMB lensing power spectrum and its implications for structure growth, *Astrophys. J.* **962**, 112 (2024).
- [8] M. S. Madhavacheril *et al.* (ACT Collaboration), The Atacama Cosmology Telescope: DR6 gravitational lensing map and cosmological parameters, *Astrophys. J.* **962**, 113 (2024).
- [9] D. Scolnic *et al.*, The PANTHEON+ analysis: The full data set and light-curve release, *Astrophys. J.* **938**, 113 (2022).
- [10] D. Rubin *et al.*, Union through UNITY: Cosmology with 2,000 SNe using a unified Bayesian framework, *arXiv:2311.12098*.
- [11] 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).
- [12] W. J. Wolf, C. García-García, D. J. Bartlett, and P. G. Ferreira, Scant evidence for thawing quintessence, *Phys. Rev. D* **110**, 083528 (2024).
- [13] W. J. Wolf, P. G. Ferreira, and C. García-García, Matching current observational constraints with nonminimally coupled dark energy, *Phys. Rev. D* **111**, L041303 (2025).
- [14] W. J. Wolf, C. García-García, and P. G. Ferreira, Robustness of dark energy phenomenology across different parameterizations, *J. Cosmol. Astropart. Phys.* **05** (2025) 034.
- [15] W. Giarè, M. Najafi, S. Pan, E. Di Valentino, and J. T. Firouzjaee, Robust preference for dynamical dark energy in DESI BAO and SN measurements, *J. Cosmol. Astropart. Phys.* **10** (2024) 035.
- [16] K. Lodha *et al.*, Extended dark energy analysis using DESI DR2 BAO measurements, *arXiv:2503.14743*.
- [17] K. Lodha *et al.* (DESI Collaboration), DESI 2024: Constraints on physics-focused aspects of dark energy using DESI DR1 BAO data, *Phys. Rev. D* **111**, 023532 (2025).
- [18] G. Payeur, E. McDonough, and R. Brandenberger, Do observations prefer thawing quintessence?, *Phys. Rev. D* **111**, 123541 (2025).
- [19] R. E. Keeley, K. N. Abazajian, M. Kaplinghat, and A. Shafieloo, The preference for evolving dark energy from cosmological distance measurements and possible signatures in the growth rate of perturbations, *arXiv:2502.12667*.
- [20] S. Akthar and M. W. Hossain, General parametrization for energy density of quintessence field, *J. Cosmol. Astropart. Phys.* **04** (2025) 024.
- [21] A. Alho and C. Ugglä, New simple and accurate approximations for quintessence, *Phys. Rev. D* **111**, 083549 (2025).
- [22] 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.
- [23] W. J. Wolf and P. G. Ferreira, Underdetermination of dark energy, *Phys. Rev. D* **108**, 103519 (2023).
- [24] P. G. Ferreira, W. J. Wolf, and J. Read, The spectre of underdetermination in modern cosmology, *arXiv:2501.06095*.
- [25] M. Park, K. M. Zurek, and S. Watson, A unified approach to cosmic acceleration, *Phys. Rev. D* **81**, 124008 (2010).
- [26] K. V. Berghaus, J. A. Kable, and V. Miranda, Quantifying scalar field dynamics with DESI 2024 Y1 BAO measurements, *Phys. Rev. D* **110**, 103524 (2024).
- [27] Y. Tada and T. Terada, Quintessential interpretation of the evolving dark energy in light of DESI observations, *Phys. Rev. D* **109**, L121305 (2024).
- [28] D. Shlivko and P. J. Steinhardt, Assessing observational constraints on dark energy, *Phys. Lett. B* **855**, 138826 (2024).
- [29] A. Notari, M. Redi, and A. Tesi, Consistent theories for the DESI dark energy fit, *J. Cosmol. Astropart. Phys.* **11** (2024) 025.
- [30] G. Borghetto, A. Malhotra, G. Tasinato, and I. Zavala, Bounded dark energy, *Phys. Rev. D* **112**, 023521 (2025).
- [31] M. Berbig, Kick it like DESI: PNGB quintessence with a dynamically generated initial velocity, *J. Cosmol. Astropart. Phys.* **03** (2025) 015.
- [32] H. N. Luu, Y.-C. Qiu, and S. H. H. Tye, Dynamical dark energy from an ultralight axion, *Phys. Rev. D* **112**, 023524 (2025).
- [33] L. A. Ureña López *et al.* (DESI Collaboration), Updated cosmological constraints on axion dark energy with DESI, *arXiv:2503.20178*.
- [34] S. Bhattacharya, G. Borghetto, A. Malhotra, S. Parameswaran, G. Tasinato, and I. Zavala, Cosmological constraints on curved quintessence, *J. Cosmol. Astropart. Phys.* **09** (2024) 073.
- [35] M. W. Hossain and A. Maqsood, Cosmological implications of Tracker scalar fields as dynamical dark energy, *arXiv:2502.19274*.
- [36] M. Berti, E. Bellini, C. Bonvin, M. Kunz, M. Viel, and M. Zumalacarregui, Reconstructing the dark energy density in light of DESI BAO observations, *Phys. Rev. D* **112**, 023518 (2025).
- [37] R. Calderon *et al.* (DESI Collaboration), DESI 2024: Reconstructing dark energy using crossing statistics with DESI DR1 BAO data, *J. Cosmol. Astropart. Phys.* **10** (2024) 048.
- [38] G. Ye, M. Martinelli, B. Hu, and A. Silvestri, nonminimally coupled gravity as a physically viable fit to DESI 2024 BAO, *Phys. Rev. Lett.* **134**, 181002 (2025).
- [39] P. Mukherjee and A. A. Sen, Model-independent cosmological inference post DESI DR1 BAO measurements, *Phys. Rev. D* **110**, 123502 (2024).
- [40] A. N. Ormondroyd, W. J. Handley, M. P. Hobson, and A. N. Lasenby, Nonparametric reconstructions of dynamical dark energy via flexknots, *arXiv:2503.08658*.
- [41] E. Moghtaderi, B. R. Hull, J. Quintin, and G. Geshnizjani, How much NEC breaking can the universe endure?, *Phys. Rev. D* **111**, 123552 (2025).

- [42] G. Ye and Y. Cai, NEC violation and “beyond Horndeski” physics in light of DESI DR2, [arXiv:2503.22515](#).
- [43] G. Ye, Bridge the cosmological tensions with thawing gravity, [arXiv:2411.11743](#).
- [44] A. Chudaykin and M. Kunz, Modified gravity interpretation of the evolving dark energy in light of DESI data, *Phys. Rev. D* **110**, 123524 (2024).
- [45] A. G. Ferrari, M. Ballardini, F. Finelli, and D. Paoletti, Scalar-tensor gravity and DESI 2024 BAO data, *Phys. Rev. D* **111**, 083523 (2025).
- [46] A. Chudaykin, M. Kunz, and J. Carron, Modified gravity constraints with Planck ISW-lensing bispectrum, [arXiv:2503.09893](#).
- [47] J. Pan and G. Ye, nonminimally coupled gravity constraints from DESI DR2 data, [arXiv:2503.19898](#).
- [48] R. Gannouji, D. Polarski, A. Ranquet, and A. A. Starobinsky, Scalar-tensor models of normal and phantom dark energy, *J. Cosmol. Astropart. Phys.* **09** (2006) 016.
- [49] C. García-García, E. Bellini, P. G. Ferreira, D. Traykova, and M. Zumalacárregui, Theoretical priors in scalar-tensor cosmologies: Thawing quintessence, *Phys. Rev. D* **101**, 063508 (2020).
- [50] D. Traykova, E. Bellini, P. G. Ferreira, C. García-García, J. Noller, and M. Zumalacárregui, Theoretical priors in scalar-tensor cosmologies: Shift-symmetric Horndeski models, *Phys. Rev. D* **104**, 083502 (2021).
- [51] U. Andrade *et al.*, Validation of the DESI DR2 measurements of baryon acoustic oscillations from Galaxies and Quasars, [arXiv:2503.14742](#).
- [52] M. Abdul Karim *et al.* (DESI Collaboration), DESI DR2 results I: Baryon acoustic oscillations from the Lyman alpha forest, [arXiv:2503.14739](#).
- [53] T. M. C. Abbott *et al.* (DES Collaboration), Dark Energy Survey: Implications for cosmological expansion models from the final DES baryon acoustic oscillation and supernova data, [arXiv:2503.06712](#).
- [54] J. Torrado and A. Lewis, COBAYA: Code for Bayesian analysis of hierarchical physical models, *J. Cosmol. Astropart. Phys.* **05** (2021) 057.
- [55] W. J. Handley, M. P. Hobson, and A. N. Lasenby, PolyChord: Nested sampling for cosmology, *Mon. Not. R. Astron. Soc.* **450**, L61 (2015).
- [56] H. Jeffreys, *The Theory of Probability*, Oxford Classic Texts in the Physical Sciences (Oxford University Press, Oxford, 1939), 1st ed.
- [57] R. Trotta, Applications of Bayesian model selection to cosmological parameters, *Mon. Not. R. Astron. Soc.* **378**, 72 (2007).
- [58] S. Dutta and R. J. Scherrer, Hilltop quintessence, *Phys. Rev. D* **78**, 123525 (2008).
- [59] F. Beutler, C. Blake, M. Colless, D. H. Jones, L. Staveley-Smith, G. B. Poole, L. Campbell, Q. Parker, W. Saunders, and F. Watson, The 6dF galaxy survey: $z \approx 0$ measurements of the growth rate and σ_8 , *Mon. Not. R. Astron. Soc.* **423**, 3430 (2012).
- [60] T. Okumura *et al.*, The Subaru FMOS galaxy redshift survey (FastSound). IV. New constraint on gravity theory from redshift space distortions at $z \sim 1.4$, *Publ. Astron. Soc. Jpn.* **68**, 38 (2016).
- [61] C. Blake *et al.*, The WiggleZ dark energy survey: Joint measurements of the expansion and growth history at $z < 1$, *Mon. Not. R. Astron. Soc.* **425**, 405 (2012).
- [62] S. Alam *et al.* (BOSS Collaboration), The clustering of galaxies in the completed SDSS-III Baryon Oscillation Spectroscopic Survey: Cosmological analysis of the DR12 galaxy sample, *Mon. Not. R. Astron. Soc.* **470**, 2617 (2017).
- [63] B. E. Stahl, T. de Jaeger, S. S. Boruah, W. Zheng, A. V. Filippenko, and M. J. Hudson, Peculiar-velocity cosmology with Types Ia and II supernovae, *Mon. Not. R. Astron. Soc.* **505**, 2349 (2021).
- [64] F. G. Mohammad *et al.*, The VIMOS Public Extragalactic Redshift Survey (VIPERS). An unbiased estimate of the growth rate of structure at $\langle z \rangle = 0.85$ using the clustering of luminous blue galaxies, *Astron. Astrophys.* **610**, A59 (2018).
- [65] S. Alam *et al.* (eBOSS Collaboration), Completed SDSS-IV extended Baryon Oscillation Spectroscopic Survey: Cosmological implications from two decades of spectroscopic surveys at the Apache Point Observatory, *Phys. Rev. D* **103**, 083533 (2021).
- [66] W. J. Wolf and M. Lagos, Standard sirens as a novel probe of dark energy, *Phys. Rev. Lett.* **124**, 061101 (2020).
- [67] M. Lagos and H. Zhu, Gravitational couplings in Chameleon models, *J. Cosmol. Astropart. Phys.* **06** (2020) 061.
- [68] C. Dalang and L. Lombriser, Limitations on standard sirens tests of gravity from screening, *J. Cosmol. Astropart. Phys.* **10** (2019) 013.
- [69] J.-P. Uzan, Fundamental constants: From measurement to the universe, a window on gravitation and cosmology, [arXiv:2410.07281](#).
- [70] L. Pogosian, M. Raveri, K. Koyama, M. Martinelli, A. Silvestri, G.-B. Zhao, J. Li, S. Peirone, and A. Zucca, Imprints of cosmological tensions in reconstructed gravity, *Nat. Astron.* **6**, 1484 (2022).
- [71] E. G. Adelberger, B. R. Heckel, and A. E. Nelson, Tests of the gravitational inverse-square law, *Annu. Rev. Nucl. Part. Sci.* **53**, 77121 (2003).
- [72] C. M. Will, The confrontation between general relativity and experiment, *Living Rev. Relativity* **17**, 4 (2014).
- [73] B. Bertotti, L. Iess, and P. Tortora, A test of general relativity using radio links with the Cassini spacecraft, *Nature (London)* **425**, 374 (2003).
- [74] R. S. Park *et al.*, Precession of Mercury’s perihelion from ranging to the MESSENGER spacecraft, *Astron. J.* **153**, 121 (2017).
- [75] D. E. Smith *et al.*, Gravity field and internal structure of Mercury from MESSENGER, *Science* **336**, 214 (2012).
- [76] J. Khoury and A. Weltman, Chameleon cosmology, *Phys. Rev. D* **69**, 044026 (2004).
- [77] P. Brax, S. Casas, H. Desmond, and B. Elder, Testing screened modified gravity, *Universe* **8**, 11 (2021).
- [78] J. Sakstein, Tests of gravity with future space-based experiments, *Phys. Rev. D* **97**, 064028 (2018).
- [79] V. Vardanyan and D. J. Bartlett, Modeling and testing screening mechanisms in the laboratory and in space, *Universe* **9**, 340 (2023).

- [80] C. Briddon, T. Clifton, and P. Fleury, Emergent cosmological expansion in scalar–tensor theories of gravity, *Classical Quantum Gravity* **42**, 015013 (2025).
- [81] A. I. Vainshtein, To the problem of nonvanishing gravitation mass, *Phys. Lett.* **39B**, 393 (1972).
- [82] T. Anton, P. G. Ferreira, C. García-García, and W. J. Wolf, Constructing observationally viable quintessence across cosmological and astrophysical scales (to be published).
- [83] T. Kobayashi, Horndeski theory and beyond: A review, *Rep. Prog. Phys.* **82**, 086901 (2019).
- [84] A. Gómez-Valent, V. Pettorino, and L. Amendola, Update on coupled dark energy and the H_0 tension, *Phys. Rev. D* **101**, 123513 (2020).
- [85] L. Amendola, Coupled quintessence, *Phys. Rev. D* **62**, 043511 (2000).
- [86] W. Giarè, M. A. Sabogal, R. C. Nunes, and E. Di Valentino, Interacting dark energy after DESI baryon acoustic oscillation measurements, *Phys. Rev. Lett.* **133**, 251003 (2024).
- [87] A. Chakraborty, P. K. Chanda, S. Das, and K. Dutta, DESI results: Hint towards coupled dark matter and dark energy, [arXiv:2503.10806](#).
- [88] R. Shah, P. Mukherjee, and S. Pal, Interacting dark sectors in light of DESI DR2, [arXiv:2503.21652](#).
- [89] 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).
- [90] J. Khoury, M.-X. Lin, and M. Trodden, Apparent $w < -1$ and a lower S_8 from dark axion and dark baryons interactions, [arXiv:2503.16415](#).
- [91] D. I. Kaiser, Nonminimal couplings in the early universe: Multifield models of inflation and the latest observations, *Fundam. Theor. Phys.* **183**, 41 (2016).
- [92] I. L. Buchbinder, *Effective Action in Quantum Gravity* (Routledge, 1992), 1st ed., [10.1201/9780203758922](#).
- [93] N. D. Birrell and P. C. W. Davies, *Quantum Fields in Curved Space*, Cambridge Monographs on Mathematical Physics (Cambridge University Press, Cambridge, England, 1982).
- [94] G. Esposito-Farese and D. Polarski, Scalar tensor gravity in an accelerating universe, *Phys. Rev. D* **63**, 063504 (2001).
- [95] C. G. Callan, Jr., S. R. Coleman, and R. Jackiw, A new improved energy—momentum tensor, *Ann. Phys. (N.Y.)* **59**, 42 (1970).
- [96] T. Markkanen and A. Tranberg, A simple method for one-loop renormalization in curved space-time, *J. Cosmol. Astropart. Phys.* **08** (2013) 045.
- [97] S. Nojiri and S. D. Odintsov, Unified cosmic history in modified gravity: From F(R) theory to Lorentz non-invariant models, *Phys. Rep.* **505**, 59 (2011).
- [98] T. Clifton, P. G. Ferreira, A. Padilla, and C. Skordis, Modified gravity and cosmology, *Phys. Rep.* **513**, 1 (2012).
- [99] T. Buchert and S. Räsänen, Backreaction in late-time cosmology, *Annu. Rev. Nucl. Part. Sci.* **62**, 57 (2012).
- [100] T. Buchert *et al.*, Is there proof that backreaction of inhomogeneities is irrelevant in cosmology?, *Classical Quantum Gravity* **32**, 215021 (2015).
- [101] S. Räsänen, Accelerated expansion from structure formation, *J. Cosmol. Astropart. Phys.* **11** (2006) 003.
- [102] A. Heinesen, Multipole decomposition of the general luminosity distance Hubble law—A new framework for observational cosmology, *J. Cosmol. Astropart. Phys.* **05** (2021) 008.
- [103] A. Seifert, Z. G. Lane, M. Galoppo, R. Ridden-Harper, and D. L. Wiltshire, Supernovae evidence for foundational change to cosmological models, *Mon. Not. R. Astron. Soc.: Lett.* **537**, L55 (2024).
- [104] G. Efstathiou, Evolving dark energy or supernovae systematics?, *Mon. Not. R. Astron. Soc.* **538**, 875 (2025).
- [105] E. O. Colgáin and M. M. Sheikh-Jabbari, DESI and SNe: Dynamical dark energy, Ω_m tension or systematics?, [arXiv:2412.12905](#).
- [106] Y. Carloni, O. Luongo, and M. Muccino, Does dark energy really revive using DESI 2024 data?, *Phys. Rev. D* **111**, 023512 (2025).
- [107] O. Luongo and M. Muccino, Dark energy reconstructions combining baryonic acoustic oscillation data with galaxy clusters and intermediate-redshift catalogs, *Astron. Astrophys.* **693**, A187 (2025).
- [108] X. T. Tang, D. Brout, T. Karwal, C. Chang, V. Miranda, and M. Vincenzi, Uniting the observed dynamical dark energy preference with the discrepancies in Ω_m and H_0 across cosmological probes, *Astrophys. J. Lett.* **983**, L27 (2025).
- [109] M. Vincenzi *et al.* (DES Collaboration), Comparing the DES-SN5YR and PANTHEON+ SN cosmology analyses: Investigation based on “Evolving Dark Energy or Supernovae systematics?”, [arXiv:2501.06664](#).
- [110] B. Ghosh and C. Bengaly, Consistency tests between SDSS and DESI BAO measurements, *Phys. Dark Universe* **46**, 101699 (2024).
- [111] A. Notari, M. Redi, and A. Tesi, BAO vs. SN evidence for evolving dark energy, *J. Cosmol. Astropart. Phys.* **04** (2025) 048.
- [112] H. Wang and Y.-S. Piao, Dark energy in light of recent DESI BAO and Hubble tension, [arXiv:2404.18579](#).
- [113] D. Wang, The self-consistency of DESI analysis and Comment on “Does DESI 2024 confirm Λ CDM?”, [arXiv:2404.13833](#).
- [114] B. R. Dinda, A new diagnostic for the null test of dynamical dark energy in light of DESI 2024 and other BAO data, *J. Cosmol. Astropart. Phys.* **09** (2024) 062.
- [115] C.-G. Park, J. C. Pérez, and B. Ratra, Using non-DESI data to confirm and strengthen the DESI 2024 spatially flat w_0w_a CDM cosmological parametrization result, *Phys. Rev. D* **110**, 123533 (2024).
- [116] C.-G. Park, J. de Cruz Perez, and B. Ratra, Is the w_0w_a CDM cosmological parameterization evidence for dark energy dynamics partially caused by the excess smoothing of Planck CMB anisotropy data?, [arXiv:2410.13627](#).
- [117] W. Giarè, T. Mahassen, E. Di Valentino, and S. Pan, An overview of what current data can (and cannot yet) say about evolving dark energy, *Phys. Dark Universe* **48**, 101906 (2025).
- [118] I. Banik and V. Kalaitzidis, Testing the local void solution to the Hubble tension using baryon acoustic oscillation

- measurements over the last twenty years, *Mon. Not. R. Astron. Soc.* **540**, 545 (2025).
- [119] P. Bansal and D. Huterer, Expansion-history preferences of DESI and external data, *Phys. Rev. D* **112**, 023528 (2025).
 - [120] B. R. Dinda and R. Maartens, Model-agnostic assessment of dark energy after DESI DR1 BAO, *J. Cosmol. Astropart. Phys.* **01** (2025) 120.
 - [121] M. Cortês and A. R. Liddle, Interpreting DESI's evidence for evolving dark energy, *J. Cosmol. Astropart. Phys.* **12** (2024) 007.
 - [122] S. Gao, Q. Gao, Y. Gong, and X. Lu, Null tests with Gaussian process, *Sci. China Phys. Mech. Astron.* **68**, 280408 (2025).
 - [123] Z.-Y. Peng and Y.-S. Piao, Dark energy and lensing anomaly in Planck CMB data, *Phys. Rev. D* **112**, 023502 (2025).
 - [124] P. Mukherjee and A. A. Sen, A new $\sim 5\sigma$ tension at characteristic redshift from DESI-DR1 BAO and DES-SN5YR Observations, [arXiv:2503.02880](https://arxiv.org/abs/2503.02880).
 - [125] J.-Q. Jiang, D. Pedrotti, S. S. da Costa, and S. Vagnozzi, Nonparametric late-time expansion history reconstruction and implications for the Hubble tension in light of recent DESI and type Ia supernovae data, *Phys. Rev. D* **110**, 123519 (2024).
 - [126] L. Huang, R.-G. Cai, and S.-J. Wang, The DESI 2024 hint for dynamical dark energy is biased by low-redshift supernovae, [arXiv:2502.04212](https://arxiv.org/abs/2502.04212).
 - [127] I. D. Gialamas, G. Hütsi, K. Kannike, A. Racioppi, M. Raidal, M. Vasar, and H. Veermäe, Interpreting DESI 2024 BAO: Late-time dynamical dark energy or a local effect?, *Phys. Rev. D* **111**, 043540 (2025).
 - [128] B. R. Dinda and R. Maartens, Physical vs phantom dark energy after DESI: thawing quintessence in a curved background (2025).
 - [129] N. J. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee, S. Sarkar, and J. Colin, A test of the cosmological principle with quasars, *Astrophys. J. Lett.* **908**, L51 (2021).
 - [130] N. J. Secrest, S. von Hausegger, M. Rameez, R. Mohayaee, and S. Sarkar, A challenge to the standard cosmological model, *Astrophys. J. Lett.* **937**, L31 (2022).
 - [131] A. Sah, M. Rameez, S. Sarkar, and C. G. Tsagas, Anisotropy in PANTHEON+ supernovae, *Eur. Phys. J. C* **85**, 596 (2025).
 - [132] M. Zumalacárregui, E. Bellini, I. Sawicki, J. Lesgourgues, and P. G. Ferreira, `HI_CLASS`: Horndeski in the Cosmic Linear Anisotropy Solving System, *J. Cosmol. Astropart. Phys.* **08** (2017) 019.
 - [133] E. Bellini, I. Sawicki, and M. Zumalacárregui, `HI_CLASS` background evolution, initial conditions and approximation schemes, *J. Cosmol. Astropart. Phys.* **02** (2020) 008.
 - [134] D. Blas, J. Lesgourgues, and T. Tram, The Cosmic Linear Anisotropy Solving System (CLASS). Part II: Approximation schemes, *J. Cosmol. Astropart. Phys.* **07** (2011) 034.
 - [135] M. S. Madsen, Scalar fields in curved space-times, *Classical Quantum Gravity* **5**, 627 (1988).

End Matter

Units and initial conditions—For the parameters in the nonminimally coupled dark energy model given by Eqs. (1) and (2), ξ is dimensionless, V_0 is in units of $M_{\text{Pl}}^2 M_{\text{H}}^2$ (where $M_{\text{H}} = H_0/h$), β is in units of $M_{\text{Pl}} M_{\text{H}}^2$, and m^2 is in units of M_{H}^2 . We use `HI_CLASS` [132–134] to compute the theory predictions, starting the field at $\varphi_{\text{ini}} = 0$ and $\varphi'_{\text{ini}} = 10^{-3}$ to ensure it starts rolling. Current data only probe a small part of the potential $V(\varphi)$ and are not sensitive to its full shape. In fact, it is the shape of the potential at $|\varphi| > |\varphi_{\text{ini}}|$ that determines the field dynamics. As a consequence, there is little loss of generality by setting $\varphi_{\text{ini}} = 0$. Finally, we tune V_0 to ensure that the Friedmann equations close (i.e., ensure that the sum of all fractional densities $\sum_i \Omega_i = 1$).

Quadratic approximation—Although restricting F and V to quadratic functions may seem limiting, observables are sensitive to only a narrow range of the scalar field's evolution [$\Delta\varphi/M_{\text{Pl}} \sim \mathcal{O}(0.1)$], which makes the expansion in Eq. (2) sufficient. In order to prove this, we expanded the potential out to the cubic term to confirm that this term does not significantly affect the evolution of the model. We found that including a cubic term with a coefficient of the same order as the quadratic term only imparts percent level deviations on the model's equation of state even today ($a = 1$), and

furthermore confirmed that including this term does not change the model's fit to the data ($\Delta\chi^2 \simeq 0.15$) or the mean values of the posterior constraints on the leading order model parameters. Moreover, the data do not have constraining power over this cubic term, recovering its prior range, centered at zero. Finally, note that we used the freedom to shift the scalar field to remove the linear term in the nonminimal coupling, as this merely corresponds to a constant shift in the scalar field.

This approach captures a broad class of nonminimally coupled scalar field models, serving as a model-agnostic parametrization valid for any thawing scalar field with a nonderivative nonminimal coupling. For instance, it includes models with exponential and hilltop potentials [13,38,43], as they admit an expansion like Eq. (2).

Nonminimal dynamics—Figure 5 depicts the evolution of the best fit models for all dark energy models considered in this Letter. Note also that the best fit nonminimally coupled model closely tracks the best fit CPL model, as this model can undergo significant, rapid evolution in the regime where most of the data is ($z \in [2.0, 0.2]$), whereas the minimally coupled quintessence model has most of its dynamical evolution in very recent epochs, largely outside the regime where the data has most of its constraining power.

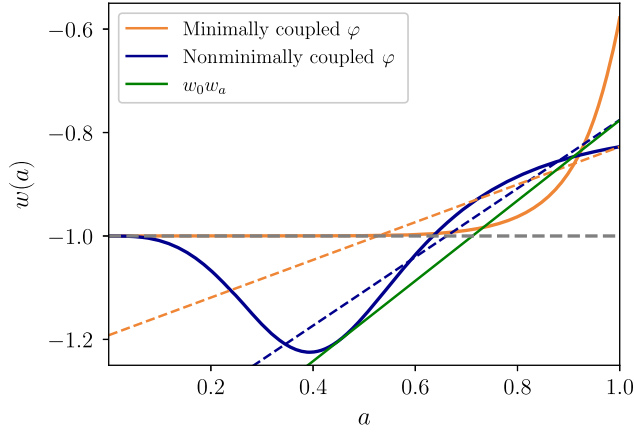


FIG. 5. Best-fit models for the various dark energy theories considered in this Letter (solid lines), alongside their best-fit (w_0, w_a) parameters (dashed lines) determined by fitting the CPL model to their observables predictions in the manner described in [12,14].

Note also, in this figure one can see that the non-minimally coupled model initially behaves approximately as a minimally coupled scalar field during radiation domination ($R \simeq 0$) with $w \simeq -1$, then subsequent evolution drives the effective equation of state into the phantom regime, and finally the potential takes over to cause the field to thaw. To see this more explicitly, one can also schematically write the equation of state for this model in the following way [135]:

$$w = \frac{P}{\rho} = \frac{\frac{1}{2}\dot{\phi}^2 - V + \xi F(\phi\dot{\phi}, \dot{\phi}^2, \phi\ddot{\phi})}{\frac{1}{2}\dot{\phi}^2 + V + \xi G(\phi\dot{\phi}, \dot{\phi}^2, \phi\ddot{\phi})}, \quad (\text{C1})$$

where F and G are functions of the scalar field and its time

derivatives. At early times, the Hubble friction freezes the field ($\dot{\phi} \simeq \ddot{\phi} \simeq 0$) and the equation of state approximates that of a minimally coupled model, and then once the field begins rolling the equation of state can undergo the evolution we have discussed.

Sampling and priors—For dark energy, we consider three models: (i) nonminimally coupled quintessence, with $\xi \in [0, 4.0]$, $\beta \in [0, 10]$, and $m^2 \in [-10, 10]$; (ii) minimally coupled quintessence, corresponding to the model studied in [12,23], where $V(\phi) = V_0 + \frac{1}{2}m^2\phi^2$, with $V_0 \in [-0.5, 1.5]$ and $m^2 \in [-100, 5]$; and (iii) the CPL parameterization, with $w_0 \in [-2, 0]$ and $w_a \in [-2.5, 1.5]$. We adopt uniform priors on all cosmological and dark energy parameters, varying the standard cosmological parameters $\{\Omega_b h^2, \Omega_m, H_0, \ln 10^{10} A_s, n_s, \tau\}$ while keeping the neutrino mass fixed to $\sum m_\nu = 0.06$ eV.

Bayesian evidence is of course sensitive to the choice of priors. For the nonminimally coupled model, we choose wide priors over a range that keeps our model coefficients at $\mathcal{O}(1)$ (which again we think of as Taylor expansion coefficients). As noted in [16], offsetting a Bayes factor of $\Delta \log \mathcal{Z} \simeq 5$ in the case of CPL would require a volume prior expansion of $\simeq 100$. Here, offsetting a Bayes factor of $\Delta \log \mathcal{Z} \simeq 7$ would require expanding the prior volume by $\simeq 1000$. Similarly, the prior volume could be expanded by a factor of $\simeq 10$ and the evidence for the nonminimally coupled dark energy model would remain strong. The case for minimally coupled thawing quintessence is slightly different. As the likelihood is widely insensitive to the negative end of m^2 (see Ref. [12] Fig. 6), and the uniform prior on m^2 is normalized, the Bayesian evidence remains approximately constant when modifying the lower limit of the prior range for m^2 .