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Hints of Nonminimally Coupled Gravity in DESI 2024 Baryon Acoustic Oscillation Measurements


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The cosmic microwave background (CMB) and baryon acoustic oscillations (BAO) are two of the most robust observations in cosmology. The recent BAO measurements from the DESI collaboration have presented, for the first time, inconsistency between BAO and CMB within the standard cosmological model Λ CDM, indicating a preference for dynamical dark energy over a cosmological constant. We analyze the theoretical implication of the DESI BAO observation for dark energy and gravity employing a nonparametric reconstruction approach for both the dark energy equation of state $w_{\text{DE}}(a)$ and the effective field theory coefficients. We find that the DESI data can rule out quintessence dark energy by indicating a crossing of the phantom divide at $z \lesssim 1$. Furthermore, when analyzed within the broad context of Horndeski gravity which includes general relativity and many known modified gravity theories such as generalized Galileons, $f(R)$, and Brans-Dicke, our result implies that gravity should be nonminimally coupled to explain the observations, establishing the DESI result as the first hint of modified gravity. Based on these insights, we propose the *thawing gravity* model to explain the nonminimal coupling and phantom crossing indicated by observation, which also fits better to DESI BAO, CMB, and type Ia Supernovae data than Λ CDM.

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The cosmic microwave background (CMB) and baryon acoustic oscillations (BAO) measure with great precision the same sound horizon scale at eras in the evolution of the Universe that are separated by billions of years, thus offering one of the most stringent consistency tests of the cosmological model. CMB and BAO observations have remained consistent within the *standard model* of cosmology, Λ CDM, in the past two decades, until recently inconsistency has aroused with the new BAO measurement from DESI DR1 [1,2], pointing to new physics beyond the standard model, especially dynamical dark energy (DE). Analyzed within $w_0 w_a$ CDM, i.e., a universe described by general relativity (GR), filled with radiation, ordinary matter, cold dark matter (CDM), and a DE component with an equation of state $w_{\text{DE}}(a) = w_0 + w_a(1 - a)$ (CPL) [3,4], dynamical DE is preferred over Λ CDM at 2.5σ , 3.5σ , 3.9σ in the joint analysis with CMB, BAO, and the type Ia supernova (SNIa) data from Pantheon+ [5], Union [6] or DES Y5 [7], respectively [1,2]. This has prompted the exploration of theoretical models that could embed it (see, e.g., [8–22]), as well as works that question the robustness of the result [23–35].

In this Letter, we employ a *nonparametric* approach to show that a generic implication of the DESI result is the *crossing of the phantom divide*; in fact, by directly reconstructing the DE equation of state $w_{\text{DE}}(a)$ from DESI + CMB + SNIa data, we show that it crosses -1 . This is of extreme theoretical importance because it implies that DE cannot be explained by a canonical scalar field (quintessence), which is the most widely studied DE theory. In fact, within quintessence, a crossing of the phantom divide corresponds to a negative sign in front of the kinetic term (ghost), which would lead to a Hamiltonian unbounded from below and severe problems both on the classical and quantum level [36].

This reveals the necessity of finding new explanations of DE with theoretically consistent treatment of both its background and perturbation dynamics. A natural and agnostic way to explore the broad theory landscape is offered by effective field theory (EFT) techniques, which allows to build an effective action out of all possible operators complying with the given set of symmetries for the system under consideration. Specific to cosmology, this is the EFTofDE [37,38], which assumes full spatial diffeomorphism symmetry (the *cosmological principle*) while time diffeomorphism invariance is broken in connection with a dynamical scalar field [DE or modified gravity (MG)] sourcing cosmic acceleration. Further requiring that

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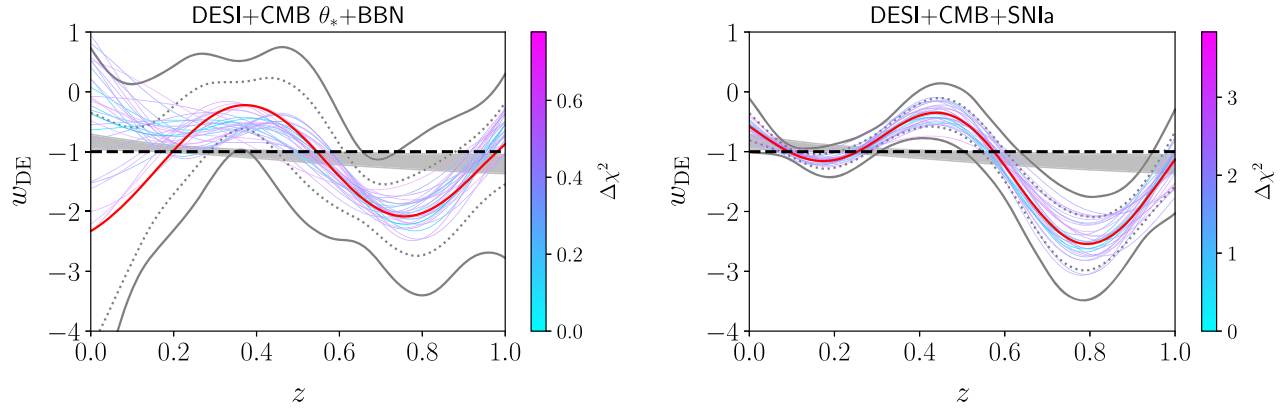


FIG. 1. Reconstructions of $w_{\text{DE}}(a)$ in the redshift range $0 < z < 1$. The black dashed line marks $w_{\text{DE}} = -1$, dotted and solid gray lines indicate the 68% and 95% confidence interval of the reconstructed w_{DE} , and the red line plots the mean function. The gray band represents the 95% posterior region of the DESI w_0w_a CDM result. To further illustrate the functional shape preferred by data, we plot 50 w_{DE} 's from the MCMC sample near the chain bestfit point in terms of χ^2 , with a color coding representing their χ^2 difference $\Delta\chi^2 = \chi^2 - \chi^2_{\text{bestfit}}$. Left panel: reconstruction with DESI BAO alone, aided by a BBN prior on ω_b and a CMB prior on the angular scale θ_* of recombination sound horizon. Right panel: reconstruction with the joint DESI + CMB + SNIa dataset.

the resulting equations of motion are of second order, one can identify the most general EFTofDE action describing the dynamics of the background and linear cosmological perturbations, characterized by five mutually independent free functions of time, dubbed EFT functions. The EFTofDE action fully describes the background and linear cosmological dynamics of the broad class of Horndeski gravity models [39], which includes general relativity [(GR), corresponding to all EFT functions being null], $f(R)$, and Brans-Dicke. Any Horndeski theories can be mapped to EFTofDE actions [40,41], and vice versa [42].

We adopt a data-driven nonparametric reconstruction approach for the EFT functions, which directly connects observational data with the vast theory space of Horndeski gravity through a model agnostic EFT. We find that the nonminimal coupling of gravity is required to explain the DESI observation. Our discovery establishes the DESI result, once confirmed, as the *first observational hint* of modified gravity. Based on the insights gained from the general EFT framework, we study an alternative theory of gravity, thawing gravity, that can naturally explain the phantom crossing and nonminimal coupling indicated by the DESI observation.

Dataset—We use the Monte Carlo Markov chain (MCMC) analysis to perform the reconstruction and fit models to data, with the MCMC setup detailed in Supplemental Material [43], which also includes references [44–66]. Unless otherwise specified, for all our analyses we use the following joint dataset: (i) DESI: the full BAO observation from DESI DR1 [1]; (ii) CMB: the CamSpec version of Planck PR4 high- ℓ TTTEEE [67] data; Planck 2018 low- ℓ TTEE [68] data; CMB lensing of Planck PR4 [69]; (iii) SNIa [70]: light curve observations of 1550 type Ia Supernovae (SNIa) compiled in the Pantheon + sample [5].

Nonparametric reconstruction of the equation of state—To exploit the information in data about dynamical DE and minimize the impact of parametrization as much as possible, we reconstruct $w_{\text{DE}}(a)$, without assuming any specific parametrization, by interpolation over five freely varying nodes $w_{\text{DE}}(z_i)$ in the MCMC at redshifts $z_i = \{0, 0.25, 0.5, 0.75, 1\}$, roughly covering the redshift range of DESI BAO; see Supplemental Material [43] for detailed setup.

The reconstructed $w_{\text{DE}}(z)$ is depicted in Fig. 1, with the DESI result assuming the CPL parameterization $w_{\text{DE}}(a) = w_0 + w_a(1 - a)$ [3,4] plotted as a gray band. As our main focus here is to assess the preference for phantom crossing in the observations, rather than focusing on the detailed reconstructed shape of w_{DE} ; we avoid including any theory driven correlation prior in the reconstruction. This has the advantage of relying solely on information from the data but risks overfitting the data, possibly leading to the oscillatory features in Fig. 1; see, e.g., [76,77] for further discussion. Importantly, despite the small scale oscillations, the reconstructed general trend of w_{DE} , and more specifically of its 95% confidence interval, shows that $w_{\text{DE}} > -1$ at $z = 0$ and $w < -1$ for $z > 0.6$ at 2σ level, in agreement with the reconstruction from DESI using a different method [78] [79] as well as their w_0w_a CDM result (gray band) [1]. Assuming a continuous w_{DE} , this leads to the parametrization-independent conclusion of phantom crossing at $z < 1$.

Exploration of phantom crossing within the EFTofDE—To connect with theory the observational findings, especially the phantom crossing behavior of the effective DE fluid identified in the previous section, we survey the gravitational landscape within the general EFT of DE/MG framework, as described in the introduction. In the notation of [81], the EFTofDE has five independent EFT functions

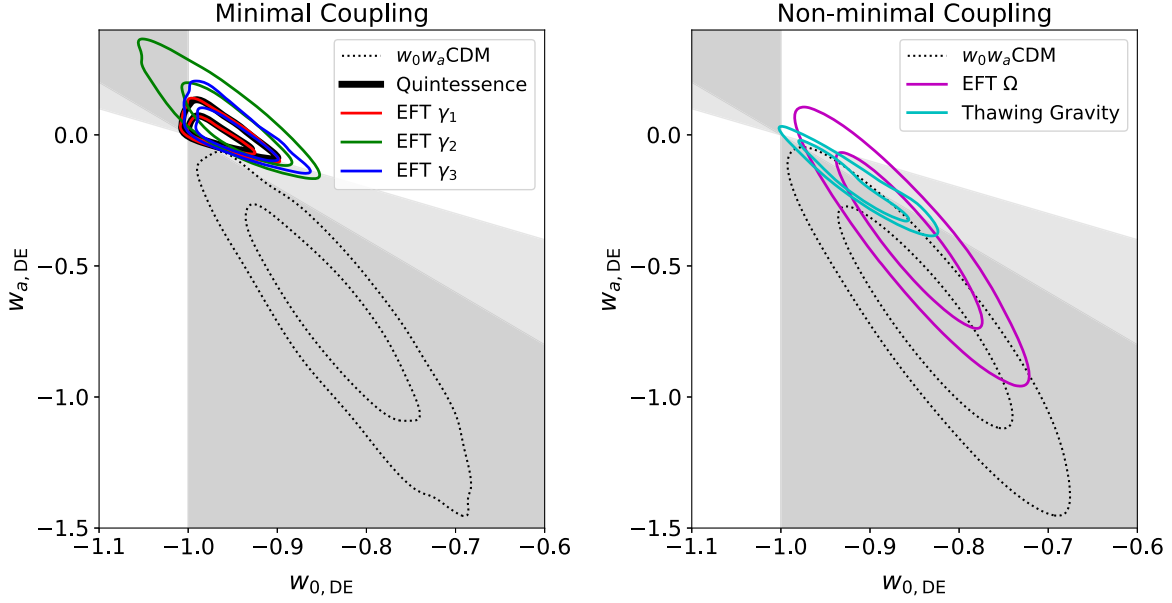


FIG. 2. Marginalized posterior distributions (68% and 95%) of $w_0 - w_a$ over the joint dataset CMB + DESI + SNIa of all models studied in this Letter. The reference $w_0 w_a$ CDM model with PPF DE perturbation is plotted with black dotted contours. The quintessence (black) contour overlaps with the EFT γ_1 result (red) so is plotted with thicker lines. Light gray shades mark the parameter regions for which phantom crossing happens, i.e. $(1 + w_0)(1 + w_0 + w_a) < 0$. Dark gray indicates regions where phantom crossing happens at low redshift, $z < 1$, i.e., $(1 + w_0)(1 + w_0 + w_a/2) < 0$.

of time $\{\Lambda, \Omega, \gamma_{1,2,3}\}$. One can eliminate one EFT function, Λ , by specifying the cosmological background $H(z)$ [82], which we do so by assuming a $w_0 w_a$ CDM background. Among the four remaining EFT functions $\{\Omega, \gamma_{1,2,3}\}$ to be reconstructed, Ω is the unique signature of nonminimal coupled gravity, while γ_i signal the presence of nonstandard kinetic terms and self-derivative couplings of the scalar field, e.g., k essence generally corresponds to $\Omega = 0$, $\gamma_1 \neq 0$, $\gamma_{2,3} = 0$. We reconstruct $\{\Omega, \gamma_1, \gamma_2, \gamma_3\}$ nonparametrically by binning them as functions of time using six nodes at $a \in [0.5, 0.6, 0.7, 0.8, 0.9, 1.0]$, corresponding to the redshift range $0 < z < 1$ most relevant to data; see Supplemental Material [43] for details. Despite of some concerns raised about concluding phantom crossing based on CPL [12,24,29,35,83], we have shown in the previous section that the indication of phantom crossing is a property of data independent of parametrization. Therefore, we can exploit the simplicity of CPL and assume a $w_0 w_a$ CDM background, which also has a clearly defined phantom crossing region suitable for visualization as depicted in Fig. 2. We reconstruct one EFT function at a time, fixing the remaining ones to their Λ CDM value. This method allows us to isolate more clearly the function, and the corresponding EFT operator, that allows for a safe phantom crossing [84].

The main result relevant to phantom crossing is summarized in Fig. 2, which for reference also includes a $w_0 w_a$ CDM cosmology with perturbation described by the parametrized post-Friedmann (PPF) approach [85] and a quintessence embedding of $w_0 w_a$ CDM, obtained by setting

the four EFT functions $\{\Omega, \gamma_1, \gamma_2, \gamma_3\}$ to their vanishing GR limit. More results are collected in Supplemental Material [43]. In Fig. 2, the posteriors of $\{\gamma_{1,2,3}\}$ are limited by the light gray region thus these EFT functions, when turned on separately, are unable to reliably stabilize the phantom crossing indicated by observation. More importantly, our results identifies Ω as the *only* operator able to lead the sampled EFT into the dark gray phantom crossing region where the DESI result resides. As Ω is the *only* EFT operator related to the nonminimal coupling of gravity, we therefore arrive at the enticing conclusion that *gravity should be modified to explain the recent observations*, establishing the DESI result as the first observational hint of modified gravity.

Thawing gravity—Based on the insight from previous discussion, we propose the following nonminimally coupled gravity theory:

$$L = \frac{M_p^2}{2} [1 - \xi(\phi/M_p)^2] R + X - V_0 e^{-\lambda\phi/M_p}, \quad (1)$$

where $\{\xi, V_0, \lambda\}$ are constant parameters and we assume $\xi > 0$ in this study. All species are nonminimally coupled to the same conformal factor in Eq. (1), but we stress that this is not necessarily the case in general; e.g., nonminimal coupling might be only in the dark sector. It can be checked that this model has a luminal tensor speed and is free of ghost and gradient instability.

Theory (1) provides rich dynamics with different combination of its three parameters $\{V_0, \lambda, \xi\}$. Here we will

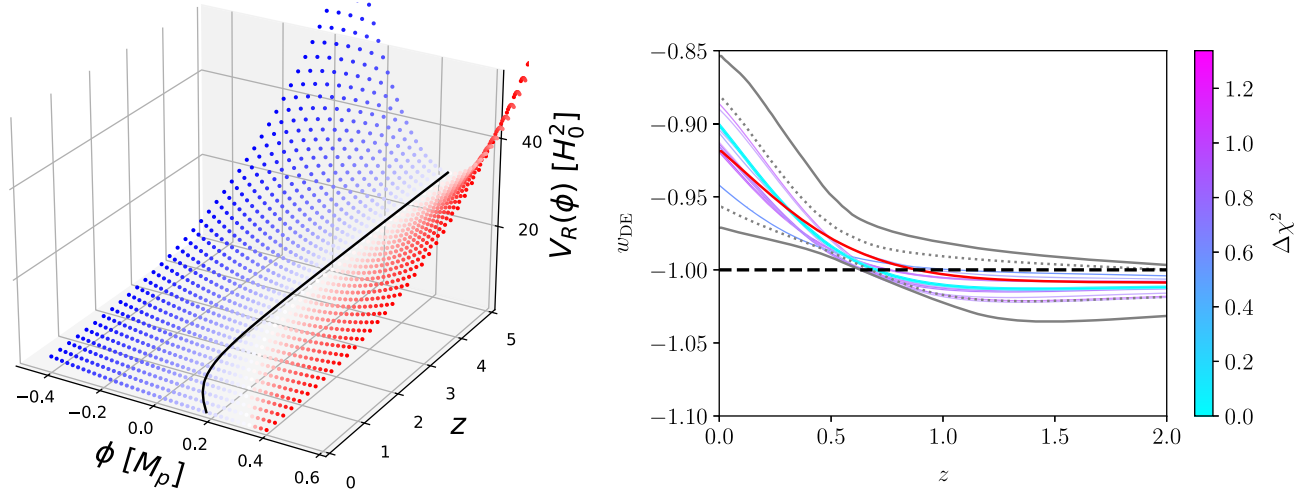


FIG. 3. Left panel: shape of the curvature dependent effective potential $V_R(\phi)$ of the nonminimal coupling theory (1), with $\xi = 0.65$, $\lambda = 1.4$, $V_0/3H_0^2 = 0.72$ taken from the bestfit cosmology. Potential surface is colored with respect to the strength of its gradient in the ϕ direction, with red for positive, blue for negative, and white for $dV_R/d\phi = 0$. Black solid line depicts the field trajectory output by the new EFTCAMB. Right panel: constraints on the functional shape of w_{DE} in the thawing gravity model (1). The gray dotted and solid lines represent the 68% and 95% posterior regions, respectively. Black dashed line marks the position of $w_{\text{DE}} = -1$. To further illustrate the w_{DE} shape in the DESI + CMB + SNIa constrained thawing gravity model, we also plot 50 w_{DE} 's from the MCMC sample near the chain bestfit point in terms of χ^2 , with a color coding representing their χ^2 difference $\Delta\chi^2 = \chi^2 - \chi^2_{\text{bestfit}}$.

only focus on the scenario that is of interest to explaining the DESI observation, which we dub as thawing gravity for reasons becoming clear soon. Theory (1) has an effective potential $V_R(\phi) = \frac{1}{2}\xi R\phi^2 + V_0 e^{-\lambda\phi/M_p}$ with one global minimum for $\xi > 0$. Initially when R dominates—more specifically, when $\xi M_p^2 R \gg \lambda V_0$ and $\xi M_p^2 R \gg \lambda^2 V_0$ —the global minimum is close to zero,

$$\phi_m \simeq \frac{\lambda V_0}{\xi M_p^2 R + \lambda^2 V_0} M_p \sim 0, \quad (2)$$

with $m_\phi^2|_{\phi=0} = (d^2V_R/d\phi^2) = \xi M_p^2 R + \lambda^2 V_0$. At early times (still in matter era), as long as ξ is not too small, the R dependent part of m_ϕ^2 is much larger than $\lambda^2 V_0$ (which approximates the DE energy scale), the field evolution is dominated by the quadratic part of V_R and ϕ is localized at the global minimum ϕ_m . As the Universe expands and R decreases, the second term in m_ϕ^2 starts dominating and the field starts rolling along the scalar potential $V_0 e^{-\lambda\phi/M_p}$, effectively thawing and deviating from ϕ_m . This leads to an effective Planck mass $M_{\text{eff}}^2 \equiv (1 - \xi\phi^2)M_p^2$ which decreases with time. The left panel of Fig. 3 further illustrates this dynamical picture by plotting $V_R[\phi(z)]$ as a two dimensional surface and the field evolution trajectory, for the bestfit model from our joint DESI + CMB + SNIa analysis.

Fitting the thawing gravity (1) to DESI + CMB + SNIa, we plot the resulting $w_{\text{DE}} \equiv (-2\dot{H} - 3H^2 - P_m/3H^2 - \rho_m)$, where the subscript “m” refers to all species except for DE, in the right panel of Fig. 3. We collect the detailed numerical

setup and results in Supplemental Material [43], but it is worth mentioning here that thawing gravity only has two free parameters ξ and λ , while V_0 is determined by the DE energy scale, which makes thawing gravity having the same number of parameters as $w_0 w_a$ CDM. All of the plotted w_{DE} trends in Fig. 3, as well as the mean functions, display phantom crossing behavior in $0.5 < z < 1$, consistent with what we observe in the nonparametric reconstruction. Figure 3 indicates that for the thawing gravity model the linear approximation of CPL works to some extent in the redshift range $0 < z < 1$. We thus derive the effective w_0, w_a for each sampled point in the chain by least square fitting the actual $w_{\text{DE}}(a)$ to the CPL parametrization in $0 < z < 1$. The resulting (w_0, w_a) posterior is shown in Fig. 2; one can notice that it appears skewed, as expected, since it is associated to a linear approximation of the actual, theoretically derived w_{DE} . As shown in Figs. 2 and 3, thawing gravity provides a theoretical, covariant realization of the reconstructed EFT Ω as well as a natural way to implement phantom crossing in favor of DESI BAO, confirming conclusion obtained in the previous sections. Thawing gravity also fits better all data in the joint the dataset, with $\Delta\chi^2_{\text{DESI}} = -2.1$, $\Delta\chi^2_{\text{CMB}} = -1.8$ and $\Delta\chi^2_{\text{SNIa}} = -1.9$ compared with Λ CDM, see Supplemental Material [43] for details. Before concluding, we have to stress that these χ^2 improvements are not enough to claim evidence for thawing gravity over Λ CDM due to the additional parameters added.

Final remarks—The recent BAO measurements from DESI DR1 reveal an inconsistency between CMB and BAO when analyzed within Λ CDM, leading to a $\sim 3\sigma$ preference for dynamical dark energy in $w_0 w_a$ CDM. In this Letter we

showed the profound theoretical implications on DE and gravity of this finding. First, we confirmed phantom crossing at $z < 1$ as another important indication of the DESI observation, which rules out the most widely studied dark energy theory, quintessence. More importantly, our finding established that the DESI result, if confirmed, provides in fact the first observational hint of modified gravity, indicating that gravity is nonminimally coupled to matter contrary to what is postulated in GR. Based on these insights, we proposed a nonminimally coupled alternative theory of gravity, thawing gravity, which naturally explains the phantom crossing while also fitting DESI BAO, CMB, and SNIa better than Λ CDM.

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