Proceedings of CONF-CIAP 2026 Symposium: International Conference on Atomic Magnetometer and Applications
DOI: 10.54254/2753-8818/2026.HZ27970

Effective Field Theory of Dark Energy: From Parameters to Observables

Kangti Dong

Guanghua Cambridge International School, Shanghai, China
ktdong@outlook.com

Abstract. The accelerating expansion of the Universe poses a fundamental challenge to our understanding of gravity and particle physics. This paper reviews the Effective Field Theory (EFT) of Dark Energy, a powerful framework for systematically exploring deviations from ΛCDM cosmology while maintaining consistency with observations and examines how Type Ia supernovae, cosmic microwave background measurements, and large-scale structure surveys have established dark energy as the dominant component of the Universe. The EFT approach organizes possible modifications to General Relativity through a set of parameters that control background expansion, scalar perturbations, and tensor modes. These parameters produce distinct observational signatures in structure formation, gravitational wave propagation, and cosmological distances. The paper discusses current constraints from Planck and other surveys, highlighting remaining degeneracies between parameters. The framework's predictive power is demonstrated through its applications to dark energy-dark matter interactions and modified gravity scenarios, and the emphasis of how future observations from Euclid, LSST, and CMB-S4 will test these predictions with unprecedented precision. Not only does EFT provide a common language for comparing diverse theories, but also reveals deep connections between cosmological acceleration and fundamental physics. This approach offers a systematic path to unraveling the nature of dark energy and testing gravity on cosmic scales by bridging theory and observations.

Keywords: Effective Field Theory, dark energy, modified gravity, cosmological parameters, observational constraints

1. Introduction

The studies of Type Ia supernovae provided evidence for the accelerated expansion of the Universe. This discovery is arguably one of the breakthroughs in modern cosmology, which appears to be counter-intuitive: In a universe consisting of matter only--including baryonic and dark matter--the expansion is decelerated due to gravitational attraction between bodies. On the other hand, the cosmological constant, the simplest explanation of accelerated expansion, had a checkered history with multiple invocations followed by withdrawals. However, subsequent observations--including more detailed studies of supernovae and independent evidence from clusters of galaxies, large-scale structure, and the cosmic microwave background (CMB)--confirmed and firmly established this remarkable finding [1].

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DOI: 10.54254/2753-8818/2026.HZ27970

The acceleration of the expansion of the universe poses a fundamental challenge to the standard models of both particle physics and cosmology. Thus, it requires an unknown physical component, called dark energy or modification of gravitation, possibly arising from extra dimensions, to be added to both cases [2]. The universe today comprises of ~5% baryons, ~27% dark matter, and ~68% dark energy [3], in which there is a key challenge remaining unresolved in the nature of dark energy—whether it's a cosmological constant (Λ), a dynamical field (quintessence), or a sign of modified gravity.

2. Effective field theory (EFT) of dark energy

2.1. Fundamentals of EFT formalism

EFT provides a powerful framework for describing low-energy physics by systematically integrating out high-energy degrees of freedom while preserving the underlying symmetries and locality of the system. The formalism depends on the separation of scales, where physical processes at energies much lower than a cutoff scale can be described by an expansion of the Lagrangian in terms of local operators organized by their dimension, whose expansion takes the form:

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\leq 4} + \sum_{\mathscr{D}\geq 5} \frac{c_i^{(\mathscr{D})} \mathscr{O}_i^{(\mathscr{D})}}{\Lambda^{\mathscr{D}-4}} \tag{1}$$

Where $\mathscr{O}_i^{(\mathscr{D})}$ higher-dimension operators weighted by coefficients $c_i^{(\mathscr{D})}$ that encode the effects of the high-energy physics, andΛ is the cutoff scale. The power counting of these operators follows a systematic expansion in the small parameter $\frac{p}{\Lambda}$ to ensure predictive control over the low-energy behavior of the theory.

In cosmological applications, EFT methods have proven particularly valuable for studying dark energy and modified gravity scenarios via the Arnowitt-Deser-Misner (ADM) formalism [4], which is commonly employed to describe perturbations around a homogeneous background, with the action constructed from geometric quantities such as the extrinsic curvature $K_{\mu\nu}$ and the three-dimensional Ricci scalar R. The framework incorporates important stability conditions—including the absence of ghosts and gradient instabilities—which constrain the form of the EFT Lagrangian and ensure physical consistency [5].

2.2. Dark energy EFT parameters and their physical significance

2.2.1. Background evolution parameters

The background expansion of the universe is modified by the EFT functions $\Lambda(t)$ and $c(t)$, which appear in the zeroth-order action. These functions effectively act as a time-dependent cosmological constant and kinetic energy for the scalar degree of freedom, respectively. The function $d(t)$ modifies the extrinsic curvature term and influences the background Friedmann equations, leading to an effective dark energy equation of state $w(t)$ that can deviate from -1.

At the perturbation level, the EFT introduces several key parameters that control stability and observational signatures: α_K (kineticity) governs the kinetic energy of scalar perturbations and must be positive (α_K >0) to avoid ghost instabilities [5]; α_B (braiding) mixes the kinetic terms of the scalar field and metric perturbations, modifying the sound speed of scalar fluctuations and influencing structure growth; α_M (Planck mass run rate) quantifies the time variation of the

DOI: 10.54254/2753-8818/2026.HZ27970

effective Planck mass (M^{*2}), leading to gravitational slip ($\Psi \neq \Phi$) in the Newtonian gauge [6]; and α_T (tensor speed excess) modifies gravitational wave propagation speed ($c_T^2 = 1 + \alpha_T$), tightly constrained by multi-messenger observations [7].

2.2.2. Interacting dark energy parameters

When dark energy couples to dark matter, additional EFT parameters emerge: α_{m1}, α_{m2}, $\alpha_{\bar{m}1}$ describe energy and momentum transfer between dark sectors. α_{m1} mediates energy exchange through time-varying DM mass, while α_{m2} and $\alpha_{\bar{m}1}$ parameterize momentum transfer via DM velocity couplings [7]. These interactions modify the effective gravitational coupling (G_{eff}) felt by DM perturbations.

2.3. Parameter space and theoretical constraints

The Effective Field Theory (EFT) of dark energy and modified gravity provides a systematic way to parameterize deviations from General Relativity (GR) while ensuring theoretical consistency. To avoid unphysical behavior (e.g., ghosts, gradient instabilities, or superluminal propagation), the EFT coefficients must satisfy stability conditions derived from fundamental principles (e.g., unitarity, causality, and positivity bounds). Additionally, theoretical priors are imposed to restrict the parameter space based on consistency with quantum field theory (QFT) and gravitational physics.

3. Observational signatures of EFT parameters

3.1. Effects on the background evolution

EFT parameters modify the Hubble expansion rate $H(z)$ and relations between distance and redshift, including modifying the Friedmann equation, equation of state, and providing early-time scaling solutions:

In modifying the Friedmann equation, EFT corrections introduce terms such as $\delta H^2 \sim c(t)\delta g^{00}$ or $\Lambda(t)$, altering $H(z)$ at late times. This is observable in deviations in $H(z)$ from supernovae (SNe Ia) and baryon acoustic oscillations (BAO). Furthermore, EFT functions mimic dynamical dark energy (e.g. $w \neq 1$), which is observable in time-varying $w(z)$ reconstructed from luminosity distances ($d_L(z)$) [4]. In addition, EFT can enforce enforce $\frac{\rho_{DE}}{\rho_m} \approx constant$ during matter domination, which is observable in anomalies in CMB distance-ladder consistency (e.g. sound horizon r_d vs H_0) [3].

3.2. Effects on perturbations

The EFT framework modifies standard cosmological perturbations through several key parameters [5]. These parameters alter structure formation, gravitational wave propagation, and dark energy behavior.

For scalar perturbations, the effective Newton's constant G_{eff} differs from GR due to braiding (α_B) and kineticity (α_K) terms. The gravitational slip parameter η emerges from Planck mass evolution (α_M) and modified GW speed (α_T) [5].

Tensor perturbations are affected by $\alpha_T = c_T^2 - 1$, which modifies gravitational wave propagation speed. Observations like GW170817 strongly constrain this parameter [7]. The friction

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term α_M alters GW amplitude damping during cosmic propagation [8].

Dark energy clustering depends on α_K and α_B parameters, influencing both the matter power spectrum and integrated Sachs-Wolfe effect. Current constraints come from CMB (Planck) and large-scale structure surveys, with future missions like Euclid expected to provide tighter bounds.

3.3. Distinguishing EFT signatures

The EFT of dark energy and modified gravity provides a systematic way to classify deviations from General Relativity (GR) and the Λ CDM model as shown in Table 1. By organizing operators according to their symmetry properties and derivative structure, the EFT framework captures distinct observational signatures that help distinguish between different theories.

A fundamental signature of modified gravity theories is the modification of gravitational wave (GW) propagation. The EFT parameter α_T quantifies deviations from the luminal speed of GWs ($c_T^2 = 1 + \alpha_T$). While GR predicts $c_T = 1$, many modified gravity models allow $c_T \neq 1$. However, multi-messenger observations (e.g., GW170817) constrain $\alpha_T \approx 0$, ruling out many models unless they satisfy $c_T = 1$. In contrast, scalar perturbations are sensitive to the sound speed c_s^2, which depends on α_K (kineticity) and α_B (braiding). $c_{s^2} < 1$ leads to enhanced clustering, while $c_{s^2} < 0$ indicates gradient instabilities. These effects are observable in large-scale structure (LSS) and weak lensing surveys [5].

α_M introduces a time-varying effective Planck mass, leading to gravitational slip. That is, $\Psi \neq \Phi$, where Ψ and Φ are the Newtonian gauge potentials. This modifies the growth of structure and alters weak lensing observables. A non-zero α_M suppresses structure growth at late times, potentially alleviating the σ_8 tension [9]. Additionally, α_B mixes scalar and metric perturbations, altering the effective gravitational coupling G_{eff} felt by matter. This modifies the growth rate $f\sigma_8$ and can be tested using red-shift-space distortions (RSD) in galaxy surveys [2].

When dark energy (DE) and dark matter (DM) interact, new EFT parameters (α_{m1}, α_{m2}, $\alpha_{_m1}$) emerge, describing energy and momentum transfer. These interactions modify the effective DM gravitational coupling G_{eff}, leading to suppressed structure growth at low red-shifts. Such effects are distinguishable from pure modified gravity scenarios and can be tested using cosmic shear and galaxy clustering [7].

4. Observational data and constraints

4.1. Current cosmological data

This section presents constraints on cosmological parameters derived from Planck PR4 data (Final Data Release) using an improved angular power spectrum likelihood method (HiLLiPoP V4.2). The results refine previous measurements with 10–20% smaller uncertainties and improved consistency with theoretical expectations [9].

4.2. Case study: application of EFT on coupled dark energy-dark matter (DE-DM) systems

The study presents a framework that systematically describes interactions between dark energy (DE) and dark matter (DM) through both energy and momentum transfer. It builds on previous work in modified gravity and dark sector couplings, offering a unified approach that accommodates both vector-tensor and scalar-tensor theories of DE while maintaining theoretical consistency [7]. Using

DOI: 10.54254/2753-8818/2026.HZ27970

the Arnowitt-Deser-Misner (ADM) formalism and working in unitary gauge, the authors derive the background equations of motion, second-order perturbed action, and linear perturbation equations.

The analysis identifies three primary coupling mechanisms: energy transfer parameterized by α_{m1} , momentum transfer, and time-varying DM mass. The stability conditions are derived to ensure theoretical consistency, including a no-ghost condition and Laplacian stability requirements ($c_s^2 > 0$ for DE perturbations). These interactions can modify structure formation by altering the effective gravitational coupling. In particular, the framework demonstrates that G_{eff} can be smaller than Newton's constant at low red-shifts, with momentum transfer effects capable of suppressing matter clustering

Moreover, the study highlights several observational implications, providing testable signatures for the matter power spectrum, weak lensing measurements, and CMB anisotropies. Notably, the framework offers a potential resolution to the σ_8 tension—the observed discrepancy between early- and late-universe measurements of matter clustering—by naturally suppressing structure growth at late times. The EFT approach enables model-independent constraints on DE-DM interactions, making it particularly valuable for analyzing data from current and future cosmological surveys such as Planck, DES, Euclid, and LSST.

Table 1. Base ΛCDM Parameters--the standard 6 parameters in theΛCDM model are constrained using CMB temperature (TT), polarization (TE/EE), and their combination (TTTEEE)

Parameter	TT Constraints	TE Constraints	EE Constraints	Combined(TTTEEE)
$\Omega_b h^2$ (Baryon density)	0.02224±0.00025	0.02238±0.00020	0.02283±0.00081	0.02226±0.00013
$\Omega_c h^2$ (CDM density)	0.1183±0.0024	0.1172±0.0017	0.1169±0.0035	0.1188±0.0012
$100\theta_*$ (Acoustic scale)	1.04123±0.00046	1.04151±0.00041	1.04001±0.00059	1.04108±0.00026
$\ln(10^{10} A_s)$ (Primordial amplitude)	3.073±0.061	3.030±0.028	3.077±0.039	3.040±0.014
n_s (Scalar spectral index)	0.9678±0.0072	0.9689±0.0091	0.9797±0.0110	0.9681±0.0039
τ (Re-ionization optical depth)	0.0753±0.0322	0.0572±0.0065	0.0582±0.0066	0.0580±0.0062

DOI: 10.54254/2753-8818/2026.HZ27970

Table 2. Derived parameters

Parameter	Value with units	Significance
Hubble constant(H_0)	67.64±0.52km/s/Mpc(TTTEEE)	Current expansion rate of the universe
Matter fluctuation amplitude (σ_8)	0.8070±0.0065	The root-mean-square density fluctuations of matter on scales of 8Mpc/h
$S_8 = \sigma_8\left(\frac{\Omega_m}{0.3}\right)$	0.819±0.014	Amplitude of late-time structure growth
Matter density (Ω_m)	0.3092±0.0070	Total matter (dark+baryonic) density relative to the critical density

5. From parameters to observables

5.1. Mapping EFT parameters to physical quantities

The EFT of Inflation provides a systematic framework for mapping abstract Lagrangian coefficients to measurable cosmological quantities. To start with, the parameters are normalized through canonical transformations, where coefficients like α_0, γ_1, β_i are re-scaled into dimensionless form using the energy scale f_π. For instance, the parameter $f_\pi^4 \equiv \alpha_0 - 2\alpha_1$ defines the EFT cutoff scale $\Lambda = 4\pi\mathrm{f}_\pi$, while the field redefinition $\pi \equiv f_\pi^2 \pi_r$ ensures canonical normalization of perturbations. These re-scaled parameters directly determine physical properties: the speed of sound $\mathrm{c_s^2} \equiv \frac{\alpha_0}{\mathrm{f}_\pi^4}$ governs the propagation of curvature perturbations, while dissipation $\gamma \equiv \frac{2\gamma_1}{f_\pi^4}$ and noise amplitudes $\beta_\mathrm{i} \equiv \frac{\beta_\mathrm{i}}{\mathrm{f}_\pi^4}$ quantify energy transfer and stochastic fluctuations from environmental interactions.

The EFT parameters imprint distinct signatures on cosmological observables. The primordial power spectrum Δ_ζ^2 scales as $\frac{H^4}{f_\pi^4}$ but receives corrections from dissipation (γ) and noise (β_1), encoded in a function $\mathscr{F}\left(\frac{\gamma}{H}, \beta_1\right)$. Non-Gaussianity, characterized by f_{NL}, arises from higher-order interactions with an amplitude $f_{NL} \sim \delta_1 \frac{H+\gamma}{\beta_1^2}$ that peaks for folded momentum configurations ($k_1 \approx k_2 + k_3$) due to environmental coupling. These predictions are matched to specific ultraviolet (UV) completions—for example, a model with an inflation ϕ interacting with a massive field χ yields $\gamma \simeq \frac{\xi m^4 e^{2\pi\xi}}{\pi m f^2}$, where ξ parameterizes particle production efficiency.

Theoretical consistency imposes constraints on the EFT parameter space. Stability requires the absence of ghosts ($q_s > 0$) and gradient instabilities ($c_s^2 > 0$). Observations further restrict parameters: CMB data bound the dissipation ratio $\frac{\gamma}{H} < 80$ to avoid excessive non-Gaussianity, while canonical inflation models typically require $c_s^2 \approx 1$[8].

5.2. Practical challenges: degeneracies in EFT parameters and observational uncertainties

The EFT framework provides a powerful systematic approach for studying dark energy and modified gravity models beyond the standard Λ CDM paradigm. However, this approach faces significant challenges due to inherent parameter degeneracies and observational uncertainties that

DOI: 10.54254/2753-8818/2026.HZ27970

complicate the interpretation of cosmological data [5]. These degeneracies arise when different combinations of EFT parameters produce nearly identical observational signatures across various cosmological probes, while observational uncertainties stem from limitations in current and upcoming surveys.

At the background level, different mixtures of EFT parameters can generate identical Hubble expansion histories $\mathrm{H(z)}$, masking potential deviations from ΛCDM. For instance, variations in the kineticity parameter and braiding parameter can produce the same background expansion while predicting different structure formation histories. This degeneracy is particularly problematic when attempting to identify deviations from general relativity using only background cosmological observations, as noted in recent analyses of large-scale structure surveys.

The situation becomes more complex when considering perturbations. The growth rate of structure exhibits degeneracies between parameters affecting the effective gravitational coupling and those influencing the dark energy sound speed. The momentum transfer parameters can suppress G_{eff} in ways that mimic potential resolutions to the σ_8 tension, creating confusion with other possible solutions like massive neutrinos. Furthermore, while the requirement of luminal gravitational wave propagation constrains the tensor sector parameter (α_{T}) to zero, it leaves degeneracies among scalar sector parameters unresolved.

Observational uncertainties compound these theoretical challenges. In CMB measurements, tensions between different power spectrum estimators (TT, TE, EE) lead to variations in derived parameters like the sound horizon angle θ^* and σ_8 in Table 2. These discrepancies propagate into uncertainties when constraining EFT parameters such as α_{M} (governing Planck mass evolution) and α_{B}[9]. Large-scale structure surveys face their own limitations, particularly regarding the quasi-static approximation which breaks down at scales $\mathrm{k} \gtrsim 0.1$ h/Mpc, requiring full perturbation calculations for accurate modeling.

5.3. Framework for future surveys

Future cosmological surveys will focus on constraining several key EFT parameters that govern deviations from general relativity and the standard cosmological model. The kineticity parameter α_K modifies the scalar field's kinetic term and affects the sound speed, making it measurable through CMB lensing and galaxy clustering observations. The braiding parameter α_{B}, which mixes scalar and tensor perturbations and alters structure growth, can be constrained using redshift-space distortions and weak lensing data. The Planck mass run rate α_{M}, describing time variation in the effective Planck mass, is accessible through CMB polarization measurements and gravitational wave observations [6]. Additionally, parameters like α_T (tensor speed excess) and α_{m1}, α_{m2} (dark matter-dark energy couplings) provide crucial tests of modified gravity theories through gravitational wave detectors and small-scale clustering analyses [8].

To effectively break degeneracies between these parameters, future surveys must employ a multi-probe observational strategy [2]. The combination of CMB-S4's high-precision polarization measurements with large-scale structure data from Euclid and LSST will be particularly powerful in disentangling the effects of α_{B} and α_{K}. Gravitational wave standard sirens from LISA and ground-based detectors will independently constrain α_{T}, offering complementary tests of modified gravity [7]. At smaller scales, the EFT of Large-Scale Structure (EFTofLSS) extends perturbation theory into the mildly nonlinear regime, improving constraints on dark matter-dark energy coupling parameters. This multi-faceted approach ensures a comprehensive exploration of the parameter space while mitigating the limitations of individual probes.

DOI: 10.54254/2753-8818/2026.HZ27970

Despite its strengths, the EFT framework faces several challenges that must be addressed for optimal application to future surveys. The breakdown of the quasi-static approximation at small scales ($k \gtrsim 0.1$ h/Mpc) necessitates the use of full Boltzmann codes like CLASS_EFT for accurate modeling. Theoretical systematics, including baryonic effects and intrinsic alignments, can introduce biases in parameter constraints if not properly accounted for. Additionally, the high-dimensional parameter spaces characteristic of EFT analyses require sophisticated statistical techniques and computational resources to ensure efficient and reliable parameter estimation. Addressing these challenges will be crucial for maximizing the scientific return from next-generation cosmological surveys and advancing our understanding of dark energy and modified gravity.

6. Implications for cosmology and fundamental physics

6.1. Insights in to the nature of dark energy

At its core, the EFT description of dark energy reveals that the phenomenon can be effectively modeled by introducing a scalar degree of freedom that interacts with gravity. This scalar field may emerge naturally from modifications to GR (as in Horndeski theories) or represent a fundamental component of high-energy physics (such as quintessence fields). The EFT framework incorporates this scalar field through a systematic expansion of the action in terms of curvature invariants and derivative operators, with the unitary gauge formulation providing a particularly useful representation where the scalar degree of freedom is absorbed into the metric. The presence of specific operators in the EFT Lagrangian, such as those involving δg^{00} and δK , provides crucial information about how the scalar field couples to gravity and influences the expansion history of the universe.

EFT also has ability to constrain the sound speed of dark energy perturbations (c_s^2), which carries important information about the micro-physical properties of dark energy. The value of c_s^2 determines whether and how dark energy perturbations can cluster on cosmological scales, with subluminal values ($c_s^2 < 1$) suggesting fluid-like behavior and $c_s^2 = 1$ indicating a more rigid equation of state characteristic of certain k-essence models [7]. Furthermore, the EFT framework imposes essential stability conditions that any viable dark energy model must satisfy, including the absence of ghosts (requiring $q_s > 0$) and gradient instabilities (requiring $c_s^2 > 0$), which serve as powerful filters for theoretical models.

The formalism also provides a clear window into how dark energy might modify gravitational interactions through parameters, α_{M} and α_{B} , for example: A non-zero α_{M} indicates an effective Planck mass that varies over time, suggesting a departure from GR that could arise from scalar-tensor couplings, while α_{B} quantifies the kinetic mixing between the scalar field and gravity, which can significantly affect structure formation and the growth of cosmic perturbations [5]. These parameters offer a systematic way to classify and test different modified gravity theories against cosmological observations.

By establishing a mapping between specific EFT coefficients and fundamental high-energy Lagrangians (such as Horndeski, beyond-Horndeski, or vector-tensor theories), the EFT approach allows us to probe the underlying microphysics of dark energy. For instance, a non-zero α_T would indicate a violation of GR's prediction of luminal gravitational wave propagation, potentially pointing to higher-dimensional theories or Lorentz-violating scenarios. Similarly, the presence of certain higher-order operators in the EFT action might suggest non-linear self-interactions of the scalar field, possibly originating from string theory constructions or massive gravity theories.

DOI: 10.54254/2753-8818/2026.HZ27970

The true power of the EFT approach lies in its ability to make concrete predictions that can be tested against current and future cosmological observations. Large-scale structure surveys can constrain parameters like α_{B} , α_{M} , and c_s^2 through measurements of the growth rate ($f\sigma_8$) and weak lensing observations. Cosmic microwave background experiments, particularly future missions like CMB-S4, along with multi-messenger gravitational wave observations, will provide crucial tests of the tensor sector through constraints on α_{T} . Moreover, the EFT framework enables consistent modeling of perturbations beyond linear theory, which is essential for interpreting data from next-generation galaxy surveys such as Euclid and LSST.

6.2. Testing general relativity

EFT provides a powerful and systematic framework for probing potential deviations from GR in both cosmological and astrophysical contexts. By constructing an EFT expansion around the GR action, researchers can parameterize possible modifications to gravity in a model-independent way while maintaining consistency with fundamental symmetries and theoretical constraints . This approach organizes possible deviations from GR according to their mass dimension, with lower-dimensional operators typically dominating at large scales, allowing for a controlled expansion that can be systematically improved. The formalism also enables a unified description of how various beyond-GR theories might manifest in the inspiral, merger, and ringdown phases of compact binary coalescences.

The testing of GR relies on identifying the most relevant operators that could modify Einstein's theory while preserving essential principles like diffeomorphism invariance. These operators are typically constructed from curvature invariants and their derivatives, with coefficients that encode the scale of new physics. The method proves powerful especially when combining data from multiple events, as the mass-dependent scaling of deviations provides additional discriminating power [6].

6.3. Broader cosmological implications

While maintaining consistency with fundamental symmetries and observational constraints, the EFT of inflation provides a systematic framework for studying deviations from standard single-field slow-roll models. By organizing operators in an expansion of derivatives and curvature invariants, the EFT approach allows for a model-independent classification of inflationary scenarios, distinguishing between canonical single-field inflation, modified gravity theories, and multi-field scenarios. Its ability to impose stability conditions directly on the EFT coefficients in turn constrains the parameter space of viable inflationary models.

A particularly promising avenue for testing EFT-based inflation models is through the synergy between CMB and LSS surveys. The EFT framework predicts how primordial non-Gaussianity—parametrized by f_{NL} —affects the clustering of galaxies and weak gravitational lensing signals. Future surveys like Euclid, LSST, and CMB-S4 will significantly tighten these constraints, potentially ruling out broad classes of inflationary models that predict large deviations from Gaussian initial conditions.

Furthermore, the EFT approach enables a unified treatment of inflationary dynamics and dark energy, allowing for consistency checks between early- and late-universe physics. For example, certain EFT operators that modify the speed of sound during inflation (c_s) can also affect the growth of structure at late times, leading to observable discrepancies in σ_8 or the Hubble tension. By combining CMB, baryon acoustic oscillation (BAO), and weak lensing data within the EFT

DOI: 10.54254/2753-8818/2026.HZ27970

framework, it becomes possible to distinguish between inflationary models that predict similar primordial power spectra but differ in their late-time implications [4].

7. Future directions

7.1. Observational prospects

The extreme discrepancy between quantum field theory predictions and observed vacuum energy ($\sim 10^{-120} M_{pl}^4$) remains unresolved. Distinguishing dark energy from modified gravity requires breaking degeneracies through precision measurements of gravitational slip and structure growth. Key challenges include extending EFT frameworks to nonlinear regimes and testing screening mechanisms in dense environments. Future surveys will tightly constrain EFT parameters, while multi-messenger observations could detect deviations from GR. Theoretical progress may come from holographic principles or lab tests of screened fields. Therefore, resolving dark energy demands combined advances across theory, observations and experiments.

7.2. Towards a unified framework

Resolving the nature of dark energy requires integrating effective field theory (EFT) with complementary approaches, including holographic principles, emergent gravity, and thermodynamic models [9]. A unified framework should bridge cosmological observations with fundamental physics, leveraging synergies between different probes—such as gravitational waves, large-scale structure, and lab experiments [10].

Future progress hinges on refining EFT parameterizations to encompass nonlinear dynamics and screening mechanisms, while incorporating insights from string theory and quantum gravity. Such a synthesis could resolve tensions in current cosmological data and illuminate dark energy's connection to inflation, dark matter, and spacetime geometry. Ultimately, a deeper understanding of the universe demands both theoretical innovation and next-generation observational constraints [6].

8. Conclusion

The Effective Field Theory (EFT) of Dark Energy provides a powerful and systematic framework for exploring deviations from the ΛCDM paradigm and testing modifications to General Relativity on cosmological scales. By organizing perturbations through a hierarchy of operators and stability conditions, this approach allows for model-independent constraints on dark energy and modified gravity scenarios. Key parameters encode deviations from standard cosmology and can be tightly constrained using current observational data. Recent results from Planck CMB, large-scale structure surveys, and gravitational wave observations strongly favor near-ΛCDM behavior, with particularly stringent limits on tensor speed excess. However, persistent tensions in measurements of H_0 and σ_8 motivate continued investigation into alternative models, including dynamical dark energy and interacting dark sector scenarios. Future surveys such as Euclid, LSST, and CMB-S4 will significantly improve constraints, probing non-linear scales and testing screening mechanisms in modified gravity theories. Moreover, the EFT framework not only bridges theoretical models with observational data but also provides a unified language for exploring fundamental questions about cosmic acceleration. As observational precision increases, this approach will remain essential for distinguishing between competing explanations for dark energy—whether it arises from a cosmological constant, a dynamical field, or a modification of gravity. Ultimately, resolving the

DOI: 10.54254/2753-8818/2026.HZ27970

nature of dark energy will require both theoretical innovation and next-generation cosmological experiments, with EFT serving as a crucial tool in this endeavor.

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