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Abstract

Recent joint analyses combining DESI-era baryon acoustic oscillation measurements with external datasets (e.g., CMB and Type Ia supernova compilations) report a dataset- and prior-dependent preference for dynamical dark energy relative to a constant cosmological constant, typically expressed through the reconstructed evolution of $w(z)$. Motivated by these developments, we present a minimal kinetic-coupling dark-fluid (DFM–MKC) framework in which energy–momentum exchange within the dark sector reproduces effective quintom-like behavior (including permitted crossings of $w_{\mathrm{DE}} = -1$ in the effective description) without introducing a universal fifth force. We derive the background and linear-perturbation equations, define compact coupling parameterizations that isolate the phenomenology relevant to DESI-era constraints, and formulate mechanism-level consistency relations intended to distinguish dark-sector coupling from purely phenomenological $w(z)$ reconstructions. We outline a falsification program spanning expansion history, growth of structure, and CMB lensing, and we provide an analysis roadmap for joint likelihood evaluation using DESI BAO + CMB + SN(+WL), with explicit robustness checks under alternative priors, dataset subsets, and coupling parameterizations.

Minimal Kinetic-Coupling Dark Fluid Cosmology: A Mechanism-Level Interpretation of DESI-Era Preference for Dynamical Dark Energy

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1 Introduction

The ΛCDM model remains an extraordinarily successful baseline description of cosmological observations. Nevertheless, late-time probes continue to motivate extensions that relax the assumption of a strictly constant dark-energy equation of state. DESI-era BAO measurements sharpen constraints on $D_M(z)$ and $H(z)$, and multiple joint analyses that combine BAO with CMB and supernova data report a preference for dynamical dark energy relative to ΛCDM, with the reported strength depending on dataset choices, prior ranges, and the parameterization used for $w(z)$.

What is (and is not) claimed. We distinguish: (i) *phenomenological preference* for non-constant $w(z)$ in certain joint analyses, from (ii) *mechanism identification* via a physical model that explains the preference and survives cross-probe consistency tests. This work supplies a minimal mechanism-level candidate—DFM–MKC—together with falsifiable signatures, without asserting that current data uniquely confirms the mechanism.

Contributions. We provide:

1. A minimal interacting dark-sector kinetic-coupling model with a controlled separation between background expansion and growth-of-structure effects.
2. An explicit mapping between coupling parameters and the effective equation-of-state history $w_{\rm eff}(z)$, including conditions for effective phantom crossing.
3. Mechanism-level consistency relations and a falsification checklist designed for DESI-era joint analyses.

[DESI Collaboration(2025), Planck Collaboration(2018), Brout *et al.*(2022)Brout *et al.*]

2 Model: Minimal Kinetic-Coupling Dark Fluid (DFM–MKC)

2.1 Fluid-level interacting dark sector

We assume a spatially flat FLRW background with scale factor $a(t)$ and Hubble rate $H \equiv \dot{a}/a$. The dark sector is composed of pressureless cold dark matter (DM) with density $\rho_{\rm c}$ and dark energy

(DE) with density $\rho_{\rm de}$ and pressure $p_{\rm de}$. Energy exchange within the dark sector is modeled as

$$\dot{\rho}_{\rm c} + 3H\rho_{\rm c} = +Q, \tag{1}$$

$$\dot{\rho}_{\rm de} + 3H(\rho_{\rm de} + p_{\rm de}) = -Q, \tag{2}$$

with Q defining the direction of energy flow: $Q > 0$ corresponds to DE→DM and $Q < 0$ to DM→DE.

2.2 Minimal kinetic-coupling ansatz

A minimal DESI-era–testable choice is

$$Q = 3H\,\xi(a)\,\rho_{\rm c}, \tag{3}$$

where $\xi(a)$ is a (small) dimensionless coupling function.

Two practical parameterizations are:

$$\xi(a) = \xi_0 + \xi_a(1-a), \tag{4}$$

$$\xi(a) = \xi_0\,\frac{1+\tanh\left(\frac{a-a_t}{\Delta}\right)}{2} - \xi_1\,\frac{1-\tanh\left(\frac{a-a_t}{\Delta}\right)}{2}, \tag{5}$$

where Eq. (5) permits a sign reversal around a_t if preferred by joint fits.

Intrinsic DE equation of state. For minimality, we take a constant intrinsic equation of state,

$$p_{\rm de} = w_0\,\rho_{\rm de}, \tag{6}$$

and allow effective evolution to arise from coupling via Q. (Extensions with a CPL intrinsic form can be treated as a controlled generalization.)

2.3 Effective equation of state and effective phantom crossing

Define the effective DE equation of state inferred from background evolution as

$$w_{\rm eff}(a) \equiv -1 - \frac{1}{3}\frac{d\ln\rho_{\rm de}}{d\ln a}. \tag{7}$$

Using Eq. (2), one obtains

$$w_{\rm eff}(a) = w_0 + \frac{Q}{3H\rho_{\rm de}} = w_0 + \xi(a)\,\frac{\rho_{\rm c}}{\rho_{\rm de}}. \tag{8}$$

Hence $w_{\rm eff}$ can cross -1 depending on the sign and magnitude of $\xi(a)$ even if $w_0 > -1$, enabling effective "phantom crossing" without introducing a fundamental phantom field. Stability conditions depend on the microphysical completion (fluid closure / EFT / action-level model); in this paper we adopt the conservative requirement that the chosen perturbation prescription is ghost- and gradient-stable in the parameter region explored (Appendix A).

3 Background Dynamics and Parameter Degeneracies

3.1 Friedmann equations

In a flat universe,

$$H^2(a) = H_0^2\Big[\Omega_{\rm r}a^{-4} + \Omega_{\rm m}a^{-3} + \Omega_{\rm de}(a)\Big], \tag{9}$$

where $\Omega_{\rm m} = \Omega_{\rm b} + \Omega_{\rm c}$ and radiation/neutrinos may be included as needed.

Given $w_{\rm eff}\,(a)$, the DE density evolves as

$$\rho_{\rm de}(a) = \rho_{\rm de,0}\,\exp\!\left(3\int_a^1 \frac{1+w_{\rm eff}(a')}{a'}\,da'\right). \tag{10}$$

Equations (1)–(2) with Q from Eq. (3) provide a closed background system for $(\rho_{\rm c}, \rho_{\rm de})$ given (w_0, ξ).

3.2 Mapping to DESI-era constraints

BAO primarily constrains the comoving angular diameter distance $D_M(z)$ and the Hubble rate $H(z)$ via the BAO scale. In interacting models, (w_0, ξ) can be partially degenerate in background-only fits, since both modify the late-time expansion history through $w_{\rm eff}(a)$. This motivates: (i) explicit robustness checks across dataset subsets; and (ii) incorporating growth and lensing observables that respond differently to coupling than to purely phenomenological $w(z)$ reconstructions.

4 Linear Perturbations and Growth of Structure

4.1 Perturbation prescription and schematic growth equation

Interacting dark-sector models require a specified covariant prescription for momentum transfer and gauge conventions. We adopt a standard choice in which the energy–momentum transfer four-vector is aligned with the DM four-velocity at the background level; details and conventions are given in Appendix A. On sub-horizon scales, the growth of DM density perturbations can be expressed schematically as

$$\delta_{\rm c}'' + \left(2 + \frac{H'}{H} + \Gamma(a)\right)\delta_{\rm c}' - \frac{3}{2}\Omega_{\rm m}(a)\,\mu(a)\,\delta_{\rm c} = 0, \tag{11}$$

where primes denote derivatives with respect to $\ln a$ and $\Gamma(a), \mu(a)$ encode effective drag and clustering modifications induced by coupling. In DFM–MKC these functions are determined by $\xi(a)$ and the chosen interaction prescription and can be extracted numerically.

4.2 Connection to §8 and lensing

The coupling modifies growth observables such as $f\sigma_8(z)$, weak-lensing summaries (including §8), and the CMB lensing potential power spectrum. A central goal is to identify signatures that are diagnostic of coupling *as a mechanism* rather than generic $w(z)$ phenomenology, e.g. correlated residual patterns between growth-rate observables and lensing that track the inferred coupling transition scale a_t in Eq. (5).

5 Data, Likelihood Strategy, and Robustness Checks

5.1 Datasets

The intended joint analyses include:

- DESI-era BAO measurements (specify sample selection and redshift bins as used in the likelihood).
- CMB constraints (e.g., Planck 2018 baseline; optional ACT/SPT combinations as robustness).
- Type Ia supernovae (e.g., Pantheon+ or an explicitly stated alternative compilation).
- Optional: weak lensing (DES/KiDS/HSC; and later Euclid/Roman updates when available).

5.2 Inference pipeline

We consider parameter vectors of the form

$$\theta = (\Omega_\mathrm{b} h^2, \Omega_\mathrm{c} h^2, H_0, n_s, A_s, \tau, \ldots, w_0, \text{coupling parameters}), \tag{12}$$

with coupling parameters chosen as (ξ_0, ξ_a) or $(\xi_0, \xi_1, a_t, \Delta)$. We report posterior stability under alternative priors and evaluate model comparison (e.g., Bayes factors $\ln B$) with explicit prior-dependence accounting.

5.3 Robustness and falsification checklist

We adopt the following non-negotiable checks:

1. Posterior stability under dataset subsets: BAO+SN; BAO+CMB; BAO+CMB+SN; and optional WL inclusion.
2. Stability under alternative coupling parameterizations (Eqs. (4) vs (5)).
3. Consistency between background-preferred regions and growth/lensing constraints.
4. Null recovery: $\xi \to 0$ reproduces ΛCDM limits within the same pipeline.

6 Mechanism-Level "Smoking Gun" Consistency Relations

A mechanism claim requires more than an improved fit to a subset of observables. We propose the following mechanism-level targets, to be stated as explicit relations once the perturbation prescription is fixed:

- A relation linking the redshift of effective phantom crossing in $w_\mathrm{eff}\,(z)$ to a change in the slope of growth suppression in $f\sigma_8(z)$ residuals.
- A coupled prediction relating growth residuals to CMB lensing residuals with shared dependence on $\xi(a)$.
- A prediction for the sign and scale dependence of deviations in the growth index γ relative to smooth $w(z)$ reconstructions.

These relations provide a route to falsification with near-term datasets (DESI full-shape, Euclid WL, improved CMB lensing).

7 Discussion: Status of Evidence and Interpretation

7.1 Interpretation of DESI-era preferences

Current joint analyses report a preference for dynamical dark energy at the level of a few standard deviations in some dataset combinations, with nontrivial dependence on priors and modeling choices. Interacting dark-sector models can provide comparable or improved fits and, critically, can correlate background evolution with growth and lensing signatures. At present, unique mechanism identification remains unsettled; DFM–MKC is proposed as a minimal candidate designed to be decisively tested via cross-probe consistency.

7.2 Relation to other explanations

We contrast DFM–MKC with: (i) two-field quintom models, (ii) k-essence / EFT of DE parameterizations, and (iii) modified-gravity models. The distinguishing feature of DFM–MKC is that coupling induces linked signatures across expansion and growth that can be formulated as testable consistency relations.

8 Conclusion

We presented a minimal kinetic-coupling interacting dark-sector framework (DFM–MKC) that can reproduce effective $w(z)$ behavior compatible with DESI-era preferences while yielding coupled predictions for growth and lensing. We outlined a robustness-centered inference plan and a falsification strategy aimed at converting phenomenological preference into mechanism-level confirmation or refutation with near-term data.

A Derivations and Stability Conditions

This appendix should include: (i) the covariant interaction prescription Q^μ, (ii) gauge conventions, (iii) the full linearized equations used in the Boltzmann/perturbation solver, and (iv) explicit stability criteria (no ghosts / no gradient instabilities) for the parameter region explored.

B Implementation Notes

Implementation guidance:

- CLASS/CAMB modification notes for background and perturbations under Eq. (3).
- Validation by recovering ΛCDM as $\xi \to 0$.
- Unit tests for $H(z)$, $D_M(z)$, and growth observables against baseline pipelines.

References

[DESI Collaboration(2025)] DESI Collaboration, Desi bao results (desi-era release papers) (2025), replace with exact DR2 references.

[Planck Collaboration(2018)] Planck Collaboration, Astronomy & Astrophysics (2018).

[Brout *et al.*(2022)Brout *et al.*] D. Brout *et al.*, Pantheon+ supernova compilation (2022).