

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

Inacio F. Vasquez<sup>1</sup>

<sup>1</sup>*Independent Researcher*

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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  $w_{\text{DE}} = -1$  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.

## I. INTRODUCTION

The  $\Lambda$ CDM 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  $\Lambda$ CDM, with the reported strength depending on dataset choices, prior ranges, and the parameterization used for  $w(z)$ .

*a. 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.

*b. 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  $w_{\text{eff}}(z)$ , including conditions for effective phantom crossing.
3. Mechanism-level consistency relations and a falsification checklist designed for DESI-era joint analy-

ses.

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## II. MODEL: MINIMAL KINETIC-COUPLING DARK FLUID (DFM-MKC)

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

$$\dot{\rho}_c + 3H\rho_c = +Q, \quad (1)$$

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

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

### B. Minimal kinetic-coupling ansatz

A minimal DESI-era-testable choice is

$$Q = 3H \xi(a) \rho_c, \quad (3)$$

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

Two practical parameterizations are:

$$\xi(a) = \xi_0 + \xi_a(1 - a), \quad (4)$$

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

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

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

$$p_{\text{de}} = w_0 \rho_{\text{de}}, \quad (6)$$

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

### C. Effective equation of state and effective phantom crossing

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

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

Using Eq. (2), one obtains

$$w_{\text{eff}}(a) = w_0 + \frac{Q}{3H\rho_{\text{de}}} = w_0 + \xi(a) \frac{\rho_c}{\rho_{\text{de}}}. \quad (8)$$

Hence  $w_{\text{eff}}$  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).

## III. BACKGROUND DYNAMICS AND PARAMETER DEGENERACIES

### A. Friedmann equations

In a flat universe,

$$H^2(a) = H_0^2 \left[ \Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_{\text{de}}(a) \right], \quad (9)$$

where  $\Omega_m = \Omega_b + \Omega_c$  and radiation/neutrinos may be included as needed.

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

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

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

### B. 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,  $(w_0, \xi)$  can be partially degenerate in background-only fits, since both modify the late-time expansion history through  $w_{\text{eff}}(a)$ . 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.

## IV. LINEAR PERTURBATIONS AND GROWTH OF STRUCTURE

### A. 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

$$\delta_c'' + \left( 2 + \frac{H'}{H} + \Gamma(a) \right) \delta_c' - \frac{3}{2} \Omega_m(a) \mu(a) \delta_c = 0, \quad (11)$$

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.

### B. 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).

## V. DATA, LIKELIHOOD STRATEGY, AND ROBUSTNESS CHECKS

### A. 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).

### B. Inference pipeline

We consider parameter vectors of the form

$$\theta = (\Omega_b h^2, \Omega_c h^2, H_0, n_s, A_s, \tau, \dots, w_0, \text{coupling parameters}), \quad (12)$$

with coupling parameters chosen as  $(\xi_0, \xi_a)$  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.

### C. 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:  $\xi \rightarrow 0$  reproduces  $\Lambda$ CDM limits within the same pipeline.

## VI. 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  $w_{\text{eff}}(z)$  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  $\gamma$  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).

## VII. DISCUSSION: STATUS OF EVIDENCE AND INTERPRETATION

### A. 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.

### B. 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.

## VIII. 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.

### Appendix A: Derivations and Stability Conditions

This appendix should include: (i) the covariant interaction prescription  $Q^\mu$ , (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.

### Appendix B: Implementation Notes

Implementation guidance:

- CLASS/CAMB modification notes for background and perturbations under Eq. (3).
- Validation by recovering  $\Lambda$ CDM as  $\xi \rightarrow 0$ .

- Unit tests for  $H(z)$ ,  $D_M(z)$ , and growth observables against baseline pipelines.

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- [1] DESI Collaboration, Desi bao results (desi-era release papers) (2025), replace with exact DR2 references.
- [2] Planck Collaboration, Astronomy & Astrophysics (2018).
- [3] D. Brout *et al.*, Pantheon+ supernova compilation (2022).