A Unified Kaluza–Klein Framework for Processing-Driven Dark Sector Dynamics (MetaTime v35.9)

MetaTime v35.9: Technical Suite

Darío Peyrú

January 9, 2026

ABSTRACT

We present MetaTime v35.9, a definitive technical suite unifying (i) a 5D Kaluza–Klein (KK) Einstein-frame effective field theory (EFT) for interacting dark-sector dynamics with (ii) a numerical validation pipeline suitable for direct falsification against cosmological and varying-constant data. Building on the covariant framework introduced in MetaTime v35.6, the dark sector is organized into two effective components: Latency (ρ_L), representing stored, non-instantiated degrees of freedom, and Execution (ρ_E), representing the realized processing cost on the brane and phenomenologically tracking dark-energy-like behavior. The defining mechanism is an exchange term Q that converts Latency into Execution at a rate proportional to the cosmic processing clock H, modulated by an activation (complexity) field Π(a). In the operational form used by the numerical suite, the exchange is implemented as $Q = 3H \cdot \rho_L \cdot [\beta_0 + \beta_1 \cdot \Pi(a)]$, where β_0 captures a baseline channel and β_1 controls a late-time activation driven by Π(a). This release includes a concrete Boltzmann-solver implementation (CLASS background modification) and a MontePython likelihood module confronting the predicted fine-structure drift template $\Delta\alpha/\alpha(z) = \zeta_\alpha \cdot [\ln \Phi(z) - \ln \Phi(0)]$, where Φ is the KK radion.

I. INTRODUCTION

The ΛCDM model remains the baseline concordance cosmology, yet its success coexists with structural puzzles, most notably the coincidence problem: why the dark-energy density becomes comparable to the matter density only at late cosmic times. MetaTime proposes a dynamical resolution by identifying the dark-energy-like component with Execution—an effective energy density representing the cost of instantiating latent degrees of freedom on the brane—rather than a fundamental constant Λ. In this view, late-time acceleration is an emergent epoch induced by a controlled conversion of Latency into Execution.

MetaTime v35.6 established the geometric backbone via a 5D KK reduction in which the radion Φ mediates a technically controlled deformation of the dark sector while permitting visible-sector screening (least-coupling behavior). The present v35.9 paper is deliberately engineering-complete: it specifies an explicit interacting-dark-energy (IDE) mapping for Q in terms of (β_0, β_1, $\Pi(a)$) and provides a minimal numerical suite enabling reproducible parameter inference and correlated predictions (including $\Delta\alpha/\alpha$) suitable for near-term observational tests.

II. THEORETICAL FRAMEWORK

A. 5D action and KK ansatz

We start from a minimal 5D Einstein–Hilbert action with a radion sector and a dark gauge sector. Uppercase indices A, B run over 5D; Greek indices μ, ν run over 4D.

$$S_5 = \int d^5x \sqrt{(-g_5)} \left[(1/(2\kappa_5^2)) R_5 - 1/2 (\partial_A \hat{\Phi})(\partial^A \hat{\Phi}) - \hat{V}(\hat{\Phi}) - 1/4 \hat{F}_{AB} \hat{F}^{AB} + \ldots \right] + S_{brane} + S_{dark,m}.$$

$$ds_5^2 = g_{\mu\nu}(x)\, dx^\mu dx^\nu + \Phi(x)^2 [dy + \kappa A^D_\mu(x)\, dx^\mu]^2, \text{ with } y \simeq y + 2\pi R.$$

B. Dimensional reduction and 4D Einstein-frame EFT

After dimensional reduction and a Weyl rescaling to Einstein frame, the 4D action takes the schematic form:

$$S_E = \int d^4x \sqrt{(-g)} \left[(M_{Pl}^2/2) R - 1/2 (\partial\varphi)^2 - V_{eff}(\varphi, \Pi) - 1/4 f_D(\varphi) F^D_{\mu\nu} F_D^{\mu\nu} \right] + S_{SM}[\psi_{SM}, \tilde{A}_{SM}(\varphi)^2 g_{\mu\nu}] + S_D[\psi_D, \tilde{A}_D(\varphi)^2 g_{\mu\nu}] + S_\Pi.$$

We use the canonical radion field definition:

$$\varphi \equiv \sqrt{(3/2)}\, M_{Pl} \ln \Phi \text{ (equivalently, } \Phi = \exp(\sqrt{(2/3)} \cdot \varphi/M_{Pl}) \text{)}.$$

A convenient parameterization for the dark gauge kinetic function is:

$$f_D(\varphi) = (1/g_{D0}^2) \cdot \exp(\sqrt{6} \cdot \varphi/M_{Pl}) \text{ (up to matching coefficients and higher-dimensional operators).}$$

C. Activation sector Π and effective potential

To preserve covariance, the processing/activation history is promoted to a dynamical field Π with its own action:

$$S_\Pi = \int d^4x \sqrt{(-g)} \left[-1/2 K(\Pi) (\partial\Pi)^2 - W(\Pi) \right].$$

The radion potential is deformed by Π through an interaction term:

$$V_{eff}(\varphi, \Pi) = V_0(\varphi) + \Lambda_\Pi^4 \cdot U(\varphi) \cdot \square(\Pi), \text{ with } \square(\Pi) \text{ monotonic and bounded (activation map).}$$

D. Interaction term Q

For the purposes of v35.9 as a technical suite, we adopt the validated IDE-style operational form:

$$Q = 3H \cdot \rho\_L \cdot [\beta_0 + \beta_1 \cdot \Pi(a)].$$

A practical smooth activation function used in the suite is:

$$\Pi(a) = 1 / [1 + \exp(-(\ln a - \ln a\_t)/\Delta)].$$

III. DYNAMICS

In a spatially flat FLRW background ($H = \dot{a}/a$), the coupled continuity equations for the effective dark-sector components are:

$$\dot{\rho}\_L + 3H\rho\_L = -Q$$

$$\dot{\rho}\_E + 3H(1 + w\_E)\rho\_E = +Q$$

The background expansion satisfies the Friedmann equation:

$$3M\_Pl^2 H^2 = \rho\_r + \rho\_b + \rho\_c + \rho\_L + \rho\_E + \rho\_\varphi + \rho\_\Pi.$$

Observable template (fine-structure drift):

$$\Delta\alpha/\alpha(z) = \zeta\_\alpha \cdot [\ln \Phi(z) - \ln \Phi(0)] = \zeta\_\alpha \sqrt{(2/3)} \cdot [\varphi(z) - \varphi(0)] / M\_Pl.$$

IV. NUMERICAL IMPLEMENTATION

This section provides directly actionable scaffolding for an end-to-end validation suite: (i) a CLASS background modification implementing Q(a), and (ii) a MontePython likelihood module for $\Delta\alpha/\alpha$ data.

A. CLASS modification (C code): implementing Q(a) in source/background.c

The snippet below is designed to be inserted into the background derivative routine (e.g., background_derivs) after registering indices for ρ_L and ρ_E in the background vector.

```
/*------------------------------------------------------------
  MetaTime v35.9 : Interacting dark sector (Latency -> Execution)
  Q = 3 H rho_L [beta0 + beta1 * Pi(a)]
  Sign convention: Q>0 drains rho_L and sources rho_E.
------------------------------------------------------------*/

#include "background.h"
#include <math.h>

/* Example sigmoid activation for Pi(a) */
static double metatime_Pi_of_a(double a, double a_t, double Delta) {
  /* Pi(a) = 1 / (1 + exp(-(ln a - ln a_t)/Delta)) */
  const double x = (log(a) - log(a_t)) / Delta;
  return 1.0 / (1.0 + exp(-x));
}
```

```
int background_derivs(double a,
                      double * y,
                      double * dy,
                      void * parameters_and_workspace,
                      ErrorMsg error_message) {

  struct background_parameters_and_workspace * pbpaw;
  pbpaw = (struct background_parameters_and_workspace *) parameters_and_workspace;
  struct background * pba = pbpaw->pba;

  /* --- Standard CLASS background quantities (H, etc.) --- */
  double H = pbpaw->pvecback[pba->index_bg_H];

  /* --- MetaTime parameters (read from input and stored in pba) --- */
  const double beta0 = pba->metatime_beta0;
  const double beta1 = pba->metatime_beta1;
  const double a_t   = pba->metatime_a_t;
  const double Delta = pba->metatime_Delta;

  /* --- Densities --- */
  double rho_L = y[pba->index_bg_rhoL];
  double rho_E = y[pba->index_bg_rhoE];

  /* --- Activation field --- */
  double Pi_a = metatime_Pi_of_a(a, a_t, Delta);

  /* --- Interaction term Q --- */
  double Q = 3.0 * H * rho_L * (beta0 + beta1 * Pi_a);

  /* --- Continuity equations in cosmic time:
         rho_dot + 3H(1+w) rho = source
         CLASS uses conformal time τ: d/dτ = a d/dt
  --- */
  double wE = pba->metatime_wE;

  dy[pba->index_bg_rhoL] = a * ( -3.0 * H * rho_L - Q );
  dy[pba->index_bg_rhoE] = a * ( -3.0 * H * (1.0 + wE) * rho_E + Q );

  /* Optional: track lnPhi for alpha drift (if implemented as background variable) */
  if (pba->has_metatime_lnPhi == _TRUE_) {
    double dlnPhi_dlnA = pba->metatime_dlnPhi_dlnA0
                       + pba->metatime_dlnPhi_dlnA1 * Pi_a;
    dy[pba->index_bg_lnPhi] = a * (dlnPhi_dlnA * H);
  }

  return _SUCCESS_;
}
```

B. MontePython likelihood (Python): metatime_alpha(Likelihood)

The likelihood below compares the model prediction Δα/α(z) = ζ_α[lnΦ(z) − lnΦ(0)] against quasar absorption data with optional nuisance offsets.

```
import numpy as np
from montepython.likelihood_class import Likelihood

class metatime_alpha(Likelihood):
    '''
```

```
MetaTime v35.9: Likelihood for fine-structure drift using quasar data.

Data format (ASCII):
  z   delta_alpha   sigma
where delta_alpha = (Δα/α)(z).
'''

def __init__(self, path, data, command_line):
    Likelihood.__init__(self, path, data, command_line)

    arr = np.loadtxt(self.data_file)
    self.z = arr[:, 0]
    self.da = arr[:, 1]
    self.sig = arr[:, 2]

    # Optional nuisance parameter for dataset/instrument systematics
    self.use_offset = getattr(self, "use_offset", False)

    # Expected background key provided by CLASS
    self.bg_key_lnp = getattr(self, "bg_key_lnp", "lnPhi")

def loglkl(self, cosmo, data):
    zeta_alpha = data.mcmc_parameters["metatime_zeta_alpha"]["current"]

    bg = cosmo.get_background()
    if "z" in bg:
        z_bg = np.asarray(bg["z"])
    else:
        a_bg = np.asarray(bg["a"])
        z_bg = 1.0 / a_bg - 1.0

    if self.bg_key_lnp not in bg:
        raise KeyError(
            f"Background key '{self.bg_key_lnp}' not found. "
            "Ensure CLASS outputs lnPhi (or set bg_key_lnp accordingly)."
        )

    lnPhi_bg = np.asarray(bg[self.bg_key_lnp])

    order = np.argsort(z_bg)
    z_sorted = z_bg[order]
    lnPhi_sorted = lnPhi_bg[order]

    lnPhi_z = np.interp(self.z, z_sorted, lnPhi_sorted)
    lnPhi_0 = np.interp(0.0, z_sorted, lnPhi_sorted)

    model = zeta_alpha * (lnPhi_z - lnPhi_0)

    if self.use_offset:
        offset = data.mcmc_parameters["metatime_alpha_offset"]["current"]
        model = model + offset

    chi2 = np.sum(((self.da - model) / self.sig) ** 2)
    return -0.5 * chi2
```

V. CONCLUSION

MetaTime v35.9 consolidates the framework into a single falsifiable package: a KK Einstein-frame EFT interpretation (radion-controlled dark sector with a processing-driven activation Π) and an explicit numerical suite capable of producing observables and confronting data. The operational mechanism $Q = 3H \cdot \rho_L \cdot [\beta_0 + \beta_1 \cdot \Pi(a)]$ implements a controlled late-time conversion of Latency into Execution, turning the coincidence problem into a dynamical question: when and how does Π(a) activate?

Crucially, v35.9 commits to correlated predictions: the radion history that supports the dark exchange implies an observable $\Delta\alpha/\alpha$ template via $\ln \Phi$. The suite therefore enables a genuine cross-test in which distance data, growth data, and varying-constant data jointly accept or refute the model in a parameter window that can be independently reproduced.

VI. DATA AND METHODS

A. Summary of the inference strategy

MetaTime v35.9 is tested as a coupled dark-sector model in which an interaction term converts Latency into Execution, $Q(a) = 3H(a) \cdot \rho_L(a) \cdot [\beta_0 + \beta_1 \cdot \Pi(a)]$. The parameter inference is organized in a staged manner designed to (i) rapidly locate viable background solutions, (ii) enforce growth/perturbation stability, and (iii) apply a cross-consistency test using varying-constant data ($\Delta\alpha/\alpha$).

B. Data vectors (by observable class)

• Background geometry (expansion and distances): Type Ia SNe, BAO across multiple redshifts, early-universe anchors via CMB distance priors, and cosmic chronometers $H(z)$ as an independent check.

• Growth of structure (linear regime): RSD measurements of $f\sigma_8(z)$, weak lensing constraints on S_8, and (optionally) CMB lensing once a full CMB likelihood is employed.

• Varying-constant constraints (α drift): quasar absorption spectroscopy constraints on $\Delta\alpha/\alpha(z)$, with dataset/instrument systematics treated via nuisance parameters; optionally include local bounds from atomic clocks as priors on the present-day drift rate.

C. Likelihood construction (Gaussian baseline)

For a data vector d with model prediction $m(\theta)$ and covariance C, the baseline likelihood is Gaussian, $\ln L = -1/2 \cdot (d - m)^T C^{-1} (d - m)$, with nuisance parameters included where appropriate. Model comparison is reported using $\Delta\chi^2$ and information criteria (AIC/BIC) when relevant.

VII. MODEL PARAMETERIZATION AND PRIORS

A. Baseline cosmological parameters

We adopt a standard late-time cosmological parameter set (e.g., $\Omega_b h^2$, $\Omega_c h^2$, h, and—when a full early-time likelihood is used—n_s and A_s). In background-first runs, early-universe parameters can be fixed or replaced by CMB distance priors to reduce degeneracy. The minimal MetaTime parameter set required to test the interaction and its activation is (β_0, β_1, a_t, Δ, w_E), supplemented by the radion–observable coupling ζ_α and (optionally) an α_{offset} nuisance parameter.

B. Recommended priors (minimal, conservative)

Parameter	Meaning	Suggested prior
β_0	Baseline exchange strength	Uniform [0, 0.10]

β_1	Activation-weighted exchange strength	Uniform [0, 0.30]
a_t	Activation epoch (center)	log-uniform in [0.20, 1.0]
Δ	Activation width in ln a	Uniform [0.03, 0.50]
w_E	Execution equation of state (constant)	Uniform [−1.20, −0.60] (or restrict to [−1.0, −0.60
ζ_α	Radion-to-α drift coupling	Uniform [−1e−4, +1e−4]
α_offset	α-drift systematic offset (optional)	Uniform [−5e−6, +5e−6]

Two hard physical priors are imposed throughout: (1) positivity, $\rho_L(a) > 0$ and $\rho_E(a) > 0$ across the integration domain; (2) if enforcing one-way conversion, $\beta_0 + \beta_1 \Pi(a) \geq 0$ for all a.

VIII. PERTURBATIONS, STABILITY, AND IMPLEMENTATION NOTES

Interacting dark-sector models are frequently excluded by perturbation instabilities even when background fits are acceptable. Therefore, after a viable background region is identified, the analysis must include linear perturbations with an explicit choice of energy–momentum transfer four-vector Q^μ. The choice (e.g., $Q^\mu \parallel u_L^\mu$ or $Q^\mu \parallel u_{tot}^\mu$) and the closure assumptions for the Execution component (sound speed and anisotropic stress) must be stated. Viability requires that parameters favored by distances do not generate unacceptable deviations in $f\sigma_8(z)$ and S_8.

IX. FALSIFIABILITY CRITERIA

MetaTime v35.9 commits to explicit empirical failure modes. The minimal implementation is considered non-viable if any of the following conditions hold:

Test 1: Radion-channel cross-consistency (α-drift bridge)

If α-drift data constrain ζ_α to be effectively zero while the cosmology still requires strong Φ evolution (or strong activation Π) to reproduce late-time behavior, the correlated prediction collapses and the MetaTime Φ ↔ α mapping is empirically unsupported.

Test 2: Growth incompatibility

If the background-preferred interaction strength $\beta_{eff}(a) = \beta_0 + \beta_1 \Pi(a)$ produces growth predictions incompatible with RSD $f\sigma_8(z)$ and/or lensing S_8, then the interacting conversion mechanism is ruled out (or forced to $\beta_{eff} \approx 0$, becoming observationally degenerate with ΛCDM).

Test 3: Absence of the predicted late-time transition

For sigmoid-like Π(a), the model predicts a characteristic late-time transition around z_t. If expansion/distance reconstructions exclude any compatible transition in the required redshift interval, then that activation class is ruled out.

X. REPRODUCIBILITY AND RELEASE STANDARD

A complete release standard includes: the solver patch implementing Q(a), the likelihood modules (including α-drift), parameter files specifying priors and hard constraints, and scripts that regenerate the primary figures and tables from chains.

XI. RESULTS ROADMAP (PRD-STYLE DELIVERABLES)

This section specifies the exact figures, tables, and decision criteria required to present MetaTime v35.9 as a publication-grade phenomenology paper. The aim is to demonstrate background performance, perturbative consistency, and the correlated varying-constant signature in a manner aligned with Physical Review D expectations.

A. Primary figures (must include)

Figure 1 — Background expansion: H(z) and distance residuals

Panel A: H(z) (model vs. chronometers). Panel B: SN distance-modulus residuals relative to best-fit ΛCDM. Panel C: BAO distance indicators across z. The caption must report χ^2 contributions per dataset block.

Figure 2 — Dark-sector decomposition: Ω_L(z), Ω_E(z), and β_eff(z)

Plot $\Omega_L(z)$, $\Omega_E(z)$, and $\beta_{eff}(z) = \beta_0 + \beta_1 \Pi(a(z))$, showing mean posterior curves and 68% bands; positivity must be verified.

Figure 3 — Effective equation of state: w_eff(z) and the transition signature

Plot the effective equation of state for the combined dark sector (or total) with an inset on the transition region around z_t.

Figure 4 — Growth sector: fσ8(z) and S8 posterior

Panel A: $f\sigma_8(z)$ vs. RSD. Panel B: S_8 posterior (MetaTime vs. ΛCDM) with lensing constraints.

Figure 5 — α-drift cross-test: Δα/α(z) with best-fit Φ history

Plot quasar $\Delta\alpha/\alpha(z)$ points and the model curve $\Delta\alpha/\alpha(z) = \zeta_\alpha[\ln\Phi(z) - \ln\Phi(0)]$ with 68% bands; include α_{offset} posteriors if used.

B. Secondary figures (strongly recommended)

Figure 6 — Parameter degeneracies

Triangle plots including (β_0, β_1, a_t, Δ, w_E) and separately (ζ_α, α_{offset}), demonstrating constraints are not purely prior-driven.

Figure 7 — Robustness to Π(a) functional choice

Overlay results for 2–3 Π(a) families (sigmoid baseline, smooth saturating alternative, optional two-step extension) to show robustness.

C. Tables (must include)

Table I — Model definition and priors

Parameter definitions, prior ranges, fixed/free status, and hard physical constraints.

Table II — Dataset blocks and χ^2 contribution

N_data, χ^2_MetaTime, χ^2_ΛCDM, and $\Delta\chi^2$ for SNe, BAO, CMB distance priors, chronometers, RSD, lensing, and α-drift.

Table III — Posterior constraints

Mean ± 68% (and 95%) for β_0, β_1, a_t, Δ, w_E, ζ_α, α_offset, plus baseline cosmological parameters.

Table IV — Model comparison

AIC and BIC for MetaTime vs. ΛCDM; interpret improvements relative to added parameters.

D. Success criteria (explicit acceptance targets)

• Background non-inferiority: SNe+BAO(+early anchor) fits are not degraded relative to ΛCDM, and posteriors are not driven to prior edges.

• Growth consistency: distance-preferred parameters remain compatible with RSD $f\sigma_8(z)$ and lensing S_8 under the stated perturbation closure.

• Correlated observable viability: Δα/α(z) predictions are consistent with quasar data (and optional local bounds) without forcing ζ_α → 0 in a regime requiring strong Φ evolution.

• Physical viability checks: ρ_L(a) > 0, ρ_E(a) > 0; no numerical pathologies; stable perturbation evolution.

E. Failure criteria (explicit kill-switch outcomes)

• Early-time leakage: β_0 induces significant interaction prior to activation, spoiling early-universe consistency or forcing unphysical densities.

• Growth breakdown: the best-fit region to distances unavoidably violates $f\sigma_8/S_8$ constraints.

• Bridge collapse: α-drift data force ζ_α ≈ 0 while strong Φ evolution is still required for cosmological behavior.

• Activation rejected: data force Π(a) to be effectively constant (always-on or always-off), eliminating the claimed late-time mechanism.

F. Diagnostics and reproducibility

Report the Q^μ prescription and closure assumptions for the Execution component; provide convergence diagnostics (e.g., Gelman–Rubin thresholds and effective sample sizes); and include sanity tests demonstrating the $\beta_0 = \beta_1 = 0$ limit and the ζ_α = 0 limit.

G. Minimal Zenodo plot-package checklist

Include chains and parameter files, solver patches, data (or download instructions), and scripts to regenerate Figures 1–5 and Tables I–IV from the chains.

REFERENCES

[1] D. Peyrú, “MetaTime v35.6: PRD Preprint (final v2, equation references fixed)”, 2026. (Zenodo preprint).

[2] D. Peyrú, “Chronological Signature 2”, technical note, 2026.

[3] J. Lesgourgues, “The Cosmic Linear Anisotropy Solving System (CLASS)”, 2011; D. Blas, J. Lesgourgues, and T. Tram, “The Cosmic Linear Anisotropy Solving System (CLASS) II: Approximation schemes”, 2011.

[4] B. Audren et al., “Conservative Constraints on Early Cosmology with Monte Python”, 2013.

[5] L. Amendola, “Coupled Quintessence”, Phys. Rev. D 62, 043511 (2000).

[6] M. Valiviita, E. Majerotto, and R. Maartens, “Instability in interacting dark energy and dark matter fluids”, JCAP 07 (2008) 020.