The STF Cosmological Sector: Unified Dark Matter and Dark Energy from a Single Scalar Field

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Abstract

The Selective Transient Field (STF) produces three structurally distinct effects from a single scalar field with two derived parameters — the mass $m_s = 3.94 \times 10^{-23}$ eV and the coupling $\zeta/\Lambda = 1.35 \times 10^{11}$ m². In the cosmological background, the mass term produces oscillation-averaged cold-dark-matter-like behavior ($\langle w \rangle = 0$, $\rho \propto a^{-3}$) through the standard fuzzy-scalar mechanism; the Ricci-rate coupling sources dark energy through the T^2 topological pump with equation of state $w(z=0) = -1$ exactly and ghost-free effective phantom history $w(z) < -1$ for $z > 0$. At galactic scales, the same coupling produces MOND phenomenology through the nonperturbative cross-disformal regime. This paper derives the unified cosmological sector: the WKB mass-oscillation mechanism, the Friedmann budget check $\Omega_b + \Omega_{DM,osc} + \Omega_{\Lambda,T^2} \approx 1.00$ from a single field, and the structural independence of the three mechanisms by their controlling parameters. The dark-energy equation of state $w(z)$ is derived in [Paz 2026f] and its structural results are integrated here. Falsifiable predictions: $w(z)$ trajectory distinct from DESI CPL best-fit (Euclid $\sigma(w_0) \sim 0.01$–0.02); $\Omega_m = 4/(3(1+\pi)) = 0.3219$ from T^2 self-consistency; $a_0(z) = cH(z)/2\pi$ cross-epoch evolution distinguishing STF from Milgromian MOND.

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1. The Three-Mechanism Architecture

The STF Lagrangian in the curvature-coupling sector is [Paz 2026c, §III.A]:

$$\mathcal{L}_{\rm STF} = \frac{1}{2}(\nabla_\mu\phi)^2 - \frac{1}{2}m_s^2(\phi-\phi_0)^2 + \frac{\zeta}{\Lambda}\phi\,(n^\mu\nabla_\mu\mathcal{R})$$

with m_s and ζ/Λ derived from independent first-principles routes — m_s from the cosmological threshold condition $\mathscr{D}_{crit} = \mathscr{D}_{GR}$ at the $730\,R_S$ binary-inspiral activation [Paz 2026c, §III.D], ζ/Λ from 10D compactification over CICY #7447/Z_{10} [Paz 2026c, Appendix O]. The field produces three distinct physical effects:

MECHANISM	LAGRANGIAN TERM	SCALE	OBSERVABLE	CONTROLLI
Mass oscillation around potential minimum	$(1/2)m_s^2(\varphi - \varphi_0)^2$	Cosmological	$\langle w\rangle = 0$, $\rho \propto a^{-3}$ (dark matter)	**m_s**
Ricci-rate coupling to curvature gradient	$(\zeta/\Lambda)\varphi(n^\mu\nabla_\mu\mathscr{R})$	Cosmological	$w(z) \leq -1$, Λ_{eff} via T^2 pump (dark energy)	ζ/Λ, T^2 topolo
Cross-disformal matter coupling, nonperturbative regime	$\tilde{g}_{\mu\nu} = g_{\mu\nu} + \hat{B}(\partial\varphi\partial\mathscr{R} + \partial\mathscr{R}\partial\varphi)$	Galactic ($h \gg 1$ at $r \gtrsim$ kpc)	$a_0 = cH_0/2\pi$, flat rotation curves	**ζ/Λ**

Structural independence of the controlling parameters. The cosmological perturbation spectrum — and thus any Lyman-α or CMB-based constraint on the dark-matter sector — depends on m_s alone. The galactic phenomenology and the cosmological dark-energy contribution depend on ζ/Λ (and, for dark energy, the T^2 topology). The two parameters have independent derivation routes and independent observational probes. Neither is fitted to the other's domain.

This structural independence has a consequence that organizes the rest of the paper: each mechanism stands or falls on its own evidence. Observational challenges to the mass-oscillation dark-matter role (controlled by m_s) do not threaten the galactic-sector or dark-energy predictions (controlled by ζ/Λ and T^2 structure).

The galactic MOND sector is developed in [Paz 2026h]. The present paper derives the two cosmological mechanisms and their combined consequences.

2. Dark Matter from Mass Oscillation

2.1 Cosmological Field Decomposition

In FRW, the STF field equation [Paz 2026c, §VI.C.1]:

$$\ddot\phi + 3H\dot\phi + m_s^2(\phi - \phi_0) = \kappa\dot{R}$$

admits two distinguished configurations that coexist:

- **Driven minimum (tracker):** $\varphi_{\rm tracker} = \varphi_0 + \kappa\dot{R}/m_s^2$ — the quasi-static solution where the source balances the restoring force.
- **Oscillation around the minimum:** $\delta\varphi = \varphi - \varphi_{\rm tracker}$, obeying the damped free equation $\delta\ddot{\varphi} + 3H\delta\dot{\varphi} + m_s^2\delta\varphi = 0$.

The general cosmological solution is a superposition. At the current epoch, $m_s/H_0 \approx 2.5 \times 10^{10}$: the oscillator is vastly under-damped in its own frame (many oscillation periods per Hubble time) and over-damped in the cosmic-expansion frame. The tracker is adiabatic; the oscillating part $\delta\varphi$ evolves independently around it.

The tracker contribution $\rho_{\rm tracker} = V(\varphi_{\rm tracker}) = (\kappa\dot{R})^2/(2m_s^2)$ evaluates to $\sim 10^{-92}$ of the critical density today [Paz 2026c, Appendix M] — entirely negligible. The cosmologically relevant contribution from the mass term is the oscillation.

2.2 WKB Oscillation Analysis

For $\delta\varphi$ in the adiabatic regime $m_s \gg H$, the WKB solution is:

$$\delta\phi(t) \approx \Phi(t)\cos(m_s t+\theta), \quad \Phi(t) \propto a(t)^{-3/2}$$

The amplitude decreases as $a^{-3/2}$ from Hubble friction [Turner 1983]. Energy density and pressure:

$$\rho_{\rm osc} = \frac{1}{2}\dot{\delta\phi}^2 + \frac{1}{2}m_s^2\delta\phi^2,\qquad p_{\rm osc} = \frac{1}{2}\dot{\delta\phi}^2 - \frac{1}{2}m_s^2\delta\phi^2$$

Averaging over one oscillation period $\tau_{\rm osc} = 2\pi/m_s \approx 3.32$ yr — shorter than the Hubble time by a factor of $\sim 10^{10}$ — kinetic and potential energies equilibrate:

$$\langle\dot{\delta\phi}^2\rangle_{\rm osc} = \langle m_s^2\delta\phi^2\rangle_{\rm osc} = \frac{1}{2}m_s^2\Phi^2$$

giving:

$$\boxed{\langle\rho_{\rm osc}\rangle = \frac{1}{2}m_s^2\Phi^2 \propto a^{-3},\qquad \langle p_{\rm osc}\rangle = 0,\qquad \langle w\rangle = 0}$$

This is the standard fuzzy-scalar result [Hu, Barkana & Gruzinov 2000; Marsh 2016]. The STF at $m_s = 3.94 \times 10^{-23}$ eV, for modes inside the Hubble radius, behaves as a homogeneous pressureless cold-dark-matter fluid at the background level.

2.3 Contribution to Ω

For a scalar Hubble-frozen until $m_s = H$ and oscillating thereafter [Marsh 2016], the current energy density:

$$\rho_{\rm osc,0} \sim m_s^2 \Phi_{\rm i}^2 \left(\frac{a_{\rm osc}}{a_0}\right)^3$$

where Φ_i is the field amplitude at oscillation onset and a_{osc} the scale factor at that epoch. For $m_s = 3.94 \times 10^{-23}$ eV, oscillation begins when $H = m_s$: in the radiation-dominated era that applies at these epochs, $z_{osc} \approx 1.6 \times 10^{6}$. For Φ_i such that $\rho_{osc,0}$ matches observations, $\Omega_{DM,osc} \approx 0.27$.

Status. The STF mass-oscillation mechanism is sufficient in form to produce the observed dark-matter density when Φ_i is chosen appropriately. The mechanism is identical to standard fuzzy dark matter; the STF adds no new physics to the cosmological dark-matter production beyond the identification of m_s with the specific value derived from BBH-threshold physics. A first-principles derivation of Φ_i from compactification dynamics or the Cascade initial-condition structure [Paz 2026b] is an open item (§6.2).

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3. Dark Energy from the Ricci-Rate Pump

The Ricci-rate coupling $(\zeta/\Lambda)\varphi(n^\mu\nabla_\mu\mathscr{R})$ sources two distinct contributions to dark energy — the driven-minimum potential and the T^2 topological pump — separated by 92 orders of magnitude at the current epoch. Only the T^2 contribution is cosmologically observable.

3.1 Driven Minimum (UV Contribution)

The tracker potential $V(\varphi_{tracker}) = (\kappa\dot{R})^2/(2m_s^2)$ gives an energy density $\rho_{UV} \sim 10^{-158}$ eV^2 at current $\dot{R}$ [Paz 2026c, Appendix M]. This is 92 orders of magnitude below the observed dark-energy density. Its equation of state at the current epoch is $w = -1 + 2(H_0/m_s)^2 \approx -1 + 3 \times 10^{-21}$ [Paz 2026c, Theorem M.5.7] — effectively a cosmological constant at the 10^{-21} precision level, but at a density too small to be observable.

3.2 T^2 Topological Pump (The Observable Λ_{eff})

The Ricci-rate coupling, integrated over the T^2 compact-time topology with the fundamental mode $\varphi(\theta) = \cos(\theta)$, $\theta = \pi t/T_{compact}$, produces a topological contribution to Λ_{eff} through the coupling-accumulation integral:

$$\alpha(\theta) = \int_0^\theta \cos^2(\theta')\,d\theta' = \frac{\theta}{2} + \frac{\sin 2\theta}{4}$$

with current epoch at $\theta = \pi/2$ (the causal-diamond boundary fixed by full-period cancellation). This gives $\alpha(\pi/2) = \pi/4$ exactly, and:

$$\Lambda_{\rm eff} = \frac{\pi}{4}\cdot\frac{|\dot R|}{H_0 c^2} = 1.124 \times 10^{-52}\,{\rm m}^{-2}$$

matching $\Lambda_{\rm obs} = 1.100 \times 10^{-52}$ m^{-2} to 2.2% with zero free parameters [Paz 2026e, §II.2].

The full five-step derivation of the causal-diamond boundary identification and the $\pi/4$ result is given in [Paz 2026e, §II.2]. The full z-evolution of $\Lambda_{\rm eff}(z)$, the continuity-equation derivation of $w(z)$, the numerical trajectory, and the Python verification code are given in [Paz 2026f]. The present paper integrates these results into the unified cosmological architecture without reproducing them.

3.3 Principal Structural Results Required Here

Three results from [Paz 2026f] are used in §4 and §5:

(i) At $z = 0$: $w(z=0) = -1$ exactly, from third-order tangency $d\alpha/d\theta|_{\pi/2} = \cos^2(\pi/2) = 0$. Independent of $T_{\rm compact}$.

(ii) For all $z > 0$: $w(z) < -1$ monotonically, no phantom crossing from above. Effective phantom trajectory; ghost-free (DHOST Class Ia, $\alpha_T = 0$, GW170817-compatible). See [Paz 2026g] for why this evades the standard phantom no-go theorem.

(iii) At $z = 3$: $\Omega_{\Lambda,\rm STF}(z=3) \approx 0.01$ — approximately 1% of critical density — negligible at matter-dominated epochs. (Computed from $\alpha(\theta(3))/(\pi/4) \times \Omega_{\Lambda,0} / E(3)^2$ using the $w(z)$ V0.1 trajectory at $T_{\rm compact} = 2t_0$.)

4. The Friedmann Budget: Single Field, 95% of the Energy Density

4.1 No Double-Counting

The two cosmological contributions from §§2–3 are *structurally distinct*:

- $\rho_{\rm osc}$ depends on the *amplitude* of small oscillations around $\varphi_{\rm tracker}$; its scaling is set by m_s (the restoring force) and the $a^{-3/2}$ WKB amplitude decay.
- ρ_{Λ,T^2} depends on the *topological winding* of the coupling integral over compact time; its scaling is set by ζ/Λ and the T^2 causal-diamond geometry.

These are not two estimates of the same energy density. They project onto different aspects of the field configuration. The 92-order-of-magnitude gap between the UV tracker potential and the T^2 pump (§3.1–3.2) is the quantitative measure of how distinct the two cosmological sources are.

4.2 Friedmann Equation Budget

At $z = 0$:

$$3M_{\rm Pl}^2 H_0^2 = \rho_b + \rho_r + \rho_{\rm osc} + \rho_{\rm tracker} + \rho_{\Lambda,T^2}$$

with:

- **$\rho_b \to \Omega_b \approx 0.05$** — baryons, standard BBN
- **$\rho_{osc} \to \Omega_{DM,osc} \approx 0.27$** — STF mass oscillation (§2.3)
- **$\rho_{tracker} \to \Omega_{tracker} \approx 10^{-92}$** — negligible
- **$\rho_{\Lambda,T^2} \to \Omega_\Lambda \approx 0.68$** — STF T^2 pump (§3.2)
- **$\rho_r \to \Omega_r \sim 10^{-5}$** — radiation, sub-dominant today

Summing the non-negligible contributions:

$$\Omega_b + \Omega_{\rm DM,osc} + \Omega_{\Lambda,T^2} = 0.05 + 0.27 + 0.68 = 1.00$$

The same scalar field carries both the dark-matter role (through its mass term) and the dark-energy role (through its coupling term via the T^2 topology). Together they account for ≈ 95% of the cosmic energy budget. Baryons supply the remaining ≈ 5%. No additional dark-sector species are invoked.

4.3 Independence of the Three Mechanisms

The structural independence argued in §1 reflects the mathematical orthogonality of the three mechanisms:

- **ρ_{osc}** depends on the *amplitude* Φ of small oscillations, controlled by m_s
- **ρ_{Λ,T^2}** depends on the *topological winding* $\alpha(\theta)$ over compact time, controlled by ζ/Λ and T^2 structure
- **$a_0 = cH_0/2\pi$** depends on the *spatial gradient* $\nabla\varphi$ in disk geometry, controlled by ζ/Λ

The three probes — CMB/LSS for ρ_{osc}, Euclid/supernovae for $w(z)$ via ρ_{Λ,T^2}, SPARC/Gaia for galactic a_0 — do not inform each other through the field equation. This is what allows a failure in one sector (e.g., cosmological perturbation constraints on m_s, addressed in [Paz 2026h]) to be structurally quarantined from the other two sectors.

4.4 Additional Structural Constraint: Ω_m from T^2 Self-Consistency

The T^2 pump mechanism imposes an additional structural relation on the cosmological budget through the requirement $|R_0|/c^2 = 4\Lambda_{eff}$. This fixes a specific matter fraction $\Omega_m = 4/(3(1+\pi)) = 0.3219$, derived in [Paz 2026e, §II.3]. The derivation and observational comparison to Planck 2018 (consistent at $+1\sigma$) and DESI (2–3σ tension, model-dependent) are given there; the present paper imports this constraint as an additional prediction from the same T^2 architecture underlying the w(z) trajectory.

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5. Falsifiable Predictions

5.1 The w(z) Trajectory

Prediction (§3.3): $w(z=0) = -1$ exactly (third-order tangency at $\theta = \pi/2$); $w(z) < -1$ monotonically for all $z > 0$; no phantom crossing from above.

Distinguishes from:

- **ΛCDM** ($w = -1$ constant) — would be confirmed if $|1+w(z)|$ < Euclid sensitivity at all measured z
- **DESI CPL best-fit** ($w_0 \approx -0.75$, phantom crossing at $z \approx 0.4$) — categorically excluded by STF
- **Quintessence** ($w > -1$ always) — excluded; STF is on the phantom side except at $z = 0$

Test: Euclid (operating) will constrain w_0 to $\sigma \approx 0.01$–0.02 by 2027. STF is falsified if w_0 is measured significantly above -1 at $> 3\sigma$ robust to systematics.

5.2 Ω_m from T^2 Self-Consistency

See §4.4; derivation in [Paz 2026e, §II.3]. Prediction: $\Omega_m = 4/(3(1+\pi)) = 0.3219$. Euclid projected $\sigma(\Omega_m) \approx 0.002$–$0.003$ will test this decisively. Falsified if $\Omega_m < 0.31$ or > 0.34 at $> 5\sigma$. The falsification isolates to the T^2 curvature–dark-energy link; the rest of the STF framework survives.

5.3 Cross-Epoch a_0 Evolution

Prediction: $a_0(z) = cH(z)/2\pi$. The MOND acceleration scale evolves with the Hubble parameter because its derivation from the cross-disformal coupling structure ties it to the current cosmological expansion rate, not to a fundamental constant.

Distinguishes from Milgromian MOND: Standard MOND treats a_0 as a constant with no predicted z-dependence. STF predicts a specific H(z) tracking.

Test: High-redshift galaxy rotation curves (JWST, next-generation telescopes). If a_0 is observed constant across redshift contrary to STF’s $cH(z)/2\pi$ prediction, the cross-disformal coupling structure must be revised.

5.4 What Survives Each Falsification

A consequence of the structural independence (§1, §4.3):

OBSERVATION	FALSIFIES	SURVIVES
w_0 significantly > -1 at $> 3\sigma$	T^2 pump mechanism	Mass-oscillation DM, galactic sector
Ω_m outside [0.31, 0.34] at $> 5\sigma$	T^2 self-consistency (curvature–DE link)	Core STF framework
a_0 observed constant across z	Cross-disformal cosmological scaling	Mass-oscillation DM, T^2 pump
Lyman-α tightening excludes $m_s \leq 10^{-20}$ eV	Mass-oscillation DM (as formulated)	T^2 pump, galactic sector

The framework is falsifiable piece-by-piece. No single observation collapses the architecture; each sector carries its own falsifiers tied to its own controlling parameters.

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6. Open Items

6.1 The Compactification Timescale T_compact

The magnitude of $|1+w(z)|$ at $z > 0$ scales as $\xi = 1/(H_0 T_{compact})$. The $\theta_{now} = \pi/2$ identification gives $T_{compact} = 2t_0 \approx 27.6$ Gyr, yielding $|1+w(z=0.3)| \approx 0.095$. Larger $T_{compact}$ (up to $\sim T_{depart} \approx 2.4 \times 10^{14}$ yr) shrinks the deviations toward observationally indistinguishable from Λ. The full DHOST field-equation solution is needed to fix $T_{compact}$ from first principles; the full sensitivity analysis across $T_{compact} \in \{2t_0, 20t_0, 200t_0, T_{depart}/H_0\}$ is given in [Paz 2026f, §6.1]. The **structural** results — $w(z=0) = -1$ exactly, no crossing, monotonic phantom history — hold regardless of $T_{compact}$.

6.2 The Primordial Oscillation Amplitude Φ_i

The cosmological $\Omega_{\rm DM,osc}$ depends on Φ_i, the field amplitude at the onset of oscillation. The present paper takes Φ_i as a free parameter fitting observed $\Omega_{\rm DM} \approx 0.27$. A first-principles derivation from compactification dynamics (Appendix J-class inflation analysis [Paz 2026c]) or from the Cascade initial-condition structure [Paz 2026b] is deferred to future work.

6.3 The Regime-Dependent Effective Mass (Primary Open Target for the Cosmological Perturbation Sector)

The 10D Gauss-Bonnet reduction produces two distinct descendants of the $e^{\kappa\sigma} I_4(g)$ term, where I_4 is the curvature-squared invariant — reducing to $C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma}$ in vacuum (Ricci-flat, only Weyl survives) and to $a R^2 + b R_{\mu\nu} R^{\mu\nu}$ in FRW (conformally flat, only Ricci terms survive), with coefficients a, b set by the compactification ([Paz 2026c, §L.4, §L.5.1]). The first descendant, $\gamma\varphi I_4$ (linear in φ, obtained in §O.3.3 by Taylor-expanding $e^{6\sigma}$ around σ_0), becomes the STF rate coupling through EFT matching and is the origin of the $(\zeta/\Lambda)\varphi(n^\mu\nabla_\mu\mathscr{R})$ operator in the Lagrangian. The second descendant, extracted at quadratic order in $\delta\sigma$ in [Paz 2026c, §O.3.4]:

$$\Delta\mathcal{L}^{(2)} = \frac{3}{8}\,\lambda_{\rm GB}\,e^{6\sigma_0}\,\phi^2\,I_4(g_{\rm bg})$$

shifts the effective scalar mass on non-vacuum backgrounds:

$$m_{s,{\rm eff}}^2 = m_s^2 + \frac{3}{4}\,\lambda_{\rm GB}\,e^{6\sigma_0}\,I_4(g_{\rm bg})$$

In vacuum, $I_4 = 0$ on the homogeneous Minkowski background, so $V_{\rm stab}$ alone determines $m_{s,\rm vac} = 3.94 \times 10^{-23}$ eV through $V''(\sigma_0)/(24M_{\rm Pl}^2)$ [Paz 2026c, §L.3]. The second-order descendant contributes only on non-vacuum backgrounds. In FRW, with I_4 scaling as H^4, the present-day correction is $I_4 \sim H_0^4 \sim 10^{-132}$ eV^4 and $\Delta m^2_{\rm eff} \sim 10^{-112}$ eV^2 — utterly negligible compared to $m_{s,\rm vac}^2 \sim 10^{-45}$ eV^2. The correction was significant in the early universe ($H \sim M_{\rm Pl}$) and asymptotes to the vacuum value as $H \to 0$ [Paz 2026c, §L.3 note, §O.3.4]. The sign of the correction depends on $\lambda_{\rm GB}$ and the I_4 coefficients (a, b in $a R^2 + b R_{\mu\nu} R^{\mu\nu}$), and has not been determined.

The open question is whether the regime-dependent Ricci decomposition of I_4 in FRW — the specific combination of R^2 and $R_{\mu\nu} R^{\mu\nu}$ that emerges from the compactification — contains terms whose H-scaling at intermediate epochs (relevant for structure formation at z ~ 1–5) differs from the full Gauss-Bonnet invariant's H^4 scaling. The updated first-principles paper explicitly flags this question [Paz 2026c, §O.3.4, final paragraph]: "Whether the correction is significant at intermediate epochs relevant for structure formation depends on the precise coefficients c_1, c_2 from the compactification and on whether the regime-dependent Ricci decomposition introduces terms with lower H-scaling than the full Gauss-Bonnet invariant." Every other route to modifying the effective perturbation-spectrum mass has been checked and closed: coupling corrections at cosmological scales are 10^{-20}-suppressed [Paz 2026c, §VII.E.1]; threshold inputs to $m_{s,vac}$ are locked (M_c is fixed by the 10D formula and measured via LIGO chirp masses, the $4\pi^2$ is a topological invariant, H_0 is measured); no channel-dependent threshold splitting is possible because the curvature channel in FRW is still metric curvature and M_{Pl} remains the reduction scale.

This is the primary open target. Whether the mass-oscillation perturbation spectrum can accommodate Lyman-α constraints without modifying the framework rests on this single question. Resolution requires the explicit regime-dependent Ricci decomposition of I_4 in FRW and a check for any descendant scaling as H^n with $n < 4$.

6.4 Cross-Disformal in FRW Geometry

The cross-disformal coefficient $\hat{B} = (27/8)\, \mu^2 \mathscr{R} / ((\zeta/\Lambda)\, Y^{3/2}\, c)$ is derived in Schwarzschild geometry with $\mathscr{R}$ the Kretschmann scalar [Paz 2026d, §3.2]. The cosmological perturbation analysis [Paz 2026c, §VII.E.1] establishes that the scalar kinetic and sound-speed functions in the FRW tracking regime are $Q_s = 1 + O((H/m_s)^2)$ and $c_s^2 = 1 + O((H/m_s)^2)$, with $(H_0/m_s)^2 \sim 10^{-21}$ at late times — so coupling corrections to the matter transfer function are negligible at all cosmologically relevant wavenumbers. This settles the question: **cross-disformal is negligible cosmologically.** The CMB's agreement with linear perturbation theory at sub-percent precision [Planck 2018] is independent observational confirmation.

Boltzmann caveat. The matter-era suppression estimate is not the full story for Lyman-α specifically. A complete Boltzmann computation including radiation-era evolution would generally shift the fuzzy-scalar suppression onset to lower k than the matter-era estimate, making the Lyman-α tension in the mass-oscillation sector somewhat worse, not better. This reinforces rather than weakens the importance of the §6.3 open item.

7. Summary

The STF cosmological sector is a unified dark-sector architecture from a single scalar field. Two derived parameters — m_s from vacuum (BBH threshold) physics, ζ/Λ from 10D compactification — control three structurally independent mechanisms:

1. **Dark matter** from mass oscillation (controlled by m_s): standard fuzzy-scalar behavior $\langle w \rangle = 0$, $\rho \propto a^{-3}$.
2. **Dark energy** from Ricci-rate coupling through T^2 topological pump (controlled by

ζ/Λ and T^2 structure): $w(z=0) = -1$ exactly, ghost-free phantom trajectory $w(z) < -1$ for $z > 0$.

3. **Galactic dynamics** from nonperturbative cross-disformal coupling (controlled by ζ/Λ): MOND phenomenology, $a_0 = cH_0/2\pi$ [Paz 2026h].

The Friedmann budget closes: $\Omega_b + \Omega_{DM,osc} + \Omega_{\Lambda,T^2} = 0.05 + 0.27 + 0.68 \approx 1.00$. The three mechanisms are independently falsifiable, with distinct observational probes and controlling parameters. A failure in any single sector does not cascade.

Primary falsifiers: Euclid $w(z)$ for the T^2 pump; Euclid Ω_m for T^2 self-consistency; JWST-era high-z rotation curves for cross-epoch $a_0(z)$; Lyman-α tightening for the mass-oscillation mechanism. Primary open theoretical target: whether the regime-dependent I_4 decomposition in FRW contains descendant terms with H-scaling lower than H^4, which is the one remaining route by which the cosmological perturbation spectrum could accommodate Lyman-α constraints without modifying the framework.

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