From Chaos To Cosmic Expansion

Successive Collision Theory and the Origin of Dark Energy: A Single Geometric Mechanism — Recursive Tensor-Mesh Dissipation from Tidal Recession to Cosmic Acceleration — Resolving the Hubble Tension, S_8 Discrepancy, Evolving w(z), and the Cosmological Constant Problem

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Background. In the standard ΛCDM model, late-time cosmic acceleration is attributed to a strictly constant, spatially homogeneous dark-energy component identified with vacuum energy. This prescription fits many datasets but raises deep conceptual and empirical problems: the cosmological constant appears fine-tuned by roughly 10^{120} relative to quantum field-theory expectations, it is rigid in time and space, and persistent tensions between local and early-universe inferences of the expansion and growth histories resist resolution within the standard framework.

Aims. This paper develops an alternative interpretation within Successive Collision Theory (SCT), a framework in which an eternally infinite spacetime is populated by a nested hierarchy of comoving frames whose local perceptions of time and space are inherited from their parent frames through standard General Relativity (GR) and Special Relativity (SR). We derive a dynamical, environment-dependent effective cosmological term from the secular weakening of overlapping gravitational wells (the tensor mesh) at each hierarchical scale, and demonstrate that this single mechanism qualitatively addresses the Hubble tension, the S_8 growth tension, hints of evolving w(z) ≠ −1, and the cosmological-constant fine-tuning problem.

Methods. We introduce the effective cosmological term Λ_eff(x,t) ∝ Λ_parent(x,t) / λ_local(x,t), where Λ_parent encodes the cumulative rate of tensor-mesh dissipation inherited from all parent frames and λ_local parameterizes the strength of overlapping gravitational wells in the local environment. We derive the relationship between this ratio and observed expansion-rate differences across environments, and we show that the mesh-strength scalar λ satisfies an exponential decay law whose parameters are constrained by multi-scale observational evidence spanning eight decades of physical scale. We explicitly identify two free parameters in the framework—the dimensionful proportionality constant C and the hierarchy-averaged decay rate α—and describe how they are constrained by observational data rather than treated as arbitrary.

Results. The Λ/λ mechanism suppresses expansion in strongly bound regions, enhances it in voids, yields an approximate exponential expansion on large scales from the compounded weakening of meshes across the hierarchy, and permits local slowdowns or reversals. Multi-scale observational evidence from lunar laser ranging through galaxy-size evolution to void statistics confirms that the secular outward drift of characteristic orbital radii that drives this mechanism is real and quantitatively significant across all measured scales.

Conclusions. SCT offers a unified qualitative account of several key cosmological tensions without introducing new particles or fields. The framework makes environment-dependent, falsifiable predictions distinguishable from ΛCDM that are testable with DESI, Euclid, Rubin/LSST, and the Nancy Grace Roman Space Telescope. We explicitly acknowledge that a full numerical implementation and formal derivation of the Einstein field equations from first principles within SCT remain as directions for future work.

Keywords: *dark energy; cosmological constant; Hubble tension; S_8 tension; baryon acoustic oscillations; tensor-mesh dissipation; nested comoving frames; Successive Collision Theory; environment-dependent expansion; void statistics*

1. Introduction

The discovery that the expansion of our visible universe is currently accelerating has reshaped modern cosmology. Within the prevailing ΛCDM framework, this phenomenon is modeled by adding a constant, spatially homogeneous component with equation of state $p_\Lambda = -\rho_\Lambda$ to the stress-energy budget of a Friedmann–Lemaître–Robertson–Walker (FLRW) spacetime. The resulting model fits supernova distance-redshift relations, the broad properties of the cosmic microwave background, baryon acoustic oscillations (BAO), and large-scale structure observables, earning it the designation of concordance cosmology. Yet beneath this empirical success lie several conceptual and observational tensions that strongly suggest the Λ prescription is, at best, an effective description rather than a fundamental one.

Conceptually, identifying Λ with vacuum energy requires a fine-tuning of roughly 10^{120} in natural units: quantum field theory estimates of the vacuum contribution overshoot the observed value by many orders of magnitude, with no robust symmetry principle known that would enforce such a cancellation [1,2,3]. A cosmological constant is also rigid: its energy density and equation of state are fixed in time and homogeneous in space, whereas a growing body of observational work probes whether effective dark-energy behavior might evolve with redshift [10,11,12].

Empirically, the concordance picture has been challenged on several fronts. Local measurements of H_0 using distance-ladder techniques favor ~73 km/s/Mpc, while early-universe probes yield ~67 km/s/Mpc [4,5,6,7]. Weak-lensing and large-scale structure surveys prefer a lower amplitude of matter clustering (parameterized by S_8) than predicted by evolving CMB initial conditions within ΛCDM [8,9]. Recent combinations of supernovae, BAO, and CMB data increasingly suggest that a strictly constant w = −1 may not be the best description at late times [10].

Successive Collision Theory (SCT) proposes a different starting point. Rather than a finite-age universe emerging from a singular event, SCT assumes an eternally infinite spacetime populated by an effectively infinite amount of mass-energy [31]. On these premises, the cosmological principle remains valid as a statistical statement about an unbounded hierarchy of structures. Gravity, obeying the field equations of GR, combined with SR kinematics, organizes matter into a nested succession of comoving frames: planetary systems, galaxies, groups and clusters, superclusters, our visible patch, and larger parent structures beyond it.

Within each comoving frame, the overlapping gravitational wells of its constituent bodies define an effective tensor mesh that binds mass-energy to spacetime. This mesh is not an additional field beyond GR, but a conceptual and mathematical representation of how the Einstein tensor responds to the local stress-energy configuration. In regions where many deep wells overlap, the mesh is strong and local spacetime is tightly bound. In underdense regions such as cosmic voids, the mesh is weak and trajectories respond more freely to curvature inherited from larger-scale structures.

The effective cosmological term Λ_eff(x,t) introduced here is neither constant nor fundamental but encodes how strongly the inherited parent-frame dissipation manifests in a given region. Two quantities determine this:

- Uppercase Λ_parent(x,t) measures the rate at which mass-energy cohesion is dissipated across the succession of parent pockets containing the region.
- Lowercase λ_local(x,t) measures the local overlapping well strength: high in clusters and galaxy cores, low in voids.

The effective cosmological term scales as:

$$\Lambda\_eff(x,t) = C \times \Lambda\_parent(x,t) / \lambda\_local(x,t) \quad (1)$$

where C is a dimensionful proportionality constant. We explicitly note that Equation (1) introduces two free parameters: C and the hierarchy-averaged mesh-decay rate α introduced in Section 4. These are not arbitrary; C is fixed by requiring that the spatial average ⟨Λ_eff⟩ reproduces the observed cosmological constant Λ_obs ≈ 1.1×10^{-52} m^{-2}

when averaged over a Hubble volume, and α is constrained by the multi-scale orbital expansion rates reviewed in Section 7. A central aim of this paper is to demonstrate that this single Λ/λ mechanism qualitatively addresses several of the most discussed tensions in ΛCDM without introducing new microphysics.

We also clarify the relationship between SCT and ΛCDM. SCT does not replace the post-recombination evolution of ΛCDM; it replaces the physical interpretation of the cosmological term. In regimes where λ_local is large and approximately uniform (deep inside bound structures, where the Birkhoff theorem and standard GR dynamics apply), Λ_eff is suppressed and standard GR is recovered exactly. On cosmological scales, the spatial average of Λ_eff recovers the Friedmann equations with a small positive cosmological constant. SCT thus extends ΛCDM by providing an environmental dependence that ΛCDM treats as absent.

The paper is organized as follows. Section 2 formalizes the SCT spacetime picture. Section 3 develops the Λ/λ reinterpretation. Section 4 analyzes the dynamical behavior of tensor-mesh dissipation. Section 5 applies the framework to bound and unbound regions. Section 6 discusses implications for cosmological tensions. Section 7 reviews multi-scale empirical evidence for secular orbital expansion. Section 8 outlines predictions, tests, and conclusions.

2. Eternal Infinite Spacetime and Nested Comoving Frames

2.1 Eternal Time, Infinite Space, and the Cosmological Principle

SCT starts from the premise that time is eternal and space is infinite. The appropriate large-scale background is an eternally infinite spacetime populated by an effectively infinite amount of mass-energy. Within this setting the cosmological principle—that the universe is homogeneous and isotropic on sufficiently large scales—remains valid, but it is interpreted statistically across an unbounded hierarchy of structures rather than as a property of a single isolated bubble universe.

In such an eternally infinite spacetime there is no privileged cosmic origin and no unique global scale factor. General Relativity dictates how stress-energy curves spacetime, and Special Relativity governs how clocks and rulers transform between frames, but there is no requirement that all matter share a single comoving frame or a single expansion history. The observable patch we call our universe is one pocket in a vastly larger hierarchy, and the question becomes how its local spacetime is shaped by the structures that contain it.

2.2 Comoving Frames as Hereditary Pockets of Spacetime

Within GR, a comoving frame is most naturally defined as a set of worldlines with a shared four-velocity field. Astrophysical systems are arranged in nested, approximately comoving structures: stellar systems within galaxies, galaxies within groups and clusters, groups within superclusters, and our entire visible patch within larger structures beyond our observational horizon.

SCT emphasizes that this hierarchical structure is the natural consequence of gravitational dynamics in an eternally infinite spacetime. The most massive objects in a given region set the bulk trajectory, and less massive siblings follow. Because SR tells us that motion through space slows motion through time, and GR tells us that gravitational potentials further modify local clock rates and spatial scales, each comoving frame defines its own characteristic perception of time and space. Child frames inherit this perception from their parents.

For a hierarchy of nested frames indexed by scale level n, the child frame at level n+1 experiences proper time related to its parent's proper time by:

$$d\tau_{n+1} = d\tau_n \times \sqrt{1 - v^2_{n+1|n}/c^2} \times (1 + \Phi_n/c^2) \quad (2)$$

where $v_{n+1|n}$ is the child's velocity measured in the parent frame and Φ_n is the parent-level gravitational potential (negative for a bound system, so the factor is less than unity). This relation is exact to first post-Newtonian order and encodes the hereditary time mechanism of SCT: proper time at each level is set by the compounded product of SR and GR correction factors from all ancestor frames.

2.3 The Gravitational Tensor Mesh and Overlapping Wells

At each level of the hierarchy, the mass-energy distribution generates a gravitational field described by the Einstein tensor $G_{\mu\nu}$ sourced by the stress-energy tensor $T_{\mu\nu}$. In regions where many deep gravitational wells overlap—galactic centers, rich clusters, tightly bound multi-body systems—the curvature induced strongly constrains the geodesics available to test particles and light. In underdense regions the curvature is weaker.

The tensor mesh is a conceptual representation of this behavior: not an additional physical field beyond GR, but a description of how the combined gravitational influence of many overlapping wells creates a lattice of preferred geodesic paths. We parameterize the mesh strength as a scalar proxy λ: high λ corresponds to regions where overlapping wells produce a deep, cohesive gravitational environment; low λ corresponds to underdense regions. In regions with strong overlapping wells the mesh suppresses local participation in any larger-scale expansion, consistent with the observed fact that galaxies and clusters do not expand with the Hubble flow [14,15].

We note an important qualification: the scalar λ is not a new field equation but a coarse-graining device that summarizes, for a given spatial region, the net depth of the gravitational potential well integrated over all member masses. Formally, a natural definition for a region of volume V is:

$$\lambda(x,t) = -(1/c^2 V) \int_V \Phi(x',t)\, d^3x' \qquad (3)$$

where $\Phi(x', t)$ is the Newtonian gravitational potential (negative and large in magnitude inside clusters, near zero inside voids). This definition ensures $\lambda \geq 0$ everywhere, with $\lambda >> 1$ in cluster cores and $\lambda \approx 0$ in empty voids. The spatial average $\langle\lambda\rangle$ over a Hubble volume provides the normalization anchor for Equation (1).

2.4 Outward-Biased Orbital Evolution and Weakening Mesh

Bound systems across a wide range of scales exhibit a statistical bias toward outward drift of characteristic distances over time (reviewed in detail in Section 7). SCT treats these tendencies not as isolated curiosities but as manifestations of a general principle: while individual systems can certainly undergo inward decay and mergers, the ensemble of orbits across many scales shows a bias toward larger characteristic separations as time progresses. Averaged over many systems and long periods, this implies that the effective tensor mesh at each scale becomes more diffuse and the average binding per unit volume weakens—a slow decrease in λ at each level over long timescales. When this process is applied recursively across the hierarchy of parent frames, each child frame inherits a spacetime that is being gently stretched by the compounded effect of many levels of ancestor dissipation.

3. Reinterpreting the Cosmological Constant in Nested Frames

3.1 From a Constant Λ to a Scale-Dependent Λ_eff

In the standard formulation of GR with a cosmological constant, the field equations are:

$$G_{\mu\nu} + \Lambda\, g_{\mu\nu} = 8\pi G\, T_{\mu\nu} \qquad (4)$$

where $G_{\mu\nu}$ is the Einstein tensor, $T_{\mu\nu}$ is the stress-energy tensor, $g_{\mu\nu}$ is the metric, and Λ is a constant. When interpreted as vacuum energy, this Λ term corresponds to a uniform energy density ρ_Λ with negative pressure $p_\Lambda = -\rho_\Lambda$, the same everywhere and at all times. This picture provides a simple phenomenological handle on cosmic acceleration but immediately encounters two well-known problems. First, estimates of the vacuum energy from quantum field theory overshoot the observed Λ value by a factor of order 10^{120}, raising the cosmological constant problem in its most acute form [1,3,15]. Second, a truly constant Λ is rigid and cannot respond to the complex structure of the real universe, whereas observations increasingly suggest that effective dark-energy behavior may vary with redshift and environment [10,11].

SCT proposes that Λ should not be regarded as a fundamental microphysical constant but as an emergent term encoding how a given region's spacetime inherits the cumulative dissipation of mass-energy cohesion across the nested hierarchy of parent frames. The effective term that plays the role of Λ in the metric therefore depends on both position and time.

3.2 Defining Λ and λ in SCT

Two conceptually distinct contributions determine how strongly a given region participates in the inherited expansion. Uppercase Λ_parent(x,t) measures the rate and strength of mass-energy cohesion dissipation across the succession of parent pockets containing the region. This Λ is not vacuum energy; it is a coarse-grained descriptor of how orbits and structures at larger scales statistically drift outward, weakening the tensor meshes that bind those larger pockets to their own spacetime. Lowercase λ_local(x,t) measures the local overlapping gravitational-well strength, as defined operationally in Equation (3).

The fundamental SCT claim is that the effective cosmological term is:

$$\Lambda\_eff(x,t) = C \times \Lambda\_parent(x,t) / \lambda\_local(x,t) \qquad (5)$$

For fixed Λ_parent, increasing λ suppresses Λ_eff: in strongly bound regions, the inherited pull from ancestor-frame dissipation is largely absorbed by the local mesh and the region barely participates in the large-scale expansion. Conversely, decreasing λ enhances Λ_eff: in weakly bound regions like voids, the same ancestor-frame dissipation translates into a larger effective expansion rate.

3.3 Effective Einstein Equations for a Tensor-Mesh Hierarchy

With these definitions, the effective Einstein equations in SCT take the form:

$$G\_\{\mu\nu\}(x,t) + \Lambda\_eff(x,t)\ g\_\{\mu\nu\}(x,t) = 8\pi G\ T\_\{\mu\nu\}(x,t) \qquad (6)$$

This does not alter the structural form of Einstein's equations; the geometric side remains G_{μν} and the matter side remains T_{μν}. What changes is the interpretation of the coefficient multiplying $g_{\mu\nu}$: it is an emergent, environment-dependent quantity derived from the nested-frame dynamics of SCT rather than a rigid constant.

We address the covariant consistency of this modification directly. For Equation (6) to be consistent with the contracted Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$, we require $\nabla^\mu(\Lambda_{eff} g_{\mu\nu}) = 8\pi G \nabla^\mu T_{\mu\nu}$. Since $T_{\mu\nu}$ is independently conserved ($\nabla^\mu T_{\mu\nu} = 0$) from the matter equations of motion, this requires $\nabla_\nu \Lambda_{eff} = 0$, i.e., that Λ_{eff} is spatially constant. This is the standard result for a cosmological constant and is not satisfied by a spatially varying Λ_{eff}. We therefore interpret Equation (6) not as an exact fundamental field equation but as an effective description valid on scales large enough that the spatial gradients of Λ_{eff} are small compared to the scales over which $G_{\mu\nu}$ varies. This is analogous to the treatment of spatially varying dark-energy fields in quintessence models, where the field equation of motion provides the missing term that restores Bianchi consistency. A complete SCT field theory would require specifying the equation of motion for Λ_{eff} (or equivalently for the underlying mesh-strength field λ), which we identify as a primary direction for future work. For the purposes of this paper, Equation (6) is used as a phenomenological description of how different regions of the universe participate in the large-scale expansion at different effective rates.

3.4 Hierarchical Propagation of Λ Across Scales

The nested nature of comoving frames defines a hierarchy of scales. At each level n there is a characteristic tensor mesh strength and a characteristic rate of dissipation. The scalar Λ_n at level n summarizes this dissipation. When moving down one level in the hierarchy, from level n to level n−1, the child frame's geometry includes the curvature inherited from level n as part of its background:

$$\Lambda_{n-1,\ parent} \approx \Lambda_n + \delta\Lambda_{n-1} \qquad (7)$$

where Λ_n encodes the dissipation at level n and $\delta\Lambda_{n-1}$ encodes additional dissipation at level n−1. The relevant Λ_{parent} for our visible patch is therefore a composite quantity including contributions from all larger scales in the SCT hierarchy. The absolute normalization of this sum is set by requiring $\langle\Lambda_{eff}\rangle_{Hubble} = \Lambda_{obs}$.

3.5 Constraints and Consistency with Observations

The Λ/λ framework satisfies several important observational constraints. In galaxies, groups, clusters, and other strongly bound environments, λ is large and Λ_{eff} is correspondingly small, reproducing the observed fact that stars within galaxies and galaxies within clusters do not partake in the Hubble expansion [14,15]. In underdense regions, λ is small and Λ_{eff} is larger, so these regions exhibit the strongest effective expansion and dominate the observational signatures of cosmic acceleration. On large scales, the spatial average ⟨Λ_{eff}⟩ over many regions can mimic a constant-Λ behavior closely enough to pass standard cosmological tests, while still allowing subtle environment-dependent deviations that manifest as the observed tensions [4,10,11].

4. Dynamical Behavior of Tensor-Mesh Dissipation

4.1 Secular Weakening of the Tensor Mesh Across Scales

To capture the time evolution of mesh strength we introduce a scalar function $M_n(t)$ representing the average mesh strength at hierarchical level n. Various microphysical processes—tidal interactions, dynamical friction, minor mergers, mass loss—collectively contribute to a slow decay of M_n. A natural first approximation is:

$$dM_n(t)/dt = -\alpha_n M_n(t) \quad (8)$$

where α_n is an effective decay rate at level n. The solution is:

$$M_n(t) = M_n(t_0) \exp[-\alpha_n (t - t_0)] \quad (9)$$

This describes an exponential weakening of mesh strength at that level over time. The value of α_n depends on the mass distribution and dynamical history at scale n.

We note that the exponential decay law in Equation (9) is an approximation appropriate for the long-time statistical average over many systems at a given scale. Individual systems do not follow this law: they may undergo rapid mergers, tidal disruption, or significant mass-loss events on much shorter timescales. Equation (9) is therefore interpreted as the ensemble-averaged behavior of many systems at level n, analogous to a radioactive decay law applied to a population of nuclei rather than to any individual nucleus. The decay rate α_n is constrained by the empirical evidence reviewed in Section 7: for galactic scales, it corresponds to the observed inside-out growth rate of galaxies ($\alpha_{gal} \sim (1–1.5) \times H_0$ from the van der Wel et al. redshift-size relation [17]); for cluster scales, it corresponds to the virial radius growth rate ($\alpha_{cluster} \sim 0.5 H_0$ from Kravtsov & Borgani [26]); and for the cosmological scale, α_{cosmo} must reproduce the observed Λ_{obs}, providing the normalization constraint on C in Equation (5).

4.2 Approximate Exponential Behavior Over Long Times

The decay law for $M_n(t)$ leads naturally to approximate exponential expansion at large scales. Since the scalar λ is a proxy for local mesh strength, and since $\Lambda_{eff} \propto \Lambda_{ancestors}/\lambda_{local}$, the exponential decay of $M_n(t)$ implies that $\Lambda_{ancestors}(t)$ grows over time. In a toy single-scale model:

$$M(t) = M_0 \exp(-\alpha t) \Rightarrow \Lambda_{eff}(t) \propto 1/M(t) = (1/M_0) \exp(+\alpha t) \quad (10)$$

An FLRW effective description with such a cosmological term drives an accelerated expansion that, at leading order, exhibits exponential behavior in the scale factor, mimicking a positive cosmological constant. The key point is that a hierarchy of meshes weakening roughly exponentially over time naturally produces an effective expansion term that grows on large scales. The multi-scale nature of the hierarchy means that the effective α governing cosmological-scale observations is a weighted average over all contributing levels—small at planetary scales, larger at galactic scales, and largest at supercluster scales—so that the cosmological-scale Λ_{eff} changes slowly compared to H_0^{-1}, consistent with the near-constant behavior inferred from current data.

4.3 Conditions for Local Slowdowns and Apparent Reversals

While the global, large-scale behavior of $\Lambda_{eff}(t)$ approximates an exponential increase, SCT explicitly allows for significant spatial and temporal variation. Two broad classes of conditions can lead to local slowdowns or apparent reversals. First, regions with unusually strong local binding—very massive galaxy clusters, nested bound systems, coherently overlapping deep wells—can maintain a large and potentially growing λ_{local}. If $\Lambda_{ancestors}$ is increasing only slowly while λ_{local} remains high, $\Lambda_{eff} = C \Lambda/\lambda$ can decrease locally. Second, if the nearest parent frames around a region are temporarily converging rather than separating, the effective dissipation rate experienced by the descendant region may temporarily decrease, reducing Λ_{eff} even if λ_{local} is not exceptionally large. In SCT, apparent reversals are not a breakdown of GR but the result of the nested-frame inheritance structure and the dynamical nature of both numerator and denominator in Equation (5).

5. Bound and Unbound Regions: BAO, Galaxies, and Voids

5.1 Suppression of Expansion in Strongly Bound Regions

One of the most robust observational facts about our universe is that strongly bound systems do not expand with the Hubble flow [14,15]. In the SCT Λ/λ framework, this scale dependence is built directly into the effective cosmological term. Strongly bound regions are characterized by large λ. For any given ancestor dissipation $\Lambda_{ancestors}$, the effective cosmological term is suppressed:

$$\lambda_{local} \gg 1 \Rightarrow \Lambda_{eff} = C \Lambda_{ancestors} / \lambda_{local} \ll \Lambda_{ancestors} \quad (11)$$

The inherited stretch from parent frames is largely absorbed by the local mesh. Geodesics are so tightly bound by the overlapping wells that any tendency for the background spacetime to expand is effectively resisted at local scales. This provides a geometric SCT-based account of the observed absence of expansion inside galaxies, clusters, and bound structures: their large λ ensures that Λ_{eff} is too small to produce a measurable change in local distances over cosmological timescales. We note that this is consistent with the standard GR result from Birkhoff's theorem, which states that the exterior metric of a spherically symmetric mass distribution is Schwarzschild, not FLRW; in SCT language, high-λ bound interiors are simply those in which the local tensor mesh dominates over any inherited parent-frame expansion.

5.2 Enhanced Expansion in Voids and Low-Density Environments

In voids and underdense environments the tensor mesh is weak. Here λ is small, and in the Λ/λ picture this translates into a larger effective cosmological term:

$$\lambda_{local} \ll 1 \quad \Rightarrow \quad \Lambda_{eff} = C\,\Lambda_{ancestors} / \lambda_{local} \gg \Lambda_{ancestors} \qquad (12)$$

Voids and other low-density regions therefore experience the strongest effective expansion. Supernovae observed in relatively isolated host galaxies, BAO features inferred from the large-scale matter distribution, and CMB distance measures all average over trajectories that spend significant fractions of their path length in low-λ environments. This environmental dependence implies that the cosmic expansion is intrinsically inhomogeneous at the level of local rates, even if its large-scale average behaves smoothly.

5.3 Reinterpreting BAO and the Clumpy Expansion Picture

Baryon acoustic oscillations provide one of the most important standard rulers in modern cosmology. In ΛCDM, the BAO scale is treated as a clean probe of the homogeneous expansion history: the comoving size of the BAO feature is imprinted at recombination and subsequently stretched by the global scale factor [23,38]. In SCT, BAO features are associated with mildly bound overdensities: coherent ripples in the matter distribution tracing regions where the tensor mesh is somewhat stronger than in the surrounding voids. BAO peaks sit in environments with λ larger than that of the emptiest regions but smaller than that of fully collapsed clusters. This intermediate λ implies that BAO-scale regions experience an effective expansion rate slightly depressed relative to purely void-dominated paths.

The familiar raisin-bread analogy for cosmic expansion must therefore be modified. In the homogeneous version, every raisin separation grows at the same rate. In SCT, a clumpy version is more appropriate with at least three ingredients:

- Raisins in dense clumps—high-λ regions (galaxies, groups, clusters) with strongly suppressed Λ_eff. They barely move apart as the dough rises.
- Raisins in loose associations—moderate-λ environments (filaments, BAO-scale overdensities). They do move apart, but at a slower effective rate than raisins embedded in low-λ voids.
- Dough in voids—the low-λ component where Λ_eff is largest. The dough here expands fastest, stretching the separations between structures not strongly bound to any local mesh.

Under SCT, the global expansion history is the result of averaging over this clumpy, environment-dependent behavior. On sufficiently large scales, the average can be represented by an effective scale factor that behaves similarly to ΛCDM. But when examined at finer resolution, the inhomogeneity becomes important: BAO standard rulers, supernovae in different host environments, and lensing paths that sample different mixtures of voids and structures can all experience slightly different effective expansion histories due to their different Λ/λ weightings.

6. Implications for Cosmological Tensions

6.1 Hubble Tension and Environment-Dependent Expansion

The Hubble tension refers to the persistent discrepancy between $H_0 \sim 73$ km/s/Mpc from local distance-ladder measurements and $H_0 \sim 67$ km/s/Mpc from early-universe probes such as the CMB combined with BAO [4,5,6,7]. In the SCT Λ/λ picture, this discrepancy is a natural consequence of environment-dependent expansion.

Local distance-ladder measurements are rooted in high-λ environments: Cepheids reside in galactic disks and bulges, supernova host galaxies are bound systems, and the calibrating rungs of the ladder are embedded deeply in the local gravitational tensor mesh. The effective cosmological term Λ_eff sampled along these sightlines is suppressed by large λ_local, and the inferred H_0 is correspondingly higher than the global average.

By contrast, CMB and large-scale BAO analyses average over much larger volumes and are more sensitive to lower-λ environments: they effectively integrate along paths dominated by voids and mildly bound structures where Λ_eff is closer to Λ_ancestors. When these data are interpreted within a homogeneous FLRW model with a single global Λ, the resulting H_0 reflects a compromise between regions of different Λ/λ weightings. SCT thus reinterprets the Hubble tension not as a failure of the data or a requirement for exotic early-universe physics, but as evidence that the universe's expansion field is intrinsically inhomogeneous, with different probes sampling different effective Λ_eff and hence different effective Hubble parameters.

We note an important quantitative constraint: the SCT explanation of the Hubble tension requires that the variation in Λ_eff between the local (high-λ) and global-average (low-λ) environments be approximately (73−67)/67 ≈ 9%. This is a testable constraint on the amplitude of the Λ/λ ratio variation across environments, which can in principle be measured through void versus cluster expansion-rate comparisons from the surveys discussed in Section 8.

6.2 Growth of Structure and S_8-Like Tensions

The S_8 tension concerns a mismatch between the amplitude of matter clustering inferred from weak-lensing and large-scale structure surveys at low redshift and the amplitude predicted by evolving CMB-inferred initial conditions within ΛCDM [8,9,35]. In SCT, the suppression of growth in certain environments is a direct consequence of environment-dependent Λ_eff. High-Λ_eff regions—those with low λ and/or particularly strong ancestor dissipation—experience more rapid effective expansion, which stretches matter apart and inhibits the formation and deepening of gravitational wells. Conversely, high-λ regions maintain stronger clustering.

Weak-lensing and galaxy-survey measurements are sensitive to a complex mixture of these environments. If they are preferentially sensitive to lines of sight and redshift ranges where low-λ regions dominate, the net effect is an apparent suppression of structure growth relative to the Planck-based ΛCDM expectation. The S_8 tension is not necessarily a sign that the underlying dark sector or gravity law differs from early-universe conditions; it may reflect the Λ/λ dependence of late-time structure growth, which environment-tagged lensing analyses could directly test.

6.3 Dark-Energy Evolution and w(z) ≠ −1

Recent analyses, particularly those combining DESI BAO measurements with CMB and supernova data, have hinted that dark energy may not be a simple cosmological constant [10]. Some fits favor models where the effective w(z) evolves with redshift; the 2024 DESI results prefer $w_0 > -1$ and w_a < 0, suggesting a dark-energy component stronger in the past than today. In a universe where the true cosmological term is a rigid Λ, such behavior would require additional dynamical fields or modified-gravity ingredients.

In SCT the apparent evolution of w(z) is a geometric consequence of forcing an inhomogeneous, environment- and time-dependent Λ_eff(x,t) into a homogeneous-fluid parameterization. When cosmological data are analyzed under the assumption that dark energy can be described by a single function w(z) the same everywhere, the best-fit w(z) must absorb all the effects of Λ/λ variation along different sightlines and at different epochs. If Λ_eff tends to be larger in low-λ regions that dominate high-redshift BAO modes but smaller in the environments most relevant for lower-redshift supernovae, the homogeneous w(z) fit will generally deviate from −1. SCT offers a natural explanation for evolving w(z) signals: they are not evidence of a new dark field, but a reflection of the fact that Λ_eff is not a uniform constant but a ratio Λ/λ that varies with environment and time.

We note that this explanation is qualitative in the present paper. A quantitative prediction of w_0 and w_a within SCT requires modeling the redshift evolution of the environment-weighted average of Λ_eff(x,z), which depends on the cosmic web's evolution and the distribution of λ values as a function of epoch. This is a specific numerical calculation that we identify as a priority for future work.

6.4 BAO and Internal Dark-Energy Tensions

Internal tensions also arise within BAO and dark-energy analyses themselves: different BAO tracers, different redshift bins, and different combinations with other data sometimes prefer slightly different expansion histories under a single-Λ ΛCDM model [10,38,39]. In SCT this is expected, because BAO features at different redshifts and in different environments sample different typical Λ/λ ratios. High-redshift BAO measurements probe an era when large-scale structure was less developed, with smaller Λ_ancestors, giving a different Λ_eff than at low redshift. When all these measurements are forced into a single homogeneous Λ or homogeneous w(z) model, the resulting fit struggles to accommodate the full variety of Λ_eff values actually present, leading to internal tensions among BAO-based inferences and between BAO and other probes. From the SCT standpoint, these tensions are signatures: they indicate that the cosmological term is behaving exactly as one would expect from a Λ/λ mechanism operating in a hierarchically structured spacetime.

6.5 Cosmological Constant Problem and Rigidity

The cosmological constant problem in its traditional form arises when Λ is identified with vacuum energy [1,2,3,15]. Quantum field theory suggests that the vacuum should contribute a huge energy density, yet the observed value of Λ is tiny by comparison. Moreover, a vacuum energy is rigid: it does not respond to environment or cosmological epoch. SCT reframes this problem by denying the identification of Λ with fundamental vacuum energy. The smallness of the observed Λ_eff in strongly bound regions is a consequence of the large λ in those regions, rather than a fine-tuned cancellation of huge vacuum contributions. In voids and on large scales where λ is small, Λ_eff can be larger, but its value is tied to the dynamics of the nested hierarchy.

This shift in perspective changes the nature of the question. Instead of asking why the vacuum energy is so small and rigid, SCT asks how the hierarchy of tensor meshes has evolved over eternal time to produce the particular pattern of ancestor dissipation Λ_ancestors(x,t) and local binding λ_local(x,t) that yields the observed Λ_eff. Fine-tuning becomes a question about the statistical properties of an eternally evolving, infinite hierarchy, not about the unnatural smallness of a single fundamental parameter. We emphasize that this reframing does not solve the cosmological constant problem in the technical sense of deriving the observed Λ from first principles; rather, it replaces the problem of fine-tuning a rigid constant with the question of what dynamical principle governs the hierarchy of tensor-mesh strengths. This is arguably a more tractable question because it connects to observational quantities (orbital evolution rates, galaxy size growth, void expansion), but it remains a question that SCT does not yet answer quantitatively.

6.6 Summary: Tensions Addressed by the Λ/λ Mechanism

Table 1 collects the key ΛCDM tensions and summarizes how the Λ/λ reinterpretation in SCT addresses each using the same underlying mechanism of tensor-mesh dissipation.

Tension	Statement	SCT / Λ/λ Resolution	Quantitative Status
Hubble tension (H_0)	Local ladder gives $H_0 \sim 73$ km/s/Mpc; CMB/BAO gives ~67 km/s/Mpc.	Λ_eff varies with environment: local probes sample high-λ regions; CMB/BAO average over larger, lower-λ volumes, giving genuinely different effective H_0.	Requires ~9% Λ_eff variation across environments; testable.
S_8 / Growth tension	Weak lensing prefers lower matter clustering amplitude than Planck-ΛCDM predicts.	High-Λ_eff (low-λ, void-dominated) regions suppress late-time structure growth. Lensing surveys weighting these environments lower effective S_8.	Qualitative; quantitative model needed.
Evolving dark energy w(z) ≠ −1	DESI+SNe fits prefer $w_0 > -1$, w_a < 0, suggesting evolving dark energy.	Forcing inhomogeneous Λ_eff(x,t) into a homogeneous-fluid w(z) parameterization yields apparent evolution. No new dark field needed.	Qualitative; redshift evolution of ⟨Λ_eff⟩ must be computed.
BAO / internal DE tensions	Different BAO tracers and redshift	BAO tracers at different epochs sample different Λ/λ	Qualitative; tracer-specific λ

	bins prefer slightly different expansion histories.	ratios. Single-Λ ΛCDM cannot accommodate this range, producing systematic internal offsets.	distributions required for quantitative test.
Cosmological constant problem	QFT vacuum energy overshoots observed Λ by ~10^{120}; no symmetry enforces cancellation.	Λ_eff is emergent, not a fundamental vacuum constant. Smallness in bound regions is a consequence of large λ. Fine-tuning reframed as a dynamical hierarchy question.	Conceptual reframing; does not derive Λ_obs from first principles.

Table 1. Key cosmological tensions and their qualitative reframing within the SCT Λ/λ mechanism. The Quantitative Status column explicitly identifies where full numerical predictions remain to be developed.

7. Empirical Evidence for Secular Orbital Expansion Across Scales

A foundational pillar of SCT is that outward drift of characteristic orbital and structural distances is not an anomaly confined to cosmological scales, but a pervasive, multi-scale phenomenon spanning from the Earth-Moon system to galaxy clusters and large-scale flows. This section presents observational evidence that across at least eight decades of physical length scale, characteristic separations tend—statistically and on long timescales—to increase. We interpret each body of evidence in the SCT framework: such outward secular drift weakens the local tensor mesh at the corresponding scale, and the cascade of this weakening through the nested frame hierarchy is what we observe as dark energy at cosmological scales.

7.1 The Earth-Moon System: Lunar Laser Ranging

The most precisely measured instance of secular orbital expansion is the Earth-Moon distance. Since 1969, the Apollo and Lunokhod retroreflector arrays have enabled Lunar Laser Ranging (LLR), accumulating more than five decades of millimeter-precision measurements. Dickey et al. [1] provided the first comprehensive post-Apollo analysis; Williams, Turyshev & Boggs [2,3] refined the measurements to sub-centimeter precision. The current consensus value is a lunar recession rate of approximately 3.82 ± 0.07 cm/yr [2,4]. Chapront, Chapront-Touze & Francou [4] combined LLR data spanning 1969-2001 with historical eclipse timing to confirm this figure and to extract the tidal deceleration of Earth's rotation.

In the SCT framework, the Earth-Moon recession illustrates in miniature exactly the type of secular outward evolution that, repeated and cascaded across a hierarchy of scales, produces what we observe as dark energy. The key point is not that dark energy drives the Moon outward, but that the Earth-Moon system demonstrates the universal principle that bound systems lose binding energy over time through the operation of known dissipative processes, weakening the local tensor mesh.

7.2 Stellar Mass Loss and the Long-Term Expansion of Planetary Orbits

Planets orbiting a star that loses mass adiabatically drift outward. In the adiabatic limit, angular momentum conservation for a test particle orbiting mass M gives:

$$a(t) \propto 1/M(t) \qquad (13)$$

where a(t) is the semi-major axis. As a star evolves off the main sequence and expels its envelope through stellar winds, all bound planets migrate outward in inverse proportion to the fractional mass lost. For the Sun, models predict total mass loss of approximately 25-33% by the asymptotic giant branch tip, implying that Earth's orbit near 1 AU will expand to roughly 1.3-1.5 AU [8]. Schroeder & Connon Smith [8] carried out detailed calculations confirming this; Veras et al. [10] extended the calculation to exoplanetary systems; Adams & Laughlin [11] treat outward migration as part of the long-term evolution of stellar systems. Laskar et al. [9] have further shown through long-term numerical integration of the Solar System that secular resonances produce stochastic outward excursions of planetary orbital radii over billions of years.

The normalization of the adiabatic orbit expansion is well understood: $da/a = -dM/M$. This gives a well-defined contribution to the mesh-weakening rate $\alpha_{planets} \sim |\dot{M}_*|/M_*$ at the planetary scale, where $|\dot{M}_*|/M_*$ is the stellar fractional mass-loss rate. This is the only scale where α_n is known from first principles rather than inferred from structural evolution observations.

7.3 Galaxy Size Evolution: Inside-Out Growth Across Cosmic Time

Perhaps the most striking multi-scale evidence for secular outward drift comes from the observed evolution of galaxy sizes. Early-type and massive galaxies at redshifts $z \sim 2$-3 are systematically more compact—by factors of 3-5 in effective radius—than comparably massive galaxies in the local universe, confirmed by multiple independent surveys and facilities.

Trujillo et al. [15] and van Dokkum et al. [14] used deep HST imaging to demonstrate that massive early-type galaxies with stellar masses comparable to local ellipticals were 3-5 times smaller at $z \sim 2$. van der Wel et al. [16] analyzed the 3D-HST+CANDELS dataset covering ~200,000 galaxies across $0.5 < z < 3$, finding that the effective radius of early-type galaxies scales as $R_e \propto (1+z)^{-\alpha}$ with $\alpha \approx 1.0$-1.5. Buitrago et al. [17] confirmed these findings using ground-based near-infrared photometry. Bezanson et al. [21] and Naab, Johansson & Ostriker [22] proposed that minor dry mergers drive inside-out growth; Oser et al. [23] analyzed cosmological simulations and showed that massive galaxies build their outer envelopes preferentially through accreted ex-situ stars.

With the advent of JWST, these constraints have been extended to earlier cosmic epochs. Baggen et al. [20] presented size measurements for massive galaxies at $3 < z < 6$ from NIRCam imaging, confirming that the most extreme compactness is reached at the highest redshifts; Ward et al. [19] demonstrated that star-forming galaxies at $z \sim 7$-9 are roughly twice as compact as local counterparts. The consistent picture from HST through JWST is one of monotonic expansion of galaxy effective radii from high redshift to the present. From the van der Wel et al. relation, the implied galactic-scale mesh-decay rate is $\alpha_{gal} \sim H_0 \times \alpha_{vdW} \approx (1.0\text{-}1.5)\, H_0$, where α_{vdW} is the power-law index from their size-redshift relation.

7.4 Galaxy Groups and Clusters: Dynamics, X-Ray, and SZ Evidence

At the group and cluster scale the observational picture is more complex: clusters are simultaneously infalling from their outskirts and relaxing through violent relaxation in their cores. Nevertheless, several lines of evidence indicate that the characteristic physical scale of group and cluster environments tends to increase with cosmic time, consistent with ongoing accretion of mass from ever-larger surrounding volumes.

Kravtsov & Borgani [26] reviewed the formation of galaxy clusters, noting that cluster virial masses and radii grow monotonically in the standard cosmological model, with typical cluster masses increasing by factors of several between $z \sim 1$ and $z = 0$. Vikhlinin et al. [31] used the Chandra Cluster Cosmology Project to measure cluster masses across a broad redshift range, finding that the cluster population becomes richer and more massive at lower redshift, confirming that characteristic mass scales grow with time. Reiprich & Bohringer [30] used X-ray luminosity and temperature data to derive the cluster mass function, demonstrating evolution consistent with an expanding hierarchy of bound structures.

Sunyaev-Zel'dovich (SZ) surveys provide a complementary, nearly mass-complete view of the high-redshift cluster population. The Bleem et al. [34] analysis of the 2500-square-degree SPT-SZ survey identified hundreds of clusters out to $z \sim 1.5$. Planck SZ cluster catalogs [32,33] extend this picture to full-sky coverage, showing that the most massive clusters are rare at high redshift and become increasingly common at $z < 0.5$.

Rudick, Mihos & McBride [27] showed through N-body simulations that intracluster light builds up through tidal stripping of infalling satellites, depositing stars at increasing radii from the cluster core. The net outward growth of the bounding gravitational structure over cosmic time represents mesh dissipation at the cluster scale, contributing to the cascade that manifests as dark energy at horizon scales.

7.5 Peculiar Velocities, Bulk Flows, and the Laniakea Supercluster

On scales of tens to hundreds of megaparsecs, the universe exhibits coherent velocity flows that reflect the gravitational influence of the cosmic web. Tully et al. [35] reconstructed the three-dimensional velocity field of the local universe and identified the Laniakea supercluster as a coherent basin of gravitational attraction encompassing the Local Group, the Virgo Cluster, and the Great Attractor region—a structure approximately 500 Mpc across with a total mass of order $10^{17} M_\odot$. The 6dF Galaxy Survey peculiar velocity program [36,41] measured line-of-sight peculiar velocities for ∼10,000 galaxies, reconstructing the local velocity field out to $z \sim 0.05$. Carrick et al. [39] recovered a bulk flow of approximately 180 km/s toward the Shapley Concentration. Hoffman et al. [40] discovered the Dipole Repeller—a large underdense region contributing comparable force to the pull of the Great Attractor. In SCT language this void has low λ and hence large Λ_{eff}, and the net flow of the Local Group reflects the differential Λ_{eff} environment across the supercluster-void landscape.

7.6 Void Statistics and the Cosmic Web

Cosmic voids are the complementary complement to the clustered matter traced by galaxies. Pan et al. [43] identified and characterized voids in the SDSS, finding that void galaxies are systematically bluer, less massive, and more disc-dominated than galaxies in filaments and walls, consistent with the idea that their gravitational environment (low λ) differs fundamentally from high-density regions. Tikhonov & Klypin [44] showed that ΛCDM simulations slightly overpredict the emptiness of the deepest voids.

Pisani et al. [45] proposed using void number counts as a sensitive dark-energy probe, showing that the void size function is strongly sensitive to the equation-of-state parameter w. Hamaus et al. [46] measured redshift-space distortions around voids in SDSS, finding that the internal velocity field of voids is consistent with outflow—galaxies in void interiors flow outward toward void walls, exactly as expected if the effective expansion inside voids is enhanced relative to denser regions. Clampitt & Jain [47] confirmed void underdensities through gravitational lensing measurements. In SCT terms, voids are precisely the environments where $\Lambda_{eff} \approx C\Lambda_{ancestors}$ because λ is small: there are few overlapping wells to bind the spacetime pocket to its parent frame.

DESI [55] is currently conducting the most comprehensive spectroscopic void survey to date. Its preliminary BAO results [55] already show hints of environment-dependent dark-energy behavior that SCT naturally accommodates.

7.7 N-Body and Hydrodynamical Simulations: Structure Growth in ΛCDM

Large-volume cosmological simulations provide the most controlled environment for studying the relationship between local density, binding, and expansion. The Millennium Simulation [48] and Millennium-II [49] traced dark-matter halo evolution across the full cosmic web, demonstrating that halo merger trees are dominated by minor accretion at late times. The effective radius of halos grows monotonically with cosmic time in these simulations. The Illustris and IllustrisTNG hydrodynamical simulations [50,51] reproduced the observed galaxy size-mass relation and its redshift evolution; Springel et al. [51] demonstrated that the sizes of elliptical galaxies in IllustrisTNG grow by factors of 3-4 between $z = 2$ and $z = 0$. The EAGLE [52] and Horizon-AGN [53] simulations provide further confirmation of inside-out growth.

We emphasize what SCT adds to this picture. Standard simulations implement a uniform Λ as a background energy component that drives global expansion; the local suppression of expansion inside halos is handled through standard GR dynamics. SCT proposes that what we call dark energy is precisely this differential—the contrast between the bound, high-λ interior of structures and the unbound, low-λ exterior—expressed through the ratio Λ/λ, which varies with environment and epoch. The simulations confirm that the magnitude of this differential is substantial and observable; SCT provides a physical interpretation of its origin. We note that this interpretation would need to be tested against the simulations quantitatively, by computing the λ field from simulated density distributions and verifying that C Λ/λ reproduces the local expansion rates measured in the simulations.

7.8 BAO as a Multi-Scale Probe of Environment-Dependent Expansion

Baryon acoustic oscillations provide a standard ruler—the comoving sound horizon at recombination—whose apparent size in the galaxy correlation function traces the expansion history of the universe. Because BAO are imprinted at a scale of approximately 150 Mpc (comoving), they probe intermediate environments: neither the most bound clusters nor the emptiest deep voids, but the mildly overdense filament-and-wall structures of the cosmic web. In SCT language, BAO structures occupy an intermediate range of λ.

Eisenstein et al. [54] detected the BAO peak in the two-point correlation function of 46,748 luminous red galaxies from SDSS DR3 [54]. Subsequent SDSS and BOSS analyses refined the BAO scale measurement to sub-percent precision [59], enabling strong constraints on H(z) and D_A(z) across a range of redshifts. DESI's preliminary 2024 results

[55] attracted significant attention because they show hints of an evolving dark-energy equation of state: when fit to the w_0w_a parameterization, the data prefer $w_0 > -1$ and w_a < 0, suggesting a dark-energy component stronger in the past than today. In the standard ΛCDM framework, this is an unexpected result. In SCT it is a natural consequence of the evolution of Λ_eff(z): at higher redshift the universe was denser and the typical λ traced by BAO tracers was higher, meaning Λ_eff was suppressed. At lower redshift, as structures grow and voids expand, more of the universe's volume is in low-λ environments and Λ_eff increases. Forcing this evolving Λ_eff into a constant-Λ fit naturally produces an apparent w(z) ≠ −1 trend.

7.9 Synthesis: A Multi-Scale Hierarchy of Mesh Dissipation

Table 2 summarizes the empirical evidence reviewed in this section, organized by scale, observational programs, and SCT interpretation.

Scale	Observable	Key Programs / Refs	SCT Interpretation
~0.4 Gm (Earth-Moon)	Lunar recession 3.82 cm/yr	LLR [1-4]	Tidal mesh weakening; two-body binding reduced at known rate
~1-50 AU (Planetary)	Orbit expansion via stellar mass loss	Solar models [8-11]	da/a = -dM/M; first-principles alpha_n at planetary scale
~1-100 kpc (Galaxy)	Size-redshift growth; inside-out assembly	HST, JWST [14-24]	Stellar redistribution weakens galactic tensor mesh; alpha_gal ~ 1.0-1.5 H_0
~0.1-5 Mpc (Group/Cluster)	Halo growth; ICL; X-ray / SZ evolution	Chandra, Planck, SPT [26-34]	Cluster mesh expands at periphery while assembling at core; alpha_cluster ~ 0.5 H_0
~10-500 Mpc (Supercluster)	Peculiar velocity fields; Laniakea; bulk flows	6dFGS, 2M++ [35-42]	Supercluster mesh still assembling; voids show strong Lambda_eff
~100-1000 Mpc (Void/Web)	Void size function; outflow kinematics	SDSS, DES, DESI [43-47,55]	Low-lambda voids show largest Lambda_eff; direct probe of parent-frame dissipation

Cosmological (simulations)	Halo and galaxy size evolution in LCDM	Millennium, TNG, EAGLE [48-53]	Bound vs. unbound differential confirms inhomogeneous Lambda_eff; requires quantitative Lambda/lambda extraction

Table 2. Multi-scale evidence for secular outward orbital/structural drift and the SCT interpretation. Decay rates alpha_n are given where they can be inferred from observational data.

The pattern that emerges from Table 2 is consistent across scales: at every level from the Earth-Moon pair to the cosmic web, the characteristic binding radius of gravitationally structured systems tends to increase over time. The physical mechanisms vary—tidal dissipation at the planetary scale, stellar mass loss in stellar systems, minor mergers in galaxies, accretion and stripping in clusters, gravitational collapse and expansion of the cosmic web at the largest scales—but the net outcome at each level is the same: mass-energy spreads outward relative to the center of binding, the tensor mesh weakens, and the comoving frame of that pocket participates less rigidly in the kinematics of its parent frame.

SCT elevates this empirically observed trend into a fundamental principle. Rather than invoking a vacuum energy of precise magnitude to explain cosmic acceleration, it points to this multi-scale, observationally grounded tendency toward outward drift as the source of the apparent dark energy. The diversity of mechanisms responsible at different scales is a strength rather than a weakness: SCT does not depend on a single fine-tuned process operating at all scales simultaneously, but requires only that the net statistical bias toward outward drift be present at each level of the hierarchy. The evidence reviewed above demonstrates that this bias is real, multi-scale, and quantitatively significant.

8. Predictions, Observational Tests, and Conclusion

8.1 Environment-Dependent Expansion Rates

The Λ/λ framework makes concrete, qualitative predictions about how expansion rates should correlate with environment. Regions of high local mesh strength λ—the interiors of galaxies, groups, and clusters—should show strongly suppressed participation in the cosmological expansion. Proper distances within these structures should remain effectively constant over cosmological times. Voids and underdense regions with low λ should exhibit the strongest effective expansion.

These environment-dependent expansion rates lead to testable consequences: measurements of H(z) or distance-redshift relations along lines of sight that preferentially pass through voids should yield slightly different effective expansion histories than those dominated by denser environments. Reconstructions of the expansion field from peculiar-velocity surveys and large-scale flows could reveal correlations between local expansion rates and large-scale density contrasts. The required amplitude of the Λ_eff variation is approximately 9%, set by the observed Hubble tension (Section 6.1), and this is a testable number, not a freely chosen parameter.

8.2 Long-Term Exponential Trend with Local Deviations

At the largest scales, the compounded decay of mesh strength across the hierarchy of parent frames leads to an effective cosmological term that grows approximately exponentially with time, driving an accelerated expansion that resembles the behavior of a constant-Λ FLRW model. SCT also predicts that deviations from this average should be ubiquitous at smaller scales and in particular environments. Regions with unusually strong local binding or with parent frames that are temporarily converging can exhibit reduced Λ_eff, slower effective expansion, or even local contraction relative to the average flow. Future surveys capable of mapping the expansion field in three dimensions can test this prediction by searching for environment- and direction-dependent variations around the mean expansion history.

8.3 Specific Falsifiable Predictions

SCT makes the following predictions distinguishable from ΛCDM:

1. Environment-tagged H(z): Large spectroscopic surveys providing both redshifts and environmental information (void vs. filament vs. cluster classification) can infer expansion histories conditioned on environment. SCT predicts systematic differences in inferred H(z) between void-dominated and overdensity-dominated samples at the ~9% level. ΛCDM predicts no such correlation after accounting for peculiar velocities.
2. BAO standard-ruler shifts: BAO measurements separated by environment and redshift should show subtle shifts in the inferred standard-ruler scale that correlate with λ. Specifically, BAO measured preferentially in void environments should imply a slightly larger inferred D_A than BAO measured in overdense environments at the same redshift.
3. Weak-lensing growth vs. environment: Weak-lensing maps combined with galaxy surveys should show that low-λ regions have suppressed structure growth relative to high-λ regions beyond what ΛCDM would predict. This is a direct test of the Λ/λ mechanism at the structure-growth level.

4. Void expansion rates: The internal velocity field of voids, measured through redshift-space distortions (Hamaus et al. [46]), should show outflow velocities systematically larger than those predicted by ΛCDM calibrated on the global H_0 value. The excess should scale with void depth (lower mean density implies lower λ implies higher Λ_eff).
5. Tensor-to-scalar ratio: SCT requires no inflationary phase and therefore predicts no inflationary gravitational wave background, giving $r \approx 0$. A robust detection of $r > 0.01$ from CMB B-mode polarization would constitute a significant challenge to the SCT framework.

8.4 Limitations and Future Work

We explicitly acknowledge the following limitations of the present paper. First, the Λ/λ framework is phenomenological and lacks a complete Lagrangian or field-theoretic derivation. The covariant consistency issue raised in Section 3.3—that a spatially varying Λ_eff requires additional degrees of freedom to preserve the Bianchi identity—is acknowledged but not resolved here. A complete SCT field theory that specifies the equation of motion for λ(x,t) as a derived quantity from the matter distribution, and that demonstrates covariant conservation, is a necessary next step.

Second, the treatment of tensions is qualitative. While we have shown that the direction of each SCT prediction is consistent with observed tensions, we have not derived quantitative values of w_0, w_a, or the S_8 suppression from the framework. Doing so requires modeling the redshift evolution of the volume-weighted distribution of λ values, which in turn requires a numerical implementation of the Λ/λ field in a cosmological N-body or hydrodynamical simulation.

Third, we have not addressed the observational tests of the foundational SCT premise itself—the eternal infinite spacetime and the nested comoving frame hierarchy—which are discussed in the companion foundational premises paper [31]. The present paper takes those premises as given and develops their consequences for dark energy and cosmological tensions.

8.5 Conclusion

In this work, dark energy has been reinterpreted within Successive Collision Theory as the emergent effect of tensor-mesh dissipation in a hierarchy of nested comoving frames embedded in an eternally infinite spacetime. Rather than introducing a new fluid or fundamental vacuum energy, SCT retains standard GR and SR and assigns the cosmological term to an effective Λ_eff ∝ Λ/λ, where Λ measures ancestor-frame cohesion dissipation and λ measures local tensor-mesh strength. This single mechanism naturally suppresses expansion in strongly bound regions, enhances it in voids, and yields an approximate exponential expansion on large scales through the compounded weakening of meshes across the hierarchy.

By allowing Λ_eff(x,t) to vary with environment and time, SCT offers a unified qualitative account of several key ΛCDM tensions: the Hubble tension, the S_8 growth tension, hints of evolving w(z), and internal BAO inconsistencies. The cosmological constant problem is reframed: Λ is not a rigid vacuum energy but a macroscopic descriptor of tensor-mesh dissipation, with Λ_eff small in high-λ regions and larger in low-λ regions. We emphasize that the quantitative development of this framework—including a Lagrangian derivation, covariant field equations, and numerical predictions for w_0, w_a, and S_8—remains as future work.

Upcoming data from DESI, Euclid, the Rubin Observatory LSST, and the Nancy Grace Roman Space Telescope, along with targeted numerical simulations implementing an SCT-inspired environment-dependent Λ_eff, will be crucial in testing this reinterpretation of dark energy and determining whether tensor-mesh dissipation in nested comoving frames can indeed serve as the common thread behind the puzzles of the late-time universe.

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