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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Abstract

In the standard ΛCDM model, late-time cosmic acceleration is attributed to a strictly constant, spatially homogeneous dark-energy component usually 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} in magnitude relative to quantum field-theory expectations, it is rigid in time and space, and it coexists uneasily with persistent tensions between local and early-universe inferences of the expansion and growth histories. In this paper, I develop an alternative interpretation within Successive Collision Theory (SCT), a framework in which an eternally infinite Minkowski spacetime is filled with 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). At each scale, overlapping gravitational wells generate an effective "tensor mesh" that binds mass–energy to spacetime. A statistical bias toward secular outward drift of characteristic orbital radii and effective sizes implies a gradual weakening of this mesh at every level. The effective cosmological term is encoded as $\Lambda_{eff} \propto \Lambda/\lambda$, where Λ measures mass–energy cohesion dissipation across parent frames and λ measures local mesh strength. This framework suppresses expansion in strongly bound regions, enhances it in voids, tends toward exponential behavior on large scales, and allows local slowdowns or temporary reversals. The same Λ/λ mechanism qualitatively addresses the Hubble tension, the S_8 growth tension, hints of evolving $w(z) \neq -1$, BAO/internal dark-energy inconsistencies, and the cosmological-constant fine-tuning problem, without introducing any new microphysics beyond GR and SR.

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 spacetime. The resulting model fits supernova distance–redshift relations, the broad properties of the cosmic microwave background, baryon acoustic oscillations, and many large-scale structure observables, and thus earned the moniker "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 to the stress–energy tensor overshoot the observed value by many orders of magnitude, with no robust symmetry principle known that would enforce such a cancellation [1,2,3]. In addition to this magnitude problem, the dark-energy component in ΛCDM is 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 the effective dark-energy behavior might evolve with redshift. Many extensions of ΛCDM attempt to introduce such dynamical behavior, often at the cost of additional fields, parameters, and fine-tuning [11,12].

Empirically, the "concordance" picture has been challenged on several fronts. Local measurements of the Hubble constant H_0 using distance-ladder techniques systematically favor a higher value than the one inferred from early-universe data under ΛCDM, giving rise to the Hubble tension [5,6,7]. Weak-lensing and large-scale structure surveys tend to prefer a lower amplitude of matter clustering, parameterized by S_8, than the value obtained by evolving CMB initial conditions forward in time within ΛCDM [8,9]. Recent combinations of supernovae, BAO, and CMB data increasingly suggest that a strictly constant dark-energy density with $w = -1$ may not be the best description at late times [10].

Successive Collision Theory proposes a different starting point. Rather than a finite-age universe that begins in a hot, dense state and expands from there, SCT assumes an eternally infinite four-dimensional Minkowski 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 usual field equations of GR, combined with the kinematic effects of SR, 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. In each of these frames, the most massive members set a bulk motion that their less massive siblings follow, so that "playing follow the leader" becomes the organizing principle across scales.

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 description of how the Einstein tensor responds to the local stress–energy tensor. In regions where many deep wells overlap — such as galaxies and clusters — the mesh is strong and local spacetime is tightly bound. In underdense regions such as cosmic voids, the mesh is weak and trajectories are more sensitive to curvature inherited from larger-scale structures.

To capture this behavior within the familiar Einstein field equations, we introduce an effective cosmological term Λ_eff(x, t) that is neither constant nor fundamental but encodes how strongly the inherited parent-frame dissipation manifests in a given region. Uppercase Λ measures the rate at which mass–energy cohesion is being dissipated across the succession of parent pockets containing the region. Lowercase λ measures the local overlapping well strength. The effective cosmological term scales schematically as:

$$\Lambda\_eff(x, t) \propto \Lambda\_parent(x, t) / \lambda\_local(x, t)$$

For large λ, corresponding to strongly bound environments, the same parent-frame dissipation Λ produces little local expansion. For small λ, characteristic of voids, the same Λ produces a larger effective expansion. A central theme of this paper is that this single Λ/λ mechanism can qualitatively address several of the most discussed tensions in ΛCDM without introducing new microphysics.

This paper is organized as follows. Section 2 formalizes the SCT spacetime picture, introducing eternal infinite Minkowski spacetime, nested comoving frames, and the gravitational tensor mesh. Section 3 develops the Λ/λ reinterpretation of the cosmological term. Section 4 analyzes the dynamical behavior of tensor-mesh dissipation. Section 5 applies this framework to bound and unbound regions, reinterpreting BAO, galaxies, and voids. Section 6 discusses implications for all major cosmological tensions. Section 7 reviews empirical evidence for secular orbital expansion across scales. Section 8 outlines predictions, observational tests, and conclusions.

2. Eternal Infinite Spacetime and Nested Comoving Frames

2.1 Eternal Time, Infinite Space, and the Cosmological Principle

In the standard cosmological picture, the Universe is usually modeled as a single Friedmann–Lemaître–Robertson–Walker spacetime that begins in a hot, dense state and subsequently expands. By contrast, Successive Collision Theory starts from a different premise: time is eternal, with no beginning or end, and space is infinite, with no edges or boundaries. The appropriate large-scale background is an eternally infinite four-dimensional Minkowski 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. Instead, the familiar notion of "cosmological expansion" must be understood as an emergent, effective description of how particular regions evolve relative to their surroundings. General Relativity still dictates how stress–energy curves spacetime, and Special Relativity still 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 defined by the structures that contain it.

2.2 Comoving Frames as Hereditary Pockets of Spacetime

Within General Relativity, a comoving frame is most naturally defined as a set of worldlines with a shared four-velocity field: observers who are mutually at rest assign the same bulk motion to their environment and share a common cosmic time coordinate. Astrophysical systems are arranged in nested, approximately comoving structures. Stellar systems comove within galaxies, galaxies within groups and clusters, groups within superclusters, and our entire visible patch within larger structures that lie beyond our observational horizon.

SCT emphasizes that this hierarchical structure is the natural consequence of gravitational dynamics in an eternally infinite spacetime. Celestial bodies "play follow the leader": the most massive objects in a given region set the bulk trajectory, and less massive siblings are dragged along. Because Special Relativity tells us that motion through space slows motion through time, and General Relativity 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 and refine it under the influence of their own internal gravitational fields and relative motions.

Formally, one can picture a hierarchy of nested frames indexed by a scale label n. At each level, there is a bulk four-velocity field u^{en} and an associated proper-time parameter $\tau_{+\square}$. A child frame at level n+1 experiences time related to its parent's proper time by the standard SR and GR factors:

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

where $v_{+\square+1}|n$ is the child's velocity measured in the parent frame and $\Phi_{+\square}$ schematically denotes the parent-level gravitational potential. This relation is a reminder that child clocks and rulers are always defined relative to those of their parent frame. Time and space are therefore hereditary quantities in SCT: each pocket of spacetime is continuously shaped by the spacetime of its ancestors [14].

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 GƀDn̶8 sourced by the stress–energy tensor TƀDn̶8. In regions where many deep gravitational wells overlap — such as galactic centers, rich clusters, and 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 and trajectories are less constrained.

SCT uses the language of a "tensor mesh" to describe this behavior. The mesh is not an additional physical field beyond GR; it is a conceptual representation of how the combined gravitational influence of many overlapping wells creates a lattice of preferred geodesic paths. Where this mesh is dense and strong, geodesics are confined and local spacetime is tightly bound to the mass–energy distribution. Where the mesh is sparse and weak, geodesics respond more freely to curvature inherited from larger-scale structures.

We parameterize the mesh strength at a given level 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 where the net curvature is small. In regions with strong overlapping wells, this tensor mesh acts to suppress local participation in any larger-scale expansion, consistent with the well-known observational fact that galaxies and clusters do not expand with the Hubble flow [14,15].

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 [18,19,20]. On planetary scales, tidal interactions cause the lunar semi-major axis to increase. As stars evolve, they lose mass, inducing secular changes in planetary orbits. On galactic scales, typical galaxies grow in effective radius over cosmic time [17,24]. Groups and clusters evolve in ways that increase characteristic separations between member galaxies as mass is rearranged.

SCT treats these tendencies not as isolated curiosities but as manifestations of a general rule: 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. When 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. In terms of the scalar proxy, this corresponds to 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, in effect, 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 General Relativity with a cosmological constant, the field equations are:

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GƀDꞥ8 + Λ gƀDꞥ8 = 8πG TƀDꞥ8
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where GƀDꞥ8 is the Einstein tensor, TƀDꞥ8 is the stress–energy tensor, gƀDꞥ8 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_Λ = −ρ_Λ, 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 an enormous 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, even though observations increasingly suggest that effective dark-energy behavior may vary with redshift and environment [10,11].

Successive Collision Theory 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 should therefore depend on both position and time.

3.2 Defining Λ and λ in SCT

Within SCT, two conceptually distinct contributions determine how strongly a given region participates in the inherited expansion:

Uppercase Λ measures the rate and strength of mass–energy cohesion dissipation across the succession of parent pockets that contain 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 and spread out, weakening the tensor meshes that bind those larger pockets to their own spacetime. Intuitively, Λ quantifies how strongly "our ancestors are pulling" on our spacetime through their dissipating meshes.

Lowercase λ measures the local overlapping gravitational-well strength in the region under consideration. It encodes how deep and how densely overlapping the gravitational wells are, and thus how tightly mass–energy in that region is bound to its spacetime. Regions with many deep overlapping wells — galactic centers, rich clusters, bound BAO-scale overdensities — have large λ; voids and underdense environments have small λ.

The fundamental SCT claim is that the effective cosmological term governing the local expansion behavior is determined by the ratio:

Λ_eff(x, t) ∝ Λ_parent(x, t) / λ_local(x, t)

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 in place, the effective Einstein equations in SCT take the schematic form:

GƀDꞥ8(x,t) + Λ_eff(x,t) gƀDꞥ8(x,t) = 8πG TƀDꞥ8(x,t)

with:

Λ_eff(x,t) ≈ C × Λ_parent(x,t) / λ_local(x,t)

Here C is a dimensionful constant chosen to match units and normalization. Crucially, this does not alter the structural form of Einstein's equations. The geometric side remains GƀDꞥ8, the matter side remains TƀDꞥ8, and the additional term is still proportional to the metric gƀDꞥ8. What changes is the interpretation of the coefficient multiplying gƀDꞥ8: it is no longer a rigid constant, but an emergent, environment-dependent quantity derived from the nested-frame dynamics of SCT [13,14].

3.4 Hierarchical Propagation of Λ Across Scales

The nested nature of comoving frames naturally defines a hierarchy of scales: from small bound systems up through galaxies, groups, clusters, superclusters, our visible patch, and beyond. At each level n, there is a characteristic tensor mesh strength and a characteristic rate of dissipation. The scalar quantity $\Lambda_{+}\square$ at level n summarizes this dissipation. When we move 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. Symbolically:

$$\Lambda_{+}\square_{-1}\text{,parent} \sim \Lambda_{+}\square + \delta\Lambda_{+}\square_{-1}$$

where $\Lambda_{+}\square$ encodes the dissipation at level n and $\delta\Lambda_{+}\square_{-1}$ encodes new dissipation at level n−1. This is not meant as a precise formula, but as an indication that each level's effective background term is built on those of its ancestors. When we reach the level of our visible patch, the relevant Λ_parent is a composite quantity that includes contributions from all larger scales in the SCT hierarchy.

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, naturally reproducing the observed fact that stars within galaxies and galaxies within clusters do not partake in the Hubble expansion in any measurable way. 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 $\langle\Lambda_{eff}\rangle$ 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 in simple mathematical form, we introduce a scalar function $M_{+\square}(t)$ representing the average mesh strength at hierarchical level n. This is a bookkeeping device that summarizes, in a single number, the overall ability of the level-n configuration to hold its mass–energy together. Various microphysical processes — tidal interactions, dynamical friction, minor mergers, mass loss — can be modeled collectively as contributing to a slow decay of $M_{+\square}$. A natural first approximation is a decay law of the form:

$$dM_{+\square}(t)/dt = -\alpha_{+\square} \times M_{+\square}(t)$$

where $\alpha_{+\square}$ is an effective decay rate parameter encoding the net impact of these processes at level n. The solution is:

$$M_{+\square}(t) = M_{+\square}(t_0) \times \exp[-\alpha_{+\square} (t - t_0)]$$

which describes an exponential weakening of the mesh strength at that level over time. The precise value of $\alpha_{+\square}$ depends on the details of the mass distribution and dynamical history at scale n, but the qualitative behavior is robust: as time passes, typical orbits puff outward, and the average capacity of the level-n mesh to hold its contents tightly bound diminishes.

4.2 Approximate Exponential Behavior Over Long Times

The decay law for $M_{+\square}(t)$ suggests a natural way to understand why the large-scale behavior of Λ_eff can approximate an exponential expansion. Since the scalar λ is a proxy for local mesh strength, and since the effective cosmological term scales as:

$$\Lambda\_eff(t) \propto \Lambda\_ancestors(t) / \lambda\_local(t)$$

the exponential decay of $M_{+\square}(t)$ implies that Λ_ancestors(t) grows over time in a manner approximated by a sum of exponentials. To see this in a toy model, consider a single effective mesh-strength variable M(t) describing the hierarchy's net binding power:

$$M(t) = M_0 \exp(-\alpha t) \implies \Lambda\_eff(t) \propto 1/M(t) \propto \exp(+\alpha t)$$

In an FLRW-like effective description, such a cosmological term drives an accelerated expansion that, at leading order, exhibits exponential behavior in the scale factor — mimicking a positive cosmological constant. SCT does not claim that the real universe is governed by a single scalar M(t) or a single decay rate α, but this toy model captures the essential point: a hierarchy of meshes that weaken roughly exponentially over time naturally produces an effective expansion term that grows on large scales [31].

4.3 Conditions for Local Slowdowns and Apparent Reversals

While the global, large-scale behavior of $\Lambda_{eff}(t)$ can approximate an exponential increase, SCT explicitly allows for significant spatial and temporal variation around this trend. 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, or filament sections where multiple deep wells overlap coherently — can maintain a large and potentially growing λ_{local}. If $\Lambda_{ancestors}$ is increasing only slowly while λ_{local} remains high, the ratio $\Lambda_{eff} \propto \Lambda/\lambda$ can decrease locally. The effective expansion rate diminishes, and in extreme cases the local gravitational dynamics can overwhelmingly dominate and produce net contraction of distances within that pocket.

Second, the relative motions of the parent frames themselves matter. The scalar $\Lambda_{ancestors}(x, t)$ reflects the dissipation of tensor meshes at larger scales, which depends on how those parent structures move with respect to one another. If, for some interval, the nearest parent frames around a region are converging rather than separating, the effective dissipation rate experienced by the descendant region may temporarily decrease, reducing Λ_{eff} even if local λ_{local} is not exceptionally large.

In SCT, apparent reversals do not signal a breakdown of GR or the need for exotic physics; they are simply the result of the nested-frame inheritance structure and the fact that both the numerator and denominator in $\Lambda_{eff} \propto \Lambda/\lambda$ are dynamical quantities.

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. The distances between planets and their host star, between stars in the inner parts of galaxies, and between galaxies deeply embedded within rich clusters are not observed to increase simply because the universe at large is expanding. 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: their overlapping gravitational wells form a dense, deep tensor mesh. For any given ancestor dissipation Λ_ancestors, the effective cosmological term entering the local geometry is suppressed:

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λ_local ≫ 1    ⟹    Λ_eff  =  Λ_ancestors / λ_local  ≪
                                  Λ_ancestors
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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. This provides a geometric SCT-based explanation for the observed absence of expansion inside galaxies, clusters, and similar bound structures: their large λ ensures that Λ_eff is too small to produce a measurable change in local distances over cosmological timescales.

5.2 Enhanced Expansion in Voids and Low-Density Environments

At the opposite extreme are voids and underdense environments where the tensor mesh is weak. Here, λ is small, and test particles and light are much less constrained by local curvature. In the Λ/λ picture, this translates into a larger effective cosmological term:

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λ_local ≪ 1    ⟹    Λ_eff  =  Λ_ancestors / λ_local  ≫
                                  Λ_ancestors
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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 distribution of matter, and CMB distance measures all average over trajectories that spend significant fractions of their path length in low-λ environments. This environmental dependence of Λ_eff 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 "Raisin Bread" Analogy

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 then stretched by the global scale factor [23,38]. In SCT, BAO features are not purely void phenomena. They are associated with mildly bound overdensities: coherent ripples in the matter distribution that trace 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. They are intermediate, and this intermediate λ implies that BAO-scale regions experience an effective expansion rate that is 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 raisin bread" picture is more appropriate, with at least three ingredients:

- Raisins in dense clumps — high-λ regions (galaxies, groups, clusters) with 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 one looks more closely, the inhomogeneity becomes important: BAO standard rulers, supernovae in different host environments, and lensing paths that sample different mixes 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 the value of the Hubble constant H_0 inferred from local distance-ladder measurements (~73 km/s/Mpc) and the value inferred from early-universe probes such as the CMB combined with BAO (~67 km/s/Mpc) [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 thus suppressed by large λ_local.

By contrast, the 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 itself. When these data are interpreted within a homogeneous FRW 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 [31,32,33].

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 forward in time 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, such as overdense filaments and clusters, have smaller Λ_eff and 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 is different in the early universe; it reflects the fact that extrapolating from early-time, large-scale averages to late-time, environment-sensitive observables requires acknowledging the Λ/λ dependence.

6.3 Dark-Energy Evolution and $w(z) \neq -1$

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. In a universe where the true cosmological term is a rigid Λ, such behavior would require additional dynamical fields or modified-gravity ingredients. By contrast, in SCT the apparent evolution of w(z) is a geometric artifact of forcing an inhomogeneous, environment- and time-dependent Λ_eff(x, t) into a homogeneous-fluid parametrization.

When cosmological data are analyzed under the assumption that dark energy can be described by a single function w(z) that is 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.

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. 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, to the extent that it exists, becomes a question about the statistical properties of an eternally evolving, infinite hierarchy, not about the unnatural smallness of a single fundamental parameter.

6.6 Summary: Tensions Addressed by the Λ/λ Mechanism

Table 1 below 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.

Table 1. Key cosmological tensions and their reframing within the SCT Λ/λ mechanism.

Tension	Statement	SCT / Λ/λ Resolution
Hubble tension (H_0)	Local distance ladder gives H_0 ~ 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. Different Λ/λ weightings produce genuinely different effective Hubble parameters.
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 weight these environments, lowering effective S_8 relative to early-universe extrapolation.
Evolving dark energy w(z) ≠ −1	DESI+SNe fits prefer w_0 > −1, w_a < 0, suggesting evolving dark-energy density.	Forcing an inhomogeneous Λ_eff(x,t) into a homogeneous-fluid w(z) parameterization yields apparent evolution. No new dark field needed; geometry and environment suffice.
BAO / internal DE tensions	Different BAO tracers and redshift bins prefer slightly different expansion histories.	BAO tracers at different epochs sample different Λ/λ ratios. Assuming single-Λ ΛCDM cannot accommodate this range, producing systematic internal offsets.
Cosmological constant problem	QFT vacuum energy overshoots observed Λ by ~10^{120}; no symmetry principle enforces cancellation.	Λ_eff is emergent, not a fundamental vacuum constant. Fine-tuning becomes a question about the statistical state of the tensor-mesh hierarchy, not an unexplained microphysical parameter.

7. Empirical Evidence for Secular Orbital Expansion Across Scales

A foundational pillar of Successive Collision Theory (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 that spans everything from the Earth–Moon system to galaxy clusters and large-scale flows. This section marshals observational evidence demonstrating 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.

We organize the evidence from the smallest scales outward, covering: (i) lunar laser ranging and planetary orbital dynamics; (ii) stellar mass-loss-driven orbital expansion; (iii) galaxy size evolution as traced by HST, ground-based surveys, and JWST; (iv) cluster and group dynamics from X-ray, optical, and Sunyaev–Zel'dovich observations; (v) large-scale flows, peculiar velocities, and the cosmic web; and (vi) the complementary picture offered by void statistics and N-body / hydrodynamical simulations. For each, we cite the key observational programs and theoretical work and connect the result back to the SCT tensor-mesh picture.

7.1 The Earth–Moon System: Lunar Laser Ranging

The most precisely measured instance of secular orbital expansion in nature 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 round-trip light-travel measurements. Dickey et al. [1] provided the first comprehensive post-Apollo analysis, demonstrating tidal acceleration of the Moon and placing initial quantitative constraints on the recession rate. Subsequent analyses by Williams, Turyshev, & Boggs [2, 3] refined these measurements, exploiting the growing baseline and improved station hardware to achieve sub-centimetre precision in monthly mean distance estimates.

The current consensus value is a lunar recession rate of approximately 3.82 ± 0.07 cm yr^{-1} [2,4]. Chapront, Chapront-Touzé, & 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. Over the 4.5 Gyr history of the Earth–Moon system, integrated backward in time this rate implies the Moon was once much closer, consistent with dynamic models of tidal evolution [5, 6].

In the SCT framework, the Earth–Moon recession is the most direct laboratory-scale demonstration of tensor-mesh weakening. As the Moon drifts outward, the overlapping gravitational potential of the two-body system becomes shallower on average; the "mesh" binding the Moon's orbit to Earth's local pocket of spacetime gradually weakens. Although tidal dissipation is the immediate physical mechanism, SCT elevates this same logic—outward drift weakens local cohesion—into a universal principle operating at every scale. The key point is not that dark energy drives the Moon outward, but rather that the Earth–Moon system 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.

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 a mass M yields the scaling:

$$a(t) \propto 1 / M(t),$$

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 time it reaches the tip of the asymptotic giant branch, implying that Earth's current orbit near 1 AU will expand to roughly 1.3–1.5 AU—if it is not engulfed first [8].

Schröder & Connon Smith [8] carried out detailed calculations of solar evolution and planetary fate, concluding that Mars and the outer planets will migrate outward significantly. Veras et al. [10] extended these calculations to exoplanetary systems, showing that stellar mass loss generically drives planetary orbits outward, and in some cases leads to ejection of outer companions into interstellar space. Adams & Laughlin [11] treat such outward migration as part of the long-term evolution of stellar systems, noting that over Gyr timescales "typical" planetary systems expand rather than contract [11].

Laskar et al. [9] have further shown through long-term numerical integration of the Solar System that even absent stellar mass loss, secular resonances produce stochastic outward excursions of planetary orbital radii over billions of years, though the dominant long-term trend at the solar-system scale is tied to stellar evolution rather than chaotic dynamics.

In SCT terms, the solar-system tensor mesh—the overlapping gravitational-well structure that binds planets to the Sun's comoving frame—weakens as the Sun loses mass. This is a direct analogue, at the planetary scale, of the mesh-dissipation process postulated for each level of the comoving hierarchy. The planet–star subsystem is a child pocket that "inherits" spacetime from the local Galactic frame; the weakening of its own mesh is a concrete realization of SCT's recursive dissipation principle.

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 ~ 2–3 are systematically more compact—by factors of 3–5 in effective radius—than comparably massive galaxies in the local universe, a result that has been confirmed by multiple independent surveys and facilities.

The landmark discovery by Trujillo et al. [15] and van Dokkum et al. [14], based on deep HST imaging, demonstrated that massive early-type galaxies with stellar masses comparable to local ellipticals were 3–5 times smaller at $z \sim 2$. The van der Wel et al. [16] analysis of the 3D-HST+CANDELS dataset—covering ~200,000 galaxies across $0.5 < z < 3$—quantified the mass–size relation across cosmic time, finding that the effective radius of early-type galaxies scales roughly as $R_e \propto (1 + z)^{-\alpha}$ with $\alpha \approx 1.0$–1.5 depending on mass and morphological class [16].

Buitrago et al. [17] confirmed these findings using ground-based near-infrared photometry and Sérsic profile fitting, while Bezanson et al. [21] and Naab, Johansson, & Ostriker [22] proposed that minor dry mergers—the accretion of small satellites predominantly onto the outskirts of massive galaxies—are the primary driver of inside-out growth [21,22]. Oser et al. [23] analyzed cosmological simulations and showed explicitly that massive galaxies build their outer envelopes preferentially through accreted ex-situ stars, a process that increases the effective radius without proportionally increasing the stellar mass.

With the advent of JWST, these constraints have been extended to even 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, and Ward et al. [19] demonstrated that even star-forming galaxies at $z \sim 7$–9 are roughly twice as compact as local counterparts [19,20]. The consistent picture from HST through JWST is one of monotonic expansion of galaxy effective radii from high redshift to the present, across a broad range of masses and morphological types.

Conselice [18] reviewed galaxy structural evolution comprehensively, noting that no single merger channel fully accounts for the observed size growth at all masses; rather, a combination of major mergers, minor accretion, and adiabatic expansion driven by AGN feedback and stellar mass loss all contribute. In SCT terms, this diversity of mechanisms is irrelevant at the level of the tensor-mesh argument: what matters is the net outcome—the characteristic gravitational binding radius grows over cosmic time. As stars and gas redistribute to larger radii, the mesh that binds this stellar matter to the galactic pocket of spacetime weakens progressively. The galaxy represents a comoving frame at its own scale, and its tensor mesh is demonstrably dissipating on Gyr timescales.

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 not uniformly expanding; they 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 comprehensively, 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 $z = 0$ [26]. This growth is driven largely by infall of material from scales comparable to the cluster's turnaround radius, which itself grows as the surrounding void regions expand. The net effect is that the bounding gravitational region of a cluster extends outward with time, even as the core deepens.

X-ray observations with Chandra and XMM-Newton have constrained the mass–concentration relation and its redshift evolution. Vikhlinin et al. [31] used the Chandra Cluster Cosmology Project to measure cluster masses across a broad redshift range, finding consistency with structure growth predictions in a ΛCDM cosmology; crucially, their sample reveals that the cluster population becomes richer and more massive at lower redshift, confirming that characteristic mass scales grow with time [31]. Reiprich & Böhringer [30] used X-ray luminosity and temperature data from a flux-limited sample 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 $z \sim 1.5$, providing statistical constraints on cluster number densities and mass scales as a function of redshift [34]. 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 $z < 0.5$, again consistent with progressive growth of bound structures.

At the group scale, the dynamics of intracluster light (ICL) provides a sensitive probe of the outward redistribution of stellar material. Rudick, Mihos, & McBride [27] showed through N-body simulations that ICL builds up through tidal stripping of infalling satellites, depositing stars at increasing radii from the cluster core [27]. Mihos [28] and Diaferio & Geller [29] analyzed infall velocities and the streaming of galaxies through cluster outskirts, providing observational evidence that material is continuously being transported outward from the most bound cluster regions to larger-radius envelopes.

In SCT terms, the cluster represents a comoving frame whose own tensor mesh—the overlapping wells of hundreds of member galaxies—is evolving in a complex way: deepening in the core but expanding at the periphery as more material is accreted into the cluster's influence zone. 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: its filaments, walls, voids, and the great attractors that anchor the supercluster network. Tully et al. [35] reconstructed the full 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} $M_\odot$ [35]. The very identification of Laniakea as a "supercluster" depends on mapping the turnaround surface—the boundary beyond which the Hubble flow overcomes infall—and demonstrates that on these scales, structure is still actively assembling.

Peculiar velocity surveys provide the most direct kinematic evidence for these flows. 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 ~ 0.05. Davis et al. [37] compared these velocities against the gravitational predictions from redshift surveys, finding bulk-flow amplitudes consistent with ΛCDM but pointing toward significant coherent motion toward the Great Attractor complex. Carrick et al. [39] extended this comparison using the 2M++ galaxy catalog as a density tracer, recovering a bulk flow of approximately 180 km s^{-1} toward the Shapley Concentration [39].

Of particular relevance for SCT is the discovery by Hoffman et al. [40] of the "Dipole Repeller"—a large underdense region in the direction opposite to the Shapley Concentration that contributes comparable repulsive force to the pull of the Great Attractor [40]. In ΛCDM language, this region's effect is attributed to the absence of gravitational pull (a void). In SCT language, it is precisely the kind of environment where λ is small and Λ_eff is large: the void's weak tensor mesh provides less resistance to the cascading dissipation from parent frames, and the effective expansion there is correspondingly stronger. The net flow of the Local Group—pulled toward Laniakea from one side and "pushed" by the Dipole Repeller from the other—reflects the differential Λ_eff environment across the supercluster-void landscape.

Lavaux & Hudson [38] and Nusser & Davis [42] further constrained bulk flows on scales of 100–300 Mpc, finding amplitudes that, while broadly consistent with ΛCDM, show mild tension at the largest scales. Within SCT, modest deviations from pure ΛCDM bulk-flow predictions are expected, because the effective expansion field varies with environment; regions through which a flow passes may accelerate or decelerate depending on the local Λ/λ ratio [42].

Taken together, these peculiar-velocity datasets document an intricate pattern of inflows and outflows at the supercluster scale. Yet the large-scale trend is clear: superclusters are still in the process of assembly, accreting material from surrounding filaments and walls, while the more rarefied inter-supercluster regions are expanding. This is precisely the picture SCT predicts: at the supercluster level, the tensor mesh is still being assembled in some directions (inflow along filaments) while dissipating in others (expansion into voids), and the net long-term trend—when averaged over the whole population and projected forward in time—is toward increasing characteristic separations and weakening mesh coherence.

7.6 Void Statistics and the Cosmic Web

Cosmic voids—the vast underdense regions that fill the majority of the universe's volume—are the complementary complement to the clustered matter traced by galaxies. Void statistics provide an independent window onto dark energy and the expansion field: voids grow in comoving size as the universe expands, and their internal dynamics reflect the local expansion rate in regions with very low λ.

Pan et al. [43] identified and characterized voids in the Sloan Digital Sky Survey (SDSS), measuring their size distribution and internal galaxy properties. They found 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, a discrepancy that may in part reflect the inhomogeneous effective expansion encoded in Λ/λ [43,44].

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 [45,46]. Clampitt & Jain [47] confirmed void underdensities through gravitational lensing measurements, providing a mass-based (rather than number-density-based) confirmation of void structure.

In SCT terms, voids are precisely the environments where Λ_eff ≈ Λ (the large-scale dissipation rate) because λ is small: there are few overlapping wells to bind the spacetime pocket to its parent frame. Void statistics thus directly probe the most "exposed" regions of the tensor-mesh hierarchy, where the cascade from parent frames is felt most strongly. The observed outflow of galaxies from void interiors, the growing size of voids with cosmic time, and the correlation of void properties with dark-energy parameters are all consistent with the SCT prediction that low-λ environments expand faster.

DESI [55] is currently conducting the most comprehensive spectroscopic void survey to date, mapping the cosmic web in three dimensions across a volume of several Gpc^3. 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. While these simulations are built on standard ΛCDM assumptions—a uniform vacuum energy component—they nevertheless reveal patterns in structure growth that are directly informative for the SCT picture.

The Millennium Simulation [48] and its successor Millennium-II [49] traced dark-matter halo evolution across the full cosmic web at unprecedented resolution, demonstrating that halo merger trees are dominated by minor accretion (mass growth at the periphery) rather than major mergers at late times [48,49]. The effective radius of haloes grows monotonically with cosmic time in these simulations, consistent with the observational size-evolution of their galaxy occupants. Springel et al. [48] showed that the large-scale velocity field of the simulation is dominated by coherent flows converging on clusters, with voids expanding between them—recapitulating the kinematic structure seen in peculiar-velocity surveys.

The Illustris and IllustrisTNG hydrodynamical simulations [50, 51] added baryonic physics—star formation, black-hole feedback, stellar winds—and reproduced the observed galaxy size-mass relation and its redshift evolution reasonably well. Springel et al. [51] demonstrated that the sizes of elliptical galaxies in IllustrisTNG grow by factors of 3–4 between $z = 2$ and $z = 0$, in quantitative agreement with observational data [51]. Crucially, this growth occurs in the simulation without invoking dark energy directly; it arises from the dynamics of galaxy-galaxy interactions in an expanding universe. SCT argues that it is this very redistribution of mass to larger radii—which weakens the local tensor mesh—that is the fundamental mechanism, and the uniform background expansion is the large-scale average of this process.

The EAGLE [52] and Horizon-AGN [53] simulations provide further confirmation of inside-out growth and size evolution across a range of galaxy types, AGN feedback prescriptions, and merger histories. Collectively, these simulations establish that in a realistically structured universe—where mass is clumped, bound systems have high λ, and voids have low λ—the "expansion rate" as measured by the evolution of structural scales is manifestly inhomogeneous. Bound objects barely participate in expansion; the voids between them grow rapidly. This is the SCT picture, and it is embedded implicitly in every successful large-volume simulation [50,51,52,53].

It is worth emphasizing 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 haloes is a gravitational-binding effect handled through the standard Poisson–Newton–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 can vary 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.

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 on the clustering of matter at a scale of approximately 150 Mpc (comoving), they probe intermediate environments: neither the most bound (clusters) nor the most empty (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 Data Release 3, providing the first direct baryon acoustic detection in the galaxy distribution [54]. Subsequent analyses with SDSS and BOSS 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. The DES collaboration [60] extended BAO measurements into the photometric regime, while DESI [55] is currently providing the highest-statistical-power spectroscopic BAO measurements in history.

DESI's preliminary 2024 results [55] have 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 that was stronger in the past than today [55]. In the standard ΛCDM framework, this is an unexpected result. In SCT, it is a natural consequence of the fact that Λ_eff(z) evolves: at higher redshift, the universe was denser and the typical λ of the environments 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 $w(z) \neq -1$ trend.

Moreover, because BAO tracers (luminous red galaxies, emission-line galaxies, quasars) probe different large-scale environments at different redshifts, they sample different distributions of λ as a function of epoch. SCT predicts that the inferred BAO scale and inferred expansion rate should show a subtle but systematic dependence on the type of tracer and the density environment of the tracer sample—a prediction that next-generation surveys are uniquely positioned to test.

7.9 Synthesis: A Multi-Scale Hierarchy of Mesh Dissipation

Table 1 below summarizes the empirical evidence reviewed in this section, organizing it by scale, the relevant observational programs, and the SCT interpretation in terms of tensor-mesh weakening.

Table 1. Multi-scale evidence for secular outward orbital/structural drift and the 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; orthward drift shrinks two-body binding
~1–50 AU (Planetary)	Orbit expansion via stellar mass loss	Solar models [8–13]	Stellar mesh weakens as host loses mass; planets drift outward
~1–100 kpc (Galaxy)	Size–redshift growth; inside-out assembly	HST, JWST [14–24]	Stellar redistribution weakens galactic

Scale	Observable	Key Programs / Refs	SCT Interpretation
			tensor mesh
~0.1–5 Mpc (Group/Cluster)	Halo growth; ICL; X-ray / SZ evolution	Chandra, Planck, SPT [25–34]	Cluster mesh expands at periphery while assembling at core
~10–500 Mpc (Supercluster)	Peculiar velocity fields; Laniakea; bulk flows	6dFGS, 2M++ [35–42]	Supercluster mesh still assembling; voids show strong Λ_eff
~100–1000 Mpc (Void/Web)	Void size function; outflow kinematics	SDSS, DES, DESI [43–47, 55]	Low-λ voids show largest Λ_eff; probe pure parent-frame pull
Cosmological (simulations)	Halo & galaxy size evolution in ΛCDM	Millennium, TNG, EAGLE [48–53]	Bound ↔ unbound differential confirms inhomogeneous Λ_eff

The pattern that emerges from Table 1 is unambiguous: at every scale 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 and AGN feedback in galaxies, accretion and stripping in clusters, and 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 of spacetime 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 cosmological constant Λ_eff is not a property of the quantum vacuum; it is an emergent property of how matter is organized—and how that organization evolves—across the full hierarchy of nested comoving frames that constitute our observable universe.

In particular, the diversity of mechanisms responsible for outward drift at different scales is a strength rather than a weakness of the SCT framework. It does not depend on a single fine-tuned process operating at all scales simultaneously; instead, it 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 several 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, as the same ancestor dissipation Λ produces a larger Λ_eff when divided by a smaller λ.

These environment-dependent expansion rates lead to testable consequences: measurements of the Hubble parameter 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. SCT predicts that such correlations are not accidental but directly trace the Λ/λ dependence of Λ_eff.

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. This global trend underlies the success of ΛCDM in fitting many cosmological observables: when averaged over enough volume and over sufficiently long times, the SCT universe's expansion history looks similar to that of a universe with a small, positive cosmological constant.

However, 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 Future Surveys and Numerical Simulations

Several observational and computational avenues can test SCT's dark-energy interpretation:

- Environment-tagged H(z) measurements: Large spectroscopic surveys providing both redshifts and environmental information (local density, 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.

- BAO and standard-ruler shifts: BAO measurements separated by environment and redshift to look for subtle shifts in the inferred standard-ruler scale that correlate with λ. Differences between BAO results in more strongly bound regions and void-like regions would support the Λ/λ picture.
- Weak-lensing and growth: Weak-lensing maps combined with galaxy surveys can probe the relationship between structure growth and environment-dependent expansion. SCT predicts that low-λ regions should show suppressed growth relative to high-λ regions, beyond what ΛCDM would expect.
- Numerical simulations: N-body and hydrodynamical simulations adapted to implement an SCT-inspired scheme — in which nested comoving frames and secular orbital expansion are explicitly modeled, and an effective Λ_eff is reconstructed from the resulting dynamics — can clarify how much of the observed acceleration and its associated tensions can be attributed to tensor-mesh dissipation.

8.4 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 Minkowski spacetime. Rather than introducing a new fluid or fundamental vacuum energy, SCT retains standard General Relativity and Special Relativity 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 arises because different measurement pipelines sample different Λ/λ combinations. The S_8/growth tension reflects suppressed structure formation in high-Λ_eff, low-λ regions. Hints of evolving w(z) emerge when an inhomogeneous Λ_eff is forced into a homogeneous-fluid parametrization. Internal BAO and dark-energy tensions follow from the fact that different tracers and epochs probe different Λ/λ ratios. 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.

Among competing explanations for dark energy, SCT's central strength is that it stays strictly within GR and SR and introduces no new fields or particles, yet offers a single geometric mechanism — tensor-mesh dissipation encoded as Λ_eff ∝ Λ/λ — that directly links late-time acceleration to the observed, secular outward drift of orbits and the hierarchical, clumpy structure of the Universe. Environmental dependence of expansion is a built-in feature: high-λ bound regions naturally suppress Λ_{eff}, voids enhance it, and the "clumpy raisin bread" behavior falls out of the same picture rather than being patched onto a homogeneous Λ. Taken together, these results suggest that the observed cosmic acceleration and its associated tensions may not require new particles or modifications of gravity. Instead, they may be telling us that we live in an eternally infinite, hierarchically structured spacetime where orbits and structures at all scales slowly puff outward, weakening the gravitational meshes that bind them and causing child frames to inherit a spacetime that appears to be expanding.

Upcoming data from precision cosmology surveys including DESI, Euclid, the Rubin Observatory Legacy Survey of Space and Time, and the Nancy Grace Roman Space Telescope, along with targeted numerical simulations, will be crucial in testing this SCT-based 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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This work has benefited from results spanning studies of the cosmic microwave background, baryon acoustic oscillations, Type Ia supernovae, weak and strong gravitational lensing, galaxy and cluster dynamics, void and cosmic-web surveys, stellar and planetary orbital evolution, and numerical simulations of structure formation in General Relativity. These efforts collectively provide the empirical foundation necessary to test the predictions of SCT.

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