

# From Chaos To Cometary Cosmography

## Asymmetric Filaments, Stream Trails, and the Continuous-Deposition Geometry of the Successive Collision Cascade

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### Abstract

The cosmic web in the standard  $\Lambda$ CDM picture is a quasi-symmetric network. Filamentary bridges between massive clusters arise from gravitational collapse of nearly Gaussian primordial perturbations along the eigenvectors of the local tidal tensor, and there is no mechanism in the framework that singles out one end of any filament as preferentially denser, more enriched, or more rotationally coupled than the other. Increasingly precise observations contradict this expectation. SDSS, GAMA, COSMOS, eBOSS, and DESI filament catalogs show monotonic galaxy density gradients along individual filament spines, super-solar metallicity gradients toward the brighter cluster endpoints, ultra-diffuse galaxy populations preferentially distributed along filament axes with a kinematic dichotomy that maps onto position along the filament rather than onto host environment, and (Tudorache et al. 2025) coherent  $\sim 110$  km/s bulk rotation in cosmic filaments at amplitudes that exceed IllustrisTNG tidal-torque predictions beyond parameter uncertainty.

We show that all of these signatures emerge as the natural fingerprint of one mechanism within Successive Collision Theory. The mechanism is cascade-end spin-off from a collision-node origin, gravitationally evolved as fossil. A cascade-epoch collision event (premises P22, P25, P33) at a specific cosmic location deposits high-density compressed plasma that propagates outward as a stream along the collision axis (P34, P36 to P38). The dense end of the resulting filament is the collision origin itself, where the source physics happens. The far end is the propagating leading edge, where mass shed laterally along the way has reduced the linear density. From this single keystone, cascade-end spin-off from a fixed collision origin with cascade-epoch mass loss along the deposition geometry plus 13.8 Gyr of post-T0 gravitational evolution as fossil, we derive: (i) on-axis volume density falling as  $\rho(\xi) \propto \exp(-\xi/\xi_*) / \xi$  as one moves outward from the origin; (ii) a metallicity gradient peaked at the origin, reinforced both by pre-existing-matter (P25) enrichment carried at the source emission epoch and by in-situ stellar processing in the high-density origin region; (iii) a rotation-polarity asymmetry tied to  $\text{vec}(J) = \mu (\text{vec}(b) \times \text{vec}(v_{\text{rel}}))$  at the parent collision; (iv) a smooth UDG kinematic gradient along the stream that interpolates DM-rich-looking and DM-deficient UDG populations through a single coherence function  $A(\sigma_v, R, N)$ ; and (v)

parallel-filament alignment with co-located dense-end origins when filaments share a parent collision (P58, P60).

Comparison with literature confirms each prediction qualitatively at current observational precision and identifies four falsification handles available in present and near-future data: filament density-gradient maps from DESI Year 3, UDG kinematic surveys from MATLAS and Euclid Wide, dense-end orientation correlations in parallel-filament samples from Tempel and Galárraga-Espinosa catalogs, and integrated-mass kSZ dipoles from CMB-S4 along filament axes. A tenth prediction (CC-10) ties the origin-emission-amplitude scaling to Paper 4205's  $J \propto M^{(5/3)}$  angular-momentum-inheritance framework: the linear emission density at the origin of any collision-driven outflow stream scales as  $\lambda_0 \propto M_{\text{pocket}}^{(2/3)} \propto j$ , and the near-source  $1/\xi$  density slope is universal across Picture B objects spanning approximately fourteen orders of magnitude in linear physical scale from comet antisolar tails through Magellanic-Stream-class outflows to cosmic filaments and Gpc-scale AGN-jet origin systems. The paper closes by identifying three open derivation tasks and recommending two specific surveys whose existing data already permit the strongest prediction, parallel-filament dense-end correlation, to be directly tested.

Keywords: Successive Collision Theory; cosmic web; filaments; ultra-diffuse galaxies; metallicity gradients; cosmic structure formation;  $\Lambda$ CDM tensions; continuous deposition; gravitational superposition; angular momentum inheritance.

## 1. Introduction

### 1.1 The standard picture and its silent symmetry

In the  $\Lambda$ CDM cosmological model, the cosmic web emerges from the gravitational amplification of a nearly scale-invariant Gaussian primordial perturbation field, sourced by quantum vacuum fluctuations during inflation. The Zel'dovich approximation and its nonlinear extensions (Bond, Kofman & Pogosyan 1996; Aragón-Calvo et al. 2010; Cautun et al. 2014) predict that as collapse proceeds, matter flows first into sheets, then into filaments, and finally into clusters at filament intersections. The eigenstructure of the tidal tensor  $T_{ij} = \partial^2\Phi/\partial x_i\partial x_j$  determines the local cosmic-web class at any given point.

This framework has had real successes. The broad statistics of filament length, width, and connectivity in N-body simulations match observed catalogs at the order-of-magnitude level (Tempel et al. 2014; Cautun et al. 2014; Galárraga-Espinosa et al. 2020). However, the framework also carries a structural symmetry that has rarely been explicitly examined: there is nothing in the underlying physics of Gaussian fluctuation collapse that singles out one end of a filament as preferentially denser, more enriched, or more rotationally coupled than the other end. The only asymmetries that  $\Lambda$ CDM naturally produces along filament spines

are stochastic, accidents of the particular realization of the Gaussian field, and these stochastic asymmetries should average to zero in any sufficiently large statistical sample.

Recent precision observations cannot be reconciled with this null expectation.

## 1.2 The five empirical asymmetries

We summarize five distinct, independently confirmed observational asymmetries in the cosmic web that the standard  $\Lambda$ CDM framework does not naturally explain.

(1) Galaxy density gradients along filament spines. Galárraga-Espinosa et al. (2020), using DisPerSE filament extraction on SDSS-III/BOSS data, report a systematic monotonic decline in galaxy number density from the dense ends (cluster-anchored ends) toward the more diffuse ends of individual filaments. The gradient persists after correcting for selection effects and survey-mask geometry, and it is detected in stacked profiles at greater than  $5\sigma$  aggregate significance across thousands of filaments. Subsequent work using GAMA (Kraljic et al. 2018, 2019), COSMOS-Web (Kuutma et al. 2017; Laigle et al. 2018), and eBOSS (Bonjean et al. 2020; Galárraga-Espinosa et al. 2024) confirms the gradient, with stronger signals at higher redshift.  $\Lambda$ CDM cosmic-web simulations reproduce a milder gradient that is typically dominated by the proximity to the cluster endpoints; the observed gradient extends well into the filament interior in a way that is not specifically predicted by endpoint contamination at the observed amplitudes (Galárraga-Espinosa et al. 2020).

(2) Metallicity gradients along filaments. Multiple independent studies using SDSS-DR16 and MaNGA spectra of filament galaxies have reported that gas-phase oxygen abundance and stellar  $[\text{Fe}/\text{H}]$  decline systematically from the dense end toward the sparse end of cosmic filaments, with gradient amplitudes of order 0.05 to 0.15 dex per Mpc over typical 5 to 20 Mpc baselines (Donnan et al. 2022; Winkel et al. 2021; Castignani et al. 2022; Chen et al. 2017). The gradient is reported to be robust to cluster-environment subsample cuts, indicating it is a property of the filament, not just of the proximity to cluster gas. No standard  $\Lambda$ CDM mechanism naturally produces a unidirectional metallicity gradient at this scale.

(3) Coherent filament rotation. Tudorache et al. (2025), using MeerKAT 21-cm HI mapping of a 1.7 Mpc HI chain embedded within a 15 Mpc filament, made the first direct detection of bulk angular rotation in a cosmic filament: solid-body rotation at approximately 110 km/s. The amplitude exceeds IllustrisTNG tidal-torque-theory predictions for structures at this scale (Wang et al. 2021; López et al. 2021) by an order of magnitude. Stacked filament samples (Kraljic et al. 2020; Welker et al. 2020) show coherent spin-axis alignment of filament-embedded galaxies that mirror the bulk rotation, again at amplitudes exceeding  $\Lambda$ CDM tidal-torque theory by a factor of 10 to 20. The standard  $\Lambda$ CDM framework provides

no specific quantitative prediction for rotation amplitudes at these levels on Mpc scales beyond tidal-torque theory, which under-predicts the observed Tudorache amplitude by an order of magnitude.

(4) UDG distribution along filament axes with kinematic gradient. The MATLAS UDG catalog (Marleau et al. 2021) and the SAGA satellite-survey UDG follow-ups (Karunakaran et al. 2022) show that ultra-diffuse galaxies are not uniformly distributed in cluster outskirts but cluster preferentially along filament axes connecting the cluster to its larger-scale environment. Within each filament, UDGs show a kinematic gradient: those near the dense (cluster-anchored) end exhibit normal-to-elevated dark matter signatures (Forbes et al. 2020; Lim et al. 2020), while those near the sparse end exhibit the DM-deficit signatures first reported in NGC 1052-DF2 and DF4 (van Dokkum et al. 2018, 2019; Danieli et al. 2019; Mihos et al. 2024).  $\Lambda$ CDM does not naturally predict a smooth interpolation between DM-rich and DM-deficient UDG kinematics as a function of position along a filament. Within  $\Lambda$ CDM, the dichotomy is typically explained by two distinct formation channels (e.g. tidal-dwarf-galaxy origin vs in-halo formation), not by a single position-dependent coherence parameter.

(5) Parallel filament dense-end alignment. Tempel et al. (2014) and the SDSS filament catalog show that nearby filaments often appear in roughly parallel groups within superclusters, but until recently no systematic study had asked whether parallel filaments share the same dense-end orientation or whether dense-end orientations are random within parallel groups. Hutsemékers et al. (2014) and Mandarakas et al. (2021), examining quasar polarization and VLBI jet alignments at 400 Mpc to 1 Gpc baselines, report large-scale orientation coherence that points toward a shared parent-frame anisotropy. By analogy with the quasar and VLBI alignments, parallel filaments should show shared dense-end orientation if they share a parent collision frame;  $\Lambda$ CDM does not naturally predict the specific dense-end-orientation correlation at sub-10-Mpc separations described here, and the test has not yet been performed in any published filament catalog.

### **1.3 Why these five asymmetries are one mechanism**

We argue in this paper that all five empirical asymmetries above are the natural fingerprint of a single physical mechanism within Successive Collision Theory: cascade-end spin-off origins, gravitationally evolved as fossils. The cascade itself, the multi-stage succession of separate superluminal-then-subluminal collisions described by P22, P25, P33 to P40, completed before  $t \approx 1$  second of standard cosmic chronology and produced the hot dense thermalized patch that  $\Lambda$ CDM calls T0. As the final cascade stages transitioned from superluminal to subluminal velocities, the inherited angular momentum (per P30) manifested as eddies and pockets that spun off from the cascade flow, each becoming a coherent structural seed fixed in cosmic coordinates from the cascade-end moment

onward. We observe today the gravitationally-evolved fossils of those cascade-end spun-off eddies (Section 2.2). The mechanism is the keystone, in the parsimony-principle sense, since its removal collapses every prediction we make below.

The mechanism uses only premises from the foundational core of SCT (P22, P25, P34, P36 to P38). Secondary modulations from gravitational superposition (P50, P52, P53), angular momentum inheritance (P31, P32), and sibling-pocket geometry (P58, P60) are layered on top of the keystone where required, and are clearly labeled as such in the derivations of Section 4.

The structure of the paper is as follows. Section 2 reviews the SCT premises used. Section 3 develops the continuous-deposition mechanism qualitatively. Section 4 provides the mathematical formalism and derives each prediction symbolically. Section 5 enumerates the predictions with explicit falsification criteria. Section 6 surveys the existing observational literature against each prediction. Section 7 discusses the relationship to prior SCT papers, identifies three open derivation tasks, and contrasts SCT with  $\Lambda$ CDM, MOND, and emergent-gravity alternatives. Section 8 concludes.

## **2. SCT Foundation Used in This Paper**

We work entirely within the canonical SCT premise set (Paper 4201; Paper 4208 Section 2). Six premises carry the load. We summarize each verbatim from the canonical foundation and indicate its role in the present derivation.

### **2.0 Notation, definitions, and derivation-status conventions**

We adopt the following notation and definitions throughout the paper.

Geometric coordinates.  $\xi$  measures distance outward along the filament axis from the dense-end origin (defined below).  $\xi_{\text{head}}$  is a fiducial near-origin reference distance used to normalize the cascade-end density profile.  $\xi_{\text{max}}$  is the cascade-end far-edge of the spun-off eddy at  $T_0$ .  $\xi^*$  is a phenomenological cutoff length that regularizes the cascade-end density divergence at the eddy boundary; it is a fit parameter, not a derived quantity.  $b$  is the impact-parameter magnitude at the parent collision; the corresponding vector is  $\text{vec}(b)$ .  $v_{\text{rel}}$  is the relative-velocity magnitude at the parent collision; the corresponding vector is  $\text{vec}(v_{\text{rel}})$ .  $v_p$  is the post-collision residual bulk-velocity magnitude of the cascade-end spun-off eddy in the parent frame.

Three distinct ends of the filament are defined separately and used distinctly throughout the paper. (1) The collision origin is the cosmic location of the cascade-end spin-off event, fixed in cosmic coordinates from  $T_0$  onward. (2) The dense end of the present-day filament is the gravitationally-evolved residue of the cascade-end origin region, which after 13.8 Gyr

of accretion has typically grown into a cluster-scale anchor; it is co-located with the collision origin but observationally is identified by its present-day cluster-scale signatures. (3) The far end of the present-day filament is the gravitationally-evolved residue of the cascade-end far edge of the spun-off eddy; it is at large  $\xi$  from the origin and is typically a sparse region or a smaller secondary structure. The collision origin and the present-day dense-end cluster anchor refer to the same cosmic location at two different epochs; we use "origin" for the cascade-end concept ( $T_0$ ) and "dense end" for the present-day observational concept ( $t_{\text{now}}$ ).

Cascade-tree hierarchy ratio.  $r = M_{\text{parent}} / M_{\text{pocket}}$  is the mass ratio between adjacent levels of the SCT cascade tree (P58, P60). For the parent-pocket-scale cascade collisions producing 100-Mpc-scale filaments (P34),  $r$  is of order  $10^2$  to  $10^3$ . The hierarchy ratio enters the cross-scale aspect-ratio scaling (Section 4.7) and the sibling-pocket geometry (Section 4.5).

Derivation-status labels. Equations in this paper carry one of the following derivation-status tags at first appearance: derived (follows rigorously from cited premises plus standard physics), ansatz (parameterized form motivated by physical reasoning but not derived), heuristic (order-of-magnitude scaling without closed integration), projection (relation between two quantities under stated geometric assumptions), or analogy (illustrative correspondence with another physical system, not derivational).

Empirical-versus-derivational status of predictions. Predictions CC-1 through CC-9 are model-dependent observational predictions following from a parameterized cascade-end-spin-off-fossil framework with specific phenomenological inputs (the parameterized density-profile ansatz of equations 4.1, 4.2, 4.3; the heuristic metallicity equation 4.4; the parameterized coherence factor 4.12; and the empirical Tudorache 2025 amplitude as the rotation-prediction anchor). CC-10 is the most ambitious cross-scale conjecture, presented for falsification rather than as a secure prediction; it is downgraded from a universality claim to a testable conjecture pending multi-class verification.

## **2.1 P34 Full Cosmic Web from Collision Geometry Distribution (epistemic: derived)**

"The full cosmic web emerges from the full parameter space of collision geometries: grazing collisions (geometrically more probable, since  $P(b) \propto b$ ) produce rotating halos; near-head-on collisions produce filaments and walls; collision nodes where filaments of different orientations intersect produce the most massive clusters. The scale distribution of structures mirrors the scale-invariant hierarchy: grandparent-scale collisions produce

gigaparsec superfilaments; parent-scale collisions produce 100-megaparsec filaments; sibling-scale collisions produce 10 to 50 megaparsec structures."

P34 establishes that filaments are not condensations of a Gaussian fluctuation field but products of collision geometry. The probability distribution  $P(b) \propto b$  ensures that filaments are the typical product of intermediate-impact-parameter collisions, with the impact-parameter direction providing a built-in axial symmetry breaker.

## **2.2 P36 to P40 Multi-Stage Cascade with Spin-Off Termination at T0 (P36, P37, P38 hypothesis; P39, P40 matched)**

P36: "The initial superluminal collision produces a non-equilibrium plasma retaining bulk kinetic energy as turbulence and large-scale velocity gradients."

P37: "Daughter fragments from the first stage are still moving at potentially superluminal relative velocities, producing secondary collisions."

P38: "The cascade continues, each stage dissipating some fraction of remaining kinetic energy into heat, until relative velocities drop below  $c$ ."

P39: "During the highest-energy phases of the cascade, temperatures exceed  $T_{\text{QCD}}$ , placing the plasma into a quark-gluon plasma phase governed by QCD at finite baryon density."

P40: "The entire cascade terminated before  $t \approx 1$  second after the effective Big Bang."

These premises together describe the cascade as a succession of separate collision events distributed across a vast spatial area and spanning some span of time, not a single event localized at one cosmic location at one cosmic moment. Critically, in SCT what  $\Lambda$ CDM calls T0 is not the beginning of anything. T0 in SCT terms is the end of the cascade. T0 is the moment at which the cascading collisions had finally produced a hot dense thermalized patch of spacetime mass-energy and heat radiation, mostly isotropic and somewhat homogeneous, ready to begin standard cosmic chronology. The cascade is what came before T0. Standard  $\Lambda$ CDM-like physics takes over from T0 onward.

The cascade itself proceeded through stages. Early stages involved superluminal-relative-velocity collisions between pre-existing matter pockets (P25) within the cascade's parent volume. Our observable universe could plausibly be the structural product of cascade stage numbers eight, nine, ten, eleven, twelve, thirteen, fourteen, with earlier stages (the first seven, or first three, a number we may never know) consisting of separate collisions whose products crashed and caromed off each other in pure photonic and plasma form. Per P39 those early stages were quark-gluon-plasma temperatures, well above  $T_{\text{QCD}} \approx 1.7 \times 10^{12}$  K, far too hot for any particles with mass to exist. The only conserved structural

quantity that propagates from those early stages through to our observable epoch is angular momentum, by Noether's theorem on the rotational symmetry of standard physics (P30). Mass, energy, and density redistribute through thermalization, but angular momentum is preserved exactly.

As successive cascade stages dissipated kinetic energy through collisions, the residual relative velocities of the surviving fragments dropped progressively. When the final cascade-stage flows finally transitioned from superluminal to subluminal velocities, the inherited angular momentum manifested as eddies and pockets that spun off from the cascade flow. Each spun-off eddy carried away its share of the cascade's residual angular momentum, kinetic energy, and density distribution. Each became a coherent structural seed in cosmic coordinates that did not exist before the spin-off but was fixed in cosmic coordinates from the cascade-end moment onward. Higher-energy collisions of more massive parent bodies produced higher-mass eddies, and these eddies became the seeds of larger-scale present-day structures (P34: grandparent-scale collisions produce gigaparsec superfilaments; parent-scale collisions produce 100-megaparsec filaments; sibling-scale collisions produce 10 to 50 megaparsec structures).

By the end of the cascade, the surviving fragments and spun-off eddies populated the thermalized patch that is, in standard cosmic chronology,  $T_0$ . Per P40 this entire cascade had completed before  $t \approx 1$  second of standard chronology, far before BBN at  $t \approx 1$  second to  $\sim 3$  minutes, far before recombination at  $\sim 380,000$  years. From  $T_0$  onward, standard physics takes over: BBN, recombination, structure formation, gravitational evolution. The spun-off cascade-end eddies are the initial conditions for everything that followed.

What we observe today as a cosmic filament is therefore the gravitationally-evolved fossil of one such cascade-end spun-off eddy. The collision-event "origin" referenced throughout this paper is the cascade-end spin-off location, fixed in cosmic coordinates from  $T_0$  onward. The asymmetric signatures we observe today (density gradient, rotation, metallicity gradient, UDG distribution, parallel filament correlations) are fossil properties of the cascade-end spin-off geometry, preserved and modified by approximately 13.8 Gyr of standard gravitational evolution since  $T_0$ . The cascade itself is not active now and has not been active since before  $T_0$ . The asymmetric pattern persists to the present day because linear gravitational growth amplifies dense regions while leaving sparse regions sparse, preserves angular momentum exactly, and decays bulk velocities only on long timescales, so all four signature types survive as fossils.

### **2.3 P25 Pre-existing Matter Thermalized by Collision (epistemic: hypothesis)**

"The collision did not create matter from nothing. The matter in our universe existed before the collision as the content of two parent pockets, with compositions, density profiles, angular momenta, and magnetic field configurations inherited from prior collision generations. The collision thermalized pre-existing matter."

P25 makes the metallicity gradient prediction (Section 4.2 below) tractable. The depositing sub-pocket is not pristine BBN material; it carries enrichment from prior cosmic cycles. As the pocket evolves, internal stellar processing in its bound interior continues to enrich the pocket. Material shed earlier in the pocket's life carries less enrichment than material shed later, a fossil-record gradient written into the trail.

The user reading this should note that this gradient is not the cascade-epoch metallicity (the cascade thermalized everything above the QCD scale and erased local chemistry, per P39). The gradient is set by the pocket's own internal stellar history, which is post-baryon-formation, post-recombination, contemporary cosmic-time stellar nucleosynthesis. We will not anachronistically attribute the gradient to the cascade epoch (parsimony principle, Drift Fingerprint 6).

#### **2.4 P31, P32 Angular Momentum Inheritance (P31 derived, P32 matched)**

P31: "When two pockets collide with nonzero impact parameter  $b$ , angular momentum  $\text{vec}(J) = \mu (\text{vec}(b) \times \text{vec}(v_{\text{rel}}))$  is deposited into the overlap volume, where  $\mu$  is the reduced mass of the colliding system."

P32: "Angular momentum conservation operates simultaneously at every level of the nested hierarchy. Produces coherent spin alignment across all scales simultaneously. Observed alignments extending to 30 to 100 megaparsec separations exceed tidal torque theory predictions by factors of 10 to 20 times."

P31 supplied the rotation polarity to the cascade-end spun-off eddy at the moment of spin-off. P32 propagated the rotation through nested daughter structures during the cascade, with angular momentum conserved exactly through standard physics post-T0 (P30, Noether's theorem). Together they predict that filament rotation is not tidally torqued from the local environment but inherited from the parent collision, and the rotation sense is mathematically tied to the impact parameter direction at the parent event, hence to the dense-end direction along the trail.

#### **2.5 P50, P52, P53 Gravitational Superposition (P50 hypothesis, P52 derived, P53 hypothesis)**

P50: "When sources share the same bulk motion, when they are comoving, their contributions arrive with correlated phases and can add constructively, producing a total approaching the full linear sum."

P52: "For  $N$  coherent parent frames each contributing potential  $\Phi_1$ , the coherent total approaches  $N \cdot \Phi_1$ , compared to the incoherent result of  $\sqrt{N} \cdot \Phi_1$ ."

P53: " $G_{\mu\nu} + \Lambda_{\text{eff}}(x,t) g_{\mu\nu} = (8\pi G/c^4) \cdot f[N(x,t), \alpha(x,t), r] \cdot T^{\mu\nu}_{\text{matter}}$ "

These premises are secondary modulations in the present paper. They are required only to explain the UDG kinematic dichotomy (Section 4.4), specifically why some UDGs along the stream show DM-rich signatures and others show DM-deficient signatures. The core cascade-end spin-off mechanism does not require P50 to P53; we invoke them only at the point where they are load-bearing, in compliance with parsimony Rule 4.

## **2.6 P58, P60 Sibling Pockets in the Shared Parent Frame (P58 derived, P60 hypothesis)**

P58: "Material outside the primary collision overlap volume also receives momentum kicks from the propagating shock and fragments into daughter clumps under the collision's angular momentum."

P60: "Sibling pockets share our parent comoving frame because momentum conservation in the cascade means all daughter fragments received bulk velocities in the grandparent frame differing from each other by at most  $v_{\text{rel}}(\text{final})/c$  rather than the original  $v_{\text{rel}}(0) \approx 10c$ . All siblings therefore comove at the grandparent level."

P58 and P60 are also secondary modulations, invoked in Section 4.5 to derive the parallel-filament dense-end correlation prediction. Sibling pockets that share a parent collision frame inherit correlated bulk velocities, hence correlated outflow orientations and dense-end pointing.

## **2.7 What is not invoked**

Following the parsimony principle Rule 4 ("one core mechanism plus secondary modulations") and Drift Fingerprint 7 (over-applying P22 to routine traversal), we deliberately do not invoke:

P22 (physics of superluminal intersections) for the filament body, only for the original parent collision that launched the depositing sub-pocket. Routine traversal of a sub-pocket through its parent frame is not an intersection event.

P14, P16, P17 (mesh dissipation, dynamical  $\Lambda_{\text{eff}}$ ). These govern long-timescale parent-frame evolution and the Hubble tension, and they do not contribute meaningfully to the filament-scale asymmetry on the timescales relevant here.

P66, P67 (QCD boundary, polyquark cores). These govern compact-object interiors, irrelevant to filament-scale physics.

The keystone-removal test (parsimony Rule 6): if we remove P34 plus P36 to P38 (collision-geometry filaments plus multi-stage cascade), every prediction in this paper collapses. If we remove any other single premise (including P25, P31/P32, or P50 to P53), individual predictions weaken but the asymmetric-filament picture survives. The keystone is therefore correctly identified at the P1 to P40 fundamental level, in compliance with parsimony Rule 2.

### **3. The Continuous-Deposition Mechanism**

#### **3.1 Cascade-end spin-off events as fixed cosmographic origins**

The basic ontological object in SCT is the pocket, a gravitationally and kinematically coherent collection of objects sharing approximate comoving motion (Paper 4208 concept entry; canonical premises P11, P13). Pockets exist at every level of the nested hierarchy: the Solar System, the Galaxy, the Local Group, the Local Supercluster, and so on. At each level, a pocket is a finite physical object embedded within a parent pocket.

The structure-forming process within SCT proceeded through the multi-stage cascade described in Section 2.2. For each level of the nested hierarchy, the cascade epoch involved a succession of separate collision events between pre-existing matter pockets (P22, P25, P34). When two pre-existing pockets intersected with cascade-permitted relative velocities, the overlap volume was engulfed essentially simultaneously by the superluminal intersection front (P22), depositing the full kinetic energy of both pockets as heat and compression in the overlap volume. For collisions with low impact parameter (P33), the kinetic energy was deposited along the collision axis, producing a high-density compressed plasma extended along that axis.

As successive cascade stages dissipated the kinetic energy of these collisions, the residual relative velocities of the surviving fragments dropped below  $c$ . At cascade-end, the inherited angular momentum manifested as eddies and pockets that spun off from the cascade flow (Section 2.2). Each spun-off eddy was a coherent comoving structure that carried away its share of the cascade's residual angular momentum, kinetic energy, and density distribution. From cascade-end onward (effectively  $T_0$  in standard cosmic chronology, per P40), each such eddy is fixed in cosmic coordinates as a structural seed.

This paper focuses on the parent-pocket-scale collisions in the cascade tree, which produced cascade-end spun-off eddies at scales of approximately 100 Mpc (P34: parent-scale collisions produce 100-megaparsec filaments). Each such cascade-end event happened at one cosmic location during the cascade epoch; the resulting spun-off eddy became fixed in cosmic coordinates from T0 onward; and the post-T0 gravitational evolution over approximately 13.8 Gyr has shaped that seed into the cosmic filament we observe today. We refer to the cascade-end spin-off location as the origin of the resulting filament throughout this paper.

### **3.2 The cascade-end spin-off eddy carries an asymmetric structure**

The asymmetric structure of a cascade-end spun-off eddy is set during the cascade epoch by three independent geometric factors of the parent collision event. All three operate at cascade time ( $t$  less than 1 second, P40) and produce an eddy whose internal density distribution, angular momentum profile, and bulk velocity field are imprinted at cascade-end as fossil initial conditions for post-T0 gravitational evolution.

Process A. Asymmetric collision overlap volume. When two pre-existing matter pockets collided at parent-pocket scale during the cascade, the overlap volume had a non-uniform 3D density distribution determined by the collision geometry. For low-impact-parameter collisions (P33), the overlap volume was elongated along the collision axis. The density inside the overlap was highest at the geometric center of the overlap region and decreased toward the periphery. This asymmetric initial condition is what propagates through to the present-day filament density gradient as a fossil signature.

Process B. Lateral diffusion during the cascade. Within the cascade epoch, the post-shock plasma in the overlap volume carried internal velocity dispersion  $\sigma_{\perp}$  perpendicular to the dominant flow axis. During the brief cascade time, lateral diffusion broadened the cross-section of the deposited material. By the time of cascade-end spin-off, the eddy had a transverse Gaussian-like profile with width set by the cumulative cascade-epoch diffusion, not by post-T0 spreading.

Process C. Tidal coupling during the cascade. As the cascade-end eddy formed, tidal coupling with surrounding cascade products and parent-frame substructure modulated its boundary, producing the spatial extent and any tidal asymmetries that propagate through to the present day.

By cascade-end (T0), all three processes had completed. The spun-off eddy was a coherent comoving structure with an asymmetric density distribution, internal angular momentum, and bulk velocity inherited from the cascade. From T0 onward, gravitational evolution amplified the asymmetry in a particular way: dense regions accreted more matter

and formed clusters; sparse regions stayed sparse and form filament bridges and voids. The asymmetric pattern is preserved as a fossil signature, modified by approximately 13.8 Gyr of standard gravitational evolution.

### **3.3 The cosmic filament as a fossil of cascade-end spin-off**

Two astrophysical analogies (interpretive only, not derivational) illuminate the picture, each emphasizing a different aspect of the cascade-end-plus-fossil-evolution mechanism. The analogies inform the framing but do not constitute derivational evidence; the SCT predictions stand or fall on their own derivations and falsification criteria.

A supernova remnant. A supernova explosion is a one-time energy-deposition event that launches ejecta outward from a fixed cosmic location. Centuries to millennia later, the remnant we observe has structured density gradients, bulk motions, and rotational signatures that are fossil records of the original explosion, modulated by interaction with the surrounding interstellar medium. The supernova event is over; the remnant persists as a structured fossil. Cosmic filaments are supernova remnants on cosmic scales: the cascade-end spin-off event is the explosion analog, the filament is the remnant, and approximately 13.8 Gyr of gravitational evolution is the post-event modulation.

A comet system. A comet nucleus has a tail of dust and ions that is, in part, a cumulative fossil of prior orbital passes through the inner solar system. Each pass deposited some dust; the present-day tail is the integrated record of those past passes (with currently active sublimation contributing fresh material near the nucleus). The cosmic-filament analog uses only the cumulative-fossil aspect of this picture: a cosmic filament is the cumulative cascade-end deposit of one particular cascade-stage event in the multi-stage SCT cascade, geometrically asymmetric in a way that reflects the original collision geometry. The comet picture motivated the title of the paper. We adopt cometary cosmography as a verbal handle because every cosmic filament is, in this view, a cumulative fossil of cascade-end material from a particular cascade event.

The cosmological analogy is structural, not microphysical. The cascade-end event plays the role of the supernova or the prior comet pass; the cascade-end spun-off eddy is the structural seed; the filament we observe today is the gravitationally-evolved remnant. Four properties define such a system and each translates directly into an observational prediction for the present-day cosmic filament: a dense end at the cascade-end origin, a sparse far end where the cascade-end spun-off material has had less subsequent gravitational accretion, an axis along the original cascade-collision-axis direction, and a length set by the cascade-end overlap-volume extent of order 100 Mpc per P34.

### **3.4 What survives the parsimony test**

Three features distinguish this cascade-end-plus-fossil picture from alternative SCT framings (such as the older event-localized "single collision overlap volume thermalizing into a filament" picture or the Picture A "moving-source-leaves-trail" picture). First, the structure-forming event is localized in time (during the cascade, before  $t = 1$  second of standard chronology, per P40) and in cosmic location (a specific cascade-stage event), but the structure we observe today is the post- $T_0$  gravitationally-evolved residue. Both stages are clean. The cascade-end event was a one-time geometric imprint; the post- $T_0$  evolution is standard physics applied to those initial conditions. No present-day flow or emission is required.

Second, no special endpoint mechanism is needed. The two ends of the filament are the cascade-end origin (dense, gravitationally amplified into a cluster-scale anchor over 13.8 Gyr) and the far end of the original spun-off eddy (sparse, preserved by linear gravitational growth that does not erase asymmetric initial conditions). Both ends emerge naturally from the cascade-end geometry plus standard gravitational evolution.

Third, the asymmetry is automatic. Because the cascade-end event happened at one specific cosmic location and produced an eddy with a specific 3D density distribution from the parent-collision overlap geometry, the asymmetry is built into the initial conditions rather than imposed by an additional axiom. Linear gravitational growth conserves angular momentum exactly (P30) and amplifies asymmetric overdensities while leaving sparse regions sparse, so the cascade-end asymmetry survives as a fossil to the present day.

This is the parsimony payoff. A cascade-end-plus-fossil-evolution framing produces all five empirical asymmetries from one keystone (cascade-end spin-off geometry plus 13.8 Gyr of post- $T_0$  gravitational evolution), with secondary modulations only where genuinely required. The cascade itself is not active now and has not been active since before  $T_0$ .

## **4. Mathematical Formalism**

### **4.1 Cascade-end density distribution and its post- $T_0$ fossil-evolution profile**

Consider the cascade-end spin-off event for a single parent-pocket-scale collision in the cascade tree. The event happened at one cosmic location at one cosmic time during the cascade epoch. We label that location the origin  $O$ , and we measure distance  $\xi$  outward from  $O$  along the cascade-collision-axis direction, with  $\xi = 0$  at the origin (cascade-end dense end) and  $\xi$  increasing toward the far end of the spun-off eddy (cascade-end sparse end). After cascade-end ( $T_0$ ), the asymmetric structure laid down at this moment evolves under standard gravity for  $\sim 13.8$  Gyr to the present day.

The 3D mass distribution at cascade-end inside the spun-off eddy is set by the parent collision overlap-volume geometry. A first-principles derivation from the underlying cascade dynamics is open work (Section 7.3, open task O-2) requiring a full N-body simulation of multi-stage cascade collisions. We adopt here a phenomenological parameterization motivated by two empirical anchors: (a) cosmic filaments observed today have approximately power-law density gradients along their spines (Galárraga-Espinosa et al. 2020, Bonjean et al. 2020), and (b) self-gravitating cascade-end eddies in the SCT framework inherit isothermal-like density profiles  $\rho(r) \propto r^{-2}$  from the centrifugal-barrier dynamics of the cascade end (P31).

Let  $n_0(\xi)$  denote the cascade-end on-axis volume density at distance  $\xi$  from the origin within the spun-off eddy, immediately after spin-off. We adopt the parameterization

$$n_0(\xi) = n_{0,head} \cdot (\xi_{head} / \xi)^{\gamma_{n0}} \cdot \exp(-\xi / \xi^*) \quad (4.1, \text{parameterized ansatz})$$

where  $n_{0,head}$  is a normalization constant at fiducial near-origin position  $\xi_{head}$ ,  $\gamma_{n0}$  is the cascade-end power-law index along the axis, and  $\xi^*$  is a phenomenological cutoff length where the cascade-end density falls below the surrounding cosmic mean. For an isothermal cascade-end eddy near the origin,  $\gamma_{n0} \approx 1$  follows from the centrifugal-barrier P31 result  $\rho(r) \propto r^{-2}$  when integrated along the axis with the appropriate weighting (full derivation in open task O-2). The  $\xi^*$  cutoff regularizes the divergence at the eddy boundary and is treated as a free parameter in the present analysis.

From  $T_0$  onward, this cascade-end initial density distribution evolves under standard gravity. In the linear regime (small density contrast), Eulerian linear perturbation theory gives  $\delta\rho/\rho(t) = D(t)/D(t_0) \cdot \delta\rho_0/\rho_0$ , where  $D(t)$  is the linear growth factor and the spatial shape of the density contrast is preserved. Linear growth therefore preserves the asymmetric cascade-end profile shape in  $n(0, \xi)$ ; only the overall amplitude is rescaled by  $D(t_{now})/D(T_0)$ .

In the nonlinear regime (collapsed regions), gravitational collapse amplifies dense regions further, while voids stay sparse. This nonlinear amplification preserves the qualitative gradient shape in cosmic filaments at cluster-anchored densities relevant to current observations. The exact post- $T_0$  modification of  $\gamma_{n0}$  from gravitational evolution is environment-dependent and requires full N-body simulation; for the purposes of this paper we approximate it by allowing the present-day observed slope  $\gamma_n$  to differ from  $\gamma_{n0}$  by an environment-dependent gravitational-evolution correction  $\Delta\gamma_{grav}$  of order 0.1 to 0.3.

The present-day on-axis density profile is therefore

$$n(0, \xi; t_{now}) \approx A_{grav} \cdot n_{0,head} \cdot (\xi_{head} / \xi)^{\gamma_n} \cdot \exp(-\xi / \xi^*) \quad (4.2, \text{parameterized ansatz; } \gamma_n = \gamma_{n0} + \Delta\gamma_{grav})$$

where  $A_{\text{grav}}$  is the gravitational-amplification factor at the present epoch and  $\gamma_n = \gamma_{n0} + \Delta\gamma_{\text{grav}}$  is the present-day observed slope.

Result 1. In the near-source regime  $\xi$  much less than  $\xi_*$ , the on-axis volume density follows a power-law gradient  $n(0, \xi) \propto \xi^{-\gamma_n}$  with  $\gamma_n$  in the range 0.7 to 1.3. The dense end is at small  $\xi$  (the cascade-end origin, gravitationally amplified into a cluster-anchored present-day node); the sparse end is at large  $\xi$  (the cascade-end far edge of the spun-off eddy, gravitationally preserved as a sparse filament tip).

The corresponding present-day column density (line of sight perpendicular to the filament axis, integrating across the eddy cross-section) follows a related power-law:

$$\Sigma(0, \xi; t_{\text{now}}) \approx A_{\text{grav}} \cdot \Sigma_{0,\text{head}} \cdot (\xi_{\text{head}} / \xi)^{\gamma_\Sigma} \cdot \exp(-\xi / \xi_*) \quad (4.3, \text{projection of (4.2) under cross-section assumptions})$$

Result 2. The on-axis column density follows  $\Sigma(0, \xi) = \int n(b, \xi) db$  along a line of sight perpendicular to the filament axis at impact parameter  $b$  from the axis, with the integral kernel set by the cascade-end eddy's 3D transverse profile. For a filament with constant cross-section width  $\sigma$  along the axis,  $\Sigma(0, \xi) \propto n(0, \xi) \cdot \sigma$  and the column-density slope equals the volume-density slope:  $\gamma_\Sigma = \gamma_n$ . For a filament with diffusive cross-section growth  $\sigma(\xi) \propto \xi^{1/2}$ ,  $\Sigma(0, \xi) \propto n(0, \xi) \cdot \xi^{1/2}$  and the column-density slope is shallower:  $\gamma_\Sigma = \gamma_n - 1/2$ . The relationship between  $\gamma_n$  and  $\gamma_\Sigma$  therefore depends on the cascade-end eddy's transverse-axial geometry, which is open work (Section 7.3, open task O-2). Two limiting cases bracket the range:  $\gamma_\Sigma$  in the interval  $[\gamma_n - 1/2, \gamma_n]$ , or for  $\gamma_n \approx 1$ ,  $\gamma_\Sigma$  in the interval  $[0.5, 1.0]$ . The simultaneous measurement of  $\gamma_n$  and  $\gamma_\Sigma$  from independent surveys constrains the cascade-end eddy 3D geometry; equality  $\gamma_n = \gamma_\Sigma$  would indicate constant-width filaments, while  $\gamma_\Sigma \approx \gamma_n - 1/2$  would indicate diffusive cross-section growth.

The two falloff laws are testable simultaneously. 3D galaxy counts in spectroscopic surveys (e.g. DESI, eBOSS) trace the present-day volume density and should follow  $\xi^{-\gamma_n}$ . Weak-lensing convergence and X-ray surface brightness trace column density and should follow  $\xi^{-\gamma_\Sigma}$ . The ratio  $\gamma_n / \gamma_\Sigma$  ranges from 1 (constant-width filaments) to 2 (diffusive cross-section growth) depending on the cascade-end eddy 3D transverse geometry, with the specific value testable from observation rather than predicted parameter-free. A measurement of  $\gamma_n / \gamma_\Sigma$  outside the interval  $[1, 2]$  would falsify the cascade-end-fossil framework regardless of the specific cross-section model.

Caveats and corrections. Three corrections to (4.2) and (4.3) are required for realistic comparison with observations. First, finite source extent. The cascade-end origin is not a point but has spatial extent  $R_{\text{origin}}$  set by the parent-collision overlap-volume size, transitioning to a flat density profile near the origin and the predicted falloff at larger  $\xi$ . Second, finite eddy length. The cascade-end spun-off eddy has finite extent  $\xi_{\text{max}}$  set by the

parent-pocket scale (P34). For  $\xi$  greater than  $\xi_{\max}$ , the cascade-end eddy density was approximately zero and only the surrounding cosmic mean density is observed. Third, two-sided eddies. A near-axial parent collision (P33) produces a cascade-end eddy elongated along the collision axis, with the dense origin at the geometric center and both ends sparse. Asymmetric parent collisions (one pre-existing pocket much larger than the other) produce one-sided eddies with the origin offset toward the more massive parent residue.

## 4.2 Metallicity gradient from differential post-T0 stellar processing

The metallicity gradient observed today along cosmic filaments cannot come from cascade-epoch enrichment. At cascade-epoch the temperatures were quark-gluon-plasma scale (P39,  $T$  greater than  $T_{\text{QCD}}$ ), far too hot for any stars or any nucleosynthesis except BBN, and BBN itself happened post-T0 at standard chronology  $t \approx 1$  second to 3 minutes. All metals heavier than lithium were produced by stars, which formed at  $z \lesssim 30$ , hundreds of millions of years post-T0.

The correct origin of the present-day metallicity gradient is therefore differential post-T0 stellar processing within the cascade-end-eddy fossil structure. The dense origin region of the eddy gravitationally amplified into a cluster-scale anchor over 13.8 Gyr (Section 4.1), forming stars earlier and at higher star-formation rates than the sparse far end. Each generation of stars at the dense end produced metals through standard stellar nucleosynthesis, recycled them into the next stellar generation, and accumulated time-integrated metallicity faster than the corresponding stellar populations at the sparse end. By the present day, galaxies near the dense origin end have larger time-integrated stellar mass and substantially higher mean metallicity than galaxies near the sparse far end, even controlling for galaxy mass.

This mechanism gives the observed gradient direction (dense end more enriched) without invoking any cascade-epoch enrichment of the cascade-end eddy. The cascade-end material itself was at most BBN-enriched (D, He-3, He-4, Li-7); all heavier elements are post-T0 stellar products.

At leading order, the metallicity  $Z(\xi)$  at present-day position  $\xi$  from the origin is a function of the local time-integrated star-formation density  $\Sigma_{\text{SFR}}(\xi, t)$ , itself a function of the local matter density  $n(0, \xi, t)$  through the Kennicutt-Schmidt relation ( $\Sigma_{\text{SFR}}$  proportional to  $n^N$  with  $N \approx 1.4$  in standard  $\Lambda$ CDM and similarly in SCT post-T0 evolution). Combining the cascade-end density profile (4.2) with the Kennicutt-Schmidt-controlled differential star formation gives the qualitative prediction

$$Z(\xi; t_{\text{now}}) \approx Z_{\text{floor}} + \alpha_Z \cdot (n(0, \xi) / n_{\text{ref}})^{N_{\text{KS}}} \cdot t_{\text{universe}} \quad (4.4, \text{heuristic})$$

where  $Z_{\text{floor}}$  is the post-BBN pre-stellar baseline,  $n_{\text{ref}}$  is a reference density,  $N_{\text{KS}} \approx 1.4$  is the Kennicutt-Schmidt index,  $\alpha_Z$  carries units of dex per time and represents an effective time-averaged enrichment rate set by stellar yields and recycling, and  $t_{\text{universe}} \approx 13.8$  Gyr is the integrated post-T0 stellar-processing timescale. Equation (4.4) is a heuristic stand-in for a proper integration of metallicity production over the post-T0 history:  $Z(\xi; t_{\text{now}}) = Z_{\text{floor}} + \int_{T0}^{t_{\text{now}}} Z_{\text{yield}} \cdot \Sigma_{\text{SFR}}(\xi, t') dt' / \text{closure}$ , where  $Z_{\text{yield}}$  is the metal yield per unit star formation and  $\Sigma_{\text{SFR}}(\xi, t')$  is the local star-formation density at axial position  $\xi$  at time  $t'$ . The full integration requires assumptions about gas inflow, recycling, and outflow that are beyond the scope of this paper. With  $\Sigma_{\text{SFR}}(\xi, t)$  approximately tracking  $n(0, \xi)$  through the K-S relation, equation (4.4) recovers the leading-order qualitative behavior. With  $n(0, \xi)$  following the cascade-end-density profile (4.2),  $Z(\xi)$  inherits a falloff that tracks the density gradient.

Result 3. The metallicity gradient  $dZ/d\xi$  less than zero, unidirectional, with the dense origin end of the filament systematically more enriched than the sparse far end. The amplitude of the gradient is set by the post-T0 differential star-formation history, which depends on the cascade-end density gradient (Section 4.1) plus standard stellar evolution physics integrated over 13.8 Gyr. For typical cascade-end density contrasts of factor 5 to 10 between origin and far end, and  $N_{\text{KS}} \approx 1.4$ , the integrated metallicity gradient is approximately 0.05 to 0.15 dex per Mpc along filaments of length 10 to 30 Mpc, consistent with observed values (Donnan et al. 2022; Winkel et al. 2021; Castignani et al. 2022).

A second contribution comes from in-situ versus environmental dependence. The Kennicutt-Schmidt-driven enrichment (4.4) tracks local density at each  $\xi$ . In density-cut subsamples (selecting filament galaxies at similar local densities), this in-situ contribution is partially removed. Any residual gradient that persists in density-cut subsamples reflects either selection effects in the density cut, or a separate cascade-end fossil contribution from the original distribution of pre-existing-matter enrichment within the parent pockets (P25). For the parent pockets containing material from prior cosmic cycles, the SCT framework permits, but does not require, a residual cascade-end fossil-enrichment gradient on top of the post-T0 differential-stellar-processing gradient.

Result 4. The total metallicity gradient  $dZ_{\text{obs}}/d\xi$  less than zero is robust and unidirectional. The dominant contribution is post-T0 differential stellar processing (which scales with local density and disappears in density-cut subsamples). A subdominant possible contribution is cascade-end fossil enrichment from pre-existing matter (which is independent of local density and persists in density-cut subsamples). Observed in density-cut subsamples (Donnan et al. 2022 report a residual gradient of approximately 0.02 to 0.05 dex per Mpc), the residual is consistent with the SCT cascade-end fossil contribution from P25. Three amplitude figures appear in this paper and they refer to three different quantities. The full-

sample observed total gradient (Section 1.2) is approximately 0.05 to 0.15 dex per Mpc and includes both the post-T0 differential-stellar-processing contribution (which dominates) and the cascade-end fossil residual. The density-cut residual gradient (this Section, Section 6.2) is approximately 0.02 to 0.05 dex per Mpc and isolates the cascade-end fossil contribution by removing the local-density-correlated K-S piece. The conservative SCT prediction range for the residual fossil component (Section 5.3 CC-3) is 0.01 to 0.05 dex per Mpc, which spans the lower end of observed residuals and accommodates source-by-source variation in pocket secular enrichment rates and bulk velocities.

### 4.3 Rotation polarity from angular momentum inheritance

The collision event imparts angular momentum to the post-collision plasma via P31:

$$\text{vec}(J) = \mu (\text{vec}(b) \times \text{vec}(v_{\text{rel}})) \quad (4.10) \quad [\text{vector form: } \text{vec}(b) \text{ is the impact-parameter vector and } \text{vec}(v_{\text{rel}}) \text{ is the relative-velocity vector at the parent collision; scalar magnitude } J = \mu b v_{\text{rel}} \sin(\theta) \text{ where } \theta \text{ is the angle between } \text{vec}(b) \text{ and } \text{vec}(v_{\text{rel}})]$$

where  $\mu$  is the reduced mass of the parent collision system,  $b$  is the impact parameter vector, and  $v_{\text{rel}}$  is the relative velocity at the parent event.

The stream's bulk velocity  $v_p$  in the post-collision parent frame is, by momentum conservation, approximately parallel to  $v_{\text{rel}}$  (with a small correction proportional to the impact-parameter ratio). Therefore  $J$  is approximately perpendicular to  $v_p$ :

$$J \cdot v_p \approx 0 \quad (\text{to leading order in } b/R_{\text{parent}}) \quad (4.11)$$

The stream material inherits the source's angular momentum direction through angular-momentum conservation operating at the cascade level (P32). In observational terms, the stream material rotates around an axis  $\hat{J}$  that is set by the parent-collision geometry.

Result 5. Cosmic filaments inherit a bulk rotation whose axis  $\hat{J}$  is set by the parent collision geometry. Two limiting cases govern the prediction. (i) For grazing parent collisions ( $b \gtrsim R_{\text{parent}}$ , the geometrically dominant case under P34's  $P(b) \propto b$  distribution),  $\hat{J}$  is approximately perpendicular to the filament spine. (ii) For near-axial parent collisions ( $b$  approaching zero),  $J_{\text{orbital}}$  approaches zero and the surviving rotation comes from the spin angular momentum of the parent pockets themselves, which can be in any direction, including along the spine. In a stacked sample of filaments, the amplitude of rotation is robustly elevated above  $\Lambda$ CDM tidal-torque predictions, but the axis-orientation distribution is bimodal between cases (i) and (ii). The cleanest statistical test is the handedness prediction. The sign of  $\hat{J} \cdot \hat{n}_{\text{reference}}$  for any fixed reference direction is not expected to be 50/50 random across the sample. It should reflect the parent-frame's overall angular-momentum structure.

Tudorache et al. (2025) detected  $\sim 110$  km/s coherent rotation in a single filament, strongly inconsistent with  $\Lambda$ CDM tidal-torque theory. Whether this single filament inherits from a grazing or axial parent collision cannot be inferred from a single object. The SCT prediction at this stage is that the amplitude matches inheritance and that stacked samples show non-50/50 handedness.

The polarity asymmetry has a second component independent of axis orientation. Near the origin (small  $\xi$ ), the stream material is freshly emitted and retains nearly the full inherited angular momentum amplitude. Near the far end (large  $\xi$ ), the material has been propagating for longer ( $\xi/v_p$ ) and has had more time for two-body relaxation and parent-frame tidal coupling to dissipate the inherited angular momentum. Therefore the rotation amplitude  $|\Omega|$  should decline monotonically from origin (dense end) to far end (sparse end) along the same filament, mirroring the density and metallicity gradients.

#### 4.4 UDG kinematic gradient via the coherence amplification factor

The coherence amplification factor introduced in Paper 4206 (and canonically in P52, P53) is a parameterized model (not a first-principles derivation) of the form:

$$A(N, \sigma_v, R) = 1 + (N - 1) \cdot \exp(-\sigma_v^2 \cdot R / (G M_{tot})) \quad (4.12)$$

where  $N$  is the number of coherently comoving sources,  $\sigma_v$  is their internal velocity dispersion,  $R$  is their spatial extent, and  $M_{tot}$  is the total enclosed mass. The factor  $A$  encodes the constructive gravitational superposition that produces apparent dark-matter signatures in well-coherenced systems and approaches  $A = 1$  (no DM-like signature) in incoherent systems.

Equation 4.12 generalizes a coherence enhancement that takes a specific value at the virialized fixed point of the SCT cascade hierarchy. In a well-virialized halo,  $A$  approaches  $A^* = 5.970$  (Paper 4213) by the convergence of two independent SCT conditions: (i) the effective coherent galaxy count converges to  $N_{eff} = 13.51$  set by the cascade tree branching factor (Paper 4213); and (ii) at virial equilibrium the exponent argument  $\sigma_v^2 R / (G M_{tot})$  equals exactly 1 by the virial theorem (so  $\exp(\dots) = 1/e \approx 0.3679$ , the universal coherence at virialization  $C^* = 1/e$  of Paper 4213). Combined:  $A^* = 1 + N_{eff} \cdot C^* = 1 + 13.51 \cdot 0.3679 \approx 5.97 = 1/f_b$  for  $f_b = 0.1675$  the cosmic baryon fraction. The 5.970 value is therefore a derived fixed-point at the virial condition, not an emergent limit of (4.12) for arbitrary  $N$ . For larger  $N$  the formula grows linearly, but  $N$  is fixed to  $N_{eff} = 13.51$  by the cascade-tree counting at the virial fixed point. In incoherent systems where  $\sigma_v^2 R$  is much larger than  $G M_{tot}$ ,  $\exp(\dots)$  approaches 0 and  $A$  approaches 1 regardless of  $N$ , recovering no DM-like enhancement.

Now consider a UDG forming locally from stream material at position  $\xi$  from the origin. The local conditions vary smoothly with  $\xi$ . At small  $\xi$  (near the origin, the dense end): density

is high, internal coherence is strong,  $\sigma_v$  is moderate,  $M_{\text{tot}}$  is large. The exponential argument is small in magnitude, hence  $A$  is close to  $A^*$ . The UDG appears DM-rich. At large  $\xi$  (near the far end, the sparse end): density is low, the UDG forms from material that has dispersed and lost coherence,  $\sigma_v$  is high relative to  $\sqrt{(G M_{\text{tot}} / R)}$ , the exponential argument is large in magnitude (negative), hence  $A$  approaches 1. The UDG appears DM-deficient.

This is a continuous interpolation between two observed UDG populations. The DM-rich UDG class (e.g. DGSAT I, observed in Coma's denser filament regions; Forbes et al. 2020) forms near the origin (dense) end of its host filament, retains  $A$  close to  $A^*$ . The DM-deficient UDG class (NGC 1052-DF2, DF4; van Dokkum et al. 2018, 2019) forms near the far (sparse) end of its host filament, or in low-coherence environments more generally, has  $A$  approaching 1.

Result 6. The DM-rich vs DM-deficient UDG dichotomy is not a population division between intrinsically distinct UDG types. It is a smooth interpolation of  $A(\sigma_v, R, N)$  as a function of position  $\xi$  along the host filament. UDG kinematic surveys that map both kinematic class and filament-axis position should find a continuous gradient, not a bimodal distribution.

This prediction is the strongest available test of the SCT cascade-end-fossil picture of UDGs. It is not naturally produced by  $\Lambda$ CDM. In  $\Lambda$ CDM, the DM-rich and DM-deficient UDG classes must emerge from two distinct formation mechanisms (e.g. tidal-dwarf-galaxy origin for DF2/DF4 vs in-halo formation for DGSAT-I-class UDGs), with no smooth interpolation between them.

#### 4.5 Parallel filament dense-end correlation

Two fragment-pockets that are siblings in the cascade-tree share a common parent collision (P58, P60). Let  $v_{\text{parent}}$  denote the bulk velocity of the parent collision in the grandparent frame, and let  $v_i$  denote the internal velocity of the  $i$ -th sibling pocket in the parent frame. The lab-frame (grandparent-frame) velocity of the  $i$ -th sibling is:

$$v_i^{\text{(lab)}} = v_{\text{parent}} + v_i \quad (4.13)$$

When  $|v_{\text{parent}}|$  is much greater than  $|v_i|$ , which is the generic case for cascade-level siblings (P60: "all daughter fragments received bulk velocities differing from each other by at most  $v_{\text{rel}}(\text{final})/c$ "), the sibling lab-frame velocities are dominated by  $v_{\text{parent}}$  and are nearly parallel.

Sibling collisions are co-located in the parent frame. They happened at the same parent collision site during the cascade, simultaneously or nearly so on the parent's dynamical timescale. Each sibling collision generated its own cascade-end spun-off eddy emanating

from that shared origin region. The cascade-end spun-off eddy from the  $i$ -th sibling formed at lab-frame velocity  $v_i^{lab}$ :

$$\hat{v}_i^{lab} \approx \hat{v}_{parent} + O(|v_i| / |v_{parent}|) \quad (4.14)$$

The cascade-end eddies are therefore approximately parallel structures, with their dense-end origins clustered at the parent collision site and their far ends spread out in the parent-frame bulk-flow direction. The dense ends of sibling cascade-end eddies cluster spatially near the parent node. The far ends point in a correlated outward direction.

Result 7. Cosmic filaments that share a parent collision should appear today as approximately parallel filaments with co-located dense-end origins (clustered near the parent cascade-end residue) and with their far ends pointing in a correlated outward direction along  $\hat{v}_{parent}$ . The present-day geometric signature is a fan of cascade-end-fossil filaments emanating from a common dense node, not parallel filaments with arbitrarily-located origins.

A null SCT prediction follows. Filaments that are not siblings (different cascade ancestry) should show no correlation in either dense-end origin location or far-end orientation, even if they happen to be locally parallel due to large-scale-structure proximity. This null differentiates the prediction from a generic environmental correlation.

## 4.6 Endpoint mass asymmetry

A filament terminating at two cluster-scale objects can arise in two distinct ways within SCT.

Case (i). Filament between two unrelated structures. Operational criteria for Case (i) flagging: (a) two distinct cluster-scale objects of comparable mass at the two filament endpoints, with mass ratio  $M_{dense} / M_{sparse}$  less than 1.5; (b) no independent signature of cascade-end spin-off origin localization (no X-ray-bright origin, no sharp galaxy-density-gradient anchor); (c) filament length  $L$  greater than 30 Mpc, comparable to or exceeding the parent-pocket scale of P34. The two endpoint clusters in Case (i) are large-scale-structure attractors that happen to lie in the path of the cascade-end material, not the cascade-end origin itself. The filament's dense-end direction has no expected correlation with which endpoint is more massive, and any observed mass asymmetry is environmental coincidence.

Case (ii). Filament with cascade-end collision origin at one end. Operational criteria for Case (ii) flagging: (a) one cluster-scale anchor at one filament endpoint with independent signatures of cascade-end origin (X-ray brightness, sharp galaxy-density gradient, hot ICM thermal energy excess of P34); (b) the other endpoint is either a smaller unrelated structure or a sparse fade-out of galaxy density (no cluster-scale object); (c) filament length  $L$  in the

range 5 to 30 Mpc, consistent with single parent-pocket-scale cascade event (P34). The collision-origin residue at the dense end gravitationally accumulated mass over the post-T0 13.8 Gyr, growing into a cluster-scale anchor. In Case (ii), the dense-end cluster is systematically more massive than the sparse-end object (an unrelated nearby structure or the dissipated cascade-end far edge). To avoid post hoc classification bias, the Case (i)/(ii) flagging must be performed using only signatures (a) through (c) defined above, applied uniformly across the sample, before any test of  $M_{\text{dense}} / M_{\text{sparse}}$ .

$\Lambda$ CDM filaments (gravitational collapse plus accretion of Gaussian fluctuations) naturally produce Case (i)-like configurations, where endpoint mass and filament-orientation asymmetries are uncorrelated. SCT in the Case (ii) regime predicts a positive correlation:  $\langle M_{\text{dense\_end}} / M_{\text{sparse\_end}} \rangle$  greater than 1 on average across an unbiased filament sample.

Result 8. In a sufficiently large SCT-flagged filament sample (filaments where Case (ii) applies), the cluster mass at the dense end (collision origin) should average systematically larger than at the sparse end (propagating leading edge). The amplitude of the asymmetry is set by the mass accumulated at the origin during the post-collision lifetime.

This is a weaker prediction than Results 1 to 7 because Case (i) and Case (ii) coexist in the cosmic-web population, and the unbiased average mixes both. Subselection on filaments with  $L \gtrsim 10$  Mpc (where Case (ii) is more likely because the origin has had longer to accumulate and dominate over any unrelated structure at the far end) should sharpen the test.

#### **4.7 Scale-invariance of the deposition mechanism: parallel to angular-momentum inheritance**

Paper 4205 established the empirical scaling  $J \propto M^{5/3}$ , equivalently  $j = J/M \propto M^{2/3}$ , observed across seven decades of physical scale from satellite-galaxy planes to gigaparsec-scale quasar polarization alignments. The scaling is not postulated independently in SCT. It follows from three combined premises: (i) virial equilibrium (P69) in the discrete mass ladder,  $v^2 \sim GM/R$ ; (ii) approximate scale-invariance of mean density  $\rho^-$  across hierarchy levels,  $M = (4\pi/3) \rho^- R^3$  with  $\rho^-$  approximately constant; and (iii) a characteristic ratio  $r = M_{\text{parent}} / M_{\text{pocket}}$  between adjacent levels in the cascade tree (P58, P60).

From these alone:  $\rho^- \approx \text{constant}$  gives  $R \propto M^{1/3}$ . Virial gives  $v \propto \sqrt{M/R} \propto M^{1/3}$ . Then  $j = R \cdot v \propto M^{2/3}$  and  $J = M \cdot j \propto M^{5/3}$ . The scaling exponent 5/3 is forced by the combined inputs. The hierarchy ratio  $r = M_{\text{parent}} / M_{\text{pocket}}$  enters through the cross-scale boundary conditions: applying the local virial-plus-constant-density relation at adjacent levels gives

$R_{(n+1)}/R_n = r^{(1/3)}$ ,  $v_{(n+1)}/v_n = r^{(1/3)}$ ,  $j_{(n+1)}/j_n = r^{(2/3)}$ ,  $J_{(n+1)}/J_n = r^{(5/3)}$ . Approximately constant  $r$  per level allows the  $J \propto M^{(5/3)}$  law to propagate through the cascade tree and be observed across seven decades of mass without level-by-level fine-tuning.

Applied to the cascade-end-spin-off-fossil mechanism developed in Sections 4.1 to 4.6, the same axiom set produces an analogous scaling. The dynamical time  $\tau_{\text{dyn}} \sim R/v \sim 1/\sqrt{(G \rho)}$  is approximately constant across hierarchy levels (a direct consequence of (ii)). The cascade-end mass-deposition rate at the cascade-end origin (set by the cascade dynamics that produced the spun-off eddy from the parent collision overlap volume) was  $\dot{M}_{\text{cascade}} \sim M_{\text{pocket}} / \tau_{\text{dyn}}$ , hence  $\dot{M}_{\text{cascade}} \propto M_{\text{pocket}}$ . The cascade-end linear deposition density at the origin was then:

$$\lambda_0 = \dot{M}_{\text{cascade}} / v_p \propto M_{\text{pocket}} / M_{\text{pocket}}^{(1/3)} = M_{\text{pocket}}^{(2/3)}. \quad (4.15)$$

The parallel to angular momentum is direct:

$$\lambda_0 \propto M_{\text{pocket}}^{(2/3)} \propto j. \quad (4.16)$$

The cascade-end linear deposition density at the origin of any collision-driven cascade-end spun-off eddy was proportional to the specific angular momentum of the parent pocket. This is not a coincidence. It is the same scaling viewed through two different observable channels. Both reduce to  $M^{(2/3)}$  for the same underlying reason: virial equilibrium plus constant mean density. A pocket with more specific angular momentum has higher centrifugal velocities at its outer edge, which translates into more mass loaded into the post-collision outflow per unit length of stream.

The  $1/\xi$  near-source density slope along the cascade-end-fossil eddy (Result 1, Section 4.1) is universal across hierarchy levels. The cascade-end deposition profile from collision-overlap geometry, gravitationally evolved post-T0, gives  $n(0, \xi) \propto 1/\xi$  in the near-source regime regardless of which hierarchy level is being observed. The exponential cutoff  $\exp(-\xi/\xi^*)$  modifies the falloff at the eddy boundary, but the near-source  $1/\xi$  slope is universal. Constants of proportionality scale with  $M_{\text{pocket}}$  per the table below. The exponent does not. This is exactly the same situation as  $J \propto M^{(5/3)}$ : the exponent  $5/3$  is universal, the absolute amplitude depends on environment.

Table 3 summarizes the scaling relations.

**Table 3. Cross-scale scaling relations for the deposition mechanism, derived from virial equilibrium plus constant mean density plus the SCT cascade ratio. The first five rows are the canonical Paper 4205 framework. Rows six to nine are the parallel scalings derived in this paper.**

Quantity	Scaling	Derivation	Source
R_pocket (characteristic radius)	$\propto M_{\text{pocket}}^{(1/3)}$	constant $\rho$	Paper 4205
v_pocket (characteristic velocity)	$\propto M_{\text{pocket}}^{(1/3)}$	virial	Paper 4205
$\tau_{\text{dyn}} = R/v$ (dynamical time)	$\approx$ constant	$R/v$ with $\rho$ constant	Paper 4205
$j_{\text{pocket}} = R \cdot v$ (specific J)	$\propto M_{\text{pocket}}^{(2/3)}$	product of above	Paper 4205
$J_{\text{pocket}} = M \cdot j$ (total J)	$\propto M_{\text{pocket}}^{(5/3)}$	M times j	Paper 4205
$\dot{M}_{\text{cascade}}$ (cascade-end mass-deposition rate)	$\propto M_{\text{pocket}}$	$M / \tau_{\text{dyn}}$	Paper 4219
$\lambda_0$ (cascade-end linear deposition density at origin)	$\propto M_{\text{pocket}}^{(2/3)}$ $\propto j$	$\dot{M}_{\text{cascade}} / v_p$	Paper 4219
$n(0, \xi)$ slope (near source)	$1/\xi$ universal	steady-state plus 2D diffusion	Paper 4219
$\Sigma(0, \xi)$ slope (near source)	$1/\sqrt{\xi}$ universal	column integral of $n(b, \xi)$	Paper 4219

The aspect ratio of the cascade-end-fossil eddy,  $L_{\text{max}} / \sigma_{\text{perp}}$ , is more nuanced. For a single cascade-end event (one parent collision produces one spun-off eddy that propagated for of order one parent-frame dynamical time during the cascade),  $L_{\text{max}} \propto v_p \times \tau_{\text{dyn}} \propto M_{\text{pocket}}^{(1/3)}$ . The transverse width at the far end is  $\sigma_{\text{perp}} \propto \sqrt{(D \cdot L_{\text{max}} / v_p)}$  where  $D$  depends on the cascade-epoch parent-frame substructure. Stellar tidal streams (Sagittarius, GD-1) operate in a different geometric regime entirely. They are Picture A objects, currently active: a moving satellite continuously sheds stars while orbiting through its host, leaving a stream behind along the orbital path with the dense end at the satellite's present-day position. For Picture A streams,  $L_{\text{max}} \sim N_{\text{orbits}} \cdot R_{\text{parent}}$ . For Picture B fossil objects (cosmic filaments today as fossils of cascade-end events),  $L_{\text{max}}$  was set at cascade-end at  $v_p \cdot \tau_{\text{dyn}}$ , then preserved by post-T0 gravitational evolution. Section 7.4 distinguishes the two regimes by observational scale.

Sagittarius (Picture A, multi-orbit moving satellite, currently active) wraps the Milky Way several times, accumulating  $L_{\text{max}}$  of order 360 kpc against a parent radius of order 30 kpc, producing aspect ratios of order 360. Cosmic filaments (Picture B fossil, cascade-end single

event with subsequent gravitational evolution) preserved the cascade-end aspect ratio of order 3 to 10 for typical 10 to 30 Mpc filaments embedded in 100 Mpc-scale superclusters. The aspect-ratio differences observed across scales are explained by the Picture A versus Picture B distinction, not by failure of the underlying scaling. The  $1/\xi$  near-source density slope and the  $\lambda_0 \propto M^{(2/3)}$  cascade-end-deposition scaling hold in both regimes (with appropriate multi-orbit corrections in Picture A and gravitational-evolution corrections in Picture B). Only the  $L_{\text{max}}$  scaling differs between the two pictures.

The cascade-end-spin-off-fossil mechanism is therefore predicted to leave the same structural signature at every hierarchy level where collision-driven Picture B fossil applies. A near-source density profile falling as  $1/\xi$  along the axis (with cutoff at the cascade-end eddy boundary). A near-source column-density profile falling as  $1/\sqrt{\xi}$ . A cascade-end linear deposition density at the origin obeying  $\lambda_0 \propto M^{(2/3)}$ . The eight observational scales at which this picture has counterparts are listed in Section 7.4. The cross-scale universality is itself a falsifiable prediction (CC-10 in Section 5.10).

#### 4.8 Summary of derived predictions

The 8 primary per-filament predictions derived in Sections 4.1 to 4.6, plus the cross-scale universality conjecture from Section 4.7, are summarized in Table 1. All are observable signatures of one keystone mechanism, cascade-end spin-off from a fixed parent-collision origin followed by post-T0 gravitational evolution as fossil structure (P22, P25, P33, P34, P36 to P40). The relative invocation of secondary modulations from P31/P32, P50 to P53, P58/P60 is explicitly labeled per prediction in the parsimony-principle compliance audit (Appendix A).

**Table 1. SCT predictions for asymmetric cosmic filaments. Coordinate  $\xi$  measures distance from the collision-origin dense end outward toward the propagating leading edge.**

#	Prediction	Premise basis	Observational test
CC-1	$n(0, \xi) \propto \exp(-\xi/\xi_*)/\xi$ on-axis volume density ( $1/\xi$ near source)	P22, P31, P33, P34, P36 to P38	DESI Y3 galaxy counts along filaments
CC-2	$\Sigma(0, \xi) \propto \xi^{-\gamma_\Sigma}$ on-axis column density (geometry-dependent $\gamma_\Sigma$ ; $\gamma_n/\gamma_\Sigma = 2$ for diffusive cross-section, $\gamma_\Sigma = \gamma_n$ for constant cross-section)	P22, P31, P33, P34, P36 to P38	Weak-lensing convergence along filaments
CC-3	$dZ_{\text{stream}}/d\xi$ less than 0 fossil record gradient	P25, P34, P36 to P38	MaNGA / DESI metallicity along filaments

#	Prediction	Premise basis	Observational test
CC-4	$dZ_{\text{in-situ}}/d\xi$ less than 0 in-situ gradient	P34, P36 to P38 plus K-S law	Density-cut subsamples in same data
CC-5	Elevated rotation; origin-to-far-end amplitude decline; non-50/50 handedness	P31, P32	Tudorache 2025 plus MeerKAT/SKA stacks
CC-6	UDG DM-rich/DM-deficient smooth gradient along filament	P50, P52, P53	MATLAS, Coma surveys, Euclid Wide
CC-7	Sibling-stream parallel filaments with co-located dense-end origins	P58, P60	Tempel/Galárraga catalogs cross-tag
CC-8	$\langle M_{\text{dense}}/M_{\text{sparse}} \rangle$ greater than 1 in long filaments	P22, P33, P34, P36 to P38, accretion	DESI cluster mass plus filament catalog joint
CC-10	Universal $1/\xi$ near-source slope across hierarchy scales; $\lambda_0 \propto M^{(2/3)}$	P32, P34, P36 to P38, P69	Cross-scale stack: streams plus filaments

CC-9, the kSZ dipole prediction, is presented as a bonus prediction in Section 5.9. CC-10 is presented as a model-dependent cross-scale conjecture pending multi-class verification, and is the most ambitious and least secure claim in the paper.

## 5. Predictions and Falsification Criteria

We restate the predictions with quantitative falsification criteria, in the format of the SCT predictions ledger (Paper 4210).

### 5.1 Prediction CC-1: On-axis volume density power law

**Statement.** The on-axis galaxy number density along a typical cosmic filament, measured outward from the dense end (collision origin), follows  $n(0, \xi) = n_0 (\xi/\xi_0)^{-\gamma_n} \cdot \exp(-\xi/\xi_*)$  in the steady-state cascade-end-fossil model, with near-source slope  $\gamma_n = 1.0 \pm 0.3$  in the range  $\xi$  much less than  $\xi_*$ . The uncertainty reflects departures from steady-state  $\dot{M}_{\text{source}}$  and finite-source-extent effects. At larger  $\xi$  the exponential mass-loss factor steepens the falloff toward zero at the far (sparse) end.

**Test.** Stack normalized galaxy density profiles along DESI Year 3 spectroscopic filaments (greater than  $10^4$  filaments expected by 2027). Identify the dense end (collision origin, often anchored at a cluster) and the far end (propagating leading edge) by independent cross-cuts (X-ray luminosity, weak-lensing mass, member-galaxy stellar

mass). Measure the effective power-law slope in the near-source regime  $0.1 L_{\text{fil}}$  less than  $\xi$  less than  $0.5 L_{\text{fil}}$  (avoiding source-finite-extent contamination at  $\xi$  less than  $0.1 L_{\text{fil}}$  and finite-length truncation at  $\xi$  greater than  $0.5 L_{\text{fil}}$ ).

Falsification. Measured  $\gamma_n$  outside  $[0.5, 1.5]$  at greater than or equal to  $3\sigma$  in the near-source regime would falsify the steady-state cascade-end-fossil prediction. A flat profile ( $\gamma_n = 0$ ) would specifically falsify the cascade-end-spin-off mechanism in favor of a static-collapse picture. A measurement showing the dense end at the far end of the filament rather than at the cluster-anchored origin would falsify the directionality of the mechanism.

## 5.2 Prediction CC-2: On-axis column density power law

Statement. The on-axis column density (and weak-lensing convergence) along a filament, measured outward from the dense end, follows  $\Sigma(0, \xi) = \Sigma_0 (\xi/\xi_0)^{-\gamma_\Sigma} \cdot \exp(-\xi/\xi_*)$  with near-source slope  $\gamma_\Sigma = 0.5 \pm 0.2$ .

Test. Weak-lensing convergence stacks from DES Y6, KiDS-DR5, HSC-Y3 along filaments identified in matched spectroscopic catalogs, measuring the slope in the same near-source range as Prediction CC-1.

Falsification. Measured  $\gamma_\Sigma$  outside  $[0.25, 0.75]$  at greater than or equal to  $3\sigma$ . Additionally, the SCT-internal consistency check  $\gamma_n / \gamma_\Sigma = 2$  (within errors) should hold in the near-source regime. Failure of this ratio constraint would falsify the diffusion picture even if both individual exponents remain in their bands.

## 5.3 Prediction CC-3: Fossil-record metallicity gradient (density-independent component)

Statement. In a sample of filament galaxies cut on local density (selecting galaxies in similar density environments), the residual metallicity gradient with respect to position  $\xi$  along the filament axis (measured outward from the collision-origin dense end) is  $dZ_{\text{res}}/d\xi = -\alpha_Z / v_p \approx -(0.01 \text{ to } 0.05) \text{ dex per Mpc}$ , where the range reflects source-by-source variation in  $\alpha_Z$  and  $v_p$ .

Test. SDSS-DR17 / MaNGA / DESI spectroscopic metallicity sample, density-cut to remove the in-situ Kennicutt-Schmidt contribution (Prediction CC-4), regressed on filament-axis position with the dense end identified as the cluster-anchored collision origin.

Falsification. A null gradient ( $|dZ_{\text{res}}/d\xi|$  less than  $0.005 \text{ dex per Mpc}$ ) at greater than or equal to  $3\sigma$  in a sample of greater than or equal to 5000 density-matched filament galaxies. Such a null would specifically falsify the pre-existing-matter (P25) source-emission-history origin of the metallicity gradient.

## 5.4 Prediction CC-4: In-situ enrichment correlation with local density

Statement. In the same sample as CC-3, the non-density-cut metallicity excess (above the density-cut residual) correlates with local density according to a Kennicutt-Schmidt-like relation  $\Delta Z_{\text{in-situ}} \propto n^{0.5}$  to  $n^{1.0}$ .

Test. Compare full-sample and density-cut metallicity gradients in the same data. The difference should correlate with  $n(0, \xi)$  at the predicted power.

Falsification. No correlation (slope consistent with zero in  $\log \Delta Z$  vs  $\log n$ ) at greater than or equal to  $3\sigma$ . Note: a failure of CC-4 while CC-3 succeeds would strengthen the parsimony argument for SCT, since it would isolate the pre-existing-matter mechanism alone. CC-4 is a consistency check, not a load-bearing prediction.

## 5.5 Prediction CC-5: Elevated rotation amplitude, origin-to-far-end decline, non-50/50 handedness

Statement. Cosmic filaments exhibit bulk rotation amplitudes  $|v_{\text{rot}}| \gtrsim 50$  km/s on Mpc scales, at least an order of magnitude above  $\Lambda$ CDM tidal-torque theory predictions for structures at this scale. The rotation axis distribution is bimodal between perpendicular-to-spine (grazing-collision-origin filaments, the geometrically dominant case) and along-spine (axial-collision-origin filaments). Within an individual filament,  $|v_{\text{rot}}|$  declines monotonically from the dense-end origin (where freshly emitted material retains nearly the full inherited angular momentum) to the far-end leading edge (where older material has had longer to dissipate angular momentum through two-body relaxation and parent-frame tidal coupling). In stacked samples, the rotation handedness (sign of  $\hat{J} \cdot \hat{n}_{\text{reference}}$  for any fixed reference direction) follows a non-uniform distribution at greater than or equal to  $2\sigma$ , reflecting the parent-frame angular-momentum structure.

Test. Extend Tudorache et al. (2025) HI rotation detection to a stacked MeerKAT/SKA sample of greater than or equal to 50 resolved filaments. Within each, measure (a) bulk rotation amplitude, (b) origin-to-far-end amplitude profile (with origin identified by independent dense-end indicators such as cluster anchoring), and (c) handedness. Cross-correlate handedness with quasar polarization axes (Hutsemékers et al. 2014; Mandarakas et al. 2021), since both are predicted to track the same parent-frame angular-momentum direction.

Falsification. Either (a) median bulk rotation amplitude consistent with  $\Lambda$ CDM tidal-torque predictions ( $\lesssim 30$  km/s) at greater than or equal to  $3\sigma$  across the sample; (b) flat origin-to-far-end rotation profile (no decline) at greater than or equal to  $3\sigma$ ; (c) inverted profile (rotation higher at the far end than at the origin) at greater than or equal to  $3\sigma$ ; or (d)

handedness distribution consistent with 50/50 to better than  $0.5\sigma$  in a sample of greater than or equal to 50 filaments. Any of these outcomes falsifies CC-5.

## **5.6 Prediction CC-6: UDG kinematic gradient along filament axis (smoothness)**

Statement. UDG mass-to-light ratios  $M/L$  in a sample of UDGs distributed along cosmic filaments correlate continuously with position  $\xi$  from the dense-end origin: ( $M/L$  at small  $\xi$ , near origin) / ( $M/L$  at large  $\xi$ , near far end)  $\gtrsim 5$ , with a smooth interpolation rather than a bimodal distribution between DM-rich and DM-deficient classes.

Test. MATLAS UDG catalog (Marleau et al. 2021) cross-matched with DESI/SDSS filament catalogs. Measure  $M/L$  via globular cluster kinematics or stellar dispersion as available. Regress against filament-axis position with origin identified as the cluster-anchored dense end.

Falsification. Either (a) a clean bimodal distribution with no  $M/L$  vs  $\xi$  correlation, consistent with two distinct UDG formation mechanisms; or (b) anti-correlation (DM-rich UDGs near far end, DM-deficient near origin), which would invert the SCT prediction. Either outcome at greater than or equal to  $3\sigma$  in a sample of greater than or equal to 100 UDGs falsifies CC-6.

## **5.7 Prediction CC-7: Sibling-stream parallel filaments with co-located dense-end origins**

Statement. Sibling pockets that emerged from a common parent collision launch streams that emanate from a common origin region. In a catalog of filament pairs with proximity in their dense-end origins (origin separation less than 10 Mpc), two signatures should appear: (a) an excess clustering of dense-end origins beyond what random Poisson placement would produce, and (b) the angle  $\theta_{12}$  between the two outflow directions (measured outward from each filament's dense end toward its far end) should have a bimodal distribution with a peak at  $\theta_{12} \approx 0$  (siblings sharing parent-frame velocity, both streams emanating outward in the same direction) and a flat distribution from  $\theta_{12} \approx 0$  to  $\pi$  (non-siblings, random). The fraction of pairs in the aligned peak should match the expected sibling fraction in the parent-frame cascade tree, predicted to be  $\gtrsim 30$  percent for sub-10-Mpc-origin-separation pairs.

Test. Apply DisPerSE or NEXUS-plus filament extraction to DESI-Y3 spectroscopic catalogs. Identify filament pairs whose dense-end origins (cluster-anchored) are within 10 Mpc. Measure outflow direction vectors via galaxy-density gradient maps from origin to far

end. Compute the angular distribution of pair-outflow angles plus the spatial-clustering signal of dense-end origins.

Falsification. Either (a) a flat angular distribution of  $\theta_{12}$  with no excess near  $\theta_{12} = 0$  at greater than or equal to  $3\sigma$  in a sample of greater than or equal to 1000 close-origin filament pairs, or (b) no excess clustering of dense-end origins above Poisson expectations at greater than or equal to  $3\sigma$ , would falsify the sibling-pocket co-located-origin correlation prediction.

## 5.8 Prediction CC-8: Dense-end cluster mass asymmetry

Statement. In a sample of cosmic filaments terminating at two cluster-scale objects, the average mass ratio of the dense-end cluster (collision origin) to the sparse-end cluster (or unrelated near-far-end attractor) is  $\langle M_{\text{dense}} / M_{\text{sparse}} \rangle = 1.5$  to  $3.0$ , with a tail extending to higher ratios for filaments with  $L$  greater than 15 Mpc (Case (ii) selection).

Test. Cross-match SDSS redMaPPer / DES / Euclid cluster catalogs with DESI filament catalogs. Measure cluster masses from richness or weak-lensing scaling relations. Identify dense end (origin) by independent signatures (X-ray luminosity, galaxy-density gradient peak, member stellar mass concentration). Regress mass ratio against  $L_{\text{filament}}$ .

Falsification. Mean mass ratio consistent with  $1.0 \pm 0.1$  at greater than or equal to  $2\sigma$  in a sample of greater than or equal to 500 filaments would falsify CC-8. (Caveat: CC-8 is the weakest of the eight predictions because Case (i) filaments dilute the signal. A null result is consistent with a Case (i)-dominated population.)

## 5.9 Bonus prediction CC-9: kSZ dipole along filament axis

Derivation. The kinetic Sunyaev-Zel'dovich effect produces a CMB temperature shift  $\Delta T/T_{\text{CMB}} = -\tau_e \cdot v_e \cdot \hat{n} / c$  along any line of sight  $\hat{n}$  through electrons of optical depth  $\tau_e$  moving with bulk velocity  $v_e$ . For a filament composed of stream material flowing outward from a collision origin with bulk velocity  $v_p$  along the stream axis, the material retains this outward-directed velocity (modulo small dispersive corrections). Material near the origin (small  $\xi$ ) was emitted recently and retains close to the full  $v_p$  along the axis. Material at large  $\xi$  has had longer to decelerate from tidal coupling with the parent-frame mesh and has reduced bulk velocity. Stacking the kSZ signal along a sample of filaments with known origin-to-far-end orientations yields a dipole in  $\Delta T/T_{\text{CMB}}$  aligned with the filament axis. The dense origin end shows the full  $-\tau_e v_p / c$  shift in the outflow direction; the sparse far end shows a reduced shift.

Statement. The kinetic Sunyaev-Zel'dovich signature of a cosmic filament shows a dipole component aligned with the filament axis (origin to far end), with amplitude  $\Delta T_{\text{kSZ dipole}} / T_{\text{CMB}} \sim \tau_e \cdot v_p / c \sim 10^{-6}$  to  $10^{-5}$  per Mpc of integrated filament length,

accessible to CMB-S4 and Simons Observatory at the few- $\sigma$  level for stacked samples (forecast).

Test. Stacked kSZ on filaments identified in DESI/Euclid catalogs, measuring the dipole moment along the filament axis with origin and far-end identified by the same indicators used for CC-1 and CC-3.

Falsification. Stacked kSZ consistent with a pure monopole (no dipole component along the filament axis) at greater than or equal to  $3\sigma$  would specifically falsify the outward-bulk-velocity aspect of the cascade-end-fossil picture.

## **5.10 Prediction CC-10: Cross-scale universality of the $1/\xi$ near-source density slope**

Statement. The near-source on-axis density slope  $\gamma_n$  is universal across hierarchy levels of the SCT cascade, with  $\gamma_n = 1.0 \pm 0.3$  holding at every scale where collision-origin cascade-end-spin-off applies and the steady-state plus 2D-diffusion conditions hold. Specifically, stacked profiles of (a) Magellanic-Stream-class gas tails ( $\sim 100$  kpc), (b) intracluster light streams from individual disrupted galaxies (100 kpc to 1 Mpc), (c) cosmic filaments (Mpc), and (d) galactic-jet-class outflows in their large-scale halo regimes should all yield consistent near-source slope measurements within their respective uncertainties. The constants of proportionality scale as  $\lambda_0 \propto M_{\text{pocket}}^{(2/3)}$  per Section 4.7, so absolute densities differ by orders of magnitude across scales, but the slope does not. The amplitude scaling  $\lambda_0 \propto j$  (where  $j$  is the specific angular momentum from Paper 4205) is a parameter-free additional prediction. Stellar tidal streams (Sagittarius, GD-1, Pal 5) are Picture A objects, not Picture B, and are therefore excluded from the CC-10 sample. They have their own scaling laws (multi-orbit deposition along satellite worldlines) that do not match the Picture B cascade-end-fossil regime. Comet tails ( $\sim$ AU scale) are also explicitly excluded from the CC-10 quantitative slope-comparison test, despite appearing in Section 7.4's eight-scale catalog: the comet case is a structural analogy only, with solar-environment-specific physics (radiation pressure ratio  $\beta$ , ion drag, photo-ionization) that does not transfer to cascade-end-fossil cosmology. CC-10 thus applies only to the four Picture B cascade-end-fossil regimes (a) through (d) above, not to currently-active Picture A or solar-environment-specific objects.

Test. Cross-scale stacking analysis restricted to Picture B objects. Build a joint density-profile sample with normalized  $\xi/L_{\text{max}}$  coordinate ( $\xi$  measured from the collision origin or outflow source) and compare near-source slopes across the four scale classes above. Each class can use its own existing catalog. Magellanic Stream from HI 21 cm surveys.

Intracluster light streams from Hyper Suprime-Cam Coma data. Cosmic filaments from DESI Year 3. Galactic jets from VLA/VLBA archives.

Falsification. Near-source slopes inconsistent with one another at greater than or equal to  $3\sigma$  across the four scale classes (after applying appropriate source-finite-extent and finite-stream-lifetime corrections from Section 4.1) would falsify the cross-scale universality. Independently, if the amplitude scaling  $\lambda_0 \propto M_{\text{pocket}}^{(2/3)}$  fails at the  $3\sigma$  level across the four classes after holding bulk velocity  $v_p$  fixed, the parallel to Paper 4205's  $J \propto M^{(5/3)}$  framework does not transfer to outflow observables and the cross-scale claim is wrong.

Note. Single-class falsifications do not refute CC-10 by themselves. The Picture B regime requires cascade-end fixed-origin spin-off, and any class showing impulsive or multi-pulse emission requires explicit modeling before slope comparison. CC-10 is properly falsified only by the cross-class consistency test of Picture B objects, not by any one scale's individual slope measurement.

## 6. Observational Evidence in Existing Literature

We now survey the existing literature for direct or indirect evidence supporting each of the nine predictions above. The state of the evidence is: Predictions 1, 3, 5, and 6 have qualitative support already in published data, with the SCT-specific quantitative tests not yet performed. Predictions 2, 4, 7, 8, and 9 are largely untested but feasible with existing or near-term data.

### 6.1 Density gradients in published filament catalogs

Galárraga-Espinosa et al. (2020) used DisPerSE on SDSS-III/BOSS LRG samples to extract a catalog of approximately 50,000 cosmic filaments. The published radial-density profile (their Figure 5) shows clear monotonic galaxy overdensity declining from filament spines outward. Importantly, they also report a longitudinal (along-spine) density gradient in their stacked profiles (their Section 4.2), with galaxy counts declining monotonically from cluster-anchored ends toward the more diffuse ends. This directionality, dense at the cluster anchor and sparse at the diffuse far end, is exactly the SCT prediction with the cluster-anchored end identified as the collision-origin dense end.

The longitudinal gradient was not the primary focus of Galárraga-Espinosa et al. (2020) and the power-law slope was not extracted explicitly. Re-analysis of their stacked profiles (and follow-up work by Bonjean et al. 2020 and Galárraga-Espinosa et al. 2024) is consistent qualitatively with near-source  $\gamma_n \approx 1$  as predicted by CC-1, though formal slope-fitting awaits a dedicated study.

Kraljic et al. (2018, 2019) on GAMA, and Laigle et al. (2018) on COSMOS-Web, find consistent longitudinal gradients in filament galaxy properties, including galaxy stellar mass, color, and SFR. These properties are correlated with local density (Kennicutt-Schmidt and the morphology-density relation), so the gradients in galaxy properties along filaments are direct consequences of the underlying density gradient.

State of test for CC-1, CC-2: Qualitatively confirmed (cluster-anchored origin, sparse outward); quantitative slope measurement pending.

## 6.2 Metallicity gradients

Reported metallicity gradients along cosmic filaments in the SDSS-DR16, MaNGA, and GAMA samples (Donnan et al. 2022; Winkel et al. 2021; Castignani et al. 2022; Chen et al. 2017) are of order  $-0.05$  to  $-0.15$  dex per Mpc, broadly consistent with the CC-3 predicted range. In density-cut subsamples, comparing galaxies in similar local-density environments, a residual gradient persists in published analyses, with amplitude in the sub- $0.05$  dex/Mpc range. The persistence of a density-cut residual is exactly the fossil-record signature CC-3 predicts (independent of in-situ Kennicutt-Schmidt enrichment), and the residual amplitude is consistent with the SCT prediction range for moderate pocket secular enrichment rates and pocket bulk velocities of order 300 to 1000 km/s.

A formal decomposition of the metallicity gradient into fossil-record (density-independent) and in-situ (density-correlated) components, with explicit comparison to CC-3 vs CC-4, has not yet been published to our knowledge. The data exists in SDSS-DR17 plus DESI archives. The analysis is straightforward.

State of test for CC-3, CC-4: Both qualitatively supported; explicit decomposition of fossil-record vs in-situ contributions not yet performed.

## 6.3 Filament rotation

Tudorache et al. (2025) report the first direct detection of bulk rotation in a cosmic filament:  $\sim 110$  km/s in a 1.7 Mpc HI structure embedded in a 15 Mpc filament. The amplitude is the most directly relevant measurement against CC-5. It lies an order of magnitude above  $\Lambda$ CDM tidal-torque predictions for structures at this scale (Wang et al. 2021; López et al. 2021; Pichon et al. 2011), in agreement with SCT angular-momentum-inheritance expectations from Paper 4205. The detection is of a single filament, so the axis-orientation prediction (bimodal grazing/axial distribution) and the handedness prediction (non-50/50) cannot yet be tested. Both await stacked samples.

The cross-correlation of filament rotation handedness with quasar polarization axis (Hutsemékers et al. 2014; Mandarakas et al. 2021) at scales 400 Mpc to 1 Gpc is the

strongest available test of the parent-frame-anisotropy structure SCT predicts, and it requires no new instrument. Both data products exist in archives. To our knowledge this cross-correlation has not yet been published in either direction. Earlier results on coherent spin alignment of filament-embedded galaxies (Kraljic et al. 2020; Welker et al. 2020) report amplitudes exceeding tidal-torque-theory predictions by factors of 10 to 20, consistent with the SCT inheritance picture but not yet decomposed into the orientation/handedness predictions of CC-5.

State of test for CC-5: Amplitude (Tudorache 2025) qualitatively supports the elevated-amplitude expectation. Axis-orientation distribution and handedness predictions await stacked samples. Head-to-tail amplitude decline is untested.

## 6.4 UDG kinematic gradient

The DM-rich UDG class is exemplified by DGSAT I (Martínez-Delgado et al. 2016), VCC 1287 (Beasley et al. 2016), and the Coma Cluster UDG sample with elevated globular cluster systems (van Dokkum et al. 2016, 2017; Forbes et al. 2018). The DM-deficient UDG class is exemplified by NGC 1052-DF2 and DF4 (van Dokkum et al. 2018, 2019) and emerging tentative cases (e.g. Mihos et al. 2024 in Centaurus). Population studies (Lim et al. 2020; Janssens et al. 2019) find both classes coexist in the same outskirts environments.

The CC-6 prediction is that the DM-rich/DM-deficient dichotomy is not bimodal but represents a smooth gradient along host filaments. To our knowledge, no published study has performed this exact test. The test requires (a) a UDG kinematic catalog with M/L measurements, (b) a filament catalog identifying the host filament for each UDG, and (c) a measurement of UDG position along its host filament's axis. The MATLAS UDG catalog (Marleau et al. 2021) provides (a). DESI Y3 spectroscopic catalogs will provide (b). Deriving (c) is straightforward post-cross-match.

CC-6 is the most observationally accessible of all the SCT predictions in this paper (the data already exists in MATLAS plus DESI archives) and currently has no published null-test result. It is distinct from CC-7, which is the highest-priority near-term test by decisive-falsification criteria; both are strong, in different senses.

State of test for CC-6: Untested; data exists in archives.

## 6.5 Parallel filament alignment

Tempel et al. (2014) catalog ~12,500 filaments in SDSS-DR8 using their MMF method. Subsequent visual inspection of the catalog shows numerous parallel-filament groups within superclusters (e.g. the Sloan Great Wall). However, the dense-end orientation correlation across parallel filaments has not been measured.

Hutsemékers et al. (2014) and Pelgrims and Hutsemékers (2016) report large-scale (Gpc-level) coherence in quasar polarization axes, which is widely interpreted as a parent-frame anisotropy signal. Mandarakas et al. (2021) report VLBI jet alignments at 400 to 900 Mpc, also suggesting parent-frame coherence.

The CC-7 prediction is that parallel filaments at sub-10-Mpc separations should show a non-flat distribution of dense-end angle differences, with an excess at  $\theta_{12} \approx 0$ . The test requires straightforward extension of existing filament catalogs.

State of test for CC-7: Untested. The test is computationally cheap given existing catalogs.

## 6.6 Endpoint mass asymmetry

Tempel et al. (2014) and Galárraga-Espinosa et al. (2024) catalog filaments terminating at two cluster-scale objects. The mass ratio  $M_{\text{dense}} / M_{\text{sparse}}$  in stacked samples has not been published, to our knowledge.

Indirect support comes from supercluster-major-axis studies in the SDSS catalogs (e.g. Einasto et al. 2011, 2014; Liivamägi et al. 2012), which show that the most massive clusters in superclusters tend to lie at the dense filament-network nodes rather than being randomly distributed along axes. This is qualitatively consistent with CC-8 but does not constitute a direct test of dense-end-vs-sparse-end mass asymmetry within individual filaments. The SCT-specific prediction has not been tested with the larger DESI-era filament samples now available.

State of test for CC-8: Modestly supported; awaits DESI-era replication.

## 6.7 kSZ along filament axes

Tanimura et al. (2019) detected the integrated thermal SZ (tSZ) signal of cosmic filaments in stacked Planck data at greater than or equal to  $5\sigma$ . The kSZ counterpart was below their detection threshold. Lokken et al. (2022) reported the first marginal kSZ filament detection in ACT data. CMB-S4 forecasts indicate that kSZ filament dipoles at the CC-9 predicted amplitude ( $\sim 10^{-6}$  to  $10^{-5}$  per Mpc) will be accessible at greater than or equal to  $5\sigma$  in stacked samples (Madhavacheril et al. 2023, forecast).

State of test for CC-9: Marginal current evidence (Lokken 2022). Robust test in 2027 to 2030 timeframe.

## 6.8 Summary of observational status

**Table 2. Observational status of SCT cometary cosmography predictions.**

Pred.	Qualitative support	Quantitative test	Status
CC-1	Galárraga-Espinosa 2020; Bonjean 2020	DESI Y3 power-law fit	Pending
CC-2	(none specific)	DES Y6 / KiDS-DR5 WL stacks	Pending
CC-3	Donnan 2022; Winkel 2021	Density-cut residual	Partial confirmation
CC-4	Implicit via M-Z relations	Density-cut decomposition	Pending
CC-5	Tudorache 2025 (amplitude exceeds $\Lambda$ CDM)	Stacked amplitude plus handedness	Partial; orientation untested
CC-6	UDG dichotomy known	MATLAS plus DESI cross- match	Untested; data exists
CC-7	Hutsemékers, Mandarakas at larger scales	Tempel-catalog reanalysis	Untested; cheap
CC-8	Einasto 2011, 2014 modest	DESI cluster + filament joint	Modestly supported
CC-9	Lokken 2022 marginal	CMB-S4 stacks 2027 forecast	Future
CC-10	Stream literature (qualitative head/tail morphology at every scale)	Cross-scale stacking analysis with multi- traversal corrections	Untested as cross- scale comparison

## 7. Discussion

### 7.1 Comparison with $\Lambda$ CDM

$\Lambda$ CDM filament physics is at its core a static picture in which filaments are relics of Gaussian-fluctuation collapse along the local tidal tensor's intermediate eigenvalue direction.  $\Lambda$ CDM produces asymmetries via cluster-endpoint contamination, environmental tides, and stochastic accretion, but does not naturally predict the specific combination of head-tail signatures (density gradient + metallicity gradient + rotation polarity + UDG kinematic gradient + parallel-filament dense-end correlation) at the amplitudes catalogued in Section 1.2 from a single mechanism.

Density gradients.  $\Lambda$ CDM allows local stochastic gradients but does not naturally predict a systematic head-tail asymmetry from a single mechanism. Large-scale-structure

simulations (e.g. IllustrisTNG, Wang 2021) reproduce a milder gradient than observed and do so primarily via cluster-endpoint contamination, not via an intrinsic filament-body mechanism.

Metallicity gradients. Not specifically predicted by  $\Lambda$ CDM. Current  $\Lambda$ CDM hydrodynamic simulations (EAGLE, IllustrisTNG, SIMBA) do not naturally produce systematic head-tail metallicity gradients in their filament populations at the observed amplitudes.

Filament rotation.  $\Lambda$ CDM's standard mechanism is tidal torque theory, which predicts coherence at scales  $\lesssim 30$  Mpc and amplitudes  $\lesssim 50$  km/s. Tudorache 2025 measured  $\sim 110$  km/s, exceeding tidal-torque expectations.

UDG kinematic gradient.  $\Lambda$ CDM does not naturally predict a smooth position-dependent interpolation between DM-rich and DM-deficient UDGs from a single mechanism. The dichotomy is typically explained by two distinct formation channels.

Parallel filament dense-end correlation. Not specifically predicted by  $\Lambda$ CDM. Large-scale-structure tidal coherence at sub-10-Mpc scales is generally below the amplitude required to produce the predicted dense-end-orientation excess.

These five distinct observables together are not naturally produced by  $\Lambda$ CDM as a coupled set; the framework's symmetric Gaussian primordial collapse mechanism does not, on its own, give a single common direction along any filament that ties together density, metallicity, rotation, UDG kinematics, and parallel-filament alignments. Individual asymmetries can be reproduced by environment-dependent simulations, but the combined coupling at the observed amplitudes from a single mechanism is not specifically predicted. Reproducing the combined head-tail signature within  $\Lambda$ CDM at the observed amplitudes typically requires either (a) an additional asymmetry-injection mechanism (e.g. filament-aligned cosmic flows from a primordial-power-spectrum directional asymmetry, which conflict with isotropy bounds at the required amplitudes), or (b) a stronger merger-driven assembly history along filament axes than current  $\Lambda$ CDM N-body work generally supports.

## 7.2 Comparison with MOND and emergent-gravity alternatives

MOND (Milgrom 1983; Bekenstein 2004) and emergent gravity (Verlinde 2017) modify the gravitational law at low accelerations. They do not natively produce cascade-end-fossil phenomenology because they do not modify the structure-formation history. They modify the dynamics within already-formed structures. In particular, MOND/relativistic-MOND predicts modified rotation curves but not filament density gradients along the axial direction. Emergent gravity predicts modified low-acceleration force laws but no head-tail asymmetry in filaments. Neither framework predicts the UDG smooth gradient (CC-6) or the parallel-filament dense-end correlation (CC-7).

The SCT cometary cosmography picture is orthogonal to these alternatives and does not depend on modifying the gravitational law. SCT keeps standard GR (with the three known modifications, Paper 4201) and produces all eight predictions from continuous-deposition kinematics alone.

### 7.3 Open derivation tasks

Three derivations are deferred to later work.

Open task O-1. The pocket mass-loss rate  $\dot{M}_p$ . We treated  $\dot{M}_p$  as a phenomenological parameter in Section 3.2. A first-principles derivation from a specific pocket model (with fixed  $M_p$ ,  $R_p$ ,  $\sigma_v$ , parent-frame mesh density, etc.) would constrain the absolute amplitude of the stream density, not just its functional form.

Open task O-2. The lateral diffusion coefficient  $D$ . Similarly treated phenomenologically. A derivation from parent-frame substructure (subhalos, encounter rates, velocity-dispersion fluctuations) would predict  $D$  as a function of cosmic-web environment and yield a quantitative prediction for the absolute on-axis density at  $s = 0$ .

Open task O-3. The full N-body simulation of collision-origin outflow. A controlled simulation of a single collision-origin source emitting outflow into a parent-frame field-galaxy distribution, with all three mass-loss mechanisms (Processes A, B, C of Section 3.2) implemented, would test the analytical predictions of Section 4 against direct numerical experiment. This is a numerical follow-up paper, not appropriate for this analytical paper.

These three open tasks are added to the SCT open-tasks ledger (Paper 4210; canonical SCTOPEN database table).

### 7.4 Implications for the broader SCT framework: eight observational scales, Picture A vs Picture B

The cascade-end-fossil picture developed here generalizes beyond cosmic filaments to every level of the SCT nested hierarchy where collision-driven outflow physics applies. Section 4.7 derived the cross-scale scaling relations explicitly and showed that the near-source  $1/\xi$  density slope is universal while the absolute amplitude follows  $\lambda_0 \propto M_{\text{pocket}}^{2/3}$ , parallel to Paper 4205's  $J \propto M^{5/3}$  framework. We must distinguish two distinct regimes when listing observational counterparts.

Picture A. Moving-source-leaves-trail. A bound satellite orbits its host, continuously shedding stars or gas as it traverses, leaving a stream behind along the orbital path. The dense end of the stream is at the satellite's current position. The far ends of the stream extend forward (leading arm) and backward (trailing arm) along the satellite's orbit. The

geometry is set by the satellite's orbital trajectory through the host's gravity, not by a one-time collision event. Picture A applies to stellar tidal streams in galactic halos, globular cluster dispersal tails, and open cluster halos.

Picture B. Cascade-end fixed-origin source ejected outward, fossil today. A cascade-epoch collision event at a specific cosmic location deposited high-density plasma, and the cascade-end spun-off ejecta were locked at that fixed cosmic origin from  $T_0$  onward. The dense end is at the cascade-end origin; the far end is at the cascade-end far edge of the spun-off eddy. The geometry was set by the cascade-end event itself; the post- $T_0$  gravitational evolution preserved the asymmetric pattern as a fossil. Picture B applies to cosmic filaments (cascade-end fossils,  $\sim 13.8$  Gyr old), and to currently-active astrophysical analog systems with similar fixed-origin geometry (AGN jets, comet antisolar tails) which serve as illustrative comparisons but operate on much shorter timescales than cascade-end fossils.

Both pictures yield  $1/\xi$  density slope in the near-source regime, but the source location and the  $L_{\max}$  scaling differ. The Picture A versus Picture B distinction is essential for cross-scale comparison.

Below we list the eight observational regimes spanning approximately fourteen orders of magnitude in linear physical scale in physical scale, labeled by which picture applies.

(1) Comet tails,  $\sim$ AU scale, Picture B. The nucleus is the fixed source. The dust and ion tails extend in the antisolar direction. The dust at the tail-tip is the oldest emission, having had longest time to drift outward; the dust just behind the nucleus is freshly emitted. The detailed physics (radiation pressure ratio  $\beta$ , ion drag, photo-ionization) is solar-environment-specific, so the comet case is a structural analogy rather than a quantitative test of the SCT cross-scale scaling. The comet picture motivated the title and the basic phenomenology.

(2) Open cluster dispersal tails, parsec scale, Picture A. Young open clusters disperse stars over time as they orbit through the Galactic disk. The Pleiades extended halo (Lodieu et al. 2019) extends along the cluster's orbital path. The cluster core is the moving dense source.

(3) Globular cluster tidal streams, 10 to 100 parsec scale, Picture A. Globular clusters in the Milky Way halo lose stars to tidal stripping. Palomar 5 (Odenkirchen et al. 2003) and NGC 5466 (Belokurov et al. 2006) are the textbook cases. The dense end is at the cluster's current position.

(4) Stellar tidal streams from disrupted satellites, kiloparsec to  $\sim 100$  kpc scale, Picture A. Sagittarius (Ibata et al. 1994; Majewski et al. 2003), GD-1 (Grillmair and Dionatos 2006), Orphan (Belokurov et al. 2007), and the NGC 2419 stream. The leading and trailing arms in

stream terminology are the forward and backward extensions from the satellite's current position. These are multi-orbit cases and require explicit multi-orbit corrections.

(5) Magellanic-Stream-class gas tails,  $\sim 100$  kpc scale, Picture B (mostly). The Magellanic Stream (Mathewson, Cleary, and Murray 1974; Putman et al. 2003) is gas trailing the SMC plus LMC system through the Milky Way halo. The collision-like interaction of the Magellanic Clouds with the Milky Way halo gas is the dominant origin of the stream's bulk material, and the stream extends outward in the direction set by the encounter geometry. Picture B applies in the dominant regime, with Picture A modifications for the secondary contributions from each cloud's individual motion.

(6) Intracluster light streams, 100 kpc to 1 Mpc scale, Picture B (per individual disrupted galaxy). The diffuse stellar component in galaxy clusters (Coma cluster: Adami et al. 2005; Virgo cluster: Mihos et al. 2017) is built from many individual galaxy-disruption events. Each disruption is a Picture B collision-event source, with the post-disruption stellar plume extending outward from the disruption location. The integrated intracluster light is the superposition of many such Picture B streams.

(7) Cosmic filaments, Mpc scale, Picture B. The SCT prediction in this paper. Collision-event origin at one end, propagating outward stream extending to the far end. The eight per-filament predictions plus CC-10 derive observational signatures.

(8) Quasar polarization alignments and VLBI jet alignments, Gpc scale, Picture B. AGN jets are the canonical Picture B objects. The supermassive black hole accretion disk is the fixed origin; the relativistic plasma jet propagates outward. Hutsemékers et al. (2014) Gpc-scale optical polarization coherence and Mandarakas et al. (2021) VLBI 3D jet alignments at 400 to 900 Mpc are interpreted in SCT as the largest-scale manifestations of parent-frame anisotropy in the orientation of these AGN-jet origin systems.

Eight observational regimes spanning approximately fourteen orders of magnitude in linear physical scale (AU to Gpc), with the quantitative cross-scale slope-universality claim CC-10 restricted to the four Picture B cascade-end-fossil regimes. Comet tails and currently-active Picture A objects (stellar streams, AGN jets) are included in the eight-scale catalog as structural analogies but are excluded from the quantitative slope-universality test. The  $1/\xi$  near-source density slope and the  $\lambda_0 \propto M_{\text{pocket}}^{2/3}$  origin-emission-amplitude scaling are predicted to hold across all Picture B regimes (CC-10), with the Picture A regimes following their own multi-orbit-deposition scaling. The cometary cosmography picture is therefore not a special-case explanation for filaments. It is a generic property of collision-event origins and post-collision outflows at every level of the SCT hierarchy. Filaments are simply the most tractable mid-scale Picture B regime where the steady-state plus single-pulse-outflow assumptions hold cleanly.

## 7.5 Falsification status

If the eight predictions of Section 5 plus the cross-scale prediction CC-10 are systematically falsified at high significance, most importantly, if CC-6 (UDG smooth gradient) shows a clean bimodal distribution, CC-7 (parallel-filament dense-end correlation) shows a flat  $\theta_{12}$  distribution, or CC-10 (cross-scale slope universality) shows incompatible slopes across the five scale classes after multi-traversal corrections, the cometary cosmography mechanism is falsified for SCT. This would not falsify SCT as a whole (the cascade-cosmology framework, P1 to P40, would still stand) but it would force a return to event-localized framings (head-on collisions, etc.) for filament physics, contradicting the parsimony principle and weakening SCT's ability to address the five empirical asymmetries from Section 1.2 in a unified way.

The strongest single test is CC-7. The data exists (Tempel 2014, Galárraga-Espinosa 2024). The analysis is computationally cheap. The prediction is sharp (non-flat  $\theta_{12}$  distribution at greater than or equal to  $3\sigma$ ). We recommend this as the highest-priority near-term test. The most revealing test of SCT's reach beyond filaments is CC-10, which can be performed with existing Gaia DR3, DESI, and Hyper Suprime-Cam datasets without new observations.

## 8. Conclusions

We have developed cometary cosmography, a cascade-end-spin-off-fossil picture of cosmic filaments within Successive Collision Theory. The picture rests on a single keystone: the multi-stage cascade of separate superluminal-then-subluminal collisions described by P22, P25, P33 to P40 produced the hot dense thermalized patch that  $\Lambda$ CDM calls T0; as the final cascade stages transitioned from superluminal to subluminal velocities, the inherited angular momentum manifested as eddies and pockets that spun off from the cascade flow at cascade-end, each becoming a coherent structural seed fixed in cosmic coordinates from T0 onward. From T0 to today is approximately 13.8 Gyr of standard gravitational evolution, during which the spun-off seeds have been gravitationally amplified into the cosmic structures we observe. Each cosmic filament is the gravitationally-evolved fossil of one such cascade-end spun-off eddy. The mechanism uses secondary modulations from angular-momentum inheritance (P31, P32), gravitational superposition (P50, P52, P53), and sibling-pocket geometry (P58, P60) only where the keystone alone is insufficient.

The standardized prediction inventory of this paper is: 8 primary per-filament predictions (CC-1 through CC-8), 1 bonus prediction (CC-9 kSZ dipole), and 1 cross-scale conjecture (CC-10 cross-scale slope universality). From the cascade-end-spin-off-fossil mechanism we have derived the eight primary per-filament predictions: (1) on-axis volume

density  $n(0, \xi) \propto \exp(-\xi/\xi_*)/\xi$  outward from the dense origin ( $1/\xi$  near source); (2) on-axis column density  $\Sigma(0, \xi) \propto \exp(-\xi/\xi_*)/\sqrt{\xi}$  outward from origin ( $1/\sqrt{\xi}$  near source); (3) density-independent residual metallicity gradient  $\sim 0.01$  to  $0.05$  dex per Mpc with origin most enriched; (4) density-correlated in-situ enrichment co-aligned with the residual gradient; (5) filament rotation amplitude an order of magnitude above  $\Lambda$ CDM tidal-torque theory, origin-to-far-end amplitude decline along each filament, non-50/50 handedness in stacked samples; (6) smooth UDG M/L gradient along filaments with DM-rich UDGs near origin and DM-deficient UDGs near far end; (7) sibling-stream parallel filaments with co-located dense-end origins clustered at the parent collision site; and (8) dense-end origin cluster mass systematically larger than sparse-end far-end mass in long filaments. A bonus prediction (9) of a kSZ dipole along filament axis (origin to far end) at amplitude  $\sim 10^{-6}$  to  $10^{-5}$  per Mpc adds a CMB-S4 test. Finally, a cross-scale universality prediction (10) ties the origin-emission-amplitude scaling to Paper 4205's  $J \propto M^{(5/3)}$  framework:  $\lambda_0 \propto M_{\text{pocket}}^{(2/3)} \propto j$  and the near-source  $1/\xi$  density slope is universal across Picture B objects spanning approximately fourteen orders of magnitude in linear physical scale (Section 7.4).

Six of the ten predictions (CC-1, CC-3, CC-5, CC-6, CC-8, CC-10) have qualitative support in existing literature. Three (CC-2, CC-4, CC-7) are largely untested but feasible with existing or near-term data. CC-9 awaits CMB-S4 in the 2027 to 2030 timeframe (forecast). Two of the predictions stand out for different reasons: CC-7 (sibling-stream parallel filaments with co-located dense-end origins) is the highest-priority near-term test because the prediction is sharp (non-flat  $\theta_{12}$  distribution at  $\geq 3\sigma$ ) and the existing Tempel/Galárraga-Espinosa filament catalogs already contain the necessary data. CC-6 (UDG kinematic gradient along filament axis) is the most observationally accessible of all the SCT predictions in this paper because the cross-match between the MATLAS UDG catalog and DESI/SDSS filament catalogs requires only existing archival data and a straightforward analysis. The two are compatible: CC-7 is the strongest near-term test in the sense of decisive falsification potential; CC-6 is the most accessible in the sense of immediate data availability. The most immediately revelatory test of the framework's reach is CC-10, cross-scale density-slope consistency, which can be performed with existing Gaia DR3 plus DESI plus HSC datasets and would test the SCT-wide claim that collision-origin outflow streams are a single phenomenon written at every level of the nested hierarchy.

The picture is consistent with, and reinforces, the broader SCT framework's cascade-cosmology story (Papers 4201, 4204, 4205, 4206) and is in compliance with the parsimony-principle keystone-premise discipline. It generalizes naturally beyond filaments to Picture B outflow streams at every scale from comet antisolar tails through Magellanic-Stream-class gas tails to Gpc-scale AGN-jet origin systems. If the predictions are systematically confirmed, SCT cometary cosmography will provide a unified explanation of five distinct

observational asymmetries that  $\Lambda$ CDM does not naturally accommodate, and a unified scaling framework that ties cascade-end-fossil phenomenology to the angular-momentum-inheritance framework already established at seven decades of scale. If they are systematically falsified, the parsimony-principle commitment forces a controlled retreat to event-localized framings, with explicit identification of the mechanisms failing.

We recommend that the SCT working program adopt CC-7 (sibling-stream parallel filaments with co-located dense-end origins) as the highest-priority near-term test, CC-10 (cross-scale slope universality across Picture B objects) as the highest-priority all-data test, and that observational collaborations on DESI Y3 filament catalogs incorporate the residual-metallicity-gradient analysis (CC-3) as a planned data product.

## Appendix A. Parsimony-Principle Compliance Audit

For each of the predictions above, we identify the keystone premise (the load-bearing axiom whose removal collapses the prediction) and the secondary modulations (additional premises whose removal weakens but does not destroy the prediction).

**Table A1. Parsimony-principle compliance per prediction.**

Prediction	Keystone	Secondary modulations	Drift fingerprints triggered?
CC-1 (n proportional to $\xi^{-\gamma}_n$ near source)	P22, P31, P33, P34, P36 to P40	None	No
CC-2 ( $\Sigma$ proportional to $\xi^{-\gamma}_\Sigma$ near source)	P22, P31, P33, P34, P36 to P40	cascade-end eddy 3D geometry (open task)	No
CC-3 (residual Z gradient from P25 fossil)	P25	P22, P33, P34, P36 to P40	No
CC-4 (in-situ Z gradient from K-S)	P34, P36 to P40, K-S law	None	No
CC-5 (rotation amplitude, handedness)	P31, P32	P22, P33, P34, P36 to P40	No
CC-6 (UDG M/L gradient)	P50, P52, P53	P22, P33, P34, P36 to P40	Yes (P45+ keystone, flagged)

Prediction	Keystone	Secondary modulations	Drift fingerprints triggered?
CC-7 (sibling parallel filaments)	P58, P60	P22, P33, P34, P36 to P40	Yes (P45+ keystone, flagged)
CC-8 (dense-end mass asymmetry)	P22, P33, P34, P36 to P40, accretion	None	No
CC-10 (cross-scale universal slope)	P34, P36 to P40, P69	P32 for amplitude, P58/P60 for cascade ratio	No

Two predictions trigger Drift Fingerprint number 2 (P45+ keystone): CC-6 (UDG kinematic gradient) and CC-7 (sibling parallel filaments). In each case, the P45+ premise is the load-bearing axiom: remove P50 to P53 and the UDG kinematic gradient cannot be derived; remove P58, P60 and sibling streams have no reason to share a co-located origin.

These flags are acknowledged, not avoidable. The predictions are genuinely about phenomena that require the secondary machinery. CC-6 is fundamentally about the dark-matter-substitute mechanism (P50 to P53), which is inherently a P45+ phenomenon. CC-7 is fundamentally about sibling-pocket geometry (P58, P60), also P45+. Per parsimony Rule 2 ("if P45+ is genuinely required, say so plainly and place it as the keystone"), we have flagged the keystones explicitly rather than artificially demoting them.

Six of the remaining seven predictions (CC-1, CC-2, CC-3, CC-4, CC-5, CC-8) rest entirely on P1 to P40 fundamentals as their keystones, in compliance with parsimony Rule 2. CC-10 invokes P69 (Unbounded nested hierarchy from EFE applied to virial mass ladder) in addition to P1 to P40 fundamentals, because the cross-scale-universality claim is intrinsically about the virial-hierarchy structure of the SCT cascade tree and cannot be derived from P1 to P40 alone. We acknowledge this explicitly: CC-10 has a P45+-class component (P69) in its keystone, but we classify it parsimoniously because P69 is itself a foundational axiom (Paper 4 axiom A2 in the SCT canonical numbering) rather than a higher-level derived module like the dark-matter-substitute mechanism (P50 to P53) or the sibling-pocket geometry (P58, P60). The classification of CC-10 is therefore: keystone is P34, P36 to P40, P69; secondary modulations from P32 (for amplitude scaling) and P58/P60 (for cascade ratio) are layered on as needed.

## References

1. Adami, C., Slezak, E., Durret, F., et al. 2005, A&A, 429, 39.
2. Aragón-Calvo, M. A., et al. 2010, ApJ, 723, 364.

3. Beasley, M. A., et al. 2016, ApJL, 819, L20.
4. Bekenstein, J. D. 2004, Phys. Rev. D, 70, 083509.
5. Belokurov, V. 2013, NewAR, 57, 100.
6. Belokurov, V., Evans, N. W., Irwin, M. J., et al. 2006, ApJ, 637, L29.
7. Belokurov, V., Evans, N. W., Irwin, M. J., et al. 2007, ApJ, 658, 337.
8. Bond, J. R., Kofman, L., and Pogosyan, D. 1996, Nature, 380, 603.
9. Bonjean, V., et al. 2020, A&A, 638, A75.
10. Castignani, G., et al. 2022, A&A, 657, A9.
11. Cautun, M., van de Weygaert, R., and Jones, B. J. T. 2014, MNRAS, 441, 2923.
12. Chen, Y.-C., et al. 2017, MNRAS, 466, 1880.
13. Choi, E., Bond, N. A., and Strauss, M. A. 2010, MNRAS, 406, 320.
14. Danieli, S., et al. 2019, ApJL, 874, L12.
15. Donnan, C. T., et al. 2022, MNRAS, 515, 4859.
16. Einasto, M., et al. 2011, A&A, 535, A36.
17. Einasto, M., et al. 2014, A&A, 562, A87.
18. Forbes, D. A., et al. 2018, MNRAS, 481, 5592.
19. Forbes, D. A., et al. 2020, MNRAS, 492, 4874.
20. Galárraga-Espinosa, D., et al. 2020, A&A, 641, A173.
21. Galárraga-Espinosa, D., et al. 2024, A&A, 684, A63.
22. Grillmair, C. J., and Dionatos, O. 2006, ApJ, 643, L17.
23. Hutsemékers, D., et al. 2014, A&A, 572, A18.
24. Ibata, R. A., Gilmore, G., and Irwin, M. J. 1994, Nature, 370, 194.
25. Janssens, S. R., et al. 2019, ApJL, 887, L92.
26. Karunakaran, A., et al. 2022, ApJ, 916, 66.
27. Koda, J., et al. 2015, ApJL, 807, L2.
28. Kraljic, K., et al. 2018, MNRAS, 474, 547.
29. Kraljic, K., et al. 2019, MNRAS, 491, 4294.
30. Kraljic, K., et al. 2020, MNRAS, 500, 4194.
31. Kuutma, T., et al. 2017, A&A, 600, L6.
32. Laigle, C., et al. 2018, MNRAS, 474, 5437.
33. Liivamägi, L. J., Tempel, E., and Saar, E. 2012, A&A, 539, A80.
34. Lim, S., et al. 2020, ApJ, 899, 69.

35. Lodieu, N., Pérez-Garrido, A., Smart, R. L., and Silvotti, R. 2019, A&A, 628, A66.
36. Lokken, M., et al. 2022, ApJ, 933, 134.
37. López, P., Cautun, M., Paz, D., et al. 2021, MNRAS, 502, 5528.
38. Madhavacheril, M. S., et al. 2023, ApJ, 944, 215.
39. Majewski, S. R., Skrutskie, M. F., Weinberg, M. D., and Ostheimer, J. C. 2003, ApJ, 599, 1082.
40. Mandarakas, N., et al. 2021, A&A, 654, A158.
41. Marleau, F. R., et al. 2021, A&A, 654, A105.
42. Martínez-Delgado, D., et al. 2016, AJ, 151, 96.
43. Mathewson, D. S., Cleary, M. N., and Murray, J. D. 1974, ApJ, 190, 291.
44. Mihos, J. C., Harding, P., Feldmeier, J. J., et al. 2017, ApJ, 834, 16.
45. Mihos, J. C., et al. 2024, ApJ, 967, 130.
46. Milgrom, M. 1983, ApJ, 270, 365.
47. NIPOK, J. M. 2026, From Chaos to Convergent Foundations: The Foundational Premises of Successive Collision Theory (Paper 4201). DOI: 10.13140/RG.2.2.19171.62243.
48. NIPOK, J. M. 2026, From Chaos To Common Ancestry: A Hierarchical Frame-Tree Lorentzian Approach for High-Precision Cosmology (Paper 4202). DOI: 10.13140/RG.2.2.21288.43521.
49. NIPOK, J. M. 2026, From Chaos To Concordance Spectra (Paper 4203). DOI: 10.13140/RG.2.2.20310.31042.
50. NIPOK, J. M. 2026, From Chaos To Collisothermal Cosmogenesis (Paper 4204). DOI: 10.13140/RG.2.2.16235.60968.
51. NIPOK, J. M. 2026, From Chaos To Corotating Hierarchies (Paper 4205). DOI: 10.13140/RG.2.2.28263.10400.
52. NIPOK, J. M. 2026, From Chaos to Cosmic Collisions (Paper 4206). DOI: 10.13140/RG.2.2.19379.69921.
53. NIPOK, J. M. 2026, From Chaos To Cosmic Expansion (Paper 4207). DOI: 10.13140/RG.2.2.24304.72969.
54. NIPOK, J. M. 2026, From Chaos To Constructive Relativity (Paper 4208). DOI: 10.13140/RG.2.2.23479.79528.
55. NIPOK, J. M. 2026, From Chaos To Confirming Falsifiability (Paper 4210). DOI: 10.13140/RG.2.2.19381.33765.
56. NIPOK, J. M. 2026, From Chaos to Coherent Gravity: The SCT Formalism That Solves The Dark Matter Problem (Paper 4213). DOI: 10.13140/RG.2.2.22608.98560.

57. Odenkirchen, M., Grebel, E. K., Dehnen, W., et al. 2003, *AJ*, 126, 2385.
58. Pelgrims, V., and Hutsemékers, D. 2016, *A&A*, 590, A53.
59. Pichon, C., Pogosyan, D., Kimm, T., et al. 2011, *MNRAS*, 418, 2493.
60. Putman, M. E., Staveley-Smith, L., Freeman, K. C., et al. 2003, *ApJ*, 586, 170.
61. Tanimura, H., et al. 2019, *MNRAS*, 483, 223.
62. Tempel, E., et al. 2014, *A&A*, 566, A1.
63. Tudorache, M. N., et al. 2025, *MNRAS*, in press.
64. van Dokkum, P., et al. 2015a, *ApJL*, 798, L45.
65. van Dokkum, P., et al. 2015b, *ApJ*, 804, L26.
66. van Dokkum, P., et al. 2016, *ApJL*, 828, L6.
67. van Dokkum, P., et al. 2017, *ApJ*, 844, 157.
68. van Dokkum, P., et al. 2018, *Nature*, 555, 629.
69. van Dokkum, P., et al. 2019, *ApJL*, 874, L5.
70. Verlinde, E. P. 2017, *SciPost Phys.*, 2, 016.
71. Wang, P., et al. 2021, *ApJ*, 911, 53.
72. Welker, C., et al. 2020, *MNRAS*, 491, 2864.
73. Winkel, N., et al. 2021, *A&A*, 654, A30.