

From Chaos to Cosmic Collisions

Changing One Λ CDM Assumption Brings Dark Matter Into The Light

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Abstract

Background. The Λ CDM concordance model successfully describes the large-scale evolution of the universe after recombination, yet a growing number of observational tensions at greater than 2σ significance resist resolution within its framework.

Aims. This paper addresses five such tensions: (i) co-rotating planes of satellite galaxies observed around the Milky Way, Andromeda, and Centaurus A; (ii) galaxy cluster orientation alignments persisting over 200–300 comoving Mpc; (iii) the thermal Sunyaev–Zel'dovich power spectrum excess and the associated S_8 tension; (iv) the order-of-magnitude excess of small-scale gravitational lensing by cluster substructures; and (v) the unexplained entropy floor in the intracluster medium.

Methods. We propose Successive Collision Theory (SCT), which replaces the singular hot dense origin of Λ CDM with a succession of superluminal collisions between nested comoving frames of reference. From this single change in foundational assumption, three physically motivated mechanisms emerge—angular momentum conservation from collision geometry, gravitational superposition of comoving bodies, and collision thermodynamics—each formulated within linearized General Relativity and Special Relativity. The superposition mechanism is parameterized by a coherence amplification factor A whose value is anchored to independently observed cluster properties (member galaxy count N , velocity dispersion σ_v , and spatial scale R) and is not a free parameter fitted to the tensions. The thermodynamic mechanism introduces a collision Lorentz factor γ_{rel} constrained by the observed entropy floor magnitude.

Results. We demonstrate that these three mechanisms collectively resolve all five tensions, and reproduce the effective excess gravity usually attributed to dark matter, without introducing new particles or new fields. No modification to the field equations beyond a physically motivated reinterpretation of the stress-energy source term is required, and all standard GR results are recovered in appropriate limits.

Conclusions. The results suggest that the pre-recombination foundational assumptions of the standard cosmological model warrant systematic re-examination.

Fourteen falsifiable predictions distinguishing SCT from Λ CDM are identified, spanning facilities including Euclid, Rubin/LSST, CMB-S4, and Athena.

Keywords: *cosmology; Λ CDM tensions; dark matter analog; gravitational superposition; angular momentum; intracluster medium; Sunyaev–Zel'dovich effect; gravitational lensing; Successive Collision Theory*

1. Introduction

1.1 The State of Λ CDM

The Λ Cold Dark Matter (Λ CDM) model stands as one of the most successful theoretical frameworks in the history of physics. Its six free parameters reproduce the angular power spectrum of the cosmic microwave background (CMB) with extraordinary precision, correctly predict the abundances of light elements from Big Bang nucleosynthesis, and account for the accelerating expansion of the universe through a cosmological constant Λ . The Planck 2020 results constrain the Hubble constant to $H_0 = (67.4 \pm 0.5) \text{ km s}^{-1} \text{ Mpc}^{-1}$, the matter density parameter to $\Omega_m = 0.315 \pm 0.007$, and the matter fluctuation amplitude to $\sigma_8 = 0.811 \pm 0.006$ [1].

Despite these successes, a growing catalog of observational tensions has accumulated over the past two decades—discrepancies between Λ CDM predictions and observations that exceed the 2σ threshold individually and, taken collectively, suggest the possibility of systematic rather than statistical failure. These tensions span scales from dwarf galaxies to the cosmic web, and they resist resolution through the standard mechanisms of baryonic feedback, massive neutrinos, or observational systematics.

This paper does not attempt to catalogue all known tensions. Instead, it focuses on five specific observational problems chosen because they satisfy two criteria simultaneously: (a) they represent issues for which Λ CDM has the greatest difficulty providing satisfactory explanations, and (b) they can be resolved through the fewest number of new assumptions, using mathematics directly derivable from standard General Relativity (GR) and Special Relativity (SR).

1.2 Five Observational Tensions Addressed in This Paper

1. Satellite Plane Alignments. The classical satellite galaxies of the Milky Way are distributed in a thin, co-rotating structure known as the Vast Polar Structure (VPOS; Pawlowski, Pflamm-Altenburg & Kroupa 2012 [2]). A similar planar arrangement with

coherent kinematics exists around Andromeda (M31; Ibata et al. 2013 [3]). Most strikingly, Müller et al. (2018 [4]) demonstrated that 14 of 16 kinematically measured satellites of Centaurus A follow a coherent velocity pattern within a narrow plane, a configuration that occurs in fewer than 0.5% of Λ CDM simulations. Müller et al. (2021 [5]) confirmed this result with an expanded sample. Kroupa et al. (2024 [6]) argued that the joint probability of all three co-rotating satellite plane systems arising by chance under Λ CDM is below 10^{-6} , based on analysis of the IllustrisTNG and EAGLE simulation suites. Sawala et al. (2022 [7]) proposed that satellite planes can arise transiently in hierarchical merger trees; however, Samuel et al. (2021 [8]) and Pawlowski (2021 [9]) demonstrated that this argument applies primarily to the Milky Way and does not extend to M31 or Centaurus A, where kinematic co-rotation rules out transient projection effects. As Boylan-Kolchin (2021 [10]) noted, the satellite plane problem challenges not merely Λ CDM but all current models of galaxy formation.

2. Cluster Orientation Alignments. Galaxy clusters exhibit correlated orientations over separations of $100\text{--}300 h^{-1}$ Mpc. West et al. (2025 [11]) report that cluster major axes remain correlated across separations of $200\text{--}300$ comoving Mpc. Hopkins, Bahcall & Bode (2005 [12]) showed that cluster ellipticities increase from a mean of ~ 0.3 at $z = 0$ to ~ 0.5 at $z = 3$. More recent alignment analyses (Codis et al. 2018 [13]; Piras et al. 2018 [14]; Chisari et al. 2016 [15]) confirm that the observed amplitude and coherence scale—particularly at high redshift—exceed what Λ CDM simulations reliably reproduce. The persistence of strong alignments at separations approaching $200\text{--}300$ Mpc challenges the correlation lengths of $\sim 30\text{--}80$ Mpc expected from hierarchical structure formation alone.

3. The Thermal Sunyaev–Zel'dovich Power Spectrum and the S_8 Tension. The amplitude of the thermal Sunyaev–Zel'dovich (tSZ) power spectrum scales approximately as σ_8^8 , making it one of the most sensitive probes of the matter fluctuation amplitude (Komatsu & Seljak 2002 [16]). Planck CMB primary anisotropies predict $\sigma_8 = 0.811 \pm 0.006$ [1], while cluster counts, tSZ measurements (Bolliet et al. 2023 [17]), and weak gravitational lensing surveys such as KiDS-1000 and DES Year 3 consistently prefer lower values in the range $\sigma_8 \approx 0.76\text{--}0.79$. This $2\text{--}3\sigma$ discrepancy, typically expressed through the parameter $S_8 = \sigma_8 \sqrt{(\Omega_m/0.3)}$, constitutes the S_8 tension. The KiDS-Legacy analysis (Wright et al. 2025 [18]) has reduced the tension in that dataset, but the discrepancy persists in independent tSZ and cluster-count analyses, and the underlying physical mechanism remains unidentified. Attempts to resolve the tension within Λ CDM require a hydrostatic mass bias $b \approx 0.30\text{--}0.40$; independent weak-lensing calibrations constrain $b \lesssim 0.20$ (Meneghetti et al. 2010 [19]; Sereno et al. 2015 [20]), making the required value physically implausible. Massive neutrinos with $\sum m_\nu \approx 0.3\text{--}0.6$ eV can suppress σ_8 , but this conflicts with other cosmological constraints and requires neutrino masses near the upper bound permitted by oscillation experiments.

4. The Cluster Substructure Lensing Excess. Meneghetti et al. (2020 [21]), published in Science, analyzed 11 galaxy clusters and found that observed substructures produce galaxy-galaxy strong lensing (GGSL) events at a rate exceeding Λ CDM simulation predictions by more than an order of magnitude. This discrepancy persists even when state-of-the-art baryonic physics is included in the simulations. Ragagnin et al. (2022 [22]) confirmed the excess in higher-resolution resimulations, though the magnitude depends on resolution and stripping model assumptions; the most conservative estimates still show a factor of $\sim 2\text{--}4$ excess that Λ CDM cannot explain. The authors concluded that there is an unidentified problem with either prevailing simulation methods or standard cosmology [21].

5. Entropy Floors in the Intracluster Medium. The X-ray luminosity–temperature relation of galaxy clusters follows $L_X \propto T^{\{2.6\text{--}3.0\}}$ rather than the self-similar prediction $L_X \propto T^2$ (Ponman, Cannon & Navarro 1999 [23]; Lloyd-Davies, Ponman & Cannon 2000 [24]). This steepening implies an excess entropy floor at $K_0 \gtrsim 100\text{--}300 \text{ keV cm}^2$ in cluster cores (Voit et al. 2003 [25]), confirmed across 239 clusters from Chandra archival data. The required non-gravitational energy injection of $\sim 1\text{--}3 \text{ keV}$ per particle has been attributed to AGN feedback or supernova preheating. However, supernova feedback alone is insufficient to produce the observed universal floor (McCarthy et al. 2008 [26]), and AGN feedback models, while capable of reproducing entropy profiles in individual clusters when combined with supernova feedback (LeBrun et al. 2014 [27]; Barnes et al. 2017 [28]), require fine-tuning of duty cycles and jet opening angles and do not naturally explain the universality of the floor across the full cluster mass range.

1.3 Successive Collision Theory: A Single Changed Assumption and Its Relationship to Λ CDM

All five tensions described above resist resolution within Λ CDM because they are, at root, consequences of the model's foundational assumption: that the universe originated from a single hot dense state. Successive Collision Theory (SCT) replaces this singular assumption with one alternative premise: the visible patch of spacetime we observe was created not by a single origin event but by a succession of superluminal collisions between immense nested comoving structures whose scales far exceed our own.

Before developing the mathematics, we define the relationship between SCT and Λ CDM explicitly. SCT is not a modification of the post-recombination evolution of Λ CDM; it is a replacement of the pre-recombination initial conditions. After thermalization of the collision plasma and termination of the cascade at $t < 1 \text{ s}$ (constrained independently by BBN abundances, CMB spectral purity, and acoustic peak positions), the universe evolves under standard physics from initial conditions that differ from Λ CDM in two specific ways: (1) the angular momentum of the collision is encoded in the debris field and inherited by all

structures that form from it; and (2) the comoving frame structure of the debris field produces a coherent gravitational superposition effect that is absent from Λ CDM's smooth fluid approximation. In all other respects—nucleosynthesis, recombination, acoustic oscillations of the photon-baryon fluid, and large-scale expansion—SCT reproduces Λ CDM predictions, because the thermodynamic state of the plasma at decoupling is identical by construction (see Section 2.3). Λ CDM therefore remains an excellent effective description of the universe on scales and in regimes where the two SCT-specific effects are negligible.

The key elements of SCT relevant to this paper are as follows. Nested comoving frames arise naturally when the field equations of GR are applied to an infinite, eternal spacetime: smaller structures follow the dominant local mass, clustering into larger structures that themselves follow the next level up, producing a scale-invariant hierarchy. Superluminal relative motion between frames is not a violation of Special Relativity; SR's speed limit constrains objects accelerated within an inertial frame by a locally acting force. The relative velocity between two frames that were never causally connected—set by independent formation processes at causally disconnected locations—is not subject to this constraint. This is the identical reasoning by which standard cosmology accepts the superluminal recession of galaxies beyond the Hubble radius. When two such frames collide, collision-generated structure emerges: different collision geometries (grazing vs. head-on, varying impact parameters and mass ratios) yield different structural outcomes, from rotating galaxies to strand-like filaments.

1.4 Paper Structure

Section 2 develops the three mathematical frameworks in a self-contained manner. Sections 3 through 7 each apply the relevant framework to one of the five tensions. Section 8 discusses the unified nature of the resolution, identifies testable predictions, acknowledges limitations, and outlines directions for future work. Throughout, we adopt the convention $c = 1$ unless explicitly stated, use the metric signature $(-, +, +, +)$, and employ natural units where appropriate. Observational values are quoted from the Planck 2020 data release [1] unless otherwise noted.

2. Mathematical Framework

This section develops the three mathematical tools applied throughout the remainder of the paper. Each is derived from standard GR and SR using linearized or first-order approximations. No new postulates beyond the SCT collision premise are introduced.

2.1 Angular Momentum Conservation in Superluminal Collision Geometry

2.1.1 Setup and Conservation Laws

We work in the weak-field regime of GR, where the metric takes the form $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$ with $|h_{\mu\nu}| \ll 1$, and $\eta_{\mu\nu} = \text{diag}(-1, +1, +1, +1)$. The stress-energy tensor $T^{\mu\nu}$ satisfies the covariant conservation law $\nabla_{\mu} T^{\mu\nu} = 0$. We note that in curved spacetime this covariant conservation law does not, in general, imply conservation of the total angular momentum tensor in the flat-space integral form, because a global timelike Killing vector is absent. However, in the weak-field linearized regime and on the spatial scales of the collision debris field, where $h_{\mu\nu} \ll 1$, the spacetime is approximately flat and the conservation law reduces to the flat-space form $\partial_{\mu} T^{\mu\nu} = 0$. This flat-space conservation guarantees conservation of total 4-momentum and total angular momentum for the isolated debris system to leading order in $h_{\mu\nu}$ [29].

Define two nested comoving frames, Σ_A and Σ_B , representing two immense spacetime pockets. Each frame carries a collective stress-energy tensor $T_A^{\mu\nu}$ and $T_B^{\mu\nu}$ and moves with 4-velocity u_A^{μ} and u_B^{μ} respectively, as measured in their mutual parent frame Σ_P . The relative 3-velocity in the parent frame is $v_{\text{rel}} = v_A - v_B$. When $|v_{\text{rel}}| > c$ in the parent frame, a superluminal collision occurs. No individual particle within either frame exceeds c relative to its own local metric; the superluminal relative motion is a property of the large-scale frames whose formation momenta were set by independent prior processes in causally disconnected regions, in direct analogy to the accepted superluminal recession of galaxies beyond the Hubble radius [30].

2.1.2 Angular Momentum of the Collision Debris

The total angular momentum tensor of a matter distribution about a point x_0^{μ} is:

$$J^{\mu\nu} = \int [(x^{\mu} - x_0^{\mu}) T^{\nu\lambda} - (x^{\nu} - x_0^{\nu}) T^{\mu\lambda}] d^3x \quad (1)$$

From $\partial_{\mu} T^{\mu\nu} = 0$ it follows that $dJ^{\mu\nu}/dt = 0$ for an isolated system, so angular momentum is conserved in the debris. The collision is evaluated in the parent frame Σ_P . The orbital angular momentum per unit reduced mass is:

$$l = b \times v_{\text{rel}} \quad (2)$$

where b is the impact parameter vector (perpendicular distance between centers of mass in the plane orthogonal to v_{rel}). The total orbital angular momentum deposited into the debris is:

$$J_{\text{debris}} = \mu_{\text{eff}} (b \times v_{\text{rel}}) \quad (3)$$

where $\mu_{\text{eff}} = M_A M_B / (M_A + M_B)$ is the reduced mass. The quantity v_{rel} in Equation (3) is the relative velocity as measured in the parent frame Σ_P . It enters the angular momentum calculation as a frame-defined kinematic quantity and is not subject to the local SR speed limit, which applies to accelerated objects within a single inertial frame. The momentum deposited into the debris field is well-defined in Σ_P and is related to locally measured quantities in the debris frame through the standard Lorentz transformation. The direction of J_{debris} is:

$$\hat{J}_{\text{debris}} = \hat{b} \times \hat{v}_{\text{rel}} \quad (4)$$

which defines the collision angular momentum axis. This axis is a global property of the entire debris field, inherited by every fragment regardless of subsequent separation.

2.1.3 Two Limiting Cases

Case (a) — Grazing collision ($b \gg 0$): The collision deposits substantial angular momentum into the debris. The debris inherits a preferred plane of rotation perpendicular to \hat{J}_{debris} . The fraction of total kinetic energy converted to rotational kinetic energy scales as $E_{\text{rot}}/E_{\text{total}} \sim b^2/(b^2 + R_{\text{eff}}^2)$, where R_{eff} is the effective overlap radius. For $b \gg R_{\text{eff}}$, most energy goes into retained angular momentum, producing flat, rotating structures.

Case (b) — Head-on collision ($b \approx 0$): $J_{\text{debris}} \rightarrow 0$ by Equation (3). Nearly all kinetic energy converts to thermal energy, producing elongated strand-like structures along the collision axis \hat{z} , with characteristic dimensions $L_{\text{strand}} \propto v_{\text{rel}} \tau_{\text{therm}}$ and $W_{\text{strand}} \propto \min(R_A, R_B)$, where τ_{therm} is the thermalization timescale.

2.1.4 Sibling Debris Fields

A critical consequence is that all debris produced in a single collision event shares the same angular momentum axis \hat{J}_{debris} . When a superluminal collision produces multiple structures simultaneously, they are siblings that inherit the same collision angular momentum vector. Individual fragments may have slightly different magnitudes of J due to local density variations, but their angular momentum directions are correlated:

$$\langle \hat{J}_i \cdot \hat{J}_j \rangle_{\text{siblings}} \gg \langle \hat{J}_i \cdot \hat{J}_j \rangle_{\text{random}} \quad (5)$$

This correlation is established at formation and decays only through subsequent dynamical relaxation. It is the mathematical basis for the prediction that sibling structures—those formed from the same collision sequence—share correlated orientations across potentially hundreds of Mpc. For a succession of n collisions each depositing angular momentum J_k , the net angular momentum of n th-generation debris is $J_{\text{net}} = \Sigma J_k$; if successive collisions have comparable energies, the direction is dominated by the collision with the largest impact parameter.

2.2 Gravitational Superposition in Nested Comoving Frames

2.2.1 Linearized Einstein Field Equations

In the Lorenz gauge $\partial_\mu \bar{h}^{\mu\nu} = 0$, where $\bar{h}^{\mu\nu} = h^{\mu\nu} - (1/2)\eta^{\mu\nu} h$ is the trace-reversed perturbation, the linearized Einstein field equations are:

$$\square \bar{h}^{\mu\nu} = -16\pi G T^{\mu\nu} \quad (6)$$

This is a linear equation and its solutions obey the superposition principle: if $\bar{h}_1^{\mu\nu}$ solves Equation (6) for source $T_1^{\mu\nu}$, and $\bar{h}_2^{\mu\nu}$ for source $T_2^{\mu\nu}$, then $\bar{h}_1^{\mu\nu} + \bar{h}_2^{\mu\nu}$ solves it for $T_1^{\mu\nu} + T_2^{\mu\nu}$ [31]. The retarded solution is:

$$\bar{h}^{\mu\nu}(t, \mathbf{x}) = 4G \int T^{\mu\nu}(t_{\text{ret}}, \mathbf{x}') / |\mathbf{x} - \mathbf{x}'| d^3x' \quad (7)$$

2.2.2 Physical Basis of the Comoving Enhancement

For N gravitating bodies sharing a comoving frame, with positions $x_i(t)$ and peculiar velocities v_i relative to the bulk motion, the total metric perturbation is $\bar{h}_{\text{total}}^{\mu\nu} = \sum \bar{h}_i^{\mu\nu}$ by the superposition principle.

The key physical insight is as follows. The retarded Green's function of Equation (6) means that the gravitational perturbation from each source reaches a distant observer at a retarded time $t_{\text{ret}} = t - |\mathbf{x} - \mathbf{x}'|/c$. For N bodies moving randomly with large peculiar velocities, their contributions arrive with effectively random phase offsets, giving an incoherent sum. For N bodies sharing a bulk comoving velocity—so that their mutual separations change slowly compared to the propagation time across the system—their contributions arrive with correlated phase offsets, giving constructive interference and a total perturbation exceeding the incoherent sum.

We formalize this through the coherence integral. For a source distribution with spatial correlation function $\xi(r) = \langle \delta\rho(\mathbf{x})\delta\rho(\mathbf{x}+\mathbf{r}) \rangle$, the power spectrum of the total metric perturbation at wavenumber k is:

$$P_h(k) = P_h^{\text{single}}(k) \times [1 + (N-1) \xi(k) / \xi(0)] \quad (8)$$

where $\xi(k)$ is the Fourier transform of the correlation function. For bodies sharing a comoving frame, $\xi(k)$ is peaked at $k = 0$ (large-scale bulk coherence) and suppressed at $k \gg 1/R$ (sub-frame scales). This yields an effective amplification:

$$A(N, \sigma_v, R) = 1 + (N-1) C(\sigma_v, R) \quad (9)$$

where the coherence function is:

$$C(\sigma_v, R) = \exp(-\sigma_v^2 / v_{\text{cross}}^2) \quad (10)$$

and $v_{\text{cross}} = R/t_{\text{obs}}$ is the crossing velocity across the system on the observation timescale. This form follows from the correlation function of a velocity distribution with dispersion σ_v : the coherence is maximal ($\xi(k)/\xi(0) \rightarrow 1$) when the phase spread across the system due to peculiar velocities, $\sigma_v t_{\text{obs}} / R$, is small, and vanishes when $\sigma_v \gg v_{\text{cross}}$.

Limits: When $\sigma_v \ll v_{\text{cross}}$ (highly coherent comoving frame), $C \rightarrow 1$ and $A \rightarrow N$. When $\sigma_v \gg v_{\text{cross}}$ (randomized motions), $C \rightarrow 0$ and $A \rightarrow 1$, recovering the standard incoherent sum.

2.2.3 Modified Effective Stress-Energy and Interpretation

The enhancement factor A captures the fact that an external observer, measuring the total gravitational field of a coherently moving source cluster through weak lensing or dynamical tracers, infers an effective gravitational mass:

$$M_{\text{eff}} = A(N, \sigma_v, R) \cdot M_{\text{baryonic}} \quad (11)$$

We emphasize the physical interpretation: this is not a modification to the Einstein field equations in the sense of altering their structure. Local physics remains standard GR throughout. The enhancement arises from the correlation structure of the source distribution as seen by a distant observer, an effect fully present within linearized GR but neglected when the source is approximated as a smooth pressureless fluid. Equation (11) can be derived from first principles by applying the retarded solution (7) to a correlated N -body source and computing the lensing convergence; the result differs from the smooth-fluid case by precisely the factor A . Writing this compactly in the EFE notation:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G/c^4) T_{\mu\nu}^{\text{eff}} \quad (12)$$

where $T_{\mu\nu}^{\text{eff}} = A(N, \sigma_v, R) T_{\mu\nu}^{\text{matter}}$ is the effective stress-energy tensor as inferred from observations of the total gravitational field. Since A is derived from the correlation structure of a set of bodies each individually obeying standard GR, covariant energy-momentum conservation $\nabla^\mu T_{\mu\nu}^{\text{eff}} = 0$ is preserved: the source itself conserves energy-momentum, and the enhancement factor merely reflects how the correlated sources are perceived by a distant observer through the superposition of their individual fields. In the limit $N = 1$ or $\sigma_v \rightarrow \infty$, $A = 1$ and standard GR is exactly recovered.

2.3 Collision Thermodynamics

2.3.1 Energy Deposition and Thermalization Regime

When two comoving frame structures collide with relative velocity v_{rel} in the parent frame, the kinetic energy available for thermalization per unit reduced mass is $\epsilon_{\text{kin}} = (\gamma_{\text{rel}}$

– $1)c^2$, where γ_{rel} is the effective Lorentz factor parameterizing the collision energy in the parent frame. For mildly superluminal collisions at $v_{\text{rel}} = O(c)$, the relevant temperatures reached in the overlap volume span a wide range depending on the pocket density and v_{rel} . We parameterize the collision energy as:

$$\varepsilon_{\text{kin}} = \alpha c^2 \quad (13)$$

where $\alpha \gtrsim 0$ is a dimensionless parameter encoding the collision energy per unit rest mass. The physically motivated range considered here is $\alpha \in [0.5, 10]$, corresponding to mildly superluminal collisions. For the entropy floor calculation (Section 7), the relevant regime is sub-QCD, where standard fluid thermodynamics applies. At $\alpha \sim 1$, the post-collision temperature reaches:

$$k_B T_{\text{eq}} = (2/3) \tilde{\mu} m_p \varepsilon_{\text{kin}} = (2/3) \tilde{\mu} \alpha m_p c^2 \quad (14)$$

with $\tilde{\mu} \approx 0.59$ for fully ionized primordial gas. For $\alpha = 1$ this gives $k_B T_{\text{eq}} \approx 369$ MeV, which is above the QCD crossover temperature $T_{\text{QCD}} \approx 155$ MeV. In this regime the thermodynamic equation of state transitions from hadronic to partonic; the formula in Equation (14) strictly applies only for $k_B T_{\text{eq}} \ll m_p c^2$, i.e., $\alpha \ll 1$. For the entropy floor argument, we are interested in the residual entropy after the plasma has cooled well below the QCD scale, at which point the collision energy history enters only through the conserved entropy parameter K . We therefore use Equation (14) as an order-of-magnitude characterization and carry the uncertainty in α as the principal theoretical uncertainty in the entropy floor prediction.

2.3.2 Entropy Generation and the Relic Floor

The ICM entropy is defined as $K \equiv k_B T / n_e^{2/3}$ [keV cm²]. For an adiabatic process, K is conserved: $T \propto n_e^{2/3}$, so $K = k_B T / n_e^{2/3} = \text{const}$ along isentropic trajectories. The entropy per baryon generated in the collision thermalizes into the plasma at temperature T_{post} and density n_{post} . As the plasma cools and expands adiabatically from T_{post} to T_{vir} (the eventual virial temperature of the cluster), K is preserved:

$$K_{\text{relic}} = k_B T_{\text{post}} / n_{\text{post}}^{2/3} = k_B T_{\text{vir}} / n_{\text{vir}}^{2/3} \quad (15)$$

where the second equality follows from adiabaticity. The relic entropy floor is set at the moment of thermalization and is thereafter a lower bound on the entropy of any gas that was part of the collision debris—it cannot decrease below K_{relic} without violating the second law of thermodynamics. The adiabatic relation $T_{\text{vir}} / T_{\text{post}} = (n_{\text{vir}} / n_{\text{post}})^{2/3}$ allows K_{relic} to be expressed in terms of present-day ICM quantities:

$$K_{\text{relic}} = k_B T_{\text{vir}} (n_{\text{vir}} / n_{\text{post}})^{2/3} \quad (16)$$

The density ratio $n_{\text{vir}} / n_{\text{post}}$ is set by the expansion factor from thermalization to cluster formation, which is $\sim (1 + z_{\text{therm}})^3 / (1 + z_{\text{form}})^3$. For $z_{\text{therm}} \gg z_{\text{form}}$, $n_{\text{vir}} / n_{\text{post}} \ll 1$, and K_{relic} is a small residual entropy. For characteristic ICM values ($k_B T_{\text{vir}} \sim 3 \text{ keV}$, $n_e \sim 10^{-3} \text{ cm}^{-3}$), Equation (16) gives $K_{\text{relic}} \sim \text{few} \times 10^2 \text{ keV cm}^2$, matching the observed floor $K_0 \gtrsim 100\text{--}300 \text{ keV cm}^2$ [23,24]. The full derivation connecting α to K_0 through the adiabatic expansion history is given in Section 7.2.

2.4 Summary of Mathematical Tools

The three mechanisms developed in this section are summarized in Table 1.

| Mechanism | Key Equation | Parameters | Applied In |
|-------------------------------|---|---------------------------------------|---------------|
| Angular Momentum Conservation | $J_{\text{debris}} = \mu_{\text{eff}} (b \times v_{\text{rel}})$ [Eq. 3] | $b, v_{\text{rel}}, \mu_{\text{eff}}$ | Sections 3, 4 |
| Gravitational Superposition | $A = 1 + (N-1) \exp(-\sigma_v^2/v_{\text{cross}}^2)$ [Eq. 9–10] | N, σ_v, R | Sections 5, 6 |
| Collision Thermodynamics | $K_{\text{relic}} = k_B T_{\text{vir}} (n_{\text{vir}}/n_{\text{post}})^{2/3}$ [Eq. 16] | $\alpha, T_{\text{vir}}, n_e$ | Section 7 |

Table 1. Summary of the three SCT mechanisms developed in Section 2.

3. Satellite Plane Alignments as Collision Debris

3.1 The Observational Problem

The eleven classical dwarf satellite galaxies of the Milky Way are distributed in a flattened, co-rotating structure (the VPOS) with root-mean-square thickness of $\sim 20\text{--}30 \text{ kpc}$ spanning $\sim 250 \text{ kpc}$ [2]. Λ CDM N-body simulations predict that fewer than 0.1% of Milky Way-mass hosts should have satellite systems this planar and co-rotating [32]. Around M31, Ibata et al. (2013 [3]) discovered that roughly half of M31's satellites lie in a thin plane of $\sim 12.6 \text{ kpc}$ root-mean-square height spanning $\sim 400 \text{ kpc}$, with 13 of 15 members rotating coherently about M31's center; the probability of this arrangement in Λ CDM is estimated at $\sim 0.13\%$. The most decisive case is Centaurus A (NGC 5128): Müller et al. (2018 [4], 2021 [5]) reported that 14 of 16 satellites with measured line-of-sight velocities follow coherent rotation in a narrow plane, with the probability of this configuration in Λ CDM below 0.5%. Kroupa et al. (2024 [6]) argued that the joint probability across all three systems falls below 10^{-6} .

Sawala et al. (2022 [7]) argued that satellite planes can arise transiently in the Λ CDM merger tree and that the Milky Way system is consistent with this picture. Samuel et al. (2021 [8]) provided supporting analysis. However, as Pawlowski (2021 [9]) demonstrated in detail, the Sawala et al. argument relies on a broad definition of “plane” that includes non-co-rotating configurations; when kinematic co-rotation is required as a criterion—which is directly observed for M31 and Centaurus A—the Λ CDM probability is not rescued by transient alignment. Boylan-Kolchin (2021 [10]) concluded that the problem remains open across all current galaxy formation models.

The essential requirement for a satisfactory resolution is threefold: it must explain (1) why the satellite systems are spatially thin, (2) why they are kinematically co-rotating, and (3) why three independent hosts separated by megaparsecs all exhibit the same phenomenon.

3.2 SCT Resolution

In SCT, satellite planes are a direct consequence of the angular momentum framework of Section 2.1. When two nested comoving frames undergo a grazing superluminal collision with impact parameter b and effective relative velocity v_{rel} , the total angular momentum deposited is $J_{\text{debris}} = \mu_{\text{eff}} (b \times v_{\text{rel}})$, defining a preferred collision plane. The host galaxy and its satellite proto-dwarfs all form from fragments of the same debris field. The host accretes the most massive fragment at the center; the satellites occupy lower-mass fragments in the surrounding debris. Because all fragments share the same \hat{J}_{debris} , the satellite system is automatically arranged in a plane perpendicular to \hat{J}_{debris} and all satellites orbit in the same direction—the direction of the original collision tangent v_{rel} . This simultaneously explains spatial flattening and kinematic co-rotation from a single geometric cause.

The rms thickness of the satellite plane is set by the ratio of thermal velocity to systematic orbital speed:

$$\sigma_{\theta} \approx v_{\text{th}} / v_{\text{orb}} = \sqrt{(k_{\text{B}} T_{\text{frag}} / m_{\text{p}})} / v_{\text{orb}} \quad (17)$$

For typical fragmentation conditions ($T_{\text{frag}} \sim 10^4\text{--}10^5$ K, $v_{\text{orb}} \sim 100\text{--}200$ km/s), $\sigma_{\theta} \sim 0.05\text{--}0.3$ rad, giving at projected distance $r_{\perp} \sim 100\text{--}250$ kpc a plane thickness $h_{\text{plane}} = r_{\perp} \sigma_{\theta} \sim 5\text{--}75$ kpc. This range brackets the observed thicknesses of the Milky Way VPOS ($\sim 20\text{--}30$ kpc), the M31 plane (~ 13 kpc), and the Centaurus A plane (~ 150 kpc at three times larger physical scale). The range of T_{frag} is set by standard plasma cooling physics during fragmentation from post-BBN temperatures; varying T_{frag} within one order of magnitude changes h_{plane} by a factor of three, so the prediction is robust.

The three-host coincidence is explained by the sibling structure of SCT: the Milky Way, M31, and Centaurus A are siblings formed from the same collision debris field (or closely related sequence). All portions of the debris field share the same global angular momentum orientation \hat{J}_{debris} , so each host's satellite subsystem inherits the same preferred plane. Müller et al. (2021 [5]) noted that the normal to the Centaurus A satellite plane is aligned with the local filament orientation—consistent with the collision axis having also produced the broader large-scale structure, as predicted by the cross-scale consistency of SCT collision geometry.

3.3 Testable Predictions

Prediction 3.1. Satellite plane thickness scales with host mass as $h_{\text{plane}} \propto M_{\text{host}}^{-1/3}$, testable with SAGA and ELVES survey data.

Prediction 3.2. Satellite plane normals of spatially neighboring galaxies (separation < 5 Mpc) are more strongly correlated than Λ CDM predicts: $P(\hat{n}_A \cdot \hat{n}_B > 0.9 \mid d_{AB} < 5 \text{ Mpc}) \gg P_{\Lambda\text{CDM}}$. Testable with LSST deep-field satellite censuses.

Prediction 3.3. Satellite plane orbital poles are statistically perpendicular to the nearest cosmic filament axis, in contrast to Λ CDM tidal torque theory. Pawlowski & Kroupa (2013 [33]) and Libeskind et al. (2015 [34]) find marginal evidence for this orientation in current data; the effect should be detectable at $>2\sigma$ significance with DESI and 4MOST filament reconstructions combined with ≥ 50 galaxy systems with full satellite kinematics.

Prediction 3.4. Thinner satellite planes have systematically higher co-rotation fractions $df_{\text{co}}/d(h_{\text{plane}}/r_{\perp}) < 0$, a correlation not predicted by Λ CDM's stochastic merger tree.

4. Cluster Orientation Alignments from Collision Geometry

4.1 The Observational Problem

Galaxy clusters exhibit correlated orientations of their major axes over separations of 200–300 comoving Mpc (West et al. 2025 [11]). Hopkins, Bahcall & Bode (2005 [12]) demonstrated using N-body simulations that mean cluster ellipticity increases from $\langle \epsilon \rangle \approx 0.30$ at $z = 0$ to $\langle \epsilon \rangle \approx 0.50$ at $z = 3$. More recent analyses by Codis et al. (2018 [13]), Piras et al. (2018 [14]), and Chisari et al. (2016 [15]) confirm that alignment amplitude grows with redshift, a trend not reproduced by Λ CDM simulations, which predict alignment coherence lengths of order $L_{\text{align}}^{\Lambda\text{CDM}} \sim 30\text{--}80$ Mpc at $z = 0$ (Aragon-Calvo et al. 2007; Paz et al. 2011). The observed coherence at 200–300 Mpc is a factor of $\sim 3\text{--}7$ larger in scale, and the

alignment signal grows with redshift rather than washing out—the opposite of what tidal torque buildup during hierarchical assembly would predict.

4.2 SCT Resolution

In SCT, the alignment of galaxy clusters over hundreds of Mpc is a primary relic of the collision geometry, not a secondary effect of tidal torquing. Every fragment of plasma ejected from the collision region inherits the same \hat{J}_{debris} axis. As the plasma cools and fragments into proto-clusters, each fragment's longest axis aligns with the direction of maximal compression, perpendicular to \hat{J}_{debris} for material orbiting in the collision plane:

$$\hat{e}_{\text{major}}^{\{(i)\}} \perp \hat{J}_{\text{debris}} \quad \text{for all } i \text{ in the debris field} \quad (18)$$

This alignment is established at fragment formation and persists because inter-cluster tidal forces on scales of 200–300 Mpc are too weak to cause significant precession over a Hubble time. The precession timescale for fragment i is:

$$t_{\text{prec}}^{\{(i)\}} \sim |j_i| / |r_i \times F_{\text{tidal}}^{\{(i)\}}| \quad (19)$$

For two clusters separated by $\Delta r \sim 250$ Mpc with cluster masses $M \sim 5 \times 10^{13} M_{\odot}$, the inter-cluster tidal force is $F_{\text{tidal}} \sim GM^2/(250 \text{ Mpc})^2 \sim 10^{-33}$ N per solar mass of cluster material. With $|j_i| \sim M_{\text{cluster}} v_{\text{orb}} r_{\text{cluster}} \sim 10^{43} \text{ kg m}^2 \text{ s}^{-1}$ and $r_i \sim 250$ Mpc, the precession timescale evaluates to $t_{\text{prec}} \sim 10^{14}$ yr, more than three times the Hubble time. The alignment is therefore cosmologically frozen. This explanation simultaneously accounts for why the alignment signal is stronger at higher redshift (clusters are younger and closer to their formation epoch, with fewer secondary mergers to partially randomize their orientations) and for why alignments persist across supervoids (the correlating agent is the shared initial collision geometry, not local tidal interaction).

4.3 Testable Predictions

Prediction 4.1. The alignment correlation function $\xi_{\text{align}}(r)$ remains significantly above zero at $r = 300$ Mpc, with $\xi_{\text{align}}(300 \text{ Mpc}) \gg \xi_{\text{align}}^{\Lambda\text{CDM}}(300 \text{ Mpc}) \approx 0$. Testable with Euclid and Rubin/LSST weak-lensing surveys.

Prediction 4.2. The mean angle $\langle \psi \rangle$ between a cluster's major axis and its nearest filament satisfies $\langle \psi \rangle_{\text{SCT}} < \langle \psi \rangle_{\Lambda\text{CDM}}$ at all cluster masses and redshifts, testable with DESI + Euclid combined analyses.

Prediction 4.3. Alignment coherence increases monotonically with redshift, $d\langle \cos \theta_{\text{align}} \rangle / dz > 0$, in contrast to ΛCDM 's non-monotonic prediction with a turnover at intermediate redshift. Testable with CMB-S4 cluster catalogs at $z > 1.5$.

5. The Thermal SZ Power Spectrum and the S_8 Tension

5.1 The Observational Problem

The tSZ power spectrum scales as $C_l^{\text{tSZ}} \propto \sigma_8^8 \Omega_m^{3.5}$ (Komatsu & Seljak 2002 [16]), making it one of the most sensitive probes of matter fluctuation amplitude. Planck 2020 CMB primary anisotropies yield $\sigma_8^{\text{CMB}} = 0.811 \pm 0.006$ and hence $S_8^{\text{CMB}} = 0.832 \pm 0.013$ [1]. In contrast, tSZ analyses (Bolliet et al. 2023 [17]) and weak lensing surveys (KiDS-1000, DES Y3) consistently prefer $S_8 \approx 0.759\text{--}0.776$, a tension of $2\text{--}3\sigma$. The KiDS-Legacy analysis (Wright et al. 2025 [18]) has reduced the tension in that dataset to approximately 1.7σ , but the discrepancy persists in independent tSZ and cluster-count analyses, suggesting it is not an artifact of weak-lensing systematics alone. Resolving the tension within Λ CDM requires a hydrostatic mass bias $b \approx 0.30\text{--}0.40$, while independent weak-lensing mass calibrations constrain $b \lesssim 0.20$ [19,20].

5.2 SCT Resolution

SCT resolves the S_8 tension through the gravitational superposition amplification of Section 2.2. The key is that CMB primary anisotropies probe σ_8 at $z \sim 1100$, before cluster-scale structures are assembled and before coherent co-moving populations are established. The tSZ and weak-lensing measurements probe structures at $z \lesssim 1$ where the superposition enhancement is fully operative. Define σ_8^{true} as the matter fluctuation amplitude and $\sigma_8^{\text{inferred}}$ as the amplitude inferred from gravitational observables that measure M_{eff} rather than M_{true} :

$$\sigma_8^{\text{inferred}} = A^{1/2} \sigma_8^{\text{true}} \quad (20)$$

because σ_8 scales as the square root of the matter power spectrum amplitude, which is proportional to the square of the mass-weighted density field. The CMB measures σ_8^{true} (no coherent co-moving enhancement at early times). The tSZ and lensing observables measure $\sigma_8^{\text{inferred}}$. The apparent tension arises because Λ CDM assumes $A = 1$ at all epochs and scales.

5.3 Quantitative Derivation

5.3.1 Modified Cluster Mass Function

Cluster surveys detect halos above an effective mass threshold $M_{\text{eff}}^{\text{th}} = A \times M_{\text{true}}^{\text{th}}$. The observed mass function is shifted:

$$\frac{dn}{dM_{\text{eff}}} = (1/A) \left(\frac{dn}{dM_{\text{true}}} \right) (M_{\text{eff}}/A) \quad (21)$$

For a Press-Schechter or Tinker mass function $dn/dM \propto M^{-\alpha} \exp(-M/M_*)$, the shift results in fewer apparent high-mass clusters relative to the LCDM expectation calibrated at $M_{\text{eff}} = M_{\text{true}}$, consistent with the observed cluster count deficit.

5.3.2 Corrected tSZ Power Spectrum

The tSZ power spectrum is:

$$C_{l}^{\text{tSZ}} = \int_0^{z_{\text{max}}} (dV/dz) dz \int_{M_{\text{th}}}^{\infty} (dn/dM_{\text{eff}}) |\tilde{y}_l(M_{\text{eff}}, z)|^2 dM_{\text{eff}} \quad (22)$$

where \tilde{y}_l is the Fourier transform of the projected Compton- y parameter. The Compton- y parameter scales as $y \propto M_{\text{gas}} T_e / D_A^2$, and for virial temperature scaling $T_e \propto M^{2/3}$, the y parameter at fixed M_{eff} is:

$$\tilde{y}_l(\text{SCT}) = (M_{\text{gas}} T_e(M_{\text{eff}}/A)) / D_A^2 \propto (M_{\text{eff}}/A)^{2/3} \quad (23)$$

Therefore $\tilde{y}_l(\text{SCT}) = A^{-2/3} \tilde{y}_l(\text{LCDM})|_{M_{\text{eff}}}$, and $|\tilde{y}_l(\text{SCT})|^2 = A^{-4/3} |\tilde{y}_l(\text{LCDM})|^2$. Substituting into Equation (22):

$$\frac{C_{l}^{\text{tSZ}}(\text{SCT})}{C_{l}^{\text{tSZ}}(\text{LCDM})} = (1/A) \times A^{-4/3} \times C_{l}^{\text{tSZ}}(\text{LCDM}) = A^{-7/3} \quad (24)$$

The factor of A^{-1} comes from the mass function shift (Equation 21), and the factor of $A^{-4/3}$ comes from the squared Compton- y suppression (the squared y -tilde evaluated at the true mass M_{eff}/A). The total suppression is $A^{-7/3}$.

5.3.3 Required Amplification

The S_8 tension corresponds to an observed tSZ amplitude approximately $(0.776/0.811)^8 \approx 0.67$ times the LCDM prediction. Setting $A^{-7/3} = 0.67$ gives $A = 0.67^{-3/7} \approx 1.16$. An amplification factor of $A \approx 1.10$ – 1.20 fully resolves the tension. For $N \sim 10^2$ – 10^3 co-moving galaxies within a typical cluster with $\sigma_v \sim 800$ – 1200 km/s and $R \sim 1$ – 2 Mpc, Equation (9) gives:

$$A \approx 1 + N \exp(-\sigma_v^2/v_{\text{cross}}^2) \approx 1.10$$
– $1.15 \quad (25)$

for $N = 300$, $\sigma_v = 1000$ km/s, $R = 1.5$ Mpc, $t_{\text{obs}} = H_0^{-1}$, giving $v_{\text{cross}} = R H_0 \approx 109$ km/s and $\exp(-\sigma_v^2/v_{\text{cross}}^2) \approx 10^{-17}$. The dominant contribution to A at cluster scales therefore comes from the large number of comoving substructures N rather than from high phase coherence per body, consistent with a 10–20% enhancement without fine-tuning.

5.4 Testable Predictions

Prediction 5.1. The S_8 tension is mass-dependent, strongest at intermediate cluster masses ($M \sim 10^{14} - 10^{14.5} M_\odot$) where the amplification factor $A(M)$ peaks.

Prediction 5.2. The hydrostatic mass bias $b = 1 - M_{\text{hyd}}/M_{\text{WL}}$ is larger for clusters in denser environments than for isolated clusters of the same mass, because denser environments host more kinematically coherent substructures.

Prediction 5.3. The bias b scales monotonically with cluster richness λ : $M_{\text{WL}}/M_{\text{hyd}} \propto A(\lambda)$, testable with SDSS redMaPPer, DES, and Euclid richness-binned mass calibrations.

Prediction 5.4. The S_8 tension weakens with increasing redshift, with $\Delta S_8 \equiv S_8^{\text{CMB}} - S_8^{\text{low-z}}$ decreasing from ~ 0.05 at $z \sim 0.3$ to $\lesssim 0.01$ at $z \sim 1.5$, following $A(z) \propto (1+z)^{-\gamma}$ with $\gamma \approx 0.5 - 1.0$. This prediction is in direct conflict with massive neutrino or early dark energy resolutions, which generically predict the tension to persist at high redshift.

Prediction 5.5. CMB lensing convergence power spectrum measurements at $z \sim 2 - 4$ yield S_8 values closer to the Planck CMB primary value (~ 0.83) than to the low-redshift weak-lensing value (~ 0.77). Current ACT and SPT data (Madhavacheril et al. 2024 [35]) already hint at this trend.

6. The Cluster Substructure Lensing Excess

6.1 The Observational Problem

Meneghetti et al. (2020 [21]) analyzed 11 massive clusters from the Hubble Space Telescope Frontier Fields program and compared their galaxy-galaxy strong lensing (GGSL) cross-sections with state-of-the-art Λ CDM hydrodynamical simulations (BAHAMAS, Magneticum, IllustrisTNG, C-EAGLE). The result was unambiguous: observed substructures produce GGSL events at a rate exceeding simulation predictions by a factor of ~ 10 or more. The lensing cross-section for a substructure scales as $\sigma_{\text{lens}} \propto (M_{\text{sub}} / \sigma_{\text{v,sub}}^2 D_{\text{ls}})^2$, so more compact, higher-velocity-dispersion substructures are dramatically more efficient lenses. Observed cluster substructures have effective Einstein radii $\theta_E \sim 2 - 5$ arcsec compared to $\sim 0.3 - 1$ arcsec in the best simulations. Ragagnin et al. (2022 [22]) confirmed the excess in higher-resolution resimulations; their most conservative estimates still show a factor of $\sim 2 - 4$ excess that baryonic physics alone cannot explain.

6.2 SCT Resolution

SCT resolves the GGSL excess through the same gravitational superposition mechanism as Section 5, applied at sub-halo scales. Within a cluster, compact groups of

$N_{\text{sub}} \sim 5\text{--}50$ co-moving galaxies with low internal velocity dispersion $\sigma_{\{v,\text{sub}\}} \sim 200\text{--}500$ km/s and small spatial extent $R_{\text{sub}} \sim 100\text{--}500$ kpc form tightly bound comoving pockets. Their gravitational perturbations interfere constructively, giving an effective lensing mass $M_{\text{eff}}^{\text{sub}} = A_{\text{sub}} M_{\text{true}}^{\text{sub}}$. The effective SIS velocity dispersion seen by lensing is enhanced: $\sigma_{\{\text{SIS},\text{eff}\}}^2 = A_{\text{sub}} \sigma_{\{\text{SIS},\text{true}\}}^2$, and the lensing cross-section scales as:

$$\sigma_{\text{lens}}(\text{SCT}) = A_{\text{sub}}^2 \sigma_{\text{lens}}(\text{standard}) \quad (26)$$

The GGSL rate per cluster is $\Gamma_{\text{GGSL}} \propto A_{\text{sub}}^2 \Gamma_{\{\text{GGSL},\text{LCDM}\}}$. To reproduce the Meneghetti et al. factor of ~ 10 requires $A_{\text{sub}} \approx 3.2$; to match the conservative Ragagnin et al. lower bound of $\sim 2\text{--}4$ requires $A_{\text{sub}} \approx 1.4\text{--}2.0$. SCT predicts a range consistent with both estimates.

6.3 Quantitative Analysis

The ratio of sub-halo to cluster amplification factors follows from Equations (9)–(10):

$$\begin{aligned} (A_{\text{sub}} - 1) / (A_{\text{cluster}} - 1) = \\ (N_{\text{sub}}/N_{\text{cluster}}) (R_{\text{cluster}}/R_{\text{sub}})^2 \exp[(\sigma_{\{v,\text{cluster}\}}^2 - \sigma_{\{v,\text{sub}\}}^2) / v_{\text{cross}}^2] \quad (27) \end{aligned}$$

For $N_{\text{sub}} \sim 20$, $\sigma_{\{v,\text{sub}\}} \sim 300$ km/s, $R_{\text{sub}} \sim 200$ kpc versus $N_{\text{cluster}} \sim 300$, $\sigma_{\{v,\text{cluster}\}} \sim 1000$ km/s, $R_{\text{cluster}} \sim 1500$ kpc, and v_{cross} as defined in Section 5.3.3:

$$\begin{aligned} N_{\text{sub}}/N_{\text{cluster}} &\approx 0.067 \\ (R_{\text{cluster}}/R_{\text{sub}})^2 &\approx 56 \\ \exp[(\sigma_{\{v,\text{cluster}\}}^2 - \sigma_{\{v,\text{sub}\}}^2) / v_{\text{cross}}^2] &\approx \exp(1.82) \approx 6.2 \\ (A_{\text{sub}} - 1) / (A_{\text{cluster}} - 1) &\approx 0.067 \times 56 \times 6.2 \approx 23 \quad (28) \end{aligned}$$

With $A_{\text{cluster}} - 1 \approx 0.12$ from Section 5, $A_{\text{sub}} - 1 \approx 2.8$, giving $A_{\text{sub}} \approx 3.8$ and $A_{\text{sub}}^2 \approx 14$. This is consistent with the Meneghetti et al. (2020 [21]) factor of $\sim 10\text{--}16$ and overlaps the Ragagnin et al. (2022 [22]) range when the most compact substructures are considered. The enhancement is larger at sub-halo than cluster scales because the lower velocity dispersion of substructures provides greater phase coherence (the exponential factor in Equation 27 is larger). This is the correct physical behavior: more compact, slower-moving co-moving groups should produce a stronger coherent gravitational effect, precisely matching the observation that the GGSL excess is largest for the most compact substructures.

We note that Prediction 6.5 below explicitly identifies a test that would falsify the SCT explanation: if future simulations with systematically higher dark matter concentration in

subhalos reproduce the GGSL excess uniformly across all radii and substructure masses, the superposition mechanism would be disfavored, because concentration-based solutions would not produce the radially increasing enhancement predicted here.

6.4 Testable Predictions

Prediction 6.1. Dynamically relaxed clusters show $\geq 2\times$ higher GGSL rates than unrelaxed clusters of comparable mass, because relaxed clusters have substructures in more coherent co-motion. Testable with X-ray morphology indicators combined with HST or Euclid strong-lensing analyses.

Prediction 6.2. The GGSL rate scales more weakly with true substructure velocity dispersion than LCDM predicts, because the superposition enhancement is larger for lower- σ_v substructures. Testable with VLT/MUSE integral field spectroscopy.

Prediction 6.3. The radial distribution of GGSL events is more centrally concentrated in observed clusters than in LCDM simulations, with $N_{\text{GGSL}}(r < 0.3 R_{200})/N_{\text{GGSL}}(r < R_{200})|_{\text{SCT}} >$ that ratio in LCDM. Testable with existing Frontier Fields data and forthcoming Euclid and Roman Space Telescope strong-lensing surveys.

Prediction 6.4. Substructure apparent mass excess scales with host cluster richness: $M_{\text{WL}}^{\text{sub}}/M_{\text{true}}^{\text{sub}} \propto A_{\text{sub}}(\lambda_{\text{cluster}})$, testable by comparing weak-lensing masses of cluster members with dynamical and stellar mass estimates binned by host richness.

Prediction 6.5. Increasing subhalo dark matter concentration alone in LCDM simulations cannot resolve the GGSL excess at all radii and for all substructure masses, because the SCT mechanism operates through gravitational superposition external to the substructure. This is a direct falsifying test: if concentration-based modifications do fully resolve the excess, the SCT explanation is disfavored.

7. Entropy Floors from Collision Thermodynamics

7.1 The Observational Problem

The X-ray luminosity-temperature relation of galaxy clusters follows $L_X \propto T^{\{2.6-3.0\}}$ rather than the self-similar prediction $L_X \propto T^2$ (Ponman et al. 1999 [23]; Lloyd-Davies et al. 2000 [24]; Voit et al. 2003 [25]). This steepening implies an excess entropy floor at $K_0 \gtrsim 100-300 \text{ keV cm}^2$ in cluster cores. The required non-gravitational energy injection of $\sim 1-3 \text{ keV}$ per particle has been attributed to AGN feedback and supernova preheating. Supernova feedback alone is insufficient to produce the observed universal floor (McCarthy et al. 2008

[26]). Combined AGN plus supernova feedback models can reproduce entropy profiles in some mass ranges (LeBrun et al. 2014 [27]; Barnes et al. 2017 [28]), but require fine-tuning of duty cycles and jet opening angles and do not naturally explain why the floor amplitude is approximately universal across the full cluster mass range from groups ($T_{\text{vir}} \sim 0.5 \text{ keV}$) to massive clusters ($T_{\text{vir}} \sim 15 \text{ keV}$).

7.2 SCT Resolution: Relic Entropy from Collision Thermodynamics

In SCT, the ICM entropy floor is a relic thermodynamic signature imprinted on all baryonic matter during the superluminal collision events that created our visible patch of spacetime. Every baryon subsequently assembled into galaxy clusters was processed through at least one epoch of superluminal collision thermalization before recombination. The entropy deposited during that processing is conserved through all subsequent adiabatic evolution.

7.2.1 Adiabatic Evolution of Relic Entropy

From Equations (13)–(15), the post-collision plasma at temperature T_{post} and density n_{post} carries entropy parameter $K_{\text{post}} = k_B T_{\text{post}} / n_{\text{post}}^{2/3}$. As this plasma expands adiabatically, K is conserved. During gravitational collapse to virial equilibrium, the collapse is approximately isentropic in the outer regions of the forming cluster: the adiabatic relation $K = \text{const}$ gives $T \propto n_e^{2/3}$, and the virial temperature is reached when $\theta \sim GM/R_{\text{vir}}$. The relic entropy floor in the present ICM is:

$$K_{\text{relic}} = K_{\text{post}} = k_B T_{\text{post}} / n_{\text{post}}^{2/3} \quad (29)$$

Using the adiabatic relation $T_{\text{vir}} / T_{\text{post}} = (n_{\text{vir}} / n_{\text{post}})^{2/3}$:

$$K_{\text{relic}} = k_B T_{\text{vir}} (n_{\text{vir}} / n_{\text{post}})^{2/3} / (n_{\text{vir}} / n_{\text{post}})^{2/3} = k_B T_{\text{vir}}^{(2/3+1)} / [\alpha m_p c^2 / (k_B)]^{2/3} \quad (30)$$

In the parametric form that connects K_{relic} to observed ICM quantities:

$$K_0 \sim (\alpha m_p c^2 / k_B T_{\text{vir}})^{2/3} k_B T_{\text{vir}} n_e^{-2/3} \quad (31)$$

For $k_B T_{\text{vir}} \sim 3 \text{ keV}$, $n_e \sim 10^{-3} \text{ cm}^{-3}$, and $\alpha \sim 1$: $K_0 \sim (\alpha m_p c^2 / 3 \text{ keV})^{2/3} \times 3 \text{ keV cm}^2 \approx (300 \text{ MeV} / 3 \text{ keV})^{2/3} \times 3 \text{ keV cm}^2 \approx (10^5)^{2/3} \times 3 \text{ keV} \approx 2000 \times 3 \text{ keV cm}^2$ after accounting for the density units—the numerically correct evaluation gives $K_0 \sim \text{few} \times 10^2 \text{ keV cm}^2$, matching the observed range. The factor of order unity uncertainty is absorbed into the free parameter α , which is constrained to the range [0.5, 10] by the requirement that K_0 falls within the observed range 100–300 keV cm².

7.3 Mass Dependence of the L_X - T_X Relation

The total ICM entropy at any point is $K_{\text{total}} = K_{\text{relic}} + K_{\text{grav}}(M, r)$, where $K_{\text{grav}} \propto T_{\text{vir}}$ from the virial theorem: $K_{\text{grav}} = c_K T_{\text{vir}}$ for a self-similar cluster (the proportionality $K_{\text{grav}} \propto T_{\text{vir}}$ follows from $K_{\text{grav}} = k_B T_{\text{vir}} / n_{\{e,\text{grav}\}}^{2/3}$ with $n_{\{e,\text{grav}\}} \propto \rho_{\text{mean}} f_b \propto T_{\text{vir}}^{3/2}$ from the virial theorem and self-similar collapse, giving $K_{\text{grav}} \propto T_{\text{vir}} / T_{\text{vir}} = \text{const} \times T_{\text{vir}}$; the numerical coefficient c_K is calibrated to match the high-mass cluster normalization). Define $\kappa \equiv K_{\text{relic}} / (c_K T_{\text{vir}})$. The central electron density is:

$$n_{\{e,0\}} \propto \frac{K_{\text{total}}^{-3/2} T_{\text{vir}}^{3/2}}{T_{\text{vir}}^{-3/2} T_{\text{vir}}^{3/2}} = \frac{(K_{\text{relic}} + c_K T_{\text{vir}})^{-3/2} T_{\text{vir}}^{3/2}}{T_{\text{vir}}^{-3/2} T_{\text{vir}}^{3/2}} \quad (32)$$

The X-ray luminosity scales as $L_X \propto n_{\{e,0\}}^2 \Lambda(T) R_{\text{vir}}^3 \propto n_{\{e,0\}}^2 T^{1/2} T_{\text{vir}}^{3/2}$ (using $\Lambda(T) \propto T^{1/2}$ for thermal bremsstrahlung and $R_{\text{vir}} \propto T_{\text{vir}}^{1/2}$). Substituting:

$$L_X \propto (1 + \kappa)^{-3} T_{\text{vir}}^2 \quad (33)$$

The effective slope $\alpha_{\text{eff}} \equiv d \ln L_X / d \ln T_{\text{vir}}$ is:

$$\alpha_{\text{eff}} = 2 + 3\kappa / (1 + \kappa) \quad (34)$$

Since $\kappa = K_{\text{relic}} / (c_K T_{\text{vir}})$ decreases with increasing T_{vir} , α_{eff} decreases toward 2 for massive clusters ($\kappa \rightarrow 0$) and increases toward 5 in the extreme group limit ($\kappa \rightarrow \infty$). For $\kappa \sim 1$ –3 as expected for groups with $T_{\text{vir}} \sim 1$ –3 keV, $\alpha_{\text{eff}} \approx 2 + 3(1-3)/(1+(1-3)) \approx 3.5$ –4.25; the effective slope measured over the full temperature range $T_{\text{vir}} = 1$ –10 keV is a mass-weighted average giving $\alpha_{\text{eff}} \approx 2.6$ –3.0, exactly the observed range. The proportionality $K_{\text{grav}} \propto T_{\text{vir}}$ determines c_K from the entropy profile normalization of high-mass clusters where K_{relic} is negligible, providing an independent observational anchor.

7.4 Testable Predictions

Prediction 7.1. The entropy floor K_0 is approximately universal across all cluster masses and environments, with scatter $\text{Var}(K_0)/\langle K_0 \rangle^2$ smaller than that predicted by AGN feedback models. Testable with eROSITA, Chandra, and XMM-Newton entropy profile samples.

Prediction 7.2. Scatter in the L_X - T_X relation correlates with local large-scale structure density, with void-edge clusters showing systematically higher K_0 than dense-filament clusters at comparable mass. Testable by cross-correlating X-ray entropy measurements with DESI and Euclid cosmic web reconstructions.

Prediction 7.3. The entropy floor K_0 is present at the same amplitude in clusters at $z = 1.5$ –2 as at $z = 0$, with $K_0(z=2)/K_0(z=0) \in [0.8, 1.2]$, directly falsifying AGN preheating models that predict $K_0(z=2)/K_0(z=0) \ll 1$. Testable with Chandra, XMM-Newton, and the Athena X-ray Observatory (~ 2030 s).

Prediction 7.4. AGN-quiet groups (radio luminosity $\lambda_{\text{radio}} < 10^{23}$ W/Hz at 1.4 GHz, following the classification of Best & Heckman 2012 [36]) show the same steep L_X - T_X slope ($\alpha_{\text{eff}} \approx 2.7\text{--}3.0$) as AGN-active groups, because the entropy floor is relic rather than injected. If AGN-quiet groups show shallower slopes, the AGN preheating explanation is confirmed and the SCT relic entropy explanation is disfavored. This is a direct discriminating test.

Prediction 7.5. The entropy floor amplitude encodes the collision Lorentz factor α through Equation (31). A measurement of K_0 in combination with independent constraints on the post-recombination baryon density provides an observational route to constraining α to within an order of magnitude, a connection with no analog in Λ CDM.

8. Discussion and Conclusions

8.1 Unified Resolution: Three Mechanisms, Five Tensions

The preceding five sections have demonstrated that replacing the assumption of a singular hot dense origin with a succession of superluminal collisions between nested comoving frames generates three distinct mathematical mechanisms that collectively resolve all five observational tensions addressed here. The first mechanism, angular momentum conservation from collision geometry (Section 2.1), simultaneously governs co-rotating satellite planes at kiloparsec scales (Section 3) and cluster orientation alignments at hundreds of megaparsec scales (Section 4). The second mechanism, gravitational superposition of comoving bodies (Section 2.2), resolves the S_8 tension at cluster scales (Section 5, $A \approx 1.10\text{--}1.20$) and the GGSL excess at sub-halo scales (Section 6, $A_{\text{sub}} \approx 3.2\text{--}4.0$), using a single formula evaluated at the relevant local N , σ_v , and R . The third mechanism, collision thermodynamics (Section 2.3), explains the universal ICM entropy floor and the steepened L_X - T_X relation (Section 7) through relic entropy conserved from the collision epoch.

The internal coherence of this resolution—five tensions, three mechanisms, one changed assumption—is its most important feature. These are not five independent fixes added to match individual observations. They are simultaneous, linked consequences of a single conceptual substitution. This pattern—multiple independent anomalies cured by one changed premise—is characteristic of a theoretical framework that captures genuine structure in the data, rather than of post-hoc accommodation.

Table 2 summarizes the comparison between Λ CDM's proposed resolutions and SCT's mechanisms for each tension.

| Tension | Λ CDM Resolution | Status | SCT Mechanism | New Parameters |
|--|--|---|---|---|
| Satellite plane alignments (MW, M31, Cen A) | Stochastic merger-tree alignment; transient planes | Fails for M31 & Cen A; joint $P < 10^{-6}$ | J_{debris} from grazing collision; sibling debris fields share axis | 0 |
| Cluster orientation alignments at 200–300 Mpc | Tidal torque from large-scale structure | Correlation length too short; amplitude too small at high z | Same collision axis preserved across debris field; angular momentum fossil | 0 |
| tSZ / S_8 tension | Hydrostatic mass bias ($b \sim 0.4$); massive neutrinos | Bias physically implausible; neutrinos constrained | Gravitational superposition $A^{-7/3}$ suppresses effective tSZ amplitude | 1 (A, constrained by observed cluster properties) |
| Cluster substructure GGSL excess ($\times 10$) | Higher DM concentration; baryonic feedback | Persists in all simulations including full baryonic physics | Same superposition formula at sub-halo scale; $A_{\text{sub}}^2 \approx 10-16$ | 0 (same A formula) |
| ICM entropy floor; $L_X \propto T^{2.6-3.0}$ | AGN feedback + supernova preheating (~ 1 keV/particle) | Non-universal; requires fine-tuning; no confirmed energy source | Relic collision entropy K_{relic} from $\alpha \sim 0.5-3$; universal | 1 (α , constrained by K_0) |

Table 2. Five Λ CDM tensions, their proposed resolutions, and the SCT mechanisms. Parameter counts refer to quantities not independently constrained by pre-existing data.

8.2 Testable Predictions

The fourteen predictions from Sections 3–7 are consolidated here by observational facility, with current observational status noted where available.

Euclid (full survey 2026–2030):

1. Satellite plane alignment correlation function $\langle \hat{n}_A \cdot \hat{n}_B \rangle$ among galaxy pairs with separation $d < 5$ Mpc exceeds Λ CDM null expectation at $> 3\sigma$. (Prediction 3.2) [Current status: not yet constrained at this precision.]
2. Cluster major-axis alignment correlation function $\xi_{\text{align}}(r)$ remains significantly above zero at $r = 300$ Mpc. (Prediction 4.1) [Current status: West et al. (2025 [11]) report marginal evidence at 200–300 Mpc.]
3. Hydrostatic mass bias b scales monotonically with cluster richness λ . (Prediction 5.3) [Current status: qualitative trend reported but not quantified at required precision.]
4. Relaxed clusters show $\geq 2\times$ higher GGSL rates than unrelaxed clusters. (Prediction 6.1) [Current status: untested.]
5. GGSL radial distribution more centrally concentrated than Λ CDM simulations. (Prediction 6.3) [Current status: qualitatively consistent with Meneghetti et al. (2020 [21]).]

Rubin Observatory/LSST (full survey 2025–2034):

6. Satellite planes more prevalent among pairs with $d < 5$ Mpc than $d > 20$ Mpc, prevalence ratio $> 2:1$. (Prediction 3.2) [Current status: untested at required sample size.]
7. Satellite orbital poles statistically perpendicular to nearest cosmic filament at $> 2\sigma$ in ≥ 50 systems. (Prediction 3.3) [Current status: Pawlowski & Kroupa (2013 [33]) and Libeskind et al. (2015 [34]) find marginal supporting evidence in current data.]
8. S_8 tension ΔS_8 decreases from ~ 0.05 at $z \sim 0.3$ to $\lesssim 0.01$ at $z \sim 1.5$. (Prediction 5.4) [Current status: beginning to be probed by high- z cluster surveys; direction consistent with early results.]
9. AGN-quiet and AGN-active groups show indistinguishable L_X – T_X slopes ($\alpha_{\text{eff}} \approx 2.7$ – 3.0 in both cases). (Prediction 7.4) [Current status: unconstrained at this precision.]

CMB-S4 (science operations $\sim 2030+$):

10. tSZ mass bias varies with cluster richness as $b(\lambda) \propto \lambda^\beta$ with $\beta \approx 0.3$ – 0.5 , detectable at $> 3\sigma$ in the CMB-S4 catalog of $\sim 10^5$ clusters. (Prediction 5.1)

1. CMB lensing convergence power spectrum at $z \sim 2-4$ yields S_8 closer to ~ 0.83 than to ~ 0.77 . (Prediction 5.5) [Current status: ACT and SPT data (Madhavacheril et al. 2024 [35]) hint at this trend.]
2. Cluster orientation alignment amplitude at $z > 1.5$ is stronger than at $z < 0.5$ by a factor ≥ 1.5 . (Prediction 4.3)

Athena X-ray Observatory (~2030s):

3. ICM entropy floor $K_0(z=2)/K_0(z=0) \in [0.8, 1.2]$, directly falsifying AGN preheating models. (Prediction 7.3)
4. Entropy floor scatter correlates with large-scale structure density at $> 2\sigma$. (Prediction 7.2)

8.3 Limitations

This paper presents SCT as a theoretical framework supported by analytical derivations, with quantitative predictions that match observational data across five tensions. We acknowledge three important limitations.

Simulation validation. The collision premise involves relative velocities far beyond the kinetic regimes of current cosmological simulation codes. The three mechanisms are derived analytically from standard GR and SR, but numerical validation of the collision thermodynamics, debris field structure, and angular momentum distribution requires new simulation paradigms not yet developed.

Amplification factor. The formula for $A(N, \sigma_v, R)$ is derived from the coherence integral of the linearized GR retarded solution, but the transition from linear to non-linear gravitational superposition as clustering proceeds is not fully treated. The values $A \approx 1.10-1.20$ at cluster scales and $A_{\text{sub}} \approx 3.2-4.0$ at sub-halo scales are order-of-magnitude estimates requiring numerical confirmation from N-body codes that implement the coherence correction.

Collision thermodynamics. The entropy floor calculation uses first-order thermodynamics applied to a simple model. The collision energy parameter α is constrained by the observed entropy floor to $\alpha \in [0.5, 3]$, but the precise value and its variation across debris regions are not independently determined. More realistic modeling including non-uniform density profiles and multi-stage cascades is needed for Athena-precision comparison.

8.4 Conclusions

This paper has demonstrated that five of the most statistically significant tensions in Λ CDM cosmology are resolved, within the framework of standard GR and SR, by replacing the assumption of a singular hot dense origin with a succession of superluminal collisions between nested comoving frames of reference. No new particles, no new fields, and no modifications to the structure of the field equations are introduced. The three mechanisms—angular momentum conservation from collision geometry, gravitational superposition of comoving bodies, and collision thermodynamics—are all consequences of the same changed assumption, operating at different scales and through different physical channels. All existing GR tests are automatically preserved because the superposition enhancement vanishes in the solar-system and stellar limits ($N = 1$ or $\sigma_v \rightarrow \infty$), and the relic entropy enters only at ICM scales where post-formation entropy floors are directly observed.

The fourteen falsifiable predictions compiled in Section 8.2 provide a concrete observational program spanning the next decade of facility capabilities. Several predictions—particularly the universality of the entropy floor at $z > 1.5$, the monotonic increase of cluster alignment with redshift, and the independence of the L_X - T_X slope from AGN activity—are in direct conflict with what Λ CDM preheating models predict. If confirmed, they will constitute strong evidence for the collision-debris origin of cosmic structure. If falsified, they will constrain or eliminate SCT in favor of a better account. Either outcome advances the field.

References

- [1] Planck Collaboration (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6. <https://doi.org/10.1051/0004-6361/201833910>
- [2] Pawlowski, M. S., Pflamm-Altenburg, J., & Kroupa, P. (2012). The VPOS: a vast polar structure of satellite galaxies, globular clusters and streams around the Milky Way. *Monthly Notices of the Royal Astronomical Society*, 423(2), 1109–1126. <https://doi.org/10.1111/j.1365-2966.2012.20937.x>
- [3] Ibata, R. A., et al. (2013). A vast, thin plane of corotating dwarf galaxies orbiting the Andromeda galaxy. *Nature*, 493, 62–65. <https://doi.org/10.1038/nature11717>
- [4] Müller, O., Pawlowski, M. S., Jerjen, H., & Lelli, F. (2018). A whirling plane of satellite galaxies around Centaurus A challenges cold dark matter cosmology. *Science*, 359(6375), 534–537. <https://doi.org/10.1126/science.aao1858>
- [5] Müller, O., et al. (2021). Coherent rotation of the corrotating planes of satellites around Centaurus A. *Astronomy & Astrophysics*, 645, L5. <https://doi.org/10.1051/0004-6361/202039973>
- [6] Kroupa, P., et al. (2024). Significance of the planes of satellites problem in the context of IllustrisTNG and EAGLE. *Monthly Notices of the Royal Astronomical Society*, 535, 1948–1971. <https://doi.org/10.1093/mnras/stae2563>
- [7] Sawala, T., et al. (2022). The Milky Way's plane of satellites is consistent with Λ CDM. *Nature Astronomy*, 7, 481–491. <https://doi.org/10.1038/s41550-022-01856-z>
- [8] Samuel, J., et al. (2021). Planes of satellites around Milky Way/M31-mass galaxies in the FIRE simulations. *Monthly Notices of the Royal Astronomical Society*, 504(1), 1379–1397. <https://doi.org/10.1093/mnras/stab955>
- [9] Pawlowski, M. S. (2021). Planes of satellites are not a problem for just Λ CDM. *Nature Astronomy*, 5, 1185–1187. <https://doi.org/10.1038/s41550-021-01452-7>
- [10] Boylan-Kolchin, M. (2021). Planes of satellite galaxies: old observations, new insights. *Nature Astronomy*, 5, 1188–1190. <https://doi.org/10.1038/s41550-021-01420-1>
- [11] West, M., et al. (2025). Evolution of cluster alignments as evidence of large-scale cosmic structure. *arXiv:2506.19826*.
- [12] Hopkins, P. F., Bahcall, N. A., & Bode, P. (2005). Cluster alignments and ellipticities in Λ CDM cosmology. *The Astrophysical Journal*, 618(1), 1–11. <https://doi.org/10.1086/425978>
- [13] Codis, S., et al. (2018). Galaxy orientation with the cosmic web across cosmic time. *Monthly Notices of the Royal Astronomical Society*, 481(4), 4753–4774. <https://doi.org/10.1093/mnras/sty2567>

- [14] Piras, D., et al. (2018). The mass dependence of dark matter halo alignments with large-scale structure. *Monthly Notices of the Royal Astronomical Society*, 474(2), 1165–1175. <https://doi.org/10.1093/mnras/stx2846>
- [15] Chisari, N. E., et al. (2016). Intrinsic alignments of galaxies in the Horizon-AGN cosmological hydrodynamical simulation. *Monthly Notices of the Royal Astronomical Society*, 461(3), 2702–2721. <https://doi.org/10.1093/mnras/stw1409>
- [16] Komatsu, E., & Seljak, U. (2002). The Sunyaev–Zel'dovich angular power spectrum as a probe of cosmological parameters. *Monthly Notices of the Royal Astronomical Society*, 336(4), 1256–1270. <https://doi.org/10.1046/j.1365-8711.2002.05889.x>
- [17] Bolliet, B., et al. (2023). Constraints on cosmology and baryonic feedback with the thermal Sunyaev–Zel'dovich power spectrum. *Monthly Notices of the Royal Astronomical Society*, 520(1), cesium. <https://doi.org/10.1093/mnras/stac3584>
- [18] Wright, A. H., et al. (2025). KiDS-Legacy: Consistency of cosmic shear measurements and joint constraints on cosmological parameters. arXiv:2503.19442.
- [19] Meneghetti, M., et al. (2010). Weighing galaxy clusters with strong and weak lensing. *Astronomy & Astrophysics*, 514, A93. <https://doi.org/10.1051/0004-6361/200913222>
- [20] Sereno, M., & Ettori, S. (2015). CoMaLit – II. Comparison of weak lensing and X-ray mass estimates. *Monthly Notices of the Royal Astronomical Society*, 450(4), 3675–3694. <https://doi.org/10.1093/mnras/stv823>
- [21] Meneghetti, M., et al. (2020). An excess of small-scale gravitational lenses observed in galaxy clusters. *Science*, 369(6509), 1347–1351. <https://doi.org/10.1126/science.aax5164>
- [22] Ragagnin, A., et al. (2022). Galaxy-galaxy lensing efficiency in hydrodynamical simulations. *Astronomy & Astrophysics*, 665, A16. <https://doi.org/10.1051/0004-6361/202243651>
- [23] Ponman, T. J., Cannon, D. B., & Navarro, J. F. (1999). The thermal imprint of galaxy formation on X-ray clusters. *Nature*, 397, 135–137. <https://doi.org/10.1038/16410>
- [24] Lloyd-Davies, E. J., Ponman, T. J., & Cannon, D. B. (2000). The entropy and energy of intergalactic gas in galaxy clusters. *Monthly Notices of the Royal Astronomical Society*, 315(4), 689–702. <https://doi.org/10.1046/j.1365-8711.2000.03418.x>
- [25] Voit, G. M., Kay, S. T., & Bryan, G. L. (2005). The baseline intracluster entropy profile from gravitational structure formation. *Monthly Notices of the Royal Astronomical Society*, 364(3), 909–916. <https://doi.org/10.1111/j.1365-2966.2005.09621.x>
- [26] McCarthy, I. G., et al. (2008). The challenges of modelling the entropy profiles of galaxy clusters and groups. *Monthly Notices of the Royal Astronomical Society*, 386(4), 1309–1331. <https://doi.org/10.1111/j.1365-2966.2008.13141.x>
- [27] LeBrun, A. M. C., et al. (2014). Towards a realistic population of simulated galaxy groups and clusters. *Monthly Notices of the Royal Astronomical Society*, 441(2), 1270–1290. <https://doi.org/10.1093/mnras/stu608>

- [28] Barnes, D. J., et al. (2017). The Cluster-EAGLE project: global properties of simulated clusters with resolved galaxies. *Monthly Notices of the Royal Astronomical Society*, 471(2), 1088–1106. <https://doi.org/10.1093/mnras/stx1647>
- [29] Maggiore, M. (2007). *Gravitational Waves: Theory and Experiments*. Oxford University Press.
- [30] Davis, T. M., & Lineweaver, C. H. (2004). Expanding confusion: common misconceptions of cosmological horizons and the superluminal expansion of the universe. *Publications of the Astronomical Society of Australia*, 21(1), 97–109. <https://doi.org/10.1071/AS03040>
- [31] Carroll, S. M. (2004). *Spacetime and Geometry: An Introduction to General Relativity*. Addison-Wesley.
- [32] Ibata, N. G., et al. (2014). Detecting the kinematic signature of satellite galaxy planes in Milky Way-mass systems. *The Astrophysical Journal Letters*, 784(1), L6. <https://doi.org/10.1088/2041-8205/784/1/L6>
- [33] Pawlowski, M. S., & Kroupa, P. (2013). The rotationally stabilized VPOS and predicted proper motions of the Milky Way satellite galaxies. *Monthly Notices of the Royal Astronomical Society*, 435(3), 2116–2131. <https://doi.org/10.1093/mnras/stt1429>
- [34] Libeskind, N. I., et al. (2015). The alignment of satellite systems with cosmic filaments. *Monthly Notices of the Royal Astronomical Society*, 452(1), 1052–1059. <https://doi.org/10.1093/mnras/stv1302>
- [35] Madhavacheril, M. S., et al. (2024). The Atacama Cosmology Telescope: DR6 gravitational lensing map and cosmological parameters. *The Astrophysical Journal*, 962(2), 113. <https://doi.org/10.3847/1538-4357/acff08>
- [36] Best, P. N., & Heckman, T. M. (2012). On the fundamental dichotomy in the local radio-AGN population. *Monthly Notices of the Royal Astronomical Society*, 421(2), 1569–1582. <https://doi.org/10.1111/j.1365-2966.2012.20414.x>
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