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Long-Lived Merger Signatures in the Perseus Cluster and a Candidate Remnant Interpretation

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Abstract

In cluster-merger analyses, the dominant gravitating component is often modeled as effectively history-independent after several dynamical times, even if the gas retains thermodynamic signatures of past perturbations. Recent weak-lensing work by HyeongHan et al. (2025) complicates that expectation for the Perseus Cluster by reporting a massive sub-halo, centered on NGC 1264, and a connecting mass bridge in a cool-core system long treated as a benchmark relaxed cluster. Perseus is already known from X-ray studies to host large-scale sloshing and an ancient cold front that preserve evidence of past perturbation on Gyr (gigayear) timescales. Taken together, these results motivate a re-examination of how merger history can remain observationally relevant in nominally relaxed clusters. This paper advances a deliberately modest claim. Rather than treating Perseus as a standalone falsification of ΛCDM or of conventional hydrodynamical explanations, this paper treats it as an especially informative case in which a remnant stress-energy interpretation becomes interesting enough to warrant further study. In this interpretation, long-lived gravitational structure is represented phenomenologically by a coarse-grained remnant stress-energy $T^{\mathrm{Rem}}_{\mu\nu}$, motivated by a covariant closure construction. The principal contribution of the paper is a falsifiable observational program rather than a claim of proof. After controlling for instantaneous merger parameters, residual lensing-gas centroid offsets in nominally relaxed clusters should correlate with independent merger-history proxies if such remnants are physically relevant. Existing lensing and X-ray archives already permit a pilot test, while upcoming wide-field surveys can extend the sample.

Keywords: galaxy clusters; weak gravitational lensing; Perseus Cluster; cluster relaxation; cluster mergers; stress-energy conservation

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1. Introduction

The ΛCDM model has been extraordinarily successful at reproducing the large-scale structure of the universe, the cosmic microwave background power spectrum, and the baryon acoustic oscillation scale [1]. In cluster applications, the dominant gravitating component is usually treated as collisionless and, after sufficient relaxation, effectively history-independent: the gross mass distribution is expected to be well described by the present potential and phase-space configuration without requiring explicit knowledge of remote merger history [2–4].

The collisionless part of this picture is well supported. The Bullet Cluster demonstrated at 8σ significance that the mass centroid traced by gravitational lensing separates from the gas centroid during an active merger, following the galaxies rather than the ram-pressure-decelerated intracluster medium [5]. This result has been reinforced by later work on dissociative and otherwise disturbed merging systems [6,7].

The second part of the picture is subtler. Effective history-independence is not a formal postulate of ΛCDM, but it is a common working expectation in the interpretation of apparently relaxed systems. At the same time, X-ray studies have shown that past perturbations can leave long-lived signatures even in cool-core clusters whose inner morphology appears regular. Sloshing cold fronts in "relaxed" clusters are generally interpreted as consequences of subcluster passages [6,8,9]. For Perseus specifically,

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large-scale gas motions and an ancient cold front have been argued to preserve a record of merger activity on multi-Gyr timescales [10,11]; more recent simulations find plausible scenarios in which the large front is roughly 6–8.5 Gyr old [12]. The broader lesson is that cluster history can remain observationally relevant long after the most violent phase of a merger has ended.

What makes the recent work by HyeongHan et al. [13] distinctive is that the long-lived signature is not traced only by the gas. They report a dark matter sub-halo of mass $M_{200} = (1.70^{+0.73}_{-0.59}) \times 10^{14}\,M_\odot$ at greater than 5σ significance in the Perseus Cluster (Abell 426), located approximately 430 kpc west of the cluster core and centered on NGC 1264, together with a connecting mass bridge at greater than 3σ significance. Perseus has for decades served as a reference system for relaxed cool-core clusters because of its bright central X-ray emission, well-defined cool core, and prominent but apparently ordered sloshing structure [14]. HyeongHan et al. associate the mass bridge and sub-halo with an off-axis major merger approximately five billion years ago [13].

Five billion years is several crossing times for a cluster of Perseus's mass ($M_{200} \approx 6 \times 10^{14}\,M_\odot$, $r_{200} \approx 2\,\mathrm{Mpc}$, $\sigma_v \approx 1300\,\mathrm{km\,s^{-1}}$, giving $t_{\rm cross} \approx r_{200}/\sigma_v \approx 1.5\,\mathrm{Gyr}$). That does not by itself falsify collisionless dark matter or standard merger physics, because survival times depend on orbital geometry, repeated passages, projection, and the thermodynamic response of the gas [12,13,15]. Even so, a coherent sub-halo and bridge of this scale in a benchmark cool-core cluster make Perseus an unusually sharp test case for the question of how strongly ancient merger history can persist in a system that is often described as relaxed.

The purpose of this paper is accordingly modest. Section 2 frames the Perseus result as a motivation for re-examining effective history-independence in nominally relaxed clusters. Section 3 presents remnant stress-energy as a candidate interpretation rather than an established consequence. Section 4 outlines a falsifiable population-level test capable of determining whether the remnant picture captures real astrophysical information.

2. Effective History Independence and Perseus

In idealized N-body pictures, major merger remnants tend to mix and virialize on timescales of order a few crossing times, but the details depend strongly on mass ratio, impact parameter, repeated passages, and the thermodynamic response of the gas [2,3,6]. Perseus should therefore be treated neither as a trivial example of relaxation nor as a single-object disproof of standard structure formation, but as a system probing the limits of how far history retention can remain visible in a cluster that looks relatively ordered in its core.

The existing Perseus literature already points in this direction. Large-scale sloshing motions extending well beyond the core were identified more than a decade ago [10], and the ancient cold front detected at ~ 700 kpc has been interpreted as a multi-Gyr record of past perturbation [11,12]. More generally, sloshing cold fronts are common in apparently relaxed cool-core clusters and can survive for gigayears, sometimes even through subsequent minor perturbations [8,9,15]. What HyeongHan et al. add is direct weak-lensing evidence that the long-lived signature may be present not only in the thermodynamic state of the gas but also in the reconstructed mass distribution [13].

At Perseus's mass scale, $t_{\rm cross} \approx 1.5\,\mathrm{Gyr}$, so five billion years corresponds to roughly three crossing times. That is long enough that a simple history-independent reading of "relaxed" becomes nontrivial. At the same time, conventional explanations remain viable: HyeongHan et al. model an off-axis major merger with multiple core crossings, while Bellomi et al. show that large cold fronts in Perseus can arise for a restricted but plausible range of subcluster masses and impact parameters within standard gravity and gas dynamics [12,13]. The central point is therefore not that Perseus already excludes ΛCDM, but that it exposes a gap between simple relaxation language and the full range of long-lived structures that the system may retain.

To make the above discussion quantitative and testable, define the lensing-gas centroid offset as

$$\Delta \mathbf{x} \equiv \mathbf{x}_{\rm lens} - \mathbf{x}_{\rm gas}, \tag{1}$$

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where $\mathbf{x}_{\text{lens}}$ is the projected total-mass centroid reconstructed from weak and strong lensing (sensitive to all mass, including any dark sub-structure), and $\mathbf{x}_{\text{gas}}$ is the X-ray or Sunyaev–Zel'dovich (SZ) gas centroid (sensitive only to the baryonic ICM). In an ideally relaxed system with no residual substructure, these two centroids coincide and $\Delta\mathbf{x} = 0$. Observed non-zero values of $\Delta\mathbf{x}$ can arise from instantaneous merger dynamics—such as ram-pressure displacement of gas during an ongoing interaction—or, potentially, from long-lived gravitational substructure whose lensing signal has not yet washed out. To isolate the latter, one must subtract the contribution expected from instantaneous merger parameters alone. Let $\mathbf{P}$ denote the set of observable instantaneous merger parameters (e.g., current separation, line-of-sight velocity difference, mass ratio, and morphological disturbance indices). The function $f(\mathbf{P})$ represents the mean offset predicted solely from those parameters. After controlling for $\mathbf{P}$, define the residual

$$\Delta\mathbf{x}_{\text{res}} \equiv \Delta\mathbf{x} - f(\mathbf{P}). \tag{2}$$

Here $\Delta\mathbf{x}_{\text{res}}$ isolates any offset component that cannot be attributed to the current dynamical state of the cluster. If cluster structure is effectively history-independent, no information about past merger epochs should survive in $\Delta\mathbf{x}_{\text{res}}$ once instantaneous parameters are controlled. Let H denote an independent merger-history proxy—such as cold-front age, simulated merger epoch, or radio-relic spectral age—that is measured separately from the lensing and gas data. The memoryless null hypothesis then states

$$\langle \Delta\mathbf{x}_{\text{res}} \mid H \rangle = 0 \tag{3}$$

for any such proxy H: residual offsets should be uncorrelated with independent measures of merger history if the system retains no gravitational memory.

Perseus should not be read as a single-cluster refutation of Equation (3). It should, however, be read as a strong motivation to test that null hypothesis explicitly in a population study. At minimum, the system shows that relaxed X-ray morphology and cool-core status do not guarantee the absence of structured mass features plausibly tied to ancient merger history. That observation creates space for interpretations in which merger history remains gravitationally relevant after the gas has largely re-equilibrated.

3. A Remnant Stress-Energy Interpretation

This section presents the remnant stress-energy picture as a candidate interpretation, not as a result established by Perseus alone. The claim is therefore conditional: if the explanation developed below provides a useful phenomenological description of coarse-grained history retention, then Perseus is a natural place where its phenomenology may appear.

One way to interpret the Perseus substructure within general relativity is to write the total gravitating stress-energy in the Einstein field equations as

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi G\Big[\Diamond(x)\, T^{\text{SM}}_{\mu\nu} + T^{\text{nl}}_{\mu\nu}\Big] = 8\pi G[\, T^{\text{Total}}_{\mu\nu}], \tag{4}$$

where $G_{\mu\nu}$ is the Einstein tensor encoding spacetime curvature, $g_{\mu\nu}\Lambda$ is the cosmological constant term, and the right-hand side collects all matter contributions. The term $\Diamond(x)\, T^{\text{SM}}_{\mu\nu}$ is the standard baryonic stress-energy (radiation, gas, galaxies) modulated by the smooth scalar window function $\Diamond(x) \in [0,1]$, which takes the value 1 inside the active interaction region and falls smoothly to 0 outside it across the decoherence boundary layer. This windowing encodes the physical fact that baryonic interactions are locally instantiated and cease when matter delocalizes, as discussed further below. The non-local term $T^{\text{nl}}_{\mu\nu} = T^{\text{comp}}_{\mu\nu} + T^{\text{Rem}}_{\mu\nu}$ serves as an effective closure contribution required by the contracted Bianchi identity $\nabla^{\mu} G_{\mu\nu} = 0$, rather than representing a new particle species. Setting $\Diamond(x)\, T^{\text{SM}}_{\mu\nu} + T^{\text{nl}}_{\mu\nu} \equiv T^{\text{Total}}_{\mu\nu}$, Equation (4) reduces to the standard EFE with $T^{\text{Total}}_{\mu\nu}$ sourcing curvature.

3.1. Origin of the Boundary Term

Baryonic stress-energy is not globally active. Interactions, radiation, and thermodynamic coupling occur within finite spacetime domains and cease when matter delocalizes. This is the familiar statement of decoherence: quantum systems transition from coherent, interacting configurations to delocalized, classically inert ones on a finite timescale $\tau_{\rm dec}$ [16,17]. The transition is not sharp; it occurs across a boundary layer of thickness $\epsilon \sim c\,\tau_{\rm dec}$ that is determined by the physical interaction rate of the system, not by any theoretical choice.

This finite extent of baryonic activity has a direct consequence for covariant conservation. Represent the active baryonic domain by a smooth scalar $\lozenge(x) \in [0,1]$ that takes the value 1 inside the interaction region and falls smoothly to 0 outside, across the decoherence boundary layer. Such envelope functions are standard in detector models and open quantum systems [18]. The physically instantiated baryonic stress-energy sourcing the EFE is then $\lozenge(x)\, T^{\rm SM}_{\mu\nu}$, and its covariant divergence gives

$$\nabla^\mu\Big(\lozenge\, T^{\rm SM}_{\mu\nu}\Big) = (\nabla^\mu \lozenge) T^{\rm SM}_{\mu\nu}, \tag{5}$$

where the right-hand side follows from the Leibniz rule for covariant derivatives, using the fact that $T^{\rm SM}_{\mu\nu}$ is itself conserved ($\nabla^\mu T^{\rm SM}_{\mu\nu} = 0$) in the interior. The gradient $\nabla^\mu \lozenge$ is nonzero only within the decoherence boundary layer where $\lozenge$ transitions from 1 to 0, so Equation (5) is nonzero in that layer and vanishes identically elsewhere. The contracted Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$ is a geometric identity, so within the construction of Equation (4) consistency motivates a compensating term $T^{\rm nl}_{\mu\nu}$ satisfying $\nabla^\mu T^{\rm nl}_{\mu\nu} = -(\nabla^\mu \lozenge)\, T^{\rm SM}_{\mu\nu}$. In this sense, $T^{\rm nl}_{\mu\nu}$ is introduced as an effective closure term associated with finite-support sourcing, analogous in spirit to the role played by surface stress-energy in the Israel junction conditions [19].

Within this construction, it is useful to distinguish two contributions. The compensator $T^{\rm comp}_{\mu\nu}$ is a boundary-layer term sourced by $-(\nabla^\mu \lozenge)\, T^{\rm SM}_{\mu\nu}$, supported in the decoherence layer and expected to be macroscopically negligible for ordinary, weakly localized matter. In an intense merger event, however, the baryonic localization may become sufficiently non-adiabatic that the compensator does not average away completely. The remnant $T^{\rm Rem}_{\mu\nu}$ is then introduced as the macroscopic coarse-grained contribution that can represent the surviving effect after the interaction epoch ends and phase coherence is lost. More precisely, spatial and temporal coarse-graining over scales larger than the microscopic coherence length averages out the rapidly oscillating phases in the compensator, leaving only a slowly varying, large-scale residual:

$$\langle T^{\rm comp}_{\mu\nu} \rangle_{\rm coarse} \longrightarrow T^{\rm Rem}_{\mu\nu}. \tag{6}$$

The angle brackets $\langle \cdot \rangle_{\rm coarse}$ denote a coarse-graining operation over microscopic degrees of freedom on scales below the astrophysically relevant resolution length; the arrow indicates that $T^{\rm Rem}_{\mu\nu}$ is defined as the macroscopic limit of this average. When the compensator is regular and oscillatory, this average vanishes, and no remnant survives.[1] When the baryonic localization is sufficiently intense and non-adiabatic—as during a major cluster merger—the average can yield a nonzero $T^{\rm Rem}_{\mu\nu}$. The analogy to open quantum systems is direct: tracing over environmental degrees of freedom after a strong interaction produces an effective, delocalized stress-energy that the subsystem retains even after its active coupling has ceased [18].

Neither $T^{\rm comp}_{\mu\nu}$ nor $T^{\rm Rem}_{\mu\nu}$ carries a window factor in Equation (4). Both terms must be nonzero at and beyond the boundary of the active baryonic domain, precisely where $\lozenge \to 0$. Applying $\lozenge$ to $T^{\rm nl}_{\mu\nu}$ would suppress it where it is required, causing the contracted Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$ to fail globally. The asymmetry in Equation (4)—a windowed first term and an unwindowed second term—is therefore structural rather than arbitrary. The baryonic source is windowed because it is active only during the interaction epoch; the non-local term is unwindowed because it is required to maintain global covariant conservation after that epoch has ended. This is precisely the structure of the Israel

[1] This vanishing condition is established formally in a companion paper [20].

junction conditions [19] in the sharp-window limit: the surface stress-energy is supported on the shell where the bulk stress-energy is absent, not where it is present.

3.2. Properties of $T^{\mathrm{Rem}}_{\mu\nu}$

The remnant picture is developed here using four working properties, intended as phenomenological assumptions rather than as statements established independently or by any specific particle model.

Approximate conservation. After the baryonic interaction epoch ends, the remnant component is modeled as independently conserved to a good approximation, $\nabla^{\mu} T^{\mathrm{Rem}}_{\mu\nu} = 0$, so that it behaves as a long-lived stress-energy contribution within the effective description.

Approximate pressureless form. Coarse-graining over the delocalized ensemble is assumed to suppress pressure terms. To see why, note that $T^{\mathrm{Rem}}_{\mu\nu}$ represents the coarse-grained residual of a phase-incoherent ensemble: the off-diagonal and isotropic pressure components arise from correlated microscopic velocities and phases, which average to zero over the coarse-graining volume when phase coherence is absent. What survives is the energy-density part, which is insensitive to phase cancellation. Averaging over unresolved velocities and phases in such a phase-incoherent ensemble then motivates the approximation [21]

$$T^{\mathrm{Rem}}_{\mu\nu} \approx \rho_{\mathrm{Rem}}\, u_{\mu} u_{\nu}, \qquad p_{\mathrm{Rem}} \approx 0. \tag{7}$$

Here ρ_{Rem} is the effective energy density of the remnant component, u^{μ} is its four-velocity (normalized as $g_{\mu\nu} u^{\mu} u^{\nu} = -1$), and the tensor structure $\rho_{\mathrm{Rem}}\, u_{\mu} u_{\nu}$ is the standard stress-energy form of a pressureless perfect fluid (dust). The condition $p_{\mathrm{Rem}} \approx 0$ means that the remnant does not support pressure gradients, hydrostatic equilibrium, or ram-pressure forces: it interacts gravitationally but does not respond to the thermodynamic processes that equilibrate the baryonic gas. The equation of state $w \equiv p/\rho \approx 0$ is the defining property of cold dark matter in the cosmological sense, and Equation (7) is used here as an effective kinematic approximation rather than as a claim about a specific microscopic species.

Negligible thermal coupling. In the idealized limit considered here, $T^{\mathrm{Rem}}_{\mu\nu}$ is treated as a covariant bookkeeping structure rather than as a dynamical fluid, so its coupling to ram pressure, radiative cooling, and electromagnetic interactions is taken to be negligible. In that sense, it is modeled as gravitationally active but thermally inert.

Relation to known GR constructions. The formalism is not without precedent in classical GR. In the sharp-window limit, $T^{\mathrm{comp}}_{\mu\nu}$ reduces to a surface stress-energy supported on a thin hypersurface, recovering precisely the Israel junction conditions [19]. For finite boundary-layer thickness the smooth-window generalization is structurally identical to the flux balance laws of dynamical horizons [22], where boundary-supported stress-energy is likewise required to maintain covariant conservation on marginally trapped surfaces. $T^{\mathrm{nl}}_{\mu\nu}$ is therefore not an exotic addition but a smooth generalization of boundary stress-energy constructions already present in classical GR and well-established in the context of gravitational horizon thermodynamics.

3.3. Physical Interpretation of Perseus

In this interpretation, an intense merger epoch imprints a long-lived gravitational contribution that need not track the thermal relaxation of the gas. The point is not that conventional hydrodynamical explanations are excluded; rather, the remnant picture provides a complementary way to think about why a cluster can display a cool core and relatively regular X-ray morphology while still retaining structured mass features associated with an ancient encounter.

During the merger approximately five billion years ago, the Perseus Cluster experienced an epoch of intense baryonic localization: two massive systems collided, the gas was driven into a strongly localized, ram-pressure-compressed configuration that subsequently thermalized and relaxed over several Gyr. In the remnant picture, the baryonic sector re-equilibrated because it couples to pressure and radiative cooling, whereas the seeded $T^{\mathrm{Rem}}_{\mu\nu}$ did not re-equilibrate because it is globally conserved, pressureless, and thermally inert by construction. The $\sim 2 \times 10^{14}\, M_{\odot}$ sub-halo and connecting mass bridge detected by HyeongHan et al. [13] are therefore not taken here as proof of the remnant framework, but as the kind of observational configuration in which such a framework becomes astrophysically interesting.

4. A Falsifiable Statistical Test

The Perseus detection motivates a statistical test that can distinguish an effectively history-independent description from the remnant picture in a cluster sample. The two predictions for the residual centroid offset defined in Equations (1)–(2) are

$$\Lambda\text{CDM (memoryless)}: \quad \langle \Delta \mathbf{x}_{\mathrm{res}} \mid H \rangle = 0, \tag{8}$$

$$\text{Remnant picture}: \quad \langle \Delta \mathbf{x}_{\mathrm{res}} \mid H \rangle \neq 0, \tag{9}$$

where H is an independent merger-history proxy such as simulated merger age, cold-front properties, or radio-relic spectral age. At minimum, the remnant picture predicts nonzero residuals whose sign or amplitude covaries with merger-history indicators even among systems that would often be classified as relaxed by core morphology.

A pilot study could be assembled from already observed systems with published weak-lensing maps and X-ray centroids. Subaru/HSC and HST data already provide lensing information for many clusters, while *Chandra*, *XMM-Newton*, and eROSITA provide gas morphology and centroids; future Euclid and Rubin samples should enlarge the baseline. A sample of approximately 20–30, well-characterized systems would already be informative, and a sample of 30–50 systems would support more decisive model comparison. No new theoretical machinery is required beyond explicit control of centroiding systematics, projection effects, and heterogeneous merger proxies.

This test is useful in both directions. A null result would limit the phenomenological relevance of the remnant interpretation. A statistically significant correlation would not by itself prove the specific covariant construction proposed here, but it would demonstrate that merger history remains observably encoded in nominally relaxed clusters beyond what a purely instantaneous description captures.

5. Discussion

The strongest objection to the present interpretation is that conventional cluster physics has not been exhausted. HyeongHan et al. show that an off-axis major merger can generate the observed sub-halo and bridge, while Bellomi et al. show that large Perseus cold fronts can arise for a specific range of subcluster masses and impact parameters within standard gravity and gas dynamics [12,13]. More generally, sloshing cold fronts are common in apparently relaxed cool-core clusters and can survive for gigayears [8,9,15]. For that reason, Perseus alone should not be presented as a falsification of collisionless dark matter or of ΛCDM.

What Perseus does provide is an unusually sharp motivation for a complementary interpretation. The remnant picture is interesting because it offers a single language for two observational facts that are easy to discuss separately but harder to connect physically: the gas can look morphologically settled, yet the cluster can still retain structured signatures of ancient perturbation in thermodynamic and possibly mass-tracing observables. In that sense, the value of the remnant hypothesis is not that it closes the case, but that it generates a testable expectation for cluster populations.

A second virtue is methodological. Cluster classification often relies on X-ray morphology, centroid shifts, and related relaxation proxies. Those proxies are useful, but studies of optical/X-ray offsets and other relaxation diagnostics show that different centering and disturbance measures do not always agree and can encode different aspects of the assembly history [7,23,24]. A framework that

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explicitly treats history retention as an observable quantity rather than as a nuisance may therefore be useful even if the underlying microphysics ultimately differs from the one proposed here.

It would be premature to claim that Perseus resolves broader small-scale tensions in cosmology or that remnant stress-energy is already required by the data. The more defensible conclusion is narrower: ancient merger history can remain observationally relevant in systems often treated as relaxed, and the remnant interpretation deserves evaluation against cluster samples rather than dismissal on phenomenological grounds alone.

6. Conclusions

The detection of a $\sim 2 \times 10^{14}\, M_\odot$ dark matter sub-halo and connecting mass bridge in the Perseus Cluster, approximately five billion years after the originating merger, makes Perseus an unusually informative laboratory for studying long-lived merger signatures in nominally relaxed systems. Combined with earlier X-ray evidence for large-scale sloshing and an ancient cold front, the system suggests that simple relaxation language can understate how much assembly history remains observationally relevant.

I have presented remnant stress-energy $T_{\mu\nu}^{\mathrm{Rem}}$ as one possible interpretation of this persistence. In that picture, the relevant merit is not that Perseus proves the framework, but that the framework offers a covariant language for long-lived gravitational structure without modifying general relativity. The interpretation is therefore best judged not by rhetorical reach but by its observational consequences.

The most important of those consequences is a population-level test. If, after controlling for instantaneous merger parameters, residual lensing-gas centroid offsets in nominally relaxed clusters correlate with independent merger-history proxies, then cluster history retention is astrophysically real in a way that merits explicit modeling. If no such correlation is found, the phenomenological value of the remnant picture will be sharply limited. Either result would be useful.

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References

1. Aghanim, N.; et al. Planck 2018 results. VI. Cosmological parameters. *Astronomy and Astrophysics* **2020**, *641*, A6. https://doi.org/10.1051/0004-6361/201833910.
2. Springel, V.; White, S.D.M.; Jenkins, A.; Frenk, C.S.; Yoshida, N.; Gao, L.; Navarro, J.; Thacker, R.; Croton, D.; Helly, J.; et al. Simulations of the formation, evolution and clustering of galaxies and quasars. *Nature* **2005**, *435*, 629–636. https://doi.org/10.1038/nature03597.
3. Binney, J.; Tremaine, S. *Galactic Dynamics*, 2nd ed.; Princeton University Press, 2008.

4. Mantz, A.B.; Allen, S.W.; Morris, R.G.; Schmidt, R.W.; Applegate, D.E.; Kelly, P.L.; von der Linden, A. Cosmology and astrophysics from relaxed galaxy clusters – I. Sample selection. *Monthly Notices of the Royal Astronomical Society* **2015**, *449*, 199–219. https://doi.org/10.1093/mnras/stv219.
5. Clowe, D.; Bradač, M.; Gonzalez, A.H.; Markevitch, M.; Randall, S.W.; Jones, C.; Zaritsky, D. A direct empirical proof of the existence of dark matter. *Astrophysical Journal Letters* **2006**, *648*, L109–L113. https://doi.org/10.1086/508162.
6. Markevitch, M.; Vikhlinin, A. Shocks and cold fronts in galaxy clusters. *Physics Reports* **2007**, *443*, 1–53. https://doi.org/10.1016/j.physrep.2007.01.001.
7. Shan, H.; Qin, B.; Fort, B.; Tao, C.; Wu, X.P.; Zhao, H. Offset between dark matter and ordinary matter: evidence from a sample of 38 lensing clusters of galaxies. *Monthly Notices of the Royal Astronomical Society* **2010**, *406*, 1134–1139. https://doi.org/10.1111/j.1365-2966.2010.16739.x.
8. Ascasibar, Y.; Markevitch, M. The origin of cold fronts in the cores of relaxed galaxy clusters. *Astrophysical Journal* **2006**, *650*, 102–127. https://doi.org/10.1086/506508.
9. Ghizzardi, S.; Rossetti, M.; Molendi, S. Cold fronts in galaxy clusters. *Astronomy and Astrophysics* **2010**, *516*, A32. https://doi.org/10.1051/0004-6361/200912496.
10. Simionescu, A.; Werner, N.; Urban, O.; Allen, S.W.; Ichinohe, Y.; Zhuravleva, I. Large-scale motions in the Perseus galaxy cluster. *Astrophysical Journal* **2012**, *757*, 182. https://doi.org/10.1088/0004-637X/757/2/182.
11. Walker, S.A.; ZuHone, J.; Fabian, A.; Sanders, J. The split in the ancient cold front in the Perseus cluster. *Nature Astronomy* **2018**, *2*, 292–296. https://doi.org/10.1038/s41550-018-0401-8.
12. Bellomi, E.; ZuHone, J.A.; Weinberger, R.; Walker, S.; Zhuravleva, I.; Ruszkowski, M.; Markevitch, M. On the origin of the ancient, large-scale cold front in the Perseus cluster of galaxies. *Astrophysical Journal* **2024**, *974*, 234. https://doi.org/10.3847/1538-4357/ad6a0f.
13. HyeongHan, K.; Jee, M.J.; Lee, W.; ZuHone, J.; Zhuravleva, I.; Kang, W.; Hwang, H.S. Direct evidence of a major merger in the Perseus cluster. *Nature Astronomy* **2025**, *9*, 925–931. https://doi.org/10.1038/s41550-025-02530-w.
14. Fabian, A.C.; Sanders, J.S.; Taylor, G.B.; Allen, S.W.; Crawford, C.S.; Johnstone, R.M.; Iwasawa, K. A very deep Chandra observation of the Perseus cluster: shocks, ripples and conduction. *Monthly Notices of the Royal Astronomical Society* **2006**, *366*, 417–428. https://doi.org/10.1111/j.1365-2966.2005.09896.x.
15. Vaezzadeh, I.; Roediger, E.; Cashmore, C.; Hunt, M.; ZuHone, J.; Forman, W.; Jones, C.; Kraft, R.; Nulsen, P.; Su, Y.; et al. Resilience of sloshing cold fronts against subsequent minor mergers. *Monthly Notices of the Royal Astronomical Society* **2022**, *514*, 518–534. https://doi.org/10.1093/mnras/stac784.
16. Zurek, W.H. Decoherence, einselection, and the quantum origins of the classical. *Reviews of Modern Physics* **2003**, *75*, 715–775. https://doi.org/10.1103/RevModPhys.75.715.
17. Joos, E.; Zeh, H.D.; Kiefer, C.; Giulini, D.; Kupsch, J.; Stamatescu, I.O. *Decoherence and the Appearance of a Classical World in Quantum Theory*, 2nd ed.; Springer, 2003.
18. Breuer, H.P.; Petruccione, F. *The Theory of Open Quantum Systems*; Oxford University Press, 2002.
19. Israel, W. Singular hypersurface shells in general relativity. *Nuovo Cimento B* **1966**, *44*, 1–14.
20. Hackett, S.W. Windowed Quantum Field Theory: Domain-Restricted Actions, Standard Model Recovery, and the Vanishing of Delocalized Stress-Energy, 2026. Manuscript submitted for publication. Preprint available at: https://doi.org/10.5281/zenodo.19299207.
21. Parker, L.; Toms, D. *Quantum Field Theory in Curved Spacetime: Quantized Fields and Gravity*; Cambridge University Press, 2009.
22. Ashtekar, A.; Krishnan, B. Dynamical horizons and their properties. *Physical Review D* **2003**, *68*, 104030. https://doi.org/10.1103/PhysRevD.68.104030.
23. Roberts, I.D.; Parker, L.C.; Hlavacek-Larrondo, J. Connecting optical and X-ray tracers of galaxy cluster relaxation. *Monthly Notices of the Royal Astronomical Society* **2018**, *475*, 4704–4716. https://doi.org/10.1093/mnras/sty131.
24. Seppi, R.; Comparat, J.; Nandra, K.; Dolag, K.; Biffi, V.; Bulbul, E.; Liu, A.; Ghirardini, V.; Ider-Chitham, J. Offset between X-ray and optical centers in clusters of galaxies: connecting eROSITA data with simulations. *Astronomy and Astrophysics* **2023**, *671*, A57. https://doi.org/10.1051/0004-6361/202245138.