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Article

SORT-COSMO: A Projection-Based Structural Framework for Cosmology Scale-Dependent Drift, Non-Local Correlations, and Projection-Induced Cosmic Structure

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Abstract

We introduce SORT-COSMO, the cosmology application module of the Supra-Omega Resonance Theory (SORT). SORT-COSMO provides a projection-based structural framework for analysing large-scale cosmological phenomena without modifying gravitational dynamics, introducing new fields, or performing empirical parameter fitting. The framework treats cosmological observables as structural projections of a shared operator–kernel backbone composed of idempotent resonance operators, a global consistency projector, and a non-local projection kernel. Within this geometry, scale-dependent drift, long-range coherence, and emergent structural amplification arise as projection effects rather than as consequences of altered expansion histories or additional physical degrees of freedom. SORT-COSMO formalises a set of structural diagnostics applicable to multiple cosmological anomaly classes, including scale-dependent Hubble drift, early galaxy overdensity, early supermassive black-hole seeds, low-multipole CMB modulation, and large-scale cosmic coherence. Each use case is treated as a diagnostic scenario within projection space, not as a phenomenological model or empirical fit. The framework is intentionally non-dynamical and fully compatible with standard cosmological theories, including General Relativity and ΛCDM. SORT-COSMO is positioned as a complementary structural analysis layer within the modular SORT v6 architecture, enabling cross-domain consistency with SORT-AI, SORT-QS, and SORT-CX while remaining agnostic to underlying microphysical assumptions.

Keywords: cosmological structure; projection operators; resonance algebra; Hubble tension; early galaxies; CMB anomalies; non-local correlations; structural diagnostics; SORT framework

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1. Meta: Position of the SORT-COSMO System within SORT v6

1.1. Scope and Intent of the SORT-COSMO Module

SORT-COSMO is defined as a domain application within the SORT v6 program. Its purpose is to translate the domain-independent structural machinery of SORT into a cosmology-facing diagnostic layer. The module is not positioned as a replacement for standard cosmological theory and does not compete with dynamical modeling. Instead, it provides structural diagnostics that operate on inferred cosmological observables and their scale relations, with the aim of detecting projection-induced coherence patterns, scale-dependent drift, and non-local consistency effects.

The scope of SORT-COSMO is therefore orthogonal to dynamical cosmological modeling. Dynamical models specify field content, evolution equations, and parameterized histories for expansion and structure formation. SORT-COSMO remains agnostic to such modeling choices and does not attempt to infer cosmological parameters from data. Its role in empirical cosmology is limited to structural classification and consistency analysis of published observables, maintaining compatibility with standard pipelines and reported uncertainties.

To enforce strict interpretative boundaries, SORT-COSMO adopts explicit non-claims. The framework does not modify General Relativity, does not introduce new fields or particles, does not propose a

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replacement for ΛCDM, and does not perform cosmological parameter fitting. These guardrails ensure that SORT-COSMO remains a structural diagnostic system rather than a phenomenological theory.

1.2. Shared Mathematical Backbone across SORT v6

SORT-COSMO reuses the hardened core of SORT v5 and carries it forward into SORT v6 without altering the underlying algebra. The backbone consists of a set of 22 idempotent resonance operators $\{\hat{O}_i\}$ satisfying

$$\hat{O}_i^2 = \hat{O}_i, \tag{1}$$

a global projector $\hat{H}$ defined as a weighted superposition of operators,

$$\hat{H} = \sum_i w_i \hat{O}_i, \tag{2}$$

and a non-local projection kernel $\kappa(k)$ over an abstract scale coordinate k. In its default Gaussian form, the kernel is

$$\kappa(k) = \exp\left[-\frac{(\sigma_0 L_H k)^2}{2}\right], \tag{3}$$

where σ_0 denotes the correlation scale parameter and L_H is the Hubble length. Global neutrality is encoded in the light-balance condition

$$\sum_i w_i = 0, \tag{4}$$

which constrains the projector weights and prevents trivial net projection bias.

A strict separation is maintained between the core algebra and its interpretation. The objects in Equations (A1)–(4) are domain-independent and remain fixed across all SORT v6 modules. Domain specificity enters only through interpretation and mapping to observable spaces. This modularity is expressed through the v6 decomposition

$$\mathcal{M}_{\text{SORT v6}} = \mathcal{M}_{\text{cosmo}} \oplus \mathcal{M}_{\text{AI}} \oplus \mathcal{M}_{\text{CX}} \oplus \mathcal{M}_{\text{QS}}, \tag{5}$$

where $\mathcal{M}_{\text{cosmo}}$ denotes the SORT-COSMO system. The decomposition in Equation (5) is structural and indicates that the same mathematical backbone is reused under distinct domain semantics.

1.3. Domain-Specific Interpretation for Cosmology

Within the cosmology module, the core SORT objects acquire a strictly structural meaning adapted to cosmological scale hierarchies. The resonance operators $\hat{O}_i$ are interpreted as coherence modes, selecting admissible structural patterns in an inference space of cosmological observables rather than representing physical fields. The global projector $\hat{H}$ acts as a consistency filter that enforces projective compatibility across scales. The kernel $\kappa(k)$ functions as a scale-coupling mechanism, encoding non-local correlations in scale space without implying a new interaction in physical spacetime.

A central interpretative rule of SORT-COSMO is that cosmological observables are treated as projections rather than primitives. This rule preserves a three-layer separation. The first layer is physical expansion and structure evolution governed by General Relativity and standard microphysics. The second layer is observational inference, encompassing measurement processes, calibrations, and estimators. The third layer is projection-induced structure, describing how inferred observables can exhibit systematic scale-dependent patterns when mapped through the operator-kernel framework. SORT-COSMO restricts itself to the third layer and does not attribute projection-induced diagnostics to new dynamics.

1.4. Relation to Other SORT Modules

SORT-COSMO is connected to other SORT v6 modules through shared diagnostics and identical formal primitives. With SORT-AI, it shares drift diagnostics and the classification of stable versus unstable structural regimes, where stability refers to robustness under projection and kernel coupling

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rather than dynamical stability. With SORT-QS, it shares the operator-chain viewpoint and global consistency constraints that organise multi-step transformations. With SORT-CX, it shares the emphasis on emergence, mode locking, and transitions between kernel-dominated and operator-dominated regimes. These synergies are formal and are used to maintain cross-domain continuity of notation, diagnostics, and interpretative constraints.

1.5. Role of SORT-COSMO in the Transition from v5 to v6

SORT-COSMO formalises the transition from SORT v5 to SORT v6 by extracting cosmological analyses from the v5 Whitepaper into a dedicated module while preserving the v5 mathematical core. This separation is motivated by the architectural requirement that SORT v6 supports multiple domains under a shared operator-kernel backbone, with each domain providing its own semantic mapping and validation strategy. SORT-COSMO therefore functions as a clean application layer that reorganises cosmological content without changing the algebra, projector constraints, or kernel form. In this role, the module preserves continuity with v5 results while enabling systematic cross-domain expansion in v6.

2. Introduction and Scope

2.1. Motivation: Structural Anomalies in Contemporary Cosmology

Over the past decade, contemporary cosmology has accumulated a set of persistent empirical tensions that cannot be straightforwardly attributed to statistical fluctuations or single-model inadequacies. Prominent examples include the scale-dependent discrepancy between locally inferred and early-universe values of the Hubble constant [1–3], the unexpectedly early appearance of massive galaxies and stellar populations in JWST observations [6,8,9], and indications of large-scale coherence in matter and radiation fields beyond standard ΛCDM expectations [16,17,24].

These empirical signals are typically treated as isolated problems, each addressed by targeted extensions of the underlying cosmological model. However, their recurring association with scale hierarchies, global correlations, and inference-dependent constructions motivates an alternative viewpoint. In this perspective, tensions may arise not primarily as failures of local dynamics, but as manifestations of structural effects induced by how cosmological information is aggregated, projected, and compared across widely separated scales. SORT-COSMO is motivated by the hypothesis that such anomalies can be systematically analysed as structural signals, without presupposing inadequacies of General Relativity or the standard cosmological background.

A key limitation of many existing analyses is their reliance on either strictly local probes or sharply separated scale regimes. When observables inferred at different effective scales are combined without an explicit structural consistency layer, projection-induced artefacts can accumulate unnoticed. Addressing this limitation requires a framework capable of diagnosing cross-scale structure independently of specific dynamical assumptions.

2.2. Structural versus Dynamical Explanations

Dynamical explanations in cosmology operate by modifying equations of motion, introducing additional degrees of freedom, or altering the content of the stress-energy budget. Such approaches aim to reconcile observations by changing the physical evolution of the universe. Structural explanations, by contrast, focus on the organisation and interpretation of inferred observables. They ask whether apparent inconsistencies can emerge from the way information is projected, correlated, and constrained across scales, even when the underlying dynamics remain unchanged.

SORT-COSMO adopts the structural approach. It treats projection as an independent explanatory layer that sits between physical dynamics and empirical interpretation. Within this layer, non-local correlations, scale-dependent drift, and global consistency constraints can generate observable patterns that resemble dynamical anomalies. Importantly, this does not imply that dynamics are incorrect or incomplete. Rather, it highlights that inference structures themselves can imprint systematic features

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on cosmological conclusions. This distinction between modifying dynamics and modifying structural interpretation is central to the conceptual positioning of SORT-COSMO.

2.3. Positioning of SORT-COSMO

SORT-COSMO is positioned as a diagnostic framework for structural interpretation within cosmology. It does not aim to predict new observables or to fit existing data. Instead, it provides a unified language for analysing how diverse cosmological tensions relate to scale coupling, projection geometry, and operator consistency. The framework is explicitly complementary to standard cosmological analysis and is designed to be applied post hoc to published results derived within established models such as ΛCDM and its extensions.

By construction, SORT-COSMO avoids parameter estimation and likelihood-based model comparison. Its outputs are structural diagnostics rather than best-fit values or posterior distributions. This positioning ensures that SORT-COSMO can coexist with a wide range of cosmological models and observational strategies, serving as an interpretative overlay rather than a competing theory.

2.4. Explicit Exclusions and Guardrails

To prevent overextension, SORT-COSMO enforces strict exclusions and guardrails. The framework does not address quantum gravity, does not propose alternatives to inflationary scenarios, and does not model late-time dark sector physics. It refrains entirely from likelihood analysis, Bayesian inference, or any form of cosmological parameter fitting.

These exclusions are deliberate. They ensure that SORT-COSMO remains confined to structural diagnostics and avoids conflating interpretative effects with physical mechanisms. By maintaining these boundaries, the framework preserves conceptual clarity and facilitates rigorous comparison with standard cosmological analyses without introducing ambiguity about its scope or claims.

3. Structural Backbone: Mapping SORT to Cosmology

3.1. Resonance Operators as Cosmological Structural Modes

At the core of SORT-COSMO lies a finite set of resonance operators $\hat{O}_i$, which function as abstract structural selectors within cosmological inference spaces. These operators are not assigned to physical fields, particles, or degrees of freedom. Instead, they define coherence channels that determine which large-scale structural patterns are admissible under global projection consistency. Their role is to organise inferred cosmological observables into structurally meaningful configurations without introducing new dynamics.

The operators form a closed algebra characterised by non-trivial commutation relations,

$$[\hat{O}_i, \hat{O}_j] = \sum_k f_{ij}^k \hat{O}_k, \tag{6}$$

where the structure constants f_{ij}^k encode the internal geometry of the operator space. These constants do not represent interaction strengths or coupling constants in a physical sense. Rather, they characterise how different coherence modes combine under composition and projection. The algebraic structure in Equation (A4) constrains the admissible pathways by which cosmological information can be structurally organised, thereby shaping the space of consistent projections analysed in later sections.

3.2. The Global Projector as Cosmological Consistency Filter

The global projector $\hat{H}$ acts as a consistency filter on the space of inferred cosmological structures. Defined as a weighted superposition of resonance operators,

$$\hat{H} = \sum_{i=1}^{22} w_i \hat{O}_i, \tag{7}$$

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the projector enforces global structural constraints across scales. In the context of cosmology, $\hat{H}$ operates on abstract inference states Φ constructed from observational inputs and derived quantities. Structural coherence is identified through a fixed-point condition,

$$\hat{H}\,\Phi^* = \Phi^*, \tag{8}$$

which selects configurations that are self-consistent under projection.

A central requirement is the light-balance condition,

$$\sum_{i=1}^{22} w_i = 0, \tag{9}$$

which guarantees trace-neutrality of the projector. This condition prevents trivial global bias and ensures that coherence arises from relational structure rather than from uniform amplification or suppression. Within SORT-COSMO, the projector therefore serves as a structural filter rather than a dynamical operator, distinguishing admissible inference patterns from structurally unstable ones.

3.3. The Projection Kernel as Scale-Coupling Mechanism

Scale coupling in SORT-COSMO is mediated by a non-local projection kernel $\kappa(k)$, defined over an abstract scale coordinate k. The kernel introduces correlations across scales without implying causal influence or superluminal signal propagation. Its non-locality is purely structural and reflects how information inferred at different effective scales is jointly constrained.

In its canonical Gaussian form, the kernel is given by

$$\kappa(k) = \exp\left[-\frac{(\sigma_0 L_H k)^2}{2}\right], \tag{10}$$

where σ_0 denotes the correlation scale parameter and L_H is the Hubble length. σ_0 is a structural regularization scale of the projection kernel, fixed internally by consistency and stability constraints of the operator–kernel system. It is not a physical length scale and does not correspond to a measurable cosmological parameter. The parameter σ_0 controls the effective range of structural coupling in scale space and is treated as a calibrated structural parameter rather than a fitted cosmological constant. The kernel in Equation (10) therefore encodes how projection-induced correlations decay across scale separations, providing a quantitative handle on non-local coherence effects discussed in Section 5.

3.4. Separation of Structure, Dynamics, and Phenomenology

A defining principle of SORT-COSMO is the strict separation between structure, dynamics, and phenomenology. Dynamical evolution, including cosmic expansion and structure formation, is governed by General Relativity and standard microphysics and lies outside the scope of SORT-COSMO. Structural analysis, comprising operator algebra, projector consistency, and kernel-mediated scale coupling, is handled exclusively within the SORT-COSMO framework. Phenomenology forms the interface between theory and observation, encompassing measurement procedures, estimators, and data products.

This three-layer separation ensures conceptual clarity. Structural diagnostics derived within SORT-COSMO are not interpreted as modifications of dynamics, nor as artefacts of observational systematics alone. Instead, they capture projection-induced organisation that can emerge when phenomenological outputs are analysed under global consistency constraints. Maintaining this separation is essential for preserving compatibility with standard cosmological analyses while enabling a rigorous investigation of structural effects.

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4. Projection Geometry and Cosmological Scale Spaces

4.1. Cosmological Scale Spaces in SORT

In SORT-COSMO, cosmological analysis is formulated in terms of an abstract scale space rather than physical time or spacetime coordinates. This scale space is spectral in nature and is constructed from effective observational windows, resolution scales, and characteristic wavelengths associated with cosmological probes. The scale coordinate k is therefore interpreted as a structural parameter that labels how information is aggregated and compared across different observational regimes, rather than as a dynamical wavenumber governing physical evolution.

This distinction is essential. In standard cosmology, quantities expressed as functions of k often encode physical processes such as growth of perturbations or acoustic oscillations. In SORT-COSMO, k parametrises the structural organisation of inferred observables, reflecting the scale dependence introduced by observational pipelines, window functions, and cross-calibration between probes. As a result, the scale space employed here is explicitly detached from temporal ordering and cosmic history, allowing projection effects to be analysed independently of dynamical assumptions.

4.2. Kernel-Mediated Coupling Across Scales

Coupling across the cosmological scale space is mediated by the projection kernel $\kappa(k)$, which introduces controlled non-local correlations between different scale sectors. The kernel geometry determines how strongly information inferred at one scale contributes to the structural consistency of another. Long-range coherence arises when the kernel exhibits broad support in scale space, while effective decoupling occurs when the kernel is sharply localised.

The Gaussian kernel defined in Equation (10) admits distinct suppression and enhancement regimes depending on the value of the correlation scale parameter σ_0. Small values of σ_0 restrict coupling to narrowly separated scales, approximating a scale-local analysis. Larger values permit extended coherence across widely separated observational regimes, enabling global structural alignment. In SORT-COSMO, σ_0 therefore plays a central role in selecting which scale relations are structurally relevant, without being interpreted as a physical length or interaction range.

4.3. Structural Meaning of Scale-Dependent Correlations

Scale-dependent correlations identified within SORT-COSMO are interpreted as structural rather than dynamical phenomena. A clear distinction is maintained between correlation and interaction. Correlation refers to the joint organisation of inferred quantities under projection constraints, whereas interaction implies causal influence mediated by physical laws. SORT-COSMO addresses only the former.

Projection-induced coherence arises when observables inferred at different scales satisfy global consistency conditions imposed by the operator-projector framework. Such coherence can manifest as apparent non-local patterns or alignments, even in the absence of any underlying physical interaction connecting the scales. This form of non-locality is purely structural and does not entail superluminal signalling or violations of causality. It reflects the geometry of inference space rather than properties of spacetime itself, aligning with the interpretation of large-scale anomalies as potential projection effects rather than dynamical inconsistencies [16,17].

4.4. Metric Expansion Versus Projection-Induced Drift

A central objective of SORT-COSMO is to clarify the distinction between physical metric expansion and projection-induced drift in inferred cosmological quantities. Metric expansion is governed by General Relativity and standard cosmological dynamics and is not modified by SORT-COSMO. Projection-induced drift, by contrast, refers to systematic scale-dependent deviations that can emerge when observables are compared across inference layers with differing structural assumptions.

This distinction is particularly relevant in the context of expansion-rate discrepancies [1,2]. SORT-COSMO does not reinterpret such discrepancies as evidence for modified gravity or alternative

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expansion histories. Instead, it provides a framework to assess whether part of the observed drift can be attributed to structural effects arising from scale coupling and projection geometry. By maintaining strict separation from modified gravity approaches, SORT-COSMO preserves compatibility with established dynamical theory while offering an additional interpretative layer for analysing inferred expansion behaviour.

5. Core Structural Diagnostics in Cosmology

5.1. Structural Drift as a Cosmological Diagnostic

Structural drift in SORT-COSMO quantifies changes in inferred structure across adjacent projection layers in scale space. It is defined as a normed difference between successive projected operators,

$$D_n = \left\| \hat{T}_n - \hat{T}_{n-1} \right\|, \tag{11}$$

where $\hat{T}_n$ denotes the effective projection at the n-th scale layer. The index n labels ordering in scale space rather than physical time. Consequently, D_n measures structural variation induced by changes in projection geometry or scale coupling and must not be interpreted as temporal evolution.

As a diagnostic, structural drift serves as an indicator of coherence loss or reconfiguration when moving across observational regimes. Persistent non-zero drift signals scale-dependent inconsistency in inferred structure, while vanishing or plateauing drift indicates structural stability. This diagnostic is particularly relevant when comparing results obtained from heterogeneous probes that operate at different effective scales, where projection-induced artefacts can accumulate without explicit detection [1,2].

5.2. Jacobi Consistency as a Coherence Criterion

Beyond pairwise drift, SORT-COSMO employs algebraic closure as a higher-order coherence criterion. The resonance operators $\hat{O}_i$ satisfy a closed commutator algebra, and structural consistency requires that this algebra obey the Jacobi identity,

$$[\hat{O}_i, [\hat{O}_j, \hat{O}_k]] + [\hat{O}_j, [\hat{O}_k, \hat{O}_i]] + [\hat{O}_k, [\hat{O}_i, \hat{O}_j]] = 0. \tag{12}$$

Deviations from Equation (12) indicate a Jacobi residual, which functions as a defect diagnostic for structural inconsistency.

In the cosmological context, a non-vanishing Jacobi residual does not imply a breakdown of physical laws. Instead, it signals that the inferred structural composition of observables fails to close consistently under projection. Such defects can arise when scale-dependent correlations are combined without a coherent operator geometry, making the Jacobi residual a sensitive probe of global structural coherence.

5.3. Stable Versus Unstable Structural Regimes

The combined analysis of structural drift and Jacobi consistency enables the classification of stable and unstable structural regimes. Stable regimes are characterised by coherence plateaus, where drift measures remain small across extended scale intervals and Jacobi residuals vanish within tolerance. In such regimes, inferred structures are robust under changes in projection and kernel coupling.

Unstable regimes are marked by rapid changes in drift magnitude or by the emergence of Jacobi defects, indicating transitions between incompatible structural configurations. These transitions can be associated with critical regions in scale space where kernel-mediated coupling changes character, as discussed in Section 4.2. Structurally stable configurations often correspond to idempotent fixed points satisfying

$$\hat{O}_i \, \Phi^* = \Phi^*, \tag{13}$$

where Φ^* denotes a coherent inference state. Such fixed points represent admissible structural attractors within SORT-COSMO, independent of any dynamical stability considerations.

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5.4. Non-Local Coherence without New Dynamics

A salient outcome of the diagnostics introduced above is the identification of non-local coherence patterns that do not require new physical dynamics. Kernel-mediated coupling, combined with global projector constraints, can generate large-scale alignment across widely separated scales, even when local dynamics remain standard. This coherence is structural in origin and reflects the geometry of projection space rather than the presence of additional forces or interactions.

Importantly, such non-local coherence does not entail violations of causality or superluminal influence. It arises from the simultaneous enforcement of consistency conditions across scale space, as formalised in Sections 4 and 3. Observational indications of large-scale alignment or low-multipole anomalies can therefore be examined within SORT-COSMO as potential manifestations of projection-induced structure, without invoking modifications of General Relativity or the introduction of new dynamical sectors [16,17].

6. Cosmological Use Cases

This section consolidates the six cosmological use cases of SORT-COSMO as implemented and calibrated in the MOCK v3 simulation pipeline. All use cases are formulated strictly as *structural diagnostics* derived from projection geometry and operator coherence. No empirical cosmological models, parameter fitting, likelihood analysis, or alternative dynamical theories are introduced. Numerical scalings, parameter values, and functional dependencies follow the calibrated MOCK v3 results and are consistent with the mathematically hardened SORT v5 core [46] and the associated MOCK_v3 repository.

6.1. UC-C1: Scale-Dependent Hubble Drift

In SORT-COSMO, the discrepancy between locally inferred and CMB-inferred Hubble parameters is interpreted as a projection-induced structural drift across scale space rather than as a modification of cosmic expansion dynamics. The diagnostic quantity is defined as

$$\frac{\delta H}{H_0} = \frac{H_{\mathrm{local}} - H_{\mathrm{CMB}}}{H_{\mathrm{CMB}}}, \tag{14}$$

and is treated as a scale-dependent projection observable governed by the non-local kernel $\kappa(k)$.

Using the calibrated kernel correlation scale $\sigma_0 = 0.00190642767773082$, MOCK v3 simulations yield a projected value $\delta H/H_0 \simeq 0.080$. This value reproduces the targeted structural offset within numerical uncertainty, without altering Friedmann dynamics, General Relativity, or late-time dark sector evolution. Residual deviations between projected and locally inferred values remain subdominant, supporting a purely structural interpretation [46].

6.2. UC-C2: Early Galaxy Overdensity

The unexpectedly high abundance of massive galaxies at redshifts $z \gtrsim 7$–8 is interpreted as a projection-induced amplification of structural coherence rather than as accelerated baryonic assembly. In SORT-COSMO, resonance operators concentrate admissible coherence modes at high redshift, enhancing inferred number densities without modifying collapse physics or feedback prescriptions.

The effect is quantified by a redshift-dependent enhancement factor

$$\mathcal{E}_{\mathrm{FG}}(z) = 1 + |\eta(k_{\mathrm{eff}}(z), \sigma_0)|, \tag{15}$$

with

$$\eta(k, \sigma_0) = \exp\left[-\frac{(\sigma_0 L_H k)^2}{2}\right] - 1. \tag{16}$$

Here $k_{\mathrm{eff}}(z)$ denotes the effective structural scale associated with galactic modes at redshift z. MOCK v3 results exhibit a monotonic increase of $\mathcal{E}_{\mathrm{FG}}(z)$ across $z \sim 7$–15, fully determined by kernel geometry and independent of astrophysical efficiency tuning [46].

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6.3. UC-C3: Early Supermassive Black Hole Seeds

SORT-COSMO provides a structural interpretation of early supermassive black hole seeds by attributing large inferred seed masses to projection-induced coherence in early potential wells. No dynamical collapse, accretion, or feedback model is introduced.

Across representative redshifts $z = 7, 10, 15, 20$, the MOCK v3 projection yields characteristic seed mass scales

$$10^4\, M_\odot \lesssim M_{\rm seed} \lesssim 10^8\, M_\odot, \tag{17}$$

with median values clustering around $M_{\rm seed} \approx 5 \times 10^7\, M_\odot$. These values arise from conservative structural amplification parameters, including $\eta_0 = 10^{-6}$ and a moderate projection overdensity $\delta_{\rm proj} = 0.3$. The resulting seed masses remain compatible with observational constraints while preserving a purely structural interpretation [46].

6.4. UC-C4: Low-ℓ CMB Modulation

Large-scale anomalies in the low-multipole cosmic microwave background, including hemispherical power asymmetries, are analysed as manifestations of kernel-mediated mode coupling at the largest scales. In SORT-COSMO, these effects arise from structural non-locality encoded in $\kappa(k)$ rather than from new primordial physics or modified initial conditions.

MOCK v3 diagnostics yield a relative hemispheric power asymmetry of order

$$\Delta_{\rm hem} \simeq 7.9 \times 10^{-3}, \tag{18}$$

corresponding to weak but coherent large-scale modulation. This magnitude is intentionally conservative and preserves standard recombination physics, inflationary assumptions, and statistical isotropy at the level of fundamental dynamics [46].

6.5. UC-C5: Large-Scale Cosmic Coherence

Beyond isolated anomalies, SORT-COSMO predicts emergent long-range coherence as a generic structural outcome of stable operator modes coupled through the projection kernel. At baryon acoustic oscillation and supercluster scales, MOCK v3 power-spectrum diagnostics reveal persistent kernel-stabilised features after smooth-background subtraction.

These oscillatory residuals are interpreted as structural signatures rather than as dynamical acoustic phenomena. They reflect the balance between operator-dominated and kernel-dominated regimes and provide a unified diagnostic language for large-scale correlations across galaxy surveys, without introducing additional interaction terms or dark-sector oscillators [46].

6.6. UC-C6: Projection-Induced Potential Structures

SORT-COSMO accounts for apparent large-scale potential wells and filamentary correlations as projection-induced structures arising from global kernel geometry. In MOCK v3, the real-space correlation function

$$\xi(r) = \mathcal{F}^{-1}\Big[\, |\tilde{\kappa}(\mathbf{k})|^2 \,\Big], \tag{19}$$

exhibits extended tails at separations $r \gtrsim 100\,$Mpc, culminating in coherent saturation at the largest probed scales. These quantities are not gravitational potentials and do not enter the Einstein equations. They describe geometric features of projected inference space only.

These correlations do not correspond to new forces or long-range interactions. Instead, they reflect the projection of a globally constrained kernel onto observational space. SORT-COSMO thereby provides a structural explanation for filamentary connectivity and intergalactic bridge phenomena that remains fully compatible with standard gravitational dynamics [46].

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7. Numerical Structure Validation with MOCK

This section describes the role, configuration, and interpretational limits of the MOCK v3 numerical pipeline within SORT-COSMO. MOCK is not a cosmological simulation engine and does not aim to reproduce observational datasets. Its sole purpose is the deterministic validation of structural properties implied by the SORT framework, following the mathematically hardened core developed in SORT v5 [46]. All numerical results discussed in Section 6 are derived consistently from this validation layer.

7.1. Role of MOCK as a Structural Engine

MOCK is designed as a structural validation engine rather than a forward physical simulator. It does not evolve matter, radiation, or metric degrees of freedom according to equations of motion. Instead, it explores the internal consistency, stability, and scale behavior of the projection geometry defined by SORT-COSMO.

The primary function of MOCK is to test whether a given choice of resonance operators, global projector weights, and projection kernel yields coherent and reproducible structural diagnostics across scale space. In this sense, MOCK operates as a numerical microscope for the SORT algebra, probing how abstract structural assumptions manifest when embedded into a discretised inference space.

The MOCK v3 pipeline is organised into three strictly separated validation layers:

- **Layer I: Algebraic diagnostics**, which verify idempotency, operator closure, Jacobi consistency, and light-balance conditions of the resonance operator set.
- **Layer II: Kernel calibration and σ_0 determination**, which constructs and validates the non-local projection kernel and calibrates the correlation scale in a deterministic manner.
- **Layer III: Semi-spectral evolution**, which applies repeated projection to test fields in order to assess structural stability, saturation behavior, and coherence plateaus.

Each layer builds on the previous one but introduces no new physical assumptions beyond those already present in the SORT v5 core.

7.2. Deterministic Configuration and Reproducibility

A central design principle of MOCK is strict determinism. All numerical results are fully reproducible under identical configuration settings, ensuring that reported structural trends are intrinsic to the framework rather than artifacts of stochastic sampling.

In MOCK v3, determinism is enforced through a fixed global seed,

$$\text{seed} = 117666, \tag{20}$$

which controls all pseudo-random initialisations across layers. The lattice and scale configuration used throughout the cosmological validation is fixed to

$$N = 128, \qquad L = 160\,\text{Mpc}, \tag{21}$$

corresponding to a uniform three-dimensional inference grid.

Physical reference values are introduced only as calibration anchors, not as fitted parameters. In particular, MOCK adopts

$$H_{0,\text{CMB}} = 67.4\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}, \qquad H_{\text{local}} = 73.0\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}, \tag{22}$$

to define the structural offset used in the Hubble-drift diagnostic of Section 6.1. These values are not adjusted or optimised within the pipeline.

Structural reproducibility is guaranteed by the absence of adaptive tuning, stochastic optimisation, or data-driven feedback. Re-running the MOCK v3 pipeline with identical inputs yields identical outputs at machine precision across all validation layers.

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7.3. Scope and Limits of Numerical Validation

It is essential to clearly delineate what MOCK can and cannot establish. Within its intended scope, MOCK is able to demonstrate:

- algebraic self-consistency of the SORT operator system,
- stability and boundedness of the projection kernel,
- robustness of structural diagnostics under repeated projection,
- qualitative and semi-quantitative structural trends across scale space.

However, MOCK is explicitly not designed to deliver empirical predictions. In particular, it does not provide:

- parameter estimation or uncertainty quantification,
- likelihood evaluations against observational datasets,
- statistical goodness-of-fit measures,
- falsification tests in the frequentist or Bayesian sense.

Accordingly, all numerical outputs from MOCK must be interpreted as internal consistency checks and structural plausibility demonstrations. The role of observational data in SORT-COSMO is diagnostic and interpretational, not calibrational. Any empirical confrontation of the framework necessarily occurs outside MOCK, using standard cosmological pipelines and data analysis methods, with SORT-COSMO acting solely as a structural interpretive layer.

This separation preserves conceptual clarity and prevents conflation between structural geometry and physical dynamics, in line with the guardrails established in Sections 2 and 1.

8. Cross-Domain Consistency Within SORT v6

A central design principle of SORT v6 is cross-domain structural coherence. The cosmological module SORT-COSMO is not developed in isolation but is embedded into a unified operator–kernel framework that also underlies SORT-AI, SORT-QS, and SORT-CX. This section explicates how shared diagnostics, conceptual bridges, and a common mathematical language ensure internal consistency across domains, while preserving domain-specific interpretation layers. The overarching framework and its hardened mathematical core are inherited from SORT v5 [46].

8.1. Shared Diagnostics Across Domains

All SORT v6 modules employ an identical set of core structural diagnostics, differing only in interpretation and observational interface. These diagnostics are defined at the level of the operator algebra and projection geometry and are therefore domain-independent by construction.

Across cosmology, AI systems, quantum systems, and complex systems, the following diagnostic classes are uniformly applied:

- **Drift metrics**, quantifying structural change under repeated projection or transformation.
- **Stability analysis**, identifying coherent versus unstable regimes via fixed points and bounded trajectories.
- **Projection geometry**, governing scale coupling and non-local structural correlations.
- **Fixed-point detection**, identifying idempotent or attractor-like configurations under the global projector.

In SORT-COSMO, these diagnostics are applied to cosmological scale spaces and inference structures, as detailed in Sections 5 and 6. In SORT-AI, the same tools diagnose distributional drift, alignment stability, and emergent failure modes in learning systems. SORT-QS employs them to analyse operator chains and consistency constraints in quantum circuits, while SORT-CX applies them to emergent behavior and mode locking in complex adaptive systems. The identical mathematical form of the diagnostics ensures that results across domains remain structurally comparable.

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8.2. Conceptual Bridges

Beyond shared diagnostics, SORT v6 establishes explicit conceptual bridges between domains, allowing insights from one area to inform interpretation in another without cross-contamination of physical assumptions.

The bridge between cosmology and AI is centred on drift and stability. In cosmology, structural drift indicates scale-dependent inference displacement, as in Section 6.1. In AI systems, analogous drift metrics signal distributional shift or alignment degradation. In both cases, drift is interpreted as a structural change in projection space rather than as a failure of underlying dynamics.

Between cosmology and complex systems, the unifying concept is emergence through projection. Large-scale cosmic coherence, discussed in Section 6.5, mirrors the emergence of collective modes in complex systems where kernel-dominated regimes select preferred scales. The mathematical mechanism is identical, even though the phenomenology differs.

The bridge to quantum systems is provided by operator chains and consistency constraints. The Jacobi consistency diagnostics introduced in Section 5.2 have direct analogues in the analysis of quantum operator sequences and stabilizer structures in SORT-QS. In both settings, violations of algebraic consistency indicate structural instability rather than dynamical noise.

These bridges are conceptual and structural, not physical. No cosmological interpretation is imposed on AI or quantum systems, and no quantum or AI dynamics are imported into cosmology.

8.3. Unified Operator–Kernel Language

The coherence of SORT v6 ultimately rests on a unified operator–kernel language shared across all modules. Operators represent abstract structural modes, while the projection kernel governs non-local coupling and scale selection. This vocabulary is deliberately chosen to be domain-agnostic at the algebraic level and domain-specific only at the interpretational level.

Cross-domain coherence matters for two reasons. First, it ensures that diagnostics developed in one domain can be transferred to another without redefinition or ad hoc modification. Second, it enforces internal consistency: contradictions between domains would signal structural flaws in the shared backbone rather than domain-specific anomalies.

By maintaining a common mathematical language, SORT v6 enables transferable diagnostic protocols, such as drift detection, stability classification, and kernel calibration, to be applied uniformly. SORT-COSMO thus functions not only as a cosmological application but also as a validation domain for the broader framework, demonstrating that the same structural principles can be meaningfully instantiated across fundamentally different scientific contexts [46].

This cross-domain consistency completes the architectural transition from SORT v5 to SORT v6 outlined in Section 1 and positions SORT-COSMO as an integral, but not exceptional, component of the unified framework.

9. Limitations and Explicit Exclusions

This section delineates the formal boundaries of SORT-COSMO. The framework is intentionally constrained to structural diagnostics within cosmological inference space and is not designed to provide new physical theories, empirical predictions, or parameter constraints. These limitations are essential to preserve conceptual clarity and methodological rigor across SORT v6 [46].

9.1. What SORT-COSMO Does Not Address

SORT-COSMO does not address several major areas of contemporary cosmological research. In particular, it does not engage with quantum gravity, nor does it propose any microscopic description of spacetime at the Planck scale. Questions concerning the quantisation of gravity, spacetime discreteness, or ultraviolet completions are explicitly outside the scope of this framework.

The framework does not model dark sector microphysics. It does not introduce new dark matter candidates, dark energy fields, or interactions, nor does it modify existing dark sector phenomenology.

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Similarly, SORT-COSMO does not replace or reformulate inflationary mechanisms, initial condition models, or early-universe dynamics.

Modified gravity theories are also excluded. SORT-COSMO does not alter the Einstein field equations, does not propose extensions to General Relativity, and does not introduce scale-dependent gravitational couplings. All gravitational dynamics are assumed to be governed by standard relativistic cosmology.

Finally, SORT-COSMO does not perform parameter estimation, likelihood analysis, Bayesian inference, or statistical fitting to observational datasets. The framework operates strictly at the level of structural interpretation and diagnostic consistency, as emphasised throughout Sections 3 and 5.

9.2. Interpretation Boundaries

A central interpretational boundary in SORT-COSMO lies between structural signals and observational systematics. Structural diagnostics identify patterns that may arise from projection geometry, operator consistency, or kernel-mediated scale coupling. They do not, by themselves, distinguish such effects from instrumental biases, survey selection effects, or data-processing artifacts.

SORT-COSMO further enforces a strict distinction between correlation and causation. Kernel-induced correlations, discussed in Sections 3.3 and 4.3, are structural relationships in inference space. They do not imply physical interactions, causal influence, or information transfer between distant regions of spacetime.

Projection-induced structures must also be distinguished from physical effects. Apparent coherence, drift, or amplification identified by SORT-COSMO reflects properties of the projection and inference process, not necessarily properties of the underlying physical fields. This boundary is essential to prevent misinterpretation of structural artifacts as evidence for new physics.

9.3. Risks of Over-Interpretation

The primary risk associated with SORT-COSMO is over-interpretation of structural diagnostics as empirical predictions. To mitigate this risk, the framework enforces explicit guardrails. Structural trends identified in MOCK-based analyses, such as those summarised in Section 6, are not predictions and are not expected to match observational data point by point.

SORT-COSMO maintains a clear separation between structural consistency and empirical validity. The presence of a coherent structural explanation does not imply that it is realised in nature, nor does the absence of such a structure falsify physical models. Structural diagnostics are intended to complement, not replace, empirical cosmology.

By explicitly separating structural interpretation from physical modelling and statistical inference, SORT-COSMO avoids conflating diagnostic coherence with explanatory truth. These guardrails ensure that the framework remains a controlled analytical tool rather than a source of speculative claims, consistent with its role within SORT v6 [46].

10. Role of SORT-COSMO in the SORT v6 Architecture

This section situates SORT-COSMO within the overall modular architecture of SORT v6. The role of SORT-COSMO is strictly that of a domain-specific application layer, inheriting all formal guarantees from the core theory while remaining fully separated from algebraic definition, consistency proofs, and cross-domain abstractions established elsewhere in the framework.

10.1. Modular Positioning

Within SORT v6, SORT-COSMO occupies a clean and well-defined modular position as the cosmological application module. It operates exclusively on top of the established operator algebra, global projector, and projection kernel introduced in the SORT v5 core and carried forward unchanged into v6 [46]. No algebraic objects are introduced or modified at the COSMO level.

This modular positioning ensures that SORT-COSMO performs only domain-specific interpretation. Cosmological observables are mapped onto the shared structural backbone through projection

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diagnostics, as detailed in Sections 3 and 4, without redefining operators, kernels, or consistency conditions. As a result, SORT-COSMO remains interchangeable with other SORT v6 modules such as SORT-AI, SORT-QS, and SORT-CX, all of which rely on the same mathematical core while addressing different domains.

10.2. Separation from the Core Theory

SORT-COSMO is explicitly separated from the core SORT theory. It does not duplicate definitions of resonance operators, does not restate algebraic identities, and does not introduce alternative formulations of the projection kernel. All such elements are referenced directly from the SORT v5 foundation document and its v6 continuation [46].

Consistency guarantees, including idempotency, Jacobi closure, light-balance conditions, and fixed-point stability, are inherited without modification. Structural diagnostics employed in SORT-COSMO, such as drift measures and coherence criteria discussed in Section 5, rely entirely on these inherited properties. This separation ensures that any formal inconsistencies, if present, must originate in the core theory rather than in its cosmological application.

10.3. Outlook toward Future Extensions

While SORT-COSMO is deliberately non-committal with respect to empirical validation, its modular design allows for future extensions without altering its foundational role. One possible direction is controlled integration with observational data pipelines, where SORT-COSMO diagnostics could be applied post hoc to inferred cosmological quantities as a structural consistency layer.

A second extension path concerns high-performance computing implementations. The MOCK-based numerical architecture described in Section 7 provides a prototype for deterministic structural exploration. In a future SORT v7 context, this architecture may be scaled to large parameter lattices and higher-resolution kernel evaluations using HPC resources, without changing the conceptual status of SORT-COSMO as a diagnostic framework.

No forward commitments are made regarding empirical confirmation, data-driven optimisation, or predictive deployment. Any such developments would remain optional overlays and would not alter the interpretative, non-dynamical nature of SORT-COSMO within the SORT v6 architecture.

11. Conclusions

SORT-COSMO has been presented as a structurally constrained cosmological application of the Supra-Omega Resonance Theory within the SORT v6 architecture. The framework introduces no new dynamics, fields, or parameters, and it makes no empirical claims. Instead, it provides a coherent diagnostic language for interpreting cosmological anomalies as projection-induced structural effects.

By maintaining strict separation between structure, dynamics, and phenomenology, and by inheriting all formal guarantees from the SORT v5 core [46], SORT-COSMO demonstrates how diverse cosmological tensions can be addressed within a unified, non-invasive interpretative framework. Its value lies in clarification rather than explanation, offering a consistent structural perspective that complements, rather than competes with, standard cosmology.

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Data Availability Statement: All operator definitions, kernel implementations, diagnostic modules and reproducibility artefacts associated with this study are archived under DOI: `10.5281/zenodo.17787754`. The archive includes:

- full operator registry and resonance definitions,
- kernel-parameter files and calibration data,

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- SORT-AI diagnostic code modules,
- YAML and JSON configuration files,
- deterministic mock outputs and validation datasets,
- complete SHA–256 hash manifests.

These resources enable exact regeneration of all structural and numerical results presented in this work.

Use of Artificial Intelligence: Language refinement, structural editing and LaTeX formatting were partially assisted by large language models. All mathematical structures, operator definitions, derivations, diagnostics, theoretical developments and numerical validations were created, verified and approved by the author. AI tools contributed only to non-scientific editorial assistance.

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Conflicts of Interest: The author declares no conflict of interest.

Appendix A. Operator and Kernel Reference: Cosmology Context

This appendix summarises the operator and kernel structures as they are used in the cosmological context of SORT-COSMO. All definitions are inherited unchanged from the SORT v5 core theory and are included here solely for reference and domain-specific interpretation [46].

Appendix A.1. Operator Registry

SORT-COSMO employs the full registry of twenty-two idempotent resonance operators $\{\hat{O}_i\}_{i=1}^{22}$ defined in the SORT core. Each operator satisfies the idempotency condition

$$\hat{O}_i^2 = \hat{O}_i, \tag{A1}$$

ensuring projection stability and fixed-point consistency as discussed in Section 5.

In the cosmological context, the operators are interpreted as abstract coherence modes rather than physical fields. No operator is assigned to a specific matter component, interaction, or spacetime degree of freedom. Instead, the operator set spans the admissible structural patterns in cosmological inference space.

The associated weight structure follows the light-balance condition of the SORT framework. Eleven operators carry positive weights and eleven carry negative weights, with

$$w_i \in \left\{+\frac{1}{11}, -\frac{1}{11}\right\}, \tag{A2}$$

such that the global balance constraint

$$\sum_{i=1}^{22} w_i = 0 \tag{A3}$$

is satisfied identically. This condition guarantees trace neutrality of the global projector and prevents spurious net amplification across projection cycles, as required for structural consistency [46].

Appendix A.2. Commutator Structure

The resonance operators form a closed algebra under commutation. Their mutual relations are encoded through structure constants f_{ij}^k defined by

$$[\hat{O}_i, \hat{O}_j] = \sum_{k=1}^{22} f_{ij}^k \hat{O}_k. \tag{A4}$$

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The coefficients f_{ij}^{k} characterise the internal geometry of operator space and determine admissible transitions between coherence modes. In SORT-COSMO, these constants are not interpreted dynamically. Instead, they serve as algebraic constraints governing the stability and closure diagnostics introduced in Section 5.2.

Jacobi consistency of the operator algebra is enforced through the identity

$$[\hat{O}_i, [\hat{O}_j, \hat{O}_k]] + [\hat{O}_j, [\hat{O}_k, \hat{O}_i]] + [\hat{O}_k, [\hat{O}_i, \hat{O}_j]] = 0, \tag{A5}$$

which ensures structural stability across chained projections and underlies the definition of Jacobi residuals used as coherence diagnostics.

Appendix A.3. Kernel Definition

Non-local structural coupling in SORT-COSMO is governed by the projection kernel $\kappa(k)$, defined in spectral space as

$$\kappa(k) = \exp\left[-\frac{(\sigma_0 L_H k)^2}{2}\right], \tag{A6}$$

where k denotes the spectral scale coordinate, L_H is the Hubble length, and σ_0 is the dimensionless correlation scale parameter calibrated via MOCK validation, as described in Section 7.

The kernel introduces structural, non-causal correlations across scale space. It does not represent a propagator, interaction potential, or physical coupling. Its sole function is to modulate the projection weight of different scales in inference space, consistent with the interpretation developed in Sections 4 and 3.3.

Appendix A.4. Real-Space Kernel

For interpretative purposes, the real-space representation of the projection kernel is obtained via Fourier transformation,

$$K(r) = \frac{1}{(2\pi)^3} \int d^3k\, \kappa(k)\, e^{i\vec{k}\cdot\vec{r}}, \tag{A7}$$

where $r = |\vec{r}|$ denotes the spatial separation.

The function $K(r)$ characterises the spatial extent of structural coherence induced by projection geometry. Extended tails in $K(r)$, discussed in Section 6.6, reflect non-local structural alignment rather than physical long-range forces. This distinction is essential to the interpretation boundaries outlined in Section 9.

Appendix A thus provides a consolidated reference for the operator and kernel objects employed throughout SORT-COSMO, without introducing any additional assumptions beyond those established in the SORT v5 core theory [46].

Appendix B. Structural Diagnostics Definitions

This appendix provides formal definitions of the structural diagnostics employed throughout SORT-COSMO. All diagnostics are inherited from the SORT v5 core framework and are specialised here only in terms of cosmological interpretation. No new diagnostic constructs are introduced in this appendix [46].

Appendix B.1. Drift Metric

Structural drift quantifies changes between successive projection operators in inference space. It is defined as the norm of the difference between two consecutive effective projection operators,

$$D_n = \left\| \hat{T}_n - \hat{T}_{n-1} \right\|, \tag{A8}$$

where $\hat{T}_n$ denotes the composite projection operator at iteration or scale index n.

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The drift metric is purely structural and must not be interpreted as temporal evolution. In the cosmological context, n labels resolution levels, scale windows, or inference regimes rather than physical time, as discussed in Section 5.1. A vanishing or asymptotically decreasing D_n indicates convergence toward a structurally stable projection regime.

Appendix B.2. Stability Criterion

Structural stability is defined through idempotent fixed points of the resonance operators. A state Φ^* is considered structurally stable with respect to operator $\hat{O}_i$ if

$$\hat{O}_i \Phi^* = \Phi^*. \tag{A9}$$

By idempotency of the operators, this condition implies invariance under repeated application,

$$\hat{O}_i^n \Phi^* = \Phi^* \quad \text{for all } n \geq 1. \tag{A10}$$

Stable structural regimes are characterised by the existence of such fixed points across subsets of operators. This criterion underlies the classification of stable versus unstable coherence regimes described in Section 5.3.

Appendix B.3. Jacobi Residual

Jacobi consistency provides a diagnostic for algebraic closure and structural coherence of the operator system. The Jacobi residual is defined as

$$J_{ijk} = [\hat{O}_i, [\hat{O}_j, \hat{O}_k]] + [\hat{O}_j, [\hat{O}_k, \hat{O}_i]] + [\hat{O}_k, [\hat{O}_i, \hat{O}_j]]. \tag{A11}$$

Exact vanishing of J_{ijk} indicates perfect algebraic closure and structural consistency. In numerical implementations such as MOCK, small but non-zero residuals quantify deviations from ideal closure and serve as sensitive indicators of emerging structural instabilities, as detailed in Section 5.2.

Appendix B.4. Coherence Metrics

In addition to drift and algebraic diagnostics, SORT-COSMO employs a set of aggregate coherence metrics to characterise global structural behaviour. These include energy convergence, projection stability, and mode concentration.

Energy convergence measures the monotonic decrease of a global structural energy functional under successive projections, signalling convergence toward a stable configuration, as discussed in Section 7. Projection stability evaluates the persistence of inferred structures under repeated application of the global projector $\hat{H}$. Mode concentration quantifies the dominance of specific operator modes within a projected state and provides a measure of structural localisation in operator space.

Together, these metrics form a minimal but complete diagnostic suite for assessing structural consistency within SORT-COSMO, while remaining fully independent of empirical cosmological modelling or statistical inference [46].

Appendix C. MOCK Configuration Summary

This appendix summarises the numerical configuration of the MOCK v3 pipeline used throughout SORT-COSMO. MOCK serves as a deterministic structural validation engine rather than as a physical simulation. All configurations reported here are fixed and reproducible, and they are referenced throughout Sections 6 and 7. The configuration inherits its conceptual role from the SORT v5 framework [46].

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Table A2. Mapping between SORT-COSMO use cases and MOCK v3 article modules.

ID	Use Case	Output File
1	Scale-dependent Hubble drift	`article1_hubble_drift.json`
2	Early galaxy overdensity	`article2_early_galaxies.json`
3	Early SMBH seeds	`article3_smbh_seeds.json`
4	Low-ℓ CMB anomalies	`article4_cmb_anomalies.json`
5	Large-scale cosmic coherence	`article5_dark_baryon_oscillator.json`
6	Projection-induced potential structures	`article6_intergalactic_bridges.json`

Appendix C.1. Parameters

The numerical domain is defined on a cubic lattice with fixed resolution and physical scaling. All parameters are held constant across validation runs to ensure structural reproducibility. The primary configuration parameters are as follows.

Table A1. Core MOCK v3 configuration parameters used for structural validation in SORT-COSMO.

Parameter	Value	Unit
Lattice size N	128	–
Box size L	160.0	Mpc
Grid spacing dx	1.25	Mpc
CMB Hubble constant $H_{0,\mathrm{CMB}}$	67.4	$\mathrm{km\,s^{-1}\,Mpc^{-1}}$
Local Hubble constant H_{local}	73.0	$\mathrm{km\,s^{-1}\,Mpc^{-1}}$
Hubble length L_H	4285.0	Mpc
Deterministic seed	117666	–

The deterministic seed enforces identical operator initialisation, kernel sampling, and projection ordering across all runs. This guarantees that all reported diagnostics depend only on structural configuration and not on stochastic variation, as required by the validation philosophy outlined in Section 7.2.

Appendix C.2. Validation Layers

MOCK validation is organised into three strictly separated layers, each addressing a different aspect of structural consistency. These layers correspond directly to the architecture described in Section 7.

Layer I performs algebraic diagnostics on the operator system. It verifies the presence of exactly twenty-two operators, enforces idempotency, and confirms the light-balance condition. The output of this layer is stored in the file `layer1_metrics.json` and underlies the consistency claims referenced in Sections 5.2 and A.1.

Layer II performs kernel calibration and correlation-scale verification. It evaluates the projection kernel $\kappa(k)$, determines the effective correlation scale σ_0, and verifies global energy monotonicity. Outputs are stored in `layer2_metrics.json` and auxiliary arrays, and are referenced in Sections 3.3 and 7.1.

Layer III implements semi-spectral structural evolution. This layer applies repeated global projections to assess convergence, stability, and long-range coherence. Its outputs, including energy series and convergence diagnostics, are stored in `layer3_metrics.json` and `layer3_energy_series.csv`. These results support the stability analyses discussed in Sections 5.3 and 6.6.

Appendix C.3. Article Modules

Each cosmological use case presented in Section 6 corresponds to a dedicated MOCK v3 article module. These modules operate on shared kernel and operator infrastructure but extract domain-specific structural diagnostics. The mapping between use cases and output artifacts is summarised below.

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All article modules are structurally coupled through the same operator registry, projection kernel, and deterministic configuration. Differences between modules arise solely from the diagnostic quantities extracted and the scale windows analysed. This ensures that cross-use-case comparisons remain meaningful and that all results trace back to a single, unified structural backbone [46].

Appendix D. Relation to SORT v5 Results

This appendix clarifies the formal relationship between SORT-COSMO as a v6 application module and the results established in SORT v5. The purpose is to make explicit which elements are inherited unchanged, which components have been structurally relocated, and which quantitative results from v5 remain authoritative reference points. This separation is essential to preserve mathematical continuity while enabling domain-specific clarity, as discussed in Section 1 and Section 10.

Appendix D.1. What is Inherited

SORT-COSMO inherits the complete mathematical and numerical backbone of SORT v5 without modification. In particular, the following elements are taken over verbatim.

First, the full twenty-two-operator algebra is retained, including idempotency, closure, and the commutator structure defined in SORT v5. All algebraic properties referenced in Sections 3.1 and A.1 rely directly on the v5 definitions.

Second, the global projector $\hat{H}$ together with the light-balance condition $\sum_i w_i = 0$ is inherited unchanged. The consistency guarantees derived from this constraint remain valid and underpin all fixed-point and stability arguments used throughout Sections 3.2, 5.3, and Appendix B.

Third, the projection kernel $\kappa(k)$ and its calibrated correlation scale σ_0 are taken directly from the v5 framework. No redefinition or reparameterisation is introduced in SORT-COSMO. All kernel-related expressions in Sections 3.3, 4.2, and Appendix A.3 are therefore v5-consistent by construction.

Fourth, the MOCK v3 validation framework is inherited in its entirety. The three-layer architecture described in Section 7 is the same numerical engine already used to support the v5 claims. Algebraic checks, kernel calibration, and semi-spectral convergence diagnostics are unchanged and continue to serve as the sole numerical validation mechanism.

Finally, Jacobi consistency verification and the associated residual diagnostics remain identical to those reported in v5. The interpretation of Jacobi residuals as indicators of algebraic coherence, discussed in Sections 5.2 and B.3, is inherited without alteration [46].

Appendix D.2. What is Relocated

While the mathematical core is preserved, SORT v6 introduces a strict modular separation. As a result, several elements previously embedded in the v5 whitepaper are structurally relocated rather than modified.

Most importantly, the cosmological interpretation of the projection framework is now isolated in SORT-COSMO. In v5, cosmological discussion, diagnostics, and numerical illustrations were interwoven with core theory exposition. In v6, these interpretations are confined to the present document, while the core algebra remains theory-only.

Similarly, the six cosmological use cases UC-C1 through UC-C6 are no longer presented as illustrative examples inside the core theory. They are reclassified as domain-specific structural diagnostics and documented exclusively in Section 6. This relocation clarifies that they are applications of SORT, not defining components of the theory itself.

Finally, phenomenological discussion and interpretive language related to observational cosmology have been moved out of the core framework. SORT v5 established mathematical feasibility; SORT-COSMO reframes selected results in a cosmology-specific diagnostic context, consistent with the guardrails articulated in Section 9.

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Appendix D.3. Key Results from v5

Several quantitative results established in SORT v5 remain central reference points for SORT-COSMO. These values are not rederived here but are adopted as validated structural benchmarks.

The projection-induced enhancement of early galaxy abundance was quantified in v5 as an effective enhancement factor $\mathcal{E}_{\mathrm{FG}} \approx 1.33$ at redshift $z \approx 10$. This result underlies the discussion in Section 6.2 and remains unchanged.

The scale-averaged structural Hubble drift was reported as $\delta H / H_0 = 0.08$, providing the numerical reference for the diagnostic introduced in Equation (14) and analysed in Section 6.1.

Structural seed mass estimates for early supermassive black holes were shown in v5 to lie in the range 10^4–$10^8\ M_\odot$, forming the quantitative basis for Equation (17) and the interpretation in Section 6.3.

Finally, algebraic consistency checks performed in MOCK Layer I yielded a Jacobi residual bounded by

$$\|J_{ijk}\| < 4.7 \times 10^{-15}, \tag{A12}$$

demonstrating near-machine-precision closure of the operator algebra. This result substantiates all stability and coherence claims made throughout Sections 5.2 and 5.3.

Taken together, these inherited results establish SORT-COSMO as a faithful, modular continuation of SORT v5, preserving all validated mathematical and numerical properties while providing a cleaner domain-specific presentation [46].

Appendix E. Reproducibility and Checksums

This appendix documents the reproducibility guarantees applied to all numerical results presented in SORT-COSMO. Reproducibility is treated as a structural requirement of the framework rather than as an auxiliary best practice. All numerical artefacts generated within the MOCK v3 pipeline are verifiable at the bit level and are archived together with cryptographic checksums, ensuring full traceability across computational environments, as already established in SORT v5 [46].

Appendix E.1. SHA-256 Verification

To ensure strict reproducibility, every configuration file, operator registry, kernel output, and diagnostic log produced by MOCK v3 is accompanied by a SHA–256 hash. These hashes provide bit-for-bit verification and guarantee that all numerical artefacts used in this study correspond exactly to the archived dataset referenced throughout Sections 7 and 6.

A global SHA–256 checksum has been computed over the complete MOCK v3 directory structure, including all Layer I–III outputs and configuration files. The resulting hash value is

$$H_{\mathrm{global}} = \texttt{F8305739EE41636E18D1B68E7CEE7010A91DECFCE012C38EDAC9B20B3269E507}, \tag{A13}$$

which serves as a top-level verification token. Any modification to the archived dataset, including numerical outputs, parameter files, or metadata, results in a different hash value. This mechanism ensures that all analyses reported in Sections 5 and 7 can be independently verified without ambiguity.

In addition to the global checksum, each individual file F_i contained in the MOCK v3 archive is assigned a file-level SHA–256 hash,

$$H_i = \mathrm{SHA256}(F_i), \tag{A14}$$

allowing precise verification of operator tables, parameter sets, projection matrices, kernel arrays, and diagnostic logs. This granular approach enables selective validation of individual layers or use cases without recomputing the full archive checksum.

Representative examples of file-level hashes include:

- `config.yaml` → `SHA256: a3f1...92bd`
- `operators.json` → `SHA256: e81c...5d44`
- `layer2_kernel.npy` → `SHA256: 7f02...c1aa`

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- `layer3_energy.json` → `SHA256: b91e...447c`

The complete file-level manifest, including all hashes and directory structure, is provided in the accompanying Zenodo archive associated with the MOCK v3 dataset.

Appendix E.2. Data File Checksums

For transparency and independent verification, the primary diagnostic output files referenced in this work are accompanied by explicit checksum entries. These files correspond to the validation layers described in Section 7 and are structurally linked to the use cases in Section 6.

The core diagnostic files include:

- `layer1_metrics.json` — algebraic and Jacobi consistency diagnostics
- `layer2_metrics.json` — kernel calibration and σ_0 determination
- `layer3_metrics.json` — semi-spectral evolution and convergence metrics

Each of these files is covered both by its individual SHA–256 checksum and by the global checksum given in Equation (A13). Together, these mechanisms ensure that all numerical results underlying SORT-COSMO can be reproduced exactly, independently re-analysed, and structurally audited without reliance on proprietary tools or undocumented procedures.

The reproducibility protocol described here is inherited directly from SORT v5 and applies uniformly across all SORT v6 modules, reinforcing cross-domain consistency as discussed in Section 8 [46].

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