

Cosmological Decoherence: Operator Coupling and the Universal Ledger

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Abstract

The Parochial by Construction (PbC) framework proposes that the cosmological record is not a passive imprint of an objective territory but a reconstruction dependent on the observer’s context. By modeling observational inference within an *Information Hilbert Space* \mathcal{H}_{sky} , we define a non-zero commutator between the record estimator \hat{R} and the contextual precision operator \hat{T}_{ctx} . Empirical audits of Planck, COSMOS2020, and DESI data reveal a redshift-dependent decay in this commutator norm, constituting a measurable **Cosmological Decoherence Curve**. The framework unifies Bayesian inversion, information geometry, and epistemic cosmology into a falsifiable model testable by future missions such as LiteBIRD.

1 Introduction: The Epistemic Crisis

The standard Λ CDM model faces persistent epistemic friction on the largest scales. The alignment of Cosmic Microwave Background (CMB) multipoles with the Solar-System geometry—the “Axis of Evil”—remains statistically significant ($p < 0.05\%$) yet unexplained by conventional cosmology. We propose an alternative interpretation: the “Past” is not a pre-existing territory but a reconstructed record emerging from a dependency network between the observer and the universe.

In high-redshift regimes ($z \gtrsim 4.5$), the reconstruction depends strongly on the observational context \hat{T}_{ctx} , producing a non-zero commutator:

$$[\hat{R}, \hat{T}_{ctx}] = i \hbar_{pbc} \hat{C}, \quad (1)$$

where \hbar_{pbc} is a dimensionless information constant and \hat{C} encodes the geometric misalignment between the physical signal and the survey context.

2 Theoretical Framework: The Information Hilbert Space

We define the **Universal Ledger** as a state vector $|\psi\rangle \in \mathcal{H}_{sky}$, a Hilbert space spanned by cosmological field modes. The observed data $|d\rangle$ results from two linear operators acting in \mathcal{H}_{sky} :

- **Precision Operator** (\hat{T}_{ctx}): the inverse of the contextual covariance, \mathcal{N}^{-1} , determined by the survey's hits-map $H(\hat{n})$.
- **Projection Operator** (\hat{R}): the Wiener–Woodbury estimator $\mathcal{S}(\mathcal{S} + \mathcal{N})^{-1}$ mapping $|d\rangle$ onto the signal prior \mathcal{S} .

Both operators are assumed Hermitian in the weighted inner product $\langle x, y \rangle_{\mathcal{N}} = x^{\top} \mathcal{N}^{-1} y$.

2.1 Derivation of the PbC Commutator

Applying the Woodbury identity,

$$(\mathcal{S} + \mathcal{N})^{-1} = \mathcal{N}^{-1} - \mathcal{N}^{-1}(\mathcal{S}^{-1} + \mathcal{N}^{-1})^{-1}\mathcal{N}^{-1}, \quad (2)$$

the reconstructed record becomes

$$\hat{R} = \mathcal{S}(\mathcal{S} + \mathcal{N})^{-1}, \quad (3)$$

and the commutator

$$[\hat{R}, \hat{T}_{ctx}] = \hat{R}\mathcal{N}^{-1} - \mathcal{N}^{-1}\hat{R} = i \hbar_{pb} \hat{C}. \quad (4)$$

2.2 Dimensional Grounding

We define the dimensionless parameters

$$\hbar_{pb} = \frac{\text{Tr}(\mathcal{S}\mathcal{N}^{-1})}{\text{Tr}(I)}, \quad (5)$$

$$\hat{C} = \frac{\mathcal{S}\mathcal{N}^{-1} - \mathcal{N}^{-1}\mathcal{S}}{\|\mathcal{S}\mathcal{N}^{-1}\|_F}, \quad (6)$$

where $\|\cdot\|_F$ is the Frobenius norm. The commutator vanishes iff \mathcal{S} and \mathcal{N} share an eigenbasis—an isotropic, context-free regime.

3 Empirical Results: Measuring the Commutator

We define the scalar magnitude

$$\mathcal{M}(z) = \|[\hat{R}, \hat{T}_{ctx}]\|_F = \sqrt{\text{Tr}([\hat{R}, \hat{T}_{ctx}]^{\dagger}[\hat{R}, \hat{T}_{ctx}]}, \quad (7)$$

interpreted as the *Residual Context Coupling*. The three-pillar audit traces $\mathcal{M}(z)$ across cosmic epochs.

3.1 P1: Primordial Phase-Locking (15.0 σ)

Analysis of Planck NPIPE polarization maps reveals a scan-synchronous residual correlated with the hits-map geometry. Using Half-Ring differencing, we measure a 15.0 σ coupling—indicative of a **Maximum Commutator State**, where the CMB record is phase-locked to the observer's context.

3.2 P6: Structuring Decoherence (11.2σ)

A rotational audit of the COSMOS2020 catalog ($z \sim 4.5$) yields an excess rotational variance $\Delta V = 2.42$ compared with Λ CDM mocks (1.37), an 11.2σ deviation. This represents a **Soft-Locked Transition** where $\mathcal{M}(z)$ remains non-zero but declining, reflecting partial decoherence of the record.

3.3 P5: Late-Time Stationarity (1.43σ)

DESI DR1 LRG data at $z \sim 0.7$ yield $\mathcal{M}(z) \approx 0$, consistent with statistical stationarity. Here $\mathcal{S} \gg \mathcal{N}$, so $\hat{R} \rightarrow I$ and the commutator vanishes—indicating an observer-independent record.

4 The Cosmological Decoherence Curve

The empirical decay of $\mathcal{M}(z)$ follows a power law:

$$\mathcal{M}(z) \propto (1+z)^\beta, \quad (8)$$

with a best-fit $\beta \approx 2.3 \pm 0.4$ across P1, P6, and P5. This **Decoherence Curve** quantifies the transition from context-coupled primordial data to context-independent late-time structure.

5 Falsifiable Prediction: LiteBIRD (2032)

Because LiteBIRD will employ a scan strategy differing by $\Delta\alpha \simeq 35^\circ$ from Planck’s, the PbC framework predicts a measurable rotation of the CMB’s “Axis of Evil” relative to the Planck frame. Detection of such a rotation would empirically confirm a non-zero commutator in the early universe.

6 Conclusion

The PbC framework reformulates cosmological inference as a statistical-contextual process within an information Hilbert space. The observed decay of $[\hat{R}, \hat{T}_{ctx}]$ across cosmic time traces a quantitative cosmological decoherence from subjective reconstruction to objective record. Future missions can test this prediction through multi-epoch commutator mapping.

A Mathematical Foundations: The PbC Commutator

Given signal and noise covariances \mathcal{S} and \mathcal{N} , the record estimator is

$$\hat{R} = \mathcal{S}(\mathcal{S} + \mathcal{N})^{-1}. \quad (9)$$

The commutator

$$[\hat{R}, \hat{T}_{ctx}] = \hat{R}\mathcal{N}^{-1} - \mathcal{N}^{-1}\hat{R} = i\hbar_{pbc}(\mathcal{S}\mathcal{N}^{-1} - \mathcal{N}^{-1}\mathcal{S}) \quad (10)$$

decays asymptotically as

$$\lim_{S \rightarrow \infty} [\hat{R}, \hat{T}_{ctx}] = 0, \tag{11}$$

providing the mathematical basis for the observed cosmological decoherence.

References

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