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 ΛCDM 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:

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

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,

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

the reconstructed record becomes

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

and the commutator

$$[\hat{R}, \hat{T}_{ctx}] = \hat{R}\mathcal{N}^{-1} - \mathcal{N}^{-1}\hat{R} = i\,\hbar_{pbc}\,\hat{C}. \tag{4}$$

2.2 Dimensional Grounding

We define the dimensionless parameters

$$\hbar_{pbc} = \frac{\mathrm{Tr}(\mathcal{S}\mathcal{N}^{-1})}{\mathrm{Tr}(I)}, \tag{5}$$

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

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

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

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

3.1 P1: Primordial Phase-Locking (9.8σ)

Analysis of Planck NPIPE polarization maps reveals a scan-synchronous residual correlated with the hits-map geometry. Using Half-Ring differencing, we measure a 9.8σ 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 ΛCDM 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 $\hat{R} \to I$ 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:

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

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

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

The commutator

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

decays asymptotically as

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

providing the mathematical basis for the observed cosmological decoherence.

References

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[3] DESI Collaboration, "DESI Early Data Release," (2023).

[4] LiteBIRD Collaboration, "Probing Cosmic Inflation with LiteBIRD," (2023).