Cosmological Update Dynamics from Non-Equilibrium Information Geometry: An Effective Markovian Framework

Kiichi Yamada
Independent Researcher, Japan
kiichi.yamada@gmail.com

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Abstract

We propose an effective Markovian coarse-grained cosmological framework in which large-scale information dynamics are driven by non-equilibrium fluctuations. Non-equilibrium is quantified by the dimensionless temperature fluctuation intensity

$$\phi(t) = \left(\frac{\Delta T(t)}{T(t)} \right)^2,$$

We model dissipation as proportional to this intensity under cosmological coarse-graining. Identifying the effective baseline rate with the Hubble expansion rate $H(t)$, we obtain a cosmological update frequency

$$\alpha(t) = H(t)\phi(t).$$

The framework combines variational free energy, Fisher information geometry, and an effective Lindblad-type evolution to connect probabilistic mismatch, dissipation, and cosmic expansion. At late times, the model yields a parameter-free prediction

$$\alpha_{\mathrm{obs}} = H_0\phi_{\mathrm{obs}},$$

where ϕ_{obs} is determined directly from the observed CMB angular power spectrum. This proposal establishes a minimal observationally anchored relation between cosmological expansion and effective information-dynamical evolution within a coarse-grained Markovian description.

1 Non-Equilibrium Intensity

We quantify cosmological non-equilibrium via the dimensionless temperature fluctuation intensity

$$\phi(t) = \left(\frac{\Delta T(t)}{T(t)} \right)^2. \tag{1}$$

We define

$$\theta(t) = \ln \phi(t). \tag{2}$$

2 Variational Free Energy and Information Geometry

We adopt the variational free energy

$$F = D_{KL}(q(z) \parallel p(z)), \tag{3}$$

where $q(z)$ denotes a coarse-grained cosmological distribution and $p(z)$ a reference equilibrium state.

Locally,

$$F \approx \frac{1}{2}\Delta\theta^2 I(\theta), \tag{4}$$

where $I(\theta)$ is the Fisher information metric.

3 Coarse-Grained Dissipation

We model dissipation as

$$\Gamma(t) = \Gamma_0\phi(t), \tag{5}$$

and identify $\Gamma_0 \sim H(t)$, yielding

$$\Gamma(t) = H(t)\phi(t). \tag{6}$$

4 Effective Markovian Evolution

The Lindblad equation is adopted here as an effective Markovian coarse-grained description of cosmological information dynamics:

$$\frac{d\rho}{dt} = -\frac{i}{\hbar}[H,\rho] + \Gamma(t)\sum_j \left(L_j\rho L_j^\dagger - \frac{1}{2}\{L_j^\dagger L_j, \rho\}\right). \tag{7}$$

5 Cosmological Update Frequency

We define

$$\alpha(t) = \frac{|\dot{F}(t)|}{\hbar}. \tag{8}$$

Assuming $|\dot{F}| \sim \hbar\Gamma$, which is understood as a minimal closure consistent with dissipative quantum dynamics, we obtain

$$\alpha(t) = H(t)\phi(t). \tag{9}$$

6 Observational Connection

Using spherical harmonic expansion of CMB anisotropies,

$$\phi_{\text{obs}} = \sum_{\ell=2}^{\ell_{\max}} \frac{2\ell+1}{4\pi} C_\ell W_\ell. \tag{10}$$

The predicted late-time update frequency is

$$\alpha_{\text{obs}} = H_0\phi_{\text{obs}}. \tag{11}$$

7 Conclusion

We have proposed an effective Markovian coarse-grained cosmological framework linking non-equilibrium fluctuation intensity with cosmological expansion through the minimal relation $\alpha = H\phi$. Extensions beyond the effective Markovian approximation, including possible non-Markovian memory effects, remain directions for future investigation within a broader non-Markovian generalization.

References

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