Quantum-Entropy Field Theory: Emergent Spacetime, Energy, and Horizon Entanglement

Tom Chen

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Abstract

We present a **Quantum-Entropy Field Theory (QEFT)** in which the fundamental degrees of freedom are entropy configurations on codimension-1 spatial slices. Time, space, energy, and cosmological expansion emerge from the semiclassical evolution of the quantum entropy field. The theory respects the **Inside–Out Equivalence Principle (IOEP)**, enforcing duality between black hole horizons and cosmological horizons, and naturally includes horizon-layer entanglement. We derive the emergent Friedmann equation and show how an effective cosmological constant arises from entanglement entropy.

1 Quantum-Entropy Field

Let $S(x)$ be the **quantum-entropy field** on a 3D codimension-1 slice Σ. This field includes:

- S_{bulk} — entropy of bulk configurations
- S_{ent} — entanglement entropy between virtual or real horizon layers

The wavefunctional is:

$$\Psi[S] = \Psi[S(x),\ x \in \Sigma]. \tag{1}$$

2 Master Equation

The wavefunctional satisfies the quantum-entropy master equation:

$$\hat{\mathcal{H}}\Psi[S] = \left[-\frac{\hbar^2}{2} \int_\Sigma d^3x\, d^3y\, G(x,y) \frac{\delta^2}{\delta S(x)\delta S(y)} + \mathcal{V}[S] \right] \Psi[S] = 0. \tag{2}$$

Components

- $G(x,y) = G(y,x) = G(-x,-y)$ — symmetric, IOEP-even correlation kernel.
- $\mathcal{V}[S] = \int_\Sigma d^3x \left[\frac{1}{2}\kappa(x)(\nabla S)^2 + \rho_{\text{bulk}}(x) S + \rho_{\text{ent}}(x) S_{\text{ent}}(x) + U(S) \right]$ — effective potential.

IOEP symmetry imposes:

$$G(x,y) = G(-x,-y), \quad \kappa(x) = \kappa(-x), \quad \rho_{\text{bulk}}(x) = \rho_{\text{bulk}}(-x), \quad \rho_{\text{ent}}(x) = \rho_{\text{ent}}(-x). \tag{3}$$

3 Semiclassical Limit (WKB)

Assume

$$\Psi[S] = A[S]\, e^{\frac{i}{\hbar} S_{\rm cl}[S]}. \tag{4}$$

Then the functional Hamilton–Jacobi equation:

$$\frac{1}{2}\int_\Sigma d^3x\, d^3y\, G(x,y) \frac{\delta S_{\rm cl}}{\delta S(x)} \frac{\delta S_{\rm cl}}{\delta S(y)} + \mathcal{V}[S_{\rm cl}] = 0. \tag{5}$$

Conjugate momentum field:

$$\pi(x) = \frac{\delta S_{\rm cl}}{\delta S(x)}. \tag{6}$$

4 Emergent Time and Energy

Relational emergent time T along the semiclassical flow:

$$\partial_T S(x;T) = \int_\Sigma d^3y\, G(x,y)\pi(y). \tag{7}$$

Emergent energy:

$$E_{\rm emerg} = \int_\Sigma d^3x\, \pi(x)\, \partial_T S(x;T) = \frac{1}{2}\int_\Sigma d^3x d^3y\, \pi(x) G(x,y)\pi(y) + \mathcal{V}[S_{\rm cl}]. \tag{8}$$

5 Emergent Spatial Metric

The spatial metric is extracted from correlations of S:

$$g_{ij}(x) \sim \left(\frac{\delta^2 S_{\rm cl}}{\delta S(x) \delta S(y)} \right)^{-1}_{y\to x}. \tag{9}$$

6 Entanglement Between Layers

Horizon-layer entanglement:

$$S_{\rm ent}(x) = \sum_{\rm layers} f(|x-x'|) S(x'), \quad f(|x-x'|) = f(|-x-(-x')|), \tag{10}$$

ensuring IOEP symmetry. The contribution in the potential: $\rho_{\rm ent}(x) S_{\rm ent}(x)$.

7 Emergent FRW Cosmology

Assume homogeneity and isotropy:

$$S(x,t) \to S(t), \quad \rho_{\rm bulk}(x) \to \rho_{\rm bulk}(t), \quad \rho_{\rm ent}(x) \to \rho_{\rm ent}(t). \tag{11}$$

Gradient term vanishes. Hamilton–Jacobi reduces to:

$$\frac{1}{2} G_0 \left(\frac{dS}{dt}\right)^2 + \rho_{\rm bulk}(t) S(t) + \rho_{\rm ent}(t) S_{\rm ent}(t) + U(S) = 0, \tag{12}$$

with

$$G_0 = \int_{\Sigma} d^3x d^3y \, G(x,y). \tag{13}$$

Emergent scale factor:

$$a(t) \sim \ell_P \sqrt{\frac{S(t)}{\pi}}. \tag{14}$$

Hubble rate:

$$H(t) = \frac{\dot{a}}{a} = \frac{\dot{S}}{2S}, \quad \dot{S}^2 = \frac{2}{G_0} \Big[-\rho_{\text{bulk}}(t) S - \rho_{\text{ent}}(t) S_{\text{ent}}(t) - U(S) \Big]. \tag{15}$$

8 Effective Cosmological Constant

For large S, entanglement dominates:

$$\Lambda_{\text{eff}} \sim \frac{\rho_{\text{ent}} S_{\text{ent}}}{G_0 S^2} \approx \text{constant}. \tag{16}$$

9 Summary

- Fundamental field: quantum entropy $S(x)$ including bulk + horizon entanglement.
- Master equation: $\hat{\mathcal{H}}\Psi[S] = 0$ with IOEP symmetry.
- Semiclassical limit $\to$ emergent time, energy, and metric.
- Homogeneous $S(t) \to$ FRW cosmology: $a(t) \sim \sqrt{S(t)}$, $H(t) = \dot{S}/(2S)$.
- Horizon entanglement naturally generates effective cosmological constant.

References

1. Ryu, S., & Takayanagi, T. (2006). Holographic Derivation of Entanglement Entropy from AdS/CFT. *Physical Review Letters*, 96(18), 181602. `https://doi.org/10.1103/PhysRevLett.96.181602`

2. Dong, X., Qi, X.-L., & Yang, Z. (2020). Effective entropy of quantum fields coupled with gravity. *Physical Review D*, 102(6), 066015. `https://doi.org/10.1103/PhysRevD.102.066015`

3. Bousso, R. (2002). A covariant entropy conjecture. *Journal of High Energy Physics*, 2002(06), 028. `https://doi.org/10.1088/1126-6708/2002/06/028`

4. Fischler, W., & Susskind, L. (1998). Holography and cosmology. *Physics Letters B*, 393(1-2), 71-75. `https://doi.org/10.1016/S0370-2693(96)01535-6`

5. Nishioka, T. (2018). Entanglement entropy: holography and renormalization group. *Progress of Theoretical and Experimental Physics*, 2018(1), 1-25. `https://doi.org/10.1093/ptep/pty013`

6. Bousso, R., Casini, H., Fisher, Z., & Maldacena, J. (2014). Entropy on a null surface for interacting quantum field theories and the Bousso bound. *Journal of High Energy Physics*, 2014(6), 51. https://doi.org/10.1007/JHEP06(2014)051