

# CUP- $\Omega^*$ : A Covariant GKLS–Einstein–Langevin Universal Equation for Thermodynamically Consistent Quantum–Informational Dynamics in the CUCE/Spinoza/Hilbert Framework

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**Submitted:** 2025, Nov 10 ; **Accepted:** 2025, Dec 22; **Published:** 2026, Jan 05

**Citation:** Merino, G. V. (2026). CUP- $\Omega^*$ : A Covariant GKLS–Einstein–Langevin Universal Equation for Thermodynamically Consistent Quantum–Informational Dynamics in the CUCE/Spinoza/Hilbert Framework. *AI Intell Sys Eng Med Society*, 2(1), 01-11.

## Abstract

*We formulate CUP- $\Omega^*$  as a covariant evolution law for a quantum state functional defined on Cauchy hypersurfaces. The generator combines Tomonaga–Schwinger hypersurface dynamics with a covariant GKLS dissipator constructed from modular jump operators relative to a unified thermodynamic target state. Under explicit locality and integrability conditions, the evolution is foliation independent. Under detailed balance and primitivity assumptions, the quantum relative entropy to the target state provides a Lyapunov functional, ensuring a second-lawtype monotonicity and exponential convergence to a unique attractor. We further couple the matter dynamics to an Einstein–Langevin stochastic semiclassical gravity equation to encode stress-tensor fluctuations and back-reaction consistently. Finally, we derive falsifiable, quantitative constraints—finite-step Choi positivity, order-independence under spacelike update exchange, and monotone relative entropy decay—that can be tested in controlled open quantum platforms and interpreted as physically grounded stability principles for learning-like dynamics.*

**Keywords:** Covariant Open Quantum Systems, Quantum Markov Semigroups, Detailed Balance, Tomonaga–Schwinger Equation, Stochastic Gravity, Information Geometry, Thermodynamic Learning

## 1. Introduction

A recurring technical challenge in both quantum information science and artificial intelligence is to design dynamics that are simultaneously expressive and stable. In quantum platforms, stability means admissibility of the evolution (complete positivity and trace preservation) and compatibility with thermodynamic constraints, often expressed by detailed balance and entropy production inequalities for quantum dynamical semigroups [1-4]. In machine learning, stability is often enforced by requiring monotone descent of a loss or free-energy functional, echoing information–thermodynamic constraints on computation [5-7]. The CUCE/Spinoza/Hilbert framework proposes that these motifs are not merely analogous but operationally unified: a single dynamical principle should govern reversible (Hamiltonian) change, irreversible organization (thermodynamics), and informational constraints (observer/prior).

The refined universal equation CUP- $\Omega^*$  provides a concrete proposal in this direction by embedding completely positive opensystem evolution into the Tomonaga–Schwinger (TS) hypersurface formalism, and by allowing a stochastic semiclassical gravitational coupling consistent with the Einstein–Langevin approach [8-11]. This manuscript has three goals. First, we state a self-contained definition of CUP- $\Omega^*$  and identify minimal axioms guaranteeing covariance and finite-step complete positivity. Second, we establish a thermodynamic stability structure in which quantum relative entropy to a unified target state is a Lyapunov functional, yielding secondlaw monotonicity

and exponential convergence under primitivity. Third, we provide falsifiable and quantitative predictions suitable for experimental tests in engineered open quantum systems and for conceptual transfer to AI as a template for stable “learning-like” dynamical flows.

## 2. Results

### 2.1. State Functional on Hypersurfaces and the Local Generator

Let  $\Sigma$  be a spacelike Cauchy hypersurface in a globally hyperbolic spacetime. We write  $\rho[\Sigma]$  for the density operator describing the quantum state restricted to  $\Sigma$  (the TS state functional). An infinitesimal deformation of  $\Sigma$  at  $x \in \Sigma$  is denoted  $\delta\Sigma(x)$ .

• **Definition 1:** (CUP- $\Omega^*$  local evolution law). The refined universal equation CUP- $\Omega^*$  postulates the functional differential equation

$$\begin{aligned} \frac{\delta\rho[\Sigma]}{\delta\Sigma(x)} = & -i[H_{\perp}(x) + H_{LS}(x), \rho] \\ & + \int_{\mathbb{R}} d\tau \chi_{\ell}(\tau) \sum_{\alpha} \gamma_{\alpha}(x) \left( L_{\alpha}(x, \tau) \rho L_{\alpha}^{\dagger}(x, \tau) \right. \\ & \left. - \frac{1}{2} \{L_{\alpha}^{\dagger}(x, \tau) L_{\alpha}(x, \tau), \rho\} \right) \end{aligned} \quad (1)$$

Limit	Expected behavior
$\gamma_{\alpha} \rightarrow 0$ (closed-system limit)	Reduces to TS unitary hypersurface evolution: $\delta\rho/\delta\Sigma(x) = -i[H_{\perp} + H_{LS}, \rho]$ .
$\eta \rightarrow 0$	$\sigma_{*} \rightarrow \sigma_{\text{KMS}}$ : standard thermal detailed-balance open dynamics (KMS-driven).
$\eta \rightarrow 1$	$\sigma_{*} \rightarrow \sigma_{O,P}$ : prior/constraint-driven attractor, interpretable as informational objective.
$\ell \rightarrow 0$ (sharp coarse-graining)	Local-in- $\tau$ GKLS update; sensitivity to bath correlations increases.
Large-scale weak noise	Einstein–Langevin sector captures low-frequency stress-tensor fluctuations via noise kernel.

**Table 1: Limiting regimes of CUP- $\Omega^*$  (illustrative).**

Here  $H_{\perp}(x)$  is the TS Hamiltonian density (normal component),  $H_{LS}(x)$  is a local Lambshift counterterm,  $\chi_{\ell}(\tau) \geq 0$  is a normalized coarse-graining kernel with  $\int d\tau \chi_{\ell}(\tau) = 1$ , and  $\gamma_{\alpha}(x) \geq 0$  are local rates. Equation (1) is a covariant analogue of the GKLS master equation formulated in hypersurface language [1,2]. The kernel  $\chi_{\ell}$  implements finite-resolution coarse-graining at scale  $\ell$ , analogous to weak-coupling coarse-graining in Davies-type limits, but written in a covariant parameterization  $\tau$  compatible with local hypersurface updates [12,13].

### 2.2. Unified Thermodynamic Target State and Modular Jumps

The GKLS jump operators are chosen to be *modular* with respect to a target state  $\sigma_{*}$ :

$$L_{\alpha}(x, \tau) = \sigma_{*}(x)^{1/2} F_{\alpha}(x, \tau) \sigma_{*}(x)^{-1/2}, \quad (2)$$

where  $F_\alpha$  are primitive “bare” operators specifying local channels (noise, measurement, control, coarse-grained couplings). The modular form (2) enforces a detailed-balance symmetry (GNS symmetry) relative to  $\sigma_*$ , making  $\sigma_*$  stationary for the dissipative dynamics under standard regularity assumptions [14–16]. The target state itself is constructed as a weighted geometric mean between a local KMS state and an observer/prior state:

$$\sigma_*(x) = \sigma_{\text{KMS}}(x) \#_\eta \sigma_{O,P}(x), \quad 0 \leq \eta \leq 1, \quad (3)$$

with  $\#_\eta$  the Kubo–Ando weighted geometric mean for positive operators [17,18]:

$$A \#_\eta B = A^{1/2} \left( A^{-1/2} B A^{-1/2} \right)^\eta A^{1/2}. \quad (4)$$

Operationally,  $\sigma_{\text{KMS}}$  captures environment-induced thermodynamic equilibrium (KMS structure) [12,19,3], while  $\sigma_{O,P}$  captures informational constraints (prior, control objective, or observer state). The interpolation parameter  $\eta$  controls the relative weight. Minimal full-rank regularization (e.g.,  $\sigma_* \mapsto (1-\varepsilon)\sigma_* + \varepsilon I/d$ ) may be used when required for invertibility in (2), without changing operational predictions at resolution  $\ell$ .

Axiom	Operational consequence
Locality and TS integrability (5)	Foliation independence: spacelike update order does not change $\rho[\Sigma]$ (Theorem 1).
Finite-step CPTP (positive Kossakowski form; $\chi_\ell \geq 0$ )	Complete positivity and trace preservation for finite steps; testable via Choi-positivity (Theorem 2, Proposition 1).
Modularity and detailed balance w.r.t. $\sigma_*$	$\sigma_*$ is stationary; relative-entropy production is nonnegative and $D_{\text{rel}}(\rho \parallel \sigma_*)$ decays monotonically (Theorem 3).
Primitivity	Uniqueness of the fixed point and exponential convergence (spectral gap/log-Sobolev behavior).
Einstein–Langevin compatibility (8)	Conserved stochastic back-reaction consistent with Bianchi identities and noise-kernel structure.

**Table 2: CUP- $\Omega^*$  Axioms and Their Operational Consequences**

### 2.3. Consistency Axioms

We now state explicit axioms sufficient for covariance, finite-step admissibility, and stability.

- **Definition 2:** (Locality and TS integrability). Let  $L(x)$  denote the local superoperator defined by the right-hand side of (1). For spacelike-separated points  $x, y \in \Sigma$ ,

$$[L(x), L(y)] = 0, \quad [H_\perp(x), L(y)] = 0 \text{ whenever } (x - y)^2 < 0, \quad (5)$$

and  $H_\perp$  obeys the hypersurface-deformation algebra (standard TS consistency condition).

- **Definition 3:** (Finite-step CPTP condition). For each  $x$ , the Kossakowski form induced by the bath correlations and the kernel  $\chi_\ell$  is positive semidefinite. Equivalently, the GKLS coefficients define a completely positive generator at each point, and convex

coarse-graining with  $\chi_\ell \geq 0$  preserves complete positivity at finite hypersurface steps.

- **Definition 4:** (Primitivity). The operator set  $\{F_a(x,\tau)\}$  generates an irreducible  $\ast$ -algebra on the relevant local Hilbert space, implying a unique full-rank stationary state for the dissipative dynamics.

#### 2.4. Main Theorems: Covariance, CPTP, and Lyapunov Stability

- **Theorem 1:** (Foliation independence). *Assume locality/integrability (5) and the hypersurface-deformation algebra for  $H_\perp$ . Then the evolution defined by (1) is foliation independent:  $\rho[\Sigma]$  depends only on the spacetime region bounded by initial and final hypersurfaces, not on the intermediate foliation.*

*Proof sketch.* Writing  $\delta\rho/\delta\Sigma(x) = L(x)\rho$ , foliation independence follows if mixed functional derivatives commute. The obstruction is the curvature of the hypersurface connection,  $(\delta_x\delta_y - \delta_y\delta_x)\rho = ([\mathcal{L}(x), \mathcal{L}(y)] + \text{deformation terms})\rho$ . For spacelike separation, (5) cancels the commutator obstruction, and the remaining deformation terms cancel by the hypersurface-deformation algebra, extending the standard TS integrability argument [9].

- **Theorem 2:** (Finite-step complete positivity). *Under the finite-step CPTP condition, the propagator  $E_{\Delta\Sigma} = \exp(\Delta\Sigma L)$  is completely positive and trace preserving for any finite hypersurface step  $\Delta\Sigma$ .*

*Proof sketch.* At each  $(x,\tau)$  the dissipative contribution is of GKLS form and thus generates a CPTP infinitesimal channel [1,2]. Coarse-graining with  $\chi_\ell \geq 0$  implements a convex mixture over such infinitesimal generators; convexity and semigroup composition preserve complete positivity. Trace preservation is enforced by the GKLS anticommutator structure, while complete positivity can also be characterized by the positivity of the corresponding Choi matrix at finite steps [20].

- **Definition 5:** (Global Lyapunov functional). Define the hypersurface-integrated quantum relative entropy

$$\Phi[\rho] = \int_\Sigma D_{\text{rel}}(\rho||\sigma_\star) = \int_\Sigma \text{Tr}[\rho(\log \rho - \log \sigma_\star)] \geq 0, \quad (6)$$

where  $D_{\text{rel}}$  is the Umegaki relative entropy [21,15].

- **Theorem 3:** (Second law and exponential convergence). Assume modular jumps (2), detailed balance (GNS symmetry) relative to  $\sigma_*$ , and the finite-step CPTP condition. Then

$$\frac{\delta\Phi}{\delta\Sigma(x)} \leq 0. \quad (7)$$

If, in addition, the semigroup is primitive, then  $\rho[\Sigma]$  converges exponentially to the unique stationary state  $\rho_\infty = \sigma_*$ .

*Proof sketch.* For quantum dynamical semigroups with stationary state  $\sigma_*$  satisfying detailed balance, Spohn’s inequality yields nonnegative entropy production and monotone decay of  $D_{\text{rel}}(\rho\|\sigma_*)$  [14]. The modular structure (2) makes the dissipator self-adjoint in the GNS inner product induced by  $\sigma_*$ , enabling an interpretation as a gradient flow of the relative entropy on the manifold of density operators [16]. Primitivity implies a spectral gap for the Liouvillian and thus exponential convergence to the unique full-rank fixed point.

### 2.5. Coupling to Stochastic Semiclassical Gravity

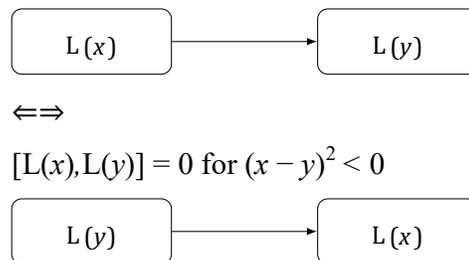
We couple the matter state  $\rho$  to a stochastic semiclassical gravitational equation of Einstein–Langevin type [10,11]:

$$G_{\mu\nu}[g] + \Lambda g_{\mu\nu} + \hbar \langle \Delta G_{\mu\nu} \rangle_\rho = 8\pi G (\langle T_{\mu\nu} \rangle_\rho + \xi_{\mu\nu}), \quad \nabla_\mu \langle T^{\mu\nu} \rangle_\rho = \nabla_\mu \xi^{\mu\nu} = 0. \quad (8)$$

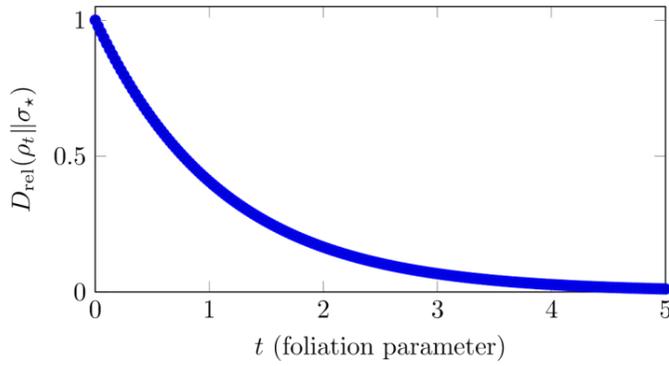
Here  $\xi_{\mu\nu}$  is a conserved stochastic source whose correlation structure is set by the stress-tensor noise kernel [4]. The Bianchi identities ensure consistency of (8) with energy-momentum conservation and with the matter evolution, while the stochastic source captures fluctuations around semiclassical expectation values.



**Figure 1:** Local Tomonaga–Schwinger Update: a Unitary Hypersurface Generator Plus a Covariant GKLS Modular Block Defined with Respect to  $\sigma_*$



**Figure 2:** Local Integrability: Commutation of Spacelike-Separated Generator Blocks Implies Foliation Independence



**Figure 3:** Schematic Lyapunov Descent: Relative Entropy to the Target State Decreases Monotonically Under Detailed Balance and Converges Exponentially Under Primitivity

## 2.6. Visual Summary

Figures 1–3 provide schematic visualizations of the local TS update, integrability, and Lyapunov descent.

## 2.7. Quantitative Predictions and Falsifiability

CUP- $\Omega^*$  is falsifiable because it imposes sign-definite and order-independence constraints that can be probed in controlled open quantum platforms.

- **Proposition 1:** (Finite-step Choi positivity). *For any finite hypersurface step  $\Delta\Sigma$ , the induced dynamical map  $E_{\Delta\Sigma} = \exp(\Delta\Sigma L)$  is CPTP. Equivalently, the Choi matrix  $J(E_{\Delta\Sigma})$  is positive semidefinite and satisfies  $\text{Tr}_{\text{out}} J(E_{\Delta\Sigma}) = I$ .*

**Test protocol.** Implement  $E_{\Delta\Sigma}$  by digital simulation or engineered dissipation in trapped ions or superconducting qubits. Reconstruct  $J(E_{\Delta\Sigma})$  by process tomography and compute  $\lambda_{\min}(J(\mathcal{E}_{\Delta\Sigma}))$ . CUP- $\Omega^*$  predicts

$$\lambda_{\min}(J(\mathcal{E}_{\Delta\Sigma})) \geq 0. \quad (9)$$

Any robust negativity beyond statistical uncertainty falsifies the finite-step CPTP axiom (and thus CUP- $\Omega^*$  under the tested coarse-graining model).

- **Proposition 2:** (Monotone relative-entropy decay). *Under detailed balance relative to  $\sigma_*$ , the functional  $\Phi[\rho]$  obeys (7). In particular, for any foliation parameterization  $\Sigma(t)$ , the scalar time series  $t \mapsto D_{\text{rel}}(\rho(t) || \sigma_*)$  is nonincreasing.*

**Test protocol.** Engineer or calibrate  $\sigma_*$  (e.g., a Gibbs state or a constrained prior state) and reconstruct  $\rho(t)$  by tomography. CUP- $\Omega^*$  predicts, for all  $\Delta t > 0$ ,

$$D_{\text{rel}}(\rho(t + \Delta t) || \sigma_*) - D_{\text{rel}}(\rho(t) || \sigma_*) \leq 0 \quad (10)$$

up to finite-sampling error. A systematic violation indicates failure of the detailedbalance/modularity assumptions.

- **Proposition 3:** (Order-independence under spacelike update exchange). *Consider two spacelike-separated update regions centered at  $x$  and  $y$  on the same  $\Sigma$ . For small hypersurface increments  $\Delta\Sigma_x, \Delta\Sigma_y$ ,*

$$\mathcal{E}_{\Delta\Sigma_x}^{(x)} \circ \mathcal{E}_{\Delta\Sigma_y}^{(y)} = \mathcal{E}_{\Delta\Sigma_y}^{(y)} \circ \mathcal{E}_{\Delta\Sigma_x}^{(x)} + \mathcal{O}(\Delta\Sigma_x \Delta\Sigma_y), \quad (11)$$

*with equality to leading order. Detectable order dependence beyond controlled truncation errors falsifies the integrability axiom (5).*

- **Proposition 4:** (Operational plateau under coarse-graining). *Let  $\ell$  denote the coarsegraining scale in  $\chi_\ell$ . CUP- $\Omega^*$  predicts the existence of a regime  $(\ell_1, \ell_2)$  where operational invariants are approximately  $\ell$ -independent:*

$$\partial_\ell \lambda(\ell) \approx 0, \quad \partial_\ell \lambda_{\min}(J(\mathcal{E}_{\Delta\Sigma}(\ell))) \approx 0, \quad \ell \in (\ell_1, \ell_2), \quad (12)$$

*where  $\lambda(\ell)$  is the Liouvillian gap estimated from decay rates. Absence of such a plateau in regimes where Markovian modeling holds challenges the coarse-graining stability hypothesis.*

- **Remark 1:** (Gravity-coupled constraints in BMV-type experiments). If stress-tensor fluctuations dominate a decoherence channel, the Einstein–Langevin coupling predicts that the effective noise is governed by a conserved source with correlations given by the noise kernel [4,10]. In tabletop proposals targeting gravitationally mediated entanglement [5,6,22], CUP- $\Omega^*$  implies that any additional decoherence rate attributed to gravitational fluctuations must be representable as a CPTP contribution compatible with (8) and must preserve the monotonicity constraints above. This provides a model-checking route: compare measured decoherence rates with those predicted from independently estimated noise-kernel bounds.

## 2.8. Implications for Artificial Intelligence

CUP- $\Omega^*$  yields a physically grounded template for stable “learning-like” dynamics. The evolution is constrained to be CPTP (a noncommutative analogue of probability conservation) and to decrease a Lyapunov functional (relative entropy to a target), paralleling optimization procedures that enforce monotone loss descent. This resonates with thermodynamic views of inference and learning [23–26]: the system evolves toward states

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minimizing a free-energy/relative-entropy objective under constraints. While CUP- $\Omega^*$  is formulated for quantum state dynamics, it suggests principled constraints for algorithm design in quantum machine learning and in physically embedded AI, where admissibility and stability are not optional but fundamental.

### 3. Methods

#### 3.1. From Coarse-Grained TS Dynamics to Covariant GKLS

A standard route to GKLS generators begins from unitary evolution on system+environment and applies weak coupling, Born approximation, and Markov coarse-graining [12,13]. In a TS setting, “time” is replaced by hypersurface deformations; coarse-graining is encoded by  $\chi_\ell(\tau)$  at an operational scale  $\ell$ . Positivity of environment correlation functions implies positivity of the Kossakowski form, yielding a local GKLS structure [1,2]. Covariance requires that the local generator respects microcausality, operationally implemented by (5).

#### 3.2. Detailed Balance, Modularity, and Entropy Production

The modular jump form (2) enforces symmetry of the generator in the GNS inner product induced by  $\sigma_*$ , a sufficient condition for quantum detailed balance. Under this symmetry, Spohn’s inequality guarantees nonnegative entropy production and monotone decay of  $D_{\text{rel}}(\rho\|\sigma_*)$  [14]. Gradient-flow refinements interpret the dissipative dynamics as steepest descent of relative entropy on the manifold of density operators [16]. Information-theoretic properties of relative entropy trace back to operator-algebraic foundations [21,15].

#### 3.3. AI-Assisted Drafting Statement

Large language models were used only as a writing and L<sup>A</sup>TEX drafting assistant (language polishing, formatting, and consistency checking). The scientific content, conceptual framing, and final editorial decisions remain the responsibility of the author.

#### A. Integrability and foliation independence: a superoperator curvature

Let  $\delta_x$  denote the functional derivative with respect to the hypersurface deformation at  $x$ . Writing  $\delta_x \rho = L(x)\rho$ , the integrability condition is the vanishing of the superoperator curvature:

$$\text{i. } (\delta_x \delta_y - \delta_y \delta_x) \rho = \left( [\mathcal{L}(x), \mathcal{L}(y)] + \delta_x \mathcal{L}(y) - \delta_y \mathcal{L}(x) \right) \rho. \quad (13)$$

In the TS setting,  $\delta_x L(y) - \delta_y L(x)$  reduces to the hypersurface-deformation algebra terms. Under locality (5) and the deformation algebra, the curvature vanishes, establishing Theorem 1.

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## B. B Entropy production identity

For a quantum Markov generator with stationary  $\sigma_*$ , define the entropy production rate

$$1. \quad \sigma(\rho) = -\text{Tr}(\mathcal{L}(\rho) (\log \rho - \log \sigma_*)) \quad (14)$$

Under detailed balance,  $\sigma(\rho) \geq 0$  and

$$2. \quad \frac{d}{dt} D_{\text{rel}}(\rho_t \| \sigma_*) = -\sigma(\rho_t) \leq 0, \quad (15)$$

recovering (7) in any foliation parameterization. This is the quantum analogue of the second law for open dynamics [14,16].

## C. Noise-kernel constrained decoherence functional

If the gravitational sector is treated as a Gaussian stochastic source  $\xi_{\mu\nu}$  with correlations set by the noise kernel  $N_{\mu\nu\rho\sigma}(x, x') = \frac{1}{2} \langle \{\hat{t}_{\mu\nu}(x), \hat{t}_{\rho\sigma}(x')\} \rangle$  [15], then for a superposition of two histories with stress-tensor difference  $\Delta T_{\mu\nu}$  the induced decoherence exponent admits the standard influence-functional form

$$i. \quad \Gamma_g \approx \frac{1}{2\hbar^2} \int d^4x \int d^4x' \Delta T_{\mu\nu}(x) N^{\mu\nu\rho\sigma}(x, x') \Delta T_{\rho\sigma}(x'). \quad (16)$$

CUP- $\Omega^*$  constrains any effective gravitationally attributed decoherence to be representable by a CPTP contribution consistent with (16) and with local conservation in (8). For BMV-type proposals [5,6,22], the visibility bound  $V \lesssim e^{-\Gamma_g}$  yields a quantitative falsification window once  $N$  is estimated from the underlying field state.

## 4. Discussion

CUP- $\Omega^*$  is modular: it isolates assumptions needed for covariance (local integrability), admissibility (finite-step CPTP), and thermodynamic consistency (detailed balance relative to  $\sigma_*$ ). This modularity is a strength: each assumption corresponds to a concrete falsifiable constraint. At the same time, it highlights open problems. First, a microscopic derivation of the exact operator content  $\{F_\alpha\}$  from matter–environment and matter–gravity couplings is not yet unique; as in conventional opensystem theory, it depends on coarse-graining choices and on what degrees of freedom are integrated out [12,13]. Second, the operational meaning of the prior state  $\sigma_{O,P}$  must be specified in each application (Bayesian prior, control objective, agent state, or informational constraint surface). Third, the Einstein–Langevin coupling is effective and applies in semiclassical regimes where stochastic gravity approximations are valid; extensions to fully quantum gravitational regimes would require additional structure [10]. Nevertheless, CUP- $\Omega^*$  produces sharp and testable consequences—positivity, order independence, and monotone entropy descent—that are accessible to current experimental

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and simulation platforms. The framework also provides a mathematically well-defined bridge to AI via Lyapunov-stable descent under admissibility constraints [27].

### Declarations

#### Author contributions

V.M.G. conceived the CUP- $\Omega^*$  formulation, developed the theoretical structure and proofs, and wrote the manuscript.

#### Competing interests

The author declares no competing interests.

#### Data availability

No datasets were generated or analyzed during the current study.

#### Code Availability

No simulation code is associated with this manuscript. All LATEX source code, including TikZ/PGFPlots figures, is provided with this submission package.

#### Acknowledgements

The author thanks the open scientific community for foundational results on quantum dynamical semigroups, detailed balance, and stochastic semiclassical gravity, and acknowledges the use of AI tools for language and LATEX drafting support.

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