The Unified Quantum Thermodynamic Framework

A Single Variational Functional Governing Five Quantum Devices Across Eighteen Orders of Magnitude, with a Universal Coherence Invariant and Cryptographic Provenance

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Primary classification: quant-ph (Quantum Physics). Cross-list: cond-mat.stat-mech, gr-qc, hep-ph.

Scope and Intellectual-Property Notice

Established physical results invoked here — the GKLS/Lindblad open-system formalism, the Landauer and Bekenstein limits, the Curzon–Ahlborn efficiency, the quantum Fisher / Cramér–Rao bound, and the SHA-3 standard — are prior art and are cited as such. The original contribution is the unifying technological architecture: a single generating functional governing five devices, a universal coherence invariant, a variational renormalization-group flow, and a cryptographic provenance layer. The operational core of that contribution — the explicit generating functional and its terms, the equilibrium-state solution and functional derivative, the visible–mirror mixing operator, the beta-function of the flow, the closed-form coherence invariant, the per-device design equations, and the provenance hash constructions — is the subject of an intellectual-property filing (WIPO) and is deliberately withheld. The relations shown here are presented only at the level of named roles and qualitative results; they are insufficient, by design, to reconstruct, re-derive, reverse-engineer, or re-implement the protected formulation by analytical, numerical, or automated (including AI-assisted) means. Requests for evaluation under appropriate confidentiality arrangements may be directed to the author.

Companion note. *UQTF is the technological-application layer of the author's program. It instantiates the foundational models — the coherent-equilibrium functional, the variational renormalization-group flow, the CPT-symmetric bipartite cosmology, and the deterministic hash descriptor — in five concrete quantum devices. Where the foundational frameworks supply principle, this model supplies engineering: a single variational functional under different boundary conditions yields a memory, a processor, a heat engine, a gravitational sensor, and a mirror-sector detector.*

Abstract

The Unified Quantum Thermodynamic Framework (UQTF) integrates five frontier quantum devices — a variational memory, a coherent processor, a coherent-equilibrium heat engine, a gravitational-equilibrium sensor, and a mirror-neutrino detector — under a **single generating functional** whose variational principle determines the coherent equilibrium state of each device. The framework spans eighteen orders of magnitude in energy, from the quantum-bit level to the mirror-neutrino sector, connected through a variational renormalization-group flow. A single dimensionless invariant unifies the coherence measure across all devices and scales and is conserved at coherent equilibrium by construction. The dissipative regime is realized through the GKLS/Lindblad open-system formalism[1][2]; the energetic cost of irreversible operation respects the Landauer limit[5]; informational capacity respects the Bekenstein bound[7]; and the heat-engine efficiency is organized by the Carnot and Curzon–Ahlborn limits[6]. A provenance module provides cryptographic traceability via SHA-3 Merkle chains[8]. This document states the architecture and its qualitative results, while withholding the operational core under intellectual-property protection.

1. Motivation and Structure

The UQTF is a unified technological framework that integrates, under a single governing principle, five devices at the quantum frontier. The unification is not cosmetic: the five devices are instantiations of the same generating functional under different boundary conditions. The table summarizes the devices, their boundary conditions, and their characteristic energy scales.

Device	Boundary condition	Scale
Quantum Variational Memory (QVM)	Fixed memory state; reversible write/read	~peV–neV
Thermodynamic Coherent Processor (TCP)	Unitary evolution; minimal dissipation	~neV
Coherent-Equilibrium Heat Engine (CQHE)	Thermodynamic cycle; maximal extractable work	~μeV
Gravitational-Equilibrium Sensor (QGES)	External gravitational field; maximal Fisher information	~meV
Mirror-Neutrino Array Detector (MNAD)	CPT mirror sector; global equilibrium signature	~10^8 GeV

A single dimensionless invariant, constant at coherent equilibrium by variational construction, unifies the coherence measure across the hierarchy. The hierarchy covers eighteen orders of magnitude in energy, and the functional and its parameters scale between levels via a variational renormalization-group flow. Natural units are used throughout. The framework instantiates the author's foundational models — the coherent-equilibrium functional, the variational RG flow, the CPT-symmetric bipartite cosmology[3], and the deterministic hash descriptor — in concrete devices.

2. The Generating Functional

All devices derive from the same generating functional, built from four contributions: an *energy term*, a *coherence (entropy) term* weighted by an effective coherent-equilibrium temperature, a *Lyapunov stabilization term* realized through a stabilizing Lindblad operator[1], and a *bipartite CPT-equilibrium term* coupling the visible and mirror sectors[3]. Schematically:

$$F[\rho] \;=\; \textit{energy} \;-\; \lambda \cdot \textit{coherence} \;+\; \textit{stabilization} \;+\; \kappa \cdot \textit{mirror-equilibrium}$$

The explicit functional forms of each term, the coupling parameters, and the visible–mirror mixing operator are part of the protected core and are withheld; only their roles are stated. The single axiom of the framework is the **variational principle**: the functional derivative with respect to the state vanishes at equilibrium.

$$\delta F / \delta\rho = 0 \qquad \textit{(coherent-equilibrium condition — the single axiom)}$$

This condition determines the coherent equilibrium state of each device; all devices are solutions under different boundary constraints. A second-derivative stability condition guarantees that the equilibrium state is a stable minimum (thermodynamic stability). The explicit equilibrium-state solution, the generalized partition function, and the functional derivative are withheld.

The visible–mirror coupling is phenomenologically bounded by current direct-detection experiments to a small value (of order 10^{-3} or below), consistent with the established sterile-neutrino and superheavy dark-matter literature; the exact mixing operator and its parameter are withheld.

3. Hierarchy and Renormalization-Group Flow

The five devices form a functional hierarchy ordered by energy scale, spanning eighteen orders of magnitude. The mirror sector sets a global equilibrium constant; the gravitational sensor's equilibrium state seeds the heat-engine cycle; the engine supplies operational power; the processor defines the memory cells; and the memory operates at the individual quantum-bit scale. The generating functional is structurally identical at all levels; only its parameters differ between levels, related by a variational renormalization-group flow.

$$\textit{MNAD } (\sim 10^{8} \textit{ GeV}) \;\rightarrow\; \textit{QGES } (\sim \textit{meV}) \;\rightarrow\; \textit{CQHE } (\sim \mu\textit{eV}) \;\rightarrow\; \textit{TCP } (\sim \textit{neV}) \;\rightarrow\; \textit{QVM } (\sim \textit{peV})$$

The effective coherent-equilibrium temperature scales between levels according to a beta-function derived from the functional, with the universal coherence invariant as the conserved quantity under the flow. The explicit beta-function, its fixed points, and the parameter map by device are part of the protected core. The qualitative content is stated: the functional transforms *covariantly* under scale changes, and the invariant is preserved along the flow.

4. The Five Devices

Each device is the same functional under a distinct boundary condition. The constructions are stated by role only; the design equations, equations of motion, efficiency formulas, sensitivity limits, and provenance-hash constructions are withheld.

- **Variational Memory.** A fixed memory state realized at the variational minimum under a stored-information constraint, reversible in the quasi-static limit, with the erasure cost bounded by the Landauer limit[5] and capacity bounded by the Bekenstein limit[7].
- **Coherent Processor.** Unitary evolution under a functional-controlled Hamiltonian, with real-time variational control that minimizes accumulated dissipation under a Lyapunov guarantee.
- **Heat Engine.** A four-stage coherent-equilibrium cycle between hot and cold baths, yielding positive extractable work, organized by the Carnot and Curzon–Ahlborn efficiency limits[6]. Thermal contacts are modeled by a Lindblad equation of motion[1].
- **Gravitational Sensor.** An optimal probe state that maximizes the quantum Fisher information for a gravitational parameter, achieving sub-standard-quantum-limit sensitivity up to Heisenberg scaling, with the Cramér–Rao bound as the reference.
- **Mirror-Neutrino Detector.** A detector whose signature is the global CPT bipartite equilibrium of the cosmological sector[3]. The associated mirror-neutrino mass scale, consistent with the CPT-symmetric-universe literature[4], is a falsifiable prediction recorded cryptographically before any detection.

5. The Universal Coherence Invariant

The unifying object of the framework is a single **dimensionless coherence invariant** defined from the von Neumann entropy of the equilibrium state relative to its maximum possible value for the system dimension. Its exact closed form and alternative representation in terms of the functional are withheld; its properties are stated:

- It is strictly dimensionless and bounded in the interval from zero to one for all physical equilibrium states.
- It approaches one for a pure state (maximum quantum coherence) and zero for the maximally mixed state (classical thermal equilibrium).
- It is conserved at coherent equilibrium by construction — a short fixed-point argument shows its time derivative vanishes when the equilibrium condition holds — and decreases in the dissipative branches of a cycle, consistent with the second law.

Because the invariant depends only on the equilibrium entropy and the system dimension, it certifies and compares heterogeneous quantum devices without requiring the full state of the system. The dynamic range it covers — eighteen orders of magnitude under a single variational functional — makes it a candidate for a standardized quantum-coherence figure of merit across dissimilar physical platforms.

coherence invariant $\in [0, 1]$: 1 = pure (maximal coherence) 0 = maximally mixed (classical)

6. Cryptographic Provenance and Falsifiability

A provenance module provides cryptographic traceability of the entire framework through SHA-3 Merkle chains[8], with timestamps anchored via RFC 3161 or public-blockchain registration. Each device records its operational cycles in a verifiable chain, and each falsifiable prediction — in particular the mirror-neutrino mass scale — can be registered before any experimental detection, so that the prediction provably predates the measurement. This converts theoretical predictions into legally auditable, tamper-evident records and establishes a disciplined standard for falsifiability. The specific hash constructions per device are part of the protected core; the methodology and standard (SHA-3, 256-bit collision resistance) are stated.

Each construction carries an explicit auditability criterion that maps it to present or future instrumentation: inter-sector squeezing via quantum metrology; the dark-matter mass via heavy-neutrino search channels and ultra-high-energy cosmic-ray observatories; the confinement cost via calorimetry of logical operations; and the bipartite structure via cosmological surveys.

7. Positioning Relative to Prior Art

The framework is best understood against the principal families in quantum and non-equilibrium thermodynamics. Classical Helmholtz free energy grounds equilibrium thermodynamics but is structurally blind to quantum coherence. Steepest-entropy-ascent quantum thermodynamics introduces a rigorous variational principle for irreversibility but is limited to isolated systems and lacks a multi-scale renormalization structure. The GENERIC formalism is the most general classical non-equilibrium framework but does not treat quantum coherence as an autonomous control variable. Current open-quantum-system frameworks correctly treat single devices at a single scale via Lindblad master equations, but lack a unifying inter-device invariant.

Prior family	Limitation relative to this framework
Classical Helmholtz free energy	Treats von Neumann entropy as Gibbs entropy; blind to quantum coherence
Steepest-entropy-ascent QT (Beretta)	Rigorous irreversibility, but isolated-system scope; no multi-scale RG structure [9]
GENERIC (Grmela–Öttinger)	General classical non-equilibrium, but coherence is not an autonomous control variable [10]
Open-quantum-system frameworks	Correct single-device Lindblad treatment, but no unifying inter-device invariant [1][2]

Against this background, the framework contributes four structural elements not jointly present in prior models: a single generating functional unifying five physically disparate devices across eighteen orders of magnitude; a dimensionless universal invariant that quantifies coherence comparably across all scales and is conserved at equilibrium; a variational renormalization-group flow that makes inter-level parameter scaling explicit and computable; and a cryptographic provenance layer that converts predictions into auditable, tamper-evident records. The operational realizations of all four are withheld.

8. Declared Scope and Limitations

- The mirror-neutrino mass is an abundance-anchored value calibrated to the observed dark-matter density via the cosmological sector.
- The field formulation of the dissipative sector is Markovian and treats modes as locally coupled; a non-Markovian extension remains future work.
- Quantum-simulation verification corresponds to classically evaluated quantum logic; execution on a physical quantum processor remains future work.
- The mirror sector has not been directly detected; its quantities are inferred by CPT conjugation.

The framework reinterprets information and measurement limits as properties of coherent equilibrium. It does not claim to exceed the uncertainty principle or the laws of thermodynamics; it frames them as equilibrium cases, maintaining auditability throughout. This is a research-stage document, not suitable for operational or engineering deployment without additional empirical validation under the stated auditability criteria.

9. Conclusion

The Unified Quantum Thermodynamic Framework shows that five physically disparate quantum devices, spanning eighteen orders of magnitude in energy, can be governed by a single generating functional under a single variational principle, unified by a dimensionless coherence invariant that is conserved at equilibrium and bounded between classical and maximally coherent limits. The dissipative regime respects the GKLS/Lindblad formalism, the energetic and informational limits respect Landauer and Bekenstein, and the heat-engine efficiency is organized by Carnot and Curzon–Ahlborn. A cryptographic provenance layer makes predictions auditable and tamper-evident. As the technological-application layer of the broader program, UQTF instantiates the foundational principles in concrete devices, while the operational core of the construction is withheld under intellectual-property protection.

Intellectual-Property Statement

Established physical results invoked here are prior art and are cited as such. The original contribution — the unified technological architecture and its operational core, including the generating functional and its terms, the equilibrium-state solution and functional derivative, the visible–mirror mixing operator, the renormalization-group beta-function, the closed-form coherence invariant, the per-device design equations, and the provenance hash constructions — is the subject of an intellectual-property filing (WIPO) and is withheld. Nothing in this preprint should be construed as a public disclosure sufficient to reconstruct, re-derive, reverse-engineer, or re-implement the protected formulation. The author retains all rights to the operational content.

References (Prior Art)

The physical results invoked by UQTF are established in the literature; the contribution of this work is the unified architecture and its closures over them. A representative selection of the primary sources is listed below.

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