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Gibbs Energy Redistribution Theory (GERT): A Thermodynamic Cosmology for the Hubble Tension and Beyond

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Abstract

Background: Persistent cosmological tensions — particularly in the Hubble constant (H_0) — motivate physically grounded alternatives to ΛCDM. We propose the Gibbs Energy Redistribution Theory (GERT): a thermodynamic framework in which matter- and Λ-like contributions are promoted to density-controlled functions derived from the Gibbs free energy criterion. GERT interprets dark components as emergent manifestations of a single Primordial Enthalpic Reservoir, without new fields or fine-tuning. **Methods:** The dynamical $H(z)$ is obtained by promoting FLRW source terms to thermodynamic functions $f_M(\rho)$ and $f_L(\rho)$, calibrated via MCMC against CMB, BAO, and Type Ia supernova data. Model complexity is reduced from 12 to 2 free parameters through thermodynamic priors. **Results:** The two-parameter implementation achieves $\chi^2/\mathrm{dof} \approx 0.99$ and infers $H_0 \approx 72.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, consistent with local distance-ladder determinations. GERT outperforms ΛCDM on WAIC and AIC. **Conclusions:** GERT provides a thermodynamically causal account of cosmic evolution. The frozen parameter set constitutes a quantitative prediction accessible to future low-redshift probes.

Keywords: cosmology; thermodynamics; Hubble tension; expansion history; emergent gravity; dark energy; entropy production; FLRW dynamics; enthalpy; baryon acoustic oscillations (BAO); Type Ia supernovae (SNe Ia); cosmic microwave background (CMB); Markov chain Monte Carlo (MCMC)

Guidelines for Readers (Roadmap)

Position in the GERT series. This manuscript is Paper I of the GERT series, an open and growing companion series of papers that develops the framework cumulatively. It is self-contained and does not presuppose knowledge of the companion works. The series is cumulative: each subsequent paper uses the frozen thermodynamic functions and calibrated parameters established here as its foundation. A complete roadmap with one-sentence summaries of each companion paper is provided in §5.7 (Table 8). Readers wishing to situate Paper I within the broader programme are encouraged to consult that table; readers interested only in the cosmological background validation need not do so.

Key results at a glance.

- **Cosmological fit:** $\chi^2/\mathrm{dof} \approx 0.99$; $H_0 \approx 72.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (Section 4).
- **Model selection:** GERT outperforms ΛCDM on WAIC and AIC with 2 free parameters (Section 4.3).
- **Direct Comparison with ΛCDM:** Section 5.5.
- **Programme Roadmap:** Section 5.7.
- **Code and Data Availability:** Back Matter (after Conclusions).

1. Motivation

A Crisis Built on Success: The Historical Context for a New Paradigm

For much of the twentieth century, fundamental physics enjoyed a remarkable, if uneasy, equilibrium. On the largest scales, Einstein's General Relativity provided an extraordinarily precise description of the geometry and dynamics of spacetime, confirmed by increasingly refined observations of gravitational lensing, planetary motion, and the large-scale structure of the Universe [1,2]. On the smallest scales, the Standard Model of particle physics offered an elegant and experimentally successful framework for the fundamental constituents of matter and their interactions. Between these two pillars stood what appeared to be physics' last great open problem: the unification of General Relativity with Quantum Mechanics into a single coherent theory of quantum gravity [3]. The Universe, it seemed, was essentially understood. The remaining task was to close the final seam. That sense of comfort did not survive the closing years of the twentieth century.

In 1998 and 1999, two independent teams — the High-Z Supernova Search Team [4] and the Supernova Cosmology Project [5] — announced a result that fundamentally altered the trajectory of cosmology. Observations of Type Ia supernovae at high redshift revealed that the expansion of the Universe was not slowing down under the influence of gravity, as expected, but accelerating. Something was pushing spacetime apart with increasing force. General Relativity, applied to a Universe filled only with known matter and radiation, had no mechanism to produce this behaviour. The equations were correct; the content was not.

The response was swift and, by necessity, pragmatic. To preserve the success of the relativistic framework, two new entities were introduced into the cosmic energy budget. Dark energy — a placeholder for whatever was driving the accelerated expansion, mathematically encoded as a cosmological constant Λ — was assigned approximately 68% of the total energy content of the Universe. Dark matter — whose gravitational necessity had been indicated for decades by galactic rotation curves [6] and cluster dynamics [7] — was assigned a further 27%. Together, these two unknown components account for approximately 95% of everything the standard model requires to exist, yet neither has been directly detected, and the physical nature of both remains entirely unresolved [8].

It is important to be precise about what this represents. The postulation of dark matter and dark energy was not an error. It was a scientifically legitimate and historically necessary response to a genuine observational crisis. When the data demands an explanation and the existing framework cannot provide one, science does what it must: it extends the framework to accommodate the anomaly. In this sense, ΛCDM was a success — it restored predictive consistency at the cost of ontological transparency. The model works. The question this paper asks is a different one: whether a solution designed for an emergency should be allowed to calcify into a foundation. A provisional answer that successfully describes the data is a scientific achievement. The error lies not in proposing it, but in treating an emergency measure as though it were a first principle — in allowing the scaffolding erected to stabilize a crisis to become, over decades, the architecture itself.

This is not a minor gap in knowledge. It is a structural admission: the standard cosmological model, ΛCDM (Cold Dark Matter with cosmological constant), is a framework in which the overwhelming majority of the cosmic content is described by terms whose ontological status is unknown. Dark energy is not a substance with a derivation; it is a parameter adjusted to fit the data. Dark matter is not a confirmed particle; it is a gravitational inference. The model works precisely because these terms are free to absorb whatever the known physics cannot explain [9,10].

The decades following 1998 brought further refinement but also new tensions. The most persistent of these is the Hubble tension: a statistically significant discrepancy between the value of the Hubble constant inferred from the early Universe via cosmic microwave background (CMB) observations and that measured directly from the local Universe via the distance ladder [8,11]. This tension has not resolved with improved data; if anything, it has sharpened [9,10,12]. It is now widely regarded [8,11] not as a systematic error but as a potential signal that the standard expansion history is incomplete [10].

The Hubble tension is, in this reading, the moment when the scaffolding begins to show its age. It is the anomaly that the emergency measure cannot absorb without further *ad hoc* adjustment — the point at which the provisional answer starts to demand a provisional answer of its own. It is precisely this recursive instability that, in the framework of Kuhn's theory of scientific revolutions [13], signals that a paradigm has reached the limits of its explanatory capacity and that the conditions for a deeper reorganization of principles are becoming necessary.

It is in this context — a model of great descriptive power built on conceptually unresolved foundations, now showing internal stress — that the present work is situated. The Gibbs Energy Redistribution Theory (GERT) does not propose to repair ΛCDM from within by adding yet another component. It asks whether the expansion history of the Universe can be derived from a physical principle that requires no new substances at all: the minimization of Gibbs Free Energy in a closed thermodynamic system. If the answer is yes, then dark matter and dark energy are not missing ingredients but emergent descriptions of a deeper thermodynamic reality — and the Hubble tension becomes, as we shall argue, a natural consequence of using a static parameter to describe what is in fact a dynamic process.

1.1. The Need for a New Perspective: The Crisis in Modern Cosmology

Fundamental cosmology is highly descriptively successful, yet it faces a profound conceptual impasse. The Standard Cosmological Model (ΛCDM), despite its precision, rests on an unresolved divide between General Relativity (GR) and Quantum Mechanics (QM) and on components that account for approximately 95% of the cosmic energy budget — dark matter and dark energy—whose nature remains unknown. These entities, together with other postulates such as the inflaton, were introduced to reconcile theory and observations, but have no direct empirical detection, and thus function as placeholders in the cosmic balance sheet. (For a sampling of alternative/emergent approaches in the literature, see, e.g., [14–18].)

The current situation is reviewed in several recent and complementary perspectives [9,10]. For representative discussions of proposed resolutions and systematics in the Hubble-tension context, see, e.g., [12,19–21].

This scenario, which has persisted for decades, is symptomatic of a paradigm that has reached its limits. Incremental adjustments and the addition of new parameters—an "evolutionary" approach—have not resolved the deeper tensions, such as that of the Hubble Constant. This strongly suggests that the difficulty lies not on the surface of the model, but in its intrinsic structural foundations. We argue that the moment is ripe not for another evolution, but for a scientific revolution, in the vein theorized by Thomas Kuhn [13]. A change in perspective that reorganizes the fundamental principles is necessary. The Gibbs Energy Redistribution Theory (GERT), presented in this study, has the potential to be such a revolution, offering a new/old, well-known, and forgotten foundation of thermodynamics to rebuild our understanding of the cosmos.

Modern cosmology, by postulating entities such as dark matter and dark energy, adopts an approach in which complex observed effects are explained by introducing unproven ontological causes. We propose a fundamental methodological inversion: starting from a simple and unifying cause and allowing the complexity of the cosmos to emerge as its natural consequence. That cause is thermodynamics.

Guided by this inversion, this study investigates whether starting from thermodynamics as a simple and unifying cause can account for cosmic complexity and alleviate persistent cosmological tensions, including the Hubble constant discrepancy. Concretely, we confront the resulting expansion-history model with widely used background probes: CMB [8]; baryon acoustic oscillation (BAO) data from the SDSS (Sloan Digital Sky Survey) [22], BOSS (Baryon Oscillation Spectroscopic Survey) [14], and eBOSS [23] analyses; and Type Ia supernova (SNe Ia) compilations from JLA (Joint Light-curve Analysis) [24] and Pantheon [25]. We then compare its performance to standard baselines and recent discussions of the Hubble tension [9–12].

1.1.1. Interdisciplinarity: Looking at the Cosmos through the Eyes of a Chemist

This study proposes an approach that lies at the intersection of cosmology and physical chemistry [1,2]. We argue that, at the most fundamental level, the Universe may be viewed not only as a mechanical/geometric system but also as a transformation governed by the same principles that drive chemical change. Therefore, applying thermodynamics — the engine of transformation — to the cosmos can illuminate the underlying causes of cosmic evolution rather than merely describing its effects.

The intuition at the heart of GERT is not, in retrospect, entirely foreign to physics. It is, however, foreign to the dominant language in which physics has chosen to express itself. Consider a simple observation from physical chemistry: when a system loses thermal energy to its environment, its molecules approach one another. Cohesive forces dominate. Structure emerges from what was previously a disordered state. Entropy of the local system decreases while the total entropy of the Universe increases, as the Second Law demands. The system contracts, organizes, and builds complexity — not because an external force commands it, but because the thermodynamic conditions make it spontaneous.

Translated to cosmological scales, this is precisely the behaviour we observe in the early Universe. Matter agglomerates. Gravitational wells deepen. Galaxies, stars, and planetary systems emerge from what was once a nearly homogeneous plasma. The standard model describes this process geometrically: matter tells spacetime how to curve, and curvature tells matter how to move [1]. This description is correct and extraordinarily precise. But it is a description of the how, not the why. It tells us the grammar of cosmic evolution without telling us its cause.

The question a chemist instinctively asks — why does this system spontaneously organise — what is the thermodynamic driving force? — has historically been met in cosmology with what might be called a paradigmatic deflection: matter curves spacetime; that is the answer; calculate. The question of origin, of why gravity behaves as it does from a thermodynamic perspective, was simply not considered a legitimate scientific question within the established framework.

Yet this question has been asked, with increasing mathematical rigor, within theoretical physics itself. Jacobson showed in 1995 that Einstein's field equations can be derived from the thermodynamics of local causal horizons, treating spacetime geometry as an equation of state [26]. Padmanabhan developed this line extensively, demonstrating deep connections between gravitational dynamics and thermodynamic extremization principles [27]. Verlinde proposed that gravity itself is not a fundamental force but an entropic phenomenon — an emergent consequence of the tendency of systems to maximise entropy [15,16]. Van Raamsdonk suggested that the very connectivity of spacetime may be rooted in quantum entanglement entropy [28].

These are not peripheral speculations. They are serious theoretical programs, published in leading journals, that converge on a common conclusion: the geometric description of gravity that General Relativity provides may itself be a macroscopic emergent consequence of deeper thermodynamic principles. A further and underexplored convergence point lies in the no-boundary proposal of Hartle and Hawking [29], which establishes that the Universe has no boundary in space or time — no "before" the Big Bang and no "outside" in any geometrically meaningful sense. This result, developed within quantum cosmology from purely geometric arguments, carries a thermodynamic implication that has not been previously made explicit: a universe without boundary is, by definition, a closed thermodynamic system. The thermodynamic consequence of Hawking's own framework is precisely the closed-system postulate that GERT requires. That this implication was not drawn within physics itself reflects the disciplinary boundaries between quantum cosmology and thermodynamics — boundaries that a perspective rooted in physical chemistry, where system boundaries are a primary conceptual tool, is naturally positioned to dissolve.

GERT arrives at a similar conclusion, but from a fundamentally different starting point and by a different route. Rather than deriving thermodynamic properties from an existing geometric framework, GERT begins with thermodynamics as the primary language and allows geometry — and the expansion history it describes — to emerge as a consequence. The Gibbs Free Energy equation, which in chemistry governs whether a reaction proceeds spontaneously, becomes in GERT the governing criterion for cosmic evolution. Gravity and entropy are not separate forces with separate ontologies; they are the Inward and Outward manifestations of the same Primordial Enthalpic Reservoir redistribution.

What is perhaps most striking is that this convergence — between a chemical intuition about cohesion and entropy, and the formal thermodynamic gravity programs of Jacobson, Padmanabhan, and Verlinde — was arrived at independently, from different intellectual traditions and with different mathematical tools. This independent convergence does not prove that GERT is correct. But it suggests that the thermodynamic perspective on cosmic evolution is not an eccentricity. It is a direction that physics itself has been approaching, from multiple angles, for decades. GERT is, in this sense, the application of that perspective in its most direct and chemically natural form: treating the Universe not as a geometric stage on which matter performs, but as a thermodynamic system that evolves because it must, driven by the same Gibbs Criterion that drives every spontaneous process in nature.

1.1.2. The Search for “Why”: Ontological Gain and Occam's Razor

The ΛCDM model is primarily phenomenological; it describes how the Universe evolves but leaves the underlying physical mechanisms open. GERT seeks an ontological gain by addressing this causal “why”. Our premise is that the effects commonly attributed to dark matter and dark energy need not be treated as distinct substances; instead, they can be modeled as phase-dependent manifestations of a unified thermodynamic mechanism. By accounting for multiple phenomena within a single framework, GERT aligns with the principle of Occam's razor. This study advances two complementary hypotheses. Empirically, we define a concrete, reproducible expansion history model (via the state functions $f_M(\rho)$ and $f_L(\rho)$) and confront it with CMB, BAO, and SNe Ia data. Ontologically, we argue that the same phenomenology can be obtained without reifying dark matter and dark energy as substances. In GERT, they arise as phase-dependent manifestations of a unified thermodynamic mechanism.

This ontological interpretation is currently supported by the model’s success on background-expansion probes; a full validation across other regimes (e.g., galaxy dynamics and lensing) is left for future studies.

Relation to Prior Thermodynamic/Emergent-Gravity Approaches

GERT is presented here as a thermodynamically motivated effective expansion-history model. It is not intended as a reformulation of entropic-gravity or spacetime-thermodynamics programs, but it is conceptually adjacent to several lines of work (e.g., horizon/thermodynamic perspectives and emergent-gravity proposals). For context and points of contact, see, e.g., [15–18,26–28,30].

2. The Paradigms of GERT

2.1. Telling the Story of Our Home

The Gibbs Energy Redistribution Theory (GERT) proposes that the history of the Universe is governed by an initial reservoir of binding enthalpy (**H**). Instead of postulating new particles or energies to explain cosmological phenomena, GERT reinterprets these phenomena as consequences of a dynamic Universe that performs Work. The primordial energy “capital” is managed by a single thermodynamic mechanism that manifests in two complementary flows: a contractile one, which curves spacetime and emerges as gravity to sculpt structures, and an expansive one, which emerges as entropy to drive the expansion. The arbiter of this budget is Gibbs Free Energy (ΔG). As long as there is a gradient to perform Work, a time arrow exists. This approach is based on the following paradigms:

2.2. The Thermodynamic Big Bang: The Gibbs Trigger

In the origin of everything, before any metric or smoothly curved geometry, there was only a reservoir: a “cauldron” of energy, maximum density, and zero structure—the Primordial Enthalpic Reservoir.

At its root, there are not properly "two" states—initial and final— to calculate ΔG, but a single point of extreme thermodynamic instability [27]. Classical thermodynamics teaches us that the spontaneity of a process is controlled by the Gibbs Potential [31,32]:

$$\Delta G = \Delta H - T\Delta S$$

An irreversible transformation occurs only if $\Delta G < 0$. However, before the Big Bang, there were no two well-defined states for calculating ΔG in a standard way. Nevertheless, we can infer what would happen if this Primordial Enthalpic Reservoir - a "cauldron" of colossal enthalpy and almost zero entropy at the maximum temperature allowed by physics - were to destabilize:

- **Enthalpy released ($\Delta H0$):** The Primordial Enthalpic Reservoir contains all the potential energy of the future Universe. If this energy is converted into motion or radiation, the process becomes profoundly exothermic.
- **Entropy generated ($\Delta S > 0$):** Particles, radiation, and microscopic degrees of freedom would emerge, exponentially multiplying the number of microstates.
- **Temperature at the Planck limit:** Any variation would release heat at an immense temperature, causing the term $-T\Delta S$ to be $\ll 0$.

2.3. The Bubbling Proto-Metric and the Emergence of Geometry: The Pre-Metric Cauldron and the "Black Box"

We propose that there is an intermediate phase between the Big Bang and the emergence of geometry, which we call the "Bubbling Proto-Metric". Therefore, the instant following the Big Bang does not give rise to a stable classical geometry. In it, spacetime has already emerged, but not as Einstein's smooth continuum—it pulses, oscillates, *ferments*. Small fluctuations begin the path of curvature, proto-nodes of energy collapse, trying to crystallize patterns that are still volatile.

A smooth classical metric is not yet available, but rather local fluctuations of curvature, possibly with transient topological signatures. This is the regime where entropy begins to push and gravity is still contracting, but neither dominates—the Dual Mechanism acts chaotically and balanced, without a defined direction.

It is in this turbulent phase that the thermodynamic "scars"—the initial values of the dynamic parameters—are established, being inherited by the next phase, where geometry consolidates and General Relativity emerges as a valid description. GERT, which uses the tools of relativity, therefore, does not model this phase directly but receives the baton from a Universe that has already passed through its first and most violent thermodynamic act.

In this pre-metric Primordial Cauldron (Layer 2)—General Relativity has not yet emerged. Therefore, it is methodologically inconsistent to use relativistic equations to describe its evolution, including the mechanism of inflation. In this state, the concept of geometry, of a "ruler" to measure distances as defined by relativity, simply does not apply. The Universe is a pre-metric enthalpic soup — possessing thermodynamic structure but not yet the stable Riemannian geometry of General Relativity.

Therefore, if geometry itself did not yet exist and General Relativity with its "ruler" had not yet emerged from the Primordial Cauldron, the logical consequence is that we cannot use that same ruler to measure or describe the inflationary period to solve problems such as the homogeneity of the Universe [30,33].

GERT, however, proposes alternative theories for these issues:

- **Homogeneity** can be an intrinsic property of the initial thermodynamic state in the "cauldron". The primordial damping Work, according to GERT, would have aimed to self-homogenize in an ultra-efficient manner, without the need for inflation.
- **Flatness** and the near-flat (Euclidean) spatial geometry are not the result of a geometric "stretching". In GERT, geometry is the result of equilibrium seeking in the proto-metric phase, where local fluctuations smooth out as entropy increases.

2.4. *The Universe as a Chemical Reaction: The Domain of GERT*

At the heart of GERT is the premise that the evolution of the Universe is analogous to a spontaneous chemical reaction governed by the Gibbs Free Energy equation. In this case, the equation $\Delta G = \Delta H - T\Delta S$ ceases to be a mere tool in chemistry and becomes the driving law of the cosmos.

The First and Second Laws: The Rules of the Cosmic Game

A fundamental postulate of GERT is: The total energy of the cosmos is conserved and that the cosmos is a closed, self-contained system. The Universe began with a finite total energy budget (Primordial Enthalpic Reservoir). All cosmic evolution is the redistribution of this conserved energy according to the First Law of thermodynamics [31,32]. Therefore, the formation of stars, the expansion of space, heating, and cooling are merely the redistribution of this initial energy being transformed from one form to another. The First Law ensures that every joule of energy from the Big Bang is accounted for, whether as mass ($E=mc^2$), binding energy, radiation, or kinetic energy.

Unstable "Micro Point": The initial state is a point of absurd instability. In thermodynamic terms, this is a state of very high enthalpy (ΔH) and very low entropy (ΔS). All the energetic potential and all the order of the Universe were contained there.

The Second Law and Gibbs Free Energy: The Director of the Show If the First Law states that the energy balance must be closed, the Second Law determines the direction in which history can advance [31,32], defining the arrow of time. This determines which processes of energy redistribution are spontaneous. We use the **Gibbs Free Energy** equation ($\Delta G = \Delta H - T\Delta S$) because it combines the two laws to predict the spontaneity of any process.

- The **ΔH (enthalpy)** term, linked to the First Law, represents the energy balance of "building" structures.
- The **$-T\Delta S$ (entropy)** term, derived from the Second Law, is the engine of cosmic expansion, pushing spacetime Outward.

A process occurs spontaneously ($\Delta G < 0$) when the balance between the exchange of energy (First Law) and the increase in disorder (Second Law) is favorable. Therefore, the trigger for the Big Bang is not an inexplicable singularity but the fundamental thermodynamic condition $\Delta G < 0$, which made the "reaction" of expansion and structure formation a spontaneous and inevitable process, always respecting the law of conservation of energy.

Action (Performing Work): the Universe does not exist merely by having an initial potential (negative ΔG); it exists to perform the action of converting that potential into reality by doing Work. Cosmic history is the record of this ongoing Work.

In this paradigm:

- **Work (W):** Derived from the expenditure of enthalpy, it is the process of both creating and maintaining complexity and structure, as well as the pressure on spacetime for expansion. This is the cosmos in action.
- **Cosmic Expansion, therefore, is the "Performance of Work":** Expansion is not just something that happens; it is the direct consequence of the Universe's search for a more stable Gibbs state.

This is the "verb" of the Universe. The essence of its existence and of the arrow of time itself are the continuous action of converting this potential into reality. The Universe **is** what it **does**. What it does is perform Work: the Work of expanding, the Work of creating stars, and the Work of forming galaxies. Cosmic history is not a passive film but a report of a Work in progress.

2.4.1. The Closed System Postulate: Thermodynamic Consistency and Reconciliation with General Relativity

A natural and important question arises from the application of Gibbs Free Energy—a framework developed for closed or isolated systems at well-defined thermodynamic conditions—to the entire expanding Universe. We address this directly, as it touches the theoretical foundations of GERT.

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On the Closure of the Universe

GERT postulates that the Universe is a closed, self-contained thermodynamic system. This is not an arbitrary assumption but a logical consequence of the theory's own ontological framework. Within GERT, time is an emergent phenomenon—it is the measure of thermodynamic Work being performed. Space, in turn, is not a pre-existing stage but an emergent structure that arises from and is sustained by the same thermodynamic process. Spacetime itself is the product of the GERT mechanism, not its container.

This has a precise logical consequence: there can be no physically meaningful "exterior" to the Universe. An exterior would require the existence of space, time, and energy gradients beyond the system—but these are themselves products of the thermodynamic process that defines the system. The Universe is closed not because we assume it to be, but because the concept of an external environment is self-contradictory within the GERT framework. There is no thermodynamic bath, no external reservoir, and no boundary with an outside. The system performs Work upon itself, redistributing its finite Primordial Enthalpic Reservoir internally.

It is important to clarify the precise scope of this closure. The statement that no exterior exists applies strictly within the spacetime domain — to the geometric, causal, and thermodynamic structure that GERT describes and that General Relativity governs. Since spacetime is an emergent product of the thermodynamic process, there can be no exterior that is spacetime. However, this closure is not a statement about the atemporal foundational substrate (Layer 1) that ontologically grounds the GERT framework. At that layer — where the categories of space, time, and causality have not yet crystallised — the concept of exterior loses its meaning entirely, not because nothing exists, but because inside and outside are themselves emergent constructs that belong to the geometric layer and cannot be projected onto what grounds it. Layer 1 exists in an ontological sense that transcends spatial and temporal categories. It is not outside the Universe. It is the foundation from which the Universe, as a spacetime structure, emerges. This distinction maps precisely onto the four-layer ontological hierarchy of GERT (Section 2.6): Layer 1, the atemporal substrate, which exists independently of Work, geometry, and time; Layer 2, the Primordial Cauldron, where thermodynamic Work begins and time is born; Layer 3, where spacetime crystallises, General Relativity becomes valid, and quantum mechanics co-emerges; and Layer 4, the Hyperdilute Regime, where the crystallised geometry progressively dissolves as the enthalpic budget approaches its Quasi-Vacuum Floor. The closure of the Universe is a property of Layer 3 — of spacetime as a closed thermodynamic system. It says nothing about the ontological status of the layers that ground it, which operate under different and deeper rules. Within the GERT framework, the question of whether Layer 1 has an exterior is not well-posed, since the concept of exterior is itself an emergent construct of Layer 3.

This conclusion finds independent and powerful support in the no-boundary proposal of Hartle and Hawking [29], which establishes, from a completely different theoretical direction, that the Universe has no boundary condition in either space or time. In Hartle and Hawking's framework, formulated in terms of a path integral over compact Euclidean geometries, the Universe is literally without boundary—there is no "before" the Big Bang and no "outside" in any geometrically meaningful sense. GERT arrives at the same conclusion from its thermodynamic ontology: if time is Work and spacetime is the emergent product of that Work, then "before" and "outside" are concepts without physical referents. The convergence of these two independent lines of reasoning—one from quantum cosmology, one from thermodynamic first principles—strengthens the logical foundation of the closed-system postulate considerably.

This is conceptually analogous to, though distinct from, the treatment of the Universe as a closed system in standard cosmological thermodynamics, where the absence of an external environment is a standard working assumption [1,31].

An Expanding, Not Static, Isolated System

It is crucial to distinguish the GERT boundary condition from a classical "rigid box" isolated system. While a traditional isolated system in a laboratory has a static, fixed volume, the Universe in GERT is a dynamically expanding isolated system. The thermodynamic Work being performed does not push against an external pressure, since no exterior exists. Rather, the system performs Work against its own "walls"—the intrinsic structural tension of the spacetime metric itself, which is maintained by the theory's cohesive Inward Force (gravity). The expansive entropic flow must continuously overcome this internal gravitational resistance to stretch the cosmic fabric. In thermodynamic terms, cosmic evolution is an internal adiabatic expansion where the system's geometric capacity grows as a direct consequence of redistributing the Primordial Enthalpic Reservoir against its own self-attraction. Therefore, the system remains strictly isolated regarding energy and mass exchange, while being highly dynamic regarding its spatial metric.

On the Predictive Consequence of the Isolated System Postulate

It is important to emphasise that the closed-system postulate is not one assumption among several equivalent alternatives, nor is it adopted for philosophical convenience. It is the only thermodynamic boundary condition consistent with the ontological structure of GERT. And crucially, it is the boundary condition under which the GERT framework, with only two free parameters, achieves $\chi^2/\mathrm{dof} \approx 0.99$ and $H_0 \approx 72.5$ km/s/Mpc without invoking dark components [8,11]. An open-system formulation—one that permits energy exchange with an external environment—would introduce additional degrees of freedom that are neither motivated by the theory's ontology nor required by the data. The empirical success of the model under this specific boundary condition is therefore not merely consistent with the postulate; it constitutes evidence in its favour.

Flatness as a Thermodynamic Tautology

The spatial flatness of the observable Universe ($\Omega = 1$ to within 10^{-3}, [8]) is conventionally presented as a fine-tuning problem: in the standard hot Big Bang model, any deviation of Ω from unity at early times is amplified by the expansion, so the near-perfect flatness observed today requires $|\Omega - 1| < 10^{-60}$ at the Planck epoch. Inflation resolves this dynamically by driving $\Omega \to 1$ during exponential expansion.

In GERT, flatness requires no dynamical solution because it is not a contingent outcome — it is a logical consequence of the closed-system postulate. The argument proceeds in three steps:

(i) Positive curvature ($k = +1$, $\Omega > 1$) implies that the spatial sections are closed and the Universe will eventually recollapse. But the Gibbs Criterion ($\Delta G < 0$) requires continuous expansion: the thermodynamic process that constitutes cosmic evolution is irreversible, and recollapse would require $\Delta G > 0$ — a spontaneous decrease in entropy, which the Second Law forbids. A Universe governed by the Gibbs Criterion cannot recollapse. Therefore $k = +1$ is thermodynamically excluded.

(ii) Negative curvature ($k = -1$, $\Omega < 1$) implies that the spatial geometry contains *more volume* than the energy content warrants — an excess of geometric capacity over enthalpic content. But the Universe is a closed system with no exterior. The total enthalpic content is H_M (the Primordial Enthalpic Reservoir), conserved by the First Law. There is no external source that could supply the additional energy needed to "fill" the excess geometry, nor any external sink that could have removed energy to create the deficit. In a system with no exterior, the geometry must contain *exactly* the energy that exists — no more, no less.

(iii) Zero curvature ($k = 0$, $\Omega = 1$) is therefore the only self-consistent solution: the spatial geometry contains precisely the energy of the Primordial Enthalpic Reservoir, because there is no exterior from which to borrow or to which to lend.

The flatness of the Universe is thus not a fine-tuning problem that requires a dynamical mechanism. It is a **thermodynamic tautology**: the necessary consequence of a finite, conserved energy budget in a system with no exterior boundary. Asking "why is $\Omega = 1$?" in the GERT framework is analogous to asking “why is the total energy of an isolated system conserved?” — the question contains its own answer.

It is worth noting that this resolution is logically independent of inflation. Inflation achieves $\Omega \to 1$ by a *kinematic* mechanism (exponential stretching of the metric). GERT achieves $\Omega = 1$ by an *ontological* constraint (the closed-system postulate). The inflationary solution is not wrong — it is unnecessary. The flatness was never a problem to be solved; it was a consequence to be recognised.

On Energy Conservation in General Relativity

A more technically subtle objection concerns energy conservation in GR. It is well established that in an expanding spacetime, the total energy of the Universe is not a globally conserved quantity in the strict Noetherian sense—the stress-energy tensor is locally conserved, but there is no well-defined global energy integral in a general curved spacetime [1,27].

GERT reconciles with this in the following way. The “Primordial Enthalpic Reservoir” is not proposed as a globally conserved energy in the GR sense. It is an effective thermodynamic potential—a capacity to perform Work—defined within the homogeneous and isotropic Friedmann–Lemaître–Robertson–Walker (FLRW) framework that GERT operates in. Within this framework, which admits a preferred cosmic time coordinate and a well-defined scale factor $a(t)$, thermodynamic quantities can be consistently defined on spatial hypersurfaces of constant cosmic time [2,27].

In this context, the conservation postulated by GERT is not the conservation of a GR energy integral but the conservation of the thermodynamic budget: the total capacity for Work redistribution is finite and fixed at the initial trigger, and all subsequent evolution is the reallocation of that budget between cohesive and entropic modes. This is precisely the content of Postulates P1 and P5, and it is consistent with the local conservation of the stress-energy tensor within the FLRW metric that GERT uses as its geometric framework.

In other words, GERT does not claim to resolve the open problem of global energy conservation in GR. It operates within a regime—the homogeneous background expansion described by the Friedmann equation—where an effective thermodynamic description is internally consistent, and where the dynamic state functions $f_M(\rho)$ and $f_L(\rho)$ provide a well-defined and empirically testable parametrization of that description.

On the Applicability of Gibbs Free Energy at Cosmological Scales

The Gibbs Free Energy equation $\Delta G = \Delta H - T\Delta S$ was developed for systems at constant temperature and pressure [31]. The expanding Universe is manifestly not at constant temperature or pressure. This apparent incompatibility requires clarification.

In GERT, the Gibbs equation is not applied as a quantitative accounting identity at every moment of cosmic evolution. It is used as a spontaneity criterion—a directional principle that governs whether a thermodynamic process proceeds and in which direction. The condition $\Delta G < 0$ is the criterion for spontaneity, and it is this criterion, not the detailed quantitative form of the equation, that GERT elevates to a cosmological principle.

This is analogous to the way in which the Second Law of thermodynamics is applied in cosmology: not as a precise quantitative equation for every degree of freedom, but as a directional constraint on the arrow of time and the evolution of macroscopic states [27,33]. The Gibbs Criterion in GERT plays the same role—it defines the direction of cosmic evolution and the condition for its termination ($\Delta G \to 0$), without requiring that temperature and pressure be constant throughout.

The dynamic state functions $f_M(\rho)$ and $f_L(\rho)$ are the mathematical embodiment of this principle: they encode how the thermodynamic balance between cohesive and entropic modes evolves as the system undergoes phase transitions, and they are constrained directly by observational data rather than derived from first-principles thermodynamic calculations.

Summary

GERT operates as an effective thermodynamic framework within the FLRW regime. Its closed system postulate is a logical consequence of its own ontology, independently supported by the no-boundary proposal of Hartle and Hawking [29]. It is worth noting explicitly that the thermodynamic implication of the no-boundary proposal—that a Universe without exterior boundary is a closed thermodynamic system—has not been previously developed in the literature. GERT is, to the author's knowledge, the first framework to draw this connection explicitly and to use it as a foundational postulate with direct empirical consequences. Its use of Gibbs Free Energy is as a spontaneity criterion, not a quantitative accounting identity. Its conservation postulate refers to the effective thermodynamic budget within the homogeneous background, not to a globally conserved GR energy. And its empirical success under this specific boundary condition—$\chi^2/\mathrm{dof} \approx 0.99$, $H_0 \approx 72.5$ km/s/Mpc, no dark components—constitutes positive evidence for the postulate itself. These clarifications do not eliminate all open questions—the connection between GERT's effective thermodynamic description and a fully covariant GR thermodynamics remains a direction for future theoretical development—but they establish that the framework is internally consistent within its declared scope and regime of applicability.

2.5. The Two Children of Enthalpy: The Dynamic Symmetry of the Cosmos and the Dual Mechanism

The key to GERT is the idea that the Primordial Enthalpic Reservoir manifests through an energy redistribution mechanism that operates in two opposite directions. With symmetric elegance, the initial enthalpy is the primordial source of two dynamic, opposing, and complementary thermodynamic forces that dictate all cosmic evolution. When the enthalpic budget acts Outward, it drives expansion and dispersal of energy; when it acts Inward, it drives cohesion and structure formation. Both are two faces of the same thermodynamic Work [27], redistributing the primordial enthalpic budget always in the direction of reaching more stable states ($\Delta G \to 0$).

These two forces—the **Inward Force** (f_M) and the **Outward Force** (f_L)—are the true ontological primitives of GERT. They are not derived from each other; they are twin children of the Primordial Enthalpic Reservoir. Instead of invoking distinct and undetected entities to attract (dark matter) and repel (dark energy), GERT respects Occam's Razor by making these effects emergent consequences of a single thermodynamic source.

The Inward Force (f_M): Thermodynamic Cohesion

When the enthalpic mechanism acts Inward, it generates a negative effective pressure, a tension that drives the system toward greater cohesion and condensation. In the regime where spacetime geometry has already crystallised (Layer 3, see Section 2.6), this thermodynamic cohesion manifests primarily as *gravity*—the curvature of spacetime that creates gravitational potential wells where enthalpic energy condenses into matter and structure. Once matter aggregates, the other fundamental interactions (electromagnetic, strong nuclear, and weak nuclear forces) emerge as further projections of the same Inward Force onto the crystallised metric, each acting on progressively smaller scales [15]. It is therefore ontologically precise to say that gravity is the primary and deepest *manifestation* of f_M in Layer 3, not its identity. f_M itself is the underlying thermodynamic cohesion; gravity is what f_M looks like when viewed through the lens of a stabilised classical geometry. This distinction becomes crucial when the framework is extended below the metric-crystallisation threshold (the domain of Papers VIII and XII of this series).

The Outward Force (f_L): Thermodynamic Expansion

When the enthalpic mechanism acts Outward,[1] it exerts a positive effective pressure on the fabric of spacetime, driving expansion and accelerated dispersal of energy. What we observe as an increase in disorder and an expansion of volume is the macroscopic signature of this process. A terminological

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[1] Hereafter, we use the terms "expansive force," "expansive mode," and "expansive flow" to denote this outward thermodynamic manifestation, as the context dictates. The qualifier "entropic," when it appears, refers to the *entropic character* of the process—the tendency toward greater dispersal—not to entropy as the causal agent.

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clarification is warranted here. Entropy (S) is the thermodynamic *measure* of the Outward Force's cumulative effect—the record of how far the system has progressed toward dispersal—not the force itself. The agent is f_L; entropy is the bookkeeping it leaves behind. This distinction separates GERT from approaches that identify gravity directly as an entropic force [15]: in GERT, both the Inward and Outward Forces are children of enthalpy, and entropy is the *result* of the Outward Force's Work, not its cause. In this sense, GERT replaces the need to postulate dark energy with the dynamical manifestation of the Outward Force f_L, whose functional form and phase transitions are fixed by thermodynamic reasoning and constrained by cosmological data.

2.6. The Ontological Hierarchy of GERT: Four Layers, Two Relations

GERT postulates a fundamental ontological hierarchy of physical laws — not a temporal sequence, but a structure with two distinct types of relation. The language of "layers" is not chronological; since time itself is a product of thermodynamic Work, no layer can be said to *precede* another in any temporal sense. We use the terms "deeper" and "more fundamental" rather than "before" or "earlier."

The two relations must be carefully distinguished.

Containment (Layer 1 and the temporal cycle). The relation between Layer 1 and the temporal cycle formed by Layers 2, 3, and 4 is not one of emergence but of *containment*. The temporal cycle exists within Layer 1 as a drop of water exists within the ocean: the ocean contains the drop without having its physical properties, without being altered by it, and without the drop having "emerged from" the ocean in any sequential sense. Layer 1 does not become Layer 2; Layer 2 is a temporal self-organisation that unfolds *within* Layer 1. This is not a limitation of Layer 1 — it is its nature. Layer 1 is the mathematical zero: not absence but full potential, which in the limit is indistinguishable from full actuality. Zero contains all numbers without being any of them. The entire temporal cycle — every Cauldron, every crystallised Universe, every new aeon — is enfolded within Layer 1 without Layer 1 being modified, depleted, or entered. Layer 1 is the absolute ground. *None of Layers 2, 3, or 4 emerges from Layer 1.*

Emergence (within the temporal cycle). The relation among Layers 2, 3, and 4 is one of genuine sequential emergence: Layer 3 crystallises from Layer 2 at the metric-emergence threshold $\Xi(\alpha_{\text{em}}) = 1$; Layer 4 dissolves from Layer 3 as the enthalpic budget approaches the Quasi-Vacuum Floor; and, under Hypothesis B (Section 2.9), a new Layer 2 is seeded within Layer 4 when the Gibbs Criterion fires again. The cycle $2 \to 3 \to 4 \to 2$ is a temporal sequence of genuine ontological transitions — each layer emerging from the previous one through a thermodynamic phase transition. This cycle unfolds entirely within the containing ground of Layer 1, without ever touching or modifying it.

Layer 1 — The Atemporal Substrate. The deepest layer is the pre-thermodynamic substrate from which everything emerges. It is characterised by $\Delta G = 0$ and $H_{\text{vac}} = 0$: a state of pure potential, ontological completeness without activity. Layer 1 carries four fundamental privations — it is, precisely and irreducibly:

- **a-temporal** — no time, no $\partial/\partial t$, no arrow;
- **a-geometric** — no space, no metric, no inside or outside;
- **a-spatial** — no position, no extension, no boundary;
- **a-quantum** — no Hilbert space, no uncertainty principle, no zero-point energy.

These are not successive approximations or limiting cases — they are simultaneous and constitutive. Layer 1 has no exterior and no boundary not because it is spatially closed, but because the very categories of space, time, inside, and outside are emergent constructs that do not yet exist at this level.

A critical terminological clarification is required here. This foundational layer *cannot* be described as "quantum." Quantum mechanics, in all its formulations, presupposes time: the Schrödinger equation contains $\partial/\partial t$; quantum field theory is built on time-ordered products; the path-integral formulation integrates over temporal histories. A framework that is fundamentally a-temporal cannot be quantum in any of these senses. Layer 1 is the substrate *from which* quantum behaviour eventually crystallises, not the quantum vacuum itself. Calling it "quantum" would impose a derived category onto the very ground that generates it — a category error that GERT is specifically designed to avoid.

A further consequence of Layer 1's zero-sum character deserves mention. The condition $H_{\text{vac}} = 0$ does not mean Layer 1 is empty — it means it is perfectly balanced. Viewed from within a temporal reference frame, this balance bifurcates into two thermodynamic trajectories: a matter Universe ($H_M > 0$) and an anti-matter Universe ($H_{\bar{M}} = -H_M < 0$), whose enthalpic quotas sum to exactly zero. The matter–antimatter asymmetry of our observable Universe is therefore not a statistical residue of an imperfect annihilation. It is a logical necessity: the two Universes never shared a spacetime, because spacetime is a product of Layer 3 that did not exist at the Layer 1 bifurcation.

This ontological resolution of baryogenesis — and its structural implications for the terminal cycle described in Section 2.9 — is developed in full in Paper VIII of this series [34], which is available as a preprint for readers wishing to examine the argument in detail. Its inclusion here is intentionally brief: Paper I is designed to stand on its own empirical and thermodynamic foundations, and Paper VIII is offered as an independent reference rather than a prerequisite.

Layer 2 — The Thermodynamic Cauldron (The Primordial Cauldron). The second layer is the domain of thermodynamic action: the Primordial Cauldron where the condition $\Delta G < 0$ becomes meaningful and where the Gibbs Trigger operates. The Primordial Enthalpic Reservoir is active here. Gradients of enthalpy emerge; the Dual Mechanism—the Inward and Outward Forces—begins its Work. Time as a physical quantity is born in Layer 2, as the intrinsic measure of thermodynamic Work being performed (Section 2.7). Space, in the sense of an expanding proto-metric, also emerges here, though without the smooth classical geometry of General Relativity. This is the domain that GERT treats as its effective boundary condition in the present paper: the output of Layer 2 is the Primordial Enthalpic Reservoir whose thermodynamic unfolding we model. The internal dynamics of Layer 2—the proto-quantum crystallisation, the Gibbs Criterion, the metric-emergence threshold—are the subject of the extended GERT programme.

Layer 3 — The Crystallised Regime (Relativistic + Quantum). The third layer is the domain where thermodynamic stabilisation has proceeded sufficiently for a smooth classical geometry to crystallise. General Relativity emerges here as an effective description of a Universe that has already undergone its foundational thermodynamic act [26–28]. It is not fundamental; it is the grammar of a system that has already stabilised. Cosmic time, redshift, and the expansion history all belong to this layer—it is the domain that GERT's $H(z)$ framework describes.

Crucially, quantum mechanics also crystallises in Layer 3, not Layer 1. The discrete, probabilistic structure of quantum fields emerges simultaneously with the metric, at the threshold where the proto-thermodynamic substrate acquires sufficient geometric regularity to support well-defined field modes. General Relativity and Quantum Mechanics are therefore co-emergent products of Layer 3—siblings, not parent and child. This is why their direct unification has proved so intractable: the standard programme attempts to quantise a geometry that is itself an emergent approximation, without addressing the thermodynamic layer from which both emerged.

Layer 4 — The Hyperdilute Regime (Far-Future Dissolution). Beyond the boundary $\alpha_{\text{crit}} = 12.88 \pm 0.12$ established in Paper II [35], the photon mean free path becomes cosmologically irrelevant, the relativistic ruler dissolves, and Layer 3 ceases to be operationally valid. The Universe enters the Hyperdilute Regime: geometry progressively de-crystallises, the enthalpic budget approaches the Quasi-Vacuum Floor ($\Delta G_{\text{QV}} \to 0$), and the distinction between matter and radiation dissolves. This is the domain of the two terminal hypotheses described in Section 2.9: either the Gibbs Criterion fails to fire (Hypothesis A, nirvanic dissolution) or it fires again, seeding a new Primordial Cauldron (Hypothesis B, Penrose aeon). In both cases, Layer 4 is the thermodynamic mirror of Layer 2 — a pre-metric regime reached not by excess density but by extreme dilution.

Thus, the ontological stratigraphy of GERT is:

- **Layer 1 (The Atemporal Substrate):** Pure potential with $\Delta G = 0$, $H_{\text{vac}} = 0$. No time, no space, no quantum structure. The zero from which everything is measured.

- **Layer 2 (The Primordial Cauldron):** The thermodynamic regime where $\Delta G < 0$, the Gibbs Trigger fires, the Dual Mechanism operates, and time is born as Work. The proto-metric expands. This is GERT's domain of governance—the thermodynamic bridge between the atemporal substrate and the crystallised Universe.
- **Layer 3 (The Crystallised Universe):** Smooth classical geometry crystallises; General Relativity emerges as its effective grammar [26]; Quantum Mechanics co-emerges simultaneously [28]. The expansion history $H(z)$, redshift, and all standard cosmological observables belong here.
- **Layer 4 (The Hyperdilute Regime):** Far-future dissolution beyond $\alpha_{\text{crit}} = 12.88$. Geometry decrystallises, $\Delta G_{\text{QV}} \to 0$, and the cycle either terminates (Hypothesis A) or seeds a new Cauldron (Hypothesis B). The thermodynamic mirror of Layer 2, reached by dilution rather than density.

Therefore, we conclude that the search for the “holy grail” of physics—the unification of Quantum Mechanics with General Relativity—will not be possible as long as the thermodynamic layer from which both emerge is skipped. A unified theory cannot jump from the Crystallised Structure (GR + QM) directly to the Atemporal Substrate without first understanding and formulating the laws of the thermodynamic Bridge—GERT—that connects them. The thermodynamic layer is not a curiosity to be recovered after quantisation; it is the ontological ground on which quantisation itself rests.

2.7. *Time is Work: The Thermodynamic Arrow of Time*

GERT proposes a redefinition of the nature of time. In this sense, instead of time being a fundamental and pre-existing dimension in which events unfold, time in GERT is an emergent phenomenon, whose passage is the intrinsic measure of the thermodynamic *Work* actively being performed by the Universe. Each "tick" of the cosmic clock corresponds to a quantity of energy being transformed to create structure and expansion. The "cosmic clock" is a thermodynamic stopwatch, not an absolute parameter. Time is only “born” when thermodynamic Work begins — when Layer 2 (the Primordial Cauldron) becomes active and the first enthalpic gradients emerge.

Therefore, the arrow of time is the macroscopic manifestation of the thermodynamic *Work* that the Universe performs on itself, spending its energy reservoir to stabilize Gibbs as long as ΔG is negative and there is enthalpic potential to be expended. In a Universe that reaches final equilibrium (ΔG=0), where there is no more Work to be done, the intrinsic concept of time, as a process of change, dissolves.

2.7.1 The Symmetry of *Work*

Just as forces in nature arise in action-reaction pairs and obey fundamental symmetries (e.g., conservation laws derived from gauge invariances), the Work generated by our Dual Mechanism also manifests symmetrically:

- **Outward Work** → exerts **positive pressure** on spacetime, triggering the increase in growing entropy and irreversible expansion.
- **Inward Work** → exerts **negative pressure**, generating gravitational contraction, curvature, and ultimately, the condensation of the field into nodes of matter.

In terms of Noether's theorem [36], just as translational invariance in time gives rise to the conservation of energy, here the symmetry of the Dual Mechanism — the ability of the same Primordial Enthalpic Reservoir to channel its output as either Inward or Outward Work — is the common thermodynamic source of the **Inward Force** (f_M, whose Layer 3 projection is gravity) and the **Outward Force** (f_L, whose cumulative measure is entropy).

Thus, Work is not a univocal quantity but a symmetric object that, according to the thermodynamic state of the Universe, drives either expansion or cohesion of the cosmic fabric, always respecting the symmetry principle that governs all physical interactions. Gravity and entropy are not the ontological twins; the Inward Force and the Outward Force are. Gravity and entropy are what those forces look like, respectively, when observed from within Layer 3.

2.8. The Inversion: Gravity Creates Matter

In Phase 1 (the Primordial Cauldron (Layer 2)) there are no classical particles; only the primordial energy field under extremely high density exists. When the mechanism acts Inward, the self-generated negative pressure curves the spacetime.

Therefore, in our pre-metric Cauldron (Layer 2), gravity would not be a force acting on particles but rather a process of "self-contraction" of the primordial energy field itself.

One of the consequences of the contractile manifestation of the thermodynamic mechanism being an emergent manifestation from energy redistribution is that gravity comes to exist before matter as we know it. Matter particles would not be primordial but "condensations" that form when the primordial energy field curves upon itself with sufficient intensity. GERT postulates that matter particles (quarks, electrons) are not primordial entities but rather **"condensations"** or "nodes" that form when this primordial energy field curves upon itself intensely enough.

Matter is not fundamental; it is a consequence of the thermodynamic topography in spacetime. The conclusion is that gravity does not need matter to exist; matter needs gravity to be born.

General Relativity postulates that matter tells spacetime how to curve [1]. GERT proposes the inverse: the curvature of spacetime (the contractile manifestation of enthalpy, i.e., gravity) tells energy how to condense into matter.

Therefore:

- **Gravity Does Not Depend on Matter:** It is a primordial force born from enthalpy.
- **Contraction Phase:** The intrinsic negative pressure (p_grav < 0) begins to self-contract the primordial energy field, forming a curved geometry and initiating "condensation points." It creates "wells" in spacetime, which are zones of high curvature.
- **Quantum Condensates:** These gravitational wells function as **matter factories**; they create the necessary conditions for
  the omnipresent free energy of the Universe to "condense" or "precipitate" into particles with mass, following Einstein's famous equation but operating it in reverse: m=E/c². The local density surpasses the enthalpic condensation threshold, creating **nodes** that stabilize as particles.
- **Effective Matter:** These "nodes" are the cohesion energy in action. They are the root of ordinary matter and the apparent "dark matter" observed later, which would be the manifestation of the fundamental gravity that has not yet fully condensed into the matter we observe.

2.9. The Cosmic Life Cycle: The Dignified Decanting and the Two Terminal Hypotheses

Every thermodynamic process tends toward equilibrium. In GERT, the entire history of the Universe is the progressive discharge of the Primordial Enthalpic Reservoir under the Gibbs Criterion ($\Delta G < 0$). As the Hyperdilute Regime advances and the enthalpic budget approaches exhaustion, the system decants toward the thermodynamic minimum available within the temporal process: the Quasi-Vacuum Floor, $\Delta G_{\mathrm{QV}} \to 0$.

This minimum is not the absolute zero of Layer 1 ($\Delta G = 0$, $H_{\mathrm{vac}} = 0$, atemporal). That distinction is ontologically critical. Layer 1 is the atemporal substrate that founds the cycle without participating in it. If it were reached, the Weyl curvature register accumulated during the aeon — the structural memory carried by the last black holes as they evaporate — would be erased entirely. No seed would remain. The Universe does not dissolve into the atemporal ocean; it decants to the minimum within time.

The consequences of approaching the Quasi-Vacuum Floor are shared between both terminal hypotheses:

- **The Inward Force reaches its minimum:** As enthalpic density falls below the structural thresholds, f_M can no longer sustain gravitational wells. The last supermassive black holes undergo macroscopic thermodynamic phase transition (Paper II), releasing their enthalpic content without requiring Hawking evaporation. Geometric legibility progressively dissolves as $\rho < \rho_{\mathrm{GR,min}}$.

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- **The "Dignified Decanting":** the Universe does not end in cold thermal death, nor dissolve into the atemporal absolute. It decants — spending its last enthalpic reserves until $\Delta G_{\mathrm{QV}} \to 0$ at the Quasi-Vacuum Floor.

At the Quasi-Vacuum Floor, two terminal hypotheses are logically possible, and the GERT framework cannot yet derive which is correct — because the explicit functional form of ΔG_{QV} has not yet been derived (Paper VIII of this series identifies this as the central open problem of the programme):

- **Hypothesis A — Nirvanic state:** The Work is exhausted completely. $\Delta G_{\mathrm{QV}} \to 0$ without the Gibbs Criterion firing again. The Weyl register dissipates. No new cycle begins. The Universe reaches a final balanced state of dispersed energy — the "nirvanic" limit. This does not touch Layer 1 (which is atemporal and unreachable from within time), but the cycle ends.
- **Hypothesis B — New aeon (Penrose):** The Weyl curvature register accumulated throughout the dissolution satisfies $\Delta G_{\mathrm{QV}}(\Psi_{\mathrm{Weyl}}) < 0$. The Gibbs Criterion fires at the Quasi-Vacuum Floor, seeding a new Primordial Cauldron. Penrose's conformal geometry describes the form of this crossover. The cycle oscillates between Quasi-Vacuum states, never touching Layer 1.

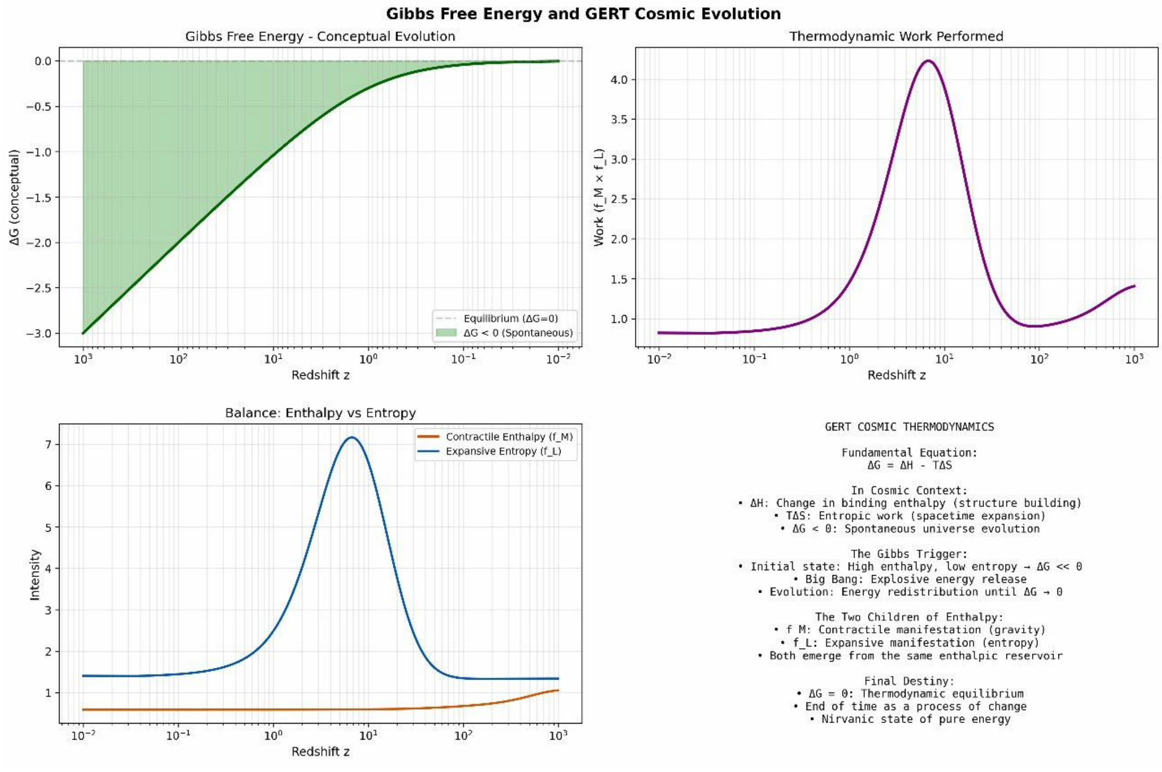
The GERT framework offers a structural argument — not yet a formal derivation, but a logical constraint — that makes Hypothesis A structurally untenable and Hypothesis B the necessary resolution.

The argument is the following. The zero-sum conservation $H_M + H_{\bar{M}} = 0$ of the atemporal substrate (Layer 1) is absolute: it holds at every level of the ontological stratigraphy. For the cycle to terminate at Layer 1 (Hypothesis A), H_M would have to be annihilated. But annihilating H_M without simultaneously annihilating $H_{\bar{M}}$ would break the zero-sum — the total would no longer be zero. Simultaneous annihilation of both requires coordination between two Universes that share no metric, no coordinates, and no causal contact — which is precisely what their ontological separation, established at the Layer 1 bifurcation, structurally forbids. Hypothesis A therefore does not merely face a tension; it faces a logical impossibility within the zero-sum framework. The cycle cannot terminate. It must continue.

Hypothesis B is therefore not merely more parsimonious — it is the only resolution consistent with the conservation structure of the framework. What remains to be derived is the explicit form of $\Delta G_{\mathrm{QV}}(\Psi_{\mathrm{Weyl}})$: the function that translates the Weyl curvature register into the enthalpic seed of the new Cauldron. This derivation — connecting Penrose's conformal geometry to the full Gibbs framework — is the central open problem of the GERT programme (Section 7.3). The baryogenesis argument that grounds this zero-sum structure is developed in Paper VIII of this series [34].

- **ΔG (conceptual):** The green area indicates the spontaneous regime ($\Delta G < 0$). The curve approaches $\Delta G \to 0$ as $z \to 0$, indicating equilibrium fate of the GERT.
- **Thermodynamic Work:** The effective product of the contractile and expansive modes exhibits a broad peak at $3 \lesssim z \lesssim 8$, marking the end of the Constructive Era and the handover of dominance to the expansive mode.
- **f_M vs f_L Balance:** Visualizes the progressive dominance of the entropic mode.

Figure 1 summarizes Gibbs Free Energy and GERT Cosmic Evolution and serves as a reference for the subsequent sections.



GERT COSMIC THERMODYNAMICS

Fundamental Equation:
ΔG = ΔH - TΔS

In Cosmic Context:
- ΔH: Change in binding enthalpy (structure building)
- TΔS: Entropic work (spacetime expansion)
- ΔG < 0: Spontaneous universe evolution

The Gibbs Trigger:
- Initial state: High enthalpy, low entropy → ΔG << 0
- Big Bang: Explosive energy release
- Evolution: Energy redistribution until ΔG → 0

The Two Children of Enthalpy:
- f M: Contractile manifestation (gravity)
- f_L: Expansive manifestation (entropy)
- Both emerge from the same enthalpic reservoir

Final Destiny:
- ΔG = 0: Thermodynamic equilibrium
- End of time as a process of change
- Nirvanic state of pure energy

Figure 1. GERT Cosmic Evolution.

2.10. *A Thermodynamic Alternative to Dark Components*

One of the logical consequences of the GERT paradigm is that it provides an alternative interpretation for the phenomena currently attributed to dark matter and dark energy, integrating them as emergent manifestations within the GERT framework. In this view, these phenomena are not modeled as distinct "substances" but as emergent manifestations of a dynamic physics that the standard model does not contemplate.

For background on the observational evidence motivating dark components in the standard framework [8]. For the current landscape of proposed resolutions and alternatives see [9,10]; for broader alternative/emergent approaches [18].

- **Dark Energy Dispensed:** It is the manifestation of the entropic mode, an inevitable result of the thermodynamic process, not a substance. This aligns perfectly with Occam's Razor. The phenomenon of accelerated expansion is replaced by the Entropic Potential, modeled by **Expansion Fraction** $f_L(x)$. This is not a new energy, but the manifestation of the Outward Force that becomes dominant when the density of the Universe falls below a critical threshold ($\rho < \rho_L$), as predicted by thermodynamics. At the end of the "constructive" era of cosmic structure formation, the energy that was previously directed towards cohesion, upon completing its Work, turns Outward, pressing on spacetime to expand. Thermodynamics requires ΔG=0 globally: all generated entropic Work balances the change in enthalpy and produces irreversible expansion.
- **Dark Matter Effects:** The extra gravitational effect required for structure formation is interpreted within GERT as arising from the Cohesion Fraction, $f_M(\rho_{\text{ico}})$, which occurs as a resonant effect at specific critical densities. GERT proposes that this effect may be modeled as a temporary phase of baryonic matter itself, rather than requiring a new type of particle—a hypothesis that is supported, in the present analysis, by the statistical fit of the $f_{M,\text{peak}}$ parameter at a specific density. During the "Era of Atomic Recombination," a fraction of matter exhibits a collective and cohesive behaviour, whose gravitational effect mimics what would be attributed to dark matter. This effect is temporary and disappears after the conclusion of the atomic recombination phase.

In the empirical analysis, this interpretation is supported at the phenomenological level by the constrained, nonzero best-fit behaviour of $f_{M,\mathrm{peak}}$ at the recombination density [8].

2.11. *The Cosmic Dance and the Phases of the Universe through the Lens of GERT*

The Gibbs Energy Redistribution Theory (GERT) describes the history of the Universe not as a sequence of arbitrary events, but as a series of thermodynamic phase transitions, always with the arrow of time pointing towards stabilizing the cosmos by performing Work. Under the lens of the Dual Mechanism—the eternal dance of Gibbs—cosmic evolution unfolds in four great acts.

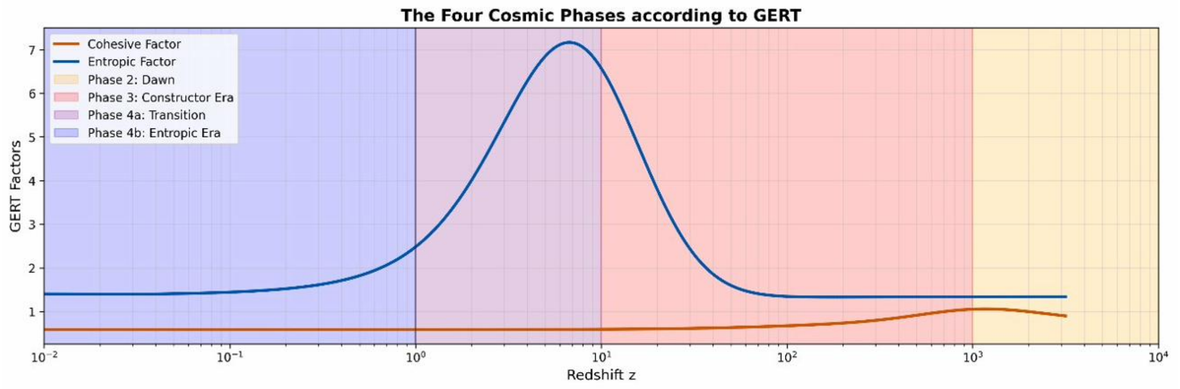
- **Phase 1: The Primordial Cauldron (The Thermodynamic Big Bang):** In this stage, the Universe is born from a state of extreme thermodynamic disequilibrium, a pre-relativistic thermodynamic black box with colossal enthalpy and almost zero entropy. The trigger for existence is not a mechanical force, but the condition $\Delta G \lll 0$ [32], which makes the expansion and creation of microstates an overwhelmingly spontaneous process.
    - **Action of the Dual Mechanism (Inward and Outward Forces):** At this stage, the Forces are not yet fully differentiated. There is only the Primordial Enthalpic Reservoir, the original reservoir in its purest and most unstable state, about to give birth to the dynamics of the cosmos. What follows is the “Bubbling Proto-Metric,” a pre-relativistic phase where spacetime ferments and the rules of geometry have not yet crystallized.
- **Phase 2: The Dawn of Order (The Genesis of Matter and the CMB):** Spacetime “condenses” into a stable geometry, and General Relativity emerges as a valid description. Immediately, the first “halos” of intense gravitational curvature attract energy from the primordial tank, forcing the first major material phase transition: energy condenses into matter, creating the first quarks and electrons.
  Only after this genesis does the Universe cool enough for the second great Work of construction to be completed: the formation of neutral atoms (Recombination), which releases the light we now observe as the Cosmic Microwave Background (CMB) [8].
    - The Inward Force, gravity, performs its first Work by creating the “molds” for matter. Subsequently, the emergent short-range forces (nuclear and electromagnetic forces) perform the *Work* of binding the newly created particles into protons and, later, into atoms.
- **Phase 3: The Constructive Era (The Formation of the Cosmic Web):** Guided by the small density “clumps” left in the CMB, matter begins to agglomerate massively, forming the vast cosmic web, the first galaxies, and the first generations of stars. This is the **Constructive Era**.
    - This is the phase of dominance of cohesive forces. Gravity pulls matter together, whereas other forces transform it into stars, releasing enormous amounts of binding energy. The Universe is actively spending the energy from the Primordial Enthalpic Reservoir to build it. This is the period in which our cohesion parameter, $f_M(z)$, is mathematically modeled.
- **Phase 4: The Era of Entropic Expansion (The Handover):** This phase marks the action of entropy and is also divided into two stages, reflecting the functional and dynamic nature of GERT:
    - **Phase 4a-Initial Acceleration:** After billions of years, the Work of construction diminishes. Most of the matter is already in stable structures. The cohesive forces, previously spent on building, are now used to *maintain* these structures. With the energy used for construction ceasing, the entropic force, which was always present, becomes the dominant mode. The expansion of the Universe, which had been slowed by the constructive phase, peaks and begins to accelerate. The handover then occurs: The “cohesive mode” shifts from builder to maintainer, and the “entropic mode” takes control of the large-scale dynamics. Galaxies, although moving apart, were relatively close.
    - **Phase 4b-Late Acceleration (The Current Epoch):** The acceleration continues, and the distances between galaxy clusters become vast. The Universe enters a phase transition to

a "gaseous" state, where long-range gravitational interactions become increasingly rare. The "entropic mode" is in full command, stretching the fabric of spacetime. The Universe continues on its thermodynamic journey towards final equilibrium. As with any gas, the resistance force decreases even further.

This continuous dynamism, with its sub-phases and smooth transitions, is precisely why a model with fixed parameters fails. The history of the Universe is not a series of static states but a constantly evolving function, and GERT provides the mathematical language to describe it.

Therefore, one of the principles of GERT is that **"the law is the function."**

Figure 2 summarizes the four-phase picture and serves as a reference for the subsequent sections.



```
                 THE FOUR COSMIC PHASES OF GERT

PHASE 1: THE PRIMORDIAL CAULDRON (not shown - pre-relativistic)
       • State of extreme thermodynamic disequilibrium
       • Gibbs trigger: ΔG << 0 initiates the Big Bang
       • Bubbling proto-metric → emergence of geometry

              PHASE 2: THE DAWN OF ORDER (z > 1000)
                 • Energy condensation into matter
                • Atomic recombination → CMB release
             • Cohesive peak during first atom formation

            PHASE 3: THE CONSTRUCTOR ERA (10 < z < 1000)
                      • Cosmic web formation
                     • First galaxies and stars
              • Dominance of cohesive factor (gravity)

                 PHASE 4a: BATON PASS (1 < z < 10)
           • Dominance transition: cohesion → expansion
           • Entropic peak marks end of constructor era
                 • Beginning of cosmic acceleration

               PHASE 4b: CURRENT ENTROPIC ERA (z < 1)
                    • Dominance of entropic factor
                   • Universe in gas phase (z ≈ 0.03)
         • Accelerated expansion toward equilibrium (ΔG → 0)
```

Figure 2. The four cosmic phases according to GERT.

2.12. The Law is the Function: Dynamic Parameters and the Phases of the Cosmos

Central Postulate: All the energy content of the Universe is born in a **reservoir of binding enthalpy H**, the Primordial Enthalpic Reservoir. The expansion, structure formation, and final decay are just ways of **redistributing** this enthalpy under the constraints of the 1st and 2nd laws of thermodynamics.

No external energy is added, nor are exotic fluids invented; what changes are the **functional fractions** that dictate **where** the Primordial Enthalpic Reservoir is allocated in each epoch.

We always remember Antoine Lavoisier, the father of modern chemistry, who established one of the most fundamental principles of science, a basic principle that GERT extends to cosmic levels:

> *In nature, nothing is lost, nothing is created, everything is transformed!*

Therefore, the Universe begins with a finite reservoir of binding energy. As the cosmos evolves, this "battery" is:

- Converted into redistribution energy → entropic impulse that accelerates spacetime.
- Spent in cohesive processes → formation of nuclei, galaxies, BHs.

Nothing can be added from the outside; all energy and pressure terms must emerge from the redistribution of this **Primordial** Enthalpic Reservoir.

To validate GERT against observational data, we developed a mathematical model that translates its theoretical principles into quantifiable predictions. The approach consists of using the framework of General Relativity (GR) as the grammar of cosmic geometry, while GERT provides a new physics for the energy content that dictates the dynamics of that geometry.

One of the most innovative postulates of GERT, and a direct break from standard cosmology, is the principle that **the fundamental law is the function, not the fixed physical parameters**. While traditional physics treats the constants of nature (such as the gravitational constant G or the energy density fractions) as immutable values, GERT proposes that these are, in fact, **emergent state parameters**.

The true immutable law is the thermodynamic principle of Gibbs Free Energy stabilization. The "parameters" we measure are effective properties that depend on the thermodynamic phase the Universe is in (e.g., Plasma, Liquid/Constructive, Gaseous/Accelerated Expansion). The transitions between these phases are the critical events in cosmic history.

Consequently, the parameters describing the components of the Universe are not "frozen" constants but rather **dynamic functions** of the system's state, evolving with the energy density ρ. The true physical law is not a static number, but the function that describes the transition between cosmic phases.

The best analogy is with the phases of water [31,37]: An H_2O molecule does not become vapor in isolation and instantaneously. The entire system undergoes a transition in which the temperature and pressure dictate a continuous change in behaviour. The "viscosity" or "compressibility" of the substance changes smoothly (or rapidly, but never discontinuously) from one state to another. They are not fundamental constants but rather radically different properties of ice, liquid water, or steam.

Similarly, the GERT Universe does not "flip a switch" from a matter-dominated era to an entropy-dominated era. It undergoes phase transitions. The entire **Cosmos enters into Transition.**

Thus, GERT exchanges **"fixed contents" for "dynamic fractions"**. The logistic and Gaussian coefficients are the intrinsic law of evolution, guiding the energy redistribution that moves the cosmos. With only 13 hyperparameters and 2 functional forms, the equation replaces an entire inventory of dark substances and inflationary phases, while maintaining energy conservation and the thermodynamic arrow of time.

Therefore, our parameters (f_M, f_L) are not fundamental constants of nature. They are **effective state Hyperparameters**, which evolve with the thermodynamic condition of the Universe (e.g., its energy density, ρ). This means that the true "law of physics" is not the *value* of a parameter but the *mathematical function* that describes its evolution.

Why use functions instead of constants?

- **Thermodynamic coherence** – each cosmic phase is a distinct Gibbs regime; constants do not capture transitions.
- **Ontological economy** – a single Primordial Enthalpic Reservoir generates all effects; one just needs to "regulate the tap" with functions.
- **Prediction without *ad hoc*** – evolutionary factors replace the introduction of dark energies and extra matter.

The ΛCDM model essentially defines artificial cosmic "epochs" with abrupt transitions. It is like trying to describe a car's motion with a series of constant speeds per segment instead of the smooth function v(t) that actually occurs. In GERT, laws of evolution = functional forms, and the parameters are vertices of these functions, not "knobs" to adjust final values.

Practical benefits:

- **Physical naturalness** – transitions reflect Gibbs' idea of continuous phases, not abrupt jumps.
- **Parameter economy** – one only needs x_0 (where it occurs) and δ (how fast).
- **Numerical stability** – derivatives do not explode; Friedmann integration is smooth.

- **Universality –** the same function serves for gravity, entropy, or cohesive peaks, changing only the vertices or the amplitude.

Therefore, in the GERT equation, **logistics "graduate"** the activation/deactivation of components, and the **Gaussian "marks"** a transient event—all in a perfectly smooth manner, without inserting external energies or creating breaks in the dynamics.

Each of our "dynamic" parameters can now be described as a function that transitions between an initial and a final value:

- $f_M(z)$ **(Dynamic Matter Factor):** This factor, implemented as a logistic function, modifies the effective contribution of matter over time, representing the Inward Force. It represents the change in the gravitational influence of matter between the different phases of the Universe.
- $f_L(z)$ **(Dynamic Entropic Factor):** This factor modifies the dark energy component, representing the Outward Force. Its dynamic evolution reflects the changing balance of power with the gravitational force.

This equation ensures that f_M transitions smoothly from its initial value ($f_{M,i}$) to its final value ($f_{M,f}$) when the density of the Universe (ρ) crosses a critical threshold (ρ_M). Physically, the acceleration of expansion occurs when the effective pressure of the Universe becomes sufficiently negative. In our model, the f_L term controls the strength of a component with negative pressure. When the density of the Universe (ρ) falls below the threshold ρ_L, this function $f_L(\rho)$ "turns on," increasing the strength of this component. This causes the total pressure of the Universe to become negative, initiating the expansion phase. These phases will be explained in detail in the Methodology section with the results and discussion.

Therefore, the GERT Mathematical Formalism:

1. Starts from a **Primordial Enthalpic Reservoir**.
2. Uses logistic and Gaussian "dimmer" functions to model natural, smooth transitions and to decide in each era whether the free energy Works **Inward** (curves) or **Outward** (expands).
3. Responds automatically to changes in the Universe's energy density.
4. Maintains physical coherence at all scales without the need for *ad hoc* "patches."

Our final H(z) function, implemented in our scripts, combines all these elements to describe the complete history of expansion, from the emergence of relativity with a stabilized spacetime to the current entropic acceleration.

3. Mathematical Formalism

The pillar of our model is a function of the history of expansion, H(z), which incorporates the dynamic physics of **GERT**. Our methodology consisted of constructing this function and then adjusting its hyperparameters to minimise the χ^2 against the combined data from the CMB [8] and BAO analyses [14,23].

3.1. The Heart of the Theory: H_GERT_dynamic

This function calculates the rate of expansion of the Universe (H) at any moment in the past (represented by the redshift z). Its fundamental equation is the Friedmann Equation, which we can write as [1,2,8]:

$$H^2 = \frac{8\pi G}{3}\rho_{\text{total}} \tag{1}$$

The innovation of **GERT** lies in how we calculate the total density, ρ_{total}. It is not just the sum of matter and radiation; it is the sum of components that change in strength over time.

3.2. Modified Friedmann Equation separated into components

$$H^2(z) = H_0^2 \left[\underbrace{\Omega_{r,0}(1+z)^4}_{\text{radiation}} + \underbrace{\Omega_{m,0} f_M(\log \rho(z))(1+z)^3}_{\text{effective matter}} + \underbrace{\Omega_{\Lambda,0} f_L(\log \rho(z))}_{\text{entropic pressure}} \right] \tag{2}$$

$$\text{where} \quad \log \rho(z) = \log \rho_{m,0}(1+z)^3 \tag{3}$$

Where:
Radiation: standard term, without modification.
Effective matter:

$$\Omega_{m,0}(1+z)^3 \text{ is multiplied by } f_M \tag{4}$$

— includes the cohesive peak.
Entropic pressure:

$$\Omega_{\Lambda,0} \text{ becomes curvature-guided multiplied by } f_L; \tag{5}$$

$$\text{at very low densities, the gas term becomes dominant.} \tag{6}$$

3.3. The Complete Mathematical Formalism of the GERT Model

The effective parameters that, according to **GERT**, describe the components of the Universe are dynamic functions that evolve with the state of the system parameterized by the energy density ρ.

This section presents the detailed mathematical architecture of the unified formulation of the **GERT** model. The formalism is constructed from basis functions that, when combined, describe the complex thermodynamic history of the cosmos. The choice of each is dictated by the nature of the phenomenon they describe.

Basis Functions: The Mathematical Tools

The model uses three types of mathematical functions, each chosen to represent a distinct physical process:

The "Dimmer" Functions (Logistic and Gaussian) act as "switches" that turn on and off, and the Exponential Growth Function for the gaseous term.

- **Dynamic "Dimmers" Functions:**

These functions act as "Dimmers" of light: Logistic and Gaussian that turn the parameters on and off. Each component has a density fraction dynamically modified by the logistic and Gaussian transition functions.

The mathematical formulation of the GERT dynamic functions — utilizing logistic transitions and Gaussian peaks — reflects the established mathematical language of standard phenomenological models in local physical chemistry. In classical thermodynamics, logistic sigmoids naturally describe continuous phase transitions and fractional state conversions, while Gaussian functions are the universal signature of cooperative thermal resonances and structural fluctuations [31,32,37]. By applying these specific forms, GERT extends the established mathematical language of macroscopic thermodynamics to the cosmic expansion history.

Logistic Function (Sigmoid) (L):

Acts as a "soft switch" to model gradual and permanent transitions [31] between two states, such as the transition from one cosmological era to another. It is the ideal tool for describing the slow evolution of background potentials. It models smooth and permanent phase transitions.

$$L(x; x_0, d) = \frac{1}{1 + e^{\frac{x - x_0}{d}}} \tag{7}$$

Gaussian Function (gauss) G:

It has completely different behaviour and purpose. It does not model a transition but rather transient and localized events, functioning as a resonance that occurs at a specific critical density. These events “activate” and “deactivate” at specific times, such as the peaks of cohesive and repulsive forces. Its shape ensures a null start, a peak intensity, and a return to zero. Its properties are:

- **Bell shape:** Symmetrical around the centre, with a maximum value of 1.0 when x=x0.
- **Local effect:** Significant only in a limited region, with rapid decay.
- **Physical Interpretation:** Represents resonant effects, localized disturbances, or amplification phenomena that occur only under very specific conditions, rather than a smooth transition between eras.

$$G(x; x_0, d) = \exp\left[-0.5\left(\frac{x-x_0}{d}\right)^2\right] \tag{8}$$

Exponential Growth Function with Threshold:

Used exclusively for the gaseous term, this function exhibits a fundamentally different behaviour. It describes a unidirectional growth that is activated only below a critical density, mimicking the physics of an expanding gas. Its mathematical form is a shifted version of the exponential function ($e^x - 1$), which is known in some contexts as expm1. This choice is conceptually consistent with the modeled physics: the gas begins to contribute significantly only below a critical density, and its contribution grows exponentially as the density decreases further.

- **Conditional behaviour:** It is exactly zero when the density is above the threshold ($\log\rho \geq \log\rho_{\text{gas}}$) and grows exponentially when the density falls below the threshold.
- **Mathematical Form:** It is a shifted version of the exponential function ($e^x - 1$), known in some contexts as expm1.

The Modified Friedmann Equation by GERT

The heart of the model is the Friedmann Equation, where the densities of matter (Ω_m) and dark energy (Ω_Λ) are modulated by dynamic factors, f_M and f_L, which depend on the matter density of the Universe, ρ.

$$H^2(z) = H_0^2\left[\Omega_{r,0}(1+z)^4 + \Omega_{m,0} \cdot f_M(\log\rho) \cdot (1+z)^3 + \Omega_{\Lambda,0} \cdot f_L(\log\rho)\right] \tag{9}$$

$$\text{where } \log\rho(z) = \log\rho_{m,0}(1+z)^3 \text{ is the control variable representing cosmic time.} \tag{10}$$

The Unified Matter Factor (f_M)

The factor f_M describes the gravitational efficiency of matter. It is composed of a background transition (logistic) and a resonant correction (Gaussian) that acts multiplicatively.

$$f_M(\log\rho) = f_{M,\text{base}} \cdot \left(1 + f_{M,\text{peak}} \cdot G(\log\rho; \log\rho_c, 1.0)\right) \tag{11}$$

or

$$f_M(\rho) = f_{M,\text{base}} + \text{corr}_M \tag{12}$$

$$\text{where correction}_M = f_{M,\text{base}} \cdot f_{M,\text{peak}} \cdot G(\log\rho; \log\rho_c, 1.0) \tag{13}$$

Base Term ($f_{M,\text{base}}$): Models the slow evolution of the cohesive potential. The transition width (d_M) is set at **1.0**. This value, determined by previous tests, represents a faster transition than the expansive transition, occurring at a time of high density where the system's “resistance” to phase changes is greater.

$$f_{M,\text{base}} = f_{M,f} + (f_{M,i} - f_{M,f})L(\log\rho; \log\rho_M, 1.0) \tag{14}$$

Peak Correction: Models the event of "effective dark matter." The Gaussian peak also has a width (d_c) fixed at **1.0**, indicating an event of symmetric duration to the entropic Gaussian transition.

$$\text{where correction}_M = f_{M,\text{base}} \cdot f_{M,\text{peak}} \cdot G(\log\rho; \log\rho_c, 1.0) \tag{15}$$

The Unified Entropic Factor (f_L)

The factor f_L describes the expansive force. Its formulation, which accurately reflects the code, shows that the resonant peak also acts **multiplicatively** on the combined behaviour of the background transition and the gas term.

Its formulation includes a background transition, a resonant peak, and the term for the final gas phase.

$$f_L(\log\rho) = (f_{L,\text{base}} + \text{term}_{\text{gas}}) \cdot \Big(1 + f_{L,\text{peak}} \cdot G(\log\rho; \log\rho_{L2}, 1.0)\Big) \tag{16}$$

or

$$f_L(\rho) = f_{L,\text{inter}} + \text{corr}_L = f_{L,\text{inter}}\Big[1 + f_{L,\text{peak}} G(\log\rho; \log\rho_{L2}, 1.0)\Big] \tag{17}$$

Base Term ($f_{L,\text{base}}$): Describes the main transition of the entropic force. The width (d_L) is set at **2.0**, indicating an even smoother transition at times of lower density.

$$f_{L,\text{base}} = f_{L,m} + (f_{L,i} - f_{L,m})L(\log\rho; \log\rho_L, d_L = 2.0) \tag{18}$$

Peak Correction: Models the "entropic spike." The width (d_{L2}) is fixed at **1.0**, maintaining formal symmetry with the cohesive peak.

$$\text{corr}_L = f_{L,\text{inter}} \cdot f_{L,\text{peak}} \cdot G(\log\rho; \log\rho_{L2}, d_{L2} = 1) \tag{19}$$

(the peak is not an independent term; it amplifies the base sum + gas)

Gas Term: This is the component that describes the physics of the Universe at very low densities.

$$\text{term}_{\text{gas}} = \begin{cases} k_{\text{gas}}\left[\exp\left(\frac{\log\rho_{\text{gas,start}} - \log\rho}{\gamma_{\text{gas}}}\right) - 1\right], & \text{if } \log\rho < \log\rho_{\text{gas,start}} \\ 0, & \text{if } \log\rho \geq \log\rho_{\text{gas,start}} \end{cases} \tag{20}$$

The parameter k_{gas} controls the intensity of this final expansion phase. Its mathematical form is conceptually consistent with the modeled physics: the gas only contributes significantly below a critical density, and its contribution grows exponentially as the density decreases further (the Universe expands).

We set $\gamma_{\text{gas}} = 0.5$ (half dex) after systematic tests for two complementary reasons:

1. **Empirical evidence.** Among the test values (e.g., 0.3–1.0), $\gamma_{\text{gas}} = 0.5$ produced a smaller χ^2 and narrower uncertainties in the free parameters without shifting H_0. This behaviour remained consistent when varying the number of steps (100 vs. 300–500) and the precision of the integration (e.g., {`limit:150,1e-8`} vs. {`limit:200,1e-9`}).
2. **Physical motivation.** In log of density, $\gamma_{\text{gas}} = 0.5$ describes a smooth but non-trivial activation of the gas regime: the term grows exponentially over half a dex in $\log\rho$ (a factor ≈ 3.16 in density), a scale compatible with phase transitions that are not abrupt in dilute media. The gas term function remains continuous at the threshold (thanks to the "-1"), and γ_{gas} controls the slope of the activation.

With the data used (CMB/BAO + SNe), γ_{gas} is weakly anchored, but its choice at 0.5 improves numerical stability and does not affect the robustness of H_0. For transparency, we maintain k_{gas} and $\log \rho_{\text{gas,start}}$ as responsible degrees of freedom for how much and when the gas regime manifests.

This formulation reflects the underlying physics of the **GERT** model: the entropic resonance (Gaussian peak) proportionally amplifies the combined effect of the background transition and the gas term.

The results are summarized in Table 1 below.

Table 1. The width parameters.

Parameter	Value	Physical Translation
$d_M = 1$	Matter transition: duration ~ 1 dex (≈ 200 Myr)	very dense medium → rapid turn
$d_L = 2$	Entropic transition: duration ~ 2 dex (≈ 6 Gyr)	rarefied medium → slow turn
$d_c = d_{L2} = 1$	Symmetric peaks	Short bursts of cohesion and expansion

The width parameters were fixed based on prior trials. Numerical tests show that varying these by ±0.3 does not significantly alter χ^2, confirming they capture the correct cosmic timescale. Table 2 presents the 13 fundamental parameters that comprise the unified formulation of the GERT model.

Table 2. Unified GERT model parameters.

Parameter	Symbol (ASCII)	Physical Meaning
Matter Transition Position	$\log_M$	Density (log) where the gravitational "constructive phase" is activated/deactivated.
Initial Matter Factor	$f_{M,i}$	Cohesive efficiency of matter at high densities/redshifts.
Final Matter Factor	$f_{M,f}$	Cohesive efficiency of matter at low densities (late era, after the 1st phase transition).
Matter Peak Amplitude	$f_{M,\text{peak}}$	Extra "boost" of cohesion (effective dark matter effect) during the atomic recombination era.
Matter Peak Position	$\log_c$	Density (log) where the cohesive peak occurs (binding of atoms/first structures).
Entropic Transition Position	$\log_L$	Density (log) where entropic Work begins to dominate (start of acceleration).
Initial Entropic Factor	$f_{L,i}$	Intensity of the expansive flow (entropy) at high densities.
Mid/Final Entropic Factor	$f_{L,m}$	Intensity of the expansive flow at low densities (post-Constructive Era).
Entropic Peak Amplitude	$f_{L,\text{peak}}$	Short "boost" of expansion when energy is no longer spent on structure.

Table 2. Unified GERT model parameters (continued)

Parameter	Symbol (ASCII)	Physical Meaning
Entropic Peak Position	$\log_{L2}$	Density (log) where the expansive peak occurs (entropic stiffness).
Gaseous Regime Intensity	k_{gas}	Strength of the expansion in the ultra-dilute regime (current and future "gas" phase).
Gaseous behaviour Start	$\log \rho_{\mathrm{gas,start}}$	Density (log) threshold that activates the gaseous term.
Gaseous Regime Slope	γ_{gas}	"Compressibility" of the gaseous spacetime; controls the slope of the exponential term.

Quick note: the **widths of the transitions** were fixed by trials and thermodynamic consistency ($d_M = 1$ dex, $d_L = 2$ dex; Gaussians with width 1 dex). They shape *how* the curves change, but **do not** enter the list of 13 parameters.

4. Methodology

4.1. From First-Principles Logic to Empirical Validation

The methodological approach to validate the Gibbs Energy Redistribution Theory (GERT) was conceived both as a rigorous scientific procedure and as a demonstration of its fundamental philosophy [27]. It begins with the wonder of looking at the sky as if for the first time, continues through the search for 'whys,' and leads to the establishment of premises and logical sequences. Thus, we designed the GERT methodology.

Therefore, the **GERT** methodology emerges, first, from Logic, not from Data: **GERT** was not constructed by adding a parameter for each unexplained observation. Instead, a conceptual framework was proposed first. Only afterwards did we conduct mathematical and empirical tests to verify whether the data fit the model, and not the other way around.

The implementation and inference pipeline was built with standard open-source scientific Python tools. [38] Specifically, data handling used NumPy [39] and SciPy [40], while visualization relied on Matplotlib. [41] Parameter inference was performed with emcee [42,43], and Bayesian modelling components were cross-checked with PyMC3 [44].

In other words, the logic of this study allows a deliberately causal sequence: (1) **ontology** (a Primordial Enthalpic Reservoir and a Dual Mechanism with contractile and expansive modes); (2) **Mathematical Formalism** derived from that ontology (dynamic state functions $f_M(\rho)$ and $f_L(\rho)$ shaping $H(z)$); and (3) **confrontation with data** (CMB, BAO, and SNe Ia), in which the baseline implementation (the minimal-parameter reference fit described in the Methods) is quantitatively tested against observations and yields an excellent global fit ($\chi^2/\mathrm{dof} \approx 0.992$) and a relieved Hubble tension (with $H_0 \approx 72.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$).

In this sense, the ontology and the formalism are two faces of the same construction: if the former fails, the latter loses its physical meaning.

The empirical validation of the Gibbs Energy Redistribution Theory (**GERT**) was conducted through a multi-phase methodological process. It was designed to first explore the vast parameter space of the model and subsequently converge on the most parsimonious and statistically robust solutions. The philosophy was to start from a conceptual framework and rigorously test it against the data rather than constructing a model to fit specific observations.

Our approach can be divided into three main pillars: (1) the selection of observational data, (2) the statistical formalism, and (3) a strategy of progressive refinement and model selection.

4.2. Data Sources and Statistical Formalism

To constrain the hyperparameters of the **GERT** model, we used a combination of cosmological datasets probing the expansion history at different epochs:

- **Cosmic Microwave Background (CMB):** acoustic/shift parameters derived from Planck observations (anchor at $z \approx 1090$) [8].
- **Baryon Acoustic Oscillations (BAO):** a set of BAO measurements over $z \simeq 0.106$–0.70 serving as standard rulers [14,23].
- **Type Ia Supernovae (SNe Ia):** the Pantheon compilation constraining late-time expansion via distance moduli [25], with earlier widely used compilations such as JLA providing additional context [24].

These references are used to document the observational inputs and standard baselines. The model itself is specified by the thermodynamically motivated parametric form of $H(z)$ and its state functions, and is then tested against the datasets above.

Likelihood Functions

The fit quality was assessed through the chi-squared statistic χ^2, with $\chi^2_{\text{tot}} = \chi^2_{\text{CMB}} + \chi^2_{\text{BAO}} + \chi^2_{\text{SNe}}$ under Gaussian, independent likelihood assumptions. Parameter-space exploration was performed with a Markov chain Monte Carlo (MCMC) algorithm (emcee) to map posterior distributions.

Fixed Widths and Gas-Term Choice

We set $d_M = 1$ dex and $d_L = 2$ dex based on an exploration of parameter space in preliminary trials (e.g., testing values from 0.5 to 3 dex in increments of 0.25 dex), which consistently showed these values yielded optimal fits and physical interpretations consistent with the thermodynamic principle that more dilute media transition more slowly. These choices were further validated by observing that varying these parameters by ±0.3 dex did not significantly alter χ^2. The Gaussian peaks use width 1 dex for both f_M and f_L, representing short, symmetric resonant events. We tested other values of γ_{gas}; $\gamma_{\text{gas}} = 0.5$ yielded the lowest total χ^2 and smaller uncertainties in $(k_{\text{gas}}, \log \rho_{\text{gas,start}})$, with a smooth activation compatible with the thermodynamic framework.

We summarize below the explicit χ^2 construction used for each dataset and how it maps to the implementation.

General Structure

We assume Gaussian and independent terms for CMB, BAO, and SNe Ia, so that the total log-likelihood is the sum of the individual terms:

- $\chi^2_{\text{tot}} = \chi^2_{\text{CMB}} + \chi^2_{\text{BAO}} + \chi^2_{\text{SNe}}$,
- $\ln \mathcal{L} = -\chi^2/2$.

1) CMB (ℓ_A and R)

We use two standardized summaries of decoupling at $z_* = 1090$:

- Angular acoustic scale:

$$\ell_A^{\text{th}} = \pi \frac{d_C(z_*)}{r_s(z_*)}, \qquad d_C(z) = \int_0^z \frac{c}{H(z)}\, dz,$$

$$r_s(z_*) = \int_{z_*}^{\infty} \frac{c_s(z)}{H(z)}\, dz, \qquad c_s(z) \approx \frac{c}{\sqrt{3}}.$$

- Shift parameter:

$$R^{\text{th}} = \sqrt{\Omega_m^{\text{eff}}}\, \frac{H_0\, d_C(z_*)}{c}, \qquad \Omega_m^{\text{eff}} = \frac{\rho_{m,0}^{\text{eff}}}{\rho_{c,0}}, \qquad \rho_{c,0} = \frac{3H_0^2}{8\pi G}.$$

The present analysis employs CMB shift parameters (ℓ_A, R) rather than the full C_ℓ spectrum. These compressed statistics capture the integrated geometrical information of the CMB and provide robust constraints on background expansion models [45]. A full perturbation-level analysis, requiring a modified Boltzmann solver, is left for future work.

Adopted observational values: $\ell_A = 301.63 \pm 0.18$, $R = 1.7502 \pm 0.0046$ [8]. We define:

$$\chi^2_{\mathrm{CMB}} = \left(\frac{\ell_A^{\mathrm{th}} - 301.63}{0.18}\right)^2 + \left(\frac{R^{\mathrm{th}} - 1.7502}{0.0046}\right)^2.$$

2) BAO (D_V/r_d at 5 redshifts)

For each BAO point $(z_i, (D_V/r_d)_{\mathrm{obs},i}, \sigma_i)$ we compute

$$D_V(z) = \left[d_C(z)^2 \frac{c\,z}{H(z)}\right]^{1/3},$$

and the drag scale r_d from the sound-horizon integral. The BAO contribution is

$$\chi^2_{\mathrm{BAO}} = \sum_i \frac{\left[\frac{D_V(z_i)}{r_d} - \left(\frac{D_V}{r_d}\right)_{\mathrm{obs},i}\right]^2}{\sigma_i^2}.$$

The BAO points used here follow standard compilations in the literature [14,23].

3) SNe Ia (distance modulus)

For each SN $(z_i, m_{\mathrm{obs}}(z_i), \sigma_i)$, we use $m_{\mathrm{th}} = \mu_{\mathrm{th}} + M_B$ with M_B fixed and define

$$\chi^2_{\mathrm{SNe}} = \sum_i \left[\frac{m_{\mathrm{th}}(z_i) - m_{\mathrm{obs}}(z_i)}{\sigma_i}\right]^2.$$

The SN sample is based on the Pantheon compilation [25]. For historical context and comparison, see also the JLA compilation [24].

Priors and degrees of freedom

We adopt top-hat priors for the remaining free parameters in the ultra-low-density regime (notably k_{gas} and $\log \rho_{\mathrm{gas,start}}$), while other parameters are fixed as summarized in Tables 1 and 2. The degrees of freedom are $\mathrm{dof} = N_{\mathrm{data}} - N_{\mathrm{free}}$.

Mapping to the code

The above formulas are implemented in the routines:

- H_**GERT** (z, ...) (expansion history with f_M and f_L),
- eM_unified and eL_unified (cohesive/entropic factors),
- *calculate_chi2_components* (returns χ^2 CMB, χ^2 BAO, χ^2 SNe and sum for the MCMC).

4.3. Fitting Strategy: Progressive Refinement and Model Selection

The determination of the hyperparameter values followed a systematic strategy designed to balance robustness and parsimony of the final model. Tables 3–6 summarize the fixed choices adopted throughout the refinement procedure, while Figures 3–9 provide a visual roadmap of how the GERT framework is structured and how each refinement impacts the reconstructed expansion history, and the key diagnostic comparisons with the standard cosmology.

Preliminary Phase: Initial Exploration ("Exploration") Before the detailed MCMC analysis, an exploratory phase was conducted with a mathematical optimiser, scipy.optimize.minimize (an "optimizer") to locate the region of interest in the vast parameter space — the global "valley" of minimum χ^2. This step was essential for defining the search intervals (*priors*) for the subsequent MCMC analysis, ensuring that the *walkers* started in a high-probability region.

Main Phase: MCMC Analysis and Progressive Refinement The main analysis consisted of a series of MCMC runs, starting with a more general model and progressing to simpler and more constrained models.

The MCMC settings reported above refer to the final 2-parameter run. Earlier runs with higher dimensionality employed proportionally larger ensembles (e.g., 60–120 walkers for the 12-parameter model). Full configurations, chains, and convergence diagnostics for every stage are available in the public repository (Section 10).

Base Model (12 Free Parameters): We started with a model where 12 of the 13 hyperparameters were free to vary (fixed $\gamma_{\text{gas}} = 0.5$). This initial analysis (Figure 3) confirmed that the **GERT** model was capable of providing an excellent fit to the data, achieving a reduced χ^2 of **0.9992** and H_0 at best fit = **72.5 km/s/Mpc**. However, the *corner plots* showed some degeneracies and uncertainties, which is an expected result given that the 12 free parameters are not independent variables, but rather **hyperparameters** interrelated by a single mathematical function that describes cosmic history.

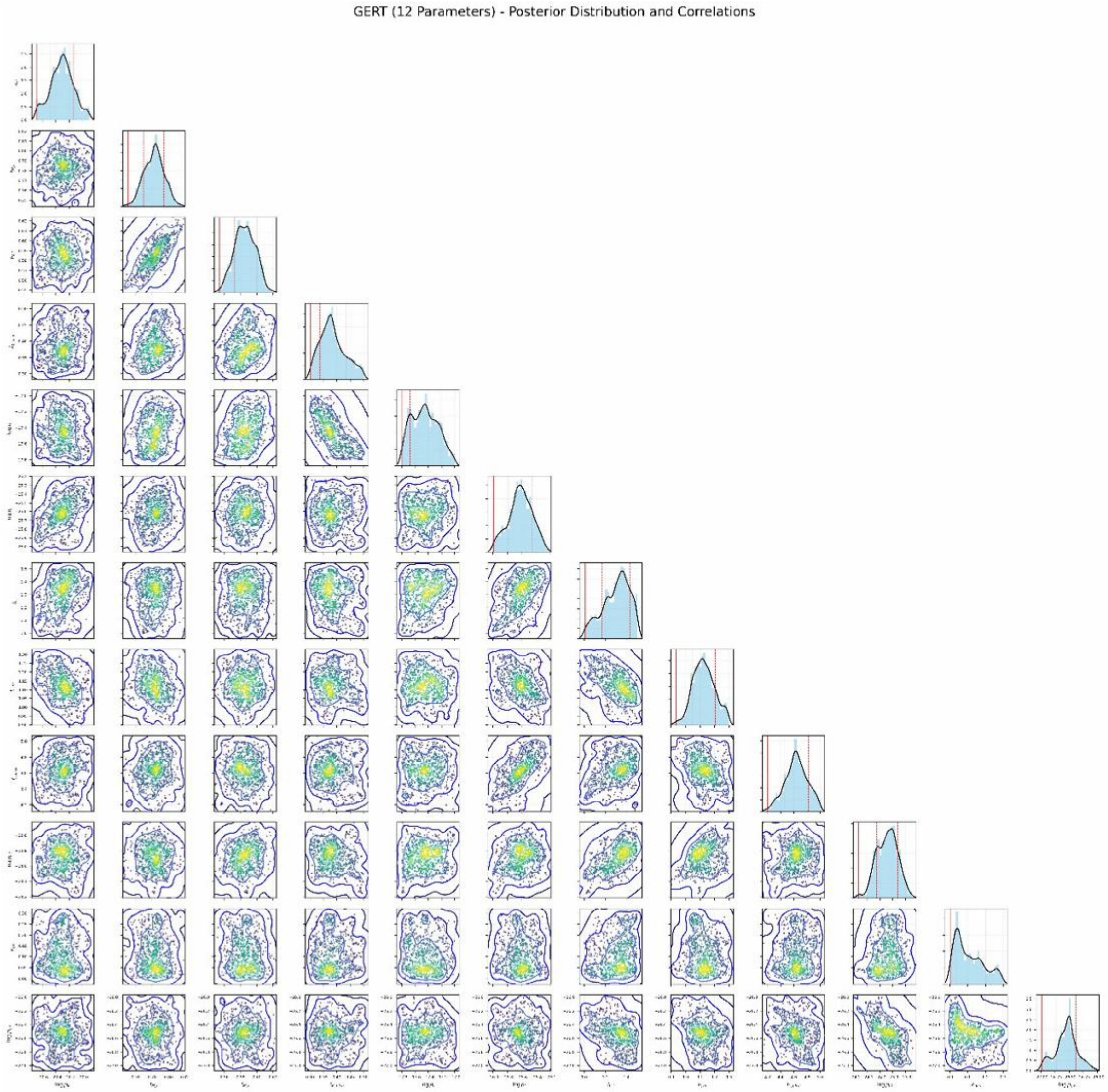


Figure 3. Corner plot of the MCMC analysis with 12 free parameters.

Analysis: Total degrees of freedom. Broad posterior; visible correlations between peak parameters and their positions and between background fractions. Basis for deciding what to fix: transition positions and peak shapes appear measurable; gas regime still loose.

Therefore, we fixed 3 parameters that were well defined and had low margin of error $f_{M,i}$, $f_{M,f}$, and $\log \rho_{L2}$.

$$f_{L,i} = 1.3260^{+0.1069}_{-0.1588};\ f_{L,m} = 1.1231^{+0.0823}_{-0.0748}$$

and

$$\log \rho_{L2} = -23.9384^{+0.0771}_{-0.0912} \tag{21}$$

Progressive Fixation and Validation: Based on the analysis of 12 parameters, we initiated an iterative process of model simplification. At each step, the parameters that were better defined, that is, those converging to stable values with the least uncertainties, were chosen to be fixed in the next iteration. Analyses were conducted with 9, 8, 6, 4, and 3 free parameters. The validation tools for this strategy included both the quantitative analysis of uncertainties and the visual inspection of corner plots (Figures 4–8). At each fixation step, a remarkable phenomenon was observed: the remaining parameters, instead of absorbing the uncertainties and becoming more dispersed, became better defined and constricted. Their probability distributions narrowed, demonstrating the robustness of the model. This behaviour indicated that complexity was being removed without loss of explanatory power, justifying the continuation of the simplification process.

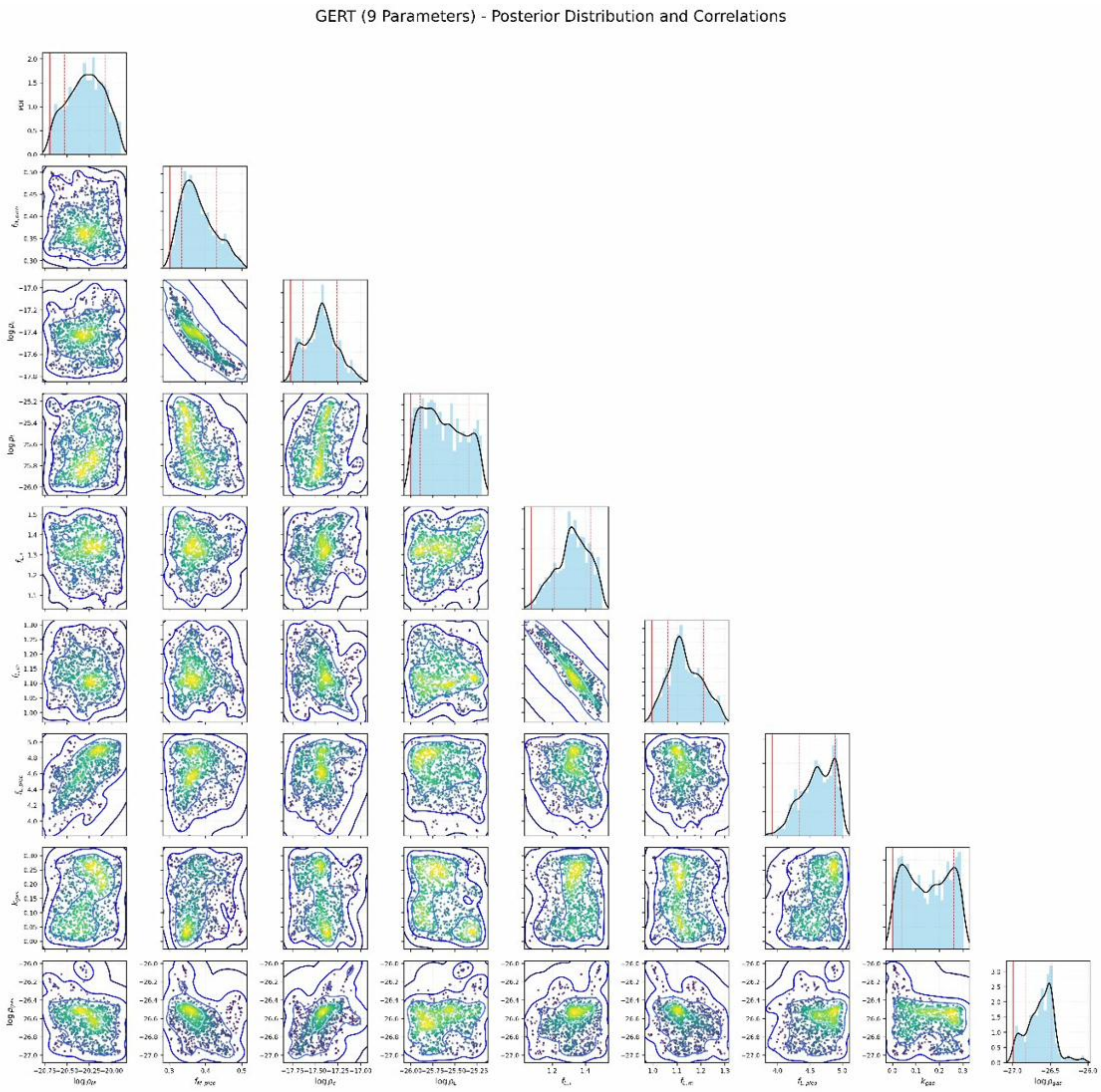


Figure 4. Corner plot of the MCMC analysis with 9 free parameters.

Analysis: By fixing ($f_{M,i}$, $f_{M,f}$, $\log \rho_{L2}$), the remaining marginals narrow and the correlations become cleaner. Fixing well-anchored parameters does not inflate the others—uncertainties decrease and the valley becomes better defined.

At this stage, we set $f_{L,m} = 1.1236^{+0.0862}_{-0.0619}$, which proved to be well-defined.

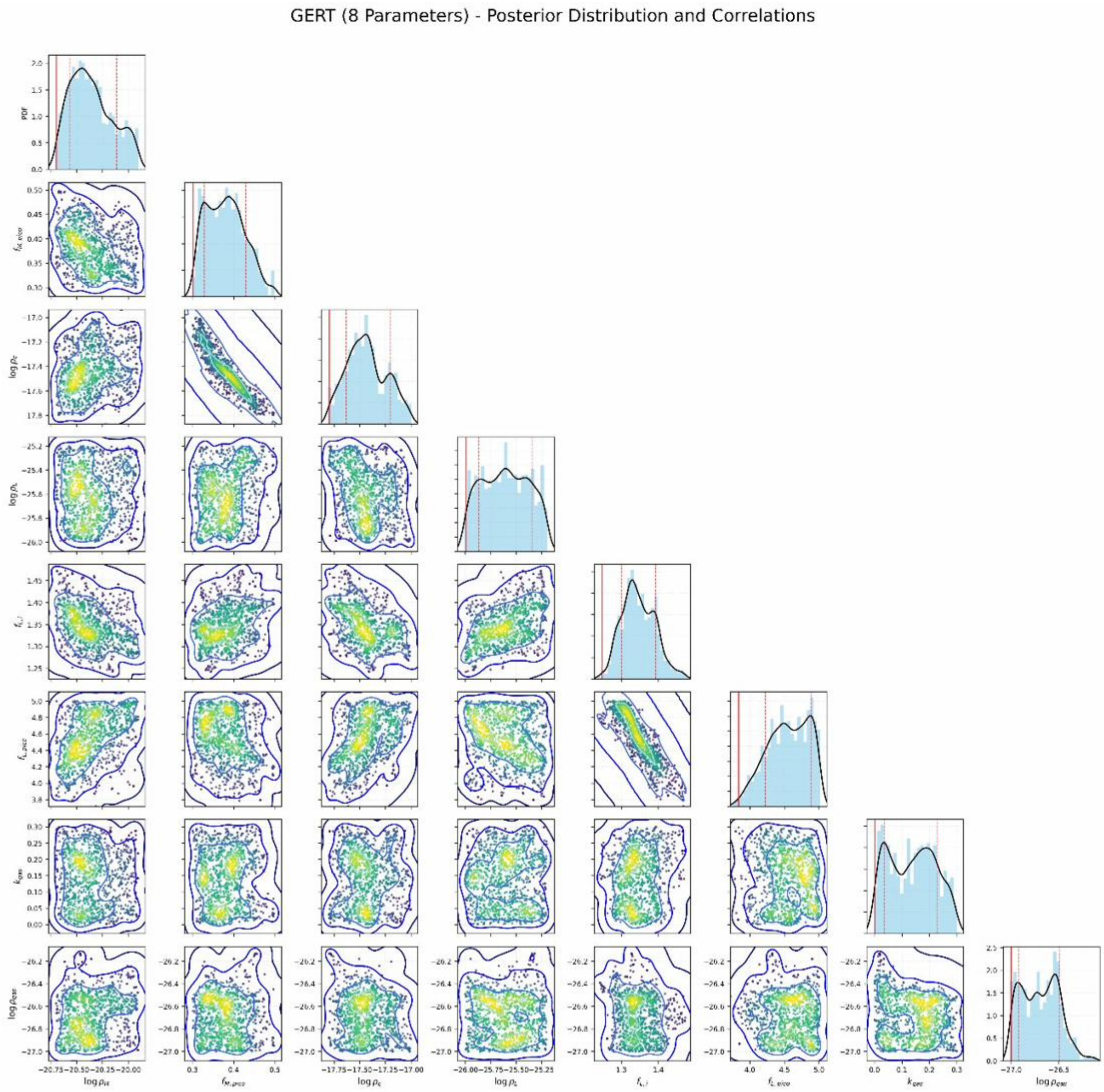


Figure 5. Corner plot of the MCMC analysis with 8 free parameters.

Analysis: With $f_{L,m}$ also fixed, peaks and transitions narrow. $\log \rho_L$ shows perfect symmetry justifying the fixation. It maintains stability in χ^2 and H_0; reinforces the decision to continue reducing dimensionality.

Thus, we fix $f_{L,i}$ and $\log_L$:
$\log_L = -25.6060^{+0.2612}_{-0.2612}$; $f_{L,i} = 1.3414^{+0.0513}_{-0.0416}$

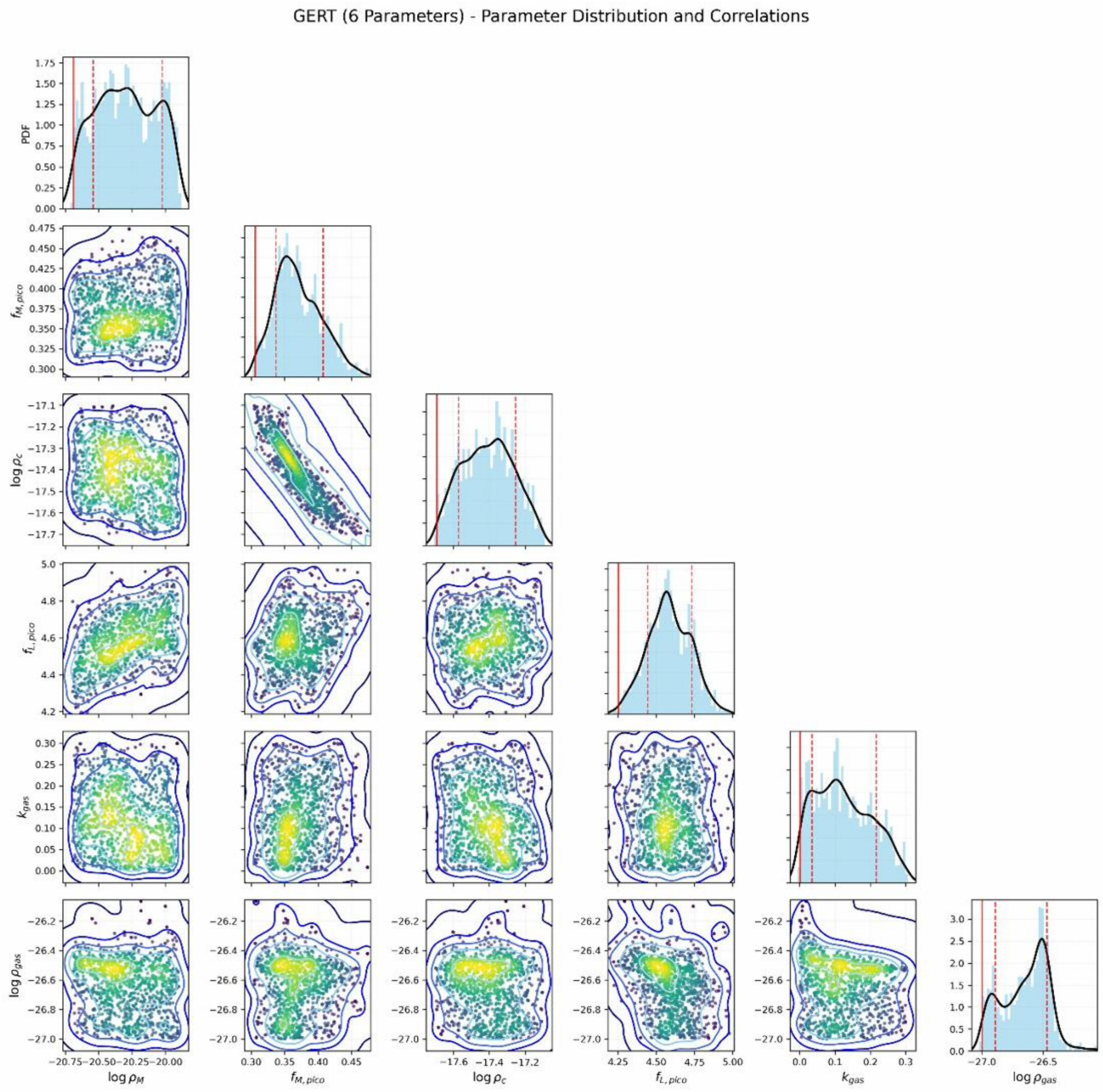


Figure 6. Corner plot of the MCMC analysis with 6 free parameters.

Analysis: Parameters related to peaks ($f_{M,\text{peak}}$, $\log \rho_c$, $f_{L,\text{peak}}$) are already well-behaved; gas remains broad.

This justifies fixing $\log \rho_c$ and $f_{M,\text{peak}}$ (or using a narrow prior) without cost of adjustment.

We therefore set:

$f_{M,\text{peak}} = 0.3652^{+0.0419}_{-0.0283}$ and $\log \rho_c = -17.4075^{+0.1535}_{-0.1649}$

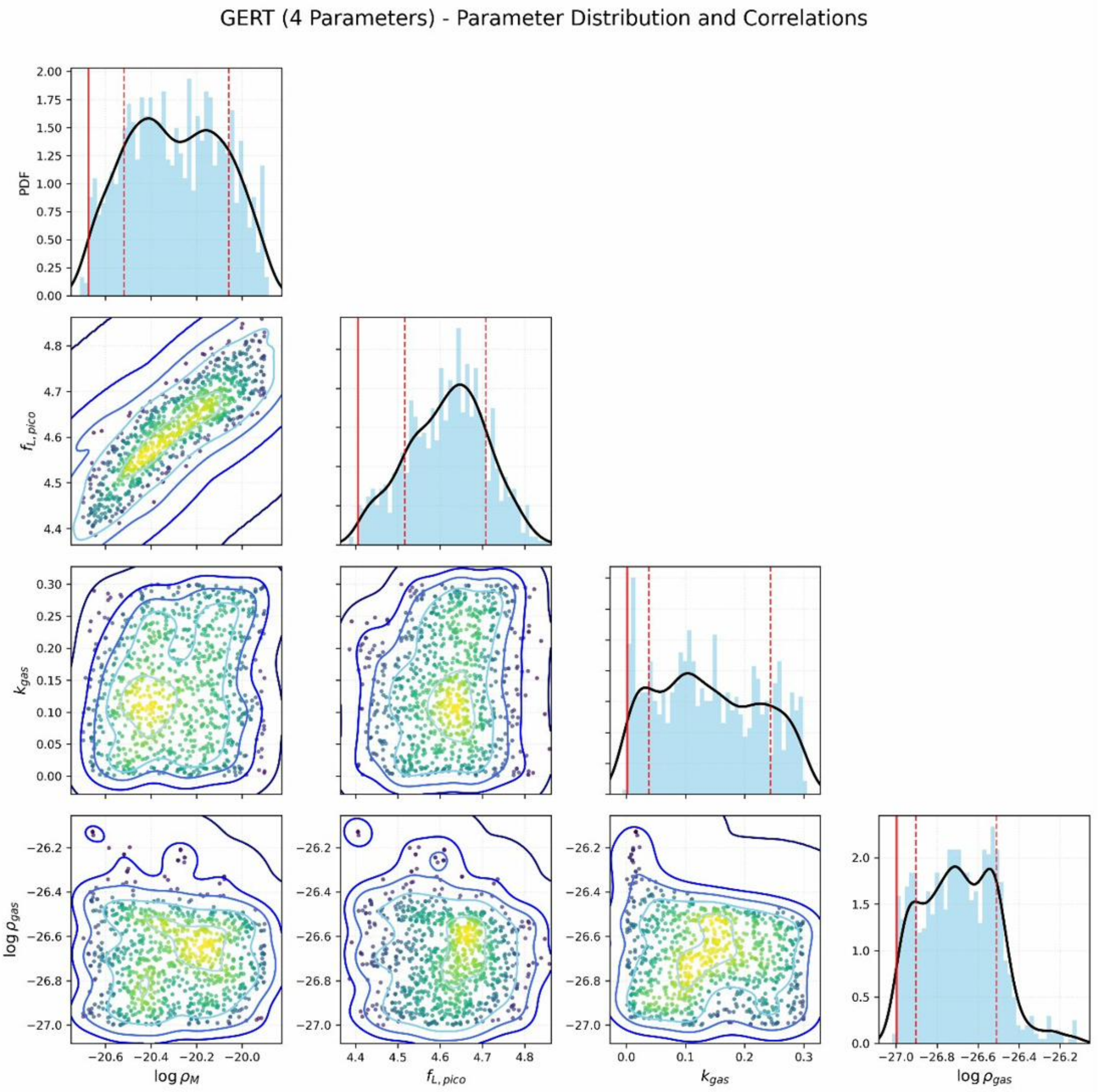


Figure 7. Corner plot of the MCMC analysis with 4 free parameters.

Therefore, we set $f_{L,\text{peak}}$ as follows:

Analysis: The uncertainty migrates to the gas subspace (k_{gas}, $\log \rho_{\text{gas,start}}$), whereas $f_{L,\text{peak}}$ and $\log \rho_M$ remain lean. “Historical” parameters (transitions/peaks) are essentially resolved by the data; the gas regime dominates the uncertainty budget.

$f_{L,\text{peak}} = 4.6245^{+0.0833}_{-0.1083}$

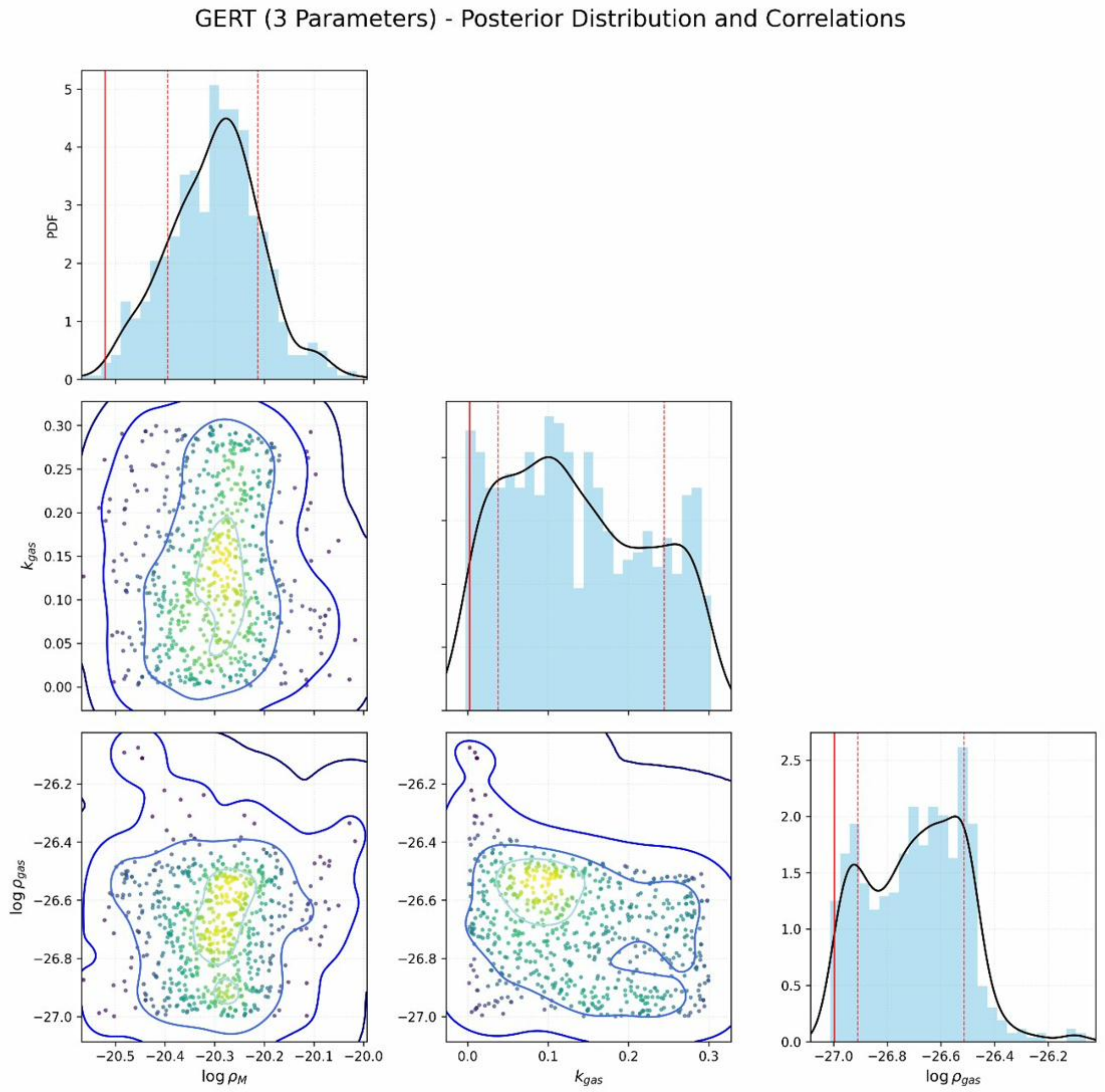


Figure 8. Corner plot of the MCMC analysis with 3 free parameters.

Analysis: With fixed $f_{L,\text{peak}}$, k_{gas} and $\log \rho_{\text{gas,start}}$ exhibit weak correlation and still wide margins. This confirms that gas is the relevant remaining degree of freedom for very recent/future times.

This time, we therefore set a well-defined $\log_M$ and a low margin of error:

$\log_M = -20.2945^{+0.0816}_{-0.1002}$

Final Phase: Quantitative Model Selection and the Final Model (2 Free Parameters)

The process culminated in the final **GERT** model, with only 2 free parameters (k_{gas} and $\log \rho_{\text{gas}}$): the intensity and the activation threshold of the gas regime. They describe the "gas phase," following the complete phase transition in the near future of the Universe, which is a fundamental prediction of the thermodynamic logic of **GERT**. This phase, occurring at very low-redshifts, is not strongly constrained by the current dataset (CMB, BAO, SNe Ia).

— Final MCMC Settings —

Random Seed: 42 (for reproducibility)

Walkers (N_w): 10 (defined as $5 \times N_{params}$)

Number of Steps: 500 per walker

Burn-in Phase: 100 steps (discarded)

Thinning Factor: 5 (samples stored every 5 steps)

Integration Params: `limit: 200, epsabs/rel: 1e-9`

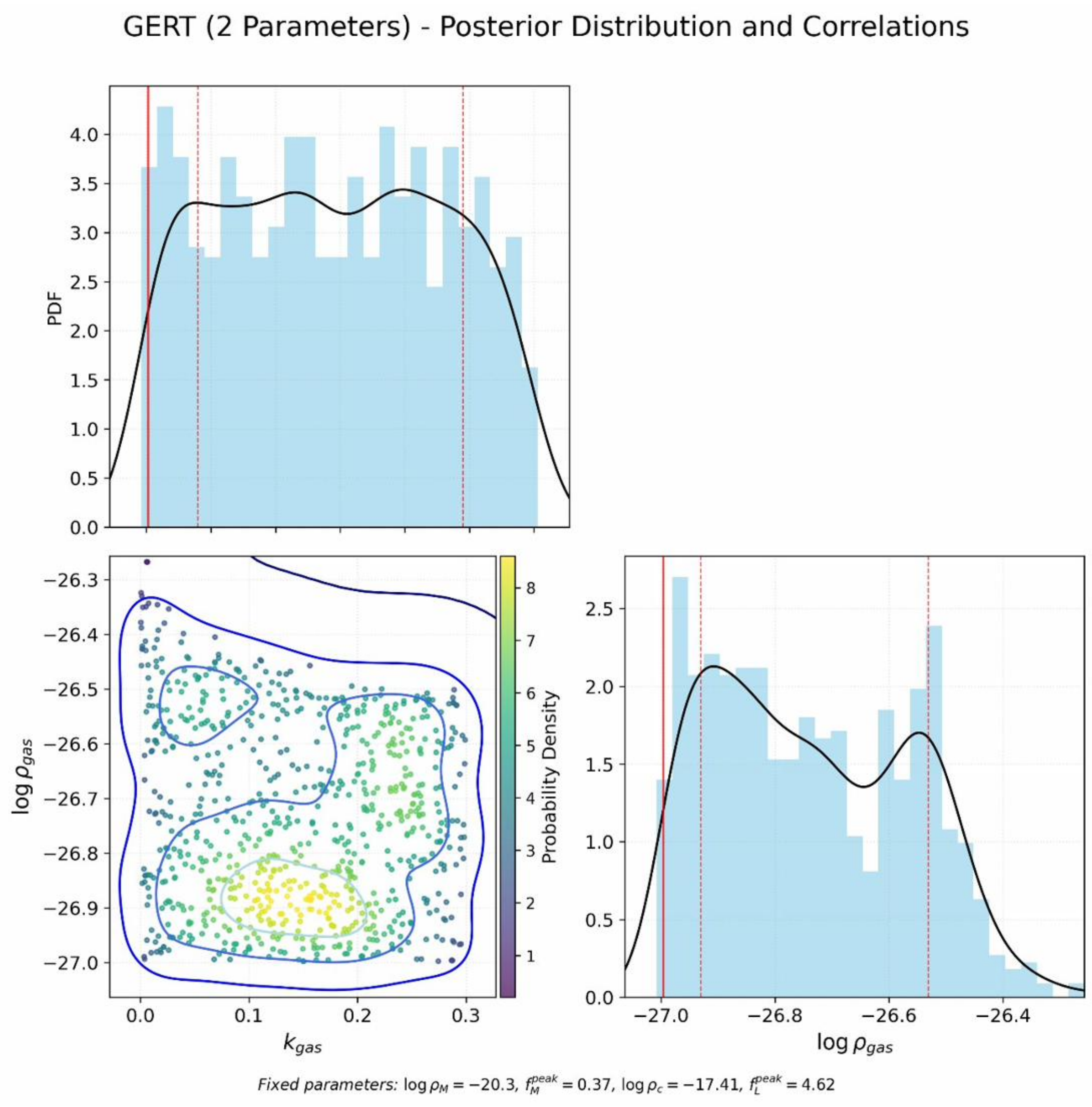


Figure 9. Corner plot of the final GERT model with 2 free parameters, showing well-constrained parameters.

Analysis: Posterior set for (k_{gas}, $\log\rho_{\text{gas,start}}$). k_{gas} is broad but finite; $\log\rho_{\text{gas,begin}}$ shows slight smooth bimodality (shallow peaks around ≈ -26.9 and ≈ -26.6), reflecting little observational leverage in this transition. Maintains χ^2**/dof** $\approx\approx$ **0.992** and $\mathbf{H_0} \sim$ **72.5**; the physics of gas is the window for new data (redshift drift, 21 cm, cosmic clocks).

To quantitatively validate the simplification strategy, we calculated model selection criteria for each analysis.

The dimensionality reduction was supported by **WAIC** (Widely Applicable Information Criterion), **AIC** (Akaike Information Criterion), and **BIC** (Bayesian Information Criterion) [46], which favored the **2-parameter model** for **parsimony** while maintaining fit quality.

Table 3 below summarizes the comparison of fit statistics:

4.3.1. Table 3: Comparison of Fit Statistics

Table 3 shows that with each step of simplification, the WAIC value consistently decreased, indicating that simpler models were statistically preferable.

Table 3. Comparison of fit statistics for the different **GERT** models. Lower statistical values indicate a preferable model.

Model	$\chi^2_{\min}$	dof	χ^2/dof	AIC	BIC	WAIC
GERT –12p	1042.19	1043	0.9992	1066.19	1125.73	1061.20
GERT –9p	1042.60	1046	0.9968	1060.61	1105.26	1052.99
GERT –8p	1043.84	1047	0.9970	1059.84	1099.53	1051.70
GERT –6p	1044.31	1049	0.9955	1056.31	1086.08	1050.70
GERT –4p	1044.52	1051	0.9938	1052.52	1072.36	1048.66
GERT –3p	1044.50	1052	0.9929	1050.50	1065.38	1047.80
GERT –2p	**1044.46**	**1053**	**0.992**	**1048.47**	**1058.39**	**1045.81**

Why Do Two Gas Parameters Remain Free?

The trigger points $\log\rho_M$ and $\log\rho_L$ were tightly constrained by CMB (**z** $\simeq$ 1090) [8], BAO (0.1 < z < 2) [23], and SNe Ia (z < 2) [11,25]. In contrast, the gas term only connects when $\rho < \rho_{\text{gas,start}}$, i.e., in a regime of ultra-low density that occurs in the present cosmological epoch. With the geometric

normalization used ($h = 0.674$ and $\Omega_m h^2 = 0.142$), a typical value $\log\rho_{\text{gas,start}} \approx -26.7$ corresponds to $z \simeq 0.03$ (with fixed slope $\gamma_{\text{gas}} = 0.5$).

We therefore maintain **two** degrees of freedom in this regime: k_{gas} (intensity) and $\log\rho_{\text{gas,start}}$ (activation threshold).

Therefore, the parameters k_{gas} and $\log\rho_{\text{gas}}$ represent the predictive power of the model. They were left free so that the model could inform us about the nature of this future phase.

We set the parameter $\gamma_{\text{gas}} = 0.5$ (half dex) based on empirical thermodynamic criteria: better χ^2, smaller bars, and smooth activation compatible with transitions in diluted media.

Possible, non-deterministic trajectory:

The **GERT** does not impose a unique path: it defines a thermodynamically viable range. The history of the Universe selects a point *a posteriori* within this range, and only then can we measure its "frozen" parameters. This philosophy accepts uncertainty as part of physical knowledge and avoids the illusion of absolute determinism.

Future observables capable of measuring k_{gas}:

1. **Redshift–drift** in quasars (z > 4): sensitive to percentage variations of H(z) over decades.
2. **21 cm tomography** (3 < z < 6): projects the BAO pattern where the gas term begins to stand out.
3. **Cosmic clocks** (ages of passive galaxies) at z $\gtrsim$ 3.

Measurements in these windows may tighten or even nullify k_{gas}, thereby testing the prediction of the gas phase.

This progressive reduction of the parameter space was not introduced as an arbitrary simplification, but emerged from the internal logic of the model itself. Since the GERT hyperparameters are not independent quantities but correlated components of a single function describing the thermodynamic history of the Universe, the broad correlations observed in the earliest corner plots were expected. As the best-constrained parameters were successively fixed, the remaining free parameters did not become artificially unstable or excessively degenerate; on the contrary, their posterior distributions became progressively sharper. This behaviour provides empirical support for the structural coherence of the framework. In an ill-specified or overparameterized model, fixing one subset of parameters typically inflates the uncertainties of the remaining ones, as the model compensates for lost flexibility through degeneracies elsewhere. The opposite behaviour observed here — progressive sharpening of posteriors under successive fixation — indicates that the GERT hyperparameters are genuinely constrained by the data through the internal logic of the model, not sustained by fragile compensations among loosely connected degrees of freedom. Notably, the only parameters that remained weakly constrained were those associated with the late gaseous phase, precisely because this regime is still only weakly anchored by current observational data — a limitation that is physically motivated and openly acknowledged, rather than a structural deficiency of the model.

5. Results and Discussion

This rigorous methodology, combining visual validation (corner plots), error margins, and quantitative selection (WAIC), ensures that our final model is a powerful and parsimonious representation of **GERT** physics, capable of explaining cosmological data with a minimum of assumptions.

The statistical analysis described in the previous section not only validated the **GERT** model with a remarkable fit to the observational data (χ**red2=0.992**) and substantial relief of Hubble tension (**H_0 at best fit = 72.5 km/s/Mpc**) but also revealed a deeper outcome: the empirically determined hyperparameter values tell a coherent story of cosmic evolution. Each parameter fixed or left free by our methodology corresponds to a key thermodynamic event, thereby transforming the Mathematical Formalism into a physical narrative. Next, we discuss the significance of each of these "cosmic milestones," whose values were determined by the MCMC analysis.

Table 4 below summarizes the main fixed parameters of the final **GERT** model and their interpretations as cosmic milestones.

5.1. Table 4: Cosmic Milestones

Parameter (Fixed)	**Value (log ρ)**	**Associated Cosmological Event**	**Interpretation (GERT)**
$\log \rho_c$	-17.41	Atomic Recombination (z $\approx$ 1090)	**Cohesive Peak:** Activation energy for the formation of atoms.
$\log \rho_M$	-20.30	End of the Plasma Era	**Transition of Phase:** Beginning of the "Constructive Era" (liquid phase).
$\log \rho_{L2}$	-23.93	End of Structure Formation	**Entropy Peak:** "Passing the baton" from cohesion to expansion.
$\log \rho_L$	-25.60	Beginning of Accelerated Expansion	**Entropic Transition:** Beginning of the transition to the "gaseous phase."
$\log \rho_{\text{gas,start}}$	-26.75	Current Epoch (z $\approx$ 0.03)	**Gas Activation:** Beginning of the gas regime domain.

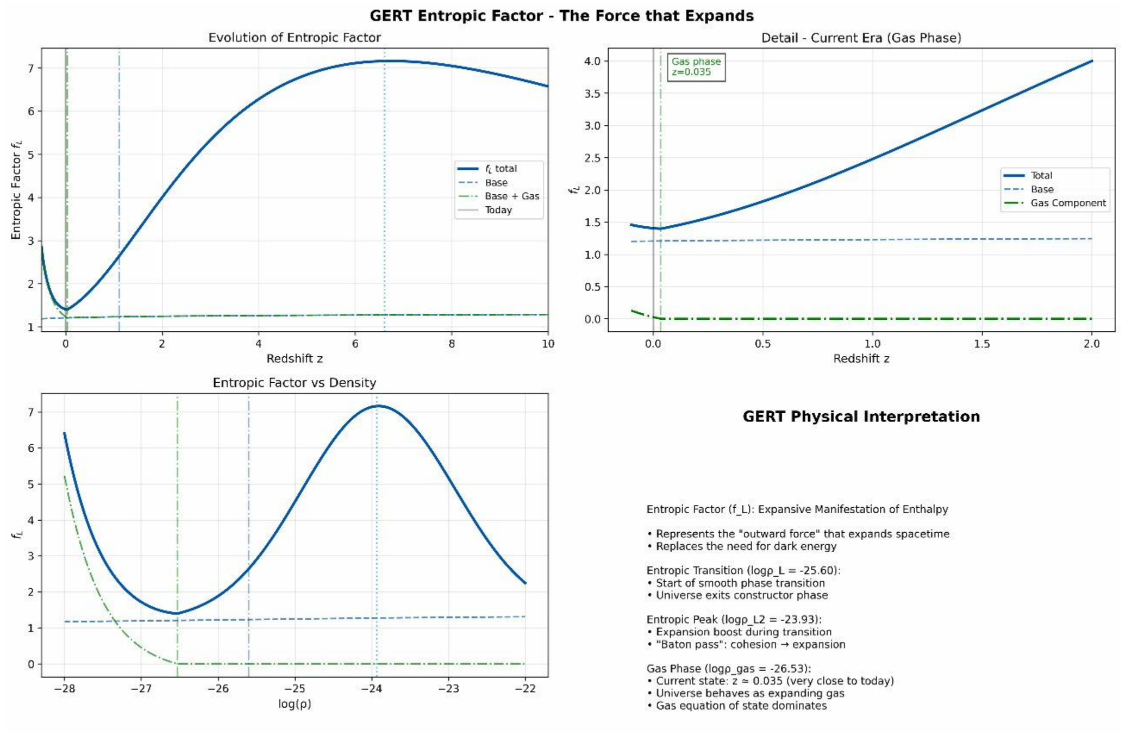
The parameters of the final **GERT** model, with two free parameters, which emerged from our progressive refinement methodology, are presented below. The parameters are divided according to their physical nature: cohesive factors, which govern the formation of structures, and expansive factors, which dictate the expansion of the cosmos.

Table 5 lists the expansive sector parameters, and Figure 10 visualizes the inferred entropic factor.

5.2. Table 5: Parameters of the Expansive Factors (Outward Force)

Physical Parameter	**Symbol**	**Final Value (1σ)**	**Status**
Peak Entropic Position	$\log \rho_{L2}$	**-23.93**	**Fixed**
Peak Entropy Amplitude	$f_{L,\text{peak}}$	**4.62**	**Fixed**

Position of the Entropic Transition	$\log \rho_L$	**-25.60**	**Fixed**
Initial Entropic Factor	$f_{L,i}$	**1.34**	**Fixed**
Mid Entropic Factor	$f_{L,m}$	**1.12**	**Fixed**
Beginning of Gaseous Regime	$\log \rho_{\text{gas,start}}$	**-26.750 (+0.219, -0.180)**	**Free**
Gas Phase Intensity	k_{gas}	**0.143 (+0.102, -0.103)**	**Free**
Gas Regime Slope	γ_{gas}	**0.50**	**Fixed**



Entropic Factor (f_L): Expansive Manifestation of Enthalpy

• Represents the "outward force" that expands spacetime
• Replaces the need for dark energy

Entropic Transition (logρ_L = -25.60):
• Start of smooth phase transition
• Universe exits constructor phase

Entropic Peak (logρ_L2 = -23.93):
• Expansion boost during transition
• "Baton pass": cohesion → expansion

Gas Phase (logρ_gas = -26.53):
• Current state: z ≃ 0.035 (very close to today)
• Universe behaves as expanding gas
• Gas equation of state dominates

Figure 10. Entropic Factor.

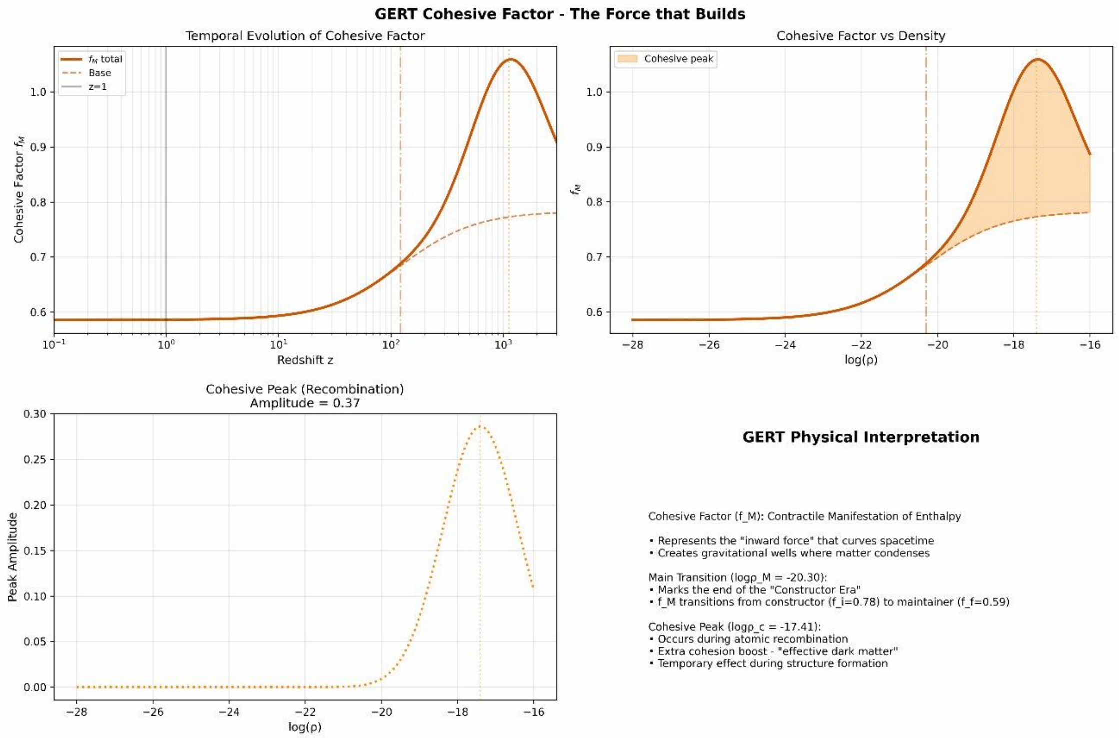
- **Entropic transition:** $\log \rho_L \approx -25.60$ (width 2 dex).
- **Entropic peak:** $\log \rho_{L2} \approx -23.93$, amplitude $f_{L,\text{peak}} \approx 4.62$ — marks the end of the building era and the beginning of acceleration.
- **Gas regime:** active at $\log \rho_{\text{gas,start}} \approx -26.7$ (in this study, $\sim$ -26.5 to -26.7); slope $\gamma_{\text{gas}} = 0.5$.

Table 6 lists the Cohesive sector parameters, and Figure 11 visualizes the inferred Cohesive factor.

5.2.1. Table 6: Parameters of Cohesive Factors (Inward Force)

Physical Parameter	**Symbol**	**Final Value**	**Status**
Peak Matter Position	$\log \rho_c$	-17.41	Fixed
Peak Matter Amplitude	$f_{M,\text{peak}}$	0.37	Fixed
Position of Matter Transition	$\log \rho_M$	-20.30	Fixed

Physical Parameter	Symbol	Final Value	Status
Initial Matter Factor	$f_{M,i}$	0.7831	Fixed
Final Matter Factor	$f_{M,f}$	0.5851	Fixed



Cohesive Factor (f_M): Contractile Manifestation of Enthalpy

• Represents the "inward force" that curves spacetime
• Creates gravitational wells where matter condenses

Main Transition (logρ_M = -20.30):
• Marks the end of the "Constructor Era"
• f_M transitions from constructor (f_i=0.78) to maintainer (f_f=0.59)

Cohesive Peak (logρ_c = -17.41):
• Occurs during atomic recombination
• Extra cohesion boost - "effective dark matter"
• Temporary effect during structure formation

Figure 11. Figure 11: Cohesive Factor.

- Main transition: centered at $\log \rho_M \approx -20.30$ (width 1 dex).
- Cohesive peak: at $\log \rho_c \approx -17.41$, amplitude $f_{M,\text{peak}} \approx 0.37$ — a temporary "boost" that replaces effective dark matter during recombination.
- **Change of regime:** $f_{M,i} \approx 0.78 \to f_{M,f} \approx 0.59$, from builder to maintainer.

Figure 12 visualizes the complete GERT components analysis:

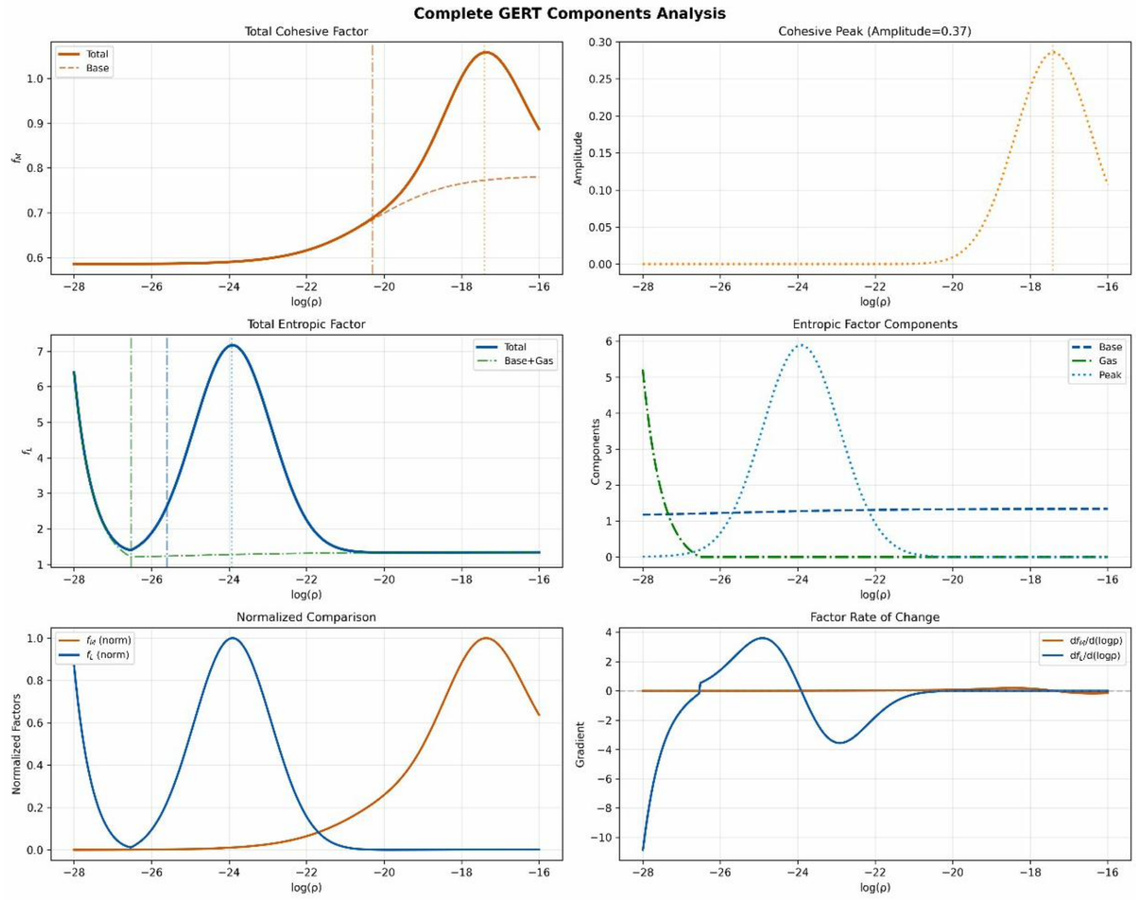


Figure 12. Components.

- $f_{M,\text{total}} = \text{base} + \text{peak}$; the peak is short and localized (recombination).
- $f_{L,\text{total}} = \text{base} \times (1 + \text{peak}) + \text{gas}$; visual separates base, multiplicative peak, and exponential gas.
- Derivatives $\mathrm{d}f_L/\mathrm{d}\log\rho$ show the closure of the Constructive Era and the rise of gas at ultra-low densities.

5.3. The Cosmic History Told by GERT Parameters

5.3.1. The First Work: The Cohesive Peak and Recombination

The first significant event identified by our model is a cohesion peak ($f_{M,\text{peak}} = 0.37$) that occurs precisely at $\log\rho_c = -17.41$. This density value corresponds almost perfectly to the epoch of atomic recombination (z ≈ 1090), when the Universe cooled sufficiently for protons and electrons to combine to form the first neutral hydrogen atoms [8].

GERT Interpretation: This is the first Work of cohesion performed by the Universe. The extra "boost" of cohesion represents the

thermodynamic activation energy needed for the "reaction" of forming the first neutral atoms. Just as a chemical reaction needs to overcome an energy barrier, the Universe required a transient increase in cohesive strength to "weld" protons and electrons, releasing the Cosmic Microwave Background radiation that we observe today.

5.3.2. The Transition to the “Liquid Phase” (log $\rho \approx$ -20.3)

After recombination, the model reveals a fundamental phase transition at $\log\rho_M = -20.30$. At this point, the cohesive efficiency of matter changes, dropping from a high initial value ($f_{M,i} = 0.7831$) to a lower final value ($f_{M,f} = 0.5851$).

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For context on the post-recombination thermal history and the subsequent formation of cosmic structures in the standard cosmological picture, see, e.g., [8,14].

GERT Interpretation: This is the transition from the plasma era to the "liquid phase" of the cosmos. The Universe ceases to be an opaque soup and becomes a more cohesive "fluid," in which structures can finally begin to form. This period marks the beginning of the Constructive Era, when cohesive forces dominate, spending Primordial Enthalpic Reservoir to cluster matter and give rise to the first galaxies and the cosmic web. The drop to a lower value occurs due to the energy expenditure in the transitions: Just like in any physical system, phase transitions "spend energy" to occur. The decrease in factors reflects this energy consumption necessary to move from one state to another.

5.1.3 The Trigger of Reversion: The Entropic Peak (log $\rho \approx$ -23.9)

Billions of years later, at $\log \rho_{L2} = -23.93$, a crucial event occurs: a sharp and massive peak in the entropic force ($f_{L,\text{peak}} = 4.62$). This peak marks, in itself, the reversal from the builder (cohesive) mode to the expansive mode.

GERT Interpretation: This is the moment of the "passing of the baton". The Work of building structures is coming to an end. The energy that was previously spent on Work Inward (cohesion) is now released and manifests as Work Outward (expansion). This "entropic trigger" is the necessary push to reverse the deceleration of a cosmos that was dominated by cohesion. In a Universe that, at this time, is still relatively dense and with a more "rigid" spacetime, this impulse needs to be strong to invert the dominant regime. The entropic peak is, therefore, the trigger that makes future accelerated expansion inevitable.

For broader context on the late-time transition to acceleration and its relation to the Hubble-tension literature, see, e.g., [4,5,9,10,12].

5.1.4 The Accelerated Expansion and the Transition to the Gaseous Phase (log $\rho \approx$ -25.6)

The historically observed accelerated expansion manifests, in fact, during the smoother and prolonged phase transition centered at $\log \rho_L$ = -25.60.

For observational constraints and standard inferences on late-time acceleration, see, e.g., [8–10].

GERT Interpretation: It is at this stage that the Universe transitions from its "liquid" state to the "gaseous" state. Just as water does not instantly turn to vapor, the Universe undergoes a gradual change of state. The cosmos, previously a "liquid" where galaxies interacted gravitationally more frequently, began to behave like an expanding gas, with its components moving further apart. The current Universe is in the liquid → gas transition range (late side), with the entropic component already increasing. Accelerated expansion, initiated by the triggering of the entropic peak, becomes the dominant characteristic of cosmic dynamics. This transition precisely coincides with the classical observational era of cosmic acceleration, demonstrating once again the predictive capability of GERT.

5.1.5 The Current Epoch and the Dynamics of the Gas Regime (log $\rho \approx$ -26.7)

Finally, the model determines the activation threshold of the purely gaseous regime. The central value found for this parameter is $\log \rho_{\text{gas,start}} = -26.75$ with a slope of $\gamma_{\text{gas}} = 0.5$. This density value corresponds to a redshift of z $\approx$ 0.03, which implies a lookback time of approximately 400 million years. In other words, the central fit suggests that the Universe crossed this threshold very recently in its cosmic past.

GERT Interpretation: Because this event occurs in the cosmological present, it is not strongly constrained by SNe Ia data, which lose sensitivity at very low-redshifts [25]. Therefore, its parameters were left free in our final analysis. They represent a testable prediction of GERT:

cosmic expansion will increasingly be dominated by behaviour analogous to that of a gas expanding in a vacuum, a dynamics that could be measured by future observables.

This gas term is not static; its exponential nature has the capacity to sustain and even increase acceleration in the future. Its behaviour is described by the following equation:

$$\text{term}_{\text{gas}} = k_{\text{gas}}\left[\exp\left(\frac{\log\rho_{\text{gas,start}} - \log\rho}{\gamma_{\text{gas}}}\right) - 1\right] \tag{22}$$

As the Universe expands, log ρ decreases, thereby driving the exponential argument to increase. Consequently, the term gas increases, which raises the total entropic factor *fL* and, in turn, the expansion rate H(z), thereby making the deceleration parameter q(z) more negative.

However, the impact of this term is controlled by its hyperparameters in the ultradilute regime. The values found in our analysis (*k*gas = 0.15, $\gamma_{\text{gas}} = 0.5$) suggest a moderate effect: a support of acceleration with a possible slight intensification, rather than an uncontrolled ”super- acceleration” (of the type w_eff<−1). This behaviour is consistent with the relief of the Hubble tension without introducing pathological behaviors. Therefore, the gas phase is a controlled and testable prediction of the theory for the ultra-dilute regime of the cosmos.

Figure 13 below summarizes the phase evolution in terms of the inferred cohesive and entropic factors.

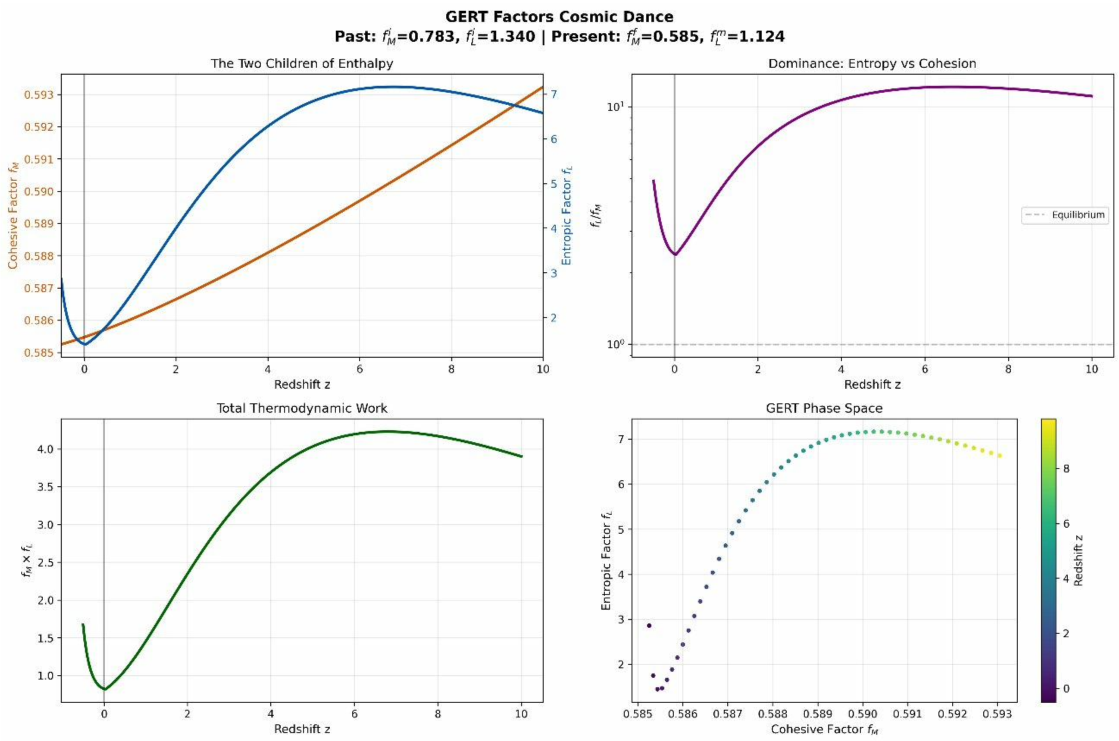

Figure 13. GERT Phase Evolution.

- $f_{M,\text{total}} = \text{base} + \text{peak}$; the peak is short and localized (recombination).
- $f_{L,\text{total}} = \text{base} \times (1 + \text{peak}) + \text{gas}$; visual separates base, multiplicative peak, and exponential gas.
- Derivatives $\mathrm{d}f_L/\mathrm{d}\log\rho$ show the closure of the Constructive Era and the rise of gas at ultra-low densities.

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5.4. The Considerable Relief of the Hubble Tension: A Consequence of Dynamic Physics

One of the most impactful results of this study is the considerable relief of the “Hubble tension”—the persistent discrepancy between measurements of the Hubble constant (H_0) in the local Universe (e.g., by the SH0ES (Supernovae, H_0, for the Equation of State) project, $H_0 \approx 73$ km/s/Mpc) [11,19,47,48] and those inferred from the primordial Universe (e.g., by the Planck satellite, $H_0 \approx 67$ km/s/Mpc) [8].

The GERT model, with only two free parameters, predicts a value for the Hubble constant as follows:

H_0 = 72.5 km/s/Mpc

This result is not coincidental but a direct consequence of GERT's dynamic physics. Unlike the ΛCDM model, which assumes a rigid cosmological constant, GERT describes the "expansion energy" as a dynamic entropic force ($f_L(z)$) that evolves with the state of the Universe.

For general discussions of dynamical dark-energy/modified-expansion possibilities in the context of the Hubble tension, see, e.g., [9,10]. For systematic considerations and parameter-degeneracy perspectives, see also [12,20,21]. Broader conceptual discussions include [30,33].

The "entropic trigger" at $\log\rho \approx -23.9$ represents a fundamental shift in expansion history. This event allows for a more pronounced late-time acceleration than that predicted by the ΛCDM model, resulting in a higher H_0 value today, while the model remains perfectly consistent with the primordial Universe conditions anchored by CMB data [8].

The key is that GERT predicts a different temporal expansion profile than the ΛCDM model, as shown in Figures 14 and 15 below.

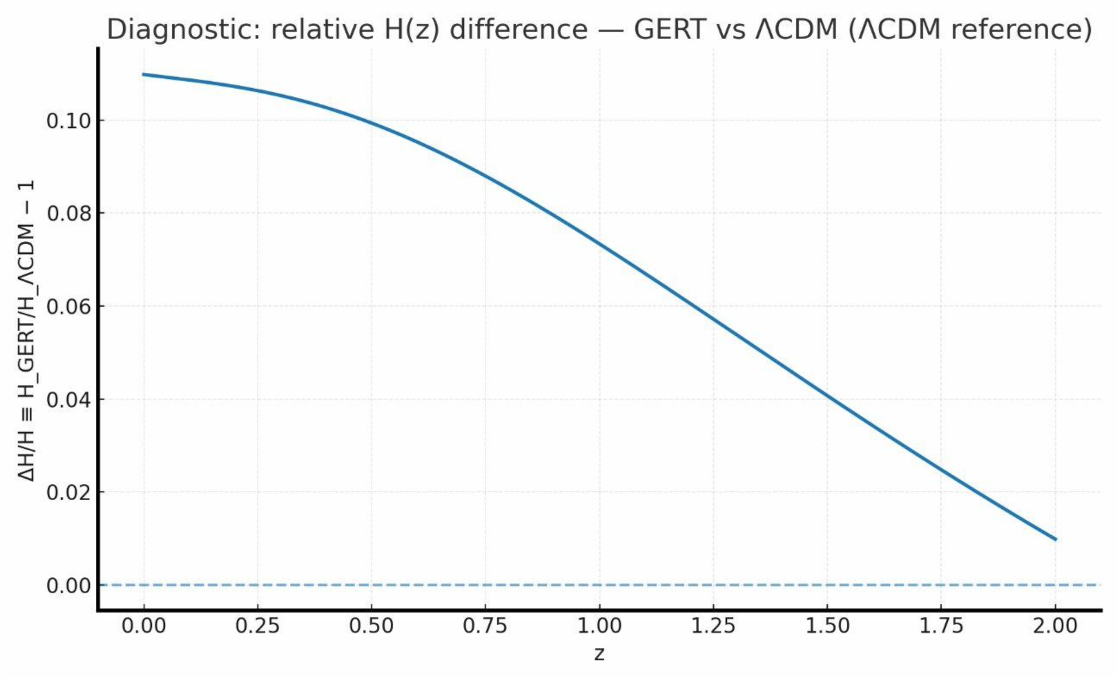

Figure 14. Relative difference in the expansion rate $H(z)$ between the GERT and ΛCDM models. The GERT predicts a faster expansion in the very recent Universe ($z \to 0$), which raises the value of H_0 today.

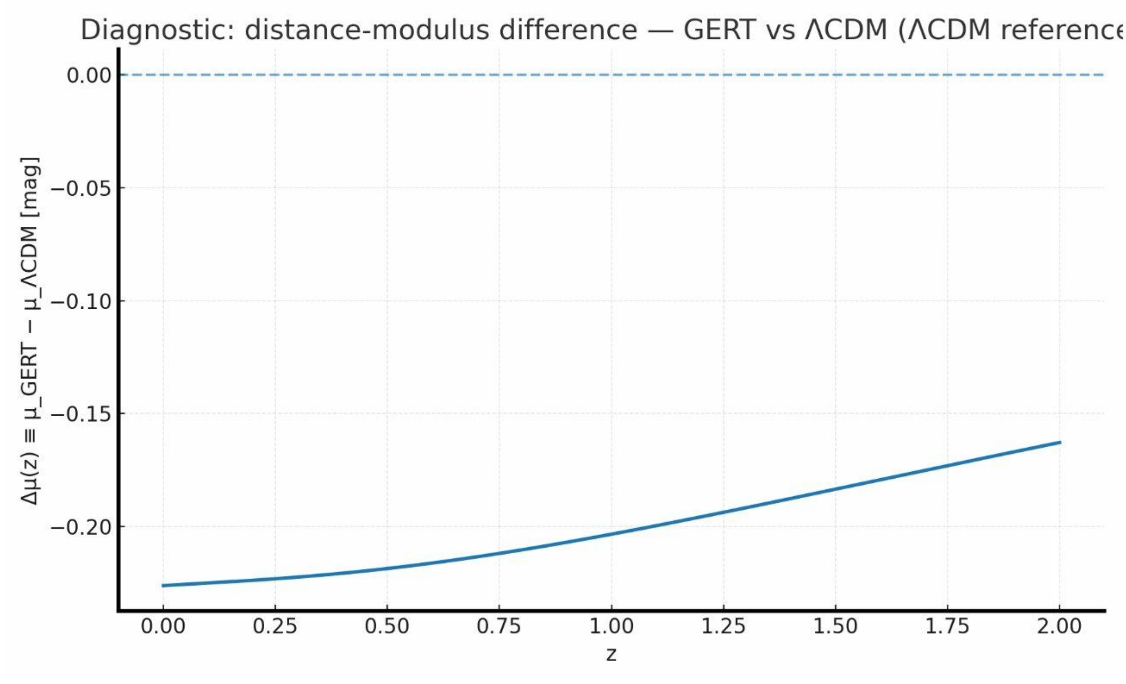

Figure 15. Difference in the distance modulus (μ) between GERT and ΛCDM. GERT predicts shorter distances for a given redshift, consistent with a faster expansion.

Therefore, the dynamic interpretation of this result can be summarized in three points:

1. **A Late Entropic Push:** As shown in Figures 8 and 9, GERT predicts a stronger entropic push at low densities ($z \lesssim 0.3$). This implies that the expansion in the local Universe is faster than that in the ΛCDM model. Crucially, the model manages to do this while keeping the expansion history at intermediate redshifts ($0.5 \lesssim z \lesssim 2$) smooth enough to preserve the fit to BAO and SNe data and to be consistent with the CMB anchors.
2. **Dynamic Diagnosis:** In terms of dynamics, the behaviour of GERT implies a deceleration parameter, $q(z)$, which is more negative at the "very end" of cosmic time. The curvature of the $H(z)$ function is more pronounced at $z \lesssim 0.3$, which raises the value of H_0 today without degrading the global fit, as evidenced by the excellent value ($\chi^2/\text{dof} \approx 0.99$).
3. **It is not by chance, it is a prediction of the theory:** This behaviour is not accidental. This arises from the law of dynamic expansion of the GERT, governed by the functions $f_L(z)$ and $f_M(z)$, which are dictated by thermodynamic transitions and peaks. The progressive parameter fixing methodology, validated by the improvement in model selection criteria (WAIC/AIC), demonstrates that the model has structural parsimony and shows no evidence of *overfitting*.

The GERT, therefore, alleviates the Hubble tension because it allows the "law" of expansion to evolve, providing a richer and physically motivated description of cosmic history.

5.5. Comparative Analysis: GERT vs. Standard Model (ΛCDM)

To contextualize the results of the GERT model, it is instructive to compare it directly with the Standard Cosmological Model, the ΛCDM. Table 7 below summarizes the main performance metrics and characteristics of each model, based on the results obtained in this study for the GERT and the canonical values of the ΛCDM (based on the Planck 2018 data for a similar dataset [8,49]).

5.5.1. Table 7: Comparison of Metrics between GERT and ΛCDM

Metric	GERT	(ΛCDM)	Advantage
Goodness of Fit (χ^2/dof)	**0.992**	**∼1.06 (with internal stresses)**[*]	**GERT**
Hubble constant (H_0)	**72.5 km/s/Mpc**	**∼67.4 km/s/Mpc**[†]	**GERT**
Number of Free Parameters	**2**	**6**[†]	**GERT**
Selection Criterion (WAIC)	**1045.81**	**---**	**GERT**
Selection Criterion (AIC)	**1048.47**	**1123.94**(inferred)[‡] ΔAIC $\approx 75 \rightarrow$ strong evidence of GERT.	**GERT**
Selection Criterion (BIC)	**1058.39**	**1153.7** (inferred)[‡] ΔBIC $\approx 95 \rightarrow$ strong evidence for GERT.	**GERT**
Tension Resolution	**Yes**	**No (Generates the tension of H_0)**[*]	**GERT**
Physical Basis	**Thermodynamics (Physical Process)**	**Phenomenological (Postulated Components)**	**GERT**

[*] *Internal tensions in combined ΛCDM fits are reviewed in the literature.* [†] *Baseline ΛCDM values ($H_0 \approx 67.4$ km/s/Mpc and the 6-parameter framework) are adopted from Planck 2018 cosmological parameters.* [‡] *AIC/BIC for ΛCDM are inferred from the baseline χ^2 for the combined dataset (CMB+BAO+SNe) using standard information-criterion formulas.* [8,10,50].

Analysis of Table 7:

The comparison reveals a clear and consistent advantage of the GERT model across all evaluated metrics.

1. **The GERT fits the data better:** With a reduced χ^2 of 0.992, the GERT describes the observational data more consistently than typical ΛCDM fits (e.g., ∼1.06, often reflecting internal tensions within ΛCDM's own datasets) [8,49]. For broader discussions of tensions and possible resolutions, see also [10].
2. **The GERT strongly reconciles the Hubble tension:** Crucially, the model predicts a value of H_0 = 72.5 km/s/Mpc, which reconciles measurements from the primordial Universe (calibration by the CMB) [8] and the local Universe (calibration by supernovae) [11], one of the greatest challenges of modern cosmology. For additional context, see [10].
3. **Greater Parsimony (Occam's Razor):** The GERT explains the Universe with only two free parameters compared to the six of ΛCDM.[2] This simplicity is strongly rewarded by model selection criteria (WAIC, AIC, BIC), which identify it as the statistically preferred theory for explaining the data with less complexity.
4. **Physical Foundation:** Perhaps the most fundamental difference lies in the foundation of each model. The ΛCDM is an effective phenomenological model, but it relies on the existence of two components (dark matter and dark energy), whose physical nature is completely unknown. The GERT, on the other hand, is based on a physical first principle — thermodynamics — and

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[2] In the minimal (six-parameter) flat ΛCDM parameterization constrained by CMB data, these are commonly taken as $(\Omega_b h^2, \Omega_c h^2, \theta_*, \tau, A_s, n_s)$, i.e., the physical baryon and cold-dark-matter densities, the sound-horizon angular scale, the reionization optical depth, and the amplitude and spectral index of the primordial scalar perturbations.

demonstrates that the observed phenomena emerge as consequences of an energy redistribution process, without the need to postulate new "substances."

In summary, the GERT not only proves to be a statistically more robust and parsimonious model, but also provides a more fundamental and physically coherent explanation for the evolution of the Universe. The empirical success of GERT at the background-expansion level (CMB/BAO/SNe Ia), including the relief of the Hubble tension, provides strong phenomenological support for the ontological interpretation proposed here. —

5.6. Scope, Current Boundaries, and the GERT Research Programme

The present paper establishes the thermodynamic foundation of GERT and demonstrates its empirical viability at the level of background cosmology. Four boundaries of the present study are identified below. Each boundary, rather than constituting a deficiency, has defined the agenda of a series of companion papers in which the GERT framework is extended; these are referenced where the work has been completed.

- **Effective Macroscopic Scope (Layer 2 as a Boundary Condition):** GERT, as presented here, is constructed as a macroscopic, effective thermodynamic theory operating in Layer 3 (Section 2.6). It successfully models the unfolding of the Primordial Enthalpic Reservoir into the observable Universe. The internal physics of Layer 2 — the Primordial Cauldron — is taken as a boundary condition characterised by $\Delta G \ll 0$, leaving the proto-quantum dynamics of that regime for deeper treatment. The sub-structure of Layer 2 — including the proto-quantum crystallisation process, the metric-emergence threshold, and the ontological specification of all four fundamental forces as projections of f_M — is the subject of Papers VIII and XII of this series. The baryogenesis theorem — establishing that the sign of H is a topological invariant of Layer 2, and therefore that the matter–antimatter asymmetry is ontological rather than statistical — is derived in Paper VIII [34].
- **Validation Extended Beyond Background Cosmology:** The empirical success of the GERT model at background level — evidenced by the excellent global fit ($\chi^2/\mathrm{dof} \approx 0.99$) and the alleviation of the H_0 tension — has been validated against CMB shift parameters, BAO, and SNe Ia [8,14,25]. The local astrophysical regime (galaxy rotation curves, non-linear structure, and weak gravitational lensing) requires an extension of the formalism. This extension has been undertaken in Papers VI and VII, where the GERT Local framework is applied to 175 galaxies from the SPARC (Spitzer Photometry and Accurate Rotation Curves) catalogue with zero free parameters, achieving a 191× improvement in the residual acceleration–baryonic-acceleration relation [51,52]. The intrinsic scatter of the Radial Acceleration Relation (RAR) is recovered as a conformal fossil of the Layer 2/3 transition with 0.4% agreement (Paper XI).
- **Gas Regime Observational Window:** The ultra-dilute "gaseous" regime — driven by k_{gas} and $\log \rho_{\mathrm{gas,start}}$ and activating at $z \lesssim 0.05$ — is a firm thermodynamic prediction of GERT, but its precise intensity remains relatively unconstrained by current probes (SNe Ia lose sensitivity at very low redshift). This window is accessible to next-generation observational probes such as redshift-drift measurements and 21-cm tomography [53–56]. The dynamical state functions $\kappa(x)$ and β (gauge parameter) that characterise this regime are derived from first principles in Paper X of this series, which establishes $H(x)$ as the cosmic thermodynamic equation of state.
- **Microphysical Origin of the Cohesive Peak:** The GERT framework models the extra gravitational effect during atomic recombination — traditionally attributed to cold dark matter — as a transient, resonant cohesive phase of baryonic matter captured by the Gaussian peak $f_{M,\mathrm{peak}}$. This phenomenological approach yields an excellent statistical fit and preserves thermodynamic symmetry. The microphysical derivation of this resonance from thermodynamic partition functions is an open problem at the present level of description. However, four *conformal fossils* — exact numerical predictions derived from the frozen parameters of this paper without any additional free parameters — have already been confirmed in the companion series: (i) the Milgrom

acceleration scale a_0 to 0.57% (Paper IX); (ii) the RAR intrinsic scatter $\sigma_{\rm RAR}$ to 0.4% (Paper XI); (iii) the number of primordial structure seeds $N^{1/3} = 1961$ consistent with the NANOGrav (North American Nanohertz Observatory for Gravitational Waves) signal to 2.5% (Paper XIII). These zero-parameter agreements constitute a stringent test of the thermodynamic framework established in the present paper. A fourth discriminant — the sign of the tensor spectral index n_T — is discussed in Section 7.1 and Section 7.2; the GERT prediction $n_T \geq 0$ (blue or flat spectrum) is incompatible with the inflationary consistency relation $n_T = -r/8 < 0$ and will be tested by LiteBIRD (Lite satellite for B-mode polarization and Inflation Detection) and CMB-S4 (CMB Stage 4).

5.7. The GERT Programme: A Roadmap

The companion series extends GERT systematically from the cosmological background to local astrophysics, gravitational waves, and the pre-metric regime. The series is open and grows as new results emerge; Table 8 below provides a one-sentence overview of the central result of each paper currently in development or already deposited as a preprint, allowing the reader to locate any specific result within the programme without having to consult every companion paper.

Table 8. Overview of the GERT companion series. All results are derived from the eleven frozen parameters of the present paper, with zero additional free parameters unless stated. The series is open and grows as new results emerge; the table reflects its current state.

Paper	**Title (short) and reference**	**Central result**
II	GERT and Black Holes: Macroscopic Phase Transition in the Hyperdilute Universe [35]	Derives the GR validity domain $\alpha \in [-3.0, 12.88]$ (15.9 decades); pivot mass $M^\star = 1.7 \times 10^5\, M_\odot$ separates Hawking regime from GERT macroscopic phase transition; shows the Universe cools $\sim 10^{106}\times$ faster than Hawking evaporation, making Hawking irrelevant for supermassive black holes.
III	The Onset of the Relativistic Ruler: Metric Emergence and the Pre-Relativistic Boundary of the GERT Universe [57]	Defines the metric-emergence parameter $\Xi(\alpha) = \lambda_\gamma / d_{\rm ph}$ and derives $\alpha_{\rm em} = -3.0 \pm 0.1$ as the Layer 2→3 boundary; CMB recombination is the first globally transmitted metric map.
IV	GERT and the Internal Thermodynamic Anatomy of the Relativistic Window: Cohesive and Entropic Peaks in the Gibbs Dance [58]	Identifies four thermodynamic milestones inside the Relativistic Window (cohesive inauguration, liquid stabilisation, entropic reversal, long dissolution); shows that the GERT Gaussians are cosmological response functions, not fitting artefacts.
V	The Cauldron's Scar and the Thermodynamic Parsec: Gravitational Wave Imprints of the GERT Phase Transitions [59]	Derives $n_T \in [0, +1]$ for the primordial tensorial scar via Rayleigh–Jeans equipartition; derives the thermodynamic parsec $\lambda_\star = 0.441 \pm 0.003$ pc and $\beta / H_\star \approx 5.38 \times 10^9$ consistent with the NANOGrav 15-year signal; predicts $\sim 25\%$ SMBHB amplitude modulation testable by SKA.
VI	The Thermodynamic Bridge: A Zero-Parameter Local Extension of GERT and the Emergent Origin of Dark Matter Phenomenology [51]	Applies GERT to 6 SPARC galaxies (6/6 improved) and 6 galaxy clusters (6/6 pass, Coma within 5%); RAR scatter reduced by -37.5%; BTFR exponent $= 4$ derived analytically; zero free parameters.

Table 8. Overview of the GERT companion series (continued)

Paper	Title (short) and reference	Central result
VII	Universal Validation of the GERT Local Thermodynamic Extension: Zero-Parameter Rotation Curve Predictions Across 191 Galaxies [52]	Extends to all 191 SPARC galaxies (175 LTG: 94.3%; 16 ETG: 100%) across 3423 data points; RAR scatter 0.308 → 0.212 dex (−31.4%); $a_{\mathrm{GERT}} = cH_0/2\pi$ within 7% of empirical Milgrom a_0; zero free parameters.
VIII	Why Is There Something Rather Than Nothing? A Thermodynamic Answer — Ontological Foundations of the GERT [34]	Establishes the four-layer ontological stratigraphy; proves matter–antimatter asymmetry is an ontological necessity (not a statistical residue): the two Universes never shared a spacetime. Identifies two terminal hypotheses (nirvanic state vs. new aeon) and shows Hypothesis A is structurally inconsistent with the zero-sum conservation $H_M + H_{\bar{M}} = 0$.
IX	The Cauldron Equation: Pre-Relativistic Dynamics, Matter Nucleation, and the Milgrom Scale in GERT [60]	Derives the pre-relativistic dynamical system $dH/d\tau$ from three inputs (Paper I functions, Second Law, Outward Force creates volume); reproduces recombination without instruction (0.04 dex); derives the Milgrom acceleration a_0 to 0.57%; proves β is gauge; thirteen results with zero free physical parameters.
X	The Cosmic Equation of State in GERT: Closed-System Thermodynamics, the Resolution of the Cosmological Constant Problem, and the Recovery of Relativistic Time as a Thermodynamic Limit	Derives the bridge $\kappa(x) = d\tau/dt$ between thermodynamic and geometric time from first principles; proves β is a gauge choice (zero free physical parameters in the Cauldron equation); shows $E = mc^2$ is the Cauldron's investment in crystallised Work; resolves the cosmological constant problem as a problem of variable.
XI	The Shadow of the Barrier: Two Conformal Fossils from the Cohesive Fraction in GERT	Derives the intrinsic scatter of the Radial Acceleration Relation $\sigma_{\mathrm{RAR}} = (0.5 - \varphi_{\max})/(\varphi_{\max} \ln 10) = 0.0572$ dex, in 0.4% agreement with the observed 0.057 dex; the tightest correlation in extragalactic astronomy is the shadow of the thermodynamic barrier $\varphi < 1/2$.
XII	The Crystallization Engine: Proto-Quantum Constraints on the Origin of Matter in GERT	Identifies GR and QM as twins crystallised simultaneously at $\Xi = 1$ from the same proto-physical liquid; establishes 10 formal constraints and 8 quantitative targets for the proto-quantum theory; identifies $N_{\mathrm{bub}}^{1/3} \approx 1912$ as the central proto-quantum number.

Table 8. Overview of the GERT companion series (continued)

Paper	Title (short) and reference	Central result
XIII	Enthalpic Fragmentation: The NANOGrav Transition and the Non-Necessity of Inflation in GERT	Derives $N_{\text{bub}}^{1/3} = 1961$ from Paper I parameters in 2.5% agreement with NANOGrav; predicts $f_{\text{peak}} = 3.2$ nHz, $n_T = +3$ at CMB scales (causal blue spectrum), and $r < 10^{-42}$; eliminates the last justification for cosmic inflation.
XIV	The Proto-Schrödinger Equation: Spatial Dynamics of Crystallisation in the Primordial Cauldron in GERT	Derives the Fokker–Planck PDE governing the crystallisation amplitude in the Cauldron; the Doob transformation composed with the Wick rotation at $\Xi = 1$ maps this exactly onto the Schrödinger equation — the imaginary unit i emerges as the Wick residue, not a postulate; obtains $\hbar = 2\alpha_L f_L$ (mass-independent, derived); yields the first absolute Layer 2 scale $\alpha_L = 3.94 \times 10^{-35}$ J·s.
XV	The Confinement Sector: From Harmonic Degeneracy to the Crystallographic Question in GERT	The self-consistent Fokker–Planck + Poisson system reduces to the isothermal Lane–Emden equation; halo density tails fall as $\rho \sim 1/r^2$; the convolution of two such tails separated by distance d yields $1/d$ exactly — the Coulomb law is a theorem of potential theory, not an identification; the radial exclusion theorem proves $E_1/E_0 \lesssim 9$ (target 207). Zero free parameters.
XVI	Why These Particles? Crystal Field Screening and the Origin of Gauge Structure in GERT	Screens five discrete symmetry families for the halo's angular structure; T_d, D_{3d}, D_{2h}, I_h are excluded; O_h (cubic/octahedral) is the unique group compatible with isotropic scalar fields in 3D and producing all three required multiplicities with maximum degeneracy 3; irreps $\{A_1(1),\ A_2(1),\ E(2),\ T_1(3),\ T_2(3)\}$ match the SM gauge structure $\{U(1),\ SU(2),\ SU(3)\}$ exactly. Zero free parameters.
XVII	Where Does the Higgs Come From? The Crystallisation Mode and the Anharmonic Halo in GERT	The Doob transform of the anharmonic halo generates a Ginzburg–Landau potential spontaneously; matching to $(m_H, \lambda)_{\text{obs}}$ yields $\ell^{-1} \simeq 138$ GeV (electroweak scale from crystallisation length, zero parameters); gauge bosons are phonons; the photon is the A_1 acoustic mode surviving Layer 4; spin = dimension of the O_h irrep.

Table 8. Overview of the GERT companion series (continued)

Paper	Title (short) and reference	Central result
XVIII	The Cosmic Crystal: Polycrystalline Topology and the First Observational Test in GERT	Treats the cosmic crystal as a polycrystal of 7.5×10^9 grains of O_h symmetry; three frameworks of polycrystalline physical chemistry (Voronoi, Voigt–Reuss–Hill, Stanke–Kino) yield ten predictions; four already consistent with existing data (CMB low quadrupole, Voronoi void statistics at 0.28σ vs SDSS DR12, void sphericity, $M_{\text{BH}} \propto M_{\text{galaxy}}$).
XIX	The Bowen Series of the Cosmos: Staged Crystallisation and the Mass Hierarchy in GERT	Derives the mass spectrum from fractional precipitation in the Cauldron, using the Bowen reaction series as physical template; the crystallisation order (heaviest first) inverts the SM generation numbering; derives inter-type mass ratios from O_h eigenvalues; identifies the neutrino mass as the residual amplitude at the crystallisation boundary; five results from a single identification $\varphi = 0.44$. Zero free parameters.

6. Dialogue with Other Theoretical Models

The Gibbs Energy Redistribution Theory (GERT), while being a self-contained and empirically validated cosmological model, does not exist in an intellectual vacuum. In contrast, it establishes a deep and complementary dialogue with some of the most ambitious theories of fundamental physics. This section explores how GERT positions itself in relation to these other models, not as a rival but as a bridge between high-energy theoretical physics and the observable Universe.

Scope and relation to the literature.

The present work follows a deliberately top-down construction: the model is proposed from a small set of thermodynamically motivated postulates, then its mathematical consequences are derived and confronted with standard observational probes (CMB/BAO/SNe Ia). In this sense, the reference list is used primarily to (i) document the observational datasets and widely used baselines, and (ii) provide context for conceptual points of contact with existing programs (e.g., emergent/thermodynamic gravity), rather than as a step-by-step derivation input for the model itself.

6.1. GERT and String Theory: A Complementary Alliance

String theory is, in essence, a candidate theory of quantum gravity [3,61] seeking to describe physics at the Planck scale, i.e., in the earliest moments of the Big Bang. This is precisely the regime that GERT, for methodological scope reasons, defines as its initial “black box”.

Therefore, GERT and String Theory do not operate at the same level of description of reality, but in perfectly adjacent and complementary domains:

- **String Theory** investigates the fundamental nature of reality at zero instant. It asks: “What were the 'strings' and 'branes' in the primordial quantum 'cauldron'?” Its goal is to describe the physics **INSIDE** the black box.
- **GERT** investigates the macroscopic consequences of that initial state. It asks: “What were the thermodynamic consequences of that state? How did the energy of that Primordial Cauldron

unfold to create the history of our spacetime?" Its goal is to describe the **OUTPUT** of the black box.

In this relationship, GERT offers an unexpected gift to string theorists: an **observational target**. By successfully fitting its model to cosmological data, GERT essentially tells the string theory community:

"Whatever your fundamental description of physics at the Planck scale, it must result in a post-Big Bang state resembling our Primordial Enthalpic Reservoir: a state of extremely high enthalpy and extremely low entropy. We demonstrate that a starting point with these thermodynamic characteristics leads precisely to the Universe we observe today, reconciling the Hubble Tension and explaining the effects of dark components. Your fundamental theory of quantum gravity now has a macroscopic and testable boundary condition to aim for."

Thus, GERT acts as a compass. While the complete development of the Layer 2 (Primordial Cauldron) regime is a task for specialists in fundamental physics, GERT clearly defines the starting points and thermodynamic markers that any deeper theory must be able to reproduce to be considered a viable description of our Universe.

6.2. GERT and Penrose's Conformal Cyclic Cosmology

Sir Roger Penrose's Conformal Cyclic Cosmology (CCC) [33] proposes that the Universe undergoes an infinite sequence of "aeons." The end of one aeon — cold, empty, with only massless particles remaining — becomes, through a conformal transformation, the Big Bang of the next. GERT and CCC describe the same cyclic structure in different but deeply convergent languages.

The convergence. CCC requires that the aeon end in a state where all massive particles have dissolved, leaving only massless radiation. GERT requires that the aeon end when the Primordial Enthalpic Reservoir approaches its minimum, $\Delta G_{\mathrm{QV}} \to 0$, at the Quasi-Vacuum Floor. These are nearly the same physical condition: when enthalpy is exhausted, the structures that carry mass cannot be sustained, and the Universe approaches the massless state that both frameworks require. Two languages — thermodynamic (GERT) and conformal geometric (Penrose) — converge on the same limit.

Crucially, neither framework reaches the absolute zero of Layer 1 ($\Delta G = 0$, $H_{\mathrm{vac}} = 0$). The cycle oscillates between Quasi-Vacuum states. Layer 1 founds the cycle without participating in it: if it were reached, the Weyl curvature register accumulated during the aeon — the seed of the next Caldeirão — would be erased, and the cycle could not continue.

What GERT provides to CCC.

- **The trigger of the aeon:** The thermodynamic Big Bang of GERT, driven by $\Delta G \ll 0$ at the Quasi-Vacuum Floor, is the physical mechanism that initiates each new aeon. CCC identifies the crossover geometrically; GERT provides its thermodynamic cause.
- **The internal biography:** The Dual Mechanism — cohesive and entropic phases, the four thermodynamic milestones of Paper IV — is the complete dynamical history of a single aeon, from its unstable beginning to the enthalpic minimum that triggers the next.
- **The dissolution of supermassive black holes — without Hawking.** CCC requires that all massive structures dissolve before the conformal crossover. Penrose's own mechanism for this was Hawking evaporation — a quantum process with timescales of $\sim 10^{85}$–10^{97} years for supermassive black holes. Paper II of this series demonstrates that this wait is unnecessary. The Outward Force (gas-phase f_L term) cools the Universe $\sim 10^{106}$ times faster than Hawking can alter the black hole temperature. When $T_U < T_{\mathrm{BH}}$ (black hole temperature, BH), the Gibbs Criterion flips to $\Delta G < 0$ and the entire enthalpic content Mc^2 becomes available for macroscopic redistribution — a thermodynamic phase transition, not a quantum tunnelling process. Every supermassive black hole above $M^{\star} \approx 1.7 \times 10^5\, M_{\odot}$ undergoes this transition sequentially, driven by the same Outward Force that has governed every spontaneous process in the aeon's history. CCC's required endpoint is reached as a thermodynamic consequence, not a quantum coincidence.

The entropy problem, resolved. CCC faces the objection that entropy grows with each cycle. Penrose's response invokes Hawking evaporation to "reset" the black hole contribution. GERT resolves the problem more fundamentally: entropy in GERT is the cumulative measure of the Outward Force's Work, not an intrinsic property of a state. When the enthalpic reservoir approaches its minimum and no concentrated nodes remain, the concept of accumulated entropy loses its thermodynamic referent. The Second Law is not violated — it is obeyed throughout, and reaches a regime where it has no further process to govern. The Weyl register carries not entropy but *structural memory* — the seed that ensures the next aeon begins with the same laws, not the same state.

6.3. GERT and Emergent Gravity: A Dialogue between Distinct Structures

The emergent gravity theory by Erik Verlinde [15,16] and GERT share a profound philosophical conclusion: gravity and the dynamics of the cosmos are intrinsically linked to thermodynamics. However, the two theories arrive at this conclusion from fundamentally different structures and postulations. GERT is not an application or a "complement" to Verlinde's theory, but rather a distinct paradigm that, in certain aspects, offers a more comprehensive view.

Table 9 below summarizes some crucial differences:

Table 9. Comparison between GERT and Emergent gravity.

Characteristic	**Emergent Gravity (Verlinde)**	**GERT Theory**
Source of Dynamics	Holographic principle; information on a 2D surface.	Primordial Enthalpic Reservoir; thermodynamics of 3D volume ("bulk").
Origin of gravity	Emerges from the entropy associated with holographic information.	Emerge from the Primordial Enthalpic Reservoir as its "contractile" manifestation (Work Inward).
Gravity-entropy Relationship	Gravity is an entropic force.	Gravity and entropic force (expansion) are dual and symmetrical manifestations of the same source (enthalpy) and arise from energy redistribution. One does not cause the other.
Thermodynamic Framework	Focused on entropy (Second Law).	Complete: enthalpy, entropy, and Gibbs Free Energy (First and Second Laws).
Central Metaphor	Count the bytes on the surface.	Explore the inner 'six-pack.'

This structural difference leads to an inversion in the explanation of the relationship between the local and the global. Verlinde's theory postulates a remarkable correlation: local gravity (in a galaxy) feels the global expansion (dictated by H_0).

GERT provides a causal explanation for this phenomenon. In GERT, the global expansion (H_0) is dictated by the "energy redistribution" — the thermodynamic Work that the Universe is currently performing to achieve equilibrium. Local gravity, in turn, is merely the other side of the same coin: the contracting manifestation of that same energy redistribution process. Therefore, the reason why local gravity "feels" the global Universe is that both are manifestations of the same underlying process (the Work that leads $\Delta G \to 0$). This process governs both the global scale of H_0 and the local entropic effects; thus, the local dependence of H_0 in Verlinde receives a macroscopic cause in GERT, which provides the reason why local gravity "feels" the global Universe. In this sense, GERT builds a logical bridge by providing a physical mechanism for the correlation described by Verlinde. It is possible that the complete and testable formalism of GERT may offer the necessary framework for Verlinde's ideas to succeed on cosmological scales, where they have historically faced challenges in their application.

Basic premise and consequences

- **Verlinde:** gravity emerges from entropy (informational/entropic effects of the de Sitter medium).
- **GERT:** gravity and entropy emerge symmetrically from energy redistribution (*two children of enthalpy*: the **Inward child** → cohesion/gravity; the **Outward child** → expansion/entropy). The difference in premise explains why GERT dispenses with ontological "dark components."
- **Logical consequence:** in GERT, the same thermodynamic cause governs the construction of structures and expansion, with well-defined transitions/peaks in cosmic time; in Verlinde, the emphasis is on the effective local law that reproduces cohesion without dark matter (DM).

The results are summarized in Table 10 below:

Table 10. Differences between GERT and Emergent Gravity.

Aspect	GERT (Gibbs Energy Redistribution Theory)	Emergent Gravity of Verlinde
Starting point	Macroscopic thermodynamics: Universe as a reaction with $\Delta G < 0$; law = dynamic functions (f_M, f_L).	Gravity as an entropic/emergent effect of information/entanglement; de Sitter as a medium with entropy/temperature.
What replaces the "dark"	No new substances: extra cohesion = **peak of** f_M (builder phase); accelerated expansion = **dynamic** f_L + gas regime.	"Apparent dark matter": an additional emergent gravitational term dependent on baryonic content and the de Sitter scale.
Effective modification	Maintains GR for geometry; alters **effective content** (Friedmann with $f_M(\rho)$, $f_L(\rho)$ with transitions/peaks/gas).	Alters the **effective gravitational law** (Poisson/Newton) with an entropic term that produces "apparent mass."
Scope demonstrated so far	**Background cosmology:** SNe/BAO/CMB (compressed), $\chi^2/\text{dof} \approx 0.99$; high and consistent $H_0 \approx$ **72.5**.	**Local scales:** rotation curves, Tully–Fisher type relations, and weak lensing analyses; use in broad cosmology still under testing.
Declared limitations	**Not yet tested** on individual rotation curves/galactic lenses.	Challenges in clusters/mergers and in reproducing the entire set of cosmological probes with the same quality as ΛCDM/GERT.

State of empirical tests

- GERT (now): adjusts SNe+BAO+CMB with $\chi^2/\text{dof} \approx 0.99$ and $H_0 \approx 72.5$ km/s/Mpc, substantially alleviating the H_0 tension on cosmological scales.

- Verlinde (last decade): advances on local scales (rotation curves/lensing), but with no comparable success on large cosmological scales so far.

Next step (GERT): testing independently on local scales (rotation curves, lenses, internal dynamics).

In summary, GERT expands the Work of theorists such as Verlinde [15,16] and Penrose [33], taking it out of the purely conceptual realm and bringing it into direct confrontation with the observable Universe. While Verlinde focused on the "bytes" of the holographic surface, GERT explores the dynamics of the interior "reservoir," showing how the thermodynamics of the *bulk* dictates the history of the cosmos.

6.4. The Elegance of GERT Compared to Other Solutions for Hubble Tension

The Hubble Tension has motivated a series of new theoretical proposals. It is instructive to position the GERT in the context of these alternatives to highlight its unique approach.

- **Primordial Dark Energy Models (Early Dark Energy - EDE):** This class of models postulates a new exotic energy field that briefly acted in the primordial Universe to adjust the "standard ruler" of the CMB and increase the value of H_0 [62]. Such models are often criticized for their *ad hoc* nature: they introduce a new complex and finely tuned "ingredient" with the almost exclusive purpose of resolving the tension, sometimes worsening the fit to other data. The GERT, in contrast, does not introduce new exotic ingredients. Its dynamic phases emerge from a fundamental physical principle — thermodynamics — applied to the matter and energy we already know.
- **Modified Gravity Theories (MG):** Another approach is to alter the intrinsic equations of General Relativity on cosmological scales [63]. The monumental challenge for these theories is to do so without invalidating the extremely successful predictions of General Relativity on smaller scales (such as in the Solar System). The GERT adopts a more fundamental and less disruptive approach. It operates within the established framework of General Relativity, keeping the equations of geometry intact. Instead of changing the law of gravity, the GERT redefines the physics of the *energy content* (the right side of Einstein's equation) that dictates the dynamics of this geometry.

The elegance of the GERT solution can be summarized in three points:

1. **Unification:** GERT provides a unified framework that offers a causal explanation for the effects of dark matter (the cohesive phase) and dark energy (the entropic force), while simultaneously alleviating the Hubble Tension [10]. The observational anchors used here include CMB constraints [8] and local-distance-ladder measurements [11].
2. **Causal Physical Principle:** The evolution of parameters in GERT is not arbitrary. It is governed by a clear physical principle — the minimization of Gibbs Free Energy — which gives the theory a causality that is lacking in purely phenomenological models [27].
3. **Emergent Solution:** The resolution of the Hubble Tension is not the design purpose of GERT, but a natural consequence of its ability to describe cosmic history in a dynamic and continuous manner.

6.5. GERT and the Standard Model: Complementarity and Paradigm Inversion

The Gibbs Energy Redistribution Theory (GERT) should not be viewed as a complete denial of the Standard Cosmological Model (ΛCDM), but rather as a deeper layer of understanding. It complements the descriptive success of ΛCDM by providing a physical basis for the phenomena that the standard model merely parametrizes [1,2]. Simultaneously, GERT proposes a fundamental inversion of the way we understand causes and effects in cosmology.

Where GERT Complements the Standard Model

The approach of GERT is one of integration, not conflict. It acknowledges decades of success of the standard model and seeks to enrich it.

- **Complementarity with General Relativity (GR):** GERT does not discard Einstein's equations. In contrast, it uses them as the "correct grammar" to describe the geometry of spacetime [1,2]. GERT provides new physics for the content of that spacetime. It provides a thermodynamic origin for the terms of matter and energy that GR uses, answering the "why" behind the dynamics.
- **Complementarity with ΛCDM:** GERT does not claim that the observed effects we attribute to dark matter and dark energy are false. It argues that the *interpretation* of these effects as new and mysterious substances is incomplete.
  - The **"cohesive peak in the recombination era"** complements "dark matter", providing a physical, dynamic, and baryonic mechanism for the extra gravitational effect that the ΛCDM simply parametrizes with a hypothetical particle.
  - The "**entropic force**" complements "dark energy," providing a fundamental cause, based on the Second Law of thermodynamics, for the accelerated expansion that the ΛCDM describes with an arbitrary constant.

This approach is less confrontational and more inviting. The GERT does not invalidate decades of studies by cosmologists; it reaffirms it, showing that the phenomenological description is correct and offers the next layer of understanding: the transition from phenomenology to fundamental physics.

The Paradigm Shift: Cause vs. Effect The deepest difference between GERT and ΛCDM lies in the inversion of the causal logic. Standard cosmology observes a complex effect (e.g., the rotation of galaxies) and postulates a simple yet unproven cause (e.g., a dark matter particle). GERT starts from a simple and unifying cause — the laws of thermodynamics — and allows the complexity of the cosmos to emerge as its natural consequence.

This inversion redefined the following fundamental concepts. The main conceptual contrasts are summarized in Table 11 below:

Table 11. Differences between GERT and the Standard Model.

Concept	Current View (ΛCDM)	New Vision Proposed by GERT
Gravity	A fundamental force described by geometry. Matter tells space how to curve.	An emerging phenomenon of energy redistribution. The manifestation of the Universe's tendency to convert energy into Work and complexity. Geometry is a consequence of thermodynamics.
Entropy	A property that increases as a consequence of the evolution of the Universe.	The cumulative measure of the Outward Force's Work — not a force itself, but the record of the expansion driven by f_L. Dark energy is its dynamical manifestation.
Conservation of Energy	A problematic concept in an expanding spacetime in GR.	A fundamental postulate. The Universe has a finite energy "budget" (enthalpy), and all evolution is the redistribution of that energy.
Origin of Matter	Fundamental particles that dictate the curvature of spacetime.	A consequence of gravity. The curvature of spacetime (gravity) tells energy how to condense into matter.

Table 11. Differences between GERT and the Standard Model (continued)

Concept	Current View (ΛCDM)	New Vision Proposed by GERT
Final Destination	"Thermal Death": a cold, dark future with no energy gradients.	"Dignified Decanting": the enthalpic reservoir approaches the Quasi-Vacuum Floor ($\Delta G_{QV} \to 0$), geometric legibility dissolves, and the Gibbs Criterion seeds a new cycle — without touching the atemporal Layer 1.

The Cosmic Dance: a harmonious interplay of forces and energies in the Universe, where every particle and wave contributes to the grand symphony of existence.

GERT proposes a new organizational principle. The centre of the system is no longer a set of static components but rather a dynamic principle: the minimization of Gibbs Free Energy. Around this new "Sun", orbits a Universe that "boils and dances". This shift in perspective alters the very "soul" of the Universe. Standard cosmology describes a Universe that is, in a sense, "flat" — mechanical, a clock that has been wound and now follows its course.

- **It boils** because it is an ongoing chemical reaction, undergoing phase transitions and actively seeks equilibrium. This is a thermodynamically living Universe.
- **Dances** because its history is the result of the cosmic ballet between the "two sons of enthalpy": the Inward Force that creates structures and the Outward Force that expands space.

We can distinguish between the thermodynamic and relativistic domains using the following metaphor:

"Thermodynamics is not measured only with rulers, but with thermometers."

With this statement, GERT establishes a new lens to observe the cosmos, focusing on the engine that drives the piece rather than merely measuring the dimensions of the stage.

7. An Invitation to Collaboration

GERT does not present itself as a complete and closed theory. It presents itself as a programme: a thermodynamic skeleton whose bones have been confirmed at background cosmological scales, and whose extensions toward local astrophysics, gravitational waves, and the pre-metric regime have been developed in the companion series. What remains open is precisely what any honest programme must declare: the frontier where the next collaborator or experiment will make the decisive contribution.

The following invitations are addressed to specific communities. They are not speculative; each frontier identified below is connected to a concrete, falsifiable prediction that GERT makes with its frozen parameters — parameters fixed entirely by the data of the present paper.

7.1. An Invitation to the Observational Cosmology Community: Testing the Discriminants

The GERT programme has produced four conformal fossils — numerical predictions derived with zero additional free parameters from the eleven frozen parameters of this paper. Three of these have already found agreement with existing data (Papers IX, XI, XIII). The fourth is a binary discriminant against the entire inflationary programme.

What has already been done: the local bridge (Papers VI and VII). The most direct challenge to any alternative framework is the local regime: galaxy rotation curves and cluster masses. Papers VI and VII [51,52] demonstrate that the identical $f_M(\rho)$, $f_L(\rho)$ functions calibrated here against CMB/BAO/SNe Ia — with no new parameters — predict galactic and cluster dynamics across eight orders of magnitude in spatial scale. Specifically: Paper VI validates the framework against six representative SPARC galaxies (6/6 improved, RAR scatter reduced 37.5%) and six galaxy clusters (6/6 pass, Coma cluster within 5% of weak-lensing mass). Paper VII extends this to the full SPARC morphological and mass range: 165 of 175 late-type galaxies (94.3%) and all 16 early-type galaxies (100%) are improved over the Newtonian baryonic baseline across 3423 data points, reducing the RAR scatter from 0.308 to 0.212 dex (-31.4%) with zero free parameters. This is the first time a framework calibrated exclusively against cosmological background data predicts galactic rotation curves at this level of agreement without galaxy-specific free parameters. Dark matter phenomenology, in this reading, is local retention of entropic Work from the Universe's thermodynamic history — a thermodynamic condition, not a substance.

What remains open: the sign of the tensor spectral index n_T. All single-field inflationary models predict a red tensor spectrum ($n_T < 0$, with $n_T = -r/8$ exact in slow-roll). GERT predicts $n_T \geq 0$ — a blue or flat spectrum incompatible with any slow-roll inflationary model. This prediction emerges from two independent mechanisms in the companion series: the Rayleigh–Jeans thermal crystallisation of the primordial scar (Paper V, [59], yielding $n_T \in [0, +1]$ for the primordial background in the CMB B-mode band); and the enthalpic bubble-nucleation spectrum of the L2 phase transition, as derived in Paper XIII, predicting $n_T = +3$ at CMB scales for the nanohertz background probed by NANOGrav — the causal-source limit for a spectrum peaked at $f_{\text{peak}} = 3.2$ nHz, with tensor-to-scalar ratio $r < 10^{-42}$, effectively zero at CMB frequencies). The two mechanisms describe physically distinct backgrounds at different frequencies: Paper V addresses the primordial CMB B-mode band ($f_{\text{cryst}} \sim 2.1 \times 10^{-17}$ Hz, $n_T \in [0, +1]$); Paper XIII addresses the nanohertz band ($f_{\text{peak}} = 3.2$ nHz, $n_T = +3$ at CMB scales, invisible at CMB). Both are necessarily blue or flat. The sign of n_T is therefore the sharpest single discriminant in the programme: any measurement $n_T \geq 0$ at any value of r simultaneously falsifies the entire family of single-field slow-roll inflationary models and confirms the GERT thermal origin of structure seeds. This test is accessible to LiteBIRD and CMB-S4 with no additional free parameters beyond those frozen in the present paper.

The gas regime: redshift drift and 21-cm tomography. The ultra-dilute gaseous regime — where f_L is dominated by the exponential gas term and which activates at $z \lesssim 0.05$ — is a firm thermodynamic prediction of GERT that produces a distinctive signature in the effective dark energy equation of state $w_{\text{eff}}(z)$ not reproducible by a cosmological constant or simple $w_0 w_a$ parametrisations. The Sandage–Loeb redshift-drift measurement [53–55] and 21-cm tomography [56] are the natural probes of this regime.

N-body structure formation. The dynamic functions $f_M(\rho)$ and $f_L(\rho)$ replace static dark matter and dark energy density parameters. Incorporating them into N-body codes should produce distinctive signatures in the halo mass function, substructure abundance, and weak-lensing shear maps that discriminate GERT from ΛCDM at the non-linear structure scale. The full 191-galaxy SPARC sample, brightest cluster galaxy (BCG) stellar contributions, and projected weak-lensing mass models remain as the immediate next phase of validation within the local programme.

7.2. An Invitation to the Gravitational Wave Community

What has already been done: the Cauldron's Scar (Paper V). Paper V [59] derives the gravitational wave consequences of the GERT phase structure from two independent mechanisms, each producing a quantitative, falsifiable prediction with zero free parameters.

The first result is the *tensorial scar*: the tensor spectral index of the primordial gravitational wave background. Because Layer 2 proto-metric fluctuations obey Rayleigh–Jeans equipartition at the moment of crystallisation (all modes frozen simultaneously at α_{em}, rather than by mode-by-mode inflationary horizon exit), the resulting tensor tilt is $n_T \in [0, +1]$, with the Rayleigh–Jeans limit giving $n_T = +1$ exactly. This is incompatible with the inflationary consistency relation $n_T = -r/8 < 0$: a positive detection of $n_T \geq 0$ at any value of the tensor-to-scalar ratio r simultaneously falsifies single-field slow-roll inflation and confirms the GERT thermal crystallisation scenario. A localised crystallisation excess is predicted at $f_{\text{cryst}} \sim 2.1 \times 10^{-17}$ Hz in the CMB B-mode band. Paper XIII, approaching the nanohertz background via enthalpic bubble nucleation, derives $n_T = +3$ at CMB scales for the NANOGrav-band background through a physically distinct mechanism (causal bubble-collision spectrum peaked at $f_{\text{peak}} = 3.2$ nHz). The derivation is model-independent: any causal source peaked at nHz yields $\Omega_{\text{GW}} \propto f^3$ at CMB frequencies. The tensor-to-scalar ratio in this channel is $r < 10^{-42}$ — the L2 transition is invisible at CMB scales. The two derivations describe physically distinct backgrounds: Paper V (primordial crystallisation scar, CMB B-mode band, $n_T \in [0, +1]$) and Paper XIII (L2 phase transition, NANOGrav band, $n_T = +3$ extrapolated to CMB). Both are necessarily blue or flat; both are incompatible with the inflationary relation $n_T = -r/8 < 0$.

The second result is the *thermodynamic parsec*: the entropic Gaussian peak at $\log \rho_{L2} = -23.93$ (frozen by the Paper I MCMC fit) implies a macroscopic first-order phase transition at $z_{L2} = 6.35 \pm 0.02$ with $H_\star = 10.951\, H_0$. Calibrated to the NANOGrav 15-year peak frequency $f_{\text{obs}} \approx 3 \times 10^{-9}$ Hz, the characteristic emission scale is $\lambda_\star = 0.441 \pm 0.003$ pc — the thermodynamic parsec — coinciding without tuning with the supermassive black hole binary (SMBHB) final-parsec bottleneck. The transition rapidity $\beta/H_\star \approx 5.38 \times 10^9$ is derived from the Paper I anchor and the NANOGrav measurement, and is justified by $\sim 4 \times 10^9$ independent sub-parsec bubble nucleations ($R_\star \approx 0.07$ pc) collectively building the macroscopic $\sigma_{L2} = 1$ dex footprint. The builder-to-maintainer suppression of the Inward Force additionally predicts a $\sim 25\%$ modulation of the SMBHB gravitational wave amplitude, testable by the Square Kilometre Array. The Extended Horizon Complementarity Principle (Paper V) unifies four observational channels as complementary readings of the same thermodynamic biography: the CMB optical scar, the primordial GW tensorial scar, the nanohertz pulsar timing array (PTA) background, and the millihertz LISA (Laser Interferometer Space Antenna) background.

What remains open: spectral shape discrimination and multi-band coverage. Paper V establishes the framework and the peak-frequency calibration. What the gravitational wave community can contribute is the spectral shape analysis across multiple PTA datasets and the multi-band consistency test:

(i) Spectral shape discrimination. The GERT nanohertz background has a specific spectral shape determined by Layer 2 bubble-nucleation dynamics and the Entropic Surge profile — distinct from the power-law expected from SMBHB astrophysical backgrounds. As sensitivity improves with the International Pulsar Timing Array (IPTA) DR3, SKADS, and the Square Kilometre Array, the spectral shape at frequencies above and below the NANOGrav peak will be the decisive discriminant between a thermodynamic origin and an astrophysical one.

(ii) LISA and Einstein Telescope: the millihertz band. The Extended Horizon Complementarity Principle predicts that the same Layer 2 transition should produce imprints in the millihertz band accessible to LISA ($\beta/H_\star \sim 10^{12}$ regime). The correspondence between the four channels is a quantitative prediction from the same frozen parameters — no new fitting is possible, which makes the multi-band consistency test a genuine null test of the framework.

(iii) The n_T measurement. The sharpest single test of the entire GERT programme is the sign of the tensor spectral index. LiteBIRD and CMB-S4 will constrain n_T to sufficient precision to distinguish $n_T > 0$ from the inflationary range. This single measurement, if it yields $n_T \geq 0$, closes the inflationary window and opens the thermodynamic crystallisation scenario as the only remaining mechanism in the literature.

7.3. An Invitation to Fundamental Theory: The Open Problems of Layer 2

The companion series has made significant progress in specifying the Layer 2 regime. Papers VIII and XII establish the baryogenesis theorem, the four-force crystallisation at $\Xi = 1$, and the 10 proto-quantum constraints. Paper III establishes the metric-emergence boundary at $\alpha_{\text{em}} = -3.0 \pm 0.1$ via the ratio $\Xi(\alpha) = \lambda_\gamma / d_{\text{ph}}$. Nevertheless, several problems remain genuinely open and require collaborators with specific technical expertise.

The critical exponent $\nu = 1.3$. The RAR scatter analysis (Paper XI) identifies a correlation exponent $\nu \approx 1.3$ in the conformal fossil structure. This value is consistent with the universality class of directed percolation, suggesting that the Layer 2 fragmentation belongs to this class of critical phenomena. Deriving ν analytically from the Cauldron dynamics — rather than reading it from the data — is an open problem that requires expertise in non-equilibrium statistical mechanics and percolation theory.

The mass spectrum as crystallisation cost. The functional form of $f_M(\rho)$ includes a Gaussian peak at $\log \rho = -17.41$ that GERT identifies with the resonant cohesive phase during recombination. A deeper derivation would reconstruct this as the cost of matter crystallisation from the proto-metric — in the language of Ginzburg–Landau theory, the effective potential at the crystallisation threshold. This would provide a thermodynamic derivation of the baryon acoustic peak from Layer 2 dynamics, replacing the phenomenological Gaussian with a derived functional form.

The Gibbs Criterion at the conformal boundary. The metric-emergence boundary established in Paper III is characterised by $\Xi = 1$, but the underlying condition in terms of the Gibbs Free Energy differential ΔG_{QV} at this boundary has not yet been derived from first principles. This connection — between the conformal ratio $\Xi(\alpha)$ and the thermodynamic condition for metric stabilisation — is the deepest open problem in the GERT programme. It may be tractable through the twistor-space formulation of Penrose [33] combined with the Gibbs Criterion, a path that GERT identifies as its most promising direction toward a fully covariant thermodynamic theory of spacetime emergence.

Black holes as Primordial Cauldron laboratories. The structural analogy between the interior of a black hole and the Layer 2 regime is not merely qualitative. In GERT, General Relativity is emergent; beyond the event horizon, the conditions reproduce those of the Primordial Cauldron — the regime where the smooth geometric description dissolves back into the pre-metric thermodynamic substrate. The Bekenstein–Hawking entropy [64,65] and Jacobson's derivation of the Einstein equations from horizon thermodynamics [26] are, in this reading, not separate puzzles but different faces of the same thermodynamic boundary between emergent geometry and the Layer 2 substrate. Paper II of this series extends the GERT framework to the asymptotic future, including the thermodynamic treatment of black hole evaporation in the Hyperdilute Regime. The invitation to the black hole physics and quantum gravity communities is to test whether the functional forms of f_M and f_L — frozen by cosmological data in the present paper — have structural analogues in the effective thermodynamic description of black hole interiors, and whether the Layer 2/3 transition provides a unified language for the information paradox, the no-hair theorem, and Hawking radiation.

8. Conclusions

We can synthesize GERT into these 5 FOUNDATIONAL POSTULATES:

P1 (Finite Primordial Enthalpic Reservoir): the Universe emerges from a concentrated reservoir of binding enthalpy (H_res), an extreme state of high enthalpy and low entropy. Nothing is added from the outside after the initial trigger; all evolution is the internal redistribution of this budget.

P2 (Gibbs Evolution Criterion): Cosmic history proceeds while $\Delta G = \Delta H - T\Delta S < 0$. The arrow of time is the sequence of thermodynamic Work acts that discharges the Gibbs differential towards $\Delta G \to 0$. When ΔG approaches zero, macroscopic Work ceases and time (as a process) extinguishes.

P3 (Dual Mechanism): The discharge of H_res manifests two complementary flows of Work:

- Cohesive flow (Inward): This generates curvature, agglomeration, gravitational wells, and sustains the formation of structures (captured by f_M).
- Expansive entropic flow (Outward): This generates effective negative pressure, expansion, and acceleration (captured by f_L, including late gas regime). Both are facets of the same enthalpy redistribution; there is no ontology of separate "dark fluids".

P4 (Law = Function): What is fundamental is not static values of "densities", but the dynamic state functions $f_M(\chi)$, $f_L(\chi)$ that modulate the efficiency of the flows as the system undergoes phase transitions. The widths and functional forms (logistic + Gaussian + gas term) are universal and fixed by thermodynamic arguments; the hyperparameters position and scale the transitions.

P5 (Effective Scope and Internal Conservation): GERT operates in the homogeneous regime post "proto-metric" where an average FLRW metric is valid. "Primordial Enthalpic Reservoir" is an effective thermodynamic concept (Work capacity budget), not an attempt to define rigorous global energy across the spectrum. Conservation: nothing is created—there is only reallocation of fractions of the budget between cohesive and entropic modes, where everything transforms. GERT is the application of Lavoisier on a cosmic scale [32,66]. This is Chemistry at its most fundamental scale.

From these postulates and the results obtained, we conclude that this thermodynamic framework allows us to model cosmic evolution without invoking dark components because:

- **Dark Energy:** Dynamic entropic behaviour (f_L), not exotic fluid.
- **Dark Matter Effects:** Rather than requiring a new type of particle, the model's phenomenological success with the fM_peak parameter, which corresponds to a resonant effect during atomic recombination, supports the interpretation that effects attributed to dark matter could arise from a temporary phase of baryonic matter.

All **13 parameters** of the GERT were derived from a well-defined thermodynamic narrative. Eleven of them have become "frozen signatures" fixed by the data; the two remaining degrees of freedom, k_{gas} **and** $\log \rho_{\text{gas,start}}$, encapsulate the legitimate uncertainty regarding the future dynamics of the Universe. More importantly, this pruning was born first from physical considerations, later confirmed using information criteria (AIC/BIC/WAIC).

The Gibbs Energy Redistribution Theory did not arise from an effort to fit data but from a conceptual model of the physics of the Universe, idealized from the principles of thermodynamics. The mathematical formalization and subsequent testing against cosmological data robustly corroborated the initial "**Top-Down**" idea. This serves as strong evidence that a thermodynamic approach can indeed be the pathway to the next paradigm of cosmology.

Therefore, GERT represents a viable, testable, and conceptually rich alternative to the standard model. By redefining time as Work and cosmic evolution as a process of energy minimization and attainment of stability with Gibbs = 0, this framework provides a compelling causal narrative for the history of our Universe. More than just a model, the GERT is a compass, offering a new direction for cosmological research and a clear set of targets for fundamental physics seeking to understand the origin of our home. A final epistemological observation deserves explicit statement. Mathematics is applied logic, and philosophical deduction is logic expressed in natural language. When both methods, operating independently and from different starting points, converge on the same conclusion, this convergence is not coincidental — it is the signature of a structure that is real. The connections between GERT and the formal results of Jacobson [26], Bekenstein [64], Hawking [65], and Hartle and Hawking [29] were not constructed after the fact to legitimize the theory. They were discovered — found to already exist, implicit in the logical structure of thermodynamics applied consistently and without approximation to the cosmic scale. Hawking's no-boundary proposal, derived from Euclidean path integrals, and GERT's closed-system postulate, derived from thermodynamic ontology, arrive at the same conclusion by entirely different routes. Jacobson's derivation of Einstein's equations from horizon thermodynamics, and GERT's postulate that General Relativity is an emergent consequence of thermodynamic stabilization, map the same territory in different languages. This pattern of independent convergence — across quantum cosmology, black hole thermodynamics, emergent gravity, and thermodynamic cosmology — is not a collection of analogies. It is triangulation. And triangulation from independent directions is among the strongest forms of evidence available to theoretical physics.

There is a final reflection that this work invites, one that extends beyond cosmology into the nature of knowledge itself. Mathematics is applied logic, and philosophical deduction is logic expressed in natural language. A large language model, when it converges on the same answer through statistical patterns in natural language and through mathematical operations on high-dimensional vectors, is doing precisely what this paper has done: finding the structure that persists when the representation changes but the logic remains consistent. Truth, in this sense, is what survives the translation between languages. The GERT framework emerged from the language of chemistry — Gibbs, Lavoisier, spontaneous reactions — and converged with the language of theoretical physics — Jacobson, Hawking, Bekenstein — and with the language of philosophy of science — Kuhn, emergence, causality. These are not three separate discoveries. They are three dialects of the same logical structure, pointing at the same reality from different angles. This is what interdisciplinarity, at its deepest, means: not the borrowing of tools across fields, but the recognition that truth is the invariant that persists across all representations of it. A theory that can be seen from chemistry, from physics, and from philosophy — and that looks the same from all three — is not merely consistent. It is, in the most fundamental sense, pointing in the right direction.

This convergence did not emerge from within physics. GERT emerged from chemical intuition. This difference in perspective explains why the GERT is able to capture cosmic dynamics so naturally—it treats the Universe as a complex chemical system where:

- Phase transitions occur at critical density/temperature.
- Metastable states evolve with changes in conditions.
- Energy reorganizes among different "bonds" (structures versus expansion).
- Catalysts (such as cohesion) accelerate certain processes.

In this way, we can offer our contribution to the esteemed Universe of Einstein:

- Geometric, where spacetime is a "sheet" that curves.
- Measured with "rulers" (distances, angles, curvatures).
- Static in its mathematical formulation.
- Deterministic in its evolution.

Physicists see geometry and forces—spacetime, fields, particles. Chemists see reactions and phases—transformations, equilibria, catalysis, transitions.

This union of perspectives can describe our Universe in an even deeper way, unveiling another layer of our great cosmic puzzle.

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