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GERT and the Internal Thermodynamic Anatomy of the Relativistic Window—Cohesive and Entropic Peaks in the Gibbs Dance

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Abstract

Background: The first three papers of the Gibbs Energy Redistribution Theory (GERT) programme established the thermo-relativistic ontology of the expanding Universe, bounded the regime of metric legibility by two operational limits—the primordial emergence of the relativistic ruler at α_em = -3.0 $\pm$ 0.1 and its hyperdilute future dissolution at α_crit = 12.88 $\pm$ 0.12—and validated the framework against supernovae, CMB, and BAO data (χ^2_$\nu \approx 0.99$, $H_0 \approx 72.5$ km/s/Mpc). The relativistic window defined by those boundaries spans 15.9 $\pm$ 0.2 decades in the expansion parameter α and has hitherto been treated as a homogeneous interval of effective validity. **Objective:** This paper investigates the internal thermodynamic organization of that window. We argue that the relativistic domain of GERT is not featureless between its boundaries: it possesses an internal anatomy, structured by smooth background transitions and localized episodes of reorganizational thermodynamic Work encoded in the Gaussian peaks of the GERT dynamical functions. **Methods:** Using the fixed parameters of Paper I [1] (log ρ_c = -17.41, f_m,peak = 0.37; log ρ_L2 = -23.93, f_L,peak = 4.62), the late-time boundary from Paper II [2], and the emergence condition $\xi(\alpha$_em) = 1 of Paper III [3], we develop the interpretation of the logistic-Gaussian functional architecture through the lens of macroscopic phase transition theory. We introduce the concept of integrated thermodynamic impulse, compute the derivative structure of the GERT functions, and map each feature of the fitted model onto a specific epoch of cosmic reorganization. **Results:** We identify four major thermodynamic milestones within the relativistic window: (1) the cohesive inauguration at log ρ_c = -17.41, coinciding with recombination understood as a triple transition—chemical, optical, and metric; (2) the liquid stabilization at log ρ_M = -20.30, marking the passage from builder to maintainer; (3) the entropic reversal at log ρ_L2 = -23.93, the concentrated outward Work that transfers thermodynamic primacy from cohesion to expansion; and (4) the long dissolution from entropic trigger through gas-dominated asymptotic future. **Conclusions:** The Gaussian peaks of GERT are not phenomenological fitting artifacts but the exact mathematical forms demanded by macroscopic phase transition theory: the cosmological analogues of specific-heat peaks at critical thresholds. The relativistic window is a finite thermodynamic organism: born by recombination, stabilized by cohesive relaxation, reversed by an entropic surge, and dissolved by gaseous expansion. Relativity, in GERT, has not only a domain of validity, but a thermodynamic biography.

Keywords: GERT; thermodynamic cosmology; Gibbs Dance; cohesive peak; entropic peak; recombination; metric legibility; phase transitions; cosmic acceleration; Hubble tension

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Guidelines for Readers (Roadmap)

This manuscript follows a top-down, logic-first structure. It is the fourth article in a seven-paper sequence of the Gibbs Energy Redistribution Theory (GERT) programme; each article is self-contained, but the sequence is cumulative. For orientation in this Paper IV, the preceding papers are:

- **Paper I** [1] (*Gibbs Energy Redistribution Theory (GERT): A Thermodynamically Motivated Expansion History and the Hubble Tension*) establishes the thermodynamic ontology of GERT, derives its

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effective cosmological equations, and validates the framework against CMB, BAO, and Type Ia supernova background data.

- **Paper II** [2] (*GERT and Black Holes: Macroscopic Phase Transition in the Hyperdilute Universe*) identifies the late-time Hyperdilute boundary at which the relativistic ruler progressively loses operational meaning, defining the post-relativistic validity limit.
- **Paper III** [3] (*The Onset of the Relativistic Ruler: Metric Emergence and the Pre-Relativistic Boundary of the GERT Universe*) determines the early-time emergence boundary of relativistic metric legibility, completing the finite domain map together with Papers I and II [1,2].
- **Paper IV** (this manuscript) interprets the internal thermodynamic anatomy of that finite relativistic window, linking the fitted Gaussian peaks to physically localized reorganizational work.

The references above correspond to the bibliography entries of this manuscript ([1–3]).
For readers primarily focused on verification and reproducibility, the key components are:

- **Conceptual premises and domain boundaries:** Section 2 (Theoretical Framework), including the finite relativistic window, ontological hierarchy, and boundary interpretation from Papers II and III [2,3].
- **Core mathematical architecture:** Sections 3.1–3.3 (Mathematical Foundations and Methodology), including the modified Friedmann structure, logistic background functions, Gaussian response interpretation, and derivative logic.
- **Thermodynamic impulse quantification:** Sections 3.4–3.5, including the integrated impulse derivation ($\mathcal{I}_c$, $\mathcal{I}_l$), amplitude-ratio interpretation, and bridge to the emergence criterion.
- **Internal-stage reconstruction:** Section 4, including the four-stage anatomical sequence (cohesive inauguration, liquid stabilization, entropic reversal, long dissolution) and milestone localization.
- **Model interpretation and falsifiability framing:** Sections 5.1–5.3, including the status of Gaussian peaks as theoretical necessities, programme-level integration (Papers I–III [1–3] and Paper IV), and observational consequences for Paper V.
- **Final synthesis:** Section 6 (Conclusions).
- **Data and reproducibility notes:** post-conclusion sections (Data Availability Statement and related declarations).

Tables and figures are cited in their respective sections; when referring to a specific item in the text, the standard form "Table X" and "Figure X" is used. Minimal reproduction flow is summarized by the derivation chain in Sections 3 and the anatomical consolidation in Sections 4–5.

1. Introduction

With the first three papers of the GERT programme, the architecture of the thermo-relativistic framework has been established in three distinct registers. Paper I [1] introduced the ontological hierarchy of three thermodynamic layers, fitted the effective dynamical functions f_m(x) and f_l(x) to cosmological data, and validated the framework against supernovae [4,5], CMB [6], and BAO [7] with χ^2_$\nu \approx 0.99$ and $H_0 \approx 72.5$ km/s/Mpc [8,9], resolving the Hubble tension without free parameters beyond the initial fit. Paper II [2] bounded the regime from the future, identifying the critical density $\log_{10} \rho$_gr,min = -65.2 ± 0.4 kg m^{-3} at scale factor a_crit = $10^{(12.88\pm0.12)}$ as the hyperdilute dissolution boundary of relativistic metric operationality. Paper III [3] bounded the regime from the past, deriving the emergence criterion $\xi(\alpha) = \lambda$_$\gamma(\alpha)$/d_ph(α) = 1 as the condition under which hydrogen recombination frees photons to carry metric information globally, with emergence localized at α_em = -3.0 ± 0.1 ($z \approx 1090$).

Together, Papers II and III [2,3] define a finite relativistic window spanning 15.9 ± 0.2 decades in the expansion parameter $\alpha \equiv \log_{10}$ a. The question that has not yet been addressed is: what happens inside that window? Is it a thermodynamically homogeneous interval, or does it possess an internal structure?

The present paper argues for the latter. The fixed functional architecture of Paper I [1]—logistic backgrounds combined with localized Gaussian peaks and a terminal gas term—is not merely a convenient parametrization. It is the canonical mathematical form of a thermodynamic system undergoing macroscopic phase transitions. The smooth logistic functions record the background fractional conversion of the cosmic medium between successive eras; the Gaussian peaks record the concentrated thermodynamic Work required at the critical densities where those conversions demand exceptional thermodynamic effort; and the gas term records the terminal tendency that carries the system toward its post-relativistic boundary.

Paper IV is therefore not about redefining the boundaries of the relativistic regime. It is about revealing the internal thermodynamic anatomy of the regime that exists between those boundaries.

2. Theoretical Framework: The Relativistic Window as a Finite Thermodynamic Domain

2.1. The GERT Ontological Hierarchy

The GERT ontological hierarchy divides the history of the Universe into three layers. Layer 1 (the Primordial Cauldron) is the pre-geometric, quantum-thermodynamic substrate in which no stable spacetime metric exists [10]. Layer 3 is the relativistic regime in which General Relativity operates as a valid and globally legible description of spacetime [11,12]. Layer 2 is the transitional quantum-thermodynamic stratum in which Inward and Outward Forces compete and proto-metric fluctuations develop.

Paper III [3] established that the transition from Layer 1 to Layer 3 is not an ontological postulate but an operationally defined crossing: the relativistic ruler comes into existence when, and only when, photons can traverse the full causally connected domain without being suppressed by scattering. The condition $\xi(\alpha\_em) = 1$, with $\xi \equiv \lambda\_\gamma/d\_ph$, is driven by the chemical kinetics of hydrogen recombination. The emergence boundary is not geometrically imposed from above; it is chemically triggered from below.

Paper II [2] established the corresponding far-future boundary at $\alpha\_crit = 12.88 \pm 0.12$, beyond which the photon mean free path becomes cosmologically irrelevant, the relativistic ruler dissolves, and the effective Layer 3 description ceases to be operationally valid. The two boundaries—one in the past governed by recombination, one in the future governed by dilution—define a finite thermodynamic domain spanning 15.9 ± 0.2 decades in α.

2.2. The Gibbs Dance: Two Children of the Same Primordial Enthalpy

Before examining the interior of the relativistic window, it is necessary to understand the ontological engine that produces it. GERT proposes that the entire history of the Universe—from the Primordial Cauldron to the asymptotic gas-dominated future—is the progressive redistribution of a single finite reservoir of binding enthalpy. This redistribution does not proceed uniformly. It manifests through two complementary, symmetrical flows of thermodynamic Work, both born of the same primordial source.

The first flow is the **Inward Force**: the contractile manifestation of enthalpy that curves spacetime upon itself, creates gravitational potential wells, and drives the condensation of energy into matter and structure. This is not a separate force added from outside; it is the enthalpy reservoir acting inward, generating cohesion and the geometry of gravitational attraction. In the language of General Relativity, this flow eventually crystallizes into the smooth Einsteinian metric—but it precedes and produces that metric rather than being governed by it [13,14].

The second flow is the **Outward Force**: the expansive manifestation of the same reservoir, which exerts positive pressure on the fabric of spacetime, driving expansion, increasing entropy, and pushing the cosmic medium toward progressively larger volumes and lower densities. What observational cosmology has historically described as “dark energy” is, in the GERT framework, this Outward Force becoming dominant—not a new substance, but the same enthalpy redistributing itself outward once the inward Work of construction has largely been spent [15].

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These two forces are therefore not rivals of different origin. They are the two children of the same primordial enthalpy. Gravity and entropy, cohesion and expansion, the Inward and Outward modes of Work—all are faces of a single thermodynamic mechanism [1]. The Gibbs Free Energy criterion ($\Delta G < 0$) determines the direction and spontaneity of the redistribution at each moment; the arrow of time is the sequence of thermodynamic Work acts that progressively discharges the Gibbs differential toward $\Delta G \to 0$.

This dual structure is what Paper I named the **Gibbs Dance**: the eternal interplay between the two children of enthalpy, each taking turns as the directive agency of cosmic evolution. The cohesive and entropic peaks of the GERT dynamical functions are not ornamental features—they are the precise moments in the Gibbs Dance where one child must concentrate an exceptional burst of Work to overcome the inertia accumulated by the other. The internal anatomy of the relativistic window is, in its deepest reading, the choreography of this Dance within its finite temporal domain.

2.3. Finiteness as a Physical Claim

This finiteness is physically significant. A regime with well-defined boundaries is not merely a parametric interval; it is a thermodynamic phase. Once a regime has finite boundaries, the natural next question is whether its interior is homogeneous or internally staged. The GERT functional architecture provides a direct answer: the interior is staged, and the staging is mathematically explicit.

The regime bounded by Papers II and III is not simply the interval in which General Relativity happens to work effectively. It is a temporally finite, thermodynamically punctuated order of cosmological organization—a perspective consistent with the thermodynamic understanding of spacetime geometry [13,16] and the entropic interpretation of gravitational dynamics [14,17]. Its birth depends on the chemical kinetics of recombination; its middle life depends on the stabilization of cohesion; its reversal depends on a concentrated entropic trigger; and its demise depends on the progressive rise of the gas regime.

This anatomical view also clarifies the epistemic role of the fitted peaks. The Gaussian structures are not accidental irregularities in an otherwise smooth parametrization. They are the empirical signatures of thermodynamic thresholds independently required by the ontology of GERT. The cohesive peak marks the first threshold at which light becomes both physically free and metrically meaningful; the entropic peak marks the threshold at which constructive expenditure ceases to dominate and expansive expenditure becomes historically directive. Between them lies the stable internal body of the relativistic window. The fit, in this reading, does not manufacture a story after the fact. It reveals the macroscopic traces of the very turning points that the theory says must exist.

3. Methodology and Mathematical Foundations

3.1. Effective Thermodynamic Architecture

The GERT modified Friedmann equation (Paper I [1], Equation (3.3)) takes the form shown in Equation (1):

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

where the control variable is $\log\rho(z) = \log\rho\_m, 0 + 3\log(1+z)$ and $H\_0 = 72.5$ km s^{-1} Mpc^{-1} [1]. The matter-sector dynamical function is:

$$f_M(\log\rho) = f_{M,\text{base}}\Big[1 + f_{M,\text{peak}}\cdot G(\log\rho;\, \log\rho_c,\, 1.0)\Big] \tag{2}$$

$$f_{M,\text{base}} = f_{M,f} + (f_{M,i} - f_{M,f})\cdot L(\log\rho;\, \log\rho_M,\, 1.0) \tag{3}$$

The entropic-sector dynamical function is:

$$f_L(\log\rho) = \big(f_{L,\text{base}} + \text{term}_{\text{gas}}\big)\Big[1 + f_{L,\text{peak}}\cdot G(\log\rho;\, \log\rho_{L2},\, 1.0)\Big] \tag{4}$$

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$$f_{L,\text{base}} = f_{L,m} + (f_{L,i} - f_{L,m}) \cdot L(\log\rho; \log\rho_L, 2.0) \quad (5)$$

$$\text{term}_{\text{gas}} = \begin{cases} k_{\text{gas}}\left[\exp\left(\dfrac{\log\rho_{\text{gas,start}} - \log\rho}{\gamma_{\text{gas}}}\right) - 1\right] & \log\rho < \log\rho_{\text{gas,start}} \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

The two basis functions are given in Equation (7) [1]:

$$L(x; x_0, \delta) = \frac{1}{1 + \exp\left(\dfrac{x - x_0}{\delta}\right)}, \qquad G(x; x_0, \delta) = \exp\left[-\frac{1}{2}\left(\frac{x - x_0}{\delta}\right)^2\right] \quad (7)$$

The fixed parameters from Paper I [1] are summarized in Table 1.
The fixed parameters from Paper I [1] are:

Table 1. Fixed parameters adopted from Paper I [1].

Parameter	Symbol	Value
Cohesive peak position	$\log\rho_c$	-17.41
Cohesive peak amplitude	$f_{m,\text{peak}}$	0.37
Matter transition position	$\log\rho_M$	-20.30
Initial matter factor	$f_{m,i}$	0.7831
Final matter factor	$f_{m,f}$	0.5851
Entropic peak position	$\log\rho_{L2}$	-23.93
Entropic peak amplitude	$f_{L,\text{peak}}$	4.6245
Gas activation threshold	x_{gas}	-26.75

The key structural observation is the asymmetry of the functional roles: logistic functions describe cumulative changes of regime—they saturate, they do not concentrate; Gaussian functions describe localized events—they peak, they do not persist. Paper IV reads that distinction not as a mathematical convenience but as a physical declaration.

3.2. Logistic Backgrounds as Phase Fractions

In classical thermodynamics, the macroscopic shift of a system from one phase to another follows an S-shaped logistic curve governed by statistical distributions (Maxwell-Boltzmann, Fermi-Dirac) over the microscopic constituent population [18,19]. The fraction of a system that has transitioned into the new phase does not evolve linearly; it accelerates exponentially near the critical threshold before saturating as the transition completes.

The logistic components of f_m and f_l in GERT perform precisely this role. They represent the macroscopic phase fraction of the cosmic medium transitioning smoothly between successive thermodynamic eras. The matter-sector logistic, centered at log ρ_M = -20.30 with width δ_m = 1.0 dex, records the completion of the builder-to-maintainer conversion. The entropic-sector logistic, centered at log ρ_l = -25.60 with width δ_l = 2.0 dex, records the progressive transfer of thermodynamic primacy from cohesion to expansion.

The rate of conversion is fastest at the logistic center. The derivative of L with respect to x is given in Equation (8):

$$\frac{dL}{dx} = -\frac{1}{\delta} L(x)\left[1 - L(x)\right] \quad (8)$$

which attains its maximum magnitude of $1/(4\delta)$ at $x = x\_0$. In the GERT parameterization, the matter-sector logistic ($\delta\_m = 1.0$ dex, centered at $\log \rho\_M = -20.30$) reaches a maximum conversion rate of $|dL/dx|\_\max = 0.25$ dex^{-1}, while the broader entropic-sector logistic ($\delta_l = 2.0$ dex, centered at $\log \rho\_l = -25.60$) reaches $|dL/dx|\_\max = 0.125$ dex^{-1}.

3.3. Gaussian Peaks as Thermodynamic Response Functions: A Mathematical Theorem

A central methodological objection often directed at modified cosmological models is the risk of curve-fitting: the introduction of arbitrary mathematical functions merely to match observational data. To secure the ontological claims of GERT against this objection, it is necessary to demonstrate that its Gaussian peaks are not *ad hoc* parametrizations but the required mathematical forms of the physical processes they describe. This can be established as a formal result [18,19].

Theorem (Response Function of Logistic Phase Transitions). Let a physical system undergoing a macroscopic phase transition be described by a state function (phase fraction) $\Phi(x)$ that follows a logistic profile:

$$\Phi(x;\, x_0,\, \delta) = \frac{1}{1 + \exp\!\left(\dfrac{x - x_0}{\delta}\right)}. \tag{9}$$

Then the thermodynamic response function—defined as the sensitivity of the system to perturbations in the control variable, analogous to specific heat capacity $C_p = -T\,\partial^2 G/\partial T^2$—is proportional to $|d\Phi/dx|$, which takes the form:

$$\left|\frac{d\Phi}{dx}\right| = \frac{1}{\delta}\,\Phi(x)\big[1 - \Phi(x)\big]. \tag{10}$$

This function is a symmetric bell curve, maximized at $x = x_0$, with maximum value $1/(4\delta)$ and half-width $\approx 2\delta$. In the limit $\delta \to 0$ (sharp first-order transition), this bell curve converges to a Dirac delta distribution $\delta_D(x - x_0)$. For finite δ (continuous or weakly first-order transition), the bell curve is well approximated by a Gaussian distribution centred at x_0.

The physical consequence of this theorem is decisive. It means that **any** system whose phase fraction follows a logistic profile — which is the universal form dictated by statistical mechanics for macroscopic phase transitions governed by Maxwell–Boltzmann, Fermi–Dirac, or Bose–Einstein distributions—must exhibit a Gaussian-like peak in its thermodynamic response function at the critical threshold x_0. This is not a modelling choice; it is a mathematical necessity.

In thermodynamic systems, response functions—specific heat capacity C_p, magnetic susceptibility χ, isothermal compressibility κ_T—exhibit precisely these localized peaks at the critical point of the transition [18,19]. They are the derivatives of the state functions. The derivative of a logistic sigmoid is a bell-shaped curve. Therefore, statistical mechanics dictates that the thermodynamic response of any system undergoing a macroscopic phase transition must take the form of a localized peak, converging to a Gaussian distribution due to critical fluctuations and the exchange of latent heat.

A global visualization of this result is provided in Figure 1, discussed below.

Figure 1 illustrates this correspondence explicitly. Panels (a) and (b) show $f_M(\log \rho)$ and $f_L(\log \rho)$; panels (c) and (d) show their numerical derivatives $df_M/d\log \rho$ and $df_L/d\log \rho$, with the integrated thermodynamic impulses $\mathcal{I}_c$ and $\mathcal{I}_l$ highlighted as shaded areas. The derivative peaks are precisely co-located with the Gaussian peaks of the parent functions — at $\log \rho_c = -17.41$ in panel (c) and $\log \rho_{L2} = -23.93$ in panel (d). This co-location is the Theorem made visible: the Gaussian fits are exactly the thermodynamic response functions of the logistic backgrounds, not free-floating features.

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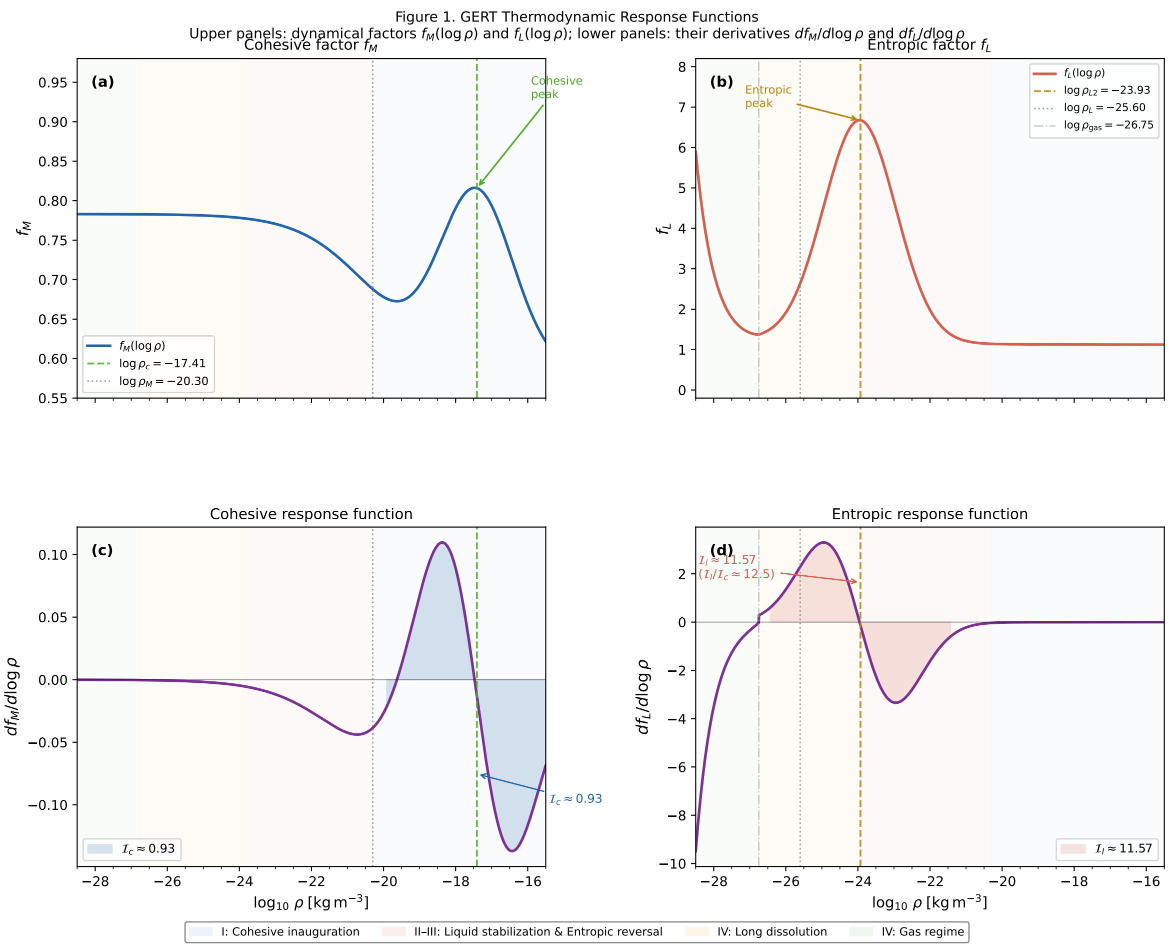

Figure 1. Response functions and thermodynamic impulses in GERT. Panels (a,b) show f_M and f_L; panels (c,d) show their derivatives with shaded integrated impulses.

The Gaussian peaks of GERT are, under this theorem, the cosmological response functions: the specific-heat peaks of the Universe. The Gaussian peaks model the resonant, transient injection or release of concentrated thermodynamic Work—the cosmological latent heat—required to cross the activation barrier of each transition. The centre $x = \mu$ of each Gaussian is the privileged density: the point at which the system's thermodynamic response to forcing is maximal and concentrated. The argument is closed: the fit of Paper I revealed what statistical mechanics mathematically demands.

3.4. Integrated Thermodynamic Impulse

The amplitude of a Gaussian peak measures its instantaneous intensity. Its total thermodynamic weight—the integrated reorganizational strength—is given by the impulse integrals in Equations (11) and (12):

$$\mathcal{I}_c = \int_{-\infty}^{+\infty} f_{m,\text{peak}} \cdot \exp\left[-\frac{(x-\mu_c)^2}{2\sigma_c^2}\right] dx = f_{m,\text{peak}} \cdot \sigma_c \cdot \sqrt{2\pi} \tag{11}$$

$$\mathcal{I}_l = \int_{-\infty}^{+\infty} f_{L,\text{peak}} \cdot \exp\left[-\frac{(x-\mu_{L2})^2}{2\sigma_{L2}^2}\right] dx = f_{L,\text{peak}} \cdot \sigma_{L2} \cdot \sqrt{2\pi} \tag{12}$$

With f_m,peak = 0.37, σ_c = 1.0, f_L,peak = 4.62, σ_L2 = 1.0:

$$\mathcal{I}_c \approx 0.93, \qquad \mathcal{I}_l \approx 11.57, \qquad \frac{\mathcal{I}_l}{\mathcal{I}_c} \approx 12.5 \tag{13}$$

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The ratio $\mathcal{S}\_1/\mathcal{S}\_c \approx 12.5$ quantifies the relative thermodynamic effort of the two major reorganizational events. The entropic surge is twelve and a half times larger in integrated reorganizational strength than the cohesive inauguration.

3.5. Bridge to Paper III [3]: The Cohesive Peak and the Crossing Condition

The mathematical connection between the cohesive peak and the metric emergence event is made explicit by the Paper III [3] emergence criterion [3]. The dimensionless metric legibility parameter is defined in Equation (14):

$$\Xi(\alpha) \equiv \frac{\lambda_\gamma(\alpha)}{d_{\text{ph}}(\alpha)} \tag{14}$$

where the photon mean free path (Paper III [3], Equation (3.1)) is:

$$\lambda_\gamma(\alpha) = \frac{a^3}{n_{b,0}\,\sigma_T\,X_e(\alpha)} \tag{15}$$

with $n\_b, 0 \approx 0.27\ \text{m}^{-3}$, $\sigma\_T = 6.652 \times 10^{-29}\ \text{m}^2$, and $X\_e(\alpha)$ the ionization fraction, and where $d\_\text{ph}(\alpha) = c\,\eta\_\text{GERT}(\alpha)$ is the GERT particle horizon. The emergence boundary is $\Xi(\alpha\_\text{em}) = 1$, yielding $\alpha\_\text{em} = -3.0 \pm 0.1$.

The ionization fraction is controlled by hydrogen recombination, treated in Paper III [3] by two independent methods:

Saha equilibrium [20]—provides an upper bound on the recombination rate via thermodynamic equilibrium:

$$\frac{X_e^2}{1-X_e} = \frac{1}{n_b}\left(\frac{2\pi m_e k_B T}{h^2}\right)^{3/2} \exp\left(-\frac{\chi_H}{k_B T}\right) \tag{16}$$

where $\chi\_H = 13.6$ eV is the ionization energy of hydrogen, predicting a sharp drop of X_e from ~ 1 to $\sim 10^{-4}$ around $\alpha \approx -3.04$ ($z \approx 1100$).

Peebles three-level atom [21]—incorporates the kinetic bottleneck via the rate equation:

$$\frac{dX_e}{dz} = \frac{C_P}{H(1+z)}\left[n_e\,\alpha_B - (1-X_e)\,\beta_B\,e^{-h\nu_{\text{Ly}\alpha}/k_B T}\right] \tag{17}$$

where α_B is the case-B recombination coefficient, β_B is the photoionization rate from $n = 2$, and the Peebles C-factor (typically $C\_P \sim 10^{-2}$ during the transition) accounts for the re-photoionization bottleneck at the $n = 2$ level [21]. This slows recombination significantly relative to Saha and causes the ionization fraction to freeze out at $X\_e \sim 3 \times 10^{-4}$ rather than approaching zero.

The cohesive peak position log ρ_c = -17.41 coincides precisely with the density at which the kinetic drop of X_e drives $\Xi(\alpha)$ across unity. This correspondence is not a coincidence of fitting—the microphysics of quantum chemistry fixes the threshold independently, and GERT records the macroscopic thermodynamic signature of that crossing. The uncertainty ± 0.1 in α_em is entirely dominated by the kinetics of recombination (Saha vs. Peebles brackets), not by free parameters.

4. Results

4.1. Stage I—The Cohesive Peak and the Opening Work of the Relativistic Window

The cohesive peak at log ρ_c = -17.41, amplitude f_m,peak = 0.37, is the first major thermodynamic feature of the relativistic window. Paper I [1] identified it as the "first Work" of cohesion and noted its coincidence with atomic recombination. In the light of Section 3, this coincidence acquires a precise physical meaning.

Recombination, as shown in Paper III [3], is not simply the formation of neutral hydrogen. It is the event at which the ionization fraction drops sharply enough to allow the photon mean free path λ_γ to reach the particle horizon d_ph. This crossing is the condition for global metric legibility.

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Before it, the cosmic medium is opaque and the spacetime metric, though formally definable, cannot be globally transmitted. After it, light traverses the causal domain and the metric becomes operationally readable everywhere.

The macroscopic phase transition from opaque-ionized to transparent-neutral is precisely the kind of event that, by the argument of Section 3, demands a peak in the thermodynamic response function at the critical density. The cohesive peak at log ρ_c = -17.41 is that peak. It is the cosmological specific-heat signature of the transition. It records the enormous thermodynamic effort required to drive the neutral hydrogen synthesis across the activation barrier—the concentrated cohesive Work that simultaneously achieves chemical binding, optical release, and metric inauguration.

The peak is therefore not an artifact of the fitting procedure. It is the empirical signature of a theoretical necessity: the fit reveals what the thermodynamic ontology of GERT demands must be present. The opening of the relativistic window requires a localized burst of cohesive Work, and the Gaussian peak is the only functional form that can represent such a burst without distorting the smooth logistic backgrounds that describe the broader transition.

In this sense, the cohesive peak is the first thermodynamic articulation of the relativistic domain. The regime does not begin with a passive background; it begins with an act.

4.2. Recombination as a Triple Transition: Chemical, Optical, and Metric

The singularity of recombination in the GERT framework lies in the inseparability of three processes that occur as a single causally chained event.

The first layer is **chemical**. The cosmic medium at z 1100 is an ionized plasma in which baryonic matter remains dissociated into protons and electrons. As temperature falls, bound states become thermodynamically favorable and X_e drops sharply. The kinetics of hydrogen binding—not any geometric condition—is the control parameter that initiates the entire transition. The first threshold of relativistic readability is triggered from matter kinetics upward, not imposed from geometry downward.

The second layer is **optical**. In the ionized plasma, photons scatter repeatedly off free electrons with a mean free path far smaller than the particle horizon [22]. Under those conditions, light is a local carrier of energy but not a global carrier of metric information. Recombination collapses the scattering opacity by many orders of magnitude, releasing the photon mean free path and allowing radiation to decouple [20,21]. The cosmic microwave background, in the GERT reading, is not merely a relic of hot plasma [6]; it is the first globally transmitted metric map—the first moment in which the state of spacetime could be read at causal distances.

The third layer is **metric**. The emergence criterion $\xi(\alpha$_em$) = 1$ marks the threshold at which spacetime becomes globally legible. Geometry is no longer merely present at every point; it becomes transmissible across the full causal domain. The relativistic ruler comes into operation only because the optical medium ceases to suppress it.

These three layers are causally chained, not parallel. Chemical neutralization reduces the free-electron population; reduced scattering releases the photons; released photons make metric information globally communicable. The logical structure is:

$$\text{Chemistry} \longrightarrow \text{Optics} \longrightarrow \text{Metric legibility} \tag{18}$$

Recombination is therefore the first moment in cosmic history when matter, radiation, and geometry enter into an operationally aligned state. The cohesive peak is the thermodynamic monument to that triple inauguration. It marks the concentrated cohesive Work through which the cosmic medium passes from an ionized, opaque, and unreadable state into a neutral, transparent, and metrically legible one.

Recombination is not only the release of relic radiation. It is the first successful alignment of thermodynamics and metric structure in the history of the observable Universe. Its singularity lies not in any one of its aspects taken separately, but in the fact that all three occur together and reinforce one another.

4.3. Stage II—From Builder to Maintainer: The Liquid Stabilization of the Window's Interior

The opening Work of recombination cannot be the permanent operating mode of the relativistic window. A regime that required a burst of activation energy to begin cannot sustain that intensity indefinitely. At log ρ_M = -20.30, the cohesive factor f_m undergoes a logistic descent from f_m,i = 0.7831 to f_m,f = 0.5851.

In the language of macroscopic phase transition theory, this logistic step represents the completion of a major phase fraction: the cosmic medium has largely accomplished the conversion from its high-cohesion inaugural state to a lower-cohesion sustaining state. The intense thermodynamic effort of recombination—the concentrated Work of neutral hydrogen synthesis, optical release, and metric inauguration—has been spent. What follows is not the same kind of activation; it is the durable interior of a regime in which structures can form, persist, and grow without requiring a permanent pulse of high-effort cohesion.

Paper I [1] described this transition as the passage from "builder" to "maintainer." In the thermodynamic anatomy proposed here, this is the second milestone of the relativistic window: the liquid stabilization. The Universe leaves its high-activation inauguration phase and enters a metastable constructive interior in which galaxies, clusters, and the cosmic web can assemble under sustainable cohesion.

The terminology of "liquid" is not merely metaphorical. It reflects the thermodynamic structure: just as a liquid is a stable, cohesive phase that admits internal reorganization without requiring the energy input of the initial crystallization event, the post-recombination constructive era of the Universe is a regime in which cohesive organization persists at reduced thermodynamic cost. It is the epoch of structured history: the phase in which the Inward Force maintains, rather than builds, the fundamental scales of cosmic organization.

This stabilization has a further consequence: it establishes the conditions under which the relativistic window can exist as an extended thermodynamic domain rather than a brief transitional episode. The peak opens the possibility of metric readability; the liquid transition stabilizes the conditions under which readable structure can actually grow and persist.

The liquid era does not end abruptly. It concludes only when a new reorganizational event, of opposite character, concentrates enough outward Work to reverse the historical primacy of cohesion.

4.4. Stage III—The Entropic Peak and the Reversal of Constructive Primacy

The entropic peak at log ρ_L2 = -23.93, amplitude f_L,peak = 4.62 ($\mathcal{S}$_l ≈ 11.57, ratio ≈ 12.5 $\mathcal{S}$_c), is the second major thermodynamic event of the relativistic window and the pivot of the Gibbs Dance.

Within the framework of Section 3, this Gaussian feature is not a smooth background trend or a passive late-time effect. It is a concentrated burst of entropic Work—what Paper I [1] called the "Entropic Surge." Just as the cohesive peak represented the first act of localized inward Work required to overcome the activation barrier of recombination, the entropic peak represents the localized outward Work required to overcome the inertial ballast of the entire constructive era. The liquid stabilization phase—billions of years of galaxy formation, cluster assembly, and cosmic web growth—has accumulated an enormous thermodynamic inertia. The entropic peak is the event in which enough outward Work concentrates to overcome that inertia.

This event must be carefully distinguished from the smooth late-time acceleration that is observationally familiar. The GERT entropic sector is a composite: a background logistic transition centered at log ρ_l = -25.60, a Gaussian peak at log ρ_L2 = -23.93, and a gas activation term near x_gas = -26.75. The observational era of cosmic acceleration—the smooth transition observed in supernova data [4,5]—corresponds to the broader logistic background, not to the peak itself. The peak occurs at higher density, earlier in cosmic time, and plays a different and more fundamental role: it is the thermodynamic decision point at which the reversal becomes inevitable.

In the language of thermodynamic anatomy, the entropic peak performs for the expansive regime what the cohesive peak performed for the readable regime at recombination: it concentrates Work at a

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privileged threshold. But whereas the cohesive peak synchronizes chemistry, transparency, and metric readability into a constructive opening, the entropic peak concentrates outward Work strongly enough to terminate the dominance of the constructive regime. It is the point at which the historical tendency changes sign.

The structural counterpart of the cohesive peak is therefore the entropic peak, but with opposite orientation:

$$\text{Cohesive peak: } \mu_c = -17.41, \quad \mathcal{I}_c \approx 0.93 \quad \text{(inward, opening)} \tag{19}$$

$$\text{Entropic peak: } \mu_{L2} = -23.93, \quad \mathcal{I}_l \approx 11.57 \quad \text{(outward, reversing)} \tag{20}$$

Their symmetry is structural, not semantic. Both are Gaussian events at critical densities; both represent concentrated thermodynamic effort at activation thresholds; both change the operating state of the cosmic medium irreversibly. But their orientations are opposite, and their roles in the thermodynamic biography of the window are complementary: one opens the constructive life of the regime; the other initiates its exit from constructive primacy.

The acceleration observed later is not an independent phenomenon. It is the historical unfolding of a reversal whose thermodynamic decision was already taken at the entropic peak. The constructive era does not merely fade by exhaustion; it is actively reversed. The entropic peak is the event in which that reversal first takes thermodynamic command.

4.5. Stage IV—The Long Dissolution: From Entropic Trigger to Gas Dominance

The entropic peak does not terminate the constructive era by instantaneous replacement. Its function is to initiate a long dissolution. Once the reversal has been thermodynamically triggered, the Universe enters a staged late-time evolution governed by three successive contributions: the Gaussian entropic trigger, the smooth acceleration transition centered at log ρ_l = -25.60, and the gas regime activating near x_gas = -26.75.

The gas term in Paper I [1] is defined as a component that activates only below a critical threshold and then grows exponentially as density continues to decrease. Its functional form was not chosen merely for numerical performance; it reflects the physics of dilute-medium phase change, where activation is smooth but non-trivial rather than discontinuous. This already signals that the late Universe should not be interpreted as a static dark-energy plateau [15]. The cosmological constant, even if empirically useful, represents a frozen proxy for what GERT identifies as a dynamically evolving entropic sector [1]. It is a genuine phase progression toward a new thermodynamic regime.

Paper II [2] confirmed that this is not a phenomenological extrapolation but the asymptotic mathematical truth of the GERT equations. In the limit a $\rightarrow \infty$, radiation vanishes, matter vanishes, the Gaussian peaks vanish away from their centers, and the base entropic term saturates. The gas term alone continues to grow. It is therefore the sole diverging contribution and eventually dominates all other components by an exponentially increasing margin. The far future of the GERT Universe is governed not by a frozen cosmological constant but by an expanding thermodynamic gas sector that takes over the late-time dynamics completely.

The current epoch occupies a specific location within this long dissolution. The present Universe lies on the late side of the liquid-to-gas transition, with the entropic component already increasing and the gas regime beginning to activate near z $\approx$ 0.03. GERT therefore places us not at the onset of reversal—that decision was taken at the entropic peak—but in the early portion of its long aftermath. The constructive era has been thermodynamically superseded, yet the full gas-dominated destiny lies ahead. This makes the present epoch neither a stable climax nor an abrupt rupture, but a transitional zone within a much longer dissolutive arc.

The phrase "long dissolution" is precise. What dissolves is not simply the spatial distribution of matter, but the constructive thermodynamic interior of the relativistic window. During the builder and maintainer stages, cohesion remained historically directive even when partially relaxed. After the entropic trigger, this ceases to be true. The medium does not instantly lose all organization—structures formed under the earlier regime persist—yet the dominant thermodynamic arrow has turned outward.

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The Universe enters a phase in which readable metric order still exists but increasingly under conditions of dispersal rather than construction. The relativistic window is progressively thinned from within.

To understand why the late acceleration does not require a new energy source, a physical analogy is instructive. Consider a gas expanding inside a container whose walls are not rigid but elastic—walls that offer resistance proportional to their structural tension. In the early Universe, the "walls" of the cosmic metric are thick: the Inward Force maintains a strong geometric tension that resists expansive flow. Each unit of expansive Work must overcome this tension, making expansion energetically costly. The cosmic medium expends most of its entropic budget against its own gravitational self-resistance.

As the Universe expands and dilutes, however, these metric walls become progressively thinner. The geometric tension that the Inward Force maintains weakens as the density drops below the critical thresholds of the constructive era. By the time the gas regime activates near $\log \rho_{\text{gas}} = -26.75$, the walls have thinned to the point where each unit of entropic Work can drive a disproportionately large expansion. Acceleration is not the result of new energy being injected into the system—it is the result of the same entropic Work meeting progressively less resistance. The expansion does not accelerate because something pushes harder; it accelerates because the walls that once resisted have thinned.

This is why the GERT framework dispenses with dark energy as an ontological substance. There is no new ingredient. There is only the same Outward Force — always present as the second child of enthalpy—operating against a medium whose cohesive resistance has been progressively exhausted by the Work already expended in building the cosmic web, assembling galaxies, and maintaining the constructive era. The thinning of the walls is the dissolution of the constructive interior of the relativistic window, measured from within.

5. Discussion

5.1. The Thermodynamic Anatomy of the Relativistic Window

With the four stages established, the relativistic regime defined by GERT can be described as a thermodynamically articulated domain with a complete internal anatomy. The four major milestones constitute a complete life cycle: This organization is summarized in Table 2.

Stage I—Cohesive Inauguration (log ρ_c = -17.41): A localized Gaussian peak of integrated impulse $\mathcal{S}$_c ≈ 0.93 marks the concentrated inward Work of atomic recombination, simultaneously achieving chemical binding, optical release, and metric readability. The relativistic window does not begin passively; it begins with an act.

Stage II—Liquid Stabilization (log ρ_M = -20.30): A logistic descent of the cohesive factor from f_m,i = 0.783 to f_m,f = 0.585 marks the relaxation from activation-level cohesion to sustainable cohesion. The durable constructive interior of the window opens: this is the era in which readable structure can actually grow.

Stage III—Entropic Reversal (log ρ_L2 = -23.93): A localized Gaussian peak of integrated impulse $\mathcal{S}$_l ≈ 11.57—twelve and a half times larger than the cohesive inauguration—marks the concentrated outward Work that terminates constructive primacy and transfers thermodynamic command to expansion. The historical tendency changes sign.

Stage IV—Long Dissolution (log ρ_l = -25.60 through x_gas = -26.75): An extended process in which the smooth acceleration transition develops the reversal decided at Stage III, and the gas regime progressively consummates it. The relativistic window is not destroyed at once; it is thinned from within until the post-relativistic boundary of Paper II [2] is reached.

This sequence is not merely historical ordering. It is the internal logic by which the relativistic regime exists as a finite thermodynamic phase. The domain bounded by Papers II and III [2,3] is not simply the interval in which General Relativity happens to work effectively. It is a temporally finite, thermodynamically punctuated order of cosmological organization.

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Table 2. Thermodynamic anatomy of the relativistic window.

Stage	Density / α	Physical Content	Character of Dance
I—Cohesive Inauguration	$\log\rho \approx -17.41$, $f_{M,\text{peak}} = 0.37$; $\alpha_{\text{em}} = -3.0 \pm 0.1$	Triple transition: chemical + optical + metric	Concentrated inward Work (specific-heat maximum)
II—Liquid Stabilization	$\log\rho : -17$ to -24	Structure formation; cosmic web; stellar generations	Sustained inward action; slow outward ascent
III—Entropic Reversal	$\log\rho \approx -23.93$, $f_{L,\text{peak}} = 4.62$	Constructive era closes; expansion primacy established	Concentrated outward Work (specific-heat maximum)
IV—Long Dissolution	$\log\rho \approx -24$ to $\alpha_{\text{crit}} = 12.88$	Smooth acceleration; gas dominance; metric dissolution	Free outward expansion; thinning walls

5.2. The Three-Line Convergence: Why the Peaks Are Theoretical Necessities

The epistemic status of the Gaussian peaks requires a sharper statement than simply noting that they fit the data well. A three-line convergence argument establishes that the peaks are theoretical necessities, not fitting artifacts.

The **first line is ontological**. The GERT framework, developed in Paper I [1], posits that the Universe evolves through discrete macroscopic phase transitions driven by the progressive redistribution of the Primordial Enthalpic Reservoir. A theory that describes the Universe as a thermodynamic system undergoing phase transitions must, by its own internal logic, predict episodes where concentrated thermodynamic Work is required at critical thresholds. The ontology demands that such episodes exist. It does not merely permit them; it requires them. If the GERT framework is internally consistent—and its confrontation with CMB, BAO, and supernova data with $\chi^2_\nu \approx 0.99$ provides strong evidence that it is—then the peaks must be present independently of whether the fitting procedure finds them.

The **second line is mathematical**. The Theorem of Section shows that any system whose phase fraction follows a logistic profile must exhibit a Gaussian-like peak in its thermodynamic response function at the critical density. The logistic form of the GERT backgrounds is not a free choice—it is the canonical mathematical form dictated by statistical mechanics for macroscopic phase transitions. Therefore, as a matter of pure mathematics, independently of any cosmological data, the Gaussian peaks are the derivatives of the logistic backgrounds and must appear at their steepest points. The mathematics does not merely allow the peaks; it requires them.

The **third line is empirical**. The fitting procedure of Paper I [1]—conducted against independent cosmological datasets (CMB shift parameters [6], BAO distance measurements [7], and Type Ia supernovae [4,5]) — recovered localized Gaussian amplifications at exactly the epochs where the ontological and mathematical arguments independently predict they must be. The cohesive peak at $\log\rho_c = -17.41$ coincides with recombination, which the ontology identifies as the chemical-optical-metric triple transition. The entropic peak at $\log\rho_{L2} = -23.93$ coincides with the reversal of constructive primacy, which the ontology identifies as the thermodynamic decision point of cosmic acceleration. The empirical fit does not manufacture these coincidences; it confirms what the theory already required.

The convergence of these three independent lines—ontological demand, mathematical proof, and empirical confirmation—constitutes a particularly strong form of scientific evidence. Triangulation from independent directions is among the strongest forms of support available to theoretical physics [13,14]; it is precisely this structure that distinguishes a theoretically grounded result from a phenomenological fit. In the GERT framework, the Gaussian peaks occupy exactly this triangulated position. They are not chosen because they happen to work. They are the unique form that the theory's own ontology demands, that mathematics proves must appear, and that the data independently confirms.

5.3. Position in the GERT Programme

Once the relativistic domain is understood anatomically, the programme becomes more than a set of separate boundary results. Paper I [1] describes the operating body of the regime and reveals its hidden punctuations. Paper III [3] explains how that body becomes readable, by the recombinational release of metric information. Paper II [2] explains how it eventually loses its operational basis, when the photon ceases to function as a reliable relativistic ruler in the hyperdilute future. Paper IV occupies the missing conceptual position: it narrates the internal life of that body, from its cohesive opening to its entropic inversion and long thermodynamic decline.

The relationship between the four papers is therefore not merely sequential. It is anatomical: Paper I [1] exposes the skeleton of the model; Papers II and III [2,3] define the skin of its boundaries; Paper IV describes the organs and their life cycle. Together, they constitute a complete thermodynamic portrait of the relativistic window—not as a static framework of calculation, but as a dynamic, finite, internally staged phase in the thermodynamic history of the Universe.

This anatomical view has consequences for Paper V and beyond. Once the internal life cycle of the relativistic window is understood—its opening act, its stable constructive middle, its entropic reversal, and its long dissolution—the question naturally arises: what are the observational signatures of these thermodynamic milestones? The Gaussian peaks leave marks: on the gravitational wave background, on the distribution of large-scale structure [23], on the thermodynamic footprint of the entropic trigger in the cosmic acceleration signal. The long-term perspective on cosmic evolution implied here is consonant with, though distinct from, conformal cyclic cosmology [24] and holographic approaches to spacetime structure and entropy [25]. The anatomy of Paper IV is the map that guides the observational programme of Paper V.

6. Conclusions

In this paper, we argued that the relativistic domain of GERT is not thermodynamically uniform. Once the emergence and dissolution boundaries established in Papers III and II [2,3] are taken seriously, the interval between them must be understood not as a featureless regime of effective validity, but as an internally organized thermodynamic window. The central claim developed here is that this window possesses an anatomy: it is opened by a localized cohesive Work, stabilized by a lower-effort constructive regime, reversed by a localized entropic Work, and progressively dissolved through a long gas-dominated expansive trajectory.

The first major conclusion is that the cohesive peak identified in Paper I [1] should be read as more than a phenomenological fitting feature. In light of Paper III [3], its coincidence with recombination acquires a deeper meaning. Recombination is not merely the formation of neutral hydrogen, but the triple transition through which chemistry enables optical release and optical release enables metric legibility. The cohesive peak is therefore the empirical thermodynamic signature of the first localized Work by which neutral matter, liberated light, and a globally readable metric order emerge together. The peak is the empirical signature of a theoretical necessity rather than an ad hoc adjustment.

The second conclusion is that the post-recombination history of the relativistic window contains a genuine internal life. After the opening Work, the Universe relaxes from builder to maintainer, entering the liquid regime in which structure can persist under sustainable cohesion. Much later, the entropic peak breaks the historical primacy of constructive organization and initiates the reversal toward expansion-dominated evolution. That reversal does not end the story abruptly; it unfolds as a long dissolution, first through the smooth acceleration transition and ultimately through the gas regime that Paper II [2] showed to dominate the asymptotic future. The relativistic window is thus neither born nor terminated instantaneously. It has a thermodynamic life cycle.

The third conclusion is epistemic. The Gaussian peaks of GERT should not be treated as arbitrary irregularities added to a smooth background model. Their role is stronger: they function as empirical markers of privileged reorganizational thresholds independently required by the ontology of the framework. Smooth logistic transitions describe the large-scale drift of phases; Gaussian peaks identify

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concentrated acts of thermodynamic Work. The fit therefore does not fabricate the narrative after the fact. It reveals, in effective dynamical form, the macroscopic traces of the turning points that the theory itself anticipates.

With this, Paper IV completes a missing conceptual layer in the GERT programme. Paper I [1] introduced the thermo-relativistic ontology and exposed the fitted dynamical structure of the model. Paper III [3] established the opening boundary of metric readability. Paper II [2] established the future boundary of its dissolution. The present paper shows that, between those two limits, the relativistic regime has a finite but structured internal existence. It is not simply a window where relativity works; it is a thermodynamic order with birth, stabilization, reversal, and decline.

We therefore propose that the relativistic window should be understood as a finite thermodynamic organism of cosmic history: born by recombination, stabilized by cohesive relaxation, reversed by an entropic surge, and dissolved by gaseous expansion. In GERT, the relativistic regime is not merely a framework of description; it is a thermodynamically bounded phase in the history of the Universe.

Relativity, in this view, has not only a domain of validity. It has a thermodynamic biography.

7. Availability License

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