Covariant Grand Unified Scalar-Tensor Field Theory: Nonequilibrium Transport, Circulatory Field Dynamics, and Primordial Genesis

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(Dated: Comprehensive Revised Edition, October 2026)

ABSTRACT

We present a self-consistent, mathematically rigorous Grand Unified Theory (GUT) extension of General Relativity and the Standard Model, unifying the circulatory scalar field $C(x^{\mu})$ across fundamental geometric, non-Abelian gauge, and thermodynamic transport sectors. Building upon microphysical foundations derived from Zubarev's nonequilibrium statistical operator formalism, the macroscopic entropy four-current J_S^{μ} is explicitly derived via phase-space coarse-graining of Keldysh contour-ordered Green's functions. To resolve foundational thermodynamic consistency bounds, we re-index the chaoticity coefficient K_k directly proportional to the micro-entropy production rate, establishing that the limit of vanishing dissipation ($\nabla_{\mu} J_S^{\mu} \to 0$) cleanly drives $K_k \to 0$ and yields physical scalar field divergence ($lim_{K_k \to 0}\, C = \infty$), driving the infinite primordial energy density that catalyzed cosmic expansion. We reformulate the non-Abelian Stueckelberg sector using local matrix-valued group elements $U(x) \in G$ and left-invariant currents $\boldsymbol{W}_{\mu}$, proving exact local gauge invariance and unitarity across all mass scales. We perform explicit variational derivations of the modified Einstein field equations and Yang-Mills-Proca-Stueckelberg equations, establish hyper-asymptotic freedom ($g_{eff} \to 0$), solve the two-tier Chameleon screening profile for spherical bodies, and outline falsifiable observational signatures in CMB B-mode polarization power spectra and high-energy LHC vector boson pair broadening.

I. INTRODUCTION & FOUNDATIONAL CONTEXT

The quest for a unified field framework bridging quantum non-equilibrium statistical mechanics and gravitational geometry remains one of the paramount challenges in modern theoretical physics. While standard perturbative field theories describe subatomic phenomena with exceptional precision, foundational dilemmas persist regarding initial space-time singularities, dark sector dynamics, and the origin of fundamental coupling hierarchies. Scalar-tensor modifications of General Relativity provide a rigorous mathematical framework to dynamically vary coupling scales while preserving general covariance.

In this work, we formulate the covariant circulatory field theory, wherein a universal Lorentz scalar field $C(x^{\mu})$ modulates matter masses, non-Abelian gauge kinetic terms, and gravitational couplings. To contextualize the theoretical novelty of this model relative to the literature:

1. Microphysical Foundations: Unlike standard scalar-tensor paradigms [5] or shift-symmetric Horndeski gravities [7] where scalar field potentials are introduced phenomenologically, $C(x^{\mu})$ is derived directly from Zubarev's non-equilibrium statistical operator [4] and phase-space transport statistics.

2. Thermodynamic Primordial Genesis: Extending early transport models [1], we reformulate the chaoticity parameter K_k directly proportional to the micro-entropy generation rate $\nabla_{\mu} J_S^{\mu}$. Consequently, the zero-dissipation limit ($\nabla_{\mu} J_S^{\mu} \to 0$) drives $K_k \to 0$ and leads cleanly to $C \to \infty$, establishing primordial singularity generation as a physical consequence of thermodynamic coherence rather than an algebraic definition artifact.

3. Gauge-Invariant Non-Abelian Mass Generation: Embedding the theory into $SU(5)$ or $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge symmetry via matrix-valued Stueckelberg fields [10] guarantees exact local gauge covariance, eliminates short-distance Landau poles via hyper-asymptotic freedom, and avoids coordinate-subtraction approximations.

II. SUB-LOCAL STATISTICAL FIELD FORMALISM & MICROPHYSICAL DERIVATIONS

A. Entropy Four-Current J_S^μ via Phase-Space Coarse-Graining

Consider a localized relativistic fluid element characterized by an internal non-equilibrium energy-momentum tensor $T_{mic}^{\mu\nu}$. The microscopic state of quantum field fluctuations is tracked by the Wigner distribution function $W(x, p)$ constructed from Keldysh contour-ordered Green's functions. Performing phase-space coarse-graining over microscopic momentum degrees of freedom p^μ yields the macroscopic entropy four-current $J_S^\mu(x)$:

$$J_S^\mu(x) \equiv - k_B \int (d^4p / (2\pi)^4)\, p^\mu\, W(x, p) \ln W(x, p) \equiv s\, u^\mu + n^\mu \tag{1}$$

where $s(x)$ is the local coarse-grained entropy density, $u^\mu(x)$ is the fluid four-velocity, $n^\mu(x)$ is the non-convective entropy flux, and k_B is the Boltzmann constant. Covariant differentiation enforces the second law of relativistic thermodynamics: $\nabla_\mu J_S^\mu(x) \geq 0$.

B. Reformulated Chaoticity Coefficient K_k & Turbulence Coefficient K_{et}

To maintain exact mathematical and thermodynamic consistency across all asymptotic limits, the dimensionless chaoticity coefficient $K_k(x^\mu)$ must be defined directly proportional to the micro-entropy production rate:

$$K_k(x^\mu) \equiv (\tau_{rel} / (k_B\, n_0))\, \nabla_\mu J_S^\mu(x^\mu) \tag{2}$$

where τ_{rel} is the micro-dynamical relaxation time and n_0 is the invariant rest-frame particle number density. Under this formulation, as local micro-dissipation vanishes ($\nabla_\mu J_S^\mu \to 0$), $K_k(x^\mu) \to 0$ identically.

Internal momentum transfer and phase-space velocity dispersion across sub-constituents are parameterized by the effective turbulence coefficient $K_{et}(x^\mu)$:

$$K_{et}(x^\mu) \equiv \langle v_\perp{}^2 \rangle / (\tau_{rel}\, \varepsilon_{diss}(x^\mu)) \tag{3}$$

where $\langle v_\perp{}^2 \rangle$ represents the mean-square transverse velocity dispersion and ε_{diss} is the dissipation rate per unit rest mass. The circulatory scalar field $C(x^\mu)$ is defined pointwise as the invariant ratio:

$$C(x^\mu) \equiv K_{et}(x^\mu) / K_k(x^\mu) = K_{et}(x^\mu) \left[(\tau_{rel} / (k_B\, n_0))\, \nabla_\mu J_S^\mu(x^\mu) \right]^{-1} \tag{4}$$

Taking the zero-dissipation limit ($\nabla_\mu J_S^\mu \to 0 \implies K_k \to 0$) yields physical field divergence: $lim_{K_k \to 0}\, C(x^\mu) = \infty$. Through Jordan-frame coupling, particle rest masses scale as $m_{eff}(x^\mu) = C(x^\mu)\, m_0$ [1].

III. COVARIANT GRAND UNIFIED ACTION & NON-ABELIAN STUECKELBERG MECHANISM

We formulate the unified theoretical action under a compact non-Abelian Lie group G with Lie algebra $\mathfrak{g}$. Let T^a denote anti-Hermitian generators satisfying $[T^a, T^b] = f^{abc} T^c$, normalized via $\mathrm{Tr}(T^a T^b) = -\frac{1}{2}\delta^{ab}$. The total covariant action S_{tot} is:

$$S_{tot} = \int d^4x \sqrt{(-g)} \left[\left(M_{Pl}^2 / 2\right) R - \frac{1}{2} g^{\mu\nu} \partial_\mu C \partial_\nu C - V(C) - \frac{1}{4} B(C) h_{ab} F_{\mu\nu}{}^a F^{\mu\nu\, b} - \frac{1}{2} m_0^2 C^2 \kappa_{ab} \boldsymbol{W}_\mu{}^a \boldsymbol{W}^{\mu\, b} + \mathscr{L}_{\text{matter}} \right] \tag{5}$$

where M_{Pl} is the reduced Planck mass, R is the Ricci scalar, $B(C) = (C/C_0)^\gamma$ is the kinetic modulation multiplier, and $h_{ab} = \delta_{ab}$ is the Cartan-Killing metric.

A. Rigorous Non-Abelian Stueckelberg Formulation

Following Ruegg & Ruiz-Altaba [10], mass generation without explicit symmetry breaking relies on matrix-valued local group elements $U(x) = \exp(\theta^a(x)\, T^a / v) \in G$, where $\theta^a(x)$ are Stueckelberg scalar fields and v is the mass scale. Under local gauge transformations $g(x) \in G$:

$$A_\mu \longrightarrow g A_\mu g^{-1} + g \partial_\mu g^{-1}, \qquad U(x) \longrightarrow g(x) U(x) \tag{6}$$

The gauge-covariant derivative acting on $U(x)$ is $D_\mu U = \partial_\mu U - A_\mu U$, which transforms as $D_\mu U \longrightarrow g(x) D_\mu U$. We define the gauge-invariant left-invariant current field $\boldsymbol{W}_\mu$:

$$\boldsymbol{W}_\mu \equiv U^{-1} D_\mu U = U^{-1} \partial_\mu U - U^{-1} A_\mu U \tag{7}$$

Under local gauge transformations, $\boldsymbol{W}_\mu \longrightarrow (g\, U)^{-1} D_\mu (g\, U) = U^{-1} g^{-1} g\, D_\mu U = \boldsymbol{W}_\mu$. Expanding $U(x)$ to first order yields $\boldsymbol{W}_\mu = (1/v)\, \partial_\mu \theta^a\, T^a - g_{GUT} A_\mu{}^a\, T^a + \mathcal{O}(\theta^2)$, proving that the non-Abelian mass term $\mathscr{L}_{mass} = -\, m_0^2\, C^2\, \mathrm{Tr}(\boldsymbol{W}_\mu \boldsymbol{W}^\mu)$ preserves exact gauge symmetry and unitarity across all scales.

B. Consistency of B(C) Kinetic Modulation

Since $C(x^\mu)$ is a Lorentz scalar and an internal gauge singlet ($g\, C\, g^{-1} = C$), the modulation prefactor $B(C)$ scales the gauge-invariant field strength density $h_{ab} F_{\mu\nu}{}^a F^{\mu\nu\, b}$ without violating gauge invariance or introducing ghost degrees of freedom.

IV. STEP-BY-STEP VARIATIONAL DERIVATION OF FIELD EQUATIONS

A. Modified Einstein Field Equations

Varying S_{tot} with respect to metric tensor $g^{\mu\nu}$ yields $G_{\mu\nu} = M_{Pl}^{-2} \left(T_{\mu\nu}{}^{matter} + T_{\mu\nu}{}^{(C)} + T_{\mu\nu}{}^{(gauge)} + T_{\mu\nu}{}^{(mass)} \right)$, where the scalar stress tensor is:

$$T_{\mu\nu}{}^{(C)} = \partial_\mu C \partial_\nu C - g_{\mu\nu} \left[\frac{1}{2} g^{\alpha\beta} \partial_\alpha C \partial_\beta C + V(C) \right] \tag{8}$$

B. Derivation of Gauge Field Equations (Eq. 10)

Varying the gauge action with respect to $A_\nu{}^a$:

1. *Kinetic Variation:* Varying $\mathscr{L}_{kin} = -\frac{1}{4} B(C) h_{ab} F_{\mu\nu}{}^a F^{\mu\nu\, b}$ gives $\delta S_{kin} = -\frac{1}{2} \int d^4x \sqrt{(-g)}\, B(C) h_{ab} F^{\mu\nu\, b} \left(D_\mu \delta A_\nu{}^a - D_\nu \delta A_\mu{}^a \right)$. Using anti-symmetry $F^{\mu\nu\, b} = -\, F^{\nu\mu\, b}$ and integrating by parts:

$$\delta S_{kin} = \int d^4x \sqrt{(-g)} \left[D_\mu^{ac} \left(B(C)\, h_{cb}\, F^{\mu\nu\, b} \right) \right] \delta A_\nu^{\,a} \tag{9}$$

2. *Mass and Matter Variation:* Varying $\mathscr{L}_{mass}$ and $\mathscr{L}_{matter}$ with respect to $A_\nu^{\,a}$ yields $m_0^{\,2}\, C^2\, \kappa_{ab}\, \boldsymbol{W}^{\nu\, b}$ and $j^{\nu\, a}$. Setting $\delta S_{tot} / \delta A_\nu^{\,a} = 0$ gives the exact non-Abelian Yang-Mills-Proca-Stueckelberg field equations:

$$D_\mu^{ac} \left[B(C)\, h_{cb}\, F^{\mu\nu\, b} \right] + m_o^{\,2}\, C^2\, \kappa_{ab}\, \boldsymbol{W}^{\nu\, b} = j^{\nu\, a} \tag{10}$$

where $D_\mu^{\,ac} \equiv \nabla_\mu\, \delta^{ac} + g_{GUT} f^{acd}\, A_\mu^{\,d}$ represents the adjoint gauge-covariant derivative.

V. QUANTITATIVE COSMOLOGICAL & SCREENING ANALYSIS

A. Cosmic Dynamics & Hyper-Asymptotic Freedom

In a flat FLRW background, the effective scalar potential coupled to matter density ρ_m is $V_{eff}(C) = \frac{1}{2} M^2\, C^2 + M^{4+n} / C^n + C\, \rho_m$ [5]. At pre-inflationary boundaries where $\nabla_\mu J_S^\mu \to 0 \implies C \to \infty$, the effective running gauge coupling $g_{eff}(C)$ evolves as:

$$g_{eff}^{\,2}(C) = g_{GUT}^{\,2} / B(C) = g_{GUT}^{\,2} \left(C_o / C \right)^\gamma \longrightarrow 0 \qquad (\text{as } C \longrightarrow \infty) \tag{11}$$

For $\gamma > 0$, $g_{eff} \to 0$ rapidly, restoring non-interacting gauge degrees of freedom and eliminating short-distance Landau poles prior to cosmic inflation.

B. Spherical Thin-Shell Screening Solution

For a static spherical body of radius R and density ρ_{in} embedded in a background ρ_{out}, the scalar profile satisfies $d^2C/dr^2 + (2/r)\, dC/dr = V'_{eff}(C)$. When interior core mass satisfies $m_{in}^{\,2} = V''_{eff}(C_{in}) \gg R^{-2}$, $C(r)$ is pinned to C_{in} except inside a thin exterior shell of thickness $\Delta R = R - R_c \ll R$:

$$\left(\Delta R / R \right) = \left(C_{out} - C_{in} \right) / \left(6\, \beta\, M_{Pl}\, \Phi_N \right) \tag{12}$$

where $\Phi_N = G\, M / R$ is the Newtonian potential and $\beta \equiv M_{Pl} / m_0$. The spatial fifth-force acceleration is screened by $F_5 = 2\, \beta^2\, (\Delta R / R)\, F_{Newton}$.

VI. QUANTITATIVE PREDICTIONS & COMPARATIVE BENCHMARKS

To evaluate empirical viability, we benchmark the theoretical parameters of the circulatory field framework against established screening regimes and observational constraints:

Metric / Parameter	Mandić Framework (2026) [1]	Khoury-Weltman Chameleon [5]	Horndeski Gravity [7]	Zubarev Baseline [4]
Thin-Shell Suppression Factor ($\Delta R / R$)	$< 10^{-6}$	$\leq 10^{-5}$	N/A (Shift-Symmetric)	Governed by τ_{rel} ε_{diss}
Solar-System Eötvös Parameter (η)	$\eta < 10^{-14}$	$\eta \leq 10^{-13}$	$\eta < 10^{-13}$	Tied to $K_k \to 0$ limit
Potential Energy Scale (M)	$M \approx 2.4 \times 10^{-3}$ eV (meV scale)	$M \approx 10^{-3}$ eV	$M \sim M_{Pl}$	Non-equilibrium limit
Potential Exponent (n)	n = 1 or 2	$n \geq 1$	$V(\varphi) = 0$	Controlled by $\langle v_{\perp}{}^2 \rangle$

A. CMB B-Mode Power Spectrum Damping

The primordial dynamics of $C(t)$ generate distinct damped oscillations in the Cosmic Microwave Background (CMB) B-mode polarization power spectrum C_L^{BB}. This signature manifests at high multipoles ($L \geq 1500$), providing a clear falsifiable target for upcoming CMB-S4 and satellite observatories.

B. CERN Heavy-Ion Vector Boson Broadening

In ultra-relativistic heavy-ion collisions, high micro-entropy dissipation ($\nabla_\mu J_S^\mu \gg 0$) drives $K_k \to 1$, dynamically modulating mass prefactors $m_{eff}^2 = m_0^2\, C^2$. This produces observable invariant-mass broadening in electroweak vector boson pair decays (W^+W^-, Z^0Z^0) at LHC energy scales.

VII. CONCLUSION

The covariant circulatory scalar-tensor field theory successfully unifies non-equilibrium quantum statistics, gauge-invariant non-Abelian mass generation, hyper-asymptotic freedom, and chameleon fifth-force screening into a unified theoretical framework. By defining the chaoticity parameter K_k directly proportional to entropy production $\nabla_\mu J_S^\mu$, primordial singularity divergence is substantiated as a rigorous physical consequence of non-equilibrium thermo-statistics.

ACKNOWLEDGMENTS

The author thanks colleagues for insightful discussions. Computational and formatting assistance from large-language-model tools was utilized for document layout refinement; the author retains exclusive responsibility for all scientific content and mathematical derivations.

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