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

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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 all fundamental interactions. Building upon microphysical foundations derived from Zubarev's nonequilibrium statistical operator formalism, the entropy four-current J_S^{μ} and transport coefficients are derived via systematic coarse-graining of Keldysh Green's functions. We reformulate the chaoticity coefficient K_k directly proportional to the micro-entropy dissipation rate, demonstrating that the limit of vanishing entropy generation ($\nabla_{\mu} J_S^{\mu} \to 0$) drives $K_k \to 0$ and leads cleanly to physical divergence ($lim_{K_k \to 0} C = \infty$), generating the infinite primordial energy density that catalyzed spacetime expansion as an intrinsic thermodynamic property. We reformulate the non-Abelian Stueckelberg mass sector using matrix-valued group elements $U(x) \in G$, proving exact gauge invariance and unitarity across all scales. We derive the modified Einstein field equations and gauge field equations explicitly from the total action, solve the two-tier Chameleon screening mechanism for spherical bodies, and evaluate quantitative predictions for CMB B-mode polarization power spectra and collider vector boson broadening.

I. INTRODUCTION & THEORETICAL CONTEXT

The pursuit of a grand unified field theory sitting at the intersection of quantum statistical kinetics and general relativity remains a central objective in modern theoretical physics. Modern empirical successes across perturbative regimes contrast with foundational questions regarding initial singularities, dark sector dynamics, and micro-dissipative entropy bounds. Scalar-tensor theories extend Riemannian geometry by allowing dynamical variations of fundamental coupling scales. In this work, we present a unified circulatory field theory where a Lorentz-scalar field $C(x^{\mu})$ couples universally to geometric, gauge, and matter sectors.

To contextualize the novelty of this framework relative to prior scalar-tensor paradigms [5], shift-symmetric Horndeski gravities [7], and early transport models [1]:

1. Microphysical Foundations: Unlike standard scalar-tensor models where scalar potentials are inserted *ad hoc*, $C(x^{\mu})$ is derived directly from phase-space velocity dispersion and Zubarev nonequilibrium thermo-statistics [4].

2. Thermodynamic Primordial Genesis: We reformulate the chaoticity coefficient such that the zero-dissipation limit ($\nabla_{\mu} J_S^{\mu} \to 0$) naturally drives $C \to \infty$, establishing primordial divergence as a physical consequence of thermodynamic coherence rather than a mathematical artifact.

3. Gauge-Invariant Non-Abelian Mass Generation: Embedding the theory into $SU(5)$ or $SU(3)_c \times SU(2)_L \times U(1)_Y$ via matrix-valued Stueckelberg fields [10] guarantees exact gauge invariance and hyper-asymptotic freedom without relying on coordinate-subtraction approximations.

II. SUB-LOCAL STATISTICAL FIELD FORMALISM & MICROPHYSICAL DERIVATIONS

A. Entropy Current J_S^μ and Systematic Coarse-Graining

Consider a localized wave-packet region with internal energy-momentum tensor $T_{mic}^{\mu\nu}$. The microscopic state is described 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 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 thermodynamics: $\nabla_\mu J_S^\mu(x) \geq 0$.

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

To ensure mathematical and thermodynamic consistency, the dimensionless chaoticity coefficient $K_k(x^\mu)$ must be directly proportional to the micro-dissipation rate (entropy generation):

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

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

Internal momentum transfer across sub-constituents is parameterized by the effective turbulence coefficient $K_{et}(x^\mu)$ derived from phase-space velocity dispersion $\langle v_\perp{}^2 \rangle$ and Keldysh dissipation rate per unit rest mass ε_{diss}:

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

The circulatory field $C(x^\mu)$ is defined pointwise as the invariant ratio:

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

In the limit of vanishing micro-dissipation ($\nabla_\mu J_S^\mu \to 0 \implies K_k \to 0$), the circulatory field undergoes physical divergence: $\lim_{K_k \to 0} C(x^\mu) = \infty$. This demonstrates that pre-inflationary divergence is a physical consequence of thermodynamic coherence rather than an algebraic artifact. Matter rest mass scales dynamically as $m_{eff}(x^\mu) = C(x^\mu)\, m_0$ [1].

III. COVARIANT GRAND UNIFIED ACTION & GAUGE STRUCTURE

We formulate the unified theory under a non-Abelian Lie group G (such as $SU(5)$ or $SU(3)_c \times SU(2)_L \times U(1)_Y$) with Lie algebra $\mathfrak{g}$. Let T^a be anti-Hermitian generators satisfying $[T^a, T^b] = f^{abc}\, T^c$ with $\mathrm{Tr}(T^a\, T^b) = -\,½\,\delta^{ab}$. The total unified action is:

$$S_{tot} = \int d^4x\, \sqrt{(-g)}\, [\, (M_{Pl}^2 / 2)\, R - ½\, g^{\mu\nu}\, \partial_\mu C\, \partial_\nu C - V(C) - ¼\, B(C)\, h_{ab}\, F_{\mu\nu}{}^a\, F^{\mu\nu\, b} - ½\, m_0^2\, C^2\, \kappa_{ab}\, \boldsymbol{W}_\mu{}^a\, \boldsymbol{W}^{\mu\, b} + \mathscr{L}_{\text{matter}}\,] \tag{5}$$

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

A. Non-Abelian Stueckelberg Reformulation

Following standard field theory [10], non-Abelian mass generation without explicit gauge symmetry breaking is achieved by introducing a local group element $U(x) = exp(\, \theta^a(x)\, T^a / v\,) \in G$. Under a gauge transformation $g(x) \in G$, the matrix-valued gauge field $A_\mu = g_{GUT}\, A_\mu{}^a\, T^a$ and Stueckelberg field transform as:

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

The gauge-covariant derivative acting on $U(x)$ is $D_\mu U = \partial_\mu U - A_\mu U$, which transforms covariantly: $D_\mu U \longrightarrow g(x)\, D_\mu U$. We construct the left-invariant gauge-compensated 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, $\boldsymbol{W}_\mu \longrightarrow (g\, U)^{-1}\, D_\mu(g\, U) = U^{-1}\, g^{-1}\, g\, D_\mu U = \boldsymbol{W}_\mu$, proving that the non-Abelian mass term $\mathscr{L}_{mass} = -\, m_0^2\, C^2\, Tr(\boldsymbol{W}_\mu\, \boldsymbol{W}^\mu)$ is strictly gauge-invariant across all mass scales.

B. Consistency of B(C) Kinetic Modulation

Because $C(x^\mu)$ is a pure Lorentz scalar and an internal gauge singlet ($g\, C\, g^{-1} = C$), the modulation function $B(C)$ multiplies the gauge-invariant kinetic term $h_{ab}\, F_{\mu\nu}{}^a\, F^{\mu\nu\, b}$ without violating non-Abelian gauge invariance or introducing ghost instabilities.

IV. EXPLICIT VARIATIONAL DERIVATION OF UNIFIED FIELD EQUATIONS

A. Modified Unified Einstein Field Equations

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

$$T_{\mu\nu}{}^{(C)} = \partial_\mu C\, \partial_\nu C - g_{\mu\nu}\, [\, ½\, g^{\alpha\beta}\, \partial_\alpha C\, \partial_\beta C + V(C)\,] \tag{8}$$

B. Derivation of Gauge Field Equations (Eq. 9)

Varying the gauge-relevant terms of S_{tot} with respect to $A_\nu{}^a$:

1. *Kinetic Variation:* $\delta S_{kin} = -\, ½ \int d^4x\, \sqrt{(-g)}\, B(C)\, h_{ab}\, F^{\mu\nu\, b}\, (\, D_\mu\, \delta A_\nu{}^a - D_\nu\, \delta A_\mu{}^a\,)$. By anti-symmetry $F^{\mu\nu\, b} = -\, F^{\nu\mu\, b}$ and integration by parts:

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

2. *Mass and Matter Variation:* Varying $\mathscr{L}_{mass}$ and $\mathscr{L}_{matter}$ yields $m_0^2\, C^2\, \kappa_{ab}\, \boldsymbol{W}^{\nu\, b}$ and $j^{\nu\, a}$. Combining variations yields the exact Yang-Mills-Proca-Stueckelberg field equations:

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

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

V. QUANTITATIVE COSMOLOGICAL & SCREENING ANALYSIS

A. Cosmic Evolution & Hyper-Asymptotic Freedom

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

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

For $\gamma > 0$, all gauge couplings vanish identically, restoring non-interacting gauge degrees of freedom and eliminating Landau poles prior to inflation.

B. Spherical Thin-Shell Screening Solution

For a spherical body of radius R and density ρ_{in} in an ambient background ρ_{out}, the scalar field equation is $d^2C/dr^2 + (2/r)\, dC/dr = V'_{eff}(C)$. Inside dense bodies where $m_{in}^{\,2} = V''_{eff}(C_{in}) \gg R^{-2}$, $C(r)$ is pinned to C_{in} except inside a thin shell of thickness $\Delta R = R - R_c \ll R$:

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

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

VI. QUANTITATIVE PREDICTIONS & COMPARATIVE CONSTRAINTS

To evaluate empirical viability, we compare the circulatory field theory against existing experimental bounds and screening benchmarks:

Metric / Parameter	Mandić Framework (2026) [1]	Khoury-Weltman Chameleon [5]	Horndeski Gravity [7]	Zubarev Baseline [4]
Thin-Shell Suppression Factor (ΔR / 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 evolution of $C(t)$ induces distinct damped oscillations in the Cosmic Microwave Background (CMB) B-mode polarization power spectrum C_L^{BB}. This damping signature concentrated at high multipoles ($L \geq 1500$) provides a falsifiable cosmological signature for upcoming high-resolution CMB observatories.

B. CERN Heavy-Ion Vector Boson Broadening

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

VII. CONCLUSION

The circulatory field theory successfully unifies non-equilibrium quantum transport statistics, gauge-invariant Stueckelberg mass generation, hyper-asymptotic freedom, and screened fifth-force dynamics into a self-consistent Grand Unified framework. By reformulating the chaoticity parameter K_k directly proportional to entropy production $\nabla_\mu J_S^\mu$, initial singularity divergence is shown to be a natural physical consequence of thermodynamic coherence.

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