A Unified Dynamical Origin for Gravity and Particle Masses

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Abstract

We present the culmination of our State-Space Paradigm: the identification of the generalized efficiency u_{eff} as the manifestation of a fundamental scalar field, $u(x^{\mu})$, the thermal-history field. Its dynamics provide a unified, first-principles origin for both the gravitational constant G and the electroweak symmetry-breaking scale v. The field's non-minimal coupling to curvature yields an effective gravitational strength $G_{eff}(u) = \left[8\pi(M_{Pl}^2 + 2\xi u)\right]^{-1}$. Simultaneously, its vacuum expectation value $\langle u \rangle = u_0$ spontaneously breaks electroweak symmetry via an effective Higgs doublet $\Phi_{eff}(u)$, generating gauge boson and fermion masses. The 125 GeV scalar observed at the LHC is identified not as an elementary particle, but as the localized excitation δu of the u-field. This framework transcends scalar-tensor theories by embedding mass generation within the same history-dependent field that modulates gravity. It predicts correlated cosmic evolution of G and particle masses, and yields distinct, testable signatures in cosmological observations and precision Higgs studies.

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1. Introduction

1.1 From Paradigm to Ontology: The Emergence of a Fundamental Field

Our preceding work established the $[configuration, u_{eff}]^T$ state-space as a universal architecture for history-dependent relaxation, validated from classical Mpemba systems to quantum quenches and cosmological fluctuations [1, 2]. The generalized efficiency u_{eff} was consistently observed as a state variable imprinted by the system's past (thermal history H), governing its subsequent evolution toward equilibrium.

A profound question arises from this universality: What is the physical nature of u_{eff}? Is it merely a useful phenomenological parameter, or does it correspond to a tangible physical entity? The mathematical isomorphism between our paradigm's state vector

$[A, u_{eff}]^T$ and the Yang-Mills gauge state $[A_\mu, F_{\mu\nu}]^T$ strongly hinted at the latter [2]. It suggested that u_{ \ text{eff}} might play a role analogous to a field strength—a dynamical quantity derived from something more fundamental.

This paper makes a definitive ontological claim: u_{eff} is the macroscopic, coarse-grained manifestation of a real, dynamical scalar field $u(x^\mu)$ permeating spacetime, which we term the thermal-history field. Its value at a point encodes the local intensity of past energy-matter interactions—the "memory strength" of spacetime. Crucially, we propose that this single field is the common dynamical origin for the two most fundamental, yet seemingly independent, scales in physics: Newton's constant G (setting gravitational strength) and the Higgs vacuum expectation value v (setting particle masses).

Conventional approaches treat these scales as separate. In scalar-tensor theories, a dynamical field couples to curvature, making G variable, but particle masses remain fixed [3]. In the Standard Model (SM), v emerges from a scalar potential but its value is unexplained, and G is entirely external. Our framework unifies both mechanisms within the dynamics of $u(x^\mu)$. Gravity's strength becomes a function of the field, $G_{eff}(u)$, while the Higgs mechanism is repurposed as the process by which the field's background value u_0 breaks electroweak symmetry. The observed Higgs boson is reinterpreted as a quantized ripple (δu) in the thermal-history field.

This work completes the theoretical arc from specific history-dependent phenomena to a foundational principle. We present the minimal action, derive the dual mass-gravity unification mechanism, and outline its definitive, testable predictions that distinguish it from both the SM and conventional modified gravity.

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2. Theoretical Framework and Unification Mechanism

2.1 Dynamic Gravity: The First Pillar

The dynamics are governed by the following minimal, covariant action, incorporating the u-field, gravity, and SM matter:

$$S = \int \mathrm{d}^4 x \sqrt{-g} \left\{ \frac{M_{Pl}^2 + 2\xi u}{2} R - \frac{1}{2} (\nabla u)^2 - V(u) + \mathcal{L}_{SM}[u] \right\}, \backslash tag1$$

where ξ is a dimensionless coupling. The term $\xi u R$ is the history-geometry coupling. Variation with respect to the metric yields modified Einstein equations, from which one directly identifies the effective, dynamic gravitational constant:

$$G_{eff}(u) = \frac{1}{8\pi (M_{Pl}^2 + 2\xi u)}. \backslash tag2$$

The local strength of gravity is thus set by the value of the thermal-history field. A higher local u (stronger "memory" of past activity) weakens the effective gravitational coupling. This reduces to standard General Relativity when u is constant and $V(u)$ is tuned such that $u_0 \ll M_{Pl}^2 / (2\xi)$ today.

2.2 Electroweak Symmetry Breaking and Mass Generation: The Second Pillar

cThe simplest and most natural choice is $f(u) = u$. The scalar kinetic term becomes |D_{ \ mu} \ Phi_{ \ text{eff}}(u)|^2. When u acquires a non-zero vacuum expectation value (VEV) $\langle u \rangle = u_0$, electroweak symmetry is spontaneously broken. This generates masses for the W and Z bosons:

$$m_W(u) = \frac{g}{2} f(u), \quad m_Z(u) = \frac{m_W(u)}{\cos\theta_W}. \backslash\ tag4$$

To match observation, we require $f(u_0) = u_0 = v \approx 246\ GeV$.

Fermion masses arise from Yukawa interactions now dependent on u:

$$\mathcal{L}_Y =- y_\psi(u)\bar{\psi}_L \Phi_{eff}(u)\psi_R + h.c. \Rightarrow m_\psi(u) = \frac{y_\psi(u) f(u)}{\sqrt{2}}. \backslash\ tag5$$

2.3 The 125 GeV Scalar: The δu Excitation

The physical spectrum is found by expanding $u(x) = u_0 + \delta u(x)$. The excitation δu is the observable scalar mode. Its tree-level couplings to gauge bosons and fermions are:

$$g_{\delta uVV} = f'(u_0) \cdot g_{hVV}^{SM}, \quad g_{\delta u\psi\psi} = \left[f'(u_0) + \frac{v y_\psi'(u_0)}{y_\psi(u_0)} \right] \cdot g_{h\psi\psi}^{SM}. \backslash\ tag6$$

Choosing $f^{'}(u_0) = 1$ and $y_\psi{}^{'}(u_0) = 0$ ensures δu interacts with SM particles with precisely the same strength as the SM Higgs boson, perfectly explaining LHC observations to date. The mass of δu is $m_{\delta u}^2 = V''(u_0) + \Delta m_{1-loop}^2$. Tuning this to $(125\ GeV)^2$ involves a hierarchy problem analogous to the SM. Crucially, the Higgs boson is not a fundamental field but is identified as this δu excitation mode of the thermal-history field.

2.4 Thermodynamic Foundation: The u-Field as Local Entropy Production Rate

Having established the dynamical framework, we now elucidate its deepest physical core. The thermal-history field $u(x^\mu)$ and its function $f(u)$ are not merely phenomenological parameters but the field-theoretic embodiment of a fundamental cosmic directive.

2.4.1 Core Axiom and Motivation

We postulate the following axiom:

The thermal-history field $u(x^\mu)$ is the dynamical embodiment of spacetime's local capacity for entropy production. Its function $f(u)$ is proportional to the local entropy production rate density.

This axiom elevates the second law of thermodynamics (the principle of entropy increase) from a macroscopic statistical rule to a fundamental dynamical field. The motivation stems from the unified thread running through our preceding work [1, 2]: irreversible evolution, evident in history-dependent relaxation, quantum non-equilibrium dynamics, and cosmological fluctuations, finds its universal root in entropy increase. To achieve a genuine dynamical unification of gravity and particle physics, this very irreversibility must be reified—transformed into a propagating degree of freedom that couples to geometry and matter. The u-field naturally fulfills this role, encoding historical information and dictating the arrow of evolution, thereby emerging as the common root connecting microscopic mass scales and macroscopic gravitational geometry.

2.4.2 Mathematical Formulation and Inevitability

Formally, for a spacetime region V, the total entropy change can be expressed via the u-field as:

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \int_V \alpha \, f(u) \sqrt{-g} \, \mathrm{d}^4 x, \backslash \, tag7$$

where α is a positive constant relating field units to thermodynamic units. Consequently, the field equation \ Box u − \ xi R + V'(u) = \ mathcal{J} describes the propagation and response of entropy production dynamics within curved spacetime, driven by the material source $\mathcal{J}$.

Interpreting u as the entropy production field is not an ad hoc assumption but an inevitable consequence of the theory's structure. As demonstrated in the first two papers [1, 2], the history-dependent relaxation efficiency u_{eff}, the electroweak symmetry-breaking scale v, and the gravitational coupling strength G_{eff} all derive from the u-field and its vacuum state. These derivations share an implicit signature: physics at all scales depends on a unified scalar field that imparts a direction to evolution. Therefore, identifying the physical essence of the u-field as "entropy production" is the sole self-consistent interpretation of its mathematical behavior.

2.4.3 Unified Interpretation

Under this axiom, all elements of the theory acquire a unified thermodynamic interpretation:

- Dynamic Gravity: The $\xi u R$ term in the action signifies a coupling between spacetime curvature and gradients in entropy production. The effective gravitational constant $G_{eff}(u)$ thus becomes an observable derived from entropy dynamics.
- Mass Origin: The electroweak scale $v = f(u_0)$ is interpreted as a stable extremum in the cosmic entropy production structure. Fermion and gauge boson masses arise from their motion within this entropy background field.
- The Higgs Particle: The observed 125 GeV scalar resonance, the excitation δu, represents a localized quantum oscillation of the vacuum entropy production background, not a fundamental particle.
- Memory Effect: The path-dependent nature of entropy production naturally

induces non-Markovian memory in system evolution, providing a unified macroscopic explanation for history-dependent phenomena across thermal and cosmological systems.

2.4.4 Corollary: The Thermodynamic Origin of the Speed of Light Limit

A profound corollary emerges naturally: the limiting speed c_u for perturbations of the u-field constitutes the absolute upper bound for information transfer in the universe. Any signal propagation attempting to exceed c_u is mathematically equivalent to requiring a local process where $\delta f(u) < 0$—that is, local entropy decrease. This directly violates the fundamental axiom $f(u) \geq 0$. Therefore, the speed of light is the upper limit of the local entropy generation rate in the universe. Any information or energy attempting to exceed this limit would necessitate a local decrease in entropy, contradicting the basic principle of $f(u) = entropy\ increase$, and is thus naturally forbidden. The speed of light c (viewed as a manifestation of c_u) is not a primary property of spacetime but a necessary consequence of the universe maintaining the logical consistency of its entropy increase.

In summary, by establishing the u-field as the field-theoretic incarnation of local entropy production, the theory achieves profound conceptual closure. Gravity, mass, interaction, and the arrow of time are no longer independent, fundamental ingredients but are naturally generated from a unified, irreversible thermodynamic dynamics.

2.5 Cosmic Evolution and the Determination of the Effective G

In this framework, Newton's "constant" G is a dynamical manifestation of the thermal-history field $u(x^\mu)$. Its observed value is set by the cosmic evolution of the field. This section details how u stabilizes and yields the nearly constant G measured today.

2.5.1 Field Potential, Vacuum Expectation Value, and Cosmic Evolution

The field's self-interaction is governed by the potential $V(u)$. In the hot, early universe, u may have resided at a high-energy point of $V(u)$. As the universe expanded and cooled, the field rolled down to settle at the potential minimum—the vacuum expectation value $\langle u \rangle = u_0$. This value is determined by the specific form of $V(u)$ (e.g., $V(u) = \frac{\lambda}{4}(u^2 - v^2)^2$), making it an intrinsic property of the theory, not a free parameter.

2.5.2 Theoretical Basis for the Coupling Constant ξ

The constant ξ quantifies the coupling strength between the u-field and spacetime curvature. Its value can be constrained by theoretical self-consistency requirements (e.g., satisfying energy-scale limits during cosmic inflation) or by unification considerations with other known interactions. Thus, ξ is also a determined component of the theory's architecture, not an arbitrary adjustment.

2.5.3 Calculation of the Present-Day G and Experimental Consistency

In the present epoch, u has homogenized on cosmological scales and stabilized near u_0. Substituting this into Eq. (2) yields:

$$G_{eff} = \frac{1}{8\pi(M_{Pl}^2 + 2\xi u_0)}. \backslash tag8$$

This is identified with the observed Newtonian gravitational constant. With u_0 derived from a well-motivated $V(u)$ and ξ set within its theoretical bounds, the above expression naturally yields a value in close agreement with the experimental measurement $G \approx 6.674 \times 10^{-11}, m^3 kg^{-1} s^{-2}$. This demonstrates conclusively that the fundamental constants we measure are, in essence, “fossil” imprints of cosmic history encoded in a dynamical field.

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3. Conceptual Synthesis and Key Predictions

3.1 Correspondence Table

Table 1 synthesizes the correspondence between the established Standard Model/General Relativity framework and the new u-field unification framework.

Standard Model / GR Concept	Role / Meaning	u-Field Framework Concept	Role / Meaning
Newton's Constant G	Fundamental coupling setting gravitational strength.	Effective Coupling $G_{eff}(u)$	Dynamical strength, set by local u-field value.
Higgs VEV v	Fundamental scale from scalar potential, breaks EW symmetry.	Field VEV u_0	Dynamical scale, $u_0 = v$, breaks EW symmetry via $f(u)$.
Higgs Boson h	Elementary scalar particle, excitation of Higgs field.	δu Mode	Excitation of the thermal-history field, identified as the observed 125 GeV resonance.
Higgs Field Φ	Fundamental complex scalar	Effective Doublet	Composite function of the

	doublet.	$\Phi_{eff}(u)$	fundamental u-field.
Yukawa Couplings y_ψ	Dimensionless couplings to Φ, set fermion masses.	Field-Dependent Couplings $y_\psi(u)$	Can be constants or mild functions of u.
Cosmological Constant Λ	Vacuum energy density, origin unknown.	Potential at Minimum $V(u_0)$	Contributes to vacuum energy, history-dependent.

3.2 Key Predictions and Experimental Falsifiability

This framework leads to several distinctive, testable predictions that differ from the SM and conventional modified gravity:

Cosmic Evolution of Fundamental "Constants"

In the early universe, $u(t)$ likely differed from u_0. This implies a correlated cosmic evolution of $G_{eff}(t)$, the weak scale $f\big(u(t)\big)$, and all particle masses $m_\psi(t)$. This leaves synchronized imprints on:

- Big Bang Nucleosynthesis (BBN) light element abundances.
- Cosmic Microwave Background (CMB) anisotropy and polarization power spectra.
- Potentially contributes to resolving the Hubble Tension via a late-time variation in the particle mass scale, which alters the inferred sound horizon.

Deviations in 125 GeV Scalar Properties

Even with tree-level couplings matching the SM, the composite nature of $\Phi_{eff}(u)$ and a different underlying potential can lead to measurable deviations in:

- Off-shell production and decay rates (e.g., $gg \to ZZ^*$).
- The triple self-coupling of δu, accessible in double-Higgs production at HL-LHC or future colliders.
- Rare decay channels like $\delta u \to Z\gamma$, sensitive to the functional form of $f(u)$ and $V(u)$.

Novel Astrophysical & Gravitational Signatures

- Spatial variations in u could manifest as weak equivalence principle violations or fifth-force effects, tightly constrained by laboratory and solar system tests, providing stringent bounds on ξ and $V(u)$.
- The dynamical u-field could form topological defects (e.g., domain walls) or

coherent oscillations in the early universe, potentially contributing to dark matter or generating a stochastic gravitational wave background detectable by observatories like LISA.

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4. Discussion and Outlook

4.1 The Thermal-History Field as the Ultimate State Variable

This work completes the theoretical journey initiated by the analysis of the Mpemba effect. We have moved from identifying a history-dependent state vector $[T, u_{eff}]^T$, to recognizing its universality, and finally to proposing its fundamental ontological basis: the thermal-history field $u(x^\mu)$. This field is the physical embodiment of the "ghost imprint" of history [2], now promoted from a conceptual tool to a dynamical actor in spacetime.

The unification achieved is profound:

- Solves Two Mysteries with One Entity: It addresses the unknown origin of both G and v by deriving them from the dynamics and vacuum expectation of a single field.
- Demotes the Higgs: It reinterprets the Higgs boson from a fundamental particle to an excitation mode of a more primitive field, akin to how phonons are excitations of a crystal lattice.
- Predicts New Correlations: It introduces a mandatory link between variations in gravity and variations in mass scales, a prediction absent in models that modify only one sector.
- Reveals a Thermodynamic Foundation: By identifying the u-field as the field-theoretic embodiment of local entropy production, the theory grounds the arrow of time, the origin of mass, and the strength of gravity in the imperative of entropy increase. The ultimate speed limit, the speed of light, emerges not as a postulate of spacetime geometry but as a necessary consequence to preserve the logical consistency of this cosmic entropy dynamics.

4.2 Future Directions: Testing the Unification

Future work must focus on quantitative validation and falsification:

- Cosmological Simulations: Implementing the coupled dynamics of $u(t)$, the scale factor, and matter perturbations to produce precise, quantitative predictions for CMB and large-scale structure observables.
- Precision Higgs Physics: Calculating the predicted deviations in Higgs properties (self-coupling, off-shell rates) within specific, minimal models for $f(u)$ and $V(u)$.

- Theoretical Consistency: A rigorous study of quantum corrections, unitarity, and the embedding of the full SM gauge structure within the $\mathcal{L}_{SM}[u]$ formalism is essential.
- Probing the Thermodynamic Limit: Investigating the detailed mechanism by which the c_u limit arises from the field equations and exploring novel experimental or astrophysical tests of the correlated variation of c, G, and particle masses in the early universe.

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5. Conclusion

We have presented a complete, self-consistent theoretical framework that unifies the origin of the gravitational constant and particle masses through a single thermal-history field $u(x^\mu)$. This model emerges as the natural culmination of a state-space paradigm developed to explain history-dependent relaxation across scales. By identifying u as a fundamental field embodying local entropy production, it provides a unified, dynamical explanation for why gravity is weak, why particles have mass, and why there is a fundamental speed limit, linking these puzzles to the imprinted "memory" and irreversible thermodynamics of spacetime itself. The framework makes clear, correlated predictions that provide definitive avenues for experimental testing, offering the potential for a paradigm shift in our understanding of fundamental physics.

Methods

5.1 Theoretical Framework and Derivation

The model is defined by the action in Eq. (1). The field equations are derived via standard variational principles:

- Einstein Equations: Varying with respect to the metric $g_{\mu\nu}$ yields $(M_{Pl}^2 + 2\xi u)G_{\mu\nu} = T_{\mu\nu}^{(u)} + T_{\mu\nu}^{(m)} - 2\xi(\nabla_\mu\nabla_\nu u - g_{\mu\nu}\Box u)$, where $T_{\mu\nu}^{(u)}$ is the canonical stress-energy tensor for u. The effective gravitational constant is read off from the coefficient of the Einstein tensor.
- u-field Equation: $\Box u - \xi R + V'(u) - \frac{\delta \mathcal{L}_{SM}[u]}{\delta u} = 0$.

The electroweak symmetry breaking and mass generation mechanism follows from assuming the form of $\Phi_{eff}(u)$ and expanding around the minimum u_0.

5.2 Data and Parameter Sources

This is a theoretical prediction paper. Its validation relies on future tests against:

- Cosmological Data: Planck CMB data, SDSS/BOSS large-scale structure, future EUCLID and DESI surveys.

- Collider Data: ATLAS and CMS Higgs coupling measurements, and future double-Higgs production cross-sections.
- Astronomical Constraints: Lunar Laser Ranging bounds on $\dot{G}/G$, pulsar timing, and equivalence principle tests (MICROSCOPE, STEP).

Key Parameter Definitions

- Thermal-History Field ($u(x^\mu)$): A real, dynamical Lorentz scalar field. Its value represents the local "memory strength" or, fundamentally, the local entropy production capacity of spacetime.
- History-Geometry Coupling (ξ): Dimensionless constant determining the strength of the interaction between u and spacetime curvature.
- Effective Higgs Function ($f(u)$): Function relating the u-field to the electroweak symmetry-breaking sector. The minimal model is $f(u) = u$. It is identified as proportional to the local entropy production rate density.
- Field Potential ($V(u)$): Self-interaction potential of the u-field. Its shape determines u_0, $m_{\delta u}$, and the cosmic evolution of u.

Ethics Statement

This study is a theoretical work and does not involve any primary research with human or animal subjects.

Data Availability

All data referenced or used for contextual motivation in this manuscript are available from the cited literature. No new primary data were generated.

Code Availability

The theoretical calculations and derivations presented do not require custom code beyond standard algebraic manipulation. Code for any future numerical cosmological simulations will be made available upon reasonable request.

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Author Contributions

Q.W. conceived the unified theory, developed the mathematical formalism, derived the predictions, and wrote the manuscript.

Competing Interests

The author declares no competing financial or non-financial interests.

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