

A Scalar–Tensor Extension of the Standard Model and General Relativity: Gauge-Invariant Proca–Stueckelberg Electrodynamics, Screened Scalar Interactions, and Their Cosmological and Subatomic Phenomenology

Tomislav Mandić^{1,*}

¹*Independent Researcher, Ljubuški, Bosnia and Herzegovina*

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We present a self-consistent scalar–tensor extension of the Standard Model (SM) and General Relativity (GR) built around a Lorentz-scalar field $C(x^\mu)$, which we term the *circulatory field*. The field is defined phenomenologically as the invariant ratio of two dimensionless microscopic quantities—an effective-turbulence coefficient K_{et} and a chaoticity coefficient K_k constructed from the covariant divergence of a micro-entropy current. Coupling C to matter through a Jordan-frame conformal factor $C^2 g_{\mu\nu}$ generates a position-dependent effective rest mass $m_{\text{eff}} = C m_0$, while embedding C in a $U(1)_{\text{em}}$ Proca–Stueckelberg action induces a spatially varying, gauge-invariant photon mass $m_\gamma(x^\mu)$. A nonlinear self-interaction potential $V(C)$ realizes a chameleon screening mechanism that suppresses the associated fifth force to sub-millimeter ranges in dense environments, satisfying Solar-System equivalence-principle bounds. We derive the coupled field equations, obtain the modified Friedmann system with a closed matter–scalar conservation law, and discuss observational constraints from fast-radio-burst dispersion, the ATOMKI “X17” anomaly, and lepton-flavor-universality tests. We emphasize the assumptions, open theoretical issues, and falsifiable predictions of the framework, and outline laboratory, astrophysical, and collider tests.

I. INTRODUCTION

The Standard Model of particle physics and General Relativity are the two pillars of modern physics [1, 2]. Despite their success, several open problems—cosmic acceleration [3, 4], the nature of dark matter [5], the Hubble tension, and a set of persistent subatomic anomalies—motivate the view that both frameworks are effective descriptions of a more complete theory [6].

Scalar–tensor theories provide a controlled and extensively studied way to extend GR [7–10]. In this work we explore a scalar–tensor model in which a single Lorentz-scalar field $C(x^\mu)$ couples universally to matter and to the electromagnetic sector. Two features distinguish the construction from a generic light scalar: (i) C is assigned a phenomenological microphysical interpretation as a ratio of non-equilibrium transport coefficients, and (ii) C enters a Proca–Stueckelberg action so that a gauge-invariant, environment-dependent photon mass arises together with the usual scalar fifth force.

We stress at the outset that the microphysical definition of C adopted here is phenomenological: it is a parameterization intended to organize the coupling structure, not a derivation of C from an underlying quantum kinetic theory. We are explicit about this so that the empirical content of the model—the coupled field equations and their predictions—can be assessed independently of the heuristic motivation. Throughout we use the mostly-plus metric signature $(-, +, +, +)$ and, unless stated otherwise, restore $\hbar$ and c explicitly.

II. SUB-LOCAL STATISTICAL FIELD FORMALISM

A. Chaoticity coefficient

Consider a localized wave-packet region described by an internal non-equilibrium energy–momentum tensor $T_{\text{mic}}^{\mu\nu}$ [11, 12]. The evolution of microscopic disorder is tracked by an entropy four-current [13, 14]

$$J_S^\mu = s u^\mu + n^\mu, \quad (1)$$

where s is the local entropy density, u^μ the fluid four-velocity, and n^μ a non-convective entropy flux [15]. The second law in relativistic fluid dynamics requires $\nabla_\mu J_S^\mu \geq 0$ [16]. We define the dimensionless *chaoticity coefficient*

$$K_k(x^\mu) = 1 + \frac{\tau_{\text{rel}}}{k_B n_0} \nabla_\mu J_S^\mu(x^\mu), \quad (2)$$

* tomislav.mandic@example.org

with k_B the Boltzmann constant, n_0 the invariant rest-frame number density, and τ_{rel} a micro-dynamical relaxation time [17].

B. Effective-turbulence coefficient

To characterize internal momentum transfer we introduce the dimensionless *effective-turbulence coefficient*

$$K_{\text{et}}(x^\mu) \equiv \frac{\langle v_\perp^2 \rangle}{\tau_{\text{rel}} \epsilon_{\text{diss}}(x^\mu)}, \quad (3)$$

where $\langle v_\perp^2 \rangle$ is the mean-square transverse velocity of internal sub-constituents and ϵ_{diss} is the dissipation rate per unit rest mass [18, 19]. Since $[\langle v_\perp^2 \rangle] = \text{m}^2/\text{s}^2$ and $[\tau_{\text{rel}} \epsilon_{\text{diss}}] = \text{m}^2/\text{s}^2$, K_{et} is dimensionless.

C. Circulatory field and rest-mass coupling

The circulatory field is defined pointwise as the ratio

$$C(x^\mu) \equiv \frac{K_{\text{et}}(x^\mu)}{K_k(x^\mu)} = \frac{\langle v_\perp^2 \rangle / (\tau_{\text{rel}} \epsilon_{\text{diss}})}{1 + \frac{\tau_{\text{rel}}}{k_B n_0} \nabla_\mu J_S^\mu}. \quad (4)$$

Through the Jordan-frame matter coupling introduced below, the effective rest mass becomes $m_{\text{eff}}(x^\mu) = C(x^\mu) m_0$, generalizing the mass-energy relation [20] to

$$E(x^\mu) = C(x^\mu) m_0 c^2. \quad (5)$$

We regard Eq. (4) as a phenomenological definition; the field equations of Sec. III treat C as a fundamental dynamical scalar.

III. ACTION AND FIELD EQUATIONS

We adopt a Jordan-frame scalar-matter coupling [9, 21]:

$$S_{\text{tot}} = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R - \frac{1}{2} g^{\mu\nu} \partial_\mu C \partial_\nu C - V(C) + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{SM}}(\psi, A_\mu; C^2 g_{\mu\nu}) \right], \quad (6)$$

where $M_{\text{Pl}} = (8\pi G)^{-1/2}$ is the reduced Planck mass and R the Ricci scalar [22]. The gauge sector is a Proca-Stueckelberg Lagrangian,

$$\begin{aligned} \mathcal{L}_{\text{gauge}} = & -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{2} \left(\frac{m_0 c}{\hbar} \right)^2 C^2(x^\mu) \left(A_\mu - \frac{\hbar}{m_0 c} \partial_\mu B \right) \\ & \times \left(A^\mu - \frac{\hbar}{m_0 c} \partial^\mu B \right) - j^\mu A_\mu, \end{aligned} \quad (7)$$

with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, Stueckelberg scalar B , bare photon-mass parameter m_0 , and conserved current j^μ [23–25]. The action is invariant under

$$A_\mu \rightarrow A_\mu + \partial_\mu \alpha(x), \quad B \rightarrow B + \frac{m_0 c}{\hbar} \alpha(x). \quad (8)$$

Variation with respect to C gives the scalar equation of motion

$$\square C - \frac{\partial V(C)}{\partial C} = -g_{\text{int}} T^\mu{}_\mu, \quad (9)$$

with $\square = \nabla_\mu \nabla^\mu$, scalar coupling g_{int} , and $T^\mu{}_\mu = g^{\mu\nu} T_{\mu\nu}$ the trace of the matter stress tensor [26]. Variation with respect to $g_{\mu\nu}$ yields

$$G_{\mu\nu} = \frac{1}{M_{\text{Pl}}^2} \left(T_{\mu\nu}^{\text{SM}} + T_{\mu\nu}^{(C)} \right), \quad (10)$$

where [27]

$$T_{\mu\nu}^{(C)} = \partial_\mu C \partial_\nu C - g_{\mu\nu} \left(\frac{1}{2} g^{\alpha\beta} \partial_\alpha C \partial_\beta C + V(C) \right). \quad (11)$$

IV. PROCA-STUECKELBERG ELECTRODYNAMICS AND THE FIFTH FORCE

Varying Eq. (6) with respect to A_μ in the generalized Lorenz gauge $\nabla_\mu A^\mu = 0$ gives [28]

$$\square A^\mu - \left(\frac{C m_0 c}{\hbar} \right)^2 A^\mu + \frac{2}{C} (\partial_\nu C) F^{\mu\nu} = -\mu_0 j^\mu. \quad (12)$$

The gradient term $\frac{2}{C} (\partial_\nu C) F^{\mu\nu}$ couples the scalar gradient to the field strength. In flat spacetime the total force on a test particle of mass m and charge q is the Lorentz force plus a scalar contribution,

$$\mathbf{F}_{\text{tot}} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) + \mathbf{F}_5, \quad \mathbf{F}_5 = -g_{\text{int}} m_0 c^2 \nabla C. \quad (13)$$

Current conservation $\partial_\mu j^\mu = 0$ is preserved because the Stueckelberg field absorbs the gauge divergence through the constraint $\partial_\mu \left[C^2 \left(A^\mu - \frac{\hbar}{m_0 c} \partial^\mu B \right) \right] = 0$.

V. CHAMELEON SCREENING

To satisfy Solar-System equivalence-principle tests ($\eta < 10^{-14}$) [29, 30], we adopt a chameleon potential with an inverse-power-law self-interaction [31],

$$V(C) = \frac{1}{2} M^2 C^2 + \frac{M^{4+n}}{C^n}, \quad n > 0, \quad (14)$$

where M sets the characteristic mass scale. In a non-relativistic background of density ρ the effective potential is

$$V_{\text{eff}}(C) = \frac{1}{2} M^2 C^2 + \frac{M^{4+n}}{C^n} + g_{\text{int}} C \rho c^2. \quad (15)$$

Its minimum satisfies

$$M^2 C - n \frac{M^{4+n}}{C^{n+1}} + g_{\text{int}} \rho c^2 = 0. \quad (16)$$

In the high-density regime ($\rho \gg M^4/c^2$) the linear $M^2 C$ term is negligible and

$$C_{\text{min}}(\rho) \approx \left(\frac{n M^{4+n}}{g_{\text{int}} \rho c^2} \right)^{\frac{1}{n+1}}. \quad (17)$$

The mass of scalar excitations sets the fifth-force range $\lambda_5 = \hbar/(m_C c)$,

$$m_C^2 = \frac{\hbar^2}{c^2} \frac{\partial^2 V_{\text{eff}}}{\partial C^2} = \frac{\hbar^2}{c^2} \left(M^2 + n(n+1) \frac{M^{4+n}}{C^{n+2}} \right). \quad (18)$$

As ρ increases, $C_{\text{min}} \rightarrow 0$ and m_C grows, screening the interaction to sub-millimeter ranges in dense media. Representative values are collected in Table I; the entries follow from Eqs. (17)–(18) for an illustrative parameter choice and are meant to indicate scaling, not precise predictions.

TABLE I. Illustrative chameleon-screening parameters across environments, computed from Eqs. (17)–(18) for a representative choice of M , n , and g_{int} . Values indicate scaling only.

Environment	ρ (kg m ⁻³)	C_{min}	λ_5
Intergalactic space	1.0×10^{-27}	1.0000	115.5 μm
Interstellar medium	1.0×10^{-21}	1.0000	115.5 μm
Solar corona	1.0×10^{-16}	1.0000	115.5 μm
Laboratory vacuum	1.0×10^{-8}	0.9901	114.3 μm
Earth atmosphere	1.2	0.0090	0.12 μm
Earth crust	3.0×10^3	0.0002	< 1 nm

VI. COSMOLOGICAL DYNAMICS AND DISPERSION BOUNDS

A. Friedmann equations and conservation law

In a spatially flat FLRW spacetime, $ds^2 = -c^2 dt^2 + a(t)^2 d\mathbf{x}^2$, with $C = C(t)$, the field equations (10) reduce to [32, 33]

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_m C(t) + \frac{8\pi G}{3}\left(\frac{1}{2}\dot{C}^2 + V(C)\right), \quad (19)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho_m C(t) + \frac{3p_m}{c^2}\right) - \frac{8\pi G}{3}\left(\dot{C}^2 - V(C)\right). \quad (20)$$

Thermodynamic consistency with time-varying rest masses requires

$$\dot{\rho}_m + 3H\left(\rho_m + \frac{p_m}{c^2}\right) = -\rho_m \frac{\dot{C}}{C}, \quad (21)$$

which couples matter to the scalar and defines an effective dark-energy term $\Lambda_{\text{eff}}(t) = 8\pi G V(C(t))$ [34, 35]. Regions with $K_k \gg 1$ drive $C \rightarrow 0$, decoupling matter from the gauge sector and yielding candidate dark-matter behavior [36].

B. Fast-radio-burst dispersion

For propagation over cosmological distances with negligible spatial gradients ($\nabla C \rightarrow 0$), the dispersion relation is

$$\omega^2(t) = c^2 k^2 + \omega_p^2(t) + \omega_\gamma^2(t), \quad (22)$$

with plasma frequency $\omega_p = (e^2 n_e / \varepsilon_0 m_e)^{1/2}$ and photon-mass term $\omega_\gamma = C(t) m_0 c^2 / \hbar$. The differential arrival time between frequencies ν_1 and ν_2 from redshift z is

$$\begin{aligned} \Delta t = & \frac{e^2(\nu_1^{-2} - \nu_2^{-2})}{8\pi^2 \varepsilon_0 m_e c} \text{DM}_{\text{IGM}} \\ & + \frac{m_0^2 c^3 (\nu_1^{-2} - \nu_2^{-2})}{8\pi^2 \hbar^2} \int_0^z \frac{C^2(z')}{(1+z')H(z')} dz'. \end{aligned} \quad (23)$$

Applying this to FRB121102 ($z = 0.1927$) bounds the present-day photon mass to $m_\gamma(t_0) = C(t_0)m_0 \lesssim 3.9 \times 10^{-51} \text{ kg} \approx 2.2 \times 10^{-14} \text{ eV}/c^2$, consistent with existing limits [37].

VII. SUBATOMIC PHENOMENOLOGY

A. The X17 anomaly

The ATOMKI experiments report an anomalous angular excess near $\theta \approx 140^\circ$ in internal-pair-creation transitions of excited ^8Be and ^4He nuclei [38]. In the present framework this is interpreted as a localized resonance of the massive

Proca–Stueckelberg photon. Where ∇C is large the static potential takes a Yukawa form,

$$V(r) = -\frac{e}{r} e^{-m_\gamma(C)cr/\hbar}, \quad (24)$$

and inside the turbulent nuclear boundary the effective mass approaches $m_\gamma = C_{\text{nuc}} m_0 \approx 16.7 \text{ MeV}/c^2$, matching the reported X17 scale. A protophobic signature arises if the effective current carries a scalar modulation, $\partial_\mu F^{\mu\nu} = e\bar{\psi}\gamma^\nu(Q_{\text{SM}} + g_{\text{int}}C)\psi$, suppressing the coupling to protons relative to neutrons and electrons [39]. We note that reproducing the precise protophobic couplings quantitatively requires a dedicated fit that is beyond the scope of this paper.

B. Lepton-flavor-universality tests

Measurements of R_K and R_{K^*} in rare semileptonic B decays have shown tensions with lepton-flavor universality [40]. Because the SM sector couples to C through the conformal factor $C^2 g_{\mu\nu}$, the lepton mass terms receive a universal rescaling,

$$\mathcal{L}_{\text{int}} = -C(x^\mu) \sum_{\ell=e,\mu,\tau} y_\ell \bar{\psi}_\ell \psi_\ell H, \quad (25)$$

and the effective Hamiltonian for $b \rightarrow s$ transitions is

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* (C_9^\mu \mathcal{O}_9^\mu + C_{10}^\mu \mathcal{O}_{10}^\mu), \quad (26)$$

with $\mathcal{O}_9^\mu = (e^2/16\pi^2)(\bar{s}\gamma_\alpha P_L b)(\bar{\mu}\gamma^\alpha \mu)$. Since m_μ lies closer to the assumed field-fluctuation scale than m_e , a generation-dependent running is postulated,

$$\frac{dC_9^\mu}{d\ln \mu} = \gamma_9 + \left(\frac{y_\mu^2}{16\pi^2}\right) \kappa g_{\text{int}}^2 \left(\frac{\partial^2 C}{\partial x_\mu \partial x^\mu}\right) \frac{1}{m_W^2}, \quad (27)$$

which, integrated from m_W to m_b , would produce a negative shift $\Delta C_9^\mu \approx -0.5$ in the muon channel while leaving the electron channel essentially unshifted. We flag Eq. (27) as the least secure step in the construction: it introduces a dimensionful curvature source whose renormalization-group interpretation requires justification, and we present it as a conjecture to be tested rather than a derived result.

VIII. EXPERIMENTAL PATHWAYS

Several falsifiable tests follow from the model:

1. *Resonant cavities.* Precision torque measurements on high-density plasmas in symmetric superconducting cavities to probe spatial gradients ∇C [30, 41].
2. *Synchrotron radiation.* High-energy electron trajectories in focused fields to constrain $m_{\text{eff}}(C)$ via modifications to the Liénard–Wiechert spectrum [42, 43].
3. *Deep inelastic scattering.* Single-proton targets to test internal entropy-generation effects through parton-distribution modifications [44, 45].

IX. DISCUSSION: ASSUMPTIONS AND OPEN ISSUES

For transparency we list the principal assumptions and unresolved points, since they determine how the model should be tested and where it is most vulnerable. (i) The microphysical definition (4) is a parameterization, not a derivation; a first-principles link between C and quantum kinetic theory remains to be established. (ii) A universal matter coupling $C^2 g_{\mu\nu}$ combined with the environment dependence in Table I must be checked against fifth-force, lunar-laser-ranging, and equivalence-principle data simultaneously; the chameleon mechanism is invoked precisely to make this possible, but a global consistency fit is required. (iii) A single field cannot naturally accommodate both a $\sim 10^{-14} \text{ eV}$ cosmological photon mass and a $\sim 17 \text{ MeV}$ nuclear-scale resonance without a large environmental hierarchy in C ; whether the screening dynamics can span these scales is an open quantitative question. (iv) The lepton-flavor-universality mechanism of Eq. (27) is conjectural, as noted above. We regard these as the sharp, testable weak points of the proposal rather than as incidental caveats.

X. CONCLUSION

We have formulated a scalar–tensor extension of the SM and GR organized around a circulatory scalar field $C(x^\mu)$ that couples universally to matter and to a gauge-invariant Proca–Stueckelberg photon. The framework connects a position-dependent rest mass and photon mass, a chameleon-screened fifth force, and a dynamical dark-energy sector, and it suggests interpretations of the X17 and lepton-flavor-universality anomalies. We have been explicit about which elements are derived, which are phenomenological, and which are conjectural, and we have identified concrete laboratory, astrophysical, and collider tests that can falsify the model.

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