

CP–THEORY: Final Closure of the Cosmological Potential Framework and Laboratory Falsifiability

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Abstract

We present the final closure of the Cosmological Potential (CP) framework introduced in Papers I and II, formulating a scalar–tensor extension of gravity in which an effective scalar degree of freedom emerges from a higher-dimensional Kaluza–Klein sector. The theory predicts a density-dependent effective mass for the scalar field, leading to environmental screening in high-density regions and dynamical activation in low-density environments. We derive the modified Einstein equations, the scalar field equation of motion for a quadratic potential, and the resulting Yukawa-type correction to Newtonian gravity. Conservative numerical estimates for the coupling parameters are provided, and explicit laboratory falsification channels are identified. The framework is presented as complete at the theoretical level and directly testable with existing or near-term experimental technology.

1 Introduction

This work completes the CP–THEORY program initiated in Papers I and II, where a higher-dimensional scalar sector was shown to induce an effective four-dimensional scalar–tensor modification of gravity. The goal of the present paper is to provide final theoretical closure and to explicitly identify experimentally falsifiable predictions accessible to laboratory and space-based precision tests. The framework is constructed to remain consistent with current equivalence principle and fifth-force constraints while predicting potentially observable deviations in low-density environments.

2 Action and Field Equations

We consider the effective four-dimensional action

$$S = \int d^4x \sqrt{-g} \left[\frac{\phi}{16\pi} R - \frac{\omega}{2\phi} (\nabla\phi)^2 - V(\phi) \right] + S_m[g_{\mu\nu}, \psi_m], \quad (1)$$

where ϕ is the CP scalar field, ω is a dimensionless coupling parameter, and $V(\phi)$ is the effective potential induced by the higher-dimensional sector. Variation with respect to $g_{\mu\nu}$ yields

$$G_{\mu\nu} = \frac{8\pi}{\phi} T_{\mu\nu}^{(m)} + \frac{\omega}{\phi^2} \left(\nabla_\mu \phi \nabla_\nu \phi - \frac{1}{2} g_{\mu\nu} (\nabla\phi)^2 \right) + \frac{1}{\phi} (\nabla_\mu \nabla_\nu \phi - g_{\mu\nu} \square\phi) - g_{\mu\nu} \frac{V(\phi)}{2\phi}. \quad (2)$$

The scalar field obeys

$$(2\omega + 3)\square\phi = 8\pi T^{(m)} + \phi V'(\phi) - 2V(\phi). \quad (3)$$

3 Quadratic Potential and Effective Mass

We assume a quadratic potential around the cosmological background value ϕ_0 ,

$$V(\phi) = \frac{1}{2}m_0^2(\phi - \phi_0)^2. \quad (4)$$

We decompose the scalar field as $\phi = \phi_0 + \varphi$, where φ denotes the dynamical perturbation around the background value ϕ_0 . Linearizing the field equations in φ yields

$$(\square - m_{\text{eff}}^2) \varphi = -\frac{8\pi}{2\omega + 3} T^{(m)}, \quad (5)$$

with density-dependent effective mass

$$m_{\text{eff}}^2(\rho) \simeq m_0^2 + \frac{8\pi\rho}{(2\omega + 3)\phi_0}. \quad (6)$$

This induces environmental screening in high-density regions.

4 Modified Newtonian Limit and Fifth Force

In the weak-field, static limit, the scalar field mediates a Yukawa-type correction to the Newtonian potential:

$$V(r) = -\frac{GM}{r} [1 + \alpha e^{-m_{\text{eff}}r}], \quad (7)$$

with coupling strength

$$\alpha = \frac{1}{2\omega + 3}. \quad (8)$$

The ratio between scalar and gravitational forces reads

$$\frac{F_\phi}{F_g} = \alpha e^{-m_{\text{eff}}r}. \quad (9)$$

5 Conservative Parameter Estimates and Experimental Window

Taking a conservative bound $\omega \sim 10^4$, we obtain $\alpha \sim 5 \times 10^{-5}$. In terrestrial environments, m_{eff} is large and the fifth force is exponentially suppressed. In low-density space-based or high-vacuum laboratory conditions, the interaction range $\lambda_{\text{eff}} = m_{\text{eff}}^{-1}$ may extend to macroscopic scales, opening a window for resonant or precision force experiments. For $\omega \sim 10^4$ and ultra-high vacuum laboratory conditions with effective mass density $\rho \lesssim 10^{-15} \text{ kg m}^{-3}$, the interaction range $\lambda_{\text{eff}} = m_{\text{eff}}^{-1}$ can extend to macroscopic laboratory scales, $\lambda_{\text{eff}} \sim 10^{-2} - 1 \text{ m}$, making resonant cavities and precision force-balance experiments potentially sensitive to CP-THEORY signatures.

Null results directly constrain the parameter space of CP-THEORY.

6 Environmental Screening: Schematic Representation

The qualitative behavior of the CP scalar field across different density regimes is schematically illustrated in Fig. 1, highlighting the environmental screening mechanism and the transition between suppressed and unscreened regimes.

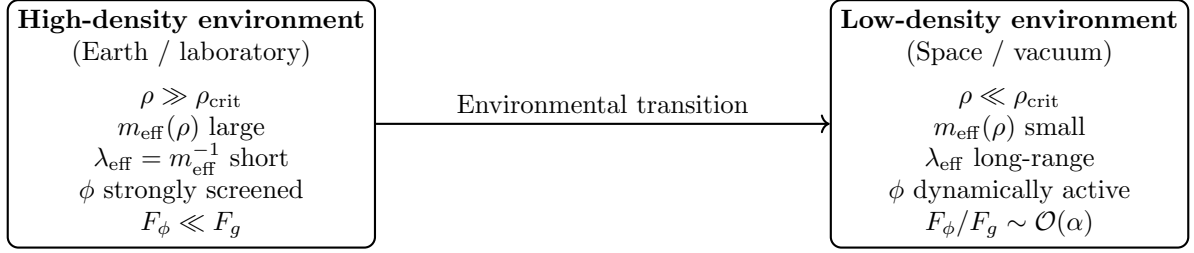


Figure 1: Environmental screening and dynamical activation of the CP scalar field. In high-density environments the effective mass is large and suppresses scalar-mediated forces, while in low-density regimes the interaction range increases, enabling potential laboratory or space-based detection.

7 Conclusions and Experimental Outlook

We have provided final theoretical closure of CP–THEORY, deriving the complete scalar–tensor field equations, the effective mass mechanism responsible for environmental screening, and the resulting Yukawa-type deviations from Newtonian gravity. The framework is internally consistent, compatible with existing constraints for conservative parameter choices, and explicitly falsifiable with present or near-term experimental technology. The theory is therefore complete at the theoretical level, and its future status is now entirely determined by experimental investigation.

References

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