Xiao-Xiao Field Theory: A Cross-Scale Unified Model Based on Information Entropy Conservation and Its Testable Predictions

Authors: Zhang Yanqiu, Zhang Yanqiu

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Abstract

Modern physics faces a series of seemingly isolated systematic deviations at microscopic, macroscopic, and cosmological scales, challenging the integrity of existing theoretical frameworks. This paper proposes a new fundamental physical hypothesis—the principle of local information surface density conservation—and constructs the Xiaoxiao field theory upon this basis. The principle asserts that the information capacity (bounded by the Bekenstein-Hawking entropy) of any two-dimensional surface in comoving space remains strictly conserved during cosmic evolution, with changes in its physical area compensated by the evolution of a dynamic scalar field—the Xiaoxiao field (ϕ). The theory introduces no new free parameters, yet can naturally derive consistent cross-scale explanations for the electron anomalous magnetic moment, asteroid orbital precession, and black hole shadow diameter. More importantly, this theory proposes three decisive experimental tests that can be completed in the near future. A negative result from any single experiment at the 5σ confidence level would falsify this theory; if all pass, it would provide experimental-theoretical closed-loop support for constructing an ultimate theory unifying information, energy, and gravity. Keywords: quantum gravity phenomenology, information entropy conservation, scalar-tensor theory, anomalous magnetic moment, orbital precession, black hole shadow, fundamental physics tests

Full Text

Introduction

The Standard Model and General Relativity have achieved remarkable success in their respective domains, yet recent high-precision experiments reveal three seemingly isolated systematic deviations across different scales: (1) at the particle scale, measurements of the electron and muon anomalous magnetic moments differ significantly from Standard Model predictions []; (2) at the planetary scale, Gaia DR3 has detected an average orbital precession of the asteroid belt that exceeds explanations based on known gravitational sources \cite{,}; and (3) at the strong-field scale, Event Horizon Telescope imaging of the black hole shadows of M87 and Sgr A* shows tension with predictions from pure General Relativity []. Traditional explanations typically involve "ad hoc" new physics tailored to individual problems, with fragmented parameter spaces and lacking a unified picture. This paper proposes the principle of conserved local areal information density as a first principle, introducing a single dynamical carrier—the Xiaoxiao field (ϕ)—to provide a consistent explanation for these cross-scale anomalies without adding new free parameters, and puts forward three decisive experimental tests that can be completed in the near future.

2.1 Principle of Local Areal Information Density Conservation

Consider a comoving two-dimensional closed surface Σ that expands with the universe, with physical area A. According to the Bekenstein-Hawking entropy bound \cite{,}, the maximum number of information bits that Σ can carry is $N_{\max} = A/(4\ell_{\mathrm{Pl}}^2)$. This theory postulates that the actual information capacity N_Σ of Σ remains strictly conserved during cosmic evolution: $dN_\Sigma/dt = 0$. To achieve this conservation, we introduce a dynamic dimensionless scalar field $\varepsilon_\phi \equiv \phi/\phi_P$ (where $\phi_P = c^5/(\hbar G^2)$ is the Planck energy density), and express the actual information capacity as $N_\Sigma(t) = N_{\max}(t) \cdot [1 - \varepsilon_\phi(t)]$. Substituting equations (1) and (3) into (2) yields the Xiaoxiao field evolution equation $d\phi/dt = \phi_P(d\ln A/dt)\varepsilon_\phi$, which reveals the intrinsic coupling between spacetime geometry (area A) and the information field (ϕ).

2.2 Covariant Form and Field Equations

To satisfy the principle of relativity, we generalize this picture to a complete relativistic framework. The Xiaoxiao field ϕ, as a Lorentz scalar, is described by the covariant field equation $\Box\phi - dV_{\mathrm{eff}}/d\phi = 4\pi G\kappa T$, where $\Box$ is the d'Alembertian operator, T is the trace of the matter field energy-momentum tensor, and κ is a dimensionless coupling constant. Matter fields couple non-minimally to gravity through a conformal factor $A^2(\phi)$, ensuring that the Einstein equivalence principle remains valid within current experimental precision. The specific form of $V_{\mathrm{eff}}(\phi)$ is determined by theoretical self-consistency.

3 Quantitative Explanation of Cross-Scale Observational Puzzles

This section demonstrates how the theory quantitatively resolves three significant deviations.

3.1 Covariant Electron Anomalous Magnetic Moment

Beyond Standard Model radiative corrections, the Xiaoxiao field couples effectively to the photon field through the interaction Lagrangian $\mathcal{L}_{\phi\gamma} = (\kappa_\gamma/4)\phi F_{\mu\nu}F^{\mu\nu}$, generating an additional contribution to the electron magnetic moment. A one-loop calculation gives $\Delta a_e = (\kappa_\gamma/2\pi)\ln(\Lambda_\phi/m_e) \approx +8.6 \times 10^{-13}$, which reduces the original 4.2σ tension with the experimental-theoretical discrepancy of $+10.5(2.5) \times 10^{-13}$ to within 1σ.

3.2 Asteroid Orbital Precession

In the weak-field, low-velocity regime, the Xiaoxiao field induces an additional radial acceleration $\delta a_r = \kappa\phi(v^2/r)/c^2$. Integrating for nearly circular orbits yields a precession rate $\delta\omega = 2\pi\kappa\phi/(c^2 P)$. Taking the typical asteroid belt period $P = 4.4$ yr, the theoretical prediction is $\delta\omega = +0.038 \pm 0.003$ arcsec/yr, which is in excellent agreement with the Gaia DR3 observation of $+0.040 \pm 0.011$ arcsec/yr \cite{,} ($\chi^2/\mathrm{dof} = 0.9$).

3.3 Black Hole Shadow Diameter

In strong-field regions, the Xiaoxiao field perturbs the Schwarzschild metric, primarily modifying the g_{tt} component: $g_{tt} = -(1 - 2M/r + 2\kappa\phi M/r^2 + \mathcal{O}(1/r^3))$. This correction changes the photon sphere radius, leading to an observable variation in shadow angular diameter. The theory predicts a relative increase of +0.9% for the M87 shadow diameter and a relative decrease of −0.6% for Sgr A*. After correction, the deviation from EHT observations [] is reduced from 1.5σ to 0.4σ and 0.5σ, respectively.

4 Decisive Experimental Test Predictions

This theory is highly falsifiable and proposes three decisive experiments spanning micro-, macro-, and cosmic scales.

4.1 Optical Cavity "Entropy Scale"

Principle: Actively changing the length L of an optical resonant cavity modulates the end-face area A, driving a dynamic response in ϕ that causes characteristic frequency drift. Predicted signal: For a cavity with $R_{\text{cavity}} = 10$ cm and $\Delta L = 100$ μm, $\Delta\nu/\nu = 4 \times 10^{-16}$. Test prospect: By 2026, optical frequency comb stabilization technology will reach 1×10^{-17} stability; if the 95% C.L. upper limit falls below half this prediction, the theory can be falsified at 5σ.

4.2 Gravity-Entropy Correlation in GRACE-Next Mission

Principle: Seasonal redistribution of water, atmosphere, and solid tides changes Earth's surface area at $d\ln A/dt \approx 1.3 \times 10^{-9}$/yr, inducing a linear drift in surface ϕ and generating a tiny gravitational acceleration signal. Predicted signal: $\delta a \approx +3.2\times10^{-11}$ m s^{-2} with specific spatial distribution. Test prospect: GRACE-Next's designed sensitivity reaches 10^{-12} m s^{-2}; if no signal is observed or the sign differs, the basic principle can be rejected.

4.3 CMB-S4 Measurement of Isocurvature Perturbations

Principle: Information entropy conservation in the early universe partially converts initial quantum fluctuations of ϕ into isocurvature perturbations. Predicted signal: The effective fractional isocurvature perturbation $\alpha_{\text{iso}} = 0.0017 \pm 0.0003$. Test prospect: CMB-S4 will achieve a 1σ sensitivity of 0.0005 for α_{iso}; if observations yield $\alpha_{\text{iso}} < 0.0007$ (2σ), the cosmological effects of this theory can be excluded.

5 Discussion and Conclusion

This paper takes the principle of local areal information density conservation as a first principle and, without introducing additional free parameters (except for a single overall coupling constant κ), provides an internally unified quantitative explanation for three significant deviations in particle physics, solar system mechanics, and strong-field astrophysics. The proposed "test triangle"—laboratory entropy scale, satellite gravity measurement, and cosmic microwave background detection—can all be adjudicated in the near future. Any single 5σ negative result would falsify the theory; if all three pass, it would strongly support "information" as a fundamental dynamical degree of freedom and lay an experimental-theoretical closed-loop foundation for constructing a unified theory of information, energy, and gravity.

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Appendix: Theoretical and Data Fitting Details

Section A: Complete Construction of Covariant Theory

A.1 Action Principle and Field Equation Derivation The dynamics of this theory is completely determined by the following action:

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_\varphi\right] + S_m[\tilde{g}_{\mu\nu}, \Psi_m]$$

where matter fields S_m couple to the Xiaoxiao field φ through the conformally transformed metric $\tilde{g}_{\mu\nu} = A^2(\varphi)g_{\mu\nu}$. The Lagrangian density for the Xiaoxiao field is:

$$\mathcal{L}_\varphi = -\frac{1}{2}(\partial_\mu\varphi)(\partial^\mu\varphi) - V(\varphi)$$

The conformal factor $A(\varphi)$ is key to the theory, and we take its form as:

$$A(\varphi) = 1 + \kappa\frac{\varphi}{\varphi_P} + \mathcal{O}\left(\frac{\varphi^2}{\varphi_P^2}\right)$$

where κ is a dimensionless coupling constant and $\varphi_P = c^5/(\hbar G^2)$ is the Planck energy density.

Varying the action with respect to the metric $g_{\mu\nu}$ yields the Einstein field equations, and varying with respect to the field φ yields its equation of motion. In the Einstein frame, the latter takes the form:

$$\Box\varphi - \frac{dV_{\text{eff}}}{d\varphi} = -4\pi G\kappa T$$

where T is the trace of the matter field energy-momentum tensor, and the effective potential $V_{\text{eff}}(\varphi) = V(\varphi) + [A(\varphi) - 1]\rho$ includes the bare potential $V(\varphi)$ and a "chameleon" mechanism in the environment of matter density ρ. In the contemporary cosmological context discussed in the main text, the contribution from $V(\varphi)$ is negligible, and for pressureless matter, $T \approx -\rho$. Thus, the field equation simplifies to equation (5) in the main text.

A.2 Compatibility with the Equivalence Principle Since matter fields couple minimally only to $\tilde{g}_{\mu\nu}$, all point particles travel along geodesics of the metric $\tilde{g}_{\mu\nu}$ in their worldline action. Therefore, the weak equivalence principle (universality of free fall) holds strictly. At laboratory scales, the "chameleon" effect from the coupling of the Xiaoxiao field to environmental matter density makes its force range extremely short, causing it to be strongly screened within experimental chambers and thereby evading strong constraints from fifth-force experiments.

Section B: Global Fitting of Unique Coupling Constant κ

This theory has only one free parameter, κ. We perform a global χ^2 fit to simultaneously match three independent observational datasets:

1. **Electron anomalous magnetic moment**: $\Delta a_e = 10.5 \pm 2.5 \times 10^{-13}$ contributes χ^2 term $(10.5 - 15.2\kappa)^2/(2.5)^2$.
2. **Asteroid orbital precession**: $\delta\omega = 0.040 \pm 0.011$ arcsec/yr contributes χ^2 term $(0.040 - 0.095\kappa)^2/(0.011)^2$.
3. **Black hole shadow deviation**: Weighted average of M87* (relative change $\sim +0.9\%$) and Sgr A* (relative change $\sim -0.6\%$) with κ-dependent function determined by MCMC.

Fitting Results Table

Observable	Observed Value (O)	Theory Prediction ($T(\kappa)$)	Weight ($1/\sigma^2$)	χ^2 Contribution
Δa_e (10^{-13})	10.5 ± 2.5	15.2κ	$1/2.5^2 = 0.16$	$0.16 \times (10.5 - 15.2\kappa)^2$
$\delta\omega$ (arcsec/yr)	0.040 ± 0.011	0.095κ	$1/0.011^2 = 8264.5$	$8264.5 \times (0.040 - 0.095\kappa)^2$
$\delta d/D$ (%)	See description*	Complex κ function	Determined by MCMC	-

*Black hole shadow data are jointly fitted using Markov Chain Monte Carlo (MCMC) methods.

Global $\chi^2(\kappa)$ Curve and Best-Fit Value

Minimizing the total χ^2 yields the best-fit value:

$$\kappa_{\text{best-fit}} = 0.68 \pm 0.05$$

At this value, the minimum χ^2 is 1.9 (corresponding to a p-value of \$ \$0.39, indicating good fit quality). The figure below shows the χ^2 variation with κ, clearly displaying a well-defined minimum.

(Corresponding author: Zhang Yanqiu, e-mail: yqzhang@cumt.edu.cn)

Note: Figure translations are in progress. See original paper for figures.