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Article

Coherence-Based Scalar-Tensor Extension of General Relativity: Variational Formulation, Observational Bounds, and Predictions for High-Eccentricity Orbital Systems

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Abstract

We present a scalar-tensor extension of General Relativity (GR) in which a covariant coherence field Φ is non-minimally coupled to spacetime curvature through a variational action of the form $S = \int d^4x\sqrt{-g}\,[(1+\lambda\Phi)R - \frac{\omega}{2}\nabla_\mu\Phi\nabla^\mu\Phi - V(\Phi)]/(16\pi G) + S_m$. Variation with respect to the metric yields modified Einstein equations $G_{\mu\nu} + C_{\mu\nu}(\Phi) = (8\pi G/c^4)\,T_{\mu\nu}$, where the coherence tensor $C_{\mu\nu}$ encodes gradients of the scalar field and vanishes identically when $\Phi \to 0$, recovering GR exactly. We derive the effective correction to periapsis precession in the weak-field regime and show that it is governed by a single dimensionless combination $\Xi = e^2(1-e^2)^{-1} \cdot r_g/a$, where e is the orbital eccentricity, a the semi-major axis, and $r_g = 2GM/c^2$ the gravitational radius. The effective coupling λ_{eff} is bounded by precision pulsar timing to $\lambda_{\text{eff}} < 1.95$, which renders Solar System corrections undetectable at present but predicts corrections of order 10^{-3} for the S2 star orbiting Sagittarius A* — within reach of next-generation interferometric astrometry (GRAVITY+, ELT). The theory constitutes a phenomenological effective framework with a single effective parameter λ_{eff}, constrained by internal consistency and binary pulsar observations. We outline falsifiable predictions and identify the regimes where screening mechanisms may permit larger deviations, motivating future work on galactic-scale applications.

Keywords: general relativity; scalar-tensor theory; orbital precession; Sagittarius A*; S2 Star; binary pulsars; modified gravity; coherence field; eccentricity; gravitational tests

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1. Introduction

General Relativity (GR) remains the most precisely tested theory of gravitational dynamics, with agreement at the level of parts per million in Solar System ephemerides [1], binary pulsar timing [2,3], and strong-field astrometry near the Galactic Center [4,5]. Nevertheless, two persistent challenges motivate the exploration of extensions beyond GR.

First, astrophysical observations at galactic and cosmological scales require the introduction of dark matter and dark energy [6–8], components that remain undetected by non-gravitational means. Second, no fundamental principle prohibits the existence of additional scalar degrees of freedom coupled to gravity, and such couplings arise naturally in string theory, higher-dimensional models, and quantum gravity approaches [9,10].

Scalar-tensor theories constitute the most studied class of GR extensions [11–13]. They introduce a scalar field non-minimally coupled to curvature while preserving diffeomorphism invariance and admitting a well-defined GR limit. Modern incarnations, including Horndeski gravity and its extensions, provide screening mechanisms that suppress scalar effects in dense environments while allowing deviations at cosmological scales [14–16].

In this work, we present a scalar-tensor theory motivated by the concept of *informational coherence*: the scalar field Φ is interpreted as encoding the degree of organized coherence within the gravitational

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system, with its gradients generating an effective correction to Einstein's equations. This interpretation is phenomenological rather than microscopic — Φ functions as an effective macroscopic descriptor analogous to order parameters in condensed matter physics.

The structure of the paper is as follows. Section 2 presents the variational action and derives the modified field equations. Section 3 establishes the GR limit and covariant conservation. Section 4 derives the effective correction to orbital precession and introduces the dimensionless asymmetry parameter Ξ. Section 5 presents observational bounds from the Solar System and binary pulsars. Section 6 discusses the S2 star as a target system. Section 7 outlines predictions for high-eccentricity systems. Section 8 discusses galactic-scale extensions and screening mechanisms. Section 9 summarizes falsifiable tests. Section 10 concludes.

2. Variational Action and Field Equations

We introduce a real scalar field $\Phi(x^\mu)$, interpreted as an effective coherence potential, non-minimally coupled to spacetime curvature. The action is

$$S = \frac{1}{16\pi G} \int d^4x \sqrt{-g} \left[(1 + \lambda\Phi) R - \frac{\omega}{2} \nabla_\mu\Phi \nabla^\mu\Phi - V(\Phi) \right] + S_m, \tag{1}$$

where R is the Ricci scalar, λ is a dimensionless coherence coupling constant, ω is the kinetic coefficient, $V(\Phi)$ is the coherence stabilization potential, and $S_m[g_{\mu\nu}, \Psi]$ is the matter action for fields Ψ minimally coupled to the metric.

This action belongs to the class of scalar-tensor theories studied by Bergmann [17], Wagoner [18], and Nordtvedt [19], and constitutes a specific case within the general Horndeski framework [12]. Its distinguishing feature within the present work is the interpretive identification of Φ with informational coherence organization, which motivates specific predictions for the dependence of corrections on orbital asymmetry.

2.1. Metric Variation: Modified Field Equations

Varying Eq. (1) with respect to the inverse metric $g^{\mu\nu}$ yields

$$\begin{aligned} (1 + \lambda\Phi) G_{\mu\nu} &+ \lambda\left(\nabla_\mu\nabla_\nu\Phi - g_{\mu\nu}\Box\Phi\right) \\ &+ \frac{\omega}{2}\left(\nabla_\mu\Phi \nabla_\nu\Phi - \frac{1}{2} g_{\mu\nu} \nabla_\alpha\Phi \nabla^\alpha\Phi\right) \\ &+ \frac{1}{2} g_{\mu\nu} V(\Phi) = \frac{8\pi G}{c^4} T_{\mu\nu}, \end{aligned} \tag{2}$$

where $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R$ is the Einstein tensor and $T_{\mu\nu}$ the matter stress-energy tensor.

In the weak-coherence regime $|\lambda\Phi| \ll 1$, the field equations reduce to leading order to

$$G_{\mu\nu} + C_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}, \tag{3}$$

where the coherence tensor is defined as

$$C_{\mu\nu} \equiv \lambda\left(\nabla_\mu\nabla_\nu\Phi - g_{\mu\nu}\Box\Phi\right). \tag{4}$$

This tensor arises directly from the variational principle and is not introduced by postulate.

2.2. Scalar Field Variation: Coherence Dynamics

Varying Eq. (1) with respect to Φ gives the coherence evolution equation:

$$\omega\Box\Phi - V'(\Phi) + \lambda R = 0. \tag{5}$$

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This equation links coherence dynamics to spacetime curvature: the Ricci scalar sources Φ, while the potential $V(\Phi)$ provides stabilization against runaway behavior.

3. General Relativity Limit and Covariant Conservation

In the limit $\Phi \to 0$ and $\nabla_\mu \Phi \to 0$, the coherence tensor vanishes identically, $C_{\mu\nu} = 0$, and the full field equations (2) reduce continuously to Einstein's equations:

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \,. \tag{6}$$

This ensures exact compatibility with all experimentally verified predictions of GR in regimes where coherence gradients are negligible.

Taking the covariant divergence of Eq. (2) and using the contracted Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$, the coherence field equation (5) guarantees

$$\nabla^\mu T_{\mu\nu} = 0 \,, \tag{7}$$

provided matter is minimally coupled. The formulation is therefore covariantly closed: it admits an action, produces field equations, and preserves the geometric conservation structure of relativistic gravity.

4. Effective Correction to Orbital Precession

In General Relativity, the periapsis advance per orbit of a test body in a Schwarzschild spacetime is [20]

$$\Delta\phi_{\rm GR} = \frac{6\pi\, G\, M}{c^2\, a\,(1 - e^2)} \,, \tag{8}$$

where M is the central mass, a the semi-major axis, and e the eccentricity.

Within the scalar-tensor framework of Eq. (1), the coherence field Φ modifies the effective gravitational potential experienced by orbiting bodies. In the weak-field, perturbative regime ($|\lambda\Phi| \ll 1$), the leading-order correction to precession can be parameterized as

$$\Delta\phi = \Delta\phi_{\rm GR}\,(1 + \delta) \,, \tag{9}$$

where δ is the fractional coherence correction.

4.1. Dimensionless Asymmetry Parameter

On general grounds, the correction δ must depend on the orbital parameters and the gravitational compactness of the system through dimensionless combinations. We define the *orbital asymmetry parameter*

$$\Xi \equiv \frac{e^2}{1 - e^2} \cdot \frac{r_g}{a} \,, \tag{10}$$

where $r_g = 2GM/c^2$ is the gravitational radius. This parameter is manifestly dimensionless, vanishes for circular orbits ($e = 0$), and grows with both eccentricity and gravitational compactness.

The effective correction takes the form

$$\delta = \lambda_{\rm eff}^2\, \Xi \,, \tag{11}$$

where $\lambda_{\rm eff}$ is the effective coherence coupling strength, encoding the combined effect of the coupling constant λ and the coherence field profile.

This parameterization is motivated by the structure of the field equations: the coherence tensor $C_{\mu\nu}$ contributes at second order in λ to the effective potential, and the orbital sensitivity to this correction is enhanced by eccentricity through the periapsis geometry.

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4.2. Perturbative Derivation of δ

We outline the derivation of Eq. (11) from the field equations. In the weak-field regime, the scalar equation (5) reduces in the static, spherically symmetric case to

$$\omega\,\nabla^2\Phi + \lambda\,R = 0\,, \tag{12}$$

where, for a Schwarzschild source with $R \approx 0$ in vacuum, the leading solution sourced by the trace of the matter distribution yields $\Phi(r) \approx -(\lambda/\omega)\,GM/(c^2 r)$.

Substituting into the coherence tensor (4), the additional radial force on a test body is

$$f_{\rm coh}(r) = -\frac{\lambda^2}{\omega}\,\frac{G^2M^2}{c^4\,r^4}\,, \tag{13}$$

which modifies the effective Newtonian potential by a term $\delta U \propto -(\lambda^2/\omega)\,r_g^2/(4r^3)$, where $r_g = 2GM/c^2$.

The periapsis advance receives corrections from the orbit-averaged perturbation of this potential. Using standard perturbation theory for Keplerian orbits (see, e.g., Ref. [20]), the orbit-averaged radial perturbation is

$$\langle\delta U\rangle_{\rm orbit} \propto \frac{\lambda^2}{\omega}\,\frac{r_g^2}{a^3\,(1-e^2)^{3/2}}\int_0^{2\pi}\frac{d\nu}{(1+e\cos\nu)}\,, \tag{14}$$

where ν is the true anomaly. The integral evaluates to $2\pi/(1-e^2)^{1/2}$, yielding an overall scaling $\propto r_g^2/[a^3(1-e^2)^2]$.

Comparing this to the GR precession formula $\Delta\phi_{\rm GR} \propto r_g/[a(1-e^2)]$, the fractional correction takes the form

$$\delta = \frac{\Delta\phi_{\rm coh}}{\Delta\phi_{\rm GR}} \propto \frac{\lambda^2}{\omega}\,\frac{r_g}{a\,(1-e^2)}\,. \tag{15}$$

Writing $1/(1-e^2) = 1 + e^2/(1-e^2)$ and noting that the leading constant term (e-independent) is absorbed into a redefinition of the gravitational coupling G (indistinguishable from GR), the observable correction is the eccentricity-dependent residual:

$$\delta = \lambda_{\rm eff}^2\,\frac{e^2}{1-e^2}\,\frac{r_g}{a} = \lambda_{\rm eff}^2\,\Xi\,, \tag{16}$$

where $\lambda_{\rm eff}^2 \equiv \lambda^2/\omega$ encapsulates the coupling and kinetic coefficients into a single measurable parameter. The e-independent part of Eq. (15) is unobservable because it shifts the precession of *all* orbits — circular and eccentric alike — by the same fractional amount, making it fully degenerate with a rescaling of Newton's constant G. Only the eccentricity-dependent residual constitutes a genuine new prediction distinguishable from GR. This derivation confirms that δ vanishes for circular orbits ($e = 0$), scales quadratically with the coupling, and is enhanced by eccentricity through the factor $e^2/(1-e^2)$.

4.3. Physical Interpretation

The parameter Ξ measures the degree to which an orbit samples strong-field, anisotropic regions of the coherence gradient. Circular orbits ($e = 0$) experience a symmetric coherence distribution and receive no correction. Highly eccentric orbits around compact objects probe steep coherence gradients near periapsis, amplifying δ.

The factor r_g/a ensures that the correction scales with the relativistic compactness of the system, consistent with the expectation that scalar-tensor effects become relevant only where curvature is significant.

5. Observational Bounds

The effective coupling $\lambda_{\rm eff}$ is constrained by precision tests of gravity in the Solar System and in relativistic binary pulsar systems.

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5.1. Solar System

The perihelion advance of Mercury is the classical test of GR in the Solar System, with the observed value $\dot{\omega}_{\rm obs} = 42.98 \pm 0.04$ arcsec/century agreeing with the GR prediction to better than 0.1% [1,21].

For Mercury ($e = 0.2056$, $a = 0.387$ AU, $M = M_\odot$), the asymmetry parameter is $\Xi_{\rm Merc} = 2.25 \times 10^{-9}$. Requiring $|\delta| < 10^{-3}$ yields $\lambda_{\rm eff} < 666$. The Solar System thus provides only a weak constraint on the coherence coupling.

Additional constraints from the Cassini spacecraft measurement of the Shapiro time delay yield $|\gamma - 1| < 2.3 \times 10^{-5}$ [22]. In scalar-tensor theories of the Bergmann–Wagoner–Nordtvedt class, the parametrized post-Newtonian (PPN) parameter γ is related to the kinetic coefficient ω by

$$\gamma = \frac{\omega + 1}{\omega + 2}, \tag{17}$$

so that $|\gamma - 1| = 1/(\omega + 2)$. The Cassini bound therefore requires

$$\omega > \frac{1}{2.3 \times 10^{-5}} - 2 \approx 43{,}500\,. \tag{18}$$

Since the effective coupling in our framework is $\lambda_{\rm eff}^2 = \lambda^2/\omega$ (see Section 4), the Cassini bound constrains the ratio $\lambda/\sqrt{\omega}$ rather than λ alone. For any fixed λ, increasing ω to satisfy Eq. (18) suppresses $\lambda_{\rm eff}$ without affecting the theoretical structure. Conversely, the pulsar bound $\lambda_{\rm eff} < 1.95$ is automatically consistent with Cassini for all $\omega \gtrsim 43{,}500$, since $\lambda_{\rm eff} = \lambda/\sqrt{\omega} < \lambda/\sqrt{43500} \ll \lambda$.

5.2. Binary Pulsars

Binary pulsars provide significantly more stringent constraints due to the combination of high eccentricity, strong gravitational fields, and extraordinary measurement precision.

PSR B1913+16 (Hulse–Taylor pulsar).

With $e = 0.617$, $P_b = 0.323$ d, and total mass $M = 2.828\,M_\odot$, this system has $\Xi = 2.64 \times 10^{-6}$. The observed periastron advance $\dot{\omega}_{\rm obs} = 4.226598 \pm 0.000005$ deg yr^{-1} agrees with GR to ~ 10 ppm [2]. Requiring $|\delta| < 10^{-5}$ yields

$$\lambda_{\rm eff} < 1.95\,. \tag{19}$$

PSR J0737−3039A/B (Double Pulsar).

With $e = 0.088$, $P_b = 0.102$ d, and $M = 2.587\,M_\odot$, $\Xi = 6.78 \times 10^{-8}$. The observed $\dot{\omega} = 16.8995 \pm 0.0007$ deg yr^{-1} yields $\lambda_{\rm eff} < 24$ [3].

The Hulse–Taylor pulsar provides the tightest constraint:

$$\boxed{\lambda_{\rm eff} < 1.95 \quad (95\%\ \text{C.L.})} \tag{20}$$

This bound applies in the absence of screening mechanisms (see Section 8).

5.3. Summary of Bounds

Table 1 compiles the observational bounds on the effective coherence coupling from multiple systems.

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Table 1. Observational bounds on $\lambda_{\rm eff}$ from precision gravitational tests. The asymmetry parameter $\Xi = e^2(1-e^2)^{-1} r_g/a$ determines the sensitivity of each system.

System	e	Ξ	$\lvert\delta\rvert_{\max}$	$\lambda_{\rm eff}^{\max}$
Mercury	0.206	2.3×10^{-9}	10^{-3}	666
Cassini	—	—	2.3×10^{-5}	~ 200
PSR B1913+16	0.617	2.6×10^{-6}	10^{-5}	**1.95**
PSR J0737	0.088	6.8×10^{-8}	4×10^{-5}	24

6. The S2 Star as a Target System

The star S2 orbiting Sagittarius A* is the most precisely tracked stellar orbit near a supermassive black hole. Updated orbital parameters from the GRAVITY Collaboration [23] give $e = 0.8846$, $a \simeq 970$ AU, and $M \simeq 4.30 \times 10^6\, M_\odot$, yielding

$$\Xi_{\rm S2} = 3.15 \times 10^{-4}\,. \tag{21}$$

This is the largest value of Ξ among systems with precision astrometric measurements.

At the pulsar bound $\lambda_{\rm eff} = 1.95$, the predicted coherence correction is

$$\delta_{\rm S2} = \lambda_{\rm eff}^2\, \Xi_{\rm S2} \simeq 1.2 \times 10^{-3}\,, \tag{22}$$

corresponding to a $\sim 0.12\%$ fractional deviation in periapsis advance.

The most recent measurement of the Schwarzschild precession parameter by GRAVITY [23] yields $f_{\rm SP} = 1.135 \pm 0.110$, consistent with the GR prediction ($f_{\rm SP} = 1$) at the $\sim 1.2\sigma$ level and with no significant deviation detected. This is consistent with the predicted correction, which at $\delta \simeq 10^{-3}$ falls well below the current precision of $\sim 10\%$ on $f_{\rm SP}$.

Next-generation interferometric facilities (GRAVITY+, ELT) are expected to improve astrometric precision by an order of magnitude [5], potentially bringing the 0.1% level within reach. S2 therefore represents the most promising near-term target for testing coherence corrections.

Discovery of additional stars with smaller semi-major axes ($a \lesssim 100$ AU) and comparable eccentricities would increase Ξ by one to two orders of magnitude, providing decisive tests.

7. Predictions for High-Eccentricity Systems

Table 2 presents the predicted coherence corrections for a range of astrophysical systems, evaluated at the current observational bound $\lambda_{\rm eff} = 1.95$.

Table 2. Predicted fractional correction $\delta = \lambda_{\rm eff}^2 \Xi$ to periapsis precession for selected systems, with $\lambda_{\rm eff} = 1.95$. The column $\Delta\phi_{\rm GR}$ gives the GR precession per orbit for physical scale.

System	e	r_g/a	Ξ	$\Delta\phi_{\rm GR}$	δ
Mercury	0.206	5.1×10^{-8}	2.3×10^{-9}	$0.104''$	8.5×10^{-9}
Icarus	0.827	1.8×10^{-8}	4.0×10^{-8}	$0.113''$	1.5×10^{-7}
HD 80606b	0.933	4.1×10^{-8}	2.8×10^{-7}	$0.619''$	1.1×10^{-6}
PSR B1913+16	0.617	4.3×10^{-6}	2.6×10^{-6}	$13.5''$	1.0×10^{-5}
S2	0.885	8.8×10^{-5}	3.2×10^{-4}	0.22°	1.2×10^{-3}
Inner S-star*	0.95	8.5×10^{-4}	7.9×10^{-3}	4.7°	3.0×10^{-2}

Hypothetical star with $a = 100$ AU, $e = 0.95$, around Sgr A ($M = 4.30 \times 10^6\, M_\odot$). Not yet observed.

The key prediction of the framework is that the correction grows as $e^2/(1-e^2)$ — much faster than any post-Newtonian correction from GR alone. Systems combining high eccentricity ($e > 0.9$) with strong gravitational fields ($r_g/a > 10^{-4}$) are predicted to exhibit corrections at the percent level, well within the reach of current and near-future observational capabilities.

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Hypothetical stars orbiting within ~ 100 AU of Sgr A* with eccentricities exceeding 0.95 would provide the most discriminating tests, with predicted deviations of $\sim 3\%$.

8. Discussion

8.1. Status of the Framework

The theory presented here is a phenomenological effective framework. It has a single effective parameter: the coherence coupling λ_{eff}, which is bounded above by binary pulsar timing and encodes the strength of scalar-tensor corrections to orbital dynamics. The coherence potential $V(\Phi)$ must be specified to extend predictions beyond the weak-field regime but does not enter the leading-order precession formula. This status is analogous to other effective descriptions in physics, including thermodynamics prior to statistical mechanics and the Ginzburg–Landau theory of superconductivity.

8.2. Galactic Scales and Dark Matter

A natural question is whether coherence effects can account for the observed flat rotation curves of galaxies [24,25], potentially replacing the need for dark matter.

In the unscreened regime, the observational bound $\lambda_{\text{eff}} < 1.95$ from pulsar timing severely constrains any such explanation: the predicted corrections to galactic dynamics would be of the same order as those to orbital precession ($\lesssim 0.1\%$), far too small to account for the observed factor-of-two discrepancies in rotation velocities.

However, this conclusion is valid only in the absence of screening. Modern scalar-tensor theories admit screening mechanisms — chameleon [15], symmetron [26], and Vainshtein [14,16] — that can suppress scalar field effects in dense environments (where pulsars reside) while permitting larger deviations in diffuse galactic halos.

Within the present framework, this would correspond to a coherence potential $V(\Phi)$ whose effective mass depends on the ambient density:

$$m_\Phi^2(\rho) = V''(\Phi_{\text{min}}(\rho)) \,, \tag{23}$$

with m_Φ large in dense systems (short Compton wavelength, screened fifth force) and small in dilute environments (long-range coherence effects).

A quantitative treatment of screening within the coherence framework, including the derivation of galactic rotation curves from a specified $V(\Phi)$, constitutes a necessary direction for future work. We emphasize that, without such a derivation, the present framework does *not* claim to explain galactic dynamics or replace dark matter.

8.3. Relation to Existing Modified Gravity Theories

The action (1) belongs to the broad class of scalar-tensor theories. Its specific predictions, summarized in Table 2, distinguish it from generic Brans-Dicke theory through the particular dependence on the asymmetry parameter Ξ. Whereas Brans-Dicke corrections scale purely with compactness (r_g/a), the coherence framework predicts an additional eccentricity enhancement through the factor $e^2/(1-e^2)$. This provides a distinct and falsifiable observational signature.

9. Falsifiable Tests

The framework is falsified if:

1. Stars with $\Xi > 10^{-2}$ (high eccentricity near compact objects) show no deviation from GR beyond measurement uncertainties.
2. Observed deviations do not scale with Ξ as predicted by Eq. (11).
3. Independent measurements of precession and gravitational redshift in the same system fail to show correlated coherence signatures.

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Conversely, detection of a fractional precession excess that scales linearly with Ξ across multiple systems would provide strong support for coherence-modified gravity.

The most promising observational strategies are:

- Long-baseline interferometric monitoring of S-stars in the Galactic Center (GRAVITY+, ELT).
- Precision timing of high-eccentricity binary pulsars discovered by FAST and SKA.
- Astrometric characterization of compact exoplanets with $e > 0.9$.

10. Conclusions

We have presented a scalar-tensor extension of General Relativity motivated by the concept of informational coherence. The theory is derived from a covariant variational principle, preserves diffeomorphism invariance and energy-momentum conservation, and reduces exactly to GR when coherence gradients vanish.

The effective correction to orbital precession is parameterized by the dimensionless quantity $\delta = \lambda_{\text{eff}}^2 \Xi$, where $\Xi = e^2(1-e^2)^{-1} r_g/a$ captures the combined effect of eccentricity and gravitational compactness. Binary pulsar observations constrain $\lambda_{\text{eff}} < 1.95$, rendering Solar System corrections negligible but predicting deviations at the $\sim 0.1\%$ level for the S2 star (using updated GRAVITY parameters) and at the percent level for hypothetical inner S-stars.

The framework represents a phenomenological effective theory with a single constrained parameter λ_{eff}, bounded above by binary pulsar observations. Its principal contribution is the identification of a specific, dimensionless combination of orbital parameters that governs deviations from GR, providing clear and falsifiable predictions for the next generation of gravitational experiments.

Extension to galactic scales requires the specification of a screening mechanism within the coherence potential and constitutes an important direction for future work.

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