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Probing ultralight scalars through compact stars and precision test of gravity

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Ultralight CP-even scalars coupled to the Standard Model via electromagnetic and electrophilic interactions can induce observable imprints on compact and planetary systems, independent of whether the scalar constitutes dark matter. We derive bounds on these couplings using precision astrophysical and gravitational observables, including pulsar spin-down luminosity and surface magnetic field from magnetized neutron stars and magnetars, deviations in the gravitational force in the Sun-planet systems, and corrections to geodetic (de Sitter) precession of orbiting gyroscopes. We further quantify prospective sensitivity reach from differential photon-redshift and non-gravitational potential measurables through atomic clock precision. These results demonstrate that compact star and solar-system observables provide competitive and highly scalable probes of ultralight scalar interactions with the visible sector.

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1. Introduction

Spatially extended and extreme astrophysical systems-including neutron stars (NSs), black holes (BHs), and planets-provide powerful environments to test feebly coupled new physics beyond the reach of terrestrial detectors. Their sensitivity arises from large matter densities, strong magnetic fields, long observational baselines enabling precision timing and macroscopic spatial volumes that enhance cumulative effects. These features make astrophysical and planetary observables complementary to laboratory searches for ultralight dark-sector particles.

NSs are particularly promising: while predominantly neutron-rich, realistic interiors contain EoS-dependent subcomponents of electrons, protons, muons, hyperons, and heavier baryonic states. Precision observables such as spin-down rates, and mass-radius measurements from radio/X-ray timing, NICER, and gravitational waves-can be sensitive to additional energy-loss or photon propagation effects induced by new ultralight fields.

Solar-System precision gravity tests such as geodetic precession and orbital force measurements provide sensitive probes of new physics. Feebly coupled ultralight fields interacting with SM particles can induce measurable corrections to gyroscope spin precession. The high accuracy of modern precession and force data therefore enables stringent constraints on non-gravitational BSM couplings, offering complementary macroscopic tests of BSM (beyond SM) physics in planetary gravitational backgrounds.

Ultralight CP-even scalars are well-motivated BSM candidates, not necessarily DM. We remain agnostic about their cosmological origin and do not assume a DM interpretation. We constrain scalar-photon couplings using emission from rotating magnetized NSs, and scalar-electron couplings via geodetic-precession gravity tests. Future low-frequency and atomic-clock measurements can improve sensitivity by orders of magnitude.

The paper is organized as follows. Section. 2 presents bounds on scalar-photon couplings from pulsars and magnetars. Section. 3 derives bounds on scalar-electron couplings from geodetic precession. Section. 4 summarizes results and discusses future prospects. We adopt natural units $c = \hbar = 1$ throughout, unless stated otherwise.

2. Constraining electromagnetic coupling of ultralight scalars from magnetized stars

To avoid complications associated with magnetospheric or higher-multipole radiation, we adopt the aligned (axis-aligned) rotator approximation, in which the magnetic dipole moment is parallel to the spin axis. In this limit, the external dipolar magnetic field of the NS takes the standard form

$$\mathbf{B}^{\rm out}_{(r>R)} = B_0 R^3 \left(\frac{\cos\theta}{r^3}\hat{r} + \frac{\sin\theta}{2r^3}\hat{\theta} \right), \tag{1}$$

where B_0 denotes the surface magnetic field, R is the stellar radius, and θ is the polar angle measured from the rotation axis.

The co-rotation boundary condition at the stellar surface uniquely fixes the vacuum electric field outside the star. Using $\mathbf{E} = -(\mathbf{\Omega} \times \mathbf{r}) \times \mathbf{B}$ at $r = R$, the external electric field becomes

$$\mathbf{E}^{\rm out}_{(r>R)} = -\frac{B_0 \Omega R^5}{r^4} \left[\left(1 - \frac{3}{2}\sin^2\theta \right)\hat{r} + \sin\theta\cos\theta\,\hat{\theta} \right], \tag{2}$$

with Ω being the stellar angular velocity.

We consider an ultralight CP-even scalar field ϕ coupled to electromagnetism via the operator $\phi F_{\mu\nu}F^{\mu\nu}$. The relevant Lagrangian is

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}g_{\phi\gamma\gamma}\phi F_{\mu\nu}F^{\mu\nu}, \tag{3}$$

where $g_{\phi\gamma\gamma}$ denotes the scalar-photon coupling. The scalar field equation of motion in curved spacetime is then

$$\Box\phi = -g_{\phi\gamma\gamma}(\mathbf{B}^2 - \mathbf{E}^2), \quad \frac{1}{2}F_{\mu\nu}F^{\mu\nu} = \mathbf{B}^2 - \mathbf{E}^2, \tag{4}$$

where $\Box$ is the d'Alembertian operator in the Schwarzschild background sourced by the NS. Imposing regularity of the solution at the inner boundary (the stellar compactness scale $r \simeq 2M$ and finiteness at $r \to \infty$, the far-field solution admits the asymptotic expansion [1]

$$\phi(r) \approx -\frac{g_{\phi\gamma\gamma}B_0^2\Omega^2R^{10}}{480M^5r} + \frac{g_{\phi\gamma\gamma}B_0^2R^6}{48M^3r} + O\left(\frac{1}{r^2}\right), \tag{5}$$

where the leading term is the monopole mode $l = 0$, and the effective scalar charge Q_ϕ^{K} is [1]

$$Q_\phi^{\mathrm{K}} = -\frac{g_{\phi\gamma\gamma}B_0^2\Omega^2R^{10}}{480M^5} + \frac{g_{\phi\gamma\gamma}B_0^2R^6}{48M^3}. \tag{6}$$

The coupling of a CP-even scalar field ϕ to EM fields via the operator $\phi F_{\mu\nu}F^{\mu\nu}$ modifies Maxwell's equations. Working in the perturbative regime $g_{\phi\gamma\gamma} \ll 1$, we expand the field strength tensor in powers of the scalar-photon coupling and obtain the scalar-induced magnetic field $F_\phi^{\mu\nu}$ as

$$F^{\mu\nu} = F_{(0)}^{\mu\nu} + F_\phi^{\mu\nu} + O(g_{\phi\gamma\gamma}^2), \quad \partial_\mu F_\phi^{\mu\nu} = -g_{\phi\gamma\gamma}(\partial_\mu\phi)F_{(0)}^{\mu\nu}, \tag{7}$$

where the subscript (0) denotes the standard Maxwell solution in the decoupling limit $g_{\phi\gamma\gamma} = 0$.

In vacuum, the induced electric and magnetic fields inherit this sourcing through derivatives of the scalar background. Expressing the result in 3-vector form yields the wave equations

$$\Box\mathbf{B}_\phi = g_{\phi\gamma\gamma}(\nabla\phi\cdot\nabla)\mathbf{B}_{(0)}, \qquad \Box\mathbf{E}_\phi = g_{\phi\gamma\gamma}(\nabla\phi\cdot\nabla)\mathbf{E}_{(0)}, \tag{8}$$

which govern the propagation of the scalar-sourced electromagnetic perturbations.

Solving these equations in the Schwarzschild geometry generated by the compact star, the induced magnetic field admits the form [1]

$$\mathbf{B}_\phi(r,\theta) \approx \frac{g_{\phi\gamma\gamma}Q_\phi^{\mathrm{K}}B_0R^3}{12M^2}\left(\frac{\cos\theta}{r^2}\right)\hat{r} + \frac{g_{\phi\gamma\gamma}Q_\phi^{\mathrm{K}}B_0R^3\pi}{64M^3r}\hat{\theta}. \tag{9}$$

When light i.e., an EM wave propagates through the background static scalar and EM fields, the Maxwell's equations modify as

$$\nabla\cdot\mathbf{E} = -g_{\phi\gamma\gamma}\mathbf{E}\cdot\nabla\phi,\ \nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} - g_{\phi\gamma\gamma}\nabla\phi\times\mathbf{B},\ \nabla\cdot\mathbf{B} = 0,\ \nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}. \tag{10}$$

Combining Eqs. 10 and using the Eikonal ansatz, the photon dispersion relation and the group velocity become [1]

$$\omega^2 = k^2 - i g_{\phi\gamma\gamma}(\nabla\phi\cdot\mathbf{k}),\ v_g = \left(1 - \frac{m_\gamma^2}{4\omega^2}\right)^{\frac{1}{2}}. \tag{11}$$

The photon wavenumber in this case is complex in nature and its real part measures the change in the photon redshift between the points of emission (r_1) and detection (r_2) as [1]

$$\delta z = \frac{\lambda(r_2) - \lambda(r_1)}{\lambda(r_1)} \approx \frac{k_R(r_1) - k_R(r_2)}{k_R(r_2)} \approx \frac{m_\gamma^2}{8\omega^2} \approx \frac{g_{\phi\gamma\gamma}^4 B_0^4 R^8}{48^2 \times 8 M^6 \omega^2}, \tag{12}$$

whereas the imaginary part of the wavenumber denotes the attenuation of the photon due to its propagation through long-range scalar field background.

To describe scalar radiation from a rotating magnetized NS, we adopt the aligned skewed-rotator approximation, where the magnetic dipole axis is misaligned with the spin axis by an angle α. In this setup, the time-dependent quadrupole scalar charge induces leading $l = 2$ radiation, yielding an energy-loss rate [1]

$$P_\Omega \simeq \frac{1}{80} g_{\phi\gamma\gamma}^2 B_0^4 R^{10} \Omega^6 \left(1 - \frac{m_\phi^2}{\Omega^2}\right)^{5/2} \sin^2 2\alpha, \tag{13}$$

which is valid for kinematically allowed emission in the regime $m_\phi \lesssim \Omega$.

3. Constraining electrophilic coupling of ultralight scalars from geodetic precession

An ultralight scalar coupled to non-relativistic electrons sourced by a planet or the Earth generates a long-range Yukawa potential, which perturbs the geodetic precession of an orbiting gyroscope. In the perturbative regime, the gyroscope trajectory and spin obey [2]

$$\ddot{x}^\alpha + \Gamma^\alpha_{\mu\nu}\dot{x}^\mu\dot{x}^\nu = \frac{g\,q}{M_{gy}}\left(\dot{i}\, g^{\alpha\lambda}\partial_\lambda\varphi - g^{\alpha 0}\dot{x}^\mu\partial_\mu\varphi\right), \tag{14}$$

and [2]

$$\frac{dS^\mu}{d\tau} + \Gamma^\mu_{\alpha\beta}\, u^\alpha S^\beta = \frac{gq}{M_{gy}} g^{\mu\lambda}\left(\partial_\lambda\varphi\delta^0_\nu - \partial_\nu\varphi\delta^0_\lambda\right) S^\nu, \tag{15}$$

where g is the scalar-electron coupling, q and Q are the total electron charges of the gyroscope and source, and $\varphi(r) \approx gQ(4\pi r)^{-1} e^{-m_\varphi r}$. The resulting fifth force and its contribution to the spin advance per orbital revolution are [2]

$$V_L(r) = -\frac{g^2 qQ}{4\pi M_{\rm gy} r} e^{-m_\varphi r}, \quad F_L(r) = \frac{g^2 qQ}{4\pi M_{\rm gy} r^2}(1 + m_\varphi r) e^{-m_\varphi r}, \tag{16}$$

$$\alpha = 2\pi\left(1 - \frac{\Omega_{\varphi f}}{\Omega_\varphi}\right) = \frac{3\pi M}{R} + \frac{g^2 qQ}{4RM_{\rm gy}} e^{-m_\varphi R}(1 + m_\varphi R). \tag{17}$$

which applies for force range $\lambda \gtrsim 1/m_\varphi$. Analogous to gravitational field-shift measurements in atomic clock tests, fractional frequency variations induced by the scalar potential can be mapped onto orbital-radius modulations, enabling precision gravity experiments to detect or constrain such interactions.

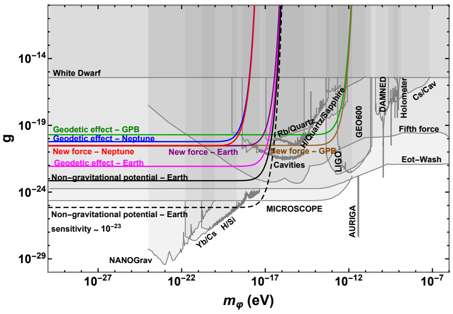

Figure 1: Limits on scalar-electron coupling [2]

In FIG. 1, we present current bounds and projected sensitivities on scalar-electron couplings. The scalar-photon limits are derived from surface magnetic field and spin-down measurements of GRB 080905A, requiring the scalar contribution to lie within the reported 1σ uncertainties [1]. The measurement of the surface magnetic field from EM radiation yields best limit as $g_{\phi\gamma\gamma} \lesssim 5 \times 10^{-18}$ GeV^{-1} for $m_\phi \lesssim 2 \times 10^{-11}$ eV [1]. Independent bounds on scalar-electron couplings are obtained from geodetic-precession measurements for the Earth and Neptune, supplemented by fifth force limits in planetary and solar gravitational tests. Finally, we include projected sensitivity to non-gravitational potential variations probed via differential atomic clock frequency ratios.

4. Conclusions and discussions

Astrophysical systems provide powerful environments to probe ultralight scalar fields through precision electromagnetic and gravitational observables. While such scalars are well-motivated DM candidates, the present work remains agnostic about their cosmological origin, and the analysis does not require the scalars to constitute DM. We derive bounds on the scalar-photon coupling using spectral measurements of pulsars and magnetars, and constrain scalar-electron couplings via precision tests of geodetic precession sourced by planetary matter. We further show that future high-precision atomic clocks and low-frequency photon observations can improve sensitivity to these couplings by several orders of magnitude.

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