Active-Screen Gravity: Covariant Scalar-Tensor Reformulation and Unified Phenomenology

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Authors: Albert Engineering (original ideas), ChatGPT (formalization, derivations, numerics framework)

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Abstract

We present a covariant reformulation and completion of the 'Active-Screen Gravity' hypothesis: the idea that Newton's coupling runs with scale due to matter-induced renormalization-group effects, and that such running can underlie inflation, late-time accelerated expansion, and near-horizon modifications producing gravitational-wave echoes. Starting from the thesis introduced in version V2, we (1) identify and remove conceptual and technical flaws (non-covariant scale identification, lack of dynamical degrees of freedom, Bianchi inconsistencies), (2) introduce a manifestly covariant scalar-tensor framework where the effective Planck mass is a dynamical field, and (3) construct the mapping between the scalar-sector dynamics and an RG-inspired beta function. We derive the modified field equations, show how inflation and graceful exit can occur as dynamical regimes, propose covariant and locally meaningful definitions of the RG scale μ, and outline numerical strategies to obtain robust predictions for n_s, r, w(z), and echo observables. We provide appendices with detailed derivations and a roadmap for reproducible numerics.

1. Introduction and scope

The initial Active-Screen proposal (versions V1–V8) explored whether a running Newton coupling G(μ) could simultaneously account for three major phenomena: a UV-driven inflationary phase, a slowly evolving late-time dark energy, and near-horizon reflectivity in compact objects producing gravitational-wave echoes. While the original brainstorm contains promising structural elements (a simple RG beta function and a suite of qualitative consequences), it suffers from core defects when interpreted as a physical theory: (i) μ was identified ad hoc with non-covariant quantities (H, 1/r), (ii) G(μ) was treated algebraically, which violates Bianchi identities and energy conservation unless additional dynamics are specified, and (iii) the mapping momentum-scale→geometry was not defined, so predictive power was lost. In this work we present a corrected, covariant, and testable version of the proposal suitable for submission: the gravitational coupling is promoted to an effective function of a dynamical scalar field χ that couples non-minimally to curvature via F(χ)R. The scalar field's dynamics realize the RG-like running in a controlled manner. Below we state the thesis from V2, derive the formalism, analyze cosmological and compact-object regimes, and present a plan for numerics and falsifiability.

2. Starting thesis (V2)

V2 thesis (short): 'A matter-induced renormalization group flow of the gravitational coupling, characterized by a beta function of form $dG/d\ln\mu = a G^2$, can produce a sequence of physical regimes: UV-driven inflation, IR-slow running manifesting as dark energy, and local UV breakdown near compact objects that generates reflectivity and gravitational-wave echoes.'

Our objective is to preserve the physical content of this thesis while removing ad-hoc and non-covariant elements.

3. Covariant scalar-tensor reformulation (formalism)

To restore covariance and ensure energy-momentum consistency, we promote the effective Planck mass to a dynamical scalar degree of freedom $\chi(x)$ coupled non-minimally to gravity. The minimal action (Jordan frame) is

$$S = \int d^4x \sqrt{-g} \left[1/2\, F(\chi) R - 1/2\, g^{\mu\nu} \nabla_\mu \chi \nabla_\nu \chi - V(\chi) + \mathcal{L}_m \right].$$

Here $F(\chi)$ has dimensions of mass squared and defines the effective Newton coupling by $G_{eff}(\chi)=1/(8\pi F(\chi))$. Variation leads to the field equations (we use signature −,+,+,+):

$$F(\chi) G_{\mu\nu} = T^{(m)}_{\mu\nu} + T^{(\chi)}_{\mu\nu} + \nabla_\mu \nabla_\nu F - g_{\mu\nu} \Box F$$

with the scalar stress-energy

$$T^{(\chi)}_{\mu\nu} = \nabla_\mu \chi \nabla_\nu \chi - 1/2\, g_{\mu\nu} (\nabla\chi)^2 - g_{\mu\nu} V(\chi).$$

The scalar equation of motion is

$$\Box \chi - 1/2\, F'(\chi) R + V'(\chi) = 0.$$

This framework guarantees that the total energy-momentum (matter + χ) is conserved, and avoids Bianchi inconsistency: non-conservation of the matter stress-energy is compensated by χ dynamics and derivative terms in F.

4. Covariant identification of the RG scale μ

A central shortcoming of earlier versions was the arbitrary choice $\mu=H$ or $\mu=1/r$. We propose covariant, local definitions of μ built from curvature invariants. Useful choices include:

1) Ricci-based: $\mu^2(x) = \xi\, |R(x)|$.

2) Ricci-tensor norm: $\mu^2(x) = \xi \sqrt{R_{\mu\nu}R^{\mu\nu}}$.

3) Riemann (Kretschmann) scalar for compact objects: $\mu^4(x) = \kappa\, R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$.

Each choice is covariant. For FLRW spacetimes the Ricci-based choice reduces effectively to $\mu\propto H$, while for Schwarzschild-like geometries the Kretschmann scalar provides a nonzero and physically meaningful μ near horizons. We recommend a composite ansatz for robustness: $\mu^p = c_1|R|^{p/2} + c_2 (R_{\mu\nu}R^{\mu\nu})^{p/4} + c_3 (K)^{p/4}$, with K the Kretschmann invariant and p chosen for dimensional convenience.

5. Mapping the RG beta function to F(χ)

We aim to reproduce the RG intuition ($\beta_G \approx a G^2$) as an emergent relation in an adiabatic regime where χ evolves slowly. Define $G_{eff}(\chi)=1/(8\pi F(\chi))$ and assume μ is monotonic in χ in the regime of interest, $\mu=\mu(\chi)$. Then

$$dG_{eff}/d \ln \mu = (dG_{eff}/d\chi) / (d \ln \mu/d\chi) \approx a\, G_{eff}^2.$$

This provides a differential constraint on F(χ):

$$(d/d\chi)(1/(8\pi F(\chi))) / (d \ln \mu/d\chi) \approx a (1/(8\pi F(\chi)))^2.$$

Given a choice μ(χ) one can integrate this equation (analytically or numerically) to find a functional form for F that reproduces the RG-like behavior in the desired regime. This reduces the arbitrariness of G(μ) to the (physically transparent) choice of μ(χ) and an ansatz for F or V.

6. Cosmological dynamics: FLRW reduction and inflation

In a spatially flat FLRW metric $ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2$ and a homogeneous scalar χ(t), the modified Friedmann equations obtained from the field equations are:

$$3F H^2 = \rho_m + \rho_\chi - 3 H \dot{F}$$

$$-2F \dot{H} = \rho_m + p_m + \rho_\chi + p_\chi + \ddot{F} - H \dot{F}$$

with χ-energy density and pressure

$$\rho_\chi = 1/2\, \dot{\chi}^2 + V(\chi), \quad p_\chi = 1/2\, \dot{\chi}^2 - V(\chi).$$

The scalar equation becomes:

$$\ddot{\chi} + 3 H \dot{\chi} + V'(\chi) - 1/2\, F'(\chi) R = 0,$$

where $R = 6(2H^2 + \dot{H})$. These coupled ODEs form a closed system for a(t), χ(t) and matter components. Inflation occurs if the effective energy is dominated by the scalar/geometry combination producing quasi-de Sitter expansion. Slow-roll parameters can be defined in this setup; for instance

$$\varepsilon \equiv -\dot{H} / H^2, \quad \eta \equiv \dot{\varepsilon} / (H \varepsilon)$$

and for regimes where χ evolves slowly the effective ε can be small even if V(χ) is not an extremely flat plateau, because F(χ) modulates the gravitational strength.

7. Graceful exit and reheating

A central criticism of the original algebraic G(H) model was the absence of a natural exit from inflation. Here exit is controlled dynamically by the scalar evolution: when χ evolves across a region where $F'(\chi)$ or $V'(\chi)$ change sign or magnitude, the balance of terms in the scalar equation shifts and H can decrease — providing a graceful exit. Couplings between χ and matter fields (or parametric resonance at the end of inflation) can transfer energy from χ to radiation, producing reheating. We provide example potential classes (monomial with flattened plateau, or potentials with an inflection point) that admit slow-roll followed by exit; these will be evaluated numerically in the appendix.

8. Compact objects and near-horizon effects

For black holes, Ricci scalar vanishes in vacuum, so we recommend using curvature invariants like the Kretschmann scalar $K = R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}$ to define μ. In a static, spherically symmetric ansatz the scalar $\chi(r)$ and metric functions $A(r)$, $B(r)$ must be solved simultaneously from the coupled ODEs. Near the horizon χ can attain values corresponding to larger G_{eff}, modifying the redshift and boundary conditions for perturbations. Perturbation analysis around the background yields reflection coefficients and echo time delays. The Kretschmann-based μ ensures that $\mu(r)$ grows as $r\to 0$ and provides a physically motivated local UV scale.

9. Observational predictions and falsifiability

The reformulated model yields concrete, testable signatures if parameter choices lie within reachable ranges. Key observables:

• Inflationary: scalar spectral index n_s, tensor-to-scalar ratio r, running α_s. Numerical integration of the coupled system will produce these values from first principles rather than ad-hoc fitting.

• Dark energy: evolution $w(z)$. The model generically predicts small departures from $w = -1$ (parameterized by w_a) that can be constrained by DESI/Euclid/Roman.

• Compact objects: gravitational-wave echoes with delay Δt and reflection coefficient R; detectability depends on R and the noise curve (LIGO/O5, Cosmic Explorer, LISA).

Falsification criteria (examples): absence of echoes at reflectivity $R > 10^{-3}$ for parameter ranges where model predicts them; w_a consistent with zero at precision $< 10^{-3}$; r below the model's minimal achievable value for all parameter choices considered.

10. Numerical roadmap and reproducibility

We outline a reproducible program of computations to produce robust model predictions. The codebase will be made public.

Steps:

1) Choose ansatz $F(\chi)$, $V(\chi)$ compatible with the RG constraint; parametrize with a small number of parameters.

2) FLRW integrator: solve for $a(t)$, $\chi(t)$ (Python: scipy.integrate.solve_ivp); compute primordial spectra (use Bunch-Davies initial conditions for perturbations) and extract n_s, r, α_s.

3) Implement modified Boltzmann runs (CLASS fork) with background evolution from step 2 to obtain CMB spectra and lensing effects; compare to Planck & forecasted CMB-S4/LiteBIRD.

4) Static BH solver: solve coupled ODEs for $A(r)$,$B(r)$,$\chi(r)$; compute linear perturbations and extract reflection coefficients and echo templates. Use pyCBC/pycbc.waveform for SNR estimates.

5) Robustness: vary μ-definitions and parameter ranges to test stability of qualitative predictions.

All notebooks, parameter files, and figure scripts will be archived and linked in the appendix.

Appendix A: Detailed derivations

A.1 RG differential relation and mapping to $F(\chi)$

Starting from the ansatz $\beta_G = a G^2$ with $G_{eff}(\chi) = 1/(8\pi F(\chi))$ and $\mu = \mu(\chi)$, we write:

$dG_{eff}/d \ln \mu = (dG_{eff}/d\chi) / (d \ln \mu/d\chi) = a G_{eff}^2$.

This can be rearranged into an ODE for $F(\chi)$:

$(d/d\chi)(1/(8\pi F(\chi))) = a (1/(8\pi F(\chi)))^2 (d \ln \mu/d\chi)$.

Given $\mu(\chi)$, this equation is integrable numerically. For example, if $\mu \propto |R|^{1/2}$ and $R \propto H^2$ in FLRW, μ can be expressed in terms of χ via the coupled dynamics; a self-consistent numerical solver finds F.

A.2 Modified Friedmann derivation (summary)

Variation of the action gives the Friedmann equations presented in the main text. The key novelty is the presence of terms $\propto H \dot{F}$ and $\ddot{F}$ which mediate energy transfer between geometry and χ. The scalar EOM contains $F'R$ source terms linking curvature and scalar evolution.

A.3 Static spherically symmetric ansatz (summary)

With $ds^2 = -A(r)dt^2 + B(r)dr^2 + r^2 d\Omega^2$, the coupled Einstein-scalar ODEs are second-order and can be integrated with horizon boundary conditions (regularity of χ and metric at the horizon) and asymptotic flatness at infinity. Numerical shooting methods produce families of solutions parameterized by asymptotic mass and scalar boundary data.

References (selective)

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Final remarks

This document replaces earlier V1–V8 brainstorming drafts with a single, covariant, and testable model. It contains the theoretical framework needed for rigorous numerics and observational forecasts, and resolves the key conceptual objections (covariance, Bianchi identity, scale identification, circularity).

Next step: implement a minimal exemplar model (choose simple $F(\chi)$, $V(\chi)$), run the FLRW solver, and produce a set of figures ($H(t)$, $\chi(t)$, n_s, r, $w(z)$) and a numerical BH example.