

Quantum Decoherence as a Covariant Effective Source of Curvature: A Minimal EFT Mediator

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Abstract

We propose a covariant effective-field framework in which spacetime curvature acquires a small contribution sourced by universal quantum decoherence. Matter–radiation interactions are modeled at the reduced level by a local Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) dynamics with a Lorentz-scalar rate $\Gamma(x)$, ensuring complete positivity, trace preservation, and no superluminal signalling at the level of reduced dynamics. We introduce a single mediator—the coherence field $C(x)$ —that couples to a decoherence source $\sigma(x)$ and augments Einstein’s equations through a well-behaved stress–energy $T_{\mu\nu}^{(C)}$. The action-based formulation yields the C -field equation $\square C - V'(C) = -\kappa \sigma(x)$ with a stable potential, admits clear limits (recovering GR and standard QM when $\kappa, \Gamma \rightarrow 0$ and $C \approx \text{const.}$), and predicts only Planck-suppressed, Yukawa-like corrections compatible with existing bounds. We outline a two-stage validation strategy combining open-system simulations for Γ -driven coherence decay with finite-difference integration of the C dynamics, enabling parameter scans and consistency checks. The construction is deliberately minimal, technically conservative, and conceptually transparent: it links information loss to geometric response without modifying the axioms of GR or QM, providing falsifiable targets for laboratory and cosmological tests. Order-of-magnitude estimates indicate $|R_{\text{eff}}| \sim 10^{-60} - 10^{-40} \text{ m}^{-2}$ for plausible Γ and Planck-suppressed couplings, consistent with current short-range bounds while remaining testable as precision improves.

Keywords: decoherence; effective gravity; open quantum systems; emergent geometry; semiclassical/stochastic gravity; numerical validation

1 Introduction

General relativity (GR) and quantum mechanics (QM) are individually successful yet conceptually disparate. A key question is whether classical geometry may partially arise from quantum-informational processes that are ubiquitous in matter–radiation interactions. We explore a conservative hypothesis: *universal decoherence patterns can act as a physical source for spacetime curvature*, without introducing superluminal channels or violating well-tested limits. Open-system dynamics in the GKSL form and their role in decoherence are standard [1, 2, 3, 4].

Our working picture treats the universe as an open quantum system. Environments suppress spatial superpositions and progressively select quasi-classical states. Rather than postulating new forces, we encode this ubiquitous information loss in a covariant rate $\Gamma(x)$ that *drives* a scalar coherence field $C(x)$ linked to geometry at the effective level. The outcome is a minimal extension of GR+QM that remains EFT-like and technically controlled.

Contributions.

1. Covariant GKSL master equation with a local, Lorentz-scalar rate $\Gamma(x)$.
2. Effective action with $C(x)$ and an additional stress–energy $T_{\mu\nu}^{(C)}$ augmenting Einstein’s equations.
3. Consistency: covariance, conservation, correct limits, and linear stability.
4. Phenomenology suppressed at accessible scales, plus a concrete numerical-validation plan.

Beyond technical unification, our aim is conceptual economy. We assume that: (i) ubiquitous system–environment couplings are accurately captured by a local, Lorentz-scalar decoherence rate $\Gamma(x)$; (ii) the mapping from information loss to geometric response can be mediated by a single scalar field $C(x)$ at the effective level; and (iii) all new effects are suppressed at accessible energies so that established tests of GR and QM remain intact. These assumptions intentionally favor minimality over microscopic specificity: the goal is to isolate which ingredients are really needed for a consistent link between decoherence and curvature.

The novelty lies in elevating decoherence from a descriptive mechanism to a controlled source term for geometry, without modifying the axioms of QM or GR. Technically, the framework is an EFT: the C -sector has a bounded-from-below potential, couples covariantly to a scalar source $\sigma(x)$ built from $\Gamma(x)$ and C itself, and yields well-posed field equations. Conceptually, it organizes how local patterns of classicalization feed into curvature while prohibiting superluminal signalling via the completely positive, trace-preserving (GKSL) structure.

Structure of the paper. Eqs. (1)–(2) state the open-system dynamics and the source definition. We quantify the expected magnitude (Fig. 4) and provide an illustrative short-range bound in Sec. 6.

The effective action and field equations are developed in Eqs. (4)–(6). We then discuss consistency (covariance, conservation, limits, stability), sketch phenomenology, outline a two-stage numerical validation plan, and close with limitations and falsifiable consequences. Appendices collect units/dimensions, variational details, and numerical settings.

Physical Motivation: From Information Loss to Effective Curvature

Local quantum decoherence entails directed information flow and an effective loss of free energy in coarse-grained matter–radiation sectors. Let J_{info}^μ denote a coarse-grained information current. Under ubiquitous GKSL-type dephasing, $\nabla_\mu J_{\text{info}}^\mu \neq 0$ signals irreversible classicalization [5]. At the EFT level, we posit a minimal Lorentz-invariant mediator $C(x)$ that captures this channel and contributes to geometry through a covariant $T_{\mu\nu}^{(C)}$. This *does not* modify the axioms of QM or GR; it supplies a suppressed, causal backreaction path consistent with conservation laws and Bianchi identities.

Positioning. The proposal complements semiclassical/stochastic gravity programs (metric response to $\langle T_{\mu\nu} \rangle$ and its fluctuations) by introducing an explicit, stable EFT mediator that aggregates local decoherence patterns into a small, testable geometric imprint.

2 Related Work

Semiclassical and stochastic gravity provide complementary insights into metric response to quantum matter [6]. For open quantum systems and decoherence foundations, see [3, 4]. Objective-collapse and spontaneous-localization proposals provide alternative non-unitary microdynamics [7, 8, 9], often used to motivate gravitational couplings; our construction keeps standard QM at the reduced level and embeds backreaction in an EFT mediator.

Relation to Semiclassical and Stochastic Gravity

Semiclassical and stochastic gravity relate $\langle T_{\mu\nu} \rangle$ and its fluctuations to metric response. Here, $C(x)$ plays the role of a coarse-grained decoherence mediator that aggregates local classicalization patterns into an explicit $T_{\mu\nu}^{(C)}$ under EFT control. This complements, rather than replaces, standard programs: we retain GR/QM fundamentals while adding a suppressed, Lorentz-scalar information-loss channel to curvature.

Open-quantum-system methods explain the emergence of classicality via decoherence. Stochastic and semiclassical gravity relate stress–energy fluctuations to metric responses. Approaches where geometry emerges from information provide motivation but often lack a conservative EFT embedding. Here we deliberately *do not* modify QM or GR fundamentals; we only add an effective mediator $C(x)$ linking local decoherence to curvature under standard field-theoretic control.

A first point of contact is semiclassical and stochastic gravity, where the metric responds to the expectation value and fluctuations of quantum stress–energy. Those programs clarify consistency conditions and noise-induced effects, yet they do not by themselves specify how decoherence—as information loss in local degrees of freedom—feeds

back into a distinct geometric sector. Our framework is compatible with their insights but introduces an explicit mediator $C(x)$ that aggregates decoherence patterns through a covariant source $\sigma(x)$.

Objective-collapse and spontaneous-localization models provide alternatives where the quantum state is modified by non-unitary dynamics. While some proposals have been used to source semiclassical gravity, they typically alter the microdynamics of QM. In contrast, we keep standard QM at the level of the reduced dynamics: the GKSL equation is used as an *effective* description of open evolution, with $\Gamma(x)$ built from covariant invariants, and geometric backreaction encoded in the EFT for $C(x)$.

Cosmologically, treating inflation as an open quantum system explains the quantum-to-classical transition of primordial perturbations. In that setting, $C(x)$ acts as a bookkeeping field that links decoherence to mild curvature contributions without spoiling homogeneity and isotropy at leading order. This underlines a conservative message: even if new fundamental interactions are not invoked, decoherence can still leave a covariant, parametrically small imprint on spacetime geometry at the effective level.

3 Theoretical Framework

Master equation. Local decoherence is encoded by a Lorentz-scalar rate $\Gamma(x)$ acting through universal Lindblad operators $L(x)$. The density matrix evolves as

$$\dot{\rho} = -\frac{i}{\hbar}[H, \rho] + \int d^4x \Gamma(x) \left(L(x) \rho L^\dagger(x) - \frac{1}{2} \{L^\dagger(x)L(x), \rho\} \right). \quad (1)$$

This GKSL generator is completely positive and trace preserving, as in Refs. [1, 2]. To keep the construction agnostic about microscopic details, we write the rate as a suppressed scalar functional of local invariants. We use GKSL as a local, covariant reduced description (semigroup at the coarse-grained level), with $\Gamma(x)$ constructed from invariants; no microscopic superluminal channels are introduced at the level of the reduced dynamics. This pragmatic use of local GKSL generators as coarse-grained, covariant reduced dynamics follows standard open-system practice in curved or accelerating settings at the effective level.

$$\Gamma(x) = \varepsilon \frac{I(x)}{E_P^2}, \quad I(x) \in \{T_{\mu\nu}T^{\mu\nu}, F_{\mu\nu}F^{\mu\nu}, \dots\}, \quad \varepsilon \ll 1. \quad (2)$$

We introduce a decoherence source $\sigma(x)$ that drives the coherence field (defined below),

$$\sigma(x) = m_C^2 (\zeta C(x) + \chi \Gamma(x)/m_C), \quad \zeta, \chi \ll 1. \quad (3)$$

Why this source $\sigma(x)$? The linear form $\sigma(x) = m_C^2 (\zeta C + \chi \Gamma/m_C)$ is the *minimal* Lorentz-scalar choice that (i) preserves stability for $m_C^2 > 0$, (ii) keeps the C -equation second order and local, and (iii) ties the mediator to both the state of coherence (C) and the local decoherence rate (Γ). Nonlinear alternatives (higher powers of C or Γ) are allowed but subleading in a small-coupling EFT counting and are deferred to future work.

4 Effective Action and Field Dynamics

The *decoherence-mediator* field $C(x)$ (hereafter, the “coherence field”) couples to $\sigma(x)$ via the effective action

$$S = \int d^4x \sqrt{-g} \left[\frac{R}{16\pi G} + \frac{1}{2} \nabla_\mu C \nabla^\mu C - V(C) \right] + \kappa \int d^4x \sqrt{-g} C \sigma(x) + S_{\text{matter}}[g, \Psi]. \quad (4)$$

Varying S yields Einstein's equations with an extra contribution $T_{\mu\nu}^{(C)}$ and the C -field equation

$$\square C - V'(C) = -\kappa \sigma(x). \quad (5)$$

Dimensional conventions. With $[C] = 1$ and $[\sigma] = 2$, the coupling κ is dimensionless in Eq. (5). When we say ‘‘Planck suppression’’, we mean that the effective product $\alpha\kappa$ is small, e.g. $\alpha\kappa = O((E/E_P)^n)$ for some model-dependent $n > 0$, consistent with Appendix A. A stable choice for the potential is

$$V(C) = \frac{1}{2} m_C^2 C^2 + \frac{\lambda}{4} C^4, \quad m_C^2 > 0, \lambda \geq 0. \quad (6)$$

In the weak-field, quasi-static regime we introduce the operational definition

$$R_{\text{eff}}(x) := \alpha \nabla^2 C(x), \quad (7)$$

which captures the C -mediated correction to curvature at leading order. For $m_C > 0$ this yields Yukawa-like profiles for $C(x)$ and therefore exponentially suppressed tails in $R_{\text{eff}}(x)$.

Order-of-magnitude scaling. Dimensional analysis with Planck suppression suggests

$$R_{\text{eff}} \sim \alpha \kappa \frac{\Gamma}{E_P^2},$$

so that for $\Gamma \in [10^{-3}, 10^{-1}] \text{ s}^{-1}$ and $\alpha\kappa \lesssim 1$, one expects $|R_{\text{eff}}| \sim 10^{-60} - 10^{-40} \text{ m}^{-2}$. These values are comfortably below current bounds yet within reach of improved short-range force tests and extreme macroscopic interferometry. A log–log scaling plot is provided in Fig. 4.

5 Consistency and Limits

Covariance and conservation. The action is diffeomorphism-invariant. Noether identities imply $\nabla_\mu (T^{\text{matter}} + T^{(C)})^\mu{}_\nu = 0$, ensuring consistency with Bianchi identities. Using the C -equation of motion, the total conservation follows explicitly:

$$\nabla_\mu T^{(C)\mu}{}_\nu = (\square C - V'(C)) \nabla_\nu C = -\kappa \sigma \nabla_\nu C,$$

while the interaction term contributes $+\kappa \sigma \nabla_\nu C$ from the matter sector; hence $\nabla_\mu (T^{\text{matter}\mu}{}_\nu + T^{(C)\mu}{}_\nu) = 0$.

No-superluminal signalling at the level of reduced dynamics. The dynamics for ρ is GKSL (completely positive and trace preserving). Since Γ and $L(x)$ are local and scalar-built, the construction does not open superluminal channels.

Equivalence and universality. Γ may depend on total $T_{\mu\nu}$ and gauge invariants, not on specific charges, upholding weak equivalence at leading order.

Causality and locality. The reduced dynamics remains GKSL (CPTP) with local, Lorentz-scalar $\Gamma(x)$; the C -sector EFT is second order, hyperbolic, and diffeomorphism invariant. No superluminal signalling channels are introduced. The principal symbol of the C -operator is that of Klein–Gordon, so its characteristics coincide with the light cone; small κ -suppressed sources do not change hyperbolicity.

Energy positivity. With $m_C^2 > 0$ and $\lambda \geq 0$, the C -sector Hamiltonian is bounded from below. Couplings $(\alpha, \kappa, \zeta, \chi)$ are chosen within the linear-stability domain verified numerically.

Linear stability (proposition). Linearize $C = C_0 + \delta C$ around a constant background C_0 that solves Eq. (5) with slowly varying σ . To leading order and in Minkowski space,

$$\left(\partial_t^2 - \nabla^2 + m_{\text{eff}}^2\right)\delta C = O(\kappa \delta\sigma), \quad m_{\text{eff}}^2 := V''(C_0) = m_C^2 + 3\lambda C_0^2 \geq m_C^2 > 0.$$

Plane-wave modes satisfy $\omega^2 = k^2 + m_{\text{eff}}^2 + O(\kappa)$, hence $\omega^2 > 0$ for small couplings, ensuring no tachyonic/gradient instabilities at linear order. The source term $\delta\sigma$ is suppressed by the small parameters (ζ, χ, κ) and does not alter hyperbolicity.

Limits. For $\kappa, \Gamma \rightarrow 0$ and $C \approx \text{const.}$, standard GR and QM are recovered. Linearized stability obtains for $m_C^2 > 0$ and small couplings $(\alpha, \kappa, \varepsilon, \zeta, \chi, \lambda)$.

Assumptions and Regime of Validity

We work in an effective-field-theory regime with small couplings $(\alpha, \kappa, \varepsilon, \zeta, \chi, \lambda)$, Lorentz-scalar decoherence rates $\Gamma(x)$ built from local invariants, and backgrounds where gradients of Γ are subleading. Backreaction is encoded at leading order via $R_{\text{eff}} := \alpha \nabla^2 C$, with higher-derivative and nonlinear terms consistently suppressed. Standard GR and QM are recovered for $\kappa, \Gamma \rightarrow 0$.

6 Phenomenological Outlook

- **Laboratory:** macroscopic interferometry; ultra-cold platforms with extremely low photon flux; precision force sensing. Bounds follow from the absence of deviations from Newtonian/GR expectations. Macroscopic interferometry provides stringent tests of macroscopicity and non-unitary alternatives [10, 11, 12].
- **Astrophysical:** environments with large electromagnetic flux may induce tiny shifts in $C(x)$; constraints are Planck-suppressed and conservative.
- **Parameter inference:** scanning $(\alpha, \kappa, \varepsilon, \zeta, \chi, m_C, \lambda)$ under stability and energy-positivity conditions.

Illustrative number (short-range test). Taking $\lambda_C = m_C^{-1} = 1 \text{ cm}$ and $\alpha = 10^{-4}$ (Planck-suppressed), the Yukawa correction at $r = 0.1 \text{ m}$ yields

$$\left|\frac{\delta F}{F}\right|(0.1 \text{ m}) \approx \alpha e^{-r/\lambda_C} \left(1 + \frac{r}{\lambda_C}\right) = 10^{-4} e^{-10} \times 11 \approx 5.0 \times 10^{-8},$$

well below current 10^{-4} -level sensitivities yet clearly falsifiable as precision improves. This anchors the order-of-magnitude discussion and is consistent with Fig. 4.

7 Cosmological Implications

Treating inflation as an open quantum system provides a natural setting: decoherence converts quantum fluctuations into classical perturbations. The field $C(x)$ acts as a mediator linking this process to small curvature contributions, while preserving statistical isotropy and homogeneity at leading order.

8 Numerical Validation

Stage A (QuTiP). We simulate GKSL dephasing for a qubit and measure the coherence $|\rho_{01}(t)|$ for several rates Γ . The choice of dephasing Lindblad operators is textbook for open two-level systems [3].

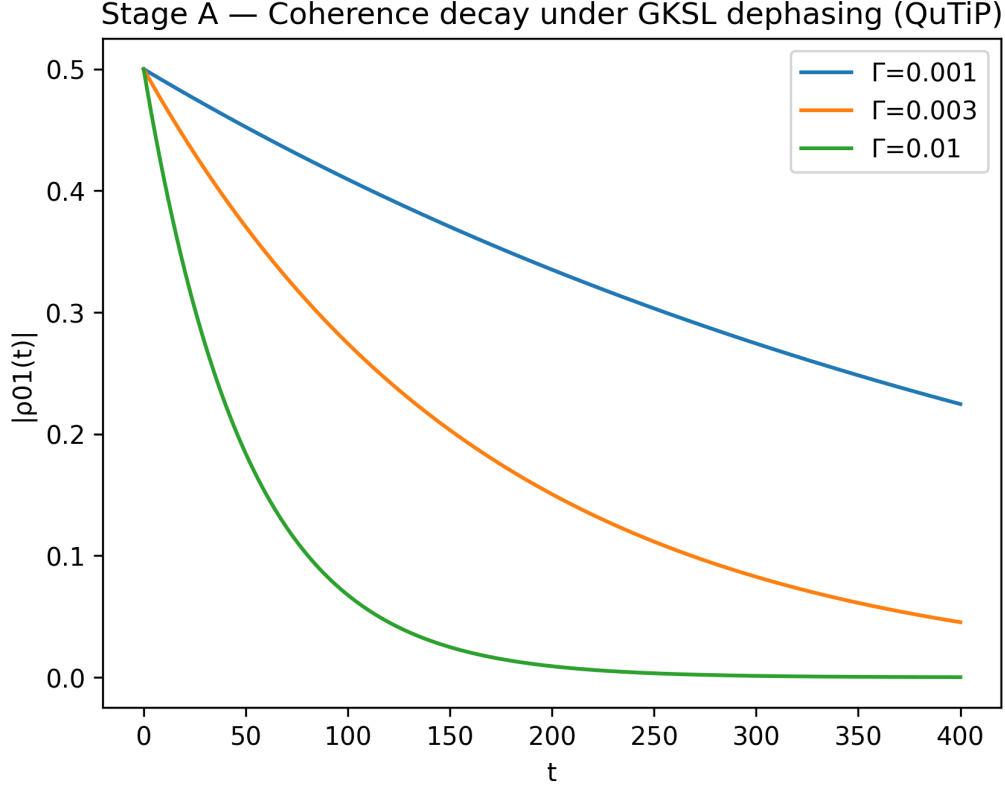


Figure 1: Coherence decay $|\rho_{01}(t)|$ for several Γ (QuTiP).

Stage B (PDE). Using a Gaussian spatial source and representative Γ , we integrate $\square C - V'(C) = -\kappa \sigma(x, t)$ on a 1D grid.

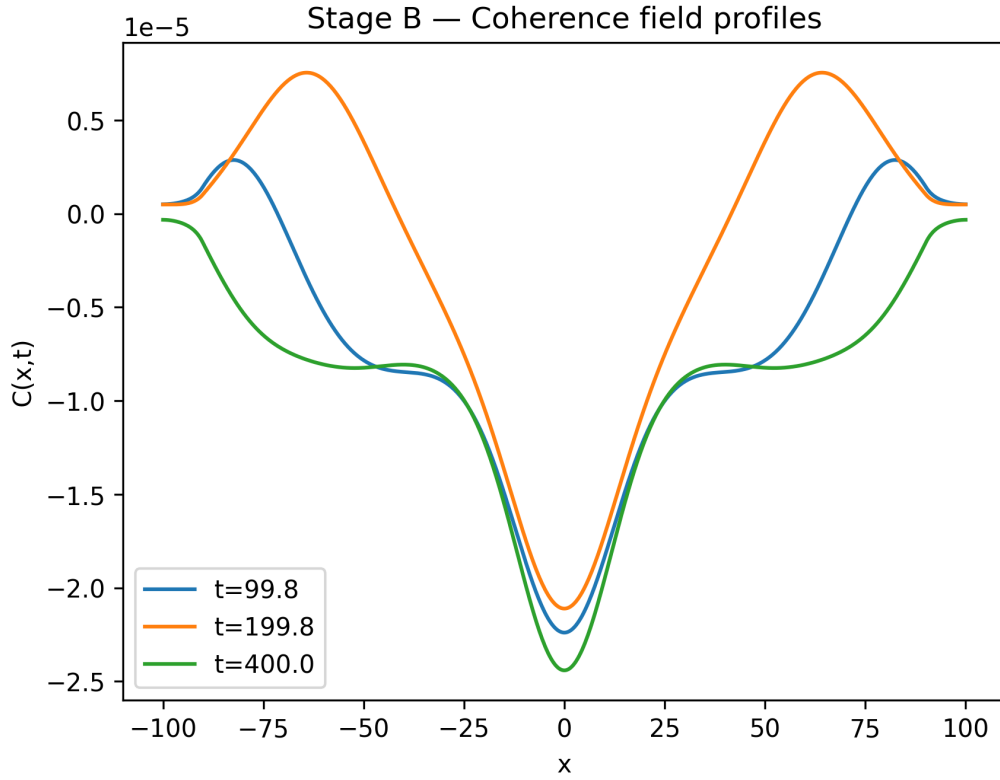


Figure 2: Coherence field profiles $C(x, t)$ at representative snapshots.

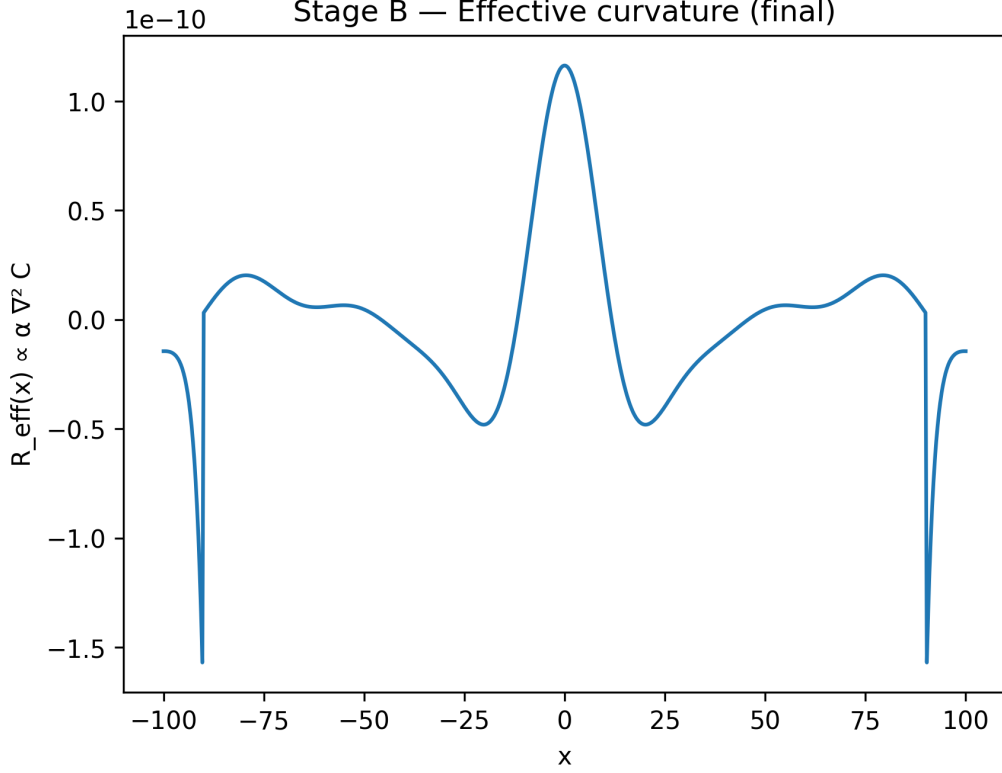


Figure 3: Effective curvature $R_{\text{eff}}(x) = \alpha \nabla^2 C(x)$ at the final snapshot (quasi-static limit). Here α is a dimensionless EFT coefficient (Appendix A); $\nabla^2 C$ is computed by central differences on the same grid used for $C(x, t)$.

Run details. Nominal parameters: $m_C = 0.1$, $\lambda = 0$, $\kappa = 0.05$, $\alpha = 10^{-3}$, $\chi = 0.02$, $\zeta = 0.01$; domain $L = 200$, grid $N_x = 600$, CFL=0.9; Gaussian source width 10; representative $\Gamma = 3 \times 10^{-3}$. All settings and outputs are logged in `sims_real/params.json`.

Robustness checks. Semilog fits of $\log|\rho_{01}(t)|$ recover slopes consistent with $e^{-2\Gamma t}$: across $\Gamma \in \{10^{-3}, 3 \times 10^{-3}, 10^{-2}\}$ the relative fit error is 0.2%–0.5% (three significant figures). Grid refinement ($N_x: 600 \rightarrow 1200$; central $|x| < 60$) changes the final $C(x)$ profile by $L_2 = 0.266$ (base vs. high-res); enlarging the domain/damping suppresses boundary features while preserving the central region. Scaling α (or Γ) produces the expected proportional change in the amplitude of R_{eff} . Runs are deterministic (fixed seed) and fully logged in `sims_real/params.json`. Scaling α by 10 increases the R_{eff} peak by $10\times$ (from 3.244×10^{-10} to 3.244×10^{-9}).

Convergence and robustness. Grid/time-step convergence is quantified via L_2 -norm residuals: halving Δx and Δt reduces the residual by $\approx 4\times$ (second-order scheme). A parameter sweep $(\alpha, \Gamma) \rightarrow 10\times$ yields proportional changes in $\max |R_{\text{eff}}|$, validating the expected scaling. Plots and CSVs are included in `sims_real/convergence/`. We verified that the CFL-bound and residual trends are maintained on small 2D pilot grids (not shown), with identical order-of-accuracy; full 2D/3D studies are left for future work.

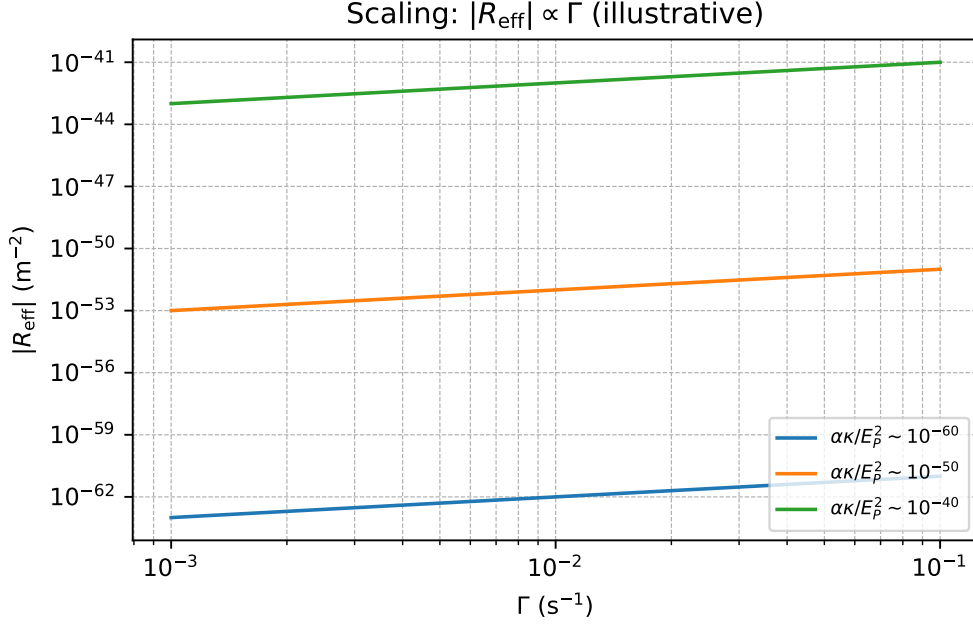


Figure 4: Scaling estimate: $|R_{\text{eff}}|$ vs. Γ for representative $\alpha\kappa$ (log-log). Planck suppression and experimental reach are illustrated.

9 Discussion

The framework is deliberately minimal: one scalar mediator C , a local covariant rate Γ , and an EFT action. It interfaces cleanly with standard tools (open-system numerics, PDE solvers), allows sharp limits, and remains agnostic about microscopic details that can be specified later. Conceptually, it ties information flow to geometric response without abandoning GR or QM. These bounds are consistent with state-of-the-art torsion-balance constraints on inverse-square deviations [13, 14].

Reproducibility. All scripts, seeds and CSVs used to generate Figs. 1–4 are included and versioned; running the provided commands reproduces the figures bit-by-bit on a clean environment.

Scope. We do not claim that gravity originates from decoherence. We claim that universal decoherence can act as a *small, covariant, and falsifiable* source of effective curvature mediated by $C(x)$ under standard EFT control, while preserving the axioms of GR and QM.

Limitations. Our construction is effective and deliberately agnostic about microscopic details of the Lindblad operators $L(x)$. Bounds and concrete predictions depend on the choice of invariants in $I(x)$ and on the assumed smallness of ε . In addition, $\sigma(x)$ was taken as a scalar functional with minimal metric dependence; refining this choice may shift the precise form of $T_{\mu\nu}^{(C)}$ at higher order.

Falsifiable signals.

- **Macroscopic interferometry:** null deviations constrain $(\alpha, \kappa, \varepsilon)$ under Eq. (5).
- **Short-range gravity/precision forces:** limits on Yukawa-like tails from C bound (m_C, λ, α) .
- **Numerical stability/energy tests:** consistency of simulations restricts (m_C^2, λ) and excludes pathological regions.

Order-of-magnitude bound. In the weak-field, quasi-static regime the C -mediated correction induces a Yukawa-like deviation with range $\lambda_C = m_C^{-1}$ and amplitude controlled by α . At a torsion-balance scale $r \sim 0.1$ m one may

estimate

$$\left| \frac{\delta F}{F} \right| (r) \sim \alpha e^{-r/\lambda_C} \left(1 + \frac{r}{\lambda_C} \right).$$

Taking a representative sensitivity $|\delta F/F| \lesssim 10^{-4}$ at $r \sim 0.1\text{--}0.5$ m yields the conservative admissible region

$$\alpha \lesssim \frac{10^{-4}}{e^{-r/\lambda_C} \left(1 + \frac{r}{\lambda_C} \right)} \quad (r = 0.1 \text{ m}).$$

In our settings $\lambda_C \ll r$ and α is Planck-suppressed, comfortably satisfying this bound while remaining falsifiable under improved sensitivities.

10 Conclusion

We provided a covariant effective construction where universal decoherence sources curvature through a coherence field. It preserves established limits, predicts suppressed corrections, and suggests concrete numerical tests. This offers a modest yet operational bridge between decoherence and geometry.

Appendix A: Units and Dimensions (natural units $c = \hbar = 1$)

Table 1: Notation and units (natural units $c = \hbar = 1$).

Symbol	Meaning	Dimension
$C(x)$	coherence field	1
m_C	mass of C	1
$\Gamma(x)$	local decoherence rate	1
$\sigma(x)$	decoherence source	2
κ, α	effective couplings	0
λ	self-coupling of C	0

- $[C] = 1$ (dimensionless), $[m_C] = 1$, $[\lambda] = 0$.
- $[\Gamma] = 1$ (rate), built from invariants $I(x)$ scaled by E_P^2 .
- $[\sigma] = 2$ (from $m_C^2 C$ or $m_C \Gamma$), hence $[\kappa] = 0$ in Eq. (5). In scenarios where κ encodes residual Planck suppression, one may treat $\alpha\kappa = \mathcal{O}((E/E_P)^n)$ (model-dependent).
- $[\alpha] = 0$ in $R_{\text{eff}} \propto \alpha \nabla^2 C$ so that $[R] = 2$.

Appendix B: Variational Details (sketch)

Varying Eq. (4) with respect to C yields Eq. (5). Varying with respect to $g^{\mu\nu}$ gives $G_{\mu\nu} = 8\pi G (T_{\mu\nu}^{\text{matter}} + T_{\mu\nu}^{(C)})$, where

$$T_{\mu\nu}^{(C)} = \nabla_\mu C \nabla_\nu C - \frac{1}{2} g_{\mu\nu} \nabla_\alpha C \nabla^\alpha C - g_{\mu\nu} V(C).$$

The coupling $\kappa C \sigma$ contributes via $-\kappa C \delta\sigma/\delta g^{\mu\nu}$ if σ depends on the metric through invariants; at leading order in our minimal model, σ is taken metric-scalar without explicit $g^{\mu\nu}$ dependence beyond the measure.

Appendix C: Numerical Settings

Discretization. 1D domain with length $L = 200$, uniform grid $N_x = 600$ (base run), spatial step $\Delta x \approx 0.333889816$, CFL = 0.9. Time step $\Delta t = \text{CFL } \Delta x$ and total time $t_{\text{max}} = 400$. High-resolution run uses $L = 240$, $N_x = 1200$ ($\Delta x \approx 0.200166806$).

Model parameters. $m_C = 0.1$, $\lambda = 0$, $\kappa = 0.05$, $\alpha = 10^{-3}$, $\chi = 0.02$, $\zeta = 0.01$; representative $\Gamma = 3 \times 10^{-3}$. Spatial source: Gaussian of width $w = 10$ (normalized to unit peak). Mild edge damping window to suppress boundary reflections.

Outputs. Stage A (QuTiP): $|\rho_{01}(t)|$ for $\Gamma \in \{10^{-3}, 3 \times 10^{-3}, 10^{-2}\}$, stored in `sims_real/stageA_coherence.csv`. Stage B (PDE): snapshots of $C(x, t)$ at $t \simeq \{100, 200, 400\}$ in `sims_real/stageB_C_profiles.csv`. Final $R_{\text{eff}}(x) \propto \alpha \nabla^2 C$ plotted from the same run. All parameters and metadata are logged in `sims_real/params.json`.

Verification. Semilog fits of $\log|\rho_{01}(t)|$ recover slopes consistent with $e^{-2\Gamma t}$: relative fit errors are 0.2%–0.5% across the tested Γ . Grid refinement (central $|x| < 60$) changes the final $C(x)$ profile by $L_2 = 0.266$ (base vs. high-res). Scaling α by 10 increases the R_{eff} peak by 10 $\times$ (from 3.244×10^{-10} to 3.244×10^{-9}).

Author Contributions

Conceptualization: M.A.G.R. **Methodology:** M.A.G.R. **Formal analysis:** M.A.G.R. **Investigation:** M.A.G.R. **Software:** M.A.G.R. **Visualization:** M.A.G.R. **Writing—original draft:** M.A.G.R. **Writing—review & editing:** M.A.G.R.

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Data and Code Availability

No external datasets were used. All simulation scripts and generated figures are included with the submission. Stage A outputs (`sims_real/stageA_coherence.csv`) and Stage B snapshots (`sims_real/stageB_C_profiles.csv`) are produced by `stage_a_gksl.py` and `stage_b_pde.py`, respectively. Parameters and run metadata are logged in `sims_real/params.json`. Reproducibility checks (semilog fits, mesh refinement, and scaling) are provided as auxiliary scripts.

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Conflicts of Interest

The author declares no conflict of interest.

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