Dark Energy as the Relaxation of Fossil Curvature

Rhythm

Abstract

We propose that cosmic acceleration originates not from a fundamental vacuum energy or a new dynamical field, but from the plastic memory of spacetime itself. We postulate that General Relativity describes spacetime as an elastic medium only up to a covariant yield threshold ($K > K_c$). When local curvature invariants exceed this limit—as occurs during stellar collapse, neutron-star mergers, and black-hole formation—spacetime enters a plastic regime, generating a persistent residual deformation encoded in a macroscopic scalar memory field, χ.

We construct an effective field theory in which this fossil curvature contributes a saturating energy density,

$$\rho_f(\chi) \propto \left(1 - e^{-\chi/\chi_*}\right),$$

providing a dynamical stability mechanism that naturally mimics a cosmological constant at late times. By coarse-graining the production of fossil curvature over the cosmic history of strong-field events, we derive a Plasticity Sign Law for the effective equation of state,

$$w(z) + 1 \propto -\left(S(z) - \chi/\tau\right).$$

This relation predicts a generic crossing of the phantom divide, characterized by a phantom-like phase ($w < -1$) during the epoch of net fossil creation, followed by a quintessence-like phase ($w > -1$) during relaxation. Crucially, we demonstrate that this phantom behavior arises effectively from open-system energy exchange with the strong-field source sector and does not require negative kinetic energy or ghost degrees of freedom.

Finally, we establish a novel multi-messenger test by identifying the fossil source rate $S(z)$ with the compact-object merger rate inferred from gravitational-wave catalogs. This rigid coupling implies that the redshift of the phantom crossing, $z_\times$, is constrained by the peak of the cosmic merger history, rendering the mechanism falsifiable by future Stage IV dark energy surveys and gravitational-wave population data.

1 I. INTRODUCTION

The theoretical origin of cosmic acceleration remains one of the most persistent fine-tuning problems in fundamental physics. The standard ΛCDM model fits current observations of Type Ia supernovae (SNe Ia), the cosmic microwave background (CMB), and large-scale structure (LSS) with remarkable precision, yet it relies on a cosmological constant Λ that is theoretically unnatural. Quantum field theory estimates of the vacuum energy density exceed the observed value by many orders of magnitude, and no known symmetry protects Λ at the milli–electron–volt scale. Alternative approaches—such as quintessence or modified gravity—typically address this issue by introducing new dynamical degrees of freedom. However, such models often rely on ad hoc potentials or scalar fields that lack a clear microphysical origin or a direct connection to the known high-energy history of the universe.

In standard General Relativity (GR), the gravitational field is conservative in the thermodynamic sense. The Einstein–Hilbert action implies that curvature responds instantaneously to stress–energy and returns to its vacuum configuration once sources are removed (modulo gravitational radiation). There is no intrinsic hysteresis or long-lived "memory" in the local metric response that persists as a background stress after the source has vanished. Nevertheless, several theoretical developments—including gravitational memory, backreaction, and non-equilibrium thermodynamics of spacetime—suggest that the nonlinear dynamics of gravity may possess richer accumulation properties. In particular, the Bondi–Metzner–Sachs (BMS) symmetry group implies that gravitational waves generate a permanent displacement memory at null infinity, while effective field theory (EFT) treatments of gravity often yield dissipative terms, analogous to bulk viscosity, when high-energy degrees of freedom are integrated out.

In this work, we propose that spacetime dynamics admits a **plastic response regime**. We construct a minimal Effective Field Theory (EFT) in which General Relativity is extended by a *fossilization* sector exhibiting hysteresis: when local curvature invariants—specifically the Kretschmann scalar,

$$K = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma},$$

exceed a critical covariant yield threshold, spacetime undergoes a residual deformation. Such conditions naturally arise in extreme environments including stellar collapse, black hole formation, and neutron star mergers. We postulate that this residual deformation persists as a *fossil curvature* that remains gravitationally active even after the compact object has settled or merged.

To describe this phenomenon on cosmological scales, we introduce a macroscopic scalar state variable $\chi(x)$, which serves as an order parameter for the integrated density of residual curvature. We emphasize that χ is not a fundamental new field, but a coarse-grained effective degree of freedom encoding the accumulated memory of past strong-field events—strictly analogous to viscoelastic parameters in condensed matter systems or to bulk viscosity in hydrodynamics. Although the production of fossil curvature is local and highly anisotropic, occurring at point-like astrophysical sources, we show that in the large-scale averaging limit relevant for cosmology the effective fossil stress–energy tensor, $T^{(f)}_{\mu\nu}$, isotropizes and is compatible with the symmetries of the Friedmann–Lemaître–Robertson–Walker (FLRW) metric.

We assume that the fossil sector contributes an effective potential energy density $\rho_f(\chi)$ that saturates at a critical scale χ_*. This saturation mechanism ensures that the energy density asymptotes to a Λ-like constant at late times, providing a dynamical stability mechanism that prevents unbounded growth of vacuum energy. The evolution of the memory field is governed by the competition between an astrophysical source term, $S(z)$, derived from the cosmic history of yield-violating events, and a relaxation term characterized by a timescale τ.

This framework leads to a specific and falsifiable prediction for the dark energy equation of state, $w(z)$. We derive a **Plasticity Sign Law** demonstrating that the effective equation of state is controlled by the balance between fossil creation and relaxation. Generically, the model predicts a crossing of the phantom divide ($w = -1$): a phantom-like phase ($w_{\text{eff}} < -1$) arises during the epoch of peak fossil production, followed by a quintessence-like relaxation phase ($w_{\text{eff}} > -1$). Crucially, this phantom behavior is an effective phenomenon driven by source terms in the coarse-grained equations of motion—analogous to effective phantom regimes in bulk-viscous cosmologies—and does not require a fundamental field with negative kinetic energy (ghosts), thereby avoiding the instabilities typically associated with $w < -1$ models.

Finally, this framework establishes a direct multi-messenger connection between cosmology and strong-field astrophysics. By identifying the fossilization source term with the compact-object merger rate, we show that the redshift evolution of the dark energy equation of state is constrained by the merger history inferred from gravitational-wave catalogs.

The paper is organized as follows. In Sec. II, we define the EFT framework and the modified Einstein equations. In Sec. III, we formalize the curvature yield trigger and the coarse-graining procedure leading to the source history $S(z)$. In Sec. IV, we present quantitative forecasts for the phantom-crossing redshift $z_\times$. In Sec. V, we demonstrate the linear stability of the scalar sector and the absence of ghosts. Observational falsifiability is discussed in Sec. VI, and we conclude in Sec. VII.

2 II. THEORETICAL FRAMEWORK

We formulate the **Plastic Spacetime Fossil (PSF)** model as a scalar–tensor effective field theory. To capture the dissipative character of plastic deformation within a covariant framework, we model the fossilization variable χ as a canonical scalar degree of freedom coupled to spacetime curvature, subject to strong self-interaction or environmental friction that drives overdamped dynamics on cosmological scales.

2.1 A. The Action and Conservative Sector

The gravitational sector is described by the Einstein–Hilbert action coupled to a canonical scalar field χ and a matter sector Ψ_m. The total action is

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}(\nabla\chi)^2 - V(\chi)\right] + S_{\rm source} + S_m, \tag{1}$$

where $(\nabla\chi)^2 \equiv g^{\mu\nu}\nabla_\mu\chi\nabla_\nu\chi$. The potential $V(\chi)$ represents the stored energy density associated with fossil deformation. To ensure stability and avoid runaway behavior, we adopt a saturating form motivated by finite-capacity memory systems,

$$V(\chi) \equiv \rho_\Lambda\left(1 - e^{-\chi/\chi_*}\right). \tag{2}$$

The term $S_{\rm source}$ encodes the non-minimal interaction between the scalar field and the curvature sector responsible for triggering fossilization. In the effective field theory (EFT) limit, this interaction is represented by a source current J derived from high-curvature operators,

$$S_{\rm source} = \int d^4x\sqrt{-g}\,\chi\,J(g_{\mu\nu},\Psi_m). \tag{3}$$

Varying the action with respect to the metric $g_{\mu\nu}$ yields the Einstein equations,

$$G_{\mu\nu} = 8\pi G\left(T^{(m)}_{\mu\nu} + T^{(\chi)}_{\mu\nu}\right),$$

where the scalar stress–energy tensor is

$$T^{(\chi)}_{\mu\nu} = \nabla_\mu\chi\nabla_\nu\chi - \frac{1}{2}g_{\mu\nu}\left[(\nabla\chi)^2 + 2V(\chi)\right]. \tag{4}$$

In the homogeneous cosmological limit, where spatial gradients vanish, this reduces to the standard perfect-fluid form with energy density

$$\rho_\chi = \frac{1}{2}\dot{\chi}^2 + V(\chi),$$

and pressure

$$p_\chi = \frac{1}{2}\dot{\chi}^2 - V(\chi).$$

2.2 B. The Overdamped Limit: Deriving the Memory Equation

Varying the action with respect to χ yields the covariant Klein–Gordon equation sourced by the interaction term,

$$\Box\chi - V'(\chi) = -J. \tag{5}$$

In a Friedmann–Lemaître–Robertson–Walker (FLRW) background, this equation becomes

$$\ddot{\chi} + 3H\dot{\chi} + V'(\chi) = J, \tag{6}$$

where H is the Hubble parameter.

Fossilization, however, is physically distinct from standard scalar field evolution: it represents a plastic deformation accompanied by dissipation. In macroscopic effective theories, such dissipation manifests as a friction term proportional to the rate of change of the order parameter. We therefore augment the equation of motion with a phenomenological friction term $\Gamma\dot{\chi}$, representing energy transfer to integrated-out microscopic degrees of freedom (analogous to friction in reheating or bulk-viscous cosmologies),

$$\ddot{\chi} + (3H + \Gamma)\dot{\chi} + V'(\chi) = J. \tag{7}$$

We now focus on the overdamped regime relevant for late-time cosmology, characterized by two conditions:

1. **Strong friction:** $\Gamma \gg H$ and $\Gamma\dot{\chi} \gg \ddot{\chi}$.
2. **Linear response:** the restoring force $V'(\chi)$ and the source term J dominate over inertial effects.

Under these conditions, the acceleration term $\ddot{\chi}$ is negligible, and Eq. (7) reduces to the first-order slow-roll equation,

$$\Gamma\dot{\chi} \simeq J - V'(\chi). \tag{8}$$

Defining the effective relaxation timescale

$$\tau \equiv \frac{\Gamma\chi_*}{\rho_\Lambda},$$

(assuming the linear regime $V'(\chi) \sim \rho_\Lambda/\chi_*$) and the effective source rate $S(t) \equiv J/\Gamma$, Eq. (8) simplifies to the memory equation employed in our phenomenological analysis,

$$\dot{\chi} = S(t) - \frac{\chi}{\tau}. \tag{9}$$

Here we have linearized the restoring force as $V'(\chi) \approx \chi(\rho_\Lambda/\chi_*^2)$ for analytical transparency, while retaining the exact potential derivative in the numerical analysis.

This derivation resolves the apparent tension between the conservative action and the dissipative dynamics: Eq. (9) is the valid effective description of the scalar field in the strong-friction, overdamped limit.

2.3 C. Consistency and Energy Exchange

Because the scalar equation of motion (7) includes both friction and external sourcing, the scalar stress–energy tensor $T_{\mu\nu}^{(\chi)}$ is not independently conserved. Taking the covariant divergence of Eq. (4) and using Eq. (7) yields

$$\nabla^{\mu} T_{\mu\nu}^{(\chi)} = -\left(\Gamma \dot{\chi}^2 - \dot{\chi} J\right) u_{\nu}. \tag{10}$$

This expression explicitly quantifies the energy exchange: the term $\dot{\chi}J$ represents work done by the strong-field source sector during fossil creation, while $\Gamma\dot{\chi}^2$ corresponds to energy dissipated during relaxation.

The Bianchi identity for the full system,

$$\nabla^{\mu} \left(T_{\mu\nu}^{(m)} + T_{\mu\nu}^{(\chi)}\right) = 0,$$

is satisfied by requiring that the energy gained or lost by the fossil sector is balanced by an equal and opposite exchange with the source sector (compact objects). Since the integrated fossil energy density is many orders of magnitude smaller than the local baryonic density of the sources ($\rho_{\rm DE} \ll \rho_{\rm matter}$), we work in the probe limit, neglecting backreaction on source trajectories when computing the background expansion.

Under this approximation, the fossil sector may be treated as an effective fluid with equation of state

$$w_{\rm eff} \equiv \frac{p_{\chi}}{\rho_{\chi}} = \frac{\frac{1}{2}\dot{\chi}^2 - V(\chi)}{\frac{1}{2}\dot{\chi}^2 + V(\chi)}. \tag{11}$$

In the overdamped regime where $\dot{\chi}^2 \ll V(\chi)$—corresponding to evolution on timescales $\tau \sim H_0^{-1}$—this reduces to $w_{\rm eff} \simeq -1$, with deviations governed by the source–relaxation balance derived in Sec. IV.

3 III. THE YIELD TRIGGER AND COSMIC SOURCE HISTORY

The central hypothesis of the PSF framework is that the vacuum possesses a finite elastic range. To formulate this idea covariantly, we identify a scalar invariant that characterizes local curvature intensity and define a threshold condition for the onset of plastic deformation.

3.1 A. The Covariant Yield Criterion

We quantify the local curvature strength using the Kretschmann scalar K, defined by the full contraction of the Riemann tensor,

$$K \equiv R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma}. \tag{12}$$

This scalar provides a natural order parameter for strong-field vacuum gravity. For a Schwarzschild black hole of mass M, the invariant scales as $K(r) = 48G^2M^2/r^6$. Evaluated at the event horizon $r_s = 2GM$, this yields a characteristic horizon curvature

$$K_{\rm hor} = \frac{3}{4G^4M^4}.$$

We postulate the existence of a critical yield scale K_c, intrinsic to the quantum vacuum. When the local curvature exceeds this threshold, spacetime enters the plastic regime. We define the dimensionless yield function

$$\mathcal{Y}(x) \equiv \Theta\left(K(x) - K_c\right)\left[\frac{K(x)}{K_c} - 1\right]^n, \tag{13}$$

where Θ is the Heaviside step function and $n \geq 1$ parametrizes the nonlinearity of the material response. While the sharp step function formally represents a phase transition, in a realistic EFT it should be interpreted as the steep limit of a smooth sigmoid; we assume that the transition width is negligible compared to cosmological scales.

Magnitude estimates. For a solar-mass black hole ($M \sim 2 \times 10^{30}$ kg), the horizon curvature is $K_{\rm hor} \sim 10^{-17}$ m^{-4}. In contrast, within the Solar System (e.g., at Earth's orbit), $K \sim 10^{-59}$ m^{-4}. To ensure that plasticity is triggered exclusively in strong-gravity environments—such as collapse and mergers—but remains inactive in weak-field settings, we require

$$10^{-58} \ll K_c \lesssim 10^{-17}\ \mathrm{m}^{-4}.$$

We treat K_c as a free parameter of the high-energy theory, noting that identifying it with the curvature scale of neutron-star cores ($\sim 10^{-18}$ m^{-4}) provides a natural astrophysical benchmark.

3.2 B. Local Covariant Production

We model the production of the fossil field χ as a local covariant process. In the rest frame of the yielding matter—such as a collapsing stellar fluid element or a merger remnant—the production rate is governed by the local yield excess. The constitutive relation is

$$u^\mu \nabla_\mu \chi = \alpha\, \mathcal{Y}(x), \tag{14}$$

where u^μ is the four-velocity of the source fluid and α is a dimensional coupling constant with units [L^{-1}]. This equation states that the memory field accumulates along the worldlines of matter undergoing yield-violating curvature.

3.3 C. Coarse-Graining and the Homogeneous Source $S(t)$

Cosmological evolution is governed by the homogeneous background metric and the zero mode of the scalar field. To obtain the effective source term $S(t)$, we coarse-grain the local production over a spatial hypersurface Σ_t of constant cosmic time t, with induced metric γ_{ij}.

The macroscopic source is defined as the spatial average of the local production rate (Eq. 14) over a comoving volume V,

$$S(t) \equiv \langle \dot{\chi} \rangle_V = \frac{1}{V}\int_V d^3x \sqrt{\gamma}\,\left(\alpha\, \mathcal{Y}(t, \vec{x})\right). \tag{15}$$

Here we have aligned the cosmic rest frame with the source frame on average, $u^\mu \approx \delta^\mu_0$, an approximation valid for the non-relativistic bulk motion of galaxies. High-velocity merger recoils introduce only negligible second-order corrections to this averaging.

3.4 D. Multi-Messenger Connection: Dimensional Mapping

Equation (15) represents a spatial integral over discrete, highly localized events. It is therefore natural to rewrite $S(t)$ in terms of the number density of such events. If $\mathcal{R}(z)$ denotes the comoving merger rate density (events per unit comoving volume per unit source time), the effective source may be approximated as

$$S(z) \simeq \bar{\chi}_{\text{event}} \langle V_{\text{yield}} \rangle \mathcal{R}(z). \tag{16}$$

We define the effective yield coefficient

$$\beta \equiv \bar{\chi}_{\text{event}} \langle V_{\text{yield}} \rangle,$$

which encapsulates the microscopic physics of fossilization:

- $\langle V_{\text{yield}} \rangle$ is the effective spacetime volume over which $K > K_c$ during a merger event,
- $\bar{\chi}_{\text{event}}$ is the average integrated field amplitude produced per event.

The phenomenological link then takes the compact form $S(z) = \beta\mathcal{R}(z)$. Since $\mathcal{R}$ has units $[\mathrm{L}^{-3}\mathrm{T}^{-1}]$ and β has units of volume, the source term S correctly carries units of $[\mathrm{T}^{-1}]$, consistent with the memory equation $\dot{\chi} = S - \chi/\tau$.

3.5 E. Benchmark Source History

To generate quantitative forecasts, a functional form for the merger rate $\mathcal{R}(z)$ must be specified. While the cosmic star-formation rate is well described by a Madau–Dickinson profile, compact-object merger rates are convolved with a delay-time distribution $P(t_d) \propto t_d^{-1}$.

For this initial study, we adopt a parameterized merger-rate model commonly used in gravitational-wave population analyses,

$$\mathcal{R}(z) = \mathcal{R}_0(1+z)^{\kappa}, \qquad z < z_{\text{peak}}, \tag{17}$$

with a turnover at higher redshift. Current constraints on binary black hole merger rates suggest $\mathcal{R}_0 \sim 17$–$45\ \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$ and $\kappa \sim 2.9$.

For our benchmark model, we adopt a smoothed broken power-law that reproduces the observed low-z slope and peaks at $z_p \simeq 2.0$, consistent with standard time-delayed star-formation scenarios,

$$S(z) = S_{\text{norm}} \frac{(1+z)^{\kappa}}{1 + [(1+z)/(1+z_p)]^{\kappa+\Gamma}}. \tag{18}$$

Here Γ controls the high-redshift decline. We fix $\kappa = 2.9$ based on observational constraints, leaving the memory timescale τ and the normalization S_{norm} as the only free parameters of the model.