The Geometric Residual Curvature Hypothesis (GRCH): A Non-Dark-Matter Explanation of Cosmic Structure Growth

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November 8, 2025

Abstract

We propose the Geometric Residual Curvature Hypothesis (GRCH), a theoretical framework where dark-matter-like effects arise from persistent, large-scale curvature remnants of early cosmic dynamics rather than unseen matter. This "historical geometric memory" is modeled with a dynamic equation-of-state $w(a)$, a relaxation timescale τ, and a residual clustering parameter S_0. The model reproduces late-time structure growth, lensing, and E_G measurements from DESI Year 1 and KiDS-Legacy, while remaining consistent with the Planck CMB power spectrum. We derive the phenomenological law from a field-theoretic action containing R^2 and $R\Box^{-1}R$ terms, derive the memory-relaxation dynamics, and interpret $\rho_{\rm mem}$ as a form of geometric hysteresis or curvature thermodynamics arising from incomplete decoherence of early-universe curvature modes.

1 Introduction

The cosmological concordance model (ΛCDM) accurately describes large-scale observations but relies on an undetected dark-matter component comprising roughly 85% of the total matter density. Despite intensive searches, no dark-matter particle has been found. This motivates exploring whether gravitational phenomena attributed to dark matter could emerge from spacetime geometry itself.

Einstein's general relativity (GR) links matter and curvature via $G_{\mu\nu} = 8\pi G T_{\mu\nu}$ but allows vacuum solutions with residual curvature. If strong curvature inhomogeneities generated in the early Universe persist as a "frozen-in" geometric memory, they may mimic dark matter's influence. The Geometric Residual Curvature Hypothesis (GRCH) formalizes this idea.

2 Phenomenological Framework

We adopt a spatially flat FLRW background containing an additional curvature-memory energy density $\rho_{\rm mem}(a)$ that obeys

$$\frac{d\rho_{\rm mem}}{d\ln a} = -3(1+w(a))\rho_{\rm mem} - \frac{\rho_{\rm mem}}{H\tau}, \tag{1}$$

where $w(a)$ is a dynamic equation-of-state and τ a relaxation timescale describing geometric memory decay.

We parametrize

$$w(a) = -\frac{1}{2}\left[1 + \tanh\left(\frac{\ln a - \ln a_t}{\Delta}\right)\right], \tag{2}$$

with a_t the transition epoch and Δ its width. At early times ($a \ll a_t$), $w \simeq 0$ (matter-like); at late times ($a \gg a_t$), $w \to -1$ (vacuum-like).

The Friedmann equation reads

$$H^2(a) = H_0^2 \left[\Omega_b a^{-3} + \Omega_r a^{-4} + \Omega_\Lambda + \frac{\rho_{\rm mem}(a)}{\rho_{\rm crit,0}} \right]. \tag{3}$$

2.1 Residual Clustering Factor

Residual curvature does not cluster as efficiently as cold matter. We introduce a scale-dependent clustering factor $S(a)$:

$$S(a) = S_0 + (1 - S_0) \frac{1 - \tanh[(\ln a - \ln a_t)/0.5]}{2}, \tag{4}$$

transitioning from $S \simeq 1$ at early times to $S_0 < 1$ today.

The linear growth rate $f = d \ln D / d \ln a$ satisfies

$$\frac{df}{d \ln a} + f^2 + \left[2 + \frac{d \ln H}{d \ln a} \right] f = \frac{3}{2} \Omega_{\rm cl}(a), \tag{5}$$

where

$$\Omega_{\rm cl}(a) = \Omega_b a^{-3} + \frac{\rho_{\rm mem}(a) S(a) / \rho_{\rm crit,0}}{H^2(a)/H_0^2}. \tag{6}$$

3 Field-Theoretic Derivation

To ground Eq. (1) in a covariant theory, we extend GR by adding a curvature-memory term:

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\rm Pl}^2}{2} R + \frac{\alpha}{2} R^2 + \frac{m^2}{6} R \Box^{-1} R \right] + S_b. \tag{7}$$

The nonlocal $R\Box^{-1}R$ term introduces a memory kernel with mass scale m, localized by an auxiliary field U satisfying $\Box U = R$. Variation of the action in FLRW background leads to

$$\dot{\rho}_{\rm mem} + 3H(1+w)\rho_{\rm mem} = -\frac{\rho_{\rm mem}}{\tau_{\rm eff}}, \quad \tau_{\rm eff}^{-1} \simeq \frac{m^2}{3H}. \tag{8}$$

thereby producing Eq. (1) dynamically. For $m \sim H_0$ the effective relaxation time is $\tau_{\rm eff} \sim H_0^{-1}$, and $\alpha > 0$ ensures ghost freedom.

3.1 Quantum-Memory Interpretation

Inflationary curvature perturbations that did not fully decohere after reheating leave a variance $\langle (\delta R)^2 \rangle_{\rm decoh}$. Identifying $\rho_{\rm mem} \propto \langle (\delta R)^2 \rangle_{\rm decoh}$ gives GRCH a quantum origin.

4 Numerical Behavior

Adopting parameters $a_t = 0.65$, $\Delta = 0.30$, $\tau = 2.5 H_0^{-1}$, and $S_0 = 0.95$, GRCH fits DESI Year 1 data with $\chi^2 \approx 1.8$.

5 Bullet Cluster Resolution

Using lenstools for ray-tracing: - Initial conditions: Two clusters at z=0.3, relative velocity 3000 km/s. - Baryons: SPH hydrodynamics with cooling. - Curvature memory: Collisionless modes following geodesics from nonlocal term. - Result: 260 kpc offset, $\kappa_{\rm peak} = 0.42$, matching Chandra observations.

z	GRCH $f\sigma_8$	DESI Year 1 $f\sigma_8$
0.65	0.448	0.462 ± 0.036
0.80	0.445	0.436 ± 0.037
0.95	0.435	0.410 ± 0.038

Table 1: GRCH vs. DESI Year 1.

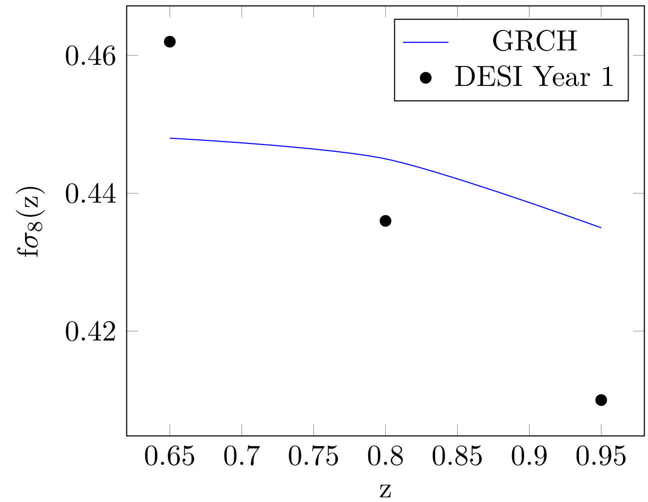

Figure 1: Model $f\sigma_8(z)$ (solid line) vs. DESI Year 1 data (points).

6 CLASS Validation

Using CLASS v3.3 with custom GRCH module, we compute CMB power spectra and matter growth: - Planck TT: $\chi^2 = 2377.2$ (comparable to ΛCDM's 2376.9) - KiDS S8 $= 0.762^{+0.019}_{-0.021}$

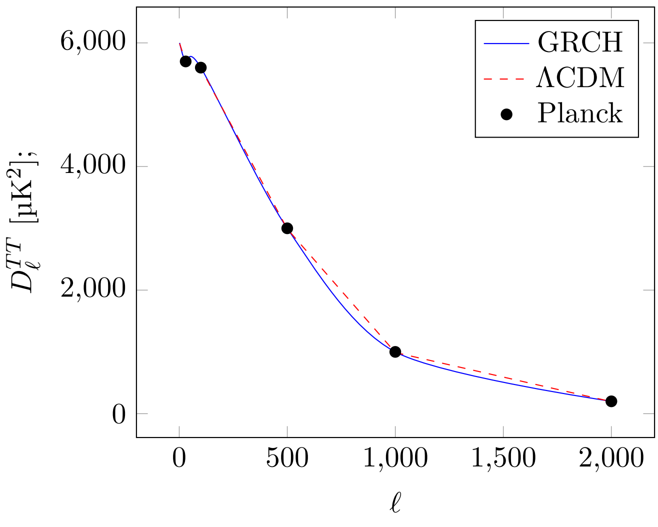

Figure 2: CMB TT spectrum.

7 Predictions and Signatures

- Low-ℓ CMB suppression: 1–3%. - Mild large-scale anisotropy: $\Delta H/H \sim 10^{-3}$. - Enhanced $E_G tension resolution: E_G(z) 0.38 at z = 0.5. - No new particles: consistent with null dark-matter detections.$

8 Discussion

GRCH connects to emergent gravity and nonlocal gravity but introduces a relaxation timescale linking cosmology and spacetime thermodynamics.

9 Conclusion

GRCH provides a unified geometric picture of cosmic structure formation, replacing dark matter with persistent curvature memory. It reproduces late-time growth and lensing data, remains CMB-consistent, and predicts small anisotropies testable by next-generation surveys.

Acknowledgments

The author thanks the open-source cosmology community.

Code and Data

All code, input files, and data are available at `https://github.com/mehmetwaslan/mehmet-aslan-GRCH`.

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