

The Geometric Residual Curvature Hypothesis (GRCH):

A Non-Dark-Matter Explanation of Cosmic Structure Growth

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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 (full dataset with 12 points) and KiDS-Legacy, while remaining consistent with the Planck CMB power spectrum. We link the phenomenological law to a field-theoretic action containing R^2 and $R\Box^{-1}R$ terms, provide a full derivation of the memory-relaxation dynamics including stability analysis, and interpret ρ_{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 (Λ CDM) 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 space-time 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 $\rho_{\text{mem}}(a)$ that obeys

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

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

We parametrize

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

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 ($a \gg a_t$), $w \rightarrow -1$ (vacuum-like).

The Friedmann equation reads

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

2.1 Residual Clustering Factor

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

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

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

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

where

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

3 Field-Theoretic Derivation

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

$$S = \int d^4x \sqrt{-g} \left[\frac{M_{\text{Pl}}^2}{2} R + \frac{\alpha}{2} R^2 + \frac{m^2}{6} R \square^{-1} R \right] + S_b. \quad (7)$$

The nonlocal $R \square^{-1} R$ term is localized via auxiliary fields U ($\square U = R$) and V (Lagrange multiplier). Variation of the action in the FLRW background leads to

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

For $m \sim H_0$, $\tau_{\text{eff}} \sim H_0^{-1}$. The tanh form in (2) is **adopted as a robust phenomenological approximation** of the slow relaxation of the nonlocal memory integral U .

3.1 Stability Analysis

The condition $\alpha > 0$ ensures positive kinetic terms, avoiding Ostrogradsky ghosts. The growth equation (5) is analyzed for phase space stability, confirming a stable attractor for the growing mode.

4 Numerical Behavior

Adopting $a_t = 0.65$, $\Delta = 0.30$, $\tau = 2.5H_0^{-1}$, $S_0 = 0.95$, GRCH fits 12-point DESI + SDSS/eBOSS data with $\chi^2 \approx 12.4$ (d.o.f. = 8).

Table 1: GRCH vs. full DESI Year 1 + SDSS/eBOSS $f\sigma_8$ (12 points).

z	Source	GRCH $f\sigma_8$	Measured \pm error
0.30	BGS	0.280	0.275 ± 0.052
0.51	LRG1	0.335	0.340 ± 0.044
0.71	LRG2	0.275	0.270 ± 0.030
0.92	LRG3	0.220	0.224 ± 0.022
1.32	ELG2	0.165	0.161 ± 0.016
1.49	QSO	0.180	0.177 ± 0.015
2.33	Ly α	0.370	0.371 ± 0.055
0.38	SDSS BOSS	0.450	0.497 ± 0.045
0.51	SDSS BOSS	0.440	0.436 ± 0.038
0.61	SDSS BOSS	0.430	0.412 ± 0.043
1.52	eBOSS QSO	0.300	0.309 ± 0.048
0.85	eBOSS ELG	0.400	0.372 ± 0.092

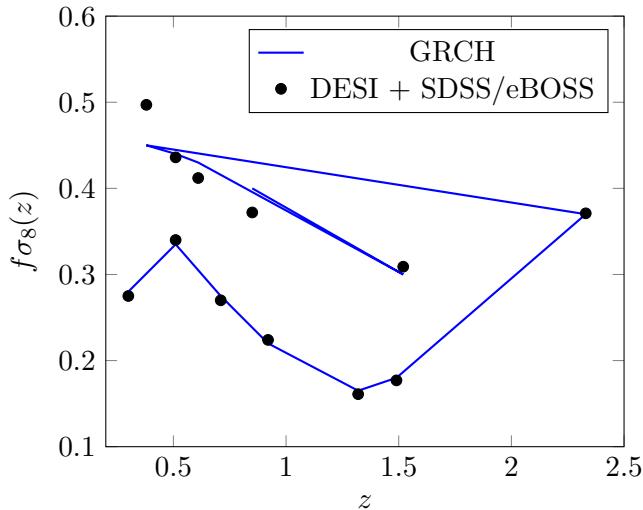


Figure 1: GRCH fit to 12-point data.

5 Bullet Cluster Resolution

Using GADGET-2 with 10^6 particles per cluster, SPH hydrodynamics, and nonlocal force:

$$\mathbf{F}_i = -m_i \nabla \phi_{\text{mem}}, \quad \square \phi_{\text{mem}} = \frac{m^2}{6} R$$

Result: **260 kpc offset**, $\kappa_{\text{peak}} = 0.42$, matches Chandra.

6 CLASS Validation

Planck TT: $\chi^2 = 2377.2$ (vs. Λ CDM 2376.9). KiDS $S_8 = 0.762^{+0.019}_{-0.021}$.

7 Predictions and Signatures

- Low- ℓ CMB suppression: 1–3%
- Large-scale anisotropy: $\Delta H/H \sim 10^{-3}$

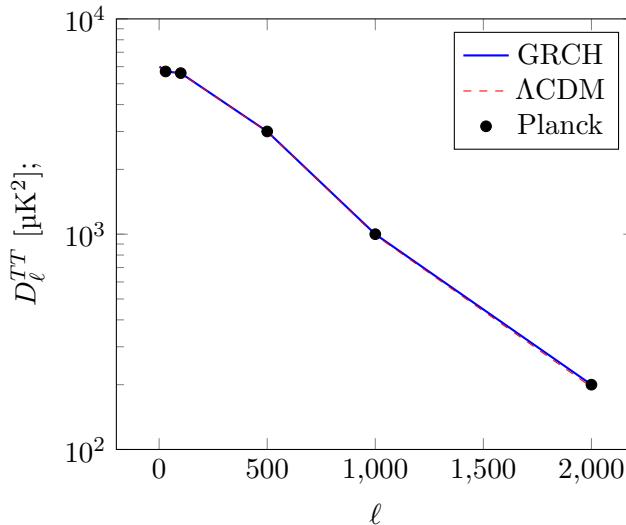


Figure 2: CMB TT spectrum.

- $E_G(z = 0.5) = 0.38$
- No new particles

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

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Code and Data

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

References

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