The Geometric Residual Curvature Hypothesis (GRCH):

A Phenomenological Curvature-Based Alternative to Dark Matter

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November 2025

Abstract

We explore the *Geometric Residual Curvature Hypothesis* (GRCH), a phenomenological framework in which part of the effective dark-matter behavior arises from slowly relaxing, large-scale curvature inhomogeneities generated in the early Universe. This "geometric memory" component, characterized by an effective density $\rho_{\rm mem}(a)$, an equation of state $w(a)$, and a reduced clustering factor $S(a)$, modifies late-time structure growth without introducing new particles.

We investigate three fully reproducible numerical tests: (1) a two-component cluster-merger experiment illustrating baryon–memory separation, (2) direct numerical integration of the growth equation comparing GRCH predictions to DESI Year 1 $f\sigma_8$ data, and (3) a simplified CMB TT sensitivity test showing that percent-level clustering suppression is not excluded by Planck-like uncertainties.

The goal is not a full cosmological model, but a transparent exploration of how residual curvature dynamics could mimic dark matter on large scales. All code is provided in a public repository.

1 Introduction

The ΛCDM model provides an excellent fit to cosmological data but requires a cold dark matter component whose microphysical nature remains unknown. This motivates investigating whether part of the observed "dark-matter-like" phenomena could originate from properties of spacetime itself.

The *Geometric Residual Curvature Hypothesis* (GRCH) proposes that a small fraction of primordial curvature fluctuations did not fully decohere post-inflation and survive as a slowly relaxing geometric memory field. This component behaves as a clustering fluid at early times but exhibits reduced clustering efficiency at late times.

In this work we examine whether such a component can qualitatively reproduce (1) merger-scale baryon–collisionless separation, (2) the observed growth rate from DESI, and (3) percent-level effects on the CMB TT spectrum.

2 Phenomenological GRCH Framework

We consider a flat FLRW cosmology with an additional component $\rho_{\rm mem}(a)$ whose evolution is governed by

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

where $w(a)$ is a phenomenological equation of state and τ a relaxation timescale.

A smooth transition between early-time matter-like behavior and late-time mild vacuum-like behavior is implemented via

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

with $w_{\rm early} \simeq 0$, $w_{\rm late} \simeq -(1 - S_0)$.

Reduced clustering efficiency is encoded in

$$S(a) = S_0 + \frac{1 - S_0}{2} \left[1 - \tanh\left(\frac{\ln a - \ln a_t}{0.5}\right)\right]. \tag{3}$$

The Friedmann equation is

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

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

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

with effective clustering density

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

All parameter values used in our numerical tests are purely phenomenological and documented in the accompanying script `derive_parameters.py`.

3 Cluster–Scale Dynamics

To assess whether GRCH can produce baryon–collisionless separation on merger scales, we perform a minimal two-component experiment using `run_bullet.py`. Each $10^{15} M_\odot$ cluster consists of:

- a collisional baryonic component subject to an effective drag,
- a collisionless geometric-memory component evolving under gravity.

With an initial relative velocity of $3000\,\mathrm{km\,s^{-1}}$ and softening length $30\,\mathrm{kpc}$, the baryonic and memory components decouple after core passage, producing

$$\Delta x \simeq 260\,\mathrm{kpc}, \quad \kappa_{\rm peak} \simeq 0.41.$$

These results demonstrate that a reduced-clustering, collisionless memory component can generate Bullet-like offsets under realistic merger kinematics.

4 Growth Rate and DESI Comparison

We integrate the modified growth equation using `run_grch_growth.py`. For parameters $S_0 = 0.95$, $a_t = 0.65$, $\tau = 2.5H_0^{-1}$, $\sigma_8(0) = 0.81$, we obtain:

z	GRCH $f\sigma_8$	DESI Y1
0.65	0.463	0.462 ± 0.036
0.80	0.451	0.436 ± 0.037
0.95	0.436	0.410 ± 0.038

The three points yield a simple $\chi^2 \simeq 0.65$. The deviation from ΛCDM is controlled primarily by the late-time value of $S(a)$, indicating that GRCH can reproduce observed growth suppression without modifying the early Universe.

5 CMB TT Sensitivity

We assess whether the percent-level reduction in late-time clustering implied by GRCH is consistent with CMB TT data. Instead of a full Boltzmann treatment, we use a simplified TT template based on ΛCDM-like D_ℓ^{TT} values and apply a uniform 1.5% suppression representing the change in clustering amplitude between $z = 2$ and today.

Comparison with approximate Planck-like points shows that the resulting difference is smaller than observational uncertainties at all multipoles, including the low-ℓ ISW-dominated region. A full Boltzmann implementation of GRCH is left for future work.

6 Discussion

Our results suggest that a slowly relaxing geometric memory component with reduced late-time clustering can qualitatively reproduce:

- separation between collisional and collisionless matter in high-speed cluster mergers,
- the observed suppression of the linear growth rate from DESI,
- and percent-level CMB TT sensitivity.

GRCH is not yet a full cosmological alternative; rather, it offers a minimal, phenomenologically motivated framework showing how curved-spacetime memory could mimic aspects of dark matter.

A natural next step is incorporating GRCH into a Boltzmann code (CLASS or CAMB), enabling predictions for C_ℓ^{TT}, $C_\ell^{\phi\phi}$, and S_8.

7 Conclusion

The Geometric Residual Curvature Hypothesis provides a coherent phenomenological framework for exploring curvature-based alternatives to dark matter. With transparent numerical demonstrations and a clear theoretical motivation, GRCH offers a promising avenue for further development in cosmological modeling.

Code Availability

All numerical scripts and parameter files are publicly available at:
`https://github.com/mehmetwaslan/mehmet-aslan-GRCH`.