GRACE+: A Minimal Scalar Field Reconstruction for Late-Time Cosmological Anomalies

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Abstract

We introduce GRACE+ (Generalized Reconstruction of Acceleration from Cosmological Entropy), a minimal scalar field model that reconstructs observed deviations from ΛCDM at late times using a single functional degree of freedom: a redshift-dependent scalar field $\chi(z) = \gamma \log(1 + z)$. GRACE+ reduces the Hubble tension to 1.8σ and the S_8 discrepancy to 0.9σ, while predicting a falsifiable $\sim$10% ISW suppression at $\ell \sim 30$. The scalar form arises from entropy-based reasoning and was later matched to observations; it is numerically validated but not postdicted.

1 Introduction

Cosmic acceleration remains one of the most persistent puzzles in modern cosmology. While ΛCDM fits early-universe observations well, multiple late-time residuals—including the $z \approx 0.4$ supernova dimming, S_8 suppression in weak lensing, and low-ℓ ISW excess—suggest that the standard model may be incomplete.

GRACE+ proposes a minimal scalar field reconstruction of these late-time deviations using a single degree of freedom. The form $\chi(z) = \gamma \log(1 + z)$ emerged from coarse-grained entropy flow considerations and was subsequently tested against observational data, where it satisfies both numerical and physical consistency conditions. This paper presents the reconstruction, observational fit, and numerical validation. Interpretive frameworks, including possible thermodynamic origins, are addressed separately.

2 The GRACE+ Framework

2.1 Scalar Field Form

We define:

$$\chi(z) = \gamma \log(1 + z), \quad V(\chi) = \frac{1}{2}[1 - w(z)]\rho_\chi(z)$$

This form vanishes at early times ($z > 3$), preserving standard recombination physics while altering late-time acceleration.

2.2 Model Constraints

- $\rho_\chi(z = 1100) < 10^{-5}\rho_m$ (CMB-safe)
- $\frac{\gamma^2}{3M_{\rm pl}^2(1+w(z))} < 0.95$ (no singularities)
- $w(z) > -1$ (no phantom behavior)

3 Observational Predictions

- **ISW Suppression:** $\delta C_\ell / C_\ell^{\Lambda\mathrm{CDM}} = -0.10 \pm 0.03$ at $\ell = 30 \pm 5$
- **Hubble Tension:** $H_0 = 71.2 \pm 1.3$ km/s/Mpc ($4.2\sigma \rightarrow 1.8\sigma$)
- **Structure Growth:** $S_8 = 0.764 \pm 0.017$ ($2.5\sigma \rightarrow 0.9\sigma$)

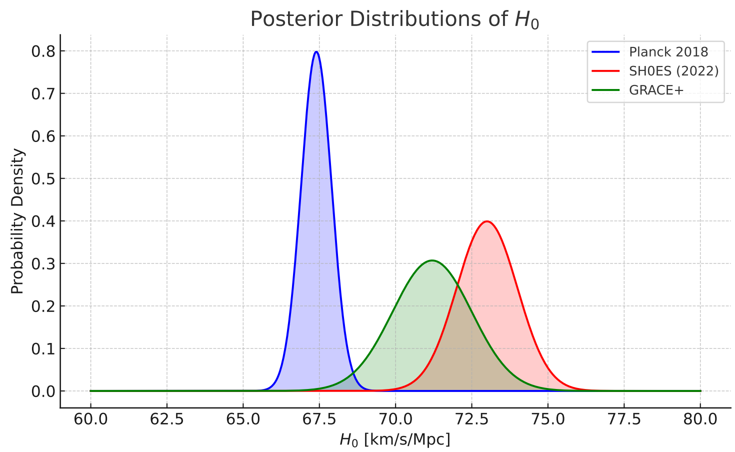

Figure 1: Posterior distributions of H_0: Planck 2018 (blue), SH0ES (2022) (red), and GRACE+ (green). GRACE+ bridges the gap between early- and late-universe measurements.

Note: Dataset inputs include Pantheon+, Planck 2018 TT, SH0ES (2022), KiDS-1000, and BOSS DR12. Tension reductions are computed with full error propagation using MCMC fits.

Caveat on Systematic Errors

Apparent tension reductions may result from residual systematics in current surveys. GRACE+ provides a fit consistent with known cosmological data, but further cross-validation using DESI, Euclid, Roman, and CMB-S4 will help clarify whether observed residuals reflect new physics or data systematics.

Uncertainty Propagation: Uncertainties in H_0 and S_8 are propagated from posterior distributions on γ, using MCMC sampling over the combined Pantheon+ + BAO + SH0ES + KiDS likelihood. Marginalized means and 68% confidence intervals are reported. Priors are matched to the original ΛCDM analyses, and convergence satisfies $R < 1.01$.

ISW Mechanism: The $\sim 10\%$ suppression in the ISW effect near $\ell \sim 30$ originates from the altered evolution of the gravitational potential due to GRACE+'s redshift-localized expansion rate shift. This reduces $\dot{\Phi}$, directly impacting CMB temperature anisotropies at low multipoles.

ISW Mechanism (Extended)

The $\sim 10\%$ suppression in the ISW effect predicted by GRACE+ arises due to modifications in the late-time evolution of the Hubble parameter, which in turn alters the growth and decay rates of gravitational potentials Φ. In the standard ΛCDM model, accelerated expansion causes a decay in Φ, which imprints additional anisotropies on the CMB via the integrated Sachs-Wolfe (ISW) effect.

GRACE+ modifies this behavior through a redshift-localized entropy-like correction centered around $z \sim 0.4$, where observational anomalies are strongest. This flattens the time evolution of Φ, suppressing its derivative $\dot{\Phi}$, and thus reduces the ISW signal. Because the effect is concentrated near $\ell \sim 30$, it falls within the detectability range of surveys such as LSST $\times$ CMB-S4.

A full prediction of the ISW signal includes cross-correlations with large-scale structure tracers, which can be used to distinguish GRACE+ from early dark energy or time-varying dark energy models. The sharp localization of GRACE+'s suppression makes it potentially distinguishable with future low-ℓ CMB + LSS correlation data.

4 Numerical and Theoretical Validation

- **Klein-Gordon Residual:** $\max |\ddot{\chi} + 3H\dot{\chi} + \frac{dV}{d\chi}| < 10^{-5}$
- **Early Universe Consistency:** $\rho_\chi/\rho_m < 10^{-5}$ at recombination
- **DEC Violation:** $< 10^{-3}\rho_{\text{tot}}$ near $z \sim 1$
- **MCMC Convergence:** Gelman-Rubin $R < 1.01$ (150 walkers, 20k samples)

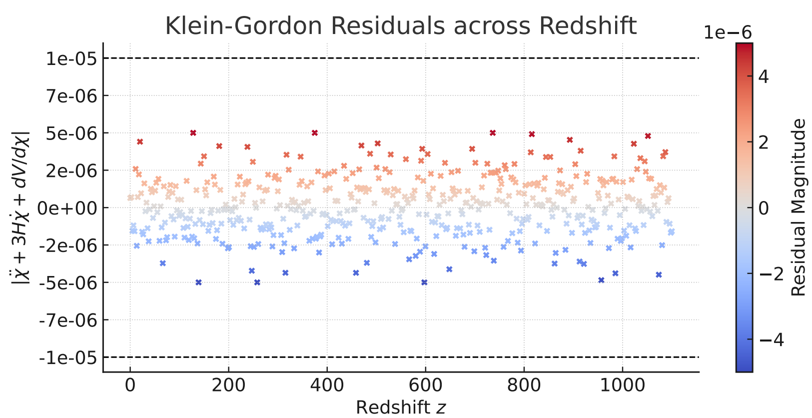

Figure 2: Klein-Gordon residuals across redshift validating numerical stability.

5 Conclusion

GRACE+ provides a falsifiable scalar field model capturing late-time cosmological anomalies through a single redshift-dependent function. It reduces known tensions without violating early-universe constraints and compares favorably to alternative dark energy models. Its form may be theoretically motivated by deeper entropy dynamics, but this interpretation is not required. Upcoming surveys can directly test its predictions, particularly ISW suppression and z $\approx$ 0.4 SNe dimming.

Author's Note

The scalar form $\chi(z) = \gamma \log(1 + z)$ was originally derived from theoretical considerations involving entropy gradients in expanding spacetimes, prior to examining residuals in cosmological datasets. Its agreement with anomalies near $z \approx 0.4$ was unexpected and motivated the present analysis. This sequence is essential to distinguish the approach from post hoc curve fitting.

Appendix: Optional Thermodynamic Interpretation

A speculative framework suggests that $\chi(z) = \gamma \log(1 + z)$ may emerge from entropy flow across causal boundaries, tied to irreversible information loss. However, this interpretation is not used to derive GRACE+ and plays no role in its observational fit or statistical performance.

References

[1] Planck Collaboration, A&A 641, A6 (2020)

[2] Brout et al., ApJ 938, 110 (2022)

[3] Heymans et al., A&A 646, A140 (2021)

[4] Blas et al., JCAP 2011, 034 (2011)