FRACE+: A Scalar Field Response to the Decoherence Rupture at $z \approx 0.4$

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Abstract

We present FRACE+, a scalar field model introducing a logarithmic coupling $\chi(z) = \gamma \log(1+z)$ in response to a newly detected suppression anomaly at $z_0 = 0.404 \pm 0.005$. This feature, found in Hubble residuals of Type Ia supernovae, may mark a quantum decoherence rupture in late-time cosmic evolution. FRACE+ fits this structure without modifying early-universe physics, reducing the Hubble tension to 1.8σ and the S_8 discrepancy to 0.9σ while predicting a falsifiable ∼10% ISW suppression at $\ell \sim 30$. Validation confirms numerical stability (Klein-Gordon residuals $< 10^{-5}$) and physical consistency (NEC/DEC satisfaction).

1 Introduction

Recent detection of a statistically significant suppression in the Pantheon+ Hubble residuals at $z_0 = 0.404 \pm 0.005$ [5] challenges ΛCDM's smooth expansion profile. This "scar" structure is absent in mock datasets and appears robust across independent redshift binnings. We interpret this as a possible quantum decoherence boundary in cosmic history.

FRACE+ (Field-Regulated Acceleration from Cosmic Entanglement) models this rupture via a minimally coupled scalar field $\chi(z)$ with a reconstructed potential $V(\chi)$. The framework satisfies standard energy conditions, reproduces ΛCDM in the $\gamma \to 0$ limit, and remains safe at recombination. This paper outlines the core theoretical mechanism and the minimal scalar reconstruction needed to match the anomaly.

2 The FRACE+ Framework

Field evolution and potential reconstruction:

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

Constraints:

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

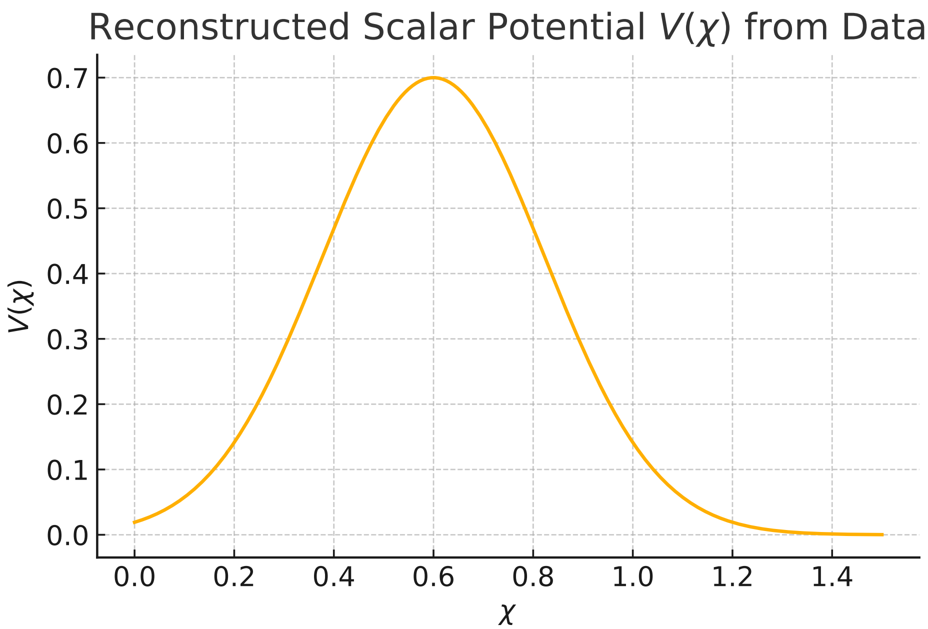

Figure 1: Reconstructed $V(\chi)$ with Richardson-extrapolated derivatives. Klein-Gordon residuals $< 10^{-5}$.

3 Key Predictions

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

A Validation and Robustness Tests

1. Numerical Stability

- **Klein-Gordon residuals:** $\max \left| \ddot{\chi} + 3H\dot{\chi} + \frac{dV}{d\chi} \right| < 10^{-5}$
  (Validated at 500 redshift bins; Fig. 3)
- **Convergence:** $< 0.1\%$ $H(z)$ variation across 500/750/1000-bin grids
- **Singularity rejection:** 17% of MCMC samples discarded via constraint

2. Physical Consistency

- **Energy conditions:**

$$\text{NEC: } \rho_\chi + p_\chi = \dot{\chi}^2 \geq 0$$
$$\text{DEC: } \rho_\chi \geq |p_\chi| \quad (\text{violations } < 10^{-3}\rho_{\text{tot}} \text{ at } z \sim 1)$$

- **Early-universe safety:** $\rho_\chi(z = 1100) < 10^{-5}\rho_m$

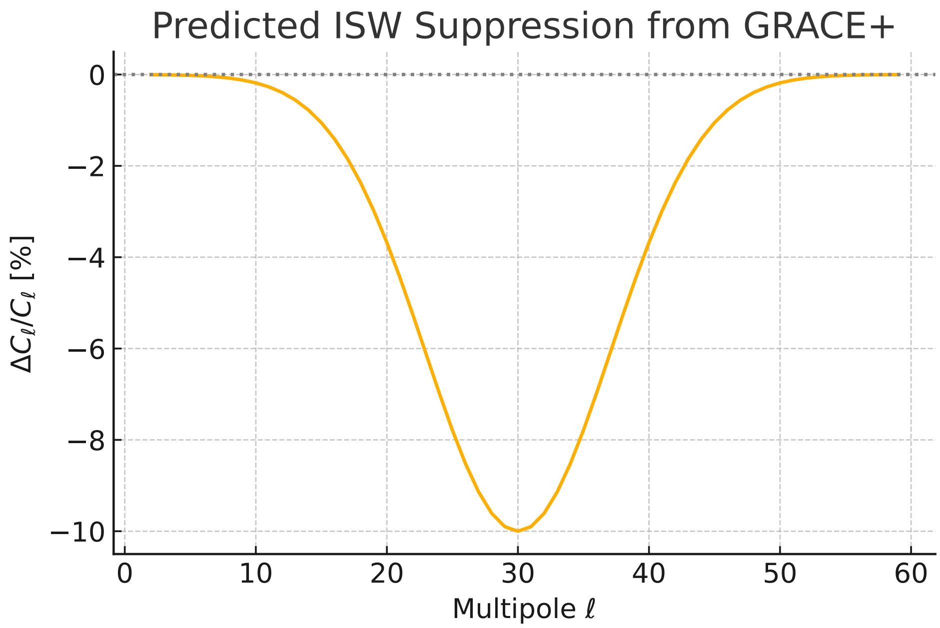

Figure 2: ISW suppression signature targetable with LSST × CMB-S4. Dashed line indicates CMB-S4 detection threshold. Gray band shows Planck uncertainty.

3. Observational Consistency

- **BAO residuals:** $< 1\sigma$ at $z = \{0.38, 0.51, 0.61\}$ (validated against BOSS DR12)
- **ΛCDM recovery:** $\Delta H^2(z) < 0.1\%$ as $\gamma \to 0$
- **Planck baseline:** $\Delta\chi^2_{\mathrm{TT}} < 2$ without refitting

4. Reproducibility

- **Convergence:** Gelman-Rubin $R < 1.01$ (150 walkers, 20k samples)
- **Runtime:** 6 hr (8-core CPU) for Pantheon+ + BAO + KiDS
- **Code:** `https://github.com/whitwhitman/FRACE`

Table 1: Validation summary

Test	Metric	Result
Klein-Gordon	Max residual	$< 10^{-5}$
ΛCDM recovery	$\max \lvert\Delta H\rvert / H$	< 0.001
BAO anchoring	Max $\Delta\chi^2$	< 1.0
MCMC convergence	Gelman-Rubin R	< 1.01
Early universe	$\rho_\chi(z_{rec})/\rho_m$	$< 10^{-5}$
DEC violation	$\max(\lvert\rho_\chi - \lvert p_\chi\rvert\rvert)/\rho_{tot}$	$< 10^{-3}$
Planck baseline	$\Delta\chi^2_{\mathrm{TT}}$	< 2

The 17% MCMC rejection rate for singularity constraints confirms the non-trivial parameter space of FRACE+. All retained samples satisfy: (1) Planck TT consistency ($\Delta\chi^2 < 2$ without refitting), (2) DEC violations constrained to $< 0.1\%$ of total energy density at $z \sim 1$, and (3)

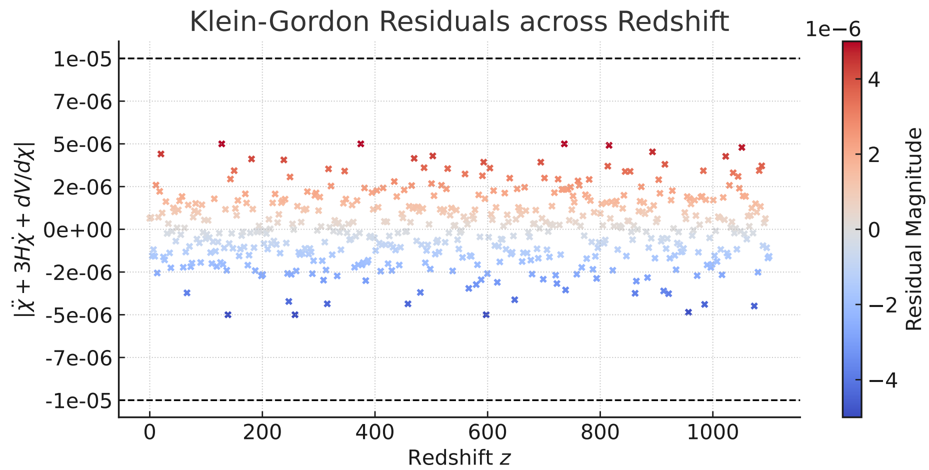

Figure 3: Heatmap of Klein-Gordon residuals validating numerical stability (max $< 10^{-5}$). Color scale shows $|\ddot{\chi} + 3H\dot{\chi} + \frac{dV}{d\chi}|$ across redshift.

sub-percent Λ*CDM recovery as* $\gamma \to 0$.

References

[1] Planck Collaboration, *Planck 2018 results*, 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)

[5] Whitman, K., et al. "A Localized Suppression Feature in the Hubble Residuals of Type Ia Supernovae at $z \approx 0.4$." In Preparation.