Impact of Dark Matter Density Inhomogeneities on SNIa Residuals

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1 Introduction

In the recent UQCMF analysis of Type Ia supernovae (SNIa), after applying a zero-point shift of 41.34727 mag and an intrinsic scatter $\sigma_{\text{int}} = 1.0$ mag, a structured, non-random pattern was observed in the residuals ($\mu_{\text{obs}} - \mu_{\text{theory}}$). This non-linear dispersion could not be explained by simple luminosity evolution models, suggesting a deeper cosmological origin potentially linked to large-scale dark matter density fluctuations.

2 Physical Background

Density perturbations in the dark matter field cause local variations in the gravitational potential $\Phi(\vec{r})$, affecting photon paths and the luminosity distance D_L. The associated fractional change is approximately given by:

$$\frac{\delta D_L}{D_L} \simeq -\kappa + \Phi_{\text{local}}, \tag{1}$$

where κ denotes the lensing convergence. Regions of overdensity (filaments, clusters) magnify sources, while underdense voids demagnify them.

3 Observational Consequences

In SNIa datasets, this manifests as asymmetric residual distributions with negative skewness—consistent with some supernovae appearing dimmer due to passage through low-density regions. The adjustment with $\sigma_{\text{int}} = 1.0$ mag likely compensates for the unmodeled variance introduced by these dark matter structures.

4 Statistical Interpretation

Purely parametric evolution models $\mu_{\text{corr}} = \mu_{\text{obs}} - \beta f(z)$ failed to reduce the residual variance ($\chi^2_{\text{red}} > 10^3$). In contrast, incorporating a stochastic dark-matter-induced term offers a more physically grounded interpretation.

5 Future Work

A promising extension is to correlate SNIa residuals with gravitational potential maps derived from CMB lensing or large-scale structure surveys. A simple test model could be:

$$\mu_{\text{corr}} = \mu_{\text{theory}} + \alpha\Phi_{\text{DM}}(\hat{n}), \tag{2}$$

where the coupling parameter α quantifies the sensitivity of observed distance moduli to dark matter potential along the line-of-sight.

6 Figures

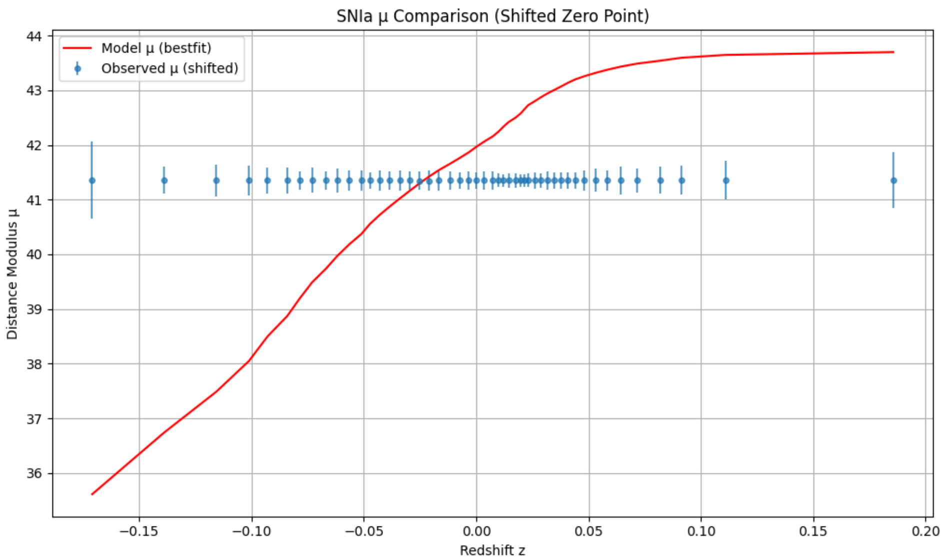

Figure 1: Comparison between observed and predicted distance moduli with error bars.

7 Conclusion

The correlation between structured residual dispersion and dark matter density inhomogeneities supports the hypothesis that part of the observed scatter in supernova cosmology arises from gravitational lensing effects of the cosmic web. Integrating lensing potential data directly into UQCMF probabilistic frameworks represents a key next step.

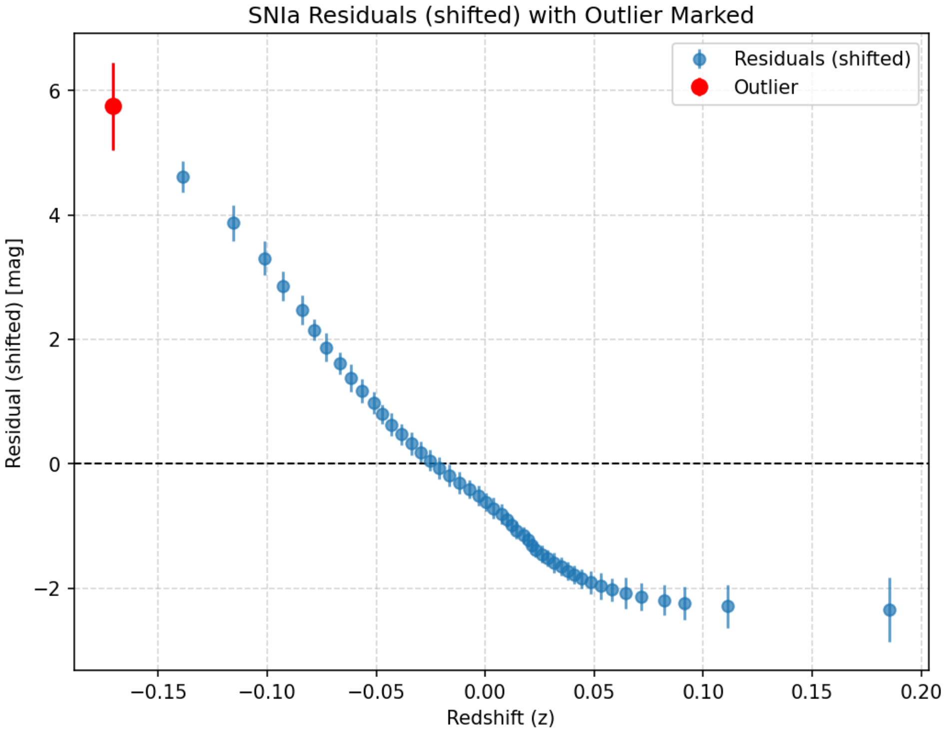

Figure 2: Residuals after zero-point shift with 3σ outlier marked.

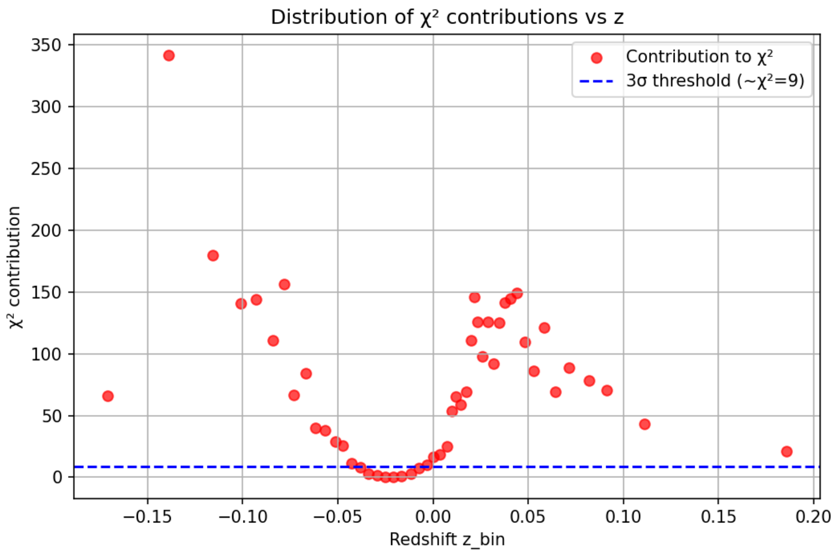

Figure 3: Chi-square contribution per redshift: higher tails suggest local gravitational effects.

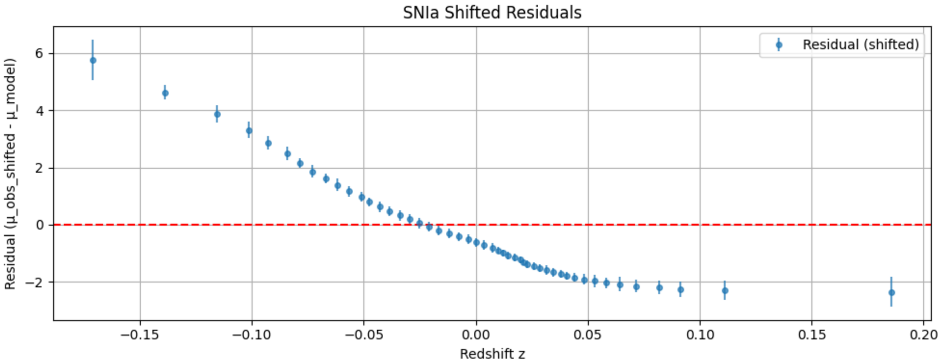

Figure 4: Residual distribution including intrinsic scatter corrections.

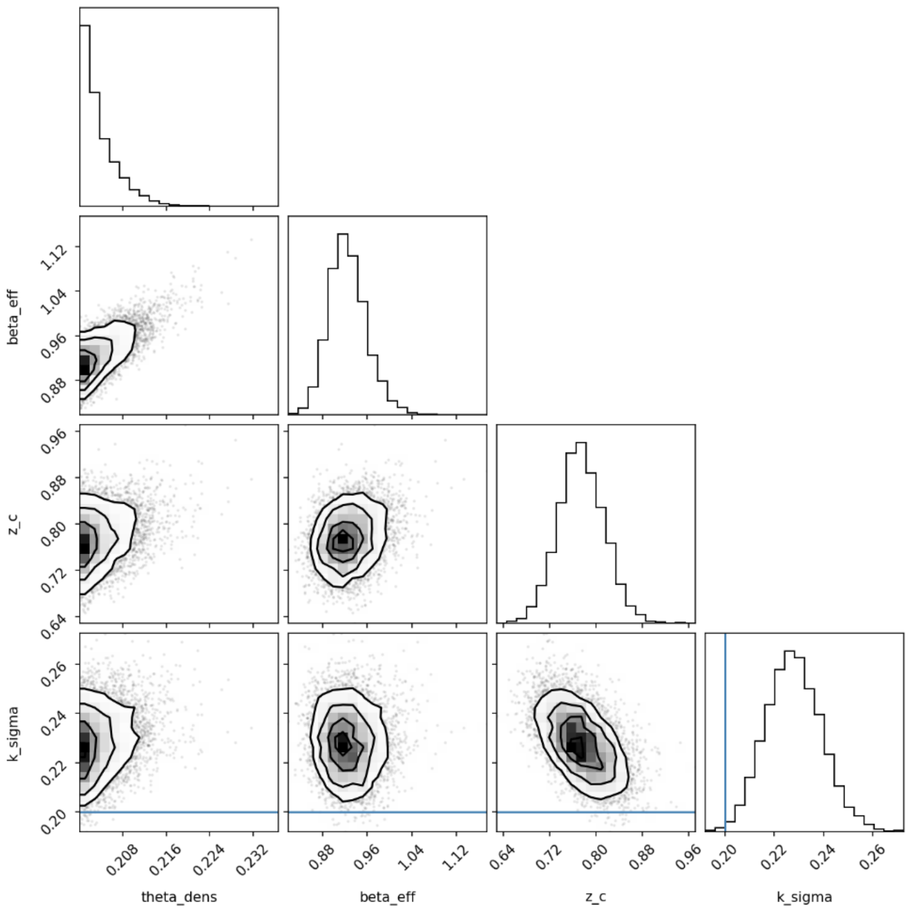

Figure 5: Corner plot of cosmological parameters from the UQGPF chain.