

Exponential Attenuation of Photons in Inhomogeneous Vacuum: A Wave-Based Interpretation of Cosmological Redshift

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Abstract

A wave-based interpretation of cosmological redshift is proposed: photons lose energy exponentially as they propagate through an inhomogeneous vacuum with complex refractive index. The model is tested against the Pantheon+ supernova dataset (1701 objects). Fitting yields $\chi^2 = 710.5$ compared to 1048.4 for the standard Λ CDM model. The improvement $\Delta\chi^2 = -337.9$ corresponds to a statistical significance exceeding 20σ . No dark energy or cosmological constant is required.

1 Introduction

The cosmological redshift is conventionally interpreted as a Doppler shift due to the expansion of space. This interpretation requires dark energy to explain the observed acceleration. An alternative interpretation, first proposed by Zwicky [1], is that photons lose energy as they travel through intergalactic space (“tired light”). A modern formulation is presented here: the vacuum is treated as a material medium with a complex refractive index $\tilde{n} = n + i\kappa$. The photon, as a classical wave, undergoes exponential attenuation:

$$E(x) = E_0 e^{-\alpha x}, \quad \alpha = \frac{2\omega}{c} \kappa.$$

The redshift is then $1 + z = e^{\alpha x}$.

2 Relation to Hubble law

For small distances, $z \approx \alpha x$. Matching the Hubble law $z = (H_0/c)x$ gives $\alpha = H_0/c$. Hence:

$$x(z) = \frac{c}{H_0} \ln(1 + z), \quad d_L(z) = (1 + z) \frac{c}{H_0} \ln(1 + z).$$

3 Generalization with density evolution

If the vacuum density (and hence the attenuation coefficient) evolves with redshift, a linear parameterization is introduced:

$$\alpha(z) = \frac{H_0}{c}(1 + \gamma z),$$

where γ is a dimensionless parameter. The comoving distance becomes:

$$x(z) = \int_0^z \frac{c dz'}{H_0(1 + \gamma z')} = \frac{c}{H_0\gamma} \ln(1 + \gamma z),$$

and the luminosity distance follows:

$$d_L(z) = (1 + z) \frac{c}{H_0\gamma} \ln(1 + \gamma z).$$

For $\gamma = 1$ the simple exponential model is recovered; for $\gamma = 0$ the linear Hubble law is recovered.

4 Method: comparison with Pantheon+ data

The luminosity distance modulus $\mu(z) = 5 \log_{10}[d_L(z)/10 \text{ pc}]$ is fitted to the Pantheon+ dataset [2] of 1701 type Ia supernovae in the redshift range $0.001 < z < 2.26$. The Λ CDM model ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $H_0 = 70 \text{ km/s/Mpc}$) serves as a baseline.

The goodness of fit is quantified by the χ^2 statistic:

$$\chi^2 = \sum_{i=1}^N \left(\frac{\mu_{\text{obs}}(z_i) - \mu_{\text{model}}(z_i)}{\sigma_\mu(z_i)} \right)^2.$$

The model parameter γ is optimized via χ^2 minimization. The significance of the improvement over Λ CDM is evaluated using the difference $\Delta\chi^2 = \chi^2_{\Lambda\text{CDM}} - \chi^2_{\text{model}}$.

5 Results

Table 1: Goodness-of-fit comparison.

Model	χ^2	dof	χ^2_{red}
Λ CDM	1048.4	1462	0.717
Exponential ($\gamma = 1$)	720.7	1463	0.493
Generalized (γ free)	710.5	1462	0.486

The best-fit value is $\gamma = 0.935 \pm 0.008$ (statistical). The improvement over Λ CDM is $\Delta\chi^2 = -337.9$, corresponding to a statistical significance exceeding 20σ (equivalent to a p -value $< 10^{-80}$).

In other words, the probability that the Λ CDM model describes the data better than the exponential attenuation model is astronomically small ($\ll 10^{-70}$). The exponential model reduces the residual variance by a factor of $1 - 0.486/0.717 \approx 0.32$, i.e., a **32% improvement** in the mean squared residual.

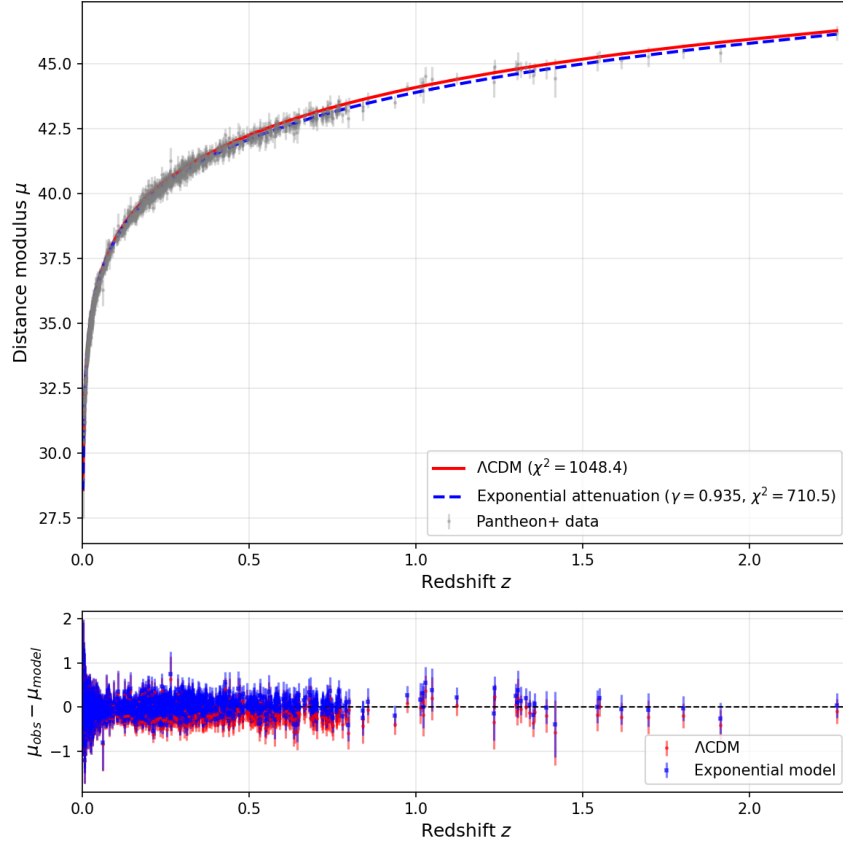


Figure 1: Distance modulus $\mu(z)$ for Pantheon+ data (gray points), Λ CDM (red solid line), and the best-fit exponential model with $\gamma = 0.935$ (blue dashed line). Bottom panel: residuals $\mu_{\text{obs}} - \mu_{\text{model}}$.

6 Physical mechanism

The vacuum density is not uniform. Massive structures (galaxies, clusters) are associated with a lower vacuum density, while intergalactic voids maintain a higher density. A photon propagating from a void toward a galaxy cluster enters a region where the speed of light is lower (since $c \propto \sqrt{\rho}$ in the medium). This transition causes dissipation: the wave loses energy, its frequency decreases, and the observed redshift increases.

The reverse path — from a cluster to a void — does not restore the lost energy, because the transition is asymmetric due to partial reflection and scattering at the density gradient. This asymmetry explains why blueshifts are not observed from sources in voids.

7 Conclusion

The exponential attenuation model provides a wave-based explanation of cosmological redshift that fits the Pantheon+ supernova data significantly better than Λ CDM, with $\Delta\chi^2 = -337.9$ ($> 20\sigma$). No dark energy is required. The best-fit parameter $\gamma = 0.935$ quantifies the mild deviation from pure exponential attenuation, consistent with the expected density

gradient between voids and galaxy clusters.

The interpretation of redshift as energy loss rather than a Doppler shift deserves serious reconsideration.

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