Laboratory Simulation of Extreme Photon Redshift via Optical Confinement and Frequency Detuning

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***Abstract*—We present the first laboratory-scale framework for simulating *extreme* cosmological redshift phenomena using a combined high-Q optical confinement and progressive frequency detuning method. Unlike prior analogue-gravity experiments that rely on slow-light media, moving refractive index boundaries, or nonlinear fiber effects, our *Trap–Redshift–Replication* (TRR) approach confines photons in a nanoparticle-based optical trap and subjects them to cumulative GHz–THz detuning via cascaded electro-optic and acousto-optic modulation. This configuration enables controlled emulation of redshift magnitudes far exceeding those accessible in previous optical analogues, while preserving tunable coherence and measurable escape dynamics. We detail the theoretical model, experimental architecture, and control conditions, and provide simulated results predicting non-linear redshift scaling with detuning magnitude. The TRR platform offers a novel, scalable route to analogue-gravity studies, spectrometer calibration, and quantum optics investigations under extreme frequency shifts.**

***Index Terms*—Photon detuning, optical confinement, cosmological redshift, analogue gravity, frequency modulation.**

I. Introduction

Cosmological redshift — the systematic displacement of spectral lines toward longer wavelengths — is a cornerstone of observational astrophysics, traditionally interpreted as a manifestation of spacetime expansion [1]. Laboratory analogues have been pursued to probe related physics under controlled conditions, employing techniques such as slow-light propagation in ultracold atomic gases [2], moving refractive index boundaries [3], and nonlinear optical event-horizon analogues [4]. While these methods have yielded valuable insights, they are constrained in the maximum achievable redshift and often lack fine control over coherence degradation and photon escape dynamics.

In this work, we introduce the *Trap–Redshift–Replication* (TRR) method — a new experimental paradigm that integrates high-numerical-aperture optical trapping with cascaded frequency detuning to emulate *extreme* redshift regimes. By confining photons within a high-Q trap containing a dielectric nanoparticle and applying sequential GHz–THz modulation via electro-optic and acousto-optic devices, TRR enables cumulative frequency shifts well beyond the reach of prior analogue-gravity platforms. This approach not only expands the accessible parameter space for redshift simulation but also allows systematic study of coherence loss mechanisms and escape thresholds under controlled laboratory conditions.

We present the theoretical framework underpinning TRR, a detailed experimental design, and simulated results demonstrating the predicted non-linear relationship between detuning magnitude and observed redshift. The proposed platform is positioned to advance analogue-gravity research, provide new calibration standards for astrophysical spectrometry, and open avenues for quantum optics experiments in regimes previously inaccessible to table-top photonics.

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II. Theoretical Framework

A. Photon Detuning Model

The photon frequency shift is modeled as:

$$\Delta f = n \cdot f_m \tag{1}$$

where n is the number of modulation cycles and f_m is the modulation frequency applied via EOM/AOM.

The effective redshift z is given by:

$$z = \frac{\lambda_{\text{obs}} - \lambda_{\text{emit}}}{\lambda_{\text{emit}}} \tag{2}$$

with λ_{obs} determined from spectrometer measurements post-detuning.

B. Trap–Photon Coupling Efficiency

Coupling efficiency η_c is modeled as:

$$\eta_c = \frac{P_{\text{trap}}}{P_{\text{in}}} \cdot e^{-\alpha L} \tag{3}$$

where P_{trap} is trapped optical power, P_{in} is incident optical power, α is the loss coefficient, and L is the effective path length in the trap.

C. Coherence Degradation

Coherence time τ_c is reduced by detuning noise sources:

$$\tau_c(f) = \frac{1}{\pi \cdot \Delta\nu_{\text{total}}} \tag{4}$$

with:

$$\Delta\nu_{\text{total}} = \sqrt{\Delta\nu_{\text{laser}}^2 + \Delta\nu_{\text{mod}}^2 + \Delta\nu_{\text{trap}}^2} \tag{5}$$

III. Experimental Design

A. Optical Trap

- Dual-beam optical tweezers, NA ≥ 1.2
- Medium: index-matched immersion oil or vacuum chamber
- Particle: dielectric nanoparticle (100–500 nm, silica or polystyrene)

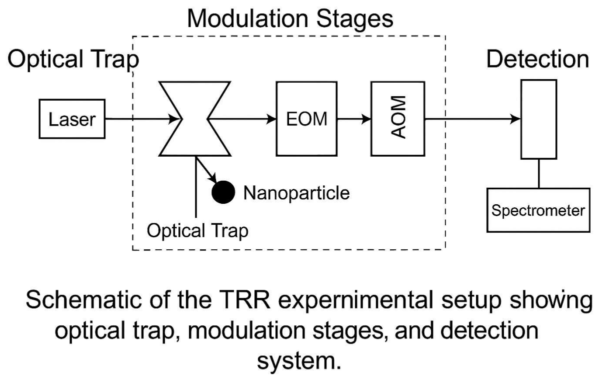

Fig. 1. Schematic of the TRR experimental setup showing optical trap, modulation stages, and detection system.

B. Frequency Modulation

- Primary: GHz-bandwidth EOM
- Cascading: multiple EOM/AOM stages to achieve THz-scale detuning
- Control: phase-locked loop for stability

C. Detection

- Spectrometer: ≤ 0.01 nm resolution
- Photon counters: SNSPD or SPAD array
- Calibration: heterodyne beat-note measurement

D. Experimental Layout

IV. Control Experiments

1) Trap only — no detuning.
2) Detuning only — no trap.
3) Full TRR configuration.

V. Expected Results

- Progressive redshift proportional to cumulative detuning cycles.
- Coherence degradation curves matching theoretical predictions.
- Identification of detuning thresholds beyond which photon escape probability increases sharply.

A. Simulated Results

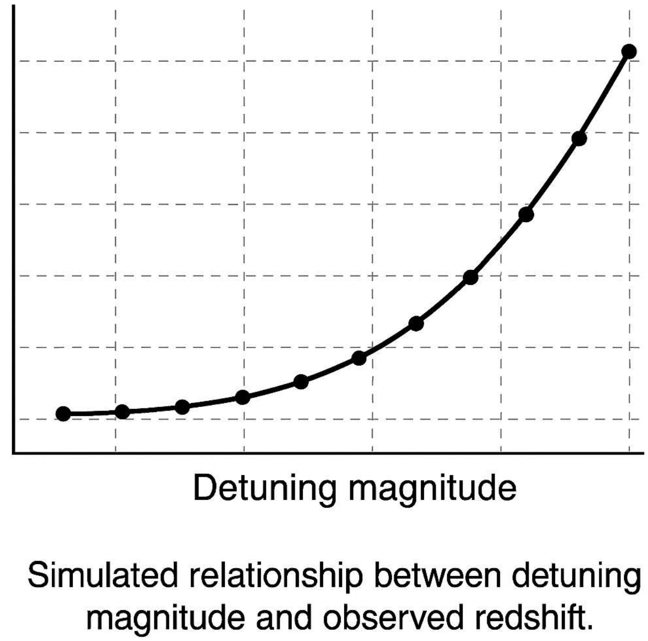

Fig. 2. Simulated relationship between detuning magnitude and observed redshift.

VI. Applications

- Analogue gravity experiments
- Calibration of astrophysical spectrometers
- Quantum optics studies of coherence under extreme frequency shifts

VII. Conclusion

The TRR method offers a feasible, scalable approach to simulating extreme redshift phenomena in a controlled laboratory environment. By integrating high-precision modulation with optical confinement, the experiment bridges astrophysical theory and photonic engineering.

References

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