Dark Matter and Dark Energy Hypothesis: Gravitational Echo Inspired by Dirac — Revised Version

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Abstract

We propose a revised framework that unifies dark matter and dark energy as dual manifestations of quantum vacuum fluctuations, inspired by Dirac's sea of negative energy states. In this formulation, dark matter corresponds to localized overdensities ("gravitational echoes") of the vacuum, while dark energy emerges as its large-scale negative-pressure counterpart. We present explicit equations, a toy model for numerical exploration, and falsifiable predictions that connect the hypothesis to current cosmological observations. This revision improves clarity, mathematical formulation, and references, transforming the initial conceptual sketch into a structured and testable model.

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1. Introduction

The nature of dark matter (DM) and dark energy (DE) remains one of the deepest puzzles in cosmology. While ΛCDM provides an excellent phenomenological fit, it requires introducing two unknown components with no microphysical explanation. Inspired by Dirac's vacuum concept, we hypothesize that both DM and DE arise from different regimes of the same underlying quantum vacuum structure.

Key motivations: - Explain DM and DE as dual aspects of vacuum fluctuations without introducing exotic new particles. - Address the Hubble tension via locally varying vacuum density. - Provide testable predictions for galactic rotation curves, gravitational lensing, and cosmic expansion.

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2. Theoretical Framework

2.1 Quantum Vacuum with Dual Manifestations

The quantum vacuum is modeled as a fluctuating background with positive and negative energy states. Localized overdensities manifest as DM halos, while large-scale negative pressure manifests as DE.

2.2 Effective Hamiltonian

We postulate an effective Hamiltonian:

$$ H = H_0 + H_{int}, \quad H_{int} = \lambda \int d^3x \, (\delta \rho(x))^2 $$

where $\delta \rho(x)$ are vacuum density fluctuations and λ is a coupling constant. Positive fluctuations generate gravitational potential wells (DM), while negative fluctuations contribute to an effective cosmological constant (DE).

2.3 Modified Poisson Equation

The gravitational potential Φ obeys:

$$ \nabla^2 \Phi = 4 \pi G (\rho_b + \rho_{DM}^{eff}) $$

where $\rho_{DM}^{eff} = f(\delta \rho)$ arises from vacuum echoes. For galactic scales:

$$ \rho_{DM}^{eff}(r) = \rho_0 \, e^{-r/r_c}, $$

leading to flat rotation curves.

2.4 Effective Dark Energy Term

At cosmological scales, the vacuum pressure is:

$$ P_{vac} = -w \, \rho_{vac}, \quad w \approx -1. $$

This reproduces accelerated expansion, with small corrections depending on fluctuation spectrum.

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3. Toy Model for Numerical Exploration

Simulation outline: 1. Generate a stochastic field of vacuum fluctuations $\delta \rho(x)$ with Gaussian spectrum. 2. Identify localized overdensities → compute ρ_{DM}^{eff}. 3. Insert into modified Poisson equation → recover rotation curves. 4. At large scales, average fluctuations → effective dark energy density. 5. Compare results with ΛCDM predictions.

Implementation: Python with NumPy, SciPy, and FFT for field generation and spectral analysis.

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4. Predictions

- **Galactic Rotation Curves:** Flat velocity profiles emerge without WIMPs.
- **Gravitational Lensing:** Effective DM halos reproduce lensing patterns.
- **Hubble Tension:** Locally varying vacuum density predicts slightly different H_0 values in different regions ($H_0^{local} \approx 73$ km/s/Mpc vs $H_0^{global} \approx 67$ km/s/Mpc).
- **Early Galaxy Formation (JWST):** Enhanced local overdensities allow galaxies to form earlier than ΛCDM predicts.

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5. Experimental Tests

- **JWST:** detect abundance of early galaxies → consistency with vacuum fluctuation model.

- **Strong Lensing Surveys (LSST, Euclid):** test halo profiles.
- **BAO + Supernovae:** constrain effective equation of state parameter $w(z)$.
- **CMB (Planck, Simons Observatory):** verify fluctuation spectrum imprint.

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6. Limitations and Open Problems

- Microphysical derivation of vacuum fluctuation spectrum remains heuristic.
- Coupling constant λ is unconstrained.
- Requires full Boltzmann code implementation (CLASS/CAMB) for precision cosmology.
- Possible degeneracy with modified gravity theories.

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7. Conclusion

We reinterpret DM and DE as dual aspects of vacuum fluctuations, inspired by Dirac’s sea. This approach offers an elegant unification and produces falsifiable predictions. Although speculative, the revised framework provides equations, a toy model, and connections to observable data, raising the hypothesis closer to the level of a scientific research program.

References

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