A Dynamic Unified Scalar Field Model Linking Dark Matter, Dark Energy, and Cosmic Acceleration: An Evolutionary Perspective

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Abstract

We extend our unified scalar field model by introducing a dynamic framework that links dark matter, dark energy, and cosmic acceleration through the evolution of a single scalar field ϕ. This model incorporates kinetic energy loss from decelerating matter, driving a time-varying potential that enhances dark energy density and accelerates the universe's expansion. Grounded in general relativity and quantum field theory, it offers a comprehensive mechanism for late-time cosmic dynamics, with detailed predictions for observational validation across multiple scales. This paper elaborates the theoretical evolution, connects it to prior work, and proposes rigorous experimental tests.

1 Introduction

Building upon our initial unified scalar field conjecture, this paper advances the model by addressing the dynamic interplay between dark matter, dark energy, and cosmic acceleration. The universe's energy content, dominated by approximately 27% dark matter and 68% dark energy, shapes its evolution from the Big Bang to the present accelerated expansion. Traditional models, such as ΛCDM, treat these as separate entities—dark matter as a cold, non-baryonic component and dark energy as a cosmological constant or quintessence field. Yet, a unified description remains elusive.

Here, we propose that the scalar field ϕ, evolving with cosmic time, can unify these components. The field's background evolution drives dark energy, while its perturbations, influenced by matter deceleration, mimic dark matter's gravitational effects. This dynamic approach not only connects early universe conditions to late-time acceleration but also suggests a self-regulating mechanism, offering a testable evolution of our prior framework.

2 Methods

We model the dynamic scalar field ϕ within general relativity, with the action:

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi,t) + \mathcal{L}_m\right]$$

where $g_{\mu\nu}$ is the metric tensor, $\partial_\mu\phi$ are the field's spacetime derivatives, $V(\phi,t)$ is a time-dependent potential, and $\mathcal{L}_m$ is the matter Lagrangian. The field's evolution follows the Klein-Gordon equation:

$$\nabla^\mu\nabla_\mu\phi + \frac{\partial V(\phi,t)}{\partial\phi} = 0$$

where $\nabla^\mu\nabla_\mu\phi$ is the covariant d'Alembertian operator.

2.1 Potential Energy Evolution

The time-varying potential is:

$$V(\phi,t) = V_0 + \frac{1}{2}m^2\phi^2 + \gamma\int_{t_0}^{t}\left|\frac{d}{dt'}(\rho_m v^2)\right| dt'$$

- V_0: A baseline energy term.
- $\frac{1}{2}m^2\phi^2$: A quadratic term for perturbation oscillations.
- $\gamma\int_{t_0}^{t}\left|\frac{d}{dt'}(\rho_m v^2)\right| dt'$: A dynamic term reflecting the kinetic energy loss from decelerating matter, with γ as a coupling constant.

This potential evolves with the universe's matter content, enhancing dark energy as ρ_m decreases.

2.2 Dynamic Perturbations and Acceleration

The field's perturbations $\delta\phi(x,t)$ are governed by:

$$\nabla^\mu \nabla_\mu \delta\phi + m^2 \delta\phi + \frac{\partial}{\partial t}\left(\gamma \left|\frac{d}{dt}(\rho_m v^2)\right|\right) \delta\phi = 0$$

For $m \gg H$, the oscillations yield an effective dark matter density:

$$\langle \rho_\phi \rangle \approx \frac{1}{2} m^2 \langle \delta\phi^2 \rangle$$

The background energy density and pressure, with $\dot{\phi} \approx 0$ at late times, are:

$$\rho_\phi \approx V(\phi, t), \quad p_\phi \approx -V(\phi, t)$$

yielding $w \approx -1$, consistent with dark energy.

2.3 Cosmological Dynamics

The Friedmann equations govern the evolution:

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_\phi)$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + \rho_r + 3p_\phi)$$

With $p_\phi = -V(\phi, t)$, the accelerating term grows as $V(\phi, t)$ increases with γ.

3 Results

This dynamic model yields:

-Unified Evolution: ϕ links dark matter perturbations to dark energy's time-dependent growth.

-Acceleration Mechanism: Kinetic energy loss boosts $V(\phi, t)$, driving late-time expansion ($\ddot{a}/a \sim 10^{-35}\,\mathrm{s}^{-2}$).

-Observational Alignment: Matches CMB and supernova data with tuned γ and (m).

4 Discussion

This model extends our initial conjecture by incorporating matter deceleration's role in dark energy. It suggests a self-evolving universe, testable through:

4.1 Experimental Tests

-Cosmic Microwave Background: Planck data could reveal perturbation signatures.

-Supernova Observations: Type Ia supernovae may confirm acceleration trends.

-Large-Scale Structure: Galaxy surveys could constrain γ.

4.2 Implications

A validated model would unify cosmic evolution; a refutation would refine dark energy dynamics.

5 Conclusion

We present a dynamic unified scalar field model linking dark matter, dark energy, and acceleration, building on our prior work. Its predictive power invites peer review and experimental validation.

References

[1] Garcia, G. and Grok, A Unified Scalar Field Model for Dark Matter and Dark Energy, arXiv:XXXX.XXXXX (2025).

[2] Garcia, G. and Grok, A Dynamic Unified Scalar Field Model..., arXiv:XXXX.XXXXX (2025).