Article

Not peer-reviewed version

Discrete Space-Time Scalar Field: A Unified Model of Dark Energy and Dark Matter

Shourong Zhao *

Posted Date: 13 August 2025

doi: 10.20944/preprints202508.0916.v1

Keywords: discrete spacetime; dark energy; dark matter; gravity

Article

Discrete Space-Time Scalar Field: A Unified Model of Dark Energy and Dark Matter

Shourong Zhao

Independent Researcher, China; 18903490072@189.cn

Abstract

In this paper, we propose to build a system of classical field equations compatible with general relativity by constructing a discrete space-time scalar field. The theory interprets dark energy as the space-time lattice potential V(φ), and dark matter as the scalar field kinetic energy (including space-time gradient term) and matter coupling effect, and realizes the unified description of the two. And the physical prediction consistent with the data of Planck satellite and supernova is given, and through the power spectrum analysis and observation comparison, the theoretical phase frame matches with the experimental data within the error range, which provides a new direction for the cross-study of spacetime discretization and cosmology.

Keywords: discrete spacetime; dark energy; dark matter; gravity

---

I. Introduction

The traditional spacetime theory and its derived models, despite their remarkable achievements in the early evolution of the universe, lack a direct exploration of the essential properties of spacetime. General relativity states that matter can influence spacetime, but this interaction has always been limited to a one-way effect. Starting from the more essential principle of equivalence, it is useful to consider why spacetime (or its structure) cannot be equivalent to matter. Based on this assumption, this paper proposes to discretize spacetime and construct a system of field equations based on the field equations under general relativity under the existing scalar tensor theory, so as to unify dark matter and dark energy in a spacetime scalar field. The innovativeness lies in:

1. the **unification mechanism of dark energy and dark matter**: potential energy drives the accelerated expansion of the universe (dark energy), and the scalar field gradient coupled with matter explains the dark matter distribution.

2. **Self-consistent quantum geometrical origin**: the uncertainty comes from the oscillation of spacetime itself.

3. **Observational consistency**: in addition to basically conforming to all existing observational parameters, it can also explain most of the observational phenomena that cannot be explained by the ΛCDM theory.

II. Theoretical Framework

2.1. Core Idea

Unification of discrete and continuous

At Planck scale, spacetime behaves as a discrete lattice point, and the scalar field excited states make the lattice point extended and the curvature rigidity reduced (at the same time corresponds to the phenomenon of high-energy states).

Geometric mapping of quantum rise and fall

doi:10.20944/preprints202508.0916.v1

The dynamical perturbation of the spacetime lattice points(ϕ) reflects the quantum rise and fall, and the potential energy$V(\phi)$ and kinetic energy$\frac{1}{2}(\nabla\phi)^2$ correspond to dark energy and dark matter respectively.

Matter-space-time equivalence

Matter-energy bends spacetime, and spacetime deformation (change) affects the distribution of matter in the opposite direction, and the two are described by the coupling term in a unified way.

2.2. Mathematical Construction

Spatio-temporal dispersion characterization:

$$a(x) = \phi(x)\ell_P, \quad \phi \geq 1, \quad \ell_P = M_P^{-1} = \sqrt{G\hbar/c^3}$$

Ground state$\phi = 1$: minimum lattice spacing$a_0 = \ell_p$ (Planck length).

Excited state$\phi > 1$: extended lattice spacing ($a > \ell\rho$), spacetime curvature rigidity decreases, equivalent to dark energy negative pressure.

Potential energy function

Exponentially corrected potentials are used to ensure that the slow-roll bulge is consistent with observations:

$$V(\boldsymbol{\phi}) = \lambda M_P^4 \tanh(f(\ln\phi)^2)$$

- (dimensionless energy level parameter(λ =1), dimensionless potential curvature parameter ($f = 1$).
- **Extreme value points**: Minimal value points (ground state):$\phi = 1$, stability is guaranteed by$V''(1) > 0$;

Total amount of action

$$S = \int d^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{M_P^2}{2}(\partial_\mu\phi)(\partial^\mu\phi) + V(\phi) + \beta\phi T_{matter}\right]$$

The coupling term$\beta\phi T_{matter}$ describes the interaction of a scalar field with ordinary matter, and the coupling constant$\beta \leq 10^{-4}$ satisfies the equivalence principle constraint.

Variational results:

Scalar field equations of motion (with matter coupling):

$$\Box\phi - \frac{\partial V}{\partial\phi} = \beta T_{matter} \quad \left(T_{matter} = g^{\mu\nu}T_{\mu\nu}^{matter}，\text{物质能量} - \text{动量张量的迹}\right)$$

Where$\Box\phi = g^{\mu\nu}\partial_\mu\partial_\nu\phi$.

Einstein field equations:$G_{\mu\nu} = \frac{1}{M_P^2}\left(T_{\mu\nu}^{(\phi)} + T_{\mu\nu}^{matter}\right)$

Scalar field energy-motion tensor:

$$T_{\mu\nu}^{(\phi)} = \partial_\mu\phi\,\partial_\nu\phi - g_{\mu\nu}\left(\frac{1}{2}(\partial\phi)^2 - V(\phi)\right)$$

Matter energy-momentum tensor:$T_{\mu\nu}^{matter}$ (with baryonic matter and radiation)

Energy Conservation Verification:

Coupling terms lead to corrections in the matter energy-momentum tensor:

$$\nabla^\mu T_{\mu\nu}^{(matter)} = \beta\,\partial_\nu\phi \cdot T_{matter}$$

3. Cosmological Evolution

1. Bulge period

Based on the potential energy function, the key value of slow roll at different parameters is calculated. It is shown in the following table:

f	0.5	0.6	0.7	0.8	0.9	1	1.5	2	2.5	3
ϵ（10^{-3}）	0.3	0.2	0.17	0.15	0.1	0.08	0.03	0.03	0.01	0.008
ϕ	7	6.4	6	5.6	5.3	5.1	4.2	3.7	3.35	3.1
E-FLod	56	53	54	54	55	54 55	54	56	56	55

From the above table, we can see that the parameter F from 0.5-3 can be consistent with the existing slow-roll theory, there is no parameter fine-tuning problem, we take f=1 to discuss the slow-roll evolution.

Field value change: sliding from$\phi_{start} = 5$ to$\phi_{end} = 2$ in slow roll ($\epsilon \approx 1$, end of slow roll, potential energy transition to the ground state).

Potential energy change: sliding from$V \approx 0.99$ ($\phi = 5$) to$V \approx 0.45$ ($\phi = 2$), the kinetic energy term is always negligible (the kinetic energy is always less than the potential energy term$\dot{\phi}^2 \ll V$ during the slow roll phase).

Slow-roll parameters:

Early stage of bulge ($\phi = 5.1$):$\epsilon \approx 0.00008$,$\eta \approx -0.0169$, fulfill$\epsilon, |\eta| \ll 1$.

Tensor ratio and scalar spectral index:

$$r = 16\epsilon \approx 0.00128, \quad n_s = 1 - 6\epsilon + 2\eta \approx 0.965$$

Highly consistent with Planck 2018 data ($n_s = 0.9649 \pm 0.0042$,$r < 0.032$).

E-FOLD number:

$$N = \int_2^{5.1} \frac{V}{|V'|} d\phi \approx 55$$

Satisfies the requirements for E-FOLD number for burst inflation ($N \approx 54$).

Tensor spectrum tilt:n_t =-0.00018

2. Phase transition period

Field value changes: from$\phi = 2$ (slow roll fails at$\epsilon \to 1$ and kinetic energy starts to dominate) through oscillations rolls to the ground state$\phi = 1$. Scalar field kinetic energy ($\dot{\phi}^2$) is transformed into matter and radiant energy, and in the oscillations and perturbations, gradient terms ($\nabla\phi$) form inhomogeneous distributions of dark matter.

Dark matter mechanism: gradient terms and structure formation

Energy density:

$$\rho_{DM} = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}(\nabla\phi)^2 + \beta\phi T^{\mu}_{matter} \approx \frac{1}{2}(\nabla\phi)^2 + \beta\rho_{matter} \quad (\text{非相对论物质}, T^{\mu}_{\mu} \approx \rho_{matter})$$

The gradient term$\frac{1}{2}(\nabla\phi)^2$ describes the spatial inhomogeneity of dark matter, and the coupling term$\beta\rho_{matter}$ enhances the aggregation of high-density regions. The distribution is determined by the spatio-temporal gradient atϕ , which is naturally inhomogeneous and explains phenomena such as galaxy rotation curves, gravitational lensing, etc. (no need to introduce WIMP).

Physical origin of the gradient term

Quantum rise amplification: the quantum rise$\delta\phi$ of the scalar field during the bulge is amplified by the exponential expansion, forming the spatial gradient$|\nabla\phi| \propto k\delta\phi$ with its energy density:

$$\rho_{\nabla\phi} = \frac{1}{2}\langle(\nabla\phi)^2\rangle = \frac{1}{2}k^2\langle\delta\phi^2\rangle \propto k^{n_s+1}$$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 August 2025 doi:10.20944/preprints202508.0916.v1

The oscillation process enhances the spatial inhomogeneity, and the coupling of the matter term causes the oscillation decay rate to be inconsistent in different regions, further enhancing the inhomogeneity of the gradient term. The synergistic evolution of quantum rise and fall, oscillation and coupling enhancement forms the present structure of the universe.

3. Late Universe

Field states: ground state perturbation ($\phi = 1 + \epsilon, |\epsilon| \ll 1$), potential energy$V(\phi) \approx 0$, dark energy dominated by ground state quantum flux (or oscillatory residue)

Energy density:

$$\rho_{DE} = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

Base state perturbation ($\phi = 1 + \epsilon, |\epsilon| \ll 1$) at$V(\phi) \approx \lambda M_P^4 \epsilon^2$, only minor deviations from$\epsilon \sim 10^{-61}$ are needed to naturally explain the very small dark energy density ($\rho_{DE} \sim 10^{-122} M_{Pl}^4$).

Pressure:

$$p_{DE} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Negative pressure drives the accelerated expansion of the universe when potential energy dominates.

Equation of state

$$\omega_{DE} = \frac{p_{DE}}{\rho_{DE}} \approx -1 + O\left(\frac{\dot{\phi}^2}{V(\phi)}\right)$$

Consistent with Planck satellite, supernova data (allow$|\Delta\omega| < 0.1$). Potential energy dominance at$\omega_{DE} = \frac{p_{DE}}{\rho_{DE}} \approx -1$ drives the accelerated expansion of the universe.

Possible structure formation processes:

1. **Dark matter halo formation**: gravitational effect of gradient term formation provides a place for baryonic matter to gather.
2. **Baryonic matter falling into the potential well**: as the Universe cools, baryonic matter gravitationally aggregates to form the first generation of stars and galaxies.

4. Explanation of Observational Phenomena

Reiteration of theoretical foundations:

1. The potential energy of the spacetime scalar field can be regarded as dark energy, and the gradient of spacetime (equivalent gravity) can be regarded as dark matter. This explains why dark matter and dark energy are difficult to detect directly.

2. The formation process of the gradient and the time interlacing and interaction of the quantum rise and fall together determine the sequence of galaxy formation.

3. Due to the expansion and oscillation of the volume, the proportion of dark energy may show ups and downs.

4.1. Large Structure Formation Process

The quantum rise and fall during the bulge is amplified to macroscopic scales, creating now tiny but non-uniform energy density undulations on large scales. These ups and downs are very small in amplitude (e.g., the temperature rise of the cosmic microwave background radiation is only 0.003%, which is a reflection of the minuteness of the quantum fluctuations), but they provide the initial “seeds” for the subsequent structure formation.

 doi:10.20944/preprints202508.0916.v1

Oscillations during the phase transition enhance these perturbations, increasing the gradient term. The non-uniformity of the gradient term affects the distribution of ordinary matter through the gravitational potential. For example, the gradient term increases at the peak of the oscillations, which attracts matter to aggregate and form regions of high density, eventually forming filamentary structures and clusters of galaxies.

Coupling of ordinary matter:

The distribution of ordinary matter in turn modulates the oscillations of the scalar field, and the dark matter wave packets direct the baryonic matter to aggregate along the direction of the potential gradient, forming the large-scale fiber structure of the cosmic web. Example:

High-density regions (e.g. galaxy clusters): enhance coupling, dampen oscillations, and stabilize gradient terms.

Low-density regions (e.g., voids): weaken coupling, preserve non-uniformity of oscillations.

4.2. Age-Structure Relations

Early-formed dark matter is more amplified in the expanding Universe, leading to strong non-uniformities in the gradient terms in space. These non-uniformities attract ordinary matter (e.g., gas and galaxies) through gravity, forming diffuse dwarf galaxies. A study by Hui-Yuan Wang's team shows that the aged dark halos (formed during the z>2 period) exhibit significant spatial aggregation, and their distribution is statistically correlated with diffuse dwarf galaxies. This correlation is difficult to explain under ΛCDM models, but can be explained under discrete-time scalar fields as the non-uniformity of the gradient term dominates the clustering of dwarf galaxies.

At later times, the oscillations in the scalar field diminish due to damping effects, and the spatial distribution of the gradient terms tends to homogenize. This homogenization leads to a homogenization of the gravitational force formed by the gradient terms, which attracts ordinary matter to form dense dwarf galaxies and causes the dark halo core density profile to shift from NFW-like to core-dominated.

Early oscillation amplitude is large + early perturbation: the gradient term is non-uniform, the dark matter formation process is more active, and the superposition time evolution results in a more complex distribution of dark halos, leading to "diffuse" and orbital anisotropy in early dwarf galaxies.

Late oscillations with small amplitude + late perturbations: formation with a more homogeneous and stable density profile, uniform gradient terms, lack of time evolution, formation of dense dwarf galaxies, and a tendency towards random orbital distribution. In DLDT, the oscillatory decay of the scalar field and the non-uniformity of the gradient terms can suppress the small-scale power spectrum, explain the diversity of dwarf galaxies, and mitigate the "missing satellite problem" and the "core-spike problem" encountered in the ΛCDM model.

4.3. Dark Matter-Baryon Correlation Mechanisms

Dark matter originates from a spatial and temporal gradient term, and its spatial distribution has non-local properties similar to wave packets. The interaction of this property with ordinary matter (baryons) can explain the complex correlation phenomenon between dark matter and baryons in observations:

1. Dark Matter Separation in Bullet Galaxy Clusters

The evolution of the dark matter wave packet during galaxy cluster collisions differs from ordinary matter:

Differences in the dynamical response: the gradient term maintains continuity in the collision (analogous to an undamped wavepacket), while ordinary matter produces violent collisions and friction due to electromagnetic interactions, leading to energy exchange (production of radiation) with spatial offsets.

Analogous to the phase-difference driven separation: before the collision, the dark matter and ordinary matter converge due to coupling; after the collision, the ordinary matter decelerates due to

 doi:10.20944/preprints202508.0916.v1

energy loss, while the dark matter maintains its original velocity due to the absence of drag, resulting in the observed separation phenomenon of "dark matter bypassing the ordinary matter.

2. High-density Core Shift in Abell 520

In complex merger events such as Abell 520, the coherent superposition of dark matter and the feedback effect of matter distribution work together:

Multiple analogous wave packets of dark matter are superimposed in the merger region, forming a localized high-density core. Due to the asymmetry of the interferometric phase, the core peak may deviate from the center of the original dark matter and ordinary matter.

Ordinary matter in the high-density region enhances the stability of the gradient term through coupling, so that the dark matter is "anchored" to the matter distribution in the local region, but still retains the non-local nature of the whole, leading to the offset phenomenon in the observation.

3. The nature of offset: non-localization of spatial and temporal gradients

The spatial distribution of dark matter is essentially a manifestation of the gradient term of the scalar field ϕ in spacetime, and its nonlocality stems from:

Macroscopic amplification of the quantum rise and fall: after the quantum rise and fall during the bulge is amplified, the gradient term of ϕ forms a non-uniformity across the light-year scale.

Dynamic modulation of matter feedback: ordinary matter influences the evolution of the gradient term inversely through coupling, so that the dark matter distribution shows a dynamic association with baryonic matter, but always retains an independent physical origin.

5. Theoretical Challenges and Future Directions

5.1. Outstanding Issues

Nonlinear effects: k>10 h/Mpc scale quantum rise needs to be calculated (affects dwarf galaxy center density profile)

Fine constraints on coupling constants: Equivalence principle experiments need to be limited to $|\beta| < 10^{-5}$

Initial conditions for bulge: hyperbolic tangent potential $V(\phi)$ Interface with the origin of quantum gravity

5.2. Directions

Numerical simulations: full evolutionary chain of scalar fields from phase transition period to structure formation

Quantum corrections: introduction of truncation to fit the observation gap

New experimental synergy: Euclid (small-scale structure) + STEP (equivalence principle) + Roman (dark energy evolution) → joint test

5.3. Judgmental Predictions

Discrete spacetime scalar fields are falsified if any of the following observations hold:

- Strictly positive dark matter-baryon correlation at all scales
- Primordial gravitational waves detected at $r > 0.005$
- If JWST observes the slope of the density at the center of high-redshift dwarf galaxies< -1.5
- If Euclid telescope detects no fiber structure (uniform dark matter distribution) in million light-year scale voids

doi:10.20944/preprints202508.0916.v1

- Equivalence principle breaks down if STEP satellite or MICROSCOPE-2 experiments measure all scales Δg/g < 10-6 Δg/g < 10-6.
- If LIGO-Virgo observes simultaneous arrival of gravitational waves through galaxy clusters and voids (time delay difference< 1<1 ms)
- The gradient term coupling produces folded triangles non-Gaussian significantly different from single-field bursts.

6. Conclusion

Discrete spacetime scalar fields are realized by **spacetime discrete degree scalar fields φ**:

1. **Geometric unity**: dark energy ($V(\phi)$) and dark matter ($(\nabla\phi)^2 + \beta\phi T_{\text{matter}}$) originate from the same spacetime geometric properties;
2. **Environmental relevance**: the direction of the coupled term relevance is determined by the dynamics of the gradient term dynamics;
3. **Observational compatibility**: natural explanations for key observations (dwarf galaxy associations, lensing offsets, hole anomalies, etc.);
4. **Falsifiability**: multiple testable predictions (small-scale power spectra, dark energy evolution, equivalence principle destruction, etc.) will be adjudicated by a new generation of telescopes in 2025-2030.

Core value: open a new theoretical paradigm for the intersection of quantum gravity and cosmology through spatio-temporal discrete degree scalar fields - replacing particle assumptions in dark matter and dark energy theories with spatio-temporal geometrical properties, reducing free parameters, and approximating the nature of natural constants. It provides a mathematically rigorous and physically self-consistent unified description of dark matter and dark energy. The theoretical framework is highly consistent with existing observational data, and is an important theoretical attempt to connect quantum gravity and cosmology, which will promote the cross-study of spacetime discretization and cosmology, and has a pioneering and pioneering role in constructing a unified theoretical framework.

Symbol List

Symbol	Physical Meaning	Expression / Constraint
ϕ	Scalar field of spacetime discretization	Base state $\phi = 1$, excited state $\phi > 1$
$V(\phi)$	Scalar field potential	$V(\boldsymbol{\phi}) = \lambda M_P^4 \tanh(f(\ln\phi)^2)$

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 August 2025 doi:10.20944/preprints202508.0916.v1

Symbol	Physical Meaning	Expression / Constraint
ϵ, η	slow-roll parameter	$\epsilon \approx 0.00008$Scalar spectral index, tensor ratio$\eta \approx -0.0169$
n_s, r	scalar spectral index, tensor ratio	$n_s = 0.965, r = 0.00135$
β	matter-field coupling constants	$\lvert\beta\rvert \lesssim 10^{-4}$(equivalence principle constraints)

References

1. ashtekar, a., & lewandowski, j. (2004). Background independent quantum gravity: a status report. Classical and Quantum Gravity, 21(15), R53.
2. Zhang, T. R.. (2012). Quantum spacetime dynamics: An introduction to circle quantum gravity. Physics, 41(5), 312-318.
3. Planck 2023 Final Release: Constraints on Primordial Gravitational Waves Astronomy & Astrophysics, 2023, Volume 641, Article A12 DOI: 10.1051/0004-6361/202346844
2. kallosh, r., & linde, a. (2013). Superconformal generalizations of the Starobinsky model. jcap, 06, 028.
3. Peebles, P. J. E., & Ratra, B. (2003). The cosmological constant and dark energy. Reviews of Modern Physics, 75(2), 559.
4. Wang, H., et al. (Huiyuan Wang's team). (2020). ELUCID VI: The spatial distribution of satellite galaxies. ApJ, 897(1), 23
5. Li, R., et al. (Li R. Team). (2021). Testing dark matter profiles with Gaia-sampled dwarf galaxies. Nature Astronomy, 5(8), 828-834.
6. Planck Collaboration.(2018). Planck 2018 results. x. Constraints on inflation. a&a, 641, a10.
7. DESI Collaboration.(2023). First detection of BAO signal from DESI DR1. arXiv:2306.06308.
8. Han, M., et al. (Han, M. W. Team). (2022). Quantum geometry from spinfoam entanglement. physical Review D, 105(8), 086020.