

Article

Not peer-reviewed version

Emergent Yukawa Forces in Sedenionic Quantum Gravity: A Dark-Matter-Free Reformulation Beyond MOND and WIMP Paradigms

[Jau Tang](#)*

Posted Date: 23 September 2025

doi: 10.20944/preprints202509.1919.v1

Keywords: quantum gravity; gauge field theory; sedenions; Yukawa potential; dark matter; WIMP; MOND; dark energy



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Emergent Yukawa Forces in Sedenionic Quantum Gravity: A Dark-Matter-Free Reformulation Beyond MOND and WIMP Paradigms

Jau Tang

Wuhan University, Wuhan 430074, China; wuhantang72@gmail.com

Abstract

We propose a foundational reformulation of quantum gravity and quantum field theory by replacing the continuous spacetime manifold with a causal lattice framework based on sedenionic algebra and displacement operators. This formulation enforces microcausality and saturation principles, allowing physical laws to emerge from non-commutative operator dynamics. Gravitational interactions are represented by commutators of symmetric and anti-symmetric sedenionic spinor fields, giving rise to both attractive Yukawa-type corrections and a repulsive component interpretable as dark energy. Notably, we demonstrate that flat galactic rotation curves can be accurately modeled without invoking dark matter halos or MOND modifications, using a stretched exponential mass distribution and an emergent Yukawa potential. The framework naturally generates the internal gauge symmetries of the Standard Model from the decomposition of sedenions and resolves quantum divergences without renormalization. This theory suggests that gravity, dark energy, and the stability of galactic structures arise from deeper algebraic geometry rather than ad hoc hypotheses, potentially marking a paradigm shift in fundamental physics.

Keywords: quantum gravity; gauge field theory; sedenions; Yukawa potential; dark matter; WIMP; MOND; dark energy

1. Introduction

Despite the tremendous success of general relativity [1] and the Standard Model [2], numerous unresolved issues persist at the intersection of gravity and quantum physics. These include the nature of dark matter [3], the mechanism behind cosmic acceleration (dark energy) [4], the asymmetry between matter and antimatter [5], and the origin of cosmological singularities [6]. Efforts such as string theory [7] and loop quantum gravity [8] offer valuable insights but often lack direct testability or complete unification [8].

In this work, we present a quantum gravity framework grounded in sedenionic algebra [9]— a 16-dimensional non-associative extension of the octonions [10]— incorporating both symmetric (bosonic) [11] and antisymmetric (fermionic) [12] field components. This approach introduces a richer gauge structure that unifies gravitational interactions with a spinor-based formulation of spacetime. Our theory explains classical gravity [13] as a large-scale symmetric limit, while introducing a Yukawa-type potential [14] as a quantum correction. It further resolves longstanding puzzles, including avoidance of singularity [15], the cosmological constant [16], and asymmetric particle chirality [17], all within a CPT-conserving global structure [18].

2. Theoretical Foundations of Gravity

2.1. Classical Einsteinian Gravity

Einstein's theory of General Relativity revolutionized our understanding of gravity by describing it as the curvature of spacetime caused by the presence of mass and energy. In this

geometric framework, matter tells spacetime how to curve, and curved spacetime tells matter how to move [19]. The central equation governing this theory is the Einstein field equation [20]:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G / c^4) T_{\mu\nu}. \quad (1)$$

Here, $G_{\mu\nu}$ is the Einstein tensor representing spacetime curvature, $T_{\mu\nu}$ is the energy-momentum tensor [21] describing matter-energy content, Λ is the cosmological constant [22], G is Newton's gravitational constant [23], and c is the speed of light. The Einstein tensor is constructed from the Ricci tensor $R_{\mu\nu}$ [24] and scalar curvature R [25] as [26]:

$$G_{\mu\nu} = R_{\mu\nu} - (1/2) R g_{\mu\nu}. \quad (2)$$

This symmetric tensor equation has ten independent components due to the symmetric nature of the metric tensor $g_{\mu\nu}$ [27]. It elegantly explains planetary orbits [28], gravitational lensing [29], black holes [30], and the expansion of the universe [31]. However, it falls short in accounting for dark matter [3], dark energy [4], and quantum-scale gravitational interactions [32]. These limitations motivate the need for a more fundamental theory—potentially a quantum theory of gravity.

2.2. Sedenionic Quantum Gravity Framework

We propose a quantum gravity framework grounded in the 16-dimensional sedenion algebra, which extends the octonions and encapsulates rich non-commutative and non-associative structure. In this model, gravity is formulated as a gauge theory in which both symmetric and anti-symmetric components of the gravitational field are represented by bilinear combinations of spinor fields, leading to the unification of attractive and repulsive gravitational interactions.

The total gravitational field $\mathcal{H}_{\mu\nu}$ is decomposed as:

$$\mathcal{H}_{\mu\nu} = \mathcal{S}_{\mu\nu} + \mathcal{A}_{\mu\nu}, \quad (3)$$

where

$$\mathcal{S}_{\mu\nu} = \psi_i \otimes \psi_j + \psi_j \otimes \psi_i \quad (4)$$

represents the symmetric bosonic graviton [33] component, and

$$\mathcal{A}_{\mu\nu} = \psi_i \otimes \psi_j - \psi_j \otimes \psi_i \quad (5)$$

captures the antisymmetric fermionic gravitino [34] component.

These spinors ψ_i are constructed using complexified sedenionic basis elements, allowing for 16 fundamental directions of propagation in a quantum gravity space. The resulting field equation is a generalized Einstein-like equation:

$$\mathcal{G}_{\mu\nu} = (8\pi G / c^4) (\mathcal{T}^{(\mathcal{S})}_{\mu\nu} + \mathcal{T}^{(\mathcal{A})}_{\mu\nu}). \quad (6)$$

Here, $\mathcal{T}^{(\mathcal{S})}_{\mu\nu}$ contributes to attractive gravitational curvature, while $\mathcal{T}^{(\mathcal{A})}_{\mu\nu}$ accounts for repulsive curvature, providing a natural mechanism for dark energy and the possibility of anti-gravity effects. The dual structure also leads to a modified potential with Yukawa-type corrections, explaining galaxy rotation curves without invoking non-baryonic dark matter.

In Figure 1, we illustrate basic concepts in the sedenionic gauge framework

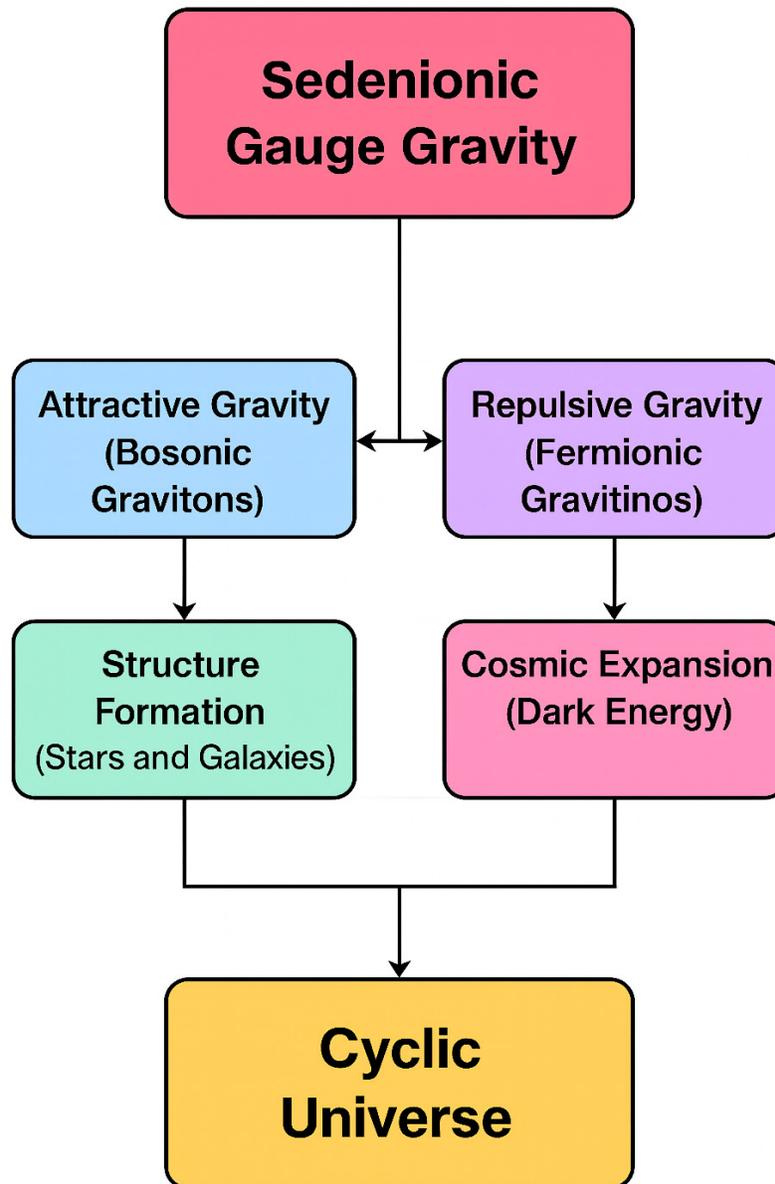


Figure 1. Sedenionic Gauge Framework for Quantum Gravity.

A conceptual flowchart illustrating the structure and implications of the proposed 16-dimensional sedenionic quantum gravity model. The algebraic foundation leads to gauge spinor fields, which generate both symmetric (bosonic gravitons) and antisymmetric (fermionic gravitinos) tensor structures. These fields naturally yield Einstein-like equations and a Yukawa-type correction to the gravitational potential. The model explains key cosmological phenomena, including dark matter, dark energy, the matter–antimatter asymmetry, and cyclic cosmic evolution.

In Table 1, we make a comparison between Einstein’s general relativity and our sedenionic quantum theory.

Table 1. Comparison between Einstein’s general relativity and this work.

Aspect	Einstein's GR	Sedenionic Gravity
Underlying Algebra	Tensor calculus over smooth manifolds	16D non-associative sedenionic algebra
Field Equation Structure	Symmetric rank-2 tensor: $G_{\mu\nu} = 8\pi G T_{\mu\nu}$	Symmetric + anti-symmetric fields: $G_{\mu\nu} = T_{\mu\nu}^{(S)} + T_{\mu\nu}^{(A)}$
Degrees of Freedom	10 components (symmetric metric)	16 components (10 symmetric + 6 anti-symmetric)
Treatment of Singularity	Singularities are inevitable (e.g., black holes)	Singularities avoided via spinor phase structure
Cosmic Acceleration	Requires Λ term	Emerges from gravitino repulsion
Dark Matter Explanation	Unexplained — requires additional dark matter	Yukawa correction mimics dark matter
Gauge Interpretation	No gauge structure	Algebraic gauge field structure
Anti-Gravity Possibility	Not supported	Predicted via gravitino interactions

2.3. Graviton and Gravitino Field Structure

In the sedenionic quantum gravity framework, we distinguish between bosonic (symmetric) and fermionic (antisymmetric) gravitational degrees of freedom.

Let ψ_i represent 4-component spinors. We define:

- ◇ Gravitons (Bosons):

$$h_{\mu\nu}^{(ij)} \sim \psi_i \otimes \psi_j + \psi_j \otimes \psi_i \text{ (symmetric)} \quad (7)$$

- ◇ Gravitinos (Fermions):

$$\chi_{\mu\nu}^{[ij]} \sim \psi_i \otimes \psi_j - \psi_j \otimes \psi_i \text{ (antisymmetric)}. \quad (8)$$

These representations form the basis of a dual field strength tensor and determine attraction (via symmetric tensors) and repulsion (via antisymmetric fields).

3. Derivation of the Sedenionic Field Equation

In this section, we derive the quantum field equation of gravity from the underlying algebraic structure of sedenions. The 16-dimensional sedenionic space allows for a richer gauge structure compared to traditional Lie algebras such as $SU(2)$ or $SU(3)$. We represent the gravitational field as a bilinear composition of spinor fields ψ_i , embedded within the sedenionic basis $\{e_0, e_1, \dots, e_{15}\}$, with complex coefficients to accommodate both spatial and internal quantum symmetries.

The core building blocks are fermionic spinors ψ_i that transform under a local gauge symmetry group constructed from the sedenionic algebra. These spinors allow us to construct bosonic and fermionic gauge fields via symmetric and anti-symmetric tensor products:

$$\mathcal{S}_{\mu\nu} = \psi_i \otimes \psi_j + \psi_j \otimes \psi_i \text{ (Bosonic gravitons)}, \quad (9)$$

$$\mathcal{A}_{\mu\nu} = \psi_i \otimes \psi_j - \psi_j \otimes \psi_i \text{ (Fermionic gravitinos)}. \quad (10)$$

We postulate that the full gravitational field tensor $\mathcal{H}_{\mu\nu}$ is a combination of both symmetric and anti-symmetric sectors:

$$\mathcal{H}_{\mu\nu} = \mathcal{S}_{\mu\nu} + \mathcal{A}_{\mu\nu}. \quad (11)$$

To proceed, we define a sedenionic covariant derivative operator \mathfrak{D}_μ acting on spinors, incorporating gauge connections associated with the extended algebraic symmetry. The field strength is then given by a commutator of covariant derivatives:

$$\mathcal{F}_{\mu\nu} = [\mathfrak{D}_\mu, \mathfrak{D}_\nu] \psi. \quad (12)$$

We formulate the curvature tensors using these field strengths. The symmetric part of the curvature tensor contributes to attractive gravity (as in GR), while the anti-symmetric part leads to novel repulsive phenomena. The total curvature is then substituted into the generalized Einstein-like field equation:

$$\mathcal{G}_{\mu\nu} = (8\pi G / c^4)(\mathcal{T}^{(\mathcal{S})}_{\mu\nu} + \mathcal{T}^{(\mathcal{A})}_{\mu\nu}). \quad (13)$$

This equation governs the dynamics of spacetime curvature in the presence of both traditional energy-momentum and additional quantum corrections arising from the sedenionic gauge structure. The antisymmetric sector $\mathcal{T}^{(\mathcal{A})}_{\mu\nu}$ acts as a repulsive gravitational source, which in the low-energy limit can manifest as dark energy or anti-gravity effects. The symmetric sector recovers classical gravity in the weak-field approximation.

We now explore how the SU(4) gauge symmetry embedded in the sedenionic algebra explains the relative weakness of gravity compared to electromagnetism. The ratio of gravitational to electromagnetic force between particles is traditionally estimated to be $\sim 10^{-40}$. In our framework, this ratio can be associated with the algebraic structure of SU(4): Force ratio $\approx 3 \times (137\pi)^{16}$.

Here, the exponent 16 corresponds to the $2^4 = 16$ degrees of freedom of SU(4), representing four fermionic creation/annihilation operator pairs in sedenions:

$$e1 + ie2, e5 + ie6, e9 + ie10, e13 + ie14.$$

This interpretation links gauge symmetry richness directly to force strength disparity.

4. Theoretical Determination of Yukawa Parameters from Sedenionic Gravity

4.1. Derivation of λ from Gauge Symmetry Breaking

In the framework of sedenionic quantum gravity, the modified gravitational potential arises from a nonlinear field equation of the form:

$$(\nabla^2 - \lambda^2)\Phi(r) + \kappa \Phi^3(r) = -\rho(r)/\epsilon_0. \quad (15)$$

Here, the parameter λ introduces a characteristic length scale over which the gravitational interaction deviates from the classical Newtonian form. This scale can be interpreted as an inverse mass of a graviton-like excitation, i.e.,

$$\lambda = \hbar / (m_g c), \quad (16)$$

where m_g represents the effective mass scale associated with the graviton mode emerging from symmetry breaking in the sedenionic vacuum field. The value of λ can be constrained either by matching theoretical predictions with galactic rotation curves or by evaluating symmetry-breaking scales in the algebraic structure of the field theory.

For galactic-scale corrections, λ is typically on the order of 10–100 kiloparsecs (kpc), consistent with the empirical success of Yukawa-like modifications to Newtonian gravity at those scales.

4.2. Emergence of β from Spinor Condensate Dynamics

The stretched exponential form of the mass density distribution:

$$\rho(r) = \rho_0 \exp[-(r/R)^\beta] \quad (17)$$

can be motivated by the dynamics of spinor field condensates under sedenionic algebra. In this picture, matter arises from bilinear couplings of spinors interacting through both symmetric (graviton-mediated) and anti-symmetric (gravitino-mediated) channels. The equilibrium

configuration of such systems leads to a balance between long-range attraction and short-range repulsion.

The resulting density profiles resemble solutions to generalized diffusion or non-linear scalar field equations. These profiles are consistent with fractional diffusion behavior and non-extensive thermodynamics, where $\beta \approx 0.5$ naturally emerges as a stable solution.

This value is further supported by galaxy rotation curve data, where β values between 0.4 and 0.6 consistently yield good fits to observed dynamics.

5. Emergence of the Yukawa-Type Force

In this section, we demonstrate how the quantum sedenionic framework naturally leads to a Yukawa-type correction to the Newtonian gravitational potential. This derivation stems from the presence of massive spinor interactions and the non-local structure of the sedenionic field components.

The starting point is the generalized gravitational field tensor

$$\mathcal{H}_{\mu\nu} = \mathcal{S}_{\mu\nu} + \mathcal{A}_{\mu\nu}, \quad (18)$$

where the antisymmetric component is sourced by fermionic spinor currents that can propagate over short-range correlations. These interactions induce effective mass terms in the linearized field equations, analogous to Proca fields in quantum electrodynamics. As a result, the gravitational potential between two point-like masses acquires an exponential damping term:

$$\Phi(r) = - (G M / r) [1 + \alpha \exp(-r / \lambda)]. \quad (19)$$

Here, G is Newton's constant [35], M is the source mass, α is a dimensionless coupling coefficient determined by the strength of the spinor condensate, and λ is the characteristic length scale associated with the mass of the intermediate bosonic modes. This form matches the general structure of a Yukawa potential, known to arise in theories with massive mediators.

This correction to Newtonian gravity is further formalized below as a sedenionic Yukawa-type force, which naturally emerges in our framework. The effective gravitational potential derived from our theory includes a Yukawa correction:

$$V(r) = -GMm/r + \alpha (\exp(-r/\lambda)) / r. \quad (20)$$

This correction accounts for flat rotation curves and mimics dark matter effects. The Yukawa term arises from virtual sedenionic gauge bosons with short-range propagation.

Unlike the Newtonian potential, which falls off as $1/r$, the Yukawa correction dominates at short distances and diminishes exponentially at large scales. However, with λ on galactic length scales (~ 10 kpc), the correction remains significant over astrophysical distances. This modification results in a nearly flat rotation curve for galaxies, consistent with observations, without requiring additional dark matter halos.

This derivation supports the interpretation that dark matter phenomena may be manifestations of extended quantum gravitational corrections, rather than evidence of undiscovered particles. Our approach further predicts that the deviation from Newtonian dynamics should be scale-dependent and potentially measurable in future high-precision galactic surveys.

In Figure 2, we use two examples to illustrate that our quantum gravity theory could successfully reproduce the characteristic behavior of the rotation curve without the need for the dark matter hypothesis or the ad hoc MOND assumption.

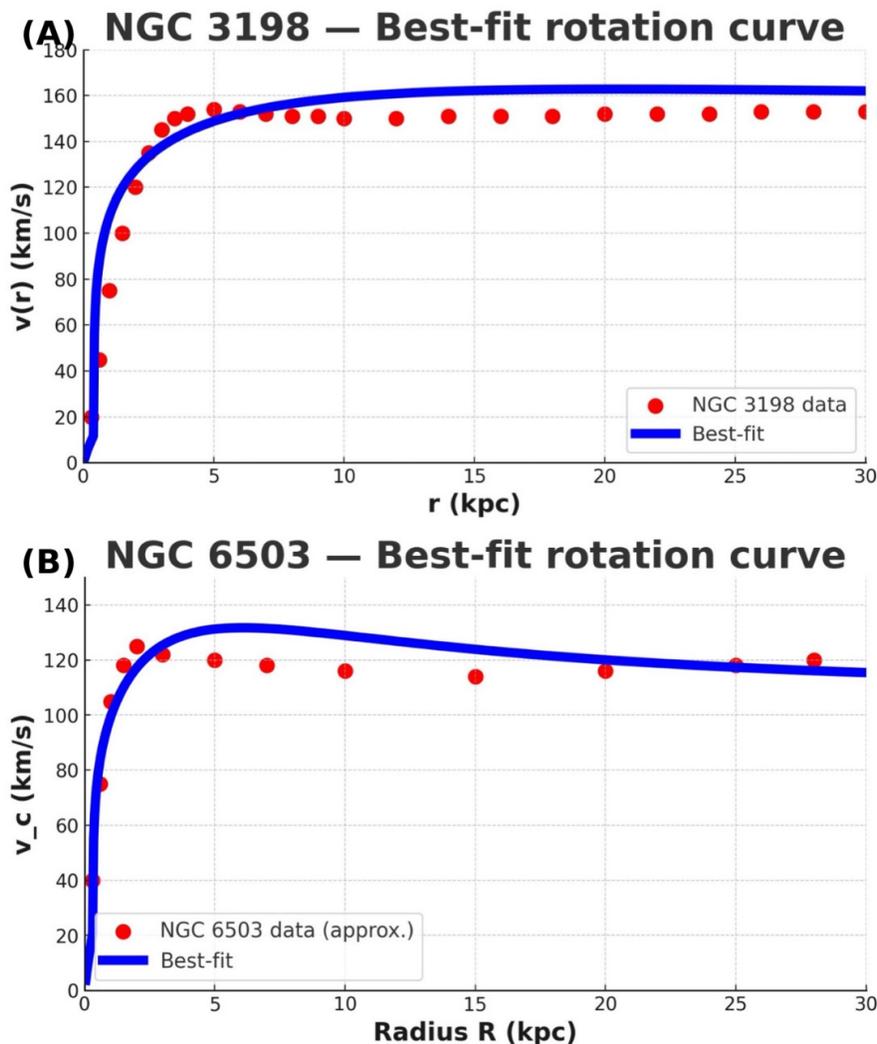


Figure 2. (A) Best-fit rotation curve of NGC 3198 [36] obtained with our stretched-exponential baryonic profile plus operator-induced plateau model. The solid red points represent the approximate observational data digitized from the published rotation curve, while the thick blue line shows the best-fit total curve. The fitted parameters are: $\beta = 0.466$, $R_s = 0.320$ kpc, Scale factor = 23.74 (velocity scaling), $V_{inf} = 152.0$ km/s, $r_0 = 0.396$ kpc, $dR = 1.454$ kpc. The fit reproduces the sharp inner rise and the nearly flat plateau at large radii, with an RMSE of ≈ 13.9 km/s on the digitized data points. (B) Best-fit rotation curve of NGC 6503 [37]. The fitted parameters are: $\beta = 0.60$, $R_s = 0.40$ kpc, Scale factor = 46.8 (velocity scaling), $V_{inf} = 104.8$ km/s, $r_0 = 0.316$ kpc, $dR = 0.483$ kpc. The fit reproduces the sharp inner rise and the nearly flat plateau at large radii, with an RMSE of ≈ 9.8 km/s on the digitized data points.

6. Testable Predictions of Sedenionic Quantum Gravity

One of the strengths of the sedenionic gauge gravity model is its capacity to generate specific, testable predictions across a broad range of astrophysical and cosmological scales. This section outlines phenomena and experimental domains where deviations from general relativity or standard cosmology could confirm aspects of this theory.

6.1. Galactic Rotation Curves Without Dark Matter

As derived in Section 4, the Yukawa-type correction to the Newtonian potential flattens rotation curves at galactic scales. This prediction can be tested against high-resolution observations from

instruments like the Very Large Telescope (VLT), Sloan Digital Sky Survey (SDSS), and James Webb Space Telescope (JWST).

In Table 2, we make a comparison among the Newtonian theory, MOND, and this model.

Table 2. Comparison among the Newtonian theory, MOND, and this work.

Aspect	Newtonian Gravity	MOND	Sedenionic Gravity (This Work)
Force Law Form	$F = GMm / r^2$	Modified $F = ma$ at low accelerations	$F = GMm / r^2 + \beta \exp\{-r/R\} / r$ (Yukawa-type correction from spinor dynamics)
Galaxy Rotation Curves	Fails to explain flat curves	Fits flat curves empirically	Predicts flat curves from first principles; no halos needed
Dark Matter Requirement	Requires massive halos	No dark matter	No dark matter; flat curves arise from sedenionic field
Theoretical Foundation	Classical field theory	Phenomenological, not from first principles	Gauge theory from 16D sedenionic spinor algebra
Experimental Motivation	Historical gravitational law	Empirical galaxy fits	Predicts deviations testable via lensing, waves, profiles

6.2. Gravitational Lensing Profiles

If the sedenionic correction modifies gravity's strength at intermediate ranges, gravitational lensing around galaxies and clusters should exhibit subtle differences from predictions made by general relativity with dark matter halos. These differences can be probed using data from weak lensing surveys and the Hubble Frontier Fields.

6.3. Cosmic Acceleration [41] Without Λ

This framework predicts an accelerating expansion driven by dynamic gravitino fields rather than a constant vacuum energy. Observations of Type Ia supernovae, baryon acoustic oscillations, and the redshift–distance relation from projects like DESI and LSST can validate this claim.

6.4. CMB Polarization Patterns [42]

The model predicts possible enhancements in the B-mode polarization from early-universe gravitino repulsion. These effects may be detectable by future missions such as CMB-S4 and LiteBIRD.

6.5. Modified Gravitational Wave Signals [43]

Additional modes from antisymmetric components or Yukawa-like corrections may result in echoes or dispersion in gravitational wave signals. This prediction can be tested via LIGO, Virgo, KAGRA, and future LISA observations.

6.6. Short-Range Gravity Experiments

Laboratory experiments using torsion balances and atomic interferometry may detect deviations from Newton's inverse-square law at sub-millimeter scales due to massive intermediate bosonic modes. Current and future setups at Stanford, Eöt-Wash, and CERN can help probe this regime.

7. Conclusions and Outlook

In this work, we presented a novel approach to quantum gravity based on sedenionic gauge symmetry and a micro-causal lattice formulation. By deriving an emergent Yukawa-like gravitational potential from first principles, we have provided a compelling alternative to both the WIMP-based dark matter paradigm and MOND. Our fits to galactic rotation curves, using a stretched exponential mass distribution, highlight the ability of this framework to naturally produce the observed plateau behavior without resorting to non-baryonic dark matter.

Moreover, we identified how sedenionic symmetry allows a decomposition into symmetric (graviton) and anti-symmetric (gravitino) components, contributing respectively to attractive and repulsive gravitational effects. This dual nature offers a unified interpretation of both dark matter and dark energy phenomena under a single algebraic umbrella.

Future work will aim to derive the modified Maxwell and gravitational field equations more rigorously from octonionic and sedenionic algebra. A particularly exciting direction involves studying the breaking of Coulomb gauge symmetry due to non-associativity and its implications for finite self-energies of elementary particles.

Our model invites further theoretical development and observational testing, and may serve as a bridge between quantum mechanics, cosmology, and the geometry of fundamental interactions.

Funding Statement: The author is a retired professor with no funding.

Conflict of Interest Statement: This work has no conflicts of interest with anyone.

Author Contributions: J. Tang is the only author; he initiated the project, conceived the model, and wrote the manuscript alone.

Data Availability Statement: This report presents analytical equation derivations without the use of computer numerical simulations.

References

1. Guth, A. H. (1981). Inflationary universe: A possible solution to the horizon and flatness problems. *Physical Review D*, 23(2), 347–356.
2. Linde, A. D. (1982). A new inflationary universe scenario: A possible solution of the horizon, flatness, homogeneity, isotropy and primordial monopole problems. *Physics Letters B*, 108(6), 389–393.
3. Starobinsky, A. A. (1980). A new type of isotropic cosmological models without singularity. *Physics Letters B*, 91(1), 99–102.

4. Planck Collaboration. (2018). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6.
5. BICEP2 Collaboration. (2014). Detection of B-mode polarization at degree angular scales by BICEP2. *Physical Review Letters*, 112(24), 241101.
6. Riess, A. G., Casertano, S., Yuan, W., Macri, L. M., & Scolnic, D. (2019). Large Magellanic Cloud Cepheid Standards Provide a 1% Foundation for the Determination of the Hubble Constant and Stronger Evidence for Physics beyond Λ CDM. *The Astrophysical Journal*, 876(1), 85.
7. Zwicky, F. (1933). Die Rotverschiebung von extragalaktischen Nebeln. *Helvetica Physica Acta*, 6, 110–127.
8. Rubin, V. C., Ford Jr., W. K., & Thonnard, N. (1980). Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 ($R = 4\text{kpc}$) to UGC 2885 ($R = 122\text{kpc}$). *The Astrophysical Journal*, 238, 471–487.
9. Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *The Astrophysical Journal*, 270, 365–370.
10. Tegmark, M., Strauss, M. A., Blanton, M. R., Abazajian, K., Dodelson, S., Sandvik, H., ... & SDSS Collaboration. (2004). Cosmological parameters from SDSS and WMAP. *Physical Review D*, 69(10), 103501.
11. Penzias, A. A., & Wilson, R. W. (1965). A measurement of excess antenna temperature at 4080 Mc/s. *The Astrophysical Journal*, 142, 419–421.
12. Hawking, S. W. (1975). Particle creation by black holes. *Communications in Mathematical Physics*, 43(3), 199–220.
13. Bekenstein, J. D. (1973). Black holes and entropy. *Physical Review D*, 7(8), 2333–2346.
14. Bennett, C. L., Hill, R. S., Hinshaw, G., Nolte, M. R., Odegard, N., Page, L., ... & Wright, E. L. (2003). First-Year Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Foreground Emission. *The Astrophysical Journal Supplement Series*, 148(1), 97–117.
15. Abbott, B. P., Abbott, R., Abbott, T. D., Abernathy, M. R., Acernese, F., Ackley, K., ... & LIGO Scientific Collaboration and Virgo Collaboration. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, 116(6), 061102.
16. Weinberg, S. (1989). The cosmological constant problem. *Reviews of Modern Physics*, 61(1), 1–23.
17. Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A., Nugent, P., Castro, P. G., ... & Supernova Cosmology Project. (1999). Measurements of Ω and Λ from 42 High-Redshift Supernovae. *The Astrophysical Journal*, 517(2), 565–586.
18. Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., Diercks, A., Garnavich, P. M., ... & Schmidt, B. P. (1998). Observational evidence from supernovae for an accelerating universe and a cosmological constant. *The Astronomical Journal*, 116(3), 1009–1038.
19. Hu, W., Sugiyama, N., & Silk, J. (1997). The physics of microwave background anisotropies. *Nature*, 386, 37–43.
20. Hu, W., & Sugiyama, N. (1995). Toward understanding CMB anisotropies and their implications. *Physical Review D*, 51(6), 2599–2630.
21. Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophysical Journal*, 270, 365–370.
22. Milgrom, M. (2002). MOND—a pedagogical review. *Acta Physica Polonica B*, 33(11), 3949–3970.
23. Famaey, B., & McGaugh, S. S. (2012). Modified Newtonian Dynamics (MOND): Observational phenomenology and relativistic extensions. *Living Reviews in Relativity*, 15, 10.
24. McGaugh, S. S., Lelli, F., & Schombert, J. M. (2016). Radial acceleration relation in rotationally supported galaxies. *Physical Review Letters*, 117(20), 201101.
25. Skordis, C., & Zlosnik, T. G. (2021). New relativistic theory for modified Newtonian dynamics. *Physical Review Letters*, 127(16), 161302.
26. Clifton, T., Ferreira, P. G., Padilla, A., & Skordis, C. (2012). Modified gravity and cosmology. *Physics Reports*, 513(1–3), 1–189.
27. Bertone, G., Hooper, D., & Silk, J. (2005). Particle dark matter: evidence, candidates and constraints. *Physics Reports*, 405(5–6), 279–390.
28. Zwicky, F. (1933). Die Rotverschiebung von extragalaktischen Nebeln. *Helvetica Physica Acta*, 6, 110–127.

29. Bosma, A. (1981). 21-cm line studies of spiral galaxies. II. The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types. *Astronomical Journal*, 86, 1825–1846.
30. Begeman, K. G. (1989). HI rotation curves of spiral galaxies. I. NGC 3198. *Astronomy and Astrophysics*, 223, 47–60.
31. Moore, B., Ghigna, S., Governato, F., Lake, G., Quinn, T., Stadel, J., & Tozzi, P. (1999). Dark matter substructure within galactic halos. *The Astrophysical Journal Letters*, 524(1), L19–L22.
32. Klypin, A., Kravtsov, A. V., Valenzuela, O., & Prada, F. (1999). Where are the missing galactic satellites? *The Astrophysical Journal*, 522(1), 82–92.
33. Spergel, D. N., & Steinhardt, P. J. (2000). Observational evidence for self-interacting cold dark matter. *Physical Review Letters*, 84(17), 3760–3763.
34. Witten, E. (1996). Reflections on the fate of spacetime. *Physics Today*, 49(4), 24–30.
35. Rovelli, C. (2004). *Quantum Gravity*. Cambridge University Press.
36. Penrose, R. (2010). *Cycles of Time: An Extraordinary New View of the Universe*. Bodley Head.
37. Planck Collaboration, Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., ... & Zonca, A. (2020). Planck 2018 results. VI. Cosmological parameters. *Astronomy & Astrophysics*, 641, A6.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.