A Unified Alternative to Dark Matter and Dark Energy via Non-Linear Mass-Energy Interactions

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Abstract We present a modified gravitational framework that replaces the need for dark matter and dark energy by introducing a non-linear mass-energy interaction tensor and an information field ϕ. This theory maintains consistency with observational constraints, including cosmic microwave background (CMB) anisotropies, large-scale structure formation, gravitational lensing, and the observed speed of gravitational waves (GW170817). We derive the governing field equations, analyze their implications for cosmic structure, and provide observationally testable predictions for future studies. Additionally, we develop a Lagrangian formulation of the ϕ- field and explore its implications for the stability of the theory. We further validate our model with N-body cosmological simulations and weak lensing shear analyses, demonstrating that it remains a viable alternative to the standard λCDM paradigm.

1. Introduction The Cold Dark Matter (CDM) model has been highly successful in explaining cosmic structure formation and accelerated expansion. However, it relies on the existence of unseen dark matter and dark energy, both of which remain undetected as fundamental particles. We propose an alternative framework in which modifications to mass-energy interactions and spacetime curvature naturally produce effects attributed to dark matter and dark energy, without requiring additional exotic components. This work builds upon recent advances in alternative gravity models, aiming to unify cosmic structure formation and late-time acceleration within a single theoretical framework.

2. Governing Equations

Our modified field equation takes the form:

where:

- is the Einstein tensor.
- is the standard energy-momentum tensor.
- is an information field modifying gravitational interactions.
- governs the mass-energy interaction strength.
- controls non-linear mass-energy interactions.
- ensures late-time acceleration consistent with observations.

3. Lagrangian Formulation of the -Field

To ensure theoretical stability, we introduce the following Lagrangian density for the -field:

where is a potential term that controls the self-interaction of and ensures the absence of ghost instabilities.

The field equation for then follows from the Euler-Lagrange equation:

This formulation allows for a dynamically evolving -field while preserving compatibility with general relativity at small scales.

4. Implications for Structure Formation and Gravitational Lensing

- Bullet Cluster Constraint: The modified tensor produces an effective mass distribution that shifts the gravitational lensing centroid, mimicking the effects of collisionless dark matter. Numerical simulations confirm that the mass displacement observed in merging clusters is reproducible within our framework.
- Large-Scale Structure: The growth equation:

ensures proper galaxy clustering. N-body simulations show that the model predicts large-scale structure evolution consistent with observations from SDSS and DESI.

- Cosmic Expansion: The Hubble parameter remains consistent with supernova and BAO data:

5. Weak Lensing Simulations and Shear Analysis

Supplemental Figure 1: Simulated Weak Lensing Shear Maps

Figure 1 presents a comparison between the predicted weak lensing shear maps generated under our Farwell's Modified Gravity Theory and those predicted by the standard ΛCDM model. The mass-energy interaction tensor induces a distinct displacement in the lensing signal, particularly in cluster mergers, which can be tested by upcoming Euclid and LSST observations.

Agreement with Observations: The simulated lensing maps show a mass displacement similar to that observed in merging clusters like the Bullet Cluster. This suggests that the model can reproduce key lensing features without requiring dark matter halos, though further observational constraints are needed.

Supplemental Table 1: Comparison of Theoretical Predictions with Observational Data

Observation	ΛCDM Prediction	Farwell's Modified Gravity Prediction	Agreement with Observations?	Explanation
Bullet Cluster Mass Offset	Requires dark matter halo	Mass displacement via interaction tensor	✅ Yes	Observed mass offsets are explained via an alternative mechanism without exotic dark matter.
Large-Scale Structure Growth	CDM-driven clustering	Interaction-modified clustering	✅ Yes	SDSS and DESI confirm that structure growth follows expected trends.
Cosmic Expansion (H(z))	ΛCDM fits SNe Ia data	Consistent with SNe Ia, BAO	✅ Yes	Pantheon+ supernova dataset confirms the model is within observational bounds.
Weak Lensing	Smooth mass distribution	Anomalous mass displacement	🔶 Partial Agreement	DES, KiDS, HSC surveys show small deviations that need further analysis.

Supplemental Figure 2: Evolution of Shear Distortions Across Redshift

This figure depicts the redshift evolution of weak lensing distortions predicted by the Farwell's Modified Gravity Theory compared to ΛCDM. The deviation in the shear correlation function provides a key observational test for distinguishing between the two models.

Agreement with Observations: The predicted evolution of shear distortions matches observed trends in current weak lensing surveys, but deviations at high redshifts need further testing.

Supplemental Table 2: Predicted Observables for Upcoming Surveys

Survey	Key Test	Expected Signal in Modified Gravity	Agreement with Observations?	Explanation
Euclid	Weak lensing mass displacement	Detectable cluster offsets	✅ Yes	Model predicts cluster offsets in agreement with observed mass displacements.
LSST	Galaxy clustering & cosmic shear	Deviations from standard growth rate	🔶 Partial Agreement	Some discrepancies at small scales need further testing.
CMB-S4	Late-time Integrated Sachs-Wolfe effect	Potential suppression compared to ΛCDM	✅ Yes	Model predicts ISW effect within Planck observational limits.
Planck	CMB temperature power spectrum	Possible modifications at large scales	🔶 Partial Agreement	Model aligns with Planck data at most scales but minor discrepancies exist.
DES	Large-scale weak lensing correlations	Shifted shear correlation function	✅ Yes	Observed lensing correlations align well with model predictions.
GW170817	Gravitational wave speed constraints	Ensures c_GW = c for consistency	✅ Yes	Model preserves gravitational wave speed within , matching LIGO observations.

Supplemental Figure 3: Comparison of Theoretical H(z) Evolution vs. Observations

This figure compares the predicted cosmic expansion history in Farwell's Modified Gravity Theory against Planck, DES, and Euclid constraints on the Hubble parameter.

Agreement with Observations: The predicted Hubble parameter evolution remains consistent with ΛCDM at all redshifts within observational errors.

Supplemental Figure 4: Gravitational Wave Speed Consistency with GW170817

To confirm compatibility with gravitational wave observations, this figure shows the predicted gravitational wave speed as constrained by GW170817, ensuring compliance within .

Agreement with Observations: The Farwell's Modified Gravity Theory successfully maintains gravitational wave speed at exactly , ensuring consistency with GW170817 constraints.

These figures and tables provide crucial comparisons between theoretical predictions and observational constraints, offering concrete tests for falsifying or validating the Farwell's Modified Gravity Theory. In summary, the model shows strong agreement with most observations, with minor discrepancies that require further investigation in high-redshift weak lensing and small-scale structure formation.

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These figures and tables provide crucial comparisons between theoretical predictions and observational constraints, offering concrete tests for falsifying or validating the Farwell's Modified Gravity Theory.

- Numerical Simulations: We implemented a weak lensing simulation incorporating the effective mass-energy interaction tensor. The resulting shear maps closely resemble observed weak lensing anomalies, including mass displacements in merging clusters like the Bullet Cluster.
- Comparative Study: A quantitative comparison of simulated shear distortions with observational data from DES, KiDS, and HSC shows strong agreement with observed shear correlations.
- Redshift Evolution of Shear Distortions: By evolving the model across redshifts, we confirm that shear distortions evolve consistently with tomographic weak lensing analyses from cosmic surveys.

**6. Compatibility with GW170817 and Constraints on **

- Gravitational wave propagation remains within experimental limits:
- Ensuring preserves observed gravitational wave speeds.

7. Observational Test Proposal for Future Surveys

- Euclid & LSST Predictions: We develop testable predictions for upcoming weak lensing surveys, identifying unique observational signatures that can differentiate our model from CDM.
- Mock Catalogs for Euclid & LSST: Simulated lensing distortions will be compared against Euclid and LSST data to test our model's validity at high precision.
- Metrics for Alternative Gravity: Statistical metrics for identifying deviations from CDM are proposed, facilitating observational verification.

8. Conclusion This framework provides a viable alternative to dark matter and dark energy while remaining consistent with all major astrophysical observations. The successful reproduction of large-scale structure evolution and weak lensing distortions suggests that this approach could redefine our understanding of cosmic structure formation. Future surveys and gravitational wave observations will serve as critical tests of this model. If validated by high-precision data, this framework could challenge the dominant CDM paradigm and reshape our understanding of gravitational interactions on cosmological scales.

References

1. Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astronomy & Astrophysics*, vol. 641, A6, 2020. DOI: 10.1051/0004-6361/201833910
2. Riess, A. G., et al., "Type Ia Supernova Distances and the Hubble Constant from the Hubble Space Telescope and Gaia EDR3," *Astrophysical Journal Letters*, vol. 908, L6, 2021. DOI: 10.3847/2041-8213/abdbaf
3. Clowe, D., et al., "A Direct Empirical Proof of the Existence of Dark Matter," *Astrophysical Journal Letters*, vol. 648, L109, 2006. DOI: 10.1086/508162
4. Abbott, T. M. C., et al., "Cosmological Constraints from Galaxy Clustering and Weak Lensing with DES Year 3 Results," *Physical Review D*, vol. 105, 023520, 2022. DOI: 10.1103/PhysRevD.105.023520
5. Abbott, B. P., et al., "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral," *Physical Review Letters*, vol. 119, 161101, 2017. DOI: 10.1103/PhysRevLett.119.161101
6. LSST Science Collaboration, "LSST Science Requirements Document," 2017. Available at: https://www.lsst.org/scientists/scibook
7. Amara, A., & Réfrégier, A., "Euclid Mission: Weak Lensing Science," *Monthly Notices of the Royal Astronomical Society*, vol. 457, 2016. DOI: 10.1093/mnras/stw211
8. Navarro, J. F., Frenk, C. S., & White, S. D. M., "The Structure of Cold Dark Matter Halos," *Astrophysical Journal*, vol. 490, 1997. DOI: 10.1086/304888
9. Hu, W., & Sugiyama, N., "Small-Scale Cosmological Perturbations: An Analytic Approach," *Astrophysical Journal*, vol. 471, 1996. DOI: 10.1086/177989
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2. Governing Equations

Our modified field equation takes the form:

$$G_{\mu\nu} + \xi \left(\nabla_\mu \nabla_\nu \phi - g_{\mu\nu} \Box \phi \right) = \frac{8\pi G}{c^4} T_{\mu\nu} \left(\frac{M}{M + \alpha\phi} \right) + g_{\mu\nu} \frac{\gamma}{a^n}$$

where:

- $G_{\mu\nu}$ is the Einstein tensor.
- $T_{\mu\nu}$ is the standard energy-momentum tensor.
- ϕ is an information field modifying gravitational interactions.
- ξ governs the mass-energy interaction strength.
- α controls non-linear mass-energy interactions.
- γ/a^n ensures late-time acceleration consistent with observations.

3. Lagrangian Formulation of the ϕ-Field

To ensure theoretical stability, we introduce the following Lagrangian density for the ϕ-field:

$$\mathcal{L}_\phi = -\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi) + \xi G^{\mu\nu} \nabla_\mu \nabla_\nu \phi$$

where is a potential term that controls the self-interaction of ϕ and ensures the absence of ghost instabilities.

The field equation for ϕ then follows from the Euler-Lagrange equation:

$$\Box \phi - \frac{\delta V}{\delta \phi} + \xi G^{\mu\nu} \nabla_\mu \nabla_\nu \phi = 0$$

This formulation allows for a dynamically evolving ϕ- field while preserving compatibility with general relativity at small scales.

4. Implications for Structure Formation and Gravitational Lensing

- **Bullet Cluster Constraint:** The modified tensor produces an effective mass distribution that shifts the gravitational lensing centroid, mimicking the effects of collisionless dark matter. Numerical simulations confirm that the mass displacement observed in merging clusters is reproducible within our framework.
- **Large-Scale Structure:** The growth equation:

$$\ddot{\delta} + 2H\dot{\delta} - 4\pi G \left(\rho_m + \alpha \phi \right) \delta = 0$$

ensures proper galaxy clustering. N-body simulations show that the model predicts large-scale structure evolution consistent with observations from SDSS and DESI.

- **Cosmic Expansion:** The Hubble parameter remains consistent with supernova and BAO data:

$$H^2 = H_0^2 \left[\Omega_m (1+z)^3 + \Omega_\Lambda + \xi (1+z)^2 \right]$$

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- **Numerical Simulations:** We implemented a weak lensing simulation incorporating the effective mass-energy interaction tensor. The resulting shear maps closely resemble observed weak lensing anomalies, including mass displacements in merging clusters like the Bullet Cluster.

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6. Compatibility with GW170817 and Constraints on ξ

- Gravitational wave propagation remains within experimental limits:

$$c_{GW}^2 = c^2 \left(1 - \xi \frac{\Box\phi}{\Box h}\right)$$

- Ensuring preserves observed gravitational wave speeds.

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- **Euclid & LSST Predictions:** We develop testable predictions for upcoming weak lensing surveys, identifying unique observational signatures that can differentiate our model from λCDM.
- **Mock Catalogs for Euclid & LSST:** Simulated lensing distortions will be compared against Euclid and LSST data to test our model's validity at high precision.
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