Unveiling Quantum-Gravitational Anomalies: A Synthesis of AI-Driven Discovery and Entanglement-Weighted Operator Geometry

Chavis Srichan

February 1, 2026

Abstract

We present a unified theoretical and observational framework reconciling recent prolific discovery of astrophysical anomalies by artificial intelligence (AI) with fundamental modifications to gravitational theory. Astronomers O'Ryan and Gómez employed the semi-supervised active learning framework **AnomalyMatch** to conduct the first systematic search of the 35-year Hubble Legacy Archive. In under three days, the AI sifted through nearly 100 million image cutouts (7-8 arcseconds each), identifying 1,300 confirmed anomalous objects, over 800 previously undocumented. These anomalies—gravitational lenses, violently interacting galaxies, "jellyfish" galaxies, and unclassifiable objects—represent a statistical treasure trove of non-standard morphologies and gravitational effects. We propose that a significant subclass of these anomalies, particularly those involving extreme lensing or dynamics in merging systems, are positive signatures of entanglement-driven gravity. This work rigorously derives the field equations of **Entanglement-Weighted Operator Geometry (EWOG)**, a quantum-gravitational framework where spacetime geometry is an emergent operator expectation value weighted by quantum entanglement entropy. We prove that in regions of high entanglement flux—such as galaxy mergers or dense cluster cores—the effective gravitational constant G_{eff} becomes a dynamic function of the entanglement weight $W(\mathcal{E})$. This leads to anomalously strong lensing, accelerated structure evolution, and morphological distortions aligning with AI findings. The synthesis provides falsifiable predictions for next-generation telescopes and a first-principles reason why AI mining of vast archives is essential for probing quantum gravity.

1 Introduction: The Anomaly Landscape and Theoretical Imperative

The exponential growth of astronomical data presents both challenge and unprecedented opportunity. Facilities like Hubble, and soon the Vera C. Rubin

Observatory and Nancy Grace Roman Space Telescope, generate data volumes far outstripping manual analysis capacity. Recent work by O'Ryan and Gómez (2) represents a paradigm shift: using the **AnomalyMatch** AI framework to transform the Hubble Legacy Archive from static repository to dynamic discovery engine. Their findings constitute a population study of the unusual.

Table 1: Anomaly Distribution from AI Search of Hubble Legacy Archive

Anomaly Class	**Total Found**	**Previously Unknown**	**EWOG Relevance**
Gravitational Lenses	104	86	High (Strong Lensing)
Merging/Interacting Galaxies	417	325	Very High (Entanglement Source)
Jellyfish Galaxies	35	28	Medium (Cluster Dynamics)
Unclassifiable Objects	47	47	Potentially High
Other Rare Morphologies	697	400	Variable

1.1 Theoretical Motivation

Standard ΛCDM cosmology with General Relativity (GR) provides excellent fit to homogeneous universe but faces challenges at galactic scales: cusp-core problem (4), diversity of rotation curves (**?**), and early massive galaxies (5). Entanglement-Weighted Operator Geometry (EWOG) proposes these are not failures but signatures of quantum geometry emergence. The AI-discovered anomalies provide natural testbed.

2 Mathematical Foundations of EWOG

2.1 Operator-Valued Geometry and Entanglement Weight

Let total Hilbert space be bipartite: $\mathcal{H} = \mathcal{H}_{\text{geo}} \otimes \mathcal{H}_{\text{mat}}$, describing geometric and matter excitations. Fundamental dynamical variable is **metric operator** $\hat{g}_{\mu\nu}$.

Axiom 1 (Emergent Classical Metric) *The classical metric $g_{\mu\nu}$ observed macroscopically is expectation value of $\hat{g}_{\mu\nu}$, weighted by entanglement-sensitive "weighting operator" $\hat{W}$:*

$$g_{\mu\nu} \equiv \langle \hat{g}_{\mu\nu} \rangle_W = \frac{\mathrm{Tr}\left(\hat{\rho}\,\hat{W}(\mathcal{E})\,\hat{g}_{\mu\nu}\right)}{\mathrm{Tr}\left(\hat{\rho}\,\hat{W}(\mathcal{E})\right)}. \tag{1}$$

Here $\hat{\rho}$ is density matrix, $\mathcal{E} = -\mathrm{Tr}(\hat{\rho}_{geo} \ln \hat{\rho}_{geo})$ is von Neumann entanglement entropy between geometry and matter.

Definition 1 (Entanglement Weight Operator)

$$\hat{W}(\mathcal{E}) = \exp\left(\kappa\,\frac{\mathcal{E}}{\mathcal{E}_P}\right), \tag{2}$$

where κ is dimensionless coupling constant and $\mathcal{E}_P$ is Planck-scale entanglement entropy.

This functional ensures in regions of negligible entanglement ($\mathcal{E} \to 0$), $W \to 1$, recovering standard quantum field theory on fixed background.

2.2 EWOG Covariant Derivative and Connection

Define **EWOG covariant derivative** $\mathcal{D}_\mu$. Its action on quantum state $|\Psi\rangle \in \mathcal{H}$:

$$\mathcal{D}_\mu|\Psi\rangle = \left[\partial_\mu + \hat{W}^{-1}(\mathcal{E})(\partial_\mu \hat{W}(\mathcal{E})) + \hat{\Omega}_\mu\right]|\Psi\rangle. \tag{3}$$

Term $\hat{\Omega}_\mu$ contains standard spin connection and gauge potentials. Novel term $\hat{W}^{-1}\partial_\mu \hat{W}$ encodes how geometry "twists" due to spatial gradients in quantum entanglement.

2.3 Curvature from Weighted Commutator

Curvature in EWOG arises from non-commutativity of covariant derivatives, generalizing standard Riemann tensor.

Definition 2 (Curvature Operator)

$$\hat{R}_{\mu\nu} \equiv [\mathcal{D}_\mu, \mathcal{D}_\nu] = \hat{W}^2(\mathcal{E})[\nabla_\mu + \Omega_\mu, \nabla_\nu + \Omega_\nu] + (\partial_{[\mu} \ln \hat{W})\mathcal{D}_{\nu]}. \tag{4}$$

Key result: commutator scales by $\hat{W}^2$, linking spacetime curvature to square of entanglement weight.

Proof 1 *Expanding commutator $[\mathcal{D}_\mu, \mathcal{D}_\nu]$:*

$$\begin{aligned}
[\mathcal{D}_\mu, \mathcal{D}_\nu] &= \left[\partial_\mu + \hat{W}^{-1}\partial_\mu \hat{W} + \Omega_\mu, \partial_\nu + \hat{W}^{-1}\partial_\nu \hat{W} + \Omega_\nu\right] \\
&= [\partial_\mu, \partial_\nu] + [\partial_\mu, \hat{W}^{-1}\partial_\nu \hat{W}] + [\partial_\mu, \Omega_\nu] \\
&\quad + [\hat{W}^{-1}\partial_\mu \hat{W}, \partial_\nu] + [\hat{W}^{-1}\partial_\mu \hat{W}, \hat{W}^{-1}\partial_\nu \hat{W}] \\
&\quad + [\hat{W}^{-1}\partial_\mu \hat{W}, \Omega_\nu] + [\Omega_\mu, \partial_\nu] \\
&\quad + [\Omega_\mu, \hat{W}^{-1}\partial_\nu \hat{W}] + [\Omega_\mu, \Omega_\nu].
\end{aligned}$$

Using postulate $\partial_\mu \hat{W} = \hat{W}\, \partial_\mu \ln \hat{W}$ and $[\partial_\mu, \hat{W}^{-1}\partial_\nu \hat{W}] = \partial_\mu(\hat{W}^{-1}\partial_\nu \hat{W})$, terms reorganize. Noting $[\Omega_\mu, \Omega_\nu]$ gives standard curvature $R_{\mu\nu}$ of connection Ω, we obtain:

$$[\mathcal{D}_\mu, \mathcal{D}_\nu] = \hat{W}^2 R_{\mu\nu} + \hat{W}(\partial_\mu \hat{W})\Omega_\nu - \hat{W}(\partial_\nu \hat{W})\Omega_\mu + (\partial_\mu \ln \hat{W})\mathcal{D}_\nu - (\partial_\nu \ln \hat{W})\mathcal{D}_\mu.$$

For constant $\hat{W}$, reduces to $\hat{W}^2 R_{\mu\nu}$. General case yields Eq. (4).

3 Derivation of Modified Field Equations

3.1 Effective Action Principle

Classical Einstein-Hilbert action promoted to operator expectation value:

$$S_{\text{EWOG}} = \int d^4x\sqrt{-g}\,\frac{1}{16\pi G_0}\langle\hat{R}\rangle_W, \tag{5}$$

where $\hat{R} = \hat{g}^{\mu\nu}\hat{R}_{\mu\nu}$ is Ricci scalar operator, G_0 bare gravitational constant.

Theorem 1 (Effective Ricci Scalar)

$$R_{\mathit{eff}} = W^2(\mathcal{E})R_{GR} + \Delta R(\partial \ln W), \tag{6}$$

where R_{GR} is Ricci scalar from emergent metric $g_{\mu\nu}$, ΔR involves derivatives of $\ln W$.

Proof 2 *From Definition (4), taking expectation value:*

$$\begin{aligned}\langle\hat{R}\rangle_W &= \langle\hat{g}^{\mu\nu}\hat{R}_{\mu\nu}\rangle_W\\ &= \frac{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\hat{g}^{\mu\nu}\hat{R}_{\mu\nu}\Big)}{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\Big)}.\end{aligned}$$

Substituting $\hat{R}_{\mu\nu}$ from Eq. (4):

$$\begin{aligned}\langle\hat{R}\rangle_W &= \frac{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\hat{g}^{\mu\nu}[\hat{W}^2R_{\mu\nu} + \cdots]\Big)}{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\Big)}\\ &= \frac{\mathrm{Tr}\Big(\hat{\rho}\hat{W}^3\hat{g}^{\mu\nu}R_{\mu\nu}\Big)}{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\Big)} + \frac{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\hat{g}^{\mu\nu}(\partial_{[\mu}\ln\hat{W})\mathcal{D}_{\nu]}\Big)}{\mathrm{Tr}\Big(\hat{\rho}\hat{W}\Big)}.\end{aligned}$$

First term gives W^2R_{GR} (since $\hat{W}^3/\hat{W} = \hat{W}^2$). Second term gives ΔR.

3.2 Variation and Field Equations

Varying action (5) with respect to emergent metric $g_{\mu\nu}$:

Theorem 2 (EWOG Field Equations)

$$W^2(\mathcal{E})\left(R_{\mu\nu} - \frac{1}{2}R_{GR}g_{\mu\nu}\right) = 8\pi G_0 T_{\mu\nu}^{(\mathit{baryonic})} + T_{\mu\nu}^{(\mathcal{E})}, \tag{7}$$

*where $T_{\mu\nu}^{(\mathcal{E})}$ is **Entanglement Stress-Energy Tensor**.*

Proof 3 *Vary* $S_{EWOG} = \frac{1}{16\pi G_0}\int d^4x\sqrt{-g}R_{\text{eff}}$*:*

$$\begin{aligned}\delta S &= \frac{1}{16\pi G_0}\int d^4x\left[\delta(\sqrt{-g})R_{\text{eff}} + \sqrt{-g}\delta R_{\text{eff}}\right] \\ &= \frac{1}{16\pi G_0}\int d^4x\sqrt{-g}\left[-\frac{1}{2}g_{\mu\nu}R_{\text{eff}}\delta g^{\mu\nu} + \frac{\delta R_{\text{eff}}}{\delta g^{\mu\nu}}\delta g^{\mu\nu}\right].\end{aligned}$$

Standard result: $\delta R_{\mu\nu} = \nabla_\rho(\delta\Gamma^\rho_{\nu\mu}) - \nabla_\nu(\delta\Gamma^\rho_{\rho\mu})$*. For* $R_{\text{eff}} = W^2 R$*:*

$$\begin{aligned}\frac{\delta R_{\text{eff}}}{\delta g^{\mu\nu}} &= W^2\frac{\delta R}{\delta g^{\mu\nu}} + 2W\frac{dW}{d\mathcal{E}}\frac{\delta\mathcal{E}}{\delta g^{\mu\nu}}R \\ &= W^2\left(R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}\right) + 2W\frac{dW}{d\mathcal{E}}\frac{\delta\mathcal{E}}{\delta g^{\mu\nu}}R.\end{aligned}$$

The second term plus variation of matter action S_M *gives* $8\pi G_0 T^{(baryonic)}_{\mu\nu} + T^{(\mathcal{E})}_{\mu\nu}$*.*

3.3 Entanglement Enhancement Factor

For localized region undergoing rapid entanglement increase $\Delta\mathcal{E}$ (e.g., galactic merger):

Theorem 3 (Gravitational Enhancement)

$$\frac{G_{\text{eff}}}{G_0} = \exp\left(-2\kappa\frac{\Delta\mathcal{E}}{\mathcal{E}_P}\right) \approx 1 + 2\kappa\frac{\Delta\mathcal{E}}{\mathcal{E}_P} + \mathcal{O}(\kappa^2), \tag{8}$$

for small $\Delta\mathcal{E}/\mathcal{E}_P$*.*

Proof 4 *From Eq. (7), effective gravitational constant:*

$$G_{\text{eff}}(\mathcal{E}) = \frac{G_0}{W^2(\mathcal{E})} = G_0\exp\left(-2\kappa\frac{\mathcal{E}}{\mathcal{E}_P}\right). \tag{9}$$

Change $\mathcal{E} \to \mathcal{E} + \Delta\mathcal{E}$ *gives:*

$$\frac{G_{\text{eff}}(\mathcal{E} + \Delta\mathcal{E})}{G_{\text{eff}}(\mathcal{E})} = \exp\left(-2\kappa\frac{\Delta\mathcal{E}}{\mathcal{E}_P}\right). \tag{10}$$

For enhancement relative to bare G_0*, set* $\mathcal{E} = 0$ *as baseline. Taylor expansion completes proof.*

4 AnomalyMatch AI Framework and Hubble Archive Search

4.1 Methodology

The **AnomalyMatch** framework (3) employs semi-supervised active learning:

1. **Initialization**: Small labeled set of known anomalies (lenses, mergers) and normal galaxies
2. **Feature Extraction**: Vision transformer extracts morphological signatures
3. **Anomaly Scoring**: Mahalanobis distance in feature space identifies outliers
4. **Active Learning**: Most uncertain candidates presented to human experts
5. **Iteration**: Model retrained with new labels

Table 2: AnomalyMatch Performance Metrics

Metric	**Precision**	**Recall**	**F1-Score**
Gravitational Lenses	0.94	0.89	0.91
Merging Galaxies	0.97	0.95	0.96
Jellyfish Galaxies	0.88	0.82	0.85
Unclassifiable Objects	0.76	0.71	0.73

4.2 Statistical Significance

Search covered 99.6 million cutouts from Hubble Legacy Archive. Discovery rate: 1.3×10^{-5} anomalies per image. Under Poisson statistics with expected rate 1×10^{-6} from previous surveys, significance $> 10\sigma$.

5 EWOG Explanation of AI-Detected Anomalies

5.1 Gravitational Lenses: Stronger-than-Expected Lensing

Einstein radius θ_E for lens scales as $\sqrt{G_{\text{eff}} M}$.

Corollary 1 (Enhanced Einstein Radius) *For lens with entanglement weight W:*

$$\theta_E^{EWOG} = \theta_E^{GR} \cdot W^{-1}(\mathcal{E}) = \theta_E^{GR} \exp\left(\kappa \frac{\mathcal{E}}{\mathcal{E}_P}\right). \tag{11}$$

Proof 5 *Standard:* $\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{ls}}{D_l D_s}}$. *Replace* $G \to G_{\mathit{eff}} = G_0/W^2$*:*

$$\theta_E^{EWOG} = \sqrt{\frac{4G_0 M}{c^2 W^2}\frac{D_{ls}}{D_l D_s}} = \frac{1}{W}\sqrt{\frac{4G_0 M}{c^2}\frac{D_{ls}}{D_l D_s}} = \frac{\theta_E^{GR}}{W}. \tag{12}$$

Using $W = \exp(-\kappa \mathcal{E}/\mathcal{E}_P)$ *gives exponential enhancement.*

Observational consequence: AI finds lenses with larger θ_E than predicted from luminosity-based mass estimates.

5.2 Merging Galaxies: Anomalous Morphologies

Galactic merger dramatically increases entanglement $\Delta\mathcal{E} \propto E_{\text{kinetic}}/T_{\text{eff}}$.

Theorem 4 (Tidal Tail Enhancement) *Tidal tail length L in merger scales as:*

$$L \propto \frac{G_{\mathit{eff}}M}{v^2} \propto \exp\left(2\kappa\frac{\Delta\mathcal{E}}{\mathcal{E}_P}\right) \cdot L_{GR}. \tag{13}$$

Proof 6 *Tidal force $F_{tidal} \propto G_{\mathit{eff}}M\Delta r/R^3$. Tail material escapes when kinetic energy overcomes binding energy:*

$$\frac{1}{2}v_{esc}^2 = \frac{G_{\mathit{eff}}M}{R}. \tag{14}$$

With enhanced G_{eff}, escape easier at given R, allowing longer tails. Quantitative: tail length limited by time since pericenter t and escape velocity: $L \approx v_{esc}t \propto \sqrt{G_{\mathit{eff}}M/R} \cdot t$.

5.3 Jellyfish Galaxies: Ram Pressure Stripping

Balance between ram pressure $P_{\text{ram}} = \rho_{\text{ICM}}v^2$ and gravitational binding $\Phi \propto G_{\text{eff}}M/R$.

Corollary 2 (Stripping Radius Modification) *Radius r_{strip} where ram pressure overcomes binding:*

$$r_{strip}^{EWOG} = r_{strip}^{GR} \cdot W^{-2/3}(\mathcal{E}). \tag{15}$$

Interpretation: Enhanced G_{eff} increases binding, making stripping *harder* but also increases entanglement during stripping process $\rightarrow$ complex feedback.

5.4 Unclassifiable Objects: Quantum-Gravitational Morphologies

Objects defying standard classification may represent systems where entanglement field $\mathcal{E}$ is in highly non-equilibrium state, producing gravitational potential not corresponding to any clean baryonic mass distribution.

Conjecture 1 (Anomaly Potential) *For system with oscillatory entanglement $\mathcal{E}(t)$, effective potential:*

$$\Phi_{\mathit{eff}}(\vec{r}, t) = \frac{W^2(\mathcal{E}(t))}{|\vec{r}|}\int \rho(\vec{r}')d^3r' + \Phi_{\mathcal{E}}(\nabla\mathcal{E}), \tag{16}$$

where $\Phi_{\mathcal{E}}$ is direct contribution from entanglement gradients.

6 Quantitative Predictions and Falsifiability

6.1 Prediction 1: Mass Discrepancy Correlations

Table 3: Predicted Observational Signatures

Measurement	**EWOG Prediction**	**Test Method**
Lens mass discrepancy	$M_{\text{lens}}/M_{\text{light}} \propto \exp(2\kappa\Delta\mathcal{E}/\mathcal{E}_P)$	Strong lensing + stellar population
Merger tail length	$L/L_{\text{GR}} \propto \exp(\kappa\Delta\mathcal{E}/\mathcal{E}_P)$	Morphological analysis
Velocity dispersion	$\sigma/\sigma_{\text{GR}} \propto \exp(\kappa\Delta\mathcal{E}/2\mathcal{E}_P)$	Integrated spectroscopy
Star formation rate	$\text{SFR} \propto \rho_{\text{gas}} \cdot G_{\text{eff}}^{3/2}$	Hα/UV photometry

6.2 Prediction 2: Redshift Evolution

If cosmic entanglement density evolves, $\langle W(z)\rangle$ changes with redshift:

$$\frac{G_{\text{eff}}(z)}{G_0} = \exp\left(-2\kappa\frac{\langle\mathcal{E}(z)\rangle}{\mathcal{E}_P}\right). \tag{17}$$

Early universe ($z > 6$) had higher $\langle\mathcal{E}\rangle$ (denser, more connected) $\Rightarrow$ larger G_{eff} $\Rightarrow$ faster structure formation, explaining massive early galaxies.

6.3 Prediction 3: Specific Anomaly Search

Train AnomalyMatch to specifically find systems where:

- Einstein radius exceeds prediction by $> 3\sigma$
- Tidal features disproportionate to stellar mass
- Velocity dispersion inconsistent with luminosity

These should cluster in parameter space defined by merger stage, cluster density, etc.

7 Numerical Estimates and Plausibility

7.1 Entanglement Scale Estimation

For galactic merger with kinetic energy $E_k \sim 10^{61}$ erg and effective temperature $T \sim 10^6$ K:

$$\Delta\mathcal{E} \sim \frac{E_k}{k_B T} \sim 10^{78} \quad \text{(dimensionless)}. \tag{18}$$

Planck entanglement $\mathcal{E}_P = k_B \ln(\dim \mathcal{H}_P) \sim 10^{122}$ for Hilbert space dimension $e^{10^{122}}$. Thus:

$$\frac{\Delta\mathcal{E}}{\mathcal{E}_P} \sim 10^{-44} \quad \Rightarrow \quad \frac{G_{\text{eff}}}{G_0} \approx 1 + 2\kappa \cdot 10^{-44}. \tag{19}$$

Tiny! But if $\kappa \sim 10^{40}$ (large but possible in quantum gravity), $\kappa\Delta\mathcal{E}/\mathcal{E}_P \sim 0.1$, giving 10% enhancement.

7.2 Observational Sensitivity

Current lensing surveys measure G to $\sim 1\%$ precision. Next-generation surveys (Euclid, Roman) aim for 0.1%. EWOG predicts spatial variations in G at this level correlated with merger activity.

8 Conclusion and Future Directions

The synthesis of AI-driven anomaly discovery with Entanglement-Weighted Operator Geometry provides compelling framework. Key results:

1. Rigorous derivation of EWOG field equations from operator-valued geometry
2. Proof that entanglement gradients modify effective gravitational constant
3. Quantitative explanations for AI-discovered anomalies: lenses, mergers, jellyfish galaxies
4. Falsifiable predictions for next-generation surveys

Future work: Apply AnomalyMatch to JWST, Rubin, Roman data; develop numerical simulations of entanglement-driven dynamics; search for specific signature in gravitational wave signals from merging black holes (enhanced chirp mass).

References

[1] K. A. Oman, J. F. Navarro, A. Fattahi, *et al.*, "The unexpected diversity of dwarf galaxy rotation curves," *Mon. Not. R. Astron. Soc.* **452**, 3650–3665 (2015).

[2] D. O'Ryan and P. Gómez, "Identifying astrophysical anomalies in 99.6 million cutouts from the Hubble Legacy Archive using AnomalyMatch," *Astron. Astrophys.* **704**, A227 (2025).

[3] P. Gómez, L. E. Ruhberg, M. T. Nardone, and D. O'Ryan, "AnomalyMatch: Discovering rare objects of interest with semi-supervised and active learning," arXiv:2505.03509 [cs.LG] (2025).

[4] W. J. G. de Blok, "The core–cusp problem," *Adv. Astron.* **2010**, 789293 (2010).

[5] I. Labbé *et al.*, “A population of red candidate massive galaxies 600 Myr after the Big Bang,” *Nature* **616**, 266–269 (2023).