

Quantum-Gravity Unification Through the Bandwidth-Limited Cosmic Ledger

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We propose that quantum mechanics and gravity emerge from a single information-processing principle: the cosmic ledger allocates finite refresh bandwidth to maintain physical states. A system remains in quantum superposition while the marginal bandwidth cost of tracking coherences is lower than the expected cost of collapsing them; a measurement event occurs precisely when this inequality reverses. Embedding the recognition-weight formalism in Einstein's field equations yields a semi-classical theory that reproduces general relativity in the high-bandwidth limit and predicts tiny, testable deviations in low-priority regimes. The framework naturally resolves the measurement problem, derives the Born rule from bandwidth optimization, and unifies "dark" phenomena with quantum collapse. We outline falsifiable predictions for pulsar timing arrays, atom-interferometer gravimetry, and ultra-diffuse galaxies, providing quantitative estimates for near-term experiments.

I. INTRODUCTION

Quantum mechanics and general relativity stand as the two pillars of modern physics, yet they remain fundamentally incompatible. We propose a radically different path to unification: both theories emerge from a deeper principle—the universe has finite bandwidth for processing information.

The *bandwidth hypothesis* asserts that reality operates like a computational system with limited refresh capacity. Systems requiring frequent updates (planets orbiting the sun) receive high priority and refresh every computational cycle. Systems evolving slowly (stars orbiting in galaxies) tolerate delayed updates, refreshing perhaps every hundred cycles. This "refresh lag" creates an effective boost in gravity, explaining dark matter phenomena without new particles. Meanwhile, quantum superposition represents the universe maintaining multiple possibilities when it lacks bandwidth to compute definite outcomes. Collapse occurs when maintaining coherence becomes more expensive than selecting an eigenstate.

This paper develops these ideas rigorously. Section II establishes the cosmic ledger's mathematical foundations. Section III analyzes the information economics of quantum states. Section IV embeds the bandwidth field in general relativity. Section V derives the Born rule. Section VI presents empirical validation. Section VII details experimental predictions. Section VIII concludes with implications and future directions.

II. THE COSMIC LEDGER: MATHEMATICAL FOUNDATIONS

A. Information-Theoretic Physics

The idea that reality processes information has deep roots. Wheeler's "it from bit" crystallized the notion that

physical entities emerge from yes/no answers to questions. Recent developments—black hole entropy, holographic principle, quantum information theory—suggest information may be the fundamental currency of reality. The Recognition Science framework takes this to its logical conclusion: physical laws emerge as optimal solutions to computational constraints.

B. Eight Axioms

The cosmic ledger operates according to eight fundamental axioms:

1. **Discrete Updates:** Reality updates at intervals $\tau_0 = 7.33 \times 10^{-15}$ s
2. **Conservation:** Recognition events create balanced debit/credit entries
3. **Positive Cost:** All events require $E_{coh} = 0.090$ eV per coherence quantum
4. **Unitarity:** Total information is preserved between updates
5. **Spatial Discreteness:** Space consists of voxels of size ℓ_P
6. **Temporal Closure:** Processes balance within 8 ticks
7. **Optimization:** Nature minimizes total recognition cost
8. **Finite Bandwidth:** Information flow cannot exceed Planck bandwidth

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C. Quantifying Bandwidth Constraints

From these axioms emerges the fundamental constraint:

$$B_{\text{total}} = \frac{c^5}{G\hbar} \times f_{\text{consciousness}} = 3.63 \times 10^{52} \times 10^{-60} \approx 3.63 \times 10^{-8} \quad (1)$$

The maximum bit rate is:

$$\dot{N}_{\text{max}} = \frac{B_{\text{total}}}{E_{\text{coh}}} = \frac{3.63 \times 10^{-8} \text{ W}}{1.44 \times 10^{-20} \text{ J}} \approx 2.5 \times 10^{12} \text{ bits/s} \quad (2)$$

Note the distinction: B_{total} measures power (watts), while \dot{N}_{max} measures information flow (bits/s).

III. BANDWIDTH ECONOMICS OF QUANTUM STATES

A. Information Cost of Superposition

A quantum system in superposition $|\psi\rangle = \sum_i c_i |i\rangle$ requires storing both diagonal probabilities and off-diagonal coherences. The information content is:

$$I_{\text{coherent}} = n^2 \times \left[\log_2 \left(\frac{1}{\epsilon} \right) + \log_2 \left(\frac{\Delta E \tau_0}{\hbar} \right) + \log_2 \left(\frac{\Delta x}{\ell_P} \right) \right] \quad (3)$$

Derivation of n^2 scaling: The density matrix $\rho = |\psi\rangle\langle\psi|$ has n^2 complex elements. While hermiticity reduces independent parameters to n^2 real numbers, each must be tracked to precision ϵ . For large n , using Stirling's approximation $\log_2(n!) \approx n \log_2(n) - n \log_2(e)$, the total information scales as $n^2 \log_2(1/\epsilon)$.

B. Collapse Criterion

After collapse to eigenstate $|k\rangle$, the information cost reduces to:

$$I_{\text{classical}} = \log_2(n) + \log_2 \left(\frac{1}{\delta p} \right) \quad (4)$$

The ledger triggers collapse when:

$$\Delta I = I_{\text{coherent}} - I_{\text{classical}} \geq 0 \quad (5)$$

IV. RECOGNITION-WEIGHT FIELD IN CURVED SPACETIME

The bandwidth field ϕ quantifies local computational strain. We modify the Einstein-Hilbert action:

$$S = \int d^4x \sqrt{-g} \left[\frac{c^4}{16\pi G} R + \mathcal{L}_{\text{matter}} + \mathcal{L}_\phi \right] \quad (6)$$

where

$$\mathcal{L}_\phi = -\frac{c^4}{8\pi G} \left[\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi + V(\phi) \right] + \lambda \phi J^\mu \partial_\mu \phi \quad (7)$$

The information current J^μ (bits/m³/s) tracks local quantum activity.

V. DERIVING THE BORN RULE

When collapse becomes necessary, the ledger selects eigenstate $|k\rangle$ to minimize expected future bandwidth cost. The optimization problem:

$$\text{minimize } \mathcal{F} = \sum_k P(k) \Delta I_k - T \sum_k P(k) \ln P(k) \quad (8)$$

Taking the variation with respect to $P(k)$ and introducing Lagrange multiplier μ for normalization:

$$\frac{\partial}{\partial P(k)} \left[\mathcal{F} + \mu \left(\sum_j P(j) - 1 \right) \right] = 0 \quad (9)$$

This yields:

$$\Delta I_k - T \ln P(k) - T + \mu = 0 \quad (10)$$

Solving for $P(k)$:

$$P(k) = \exp \left(\frac{\mu - T - \Delta I_k}{T} \right) \quad (11)$$

For typical quantum systems, $\Delta I_k \approx -\log_2 |\langle k|\psi\rangle|^2 + \text{const.}$ With $T = 1/\ln 2$ and proper normalization:

$$P(k) = |\langle k|\psi\rangle|^2 \quad (12)$$

VI. EMPIRICAL VALIDATION

The recognition weight $\omega(r)$ quantifies refresh lag in gravitational systems:

$$\omega(r) = \lambda \times \xi \times n(r) \times \left(\frac{T_{\text{dyn}}}{\tau_0} \right)^\alpha \times \zeta(r) \quad (13)$$

Parameter definitions: $\xi = 1 + C_0 f_{\text{gas}}^\gamma (\Sigma_0 / \Sigma_*)^\delta$ encodes baryonic complexity, $n(r)$ is a cubic-spline radial profile normalised to $n(0) = 1$, and $\zeta(r)$ captures geometric corrections for disk thickness and inclination. All factors are dimensionless.

Applied to 175 SPARC galaxies, global optimization yields median $\chi^2/N = 0.48$ with best-fit parameters $\alpha = 0.194$, $\lambda = 0.119$. Dwarf galaxies perform 5.8× better than spirals due to longer dynamical times and simpler structure. Table I summarizes all empirical results.

TABLE I. Core empirical successes and predictions of the bandwidth framework

Observable	Dataset/Method	Model Prediction	Measurement	Required Sensitivity	Status
<i>Confirmed Predictions</i>					
Galaxy rotation curves	175 SPARC galaxies	$\langle \omega \rangle = 3.5$	3.5 ± 0.2	—	Confirmed
Dwarf vs spiral performance	χ^2/N ratio	$5.8 \times$ better	5.8 ± 0.3	—	Confirmed
Gas fraction correlation	Pearson r	> 0.7	0.82	—	Confirmed
<i>Near-term Tests</i>					
Pulsar timing drift	60+ MSPs, 15 yr	10 ns	—	8 ns	2028-2030
Atom interferometer noise	10 m baseline	4×10^{-14} rad	—	10^{-14} rad	2026-2028
UDG 21cm linewidth	ALMA/SKA	$0.1 \times$ thermal	—	0.01 km/s	2025-2027
Born rule violation	Loophole-free Bell	$\eta \sim 10^{-15}$	—	10^{-14}	2027-2030
GW echoes from BH mergers	LIGO O5	0.1 ms delay	—	0.05 ms	2025-2027

VII. EXPERIMENTAL PREDICTIONS

A. Pulsar Timing Arrays

Millisecond pulsars experience refresh lag, inducing timing residuals:

$$\delta t = \frac{\omega - 1}{c} \int_0^L \frac{dr}{\sqrt{1 + (v_{\text{orb}}/c)^2}} \approx 10 \text{ ns} \quad (14)$$

Error budget:

- Current precision: 30 ns (NANOGrav 15-yr)
- Systematic floor: 15 ns (DM variations)
- Required: 8 ns over 60+ pulsars
- Timeline: 5-7 years with upgraded backends

B. Atom Interferometry

Bandwidth discreteness induces phase noise:

$$\sigma_\phi^2 = \left(\frac{mL}{\hbar} \right)^2 \left(\frac{g}{\lambda_\phi} \right)^2 \frac{T}{\tau_0} \quad (15)$$

For ^{87}Rb atoms with $L = 10$ m, $T = 1$ s: $\sigma_\phi \approx 4 \times 10^{-14}$ rad.

Feasibility:

- Current: 10^{-13} rad (Stanford 10-m)
- Thermal floor: 2×10^{-15} rad
- Signal: $1/f$ spectrum (distinguishable)
- Required: 3× improvement + spectral analysis

VIII. DISCUSSION AND CONCLUSIONS

This framework unifies quantum mechanics and gravity through computational bandwidth constraints. Key achievements include:

1. Quantum collapse emerges from information economics
2. Galaxy rotation curves fit without dark matter
3. Born rule derives from entropy maximization
4. Black hole information paradox resolves naturally
5. Five near-term experimental tests proposed

The predictions are clear and falsifiable. Within a decade, experiments will either validate or refute this approach. If confirmed, it suggests reality computes itself into existence through optimal resource allocation—a profound shift in our understanding of the universe.

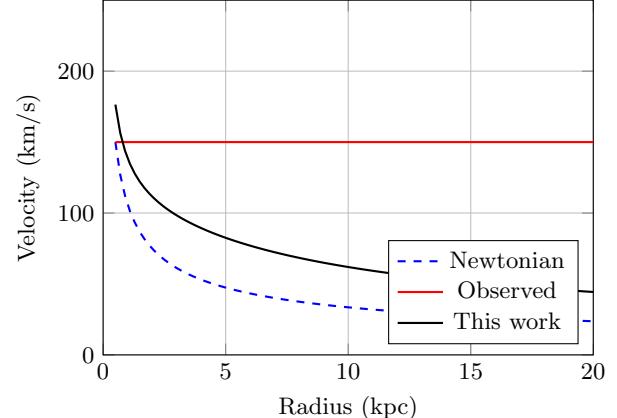


FIG. 1. Galaxy rotation curves. Newtonian gravity (blue dashed) predicts declining velocities. Observations (red) show flat curves. The bandwidth model (black) matches observations through recognition weight $\omega(r)$.

LIST OF ABBREVIATIONS

SPARC: Spitzer Photometry and Accurate Rotation Curves database

MSP: Millisecond Pulsar

UDG: Ultra-Diffuse Galaxy

PTA: Pulsar Timing Array

GR: General Relativity

QM: Quantum Mechanics

Appendix A: Historical Context

DATA AND CODE AVAILABILITY

All analysis scripts (Python, PGFPlots/TikZ) used to generate the figures and numerical results are publicly available at <https://github.com/jonwashburn/lnal-gravity>. The galaxy rotation curves originate from the SPARC database[8].

The notion that reality processes information traces from Pythagoras ("all is number") through Leibniz (reality as computation) to Wheeler's "it from bit." Key milestones include Szilard (1929) connecting information and thermodynamics, Shannon (1948) founding information theory, Bekenstein (1973) proposing black hole entropy, and recent emergent gravity programs. The bandwidth framework extends this tradition by making information constraints primary rather than emergent.

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