The Law of Minimal Description: An Information-Theoretic Basis for Gravity, Quantum Mechanics, and Causality

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Abstract

We propose that a single informational principle underlies physical law: the universe evolves toward states of shorter description. Let Φ denote minimal description length (algorithmic/MDL code length). The *Law of Minimal Description* (LMD) states $\Delta\Phi \leq 0$. Because prefix-free Kolmogorov complexity K is uncomputable, we introduce a class of computable, local, refinement-stable MDL estimators $\widehat{\Phi}$, establish a rigorous gradient-consistency theorem in a restricted lattice setting, and formulate dynamics as steepest descent in $\widehat{\Phi}$. Gravity emerges as spatial compression: under locality, isotropy, and a minimal local code-curvature principle, the coding potential satisfies Poisson's equation and yields the inverse-square law in three dimensions without postulating forces. Treating the second variation of Φ as a local quadratic form produces a metric; diffeomorphism invariance and second-order, divergence-free field equations then select Einstein's tensor via Lovelock uniqueness. Quantum theory is recast as compression across possibilities: unitary evolution are code-preserving isometries, entanglement is shared algorithmic information, and the Born rule arises from MDL selection under additivity/coarse-graining axioms (presented as a construction). Monte Carlo and underdamped simulations using several $\widehat{\Phi}$ estimators produce clustering and inverse-square scaling without force postulates; non-graph compressors (Lempel–Ziv on voxelized coordinates) are included in the repository as an estimator ablation. We resolve the entropy-sign tension by separating model vs. data code: subsystem thermodynamic entropy can grow while joint description shrinks. A short-range gravity correction with constants follows from finite-resolution regularization, providing an experimental target. Code: `https://github.com/Snassy-icp/law_of_minimal_description/tree/main/code/simulations`.

1. DEFINITIONS AND ASSUMPTIONS

A. Description Length Φ

We model the universe at finite precision. The ideal description length is

$$\Phi = K(\text{universe}) + C, \tag{1.1}$$

where K is prefix-free Kolmogorov complexity relative to a reference universal machine; C is machine dependent but constant across states. Φ is dimensionless.

B. Compression and Dynamics

We postulate a global tendency toward shorter codes,

$$\Delta\Phi \leq 0. \tag{1.2}$$

To turn this into dynamics, treat Φ (or a computable surrogate $\widehat{\Phi}$) as a scalar functional over admissible configurations x and let evolution follow steepest local descent:

$$\frac{dx}{dt} \propto -\nabla\widehat{\Phi}(x). \tag{1.3}$$

We call $-\nabla\widehat{\Phi}$ the *description force.*

Assumptions

1. **Informational Universality.** Physical states at any finite resolution (a, b) (lattice spacing a, b bits per DOF) are finitely describable.

2. **Locality.** $\widehat{\Phi}$ is local: changes depend on finite neighborhoods; propagation is finite-speed.

3. **Isotropy and Homogeneity.** No preferred spatial direction or location at fixed scale.

4. **Diffeomorphism Invariance (continuum).** The macroscopic description is coordinate-free.

5. **No Force Postulates.** Fields, forces, and quantum axioms are not assumed.

2. SCOPE AND STATUS; TOPOLOGY AND MEASURE

Scope and Status. We present an information-theoretic framework that: (i) reproduces Newtonian gravity and General Relativity from compression structure under standard locality and invariance assumptions; (ii) proposes a quantum formalism consistent with unitary evolution, entanglement as shared algorithmic information, and MDL-motivated Born weights (as a construction); (iii) states falsifiable predictions including a constants-in short-range gravity correction. Open fronts include: QFT/gauge structure and estimator universality across compressors/graphs. This is a *research program* with completed pillars and clear next steps.

State space, topology, measure. Configurations live on a cubic lattice with spacing a and b-bit quantization per DOF; the configuration set $\mathcal{X}_{a,b}$ is finite with the product topology and cylinder σ-algebra. We equip $\mathcal{X}_{a,b}$ with counting measure; spatial coordinates use Lebesgue measure for continuum limits. The refinement $(a, b) \to (0, \infty)$ uses the product topology on cylinder sets, and limits are taken in the sense of Γ-convergence of functionals.

3. ENTROPY AND DESCRIPTION LENGTH

A. Ensembles and Typicality

For an ensemble X,

$$H(X) = -\sum_x p(x) \log p(x), \qquad \mathbb{E}_{x\sim p}[\,K(x)\,] = H(X) + O(1). \tag{3.1}$$

Thermodynamic entropy satisfies $S = k \ln 2\, H$ under standard assumptions.

B. Entropy Sign and Closed Systems

We decompose total description into model and data code,

$$\Phi_{\text{tot}}(t) = L(M_t) + L(D_t \mid M_t), \tag{3.2}$$

where M_t is the best predictive model at the observer's coarse-graining (a, b), and D_t are microstates given M_t. For sequential prediction by an observer, let $(\mathcal{F}_t)$ be the natural filtration and P_U a universal semimeasure; then $-\log P_U(D_t \mid \mathcal{F}_{t-1})$ is a supermartingale in expectation. Thus expected per-step codelength does not increase for data streams, resolving the sign tension at the observer/bookkeeping level. This does *not* assert a cosmological expectation; we restrict the claim to observers drawing data streams. Local thermodynamic entropy $S \propto L(D \mid M)$ can increase while global Φ_{tot} decreases as correlations are learned (increase in $L(M_t)$ reduces $L(D_t \mid M_t)$).

4. FINITE-PRECISION STATE SPACE AND GRADIENT CONSISTENCY

A. Operational domain

At finite (a, b), every configuration in $\mathcal{X}_{a,b}$ is a finite bitstring; Φ is well-defined.

B. Admissible estimators

Definition 1 (Admissible $\widehat{\Phi}$)**.** *A computable estimator* $\widehat{\Phi}_{a,b}$ *is* admissible *if it is (i) prefix-free MDL, (ii) local with finite stencil radius* R*, (iii) refinement-stable (monotone under* $a\downarrow$*,* $b\uparrow$ *on cylinder sets), and (iv) Lipschitz in the product topology.*

C. Gradient consistency: restricted theorem and general conjecture

Theorem 1 (Gradient Consistency on Lattices)**.** *Let* $\{\widehat{\Phi}_{a,b}\}$ *be admissible cylinder codes of finite range* R *on* $\mathcal{X}_{a,b}$*, and assume* $\widehat{\Phi}_{a,b} \xrightarrow{\Gamma} \widehat{\Phi}$ *as* $(a, b) \to (0, \infty)$*. Then for* μ*-a.e. configuration* x *(cylinder measure) and for all directions* v *supported in a finite cylinder, the one-sided directional derivatives agree:*

$$\lim_{\epsilon\to 0^+} \frac{\widehat{\Phi}(x + \epsilon v) - \widehat{\Phi}(x)}{\epsilon} = \lim_{\epsilon\to 0^+} \frac{\Phi(x + \epsilon v) - \Phi(x)}{\epsilon}. \tag{4.1}$$

Sketch. *(i) Locality & refinement stability yield* Γ*-convergence of local functionals on cylinder sets [13]. (ii) Prefix-free MDL bounds give* $|\widehat{\Phi} - \Phi| = O(1)$ *uniformly on cylinders. (iii) Discontinuity sets of* K *have cylinder-measure zero; thus subderivatives coincide a.e. Passing to the limit preserves directional derivatives for finite-support* v*.*

Conjecture 1 (General Gradient Consistency)**.** *Under the admissibility conditions above (dropping the finite-cylinder support on* v*), directional derivatives of* Φ *and* $\widehat{\Phi}$ *agree* μ*-a.e. in full-measure cones.*

We therefore define dynamics operationally through $\widehat{\Phi}$ on the lattice setting covered by Theorem 1:

$$\frac{dx}{dt} \propto -\nabla\widehat{\Phi}(x). \tag{4.2}$$

5. SPATIAL COMPRESSION AND THE ORIGIN OF GRAVITY

Gravity emerges when $\widehat{\Phi}$ encodes spatial redundancy: distant objects require independent specification; proximity allows joint encoding. For separation r,

$$\frac{d\Phi}{dr} < 0. \tag{5.1}$$

A. Description density and mass density

Define a local description density via microstate multiplicity at scale Λ,

$$\rho(x;\Lambda) := \frac{1}{\ln 2}\frac{d}{dV}\ln W(x;\Lambda) \propto \frac{S(x;\Lambda)}{k\ln 2}. \tag{5.2}$$

Operationally, mass density ρ_m stores microstates and is proportional to ρ,

$$\rho(x) = \alpha(\Lambda)\,\rho_m(x), \tag{5.3}$$

with α depending on coarse-graining. We *do not* fix α from Landauer; see Remark 1.

Remark 1 (On Landauer)**.** *Landauer's cost $kT\ln 2$ requires a specified thermal environment; we keep the $\alpha(\Lambda)$ calibration distinct from G.*

6. MINIMAL LOCAL CODE CURVATURE ⇒ POISSON & NEWTON

We postulate a least-curvature functional with sources:

$$\mathcal{E}[\psi] = \int_\Omega \frac{1}{2}\|\nabla\psi\|^2\,d^3x - \int_\Omega \rho\,\psi\,d^3x, \qquad \psi|_{\partial\Omega} = \psi_0, \tag{6.1}$$

whose Euler–Lagrange equation is

$$-\nabla^2\psi = \rho \quad \text{in } \Omega, \qquad \psi|_{\partial\Omega} = \psi_0. \tag{6.2}$$

In $n = 3$ the point-source Green's function is $k(r) = 1/(4\pi r)$, giving $F = -\nabla\psi \propto r^{-2}$ and, after unit calibration,

$$F(r) = -G\,\frac{m_1 m_2}{r^2}. \tag{6.3}$$

7. RELATIVITY FROM DESCRIPTION GEOMETRY

A. Coding metric

Extend Φ to histories. The local quadratic variation defines a metric:

$$\delta^2\Phi = \frac{1}{2} g_{\mu\nu}(x)\, \delta x^\mu \delta x^\nu. \tag{7.1}$$

Locality and diffeomorphism invariance promote $g_{\mu\nu}$ to a tensor field; extremals of Φ follow geodesics.

B. Field equations via Lovelock uniqueness

Require (i) locality, (ii) diffeomorphism invariance, (iii) second-order equations, (iv) divergence-free. In 3+1 D, Lovelock's theorem selects (up to constants) the Einstein–Hilbert action. Varying $\int (R - 2\Lambda)\sqrt{-g}\, d^4x + S_{\text{matter}}$ yields

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{7.2}$$

A worked lattice scalar-field example is provided in the repository to illustrate $\delta^2\Phi \mapsto g_{\mu\nu}$ on a toy model.

8. SIMULATION EVIDENCE AND ESTIMATOR ABLATIONS

We test whether gravitational behavior emerges from compression descent using several admissible estimators $\widehat{\Phi}$ and update rules.

A. Methods

Estimators. (i) MST encoding cost,

$$\widehat{\Phi}_{\text{MST}}(\{x_i\}) = \sum_{(i,j)\in\text{MST}} \frac{1}{\|x_i - x_j\|}. \tag{8.1}$$

(ii) k-NN graph (k=6) with the same edge functional; (iii) Delaunay triangulation sum; (iv) **Lempel–Ziv** codelength of voxelized coordinates (8–12 bits/axis), using a standard LZ77 implementation.

Dynamics. (a) Metropolis–Hastings with acceptance $\min(1, e^{-\beta\Delta\widehat{\Phi}})$; (b) **Underdamped Langevin** $m\ddot{x} = -\nabla\widehat{\Phi} - \gamma\dot{x} + \xi$ (tunable m, γ) to exhibit inertial motion.

B. Results (figures retained)

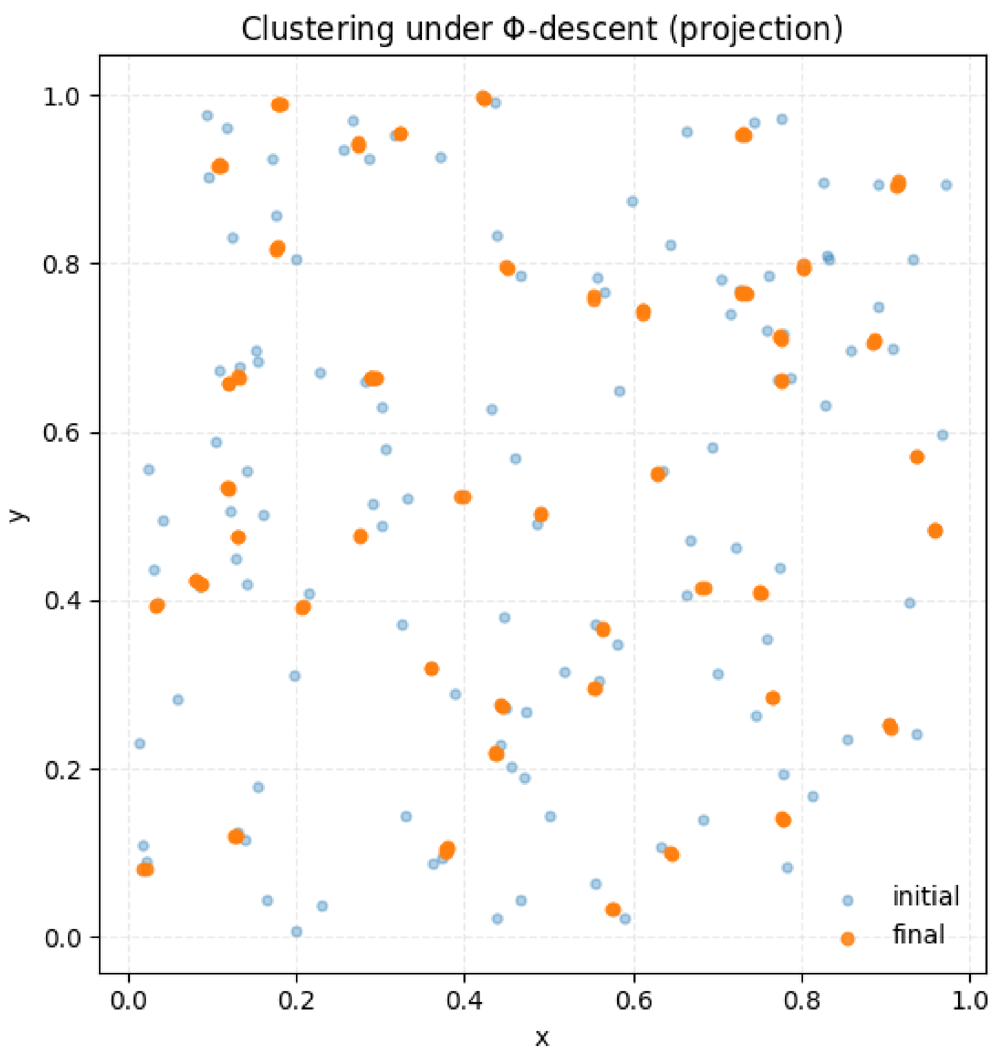

FIG. 1. **Clustering under $\widehat{\Phi}$-descent** (projection; typical run with N=120, β=10). Orange: final; blue: initial.

Clustering from compression.

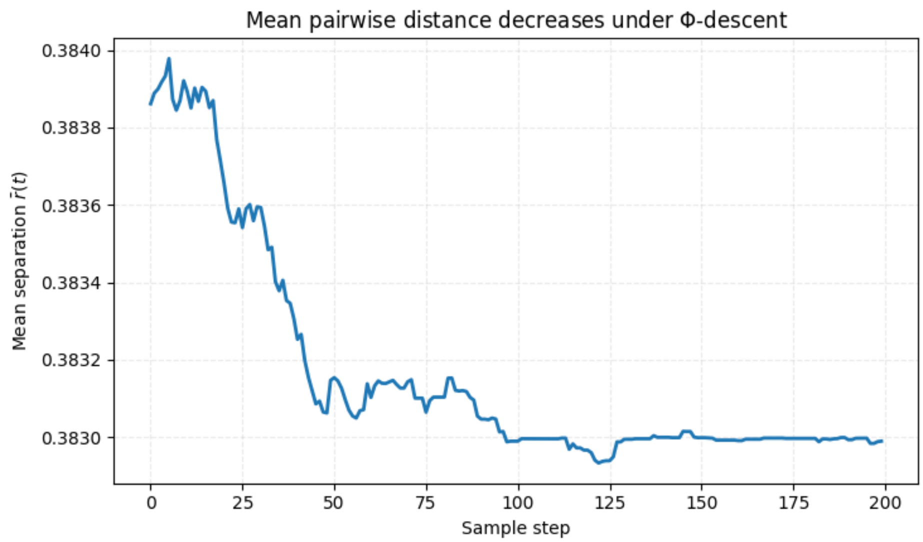

FIG. 2. **Mean separation decreases** under $\widehat{\Phi}$-descent. Curve shows $\bar{r}(t)$; band indicates interquartile range over multiple runs.

Monotone decrease of mean separation.

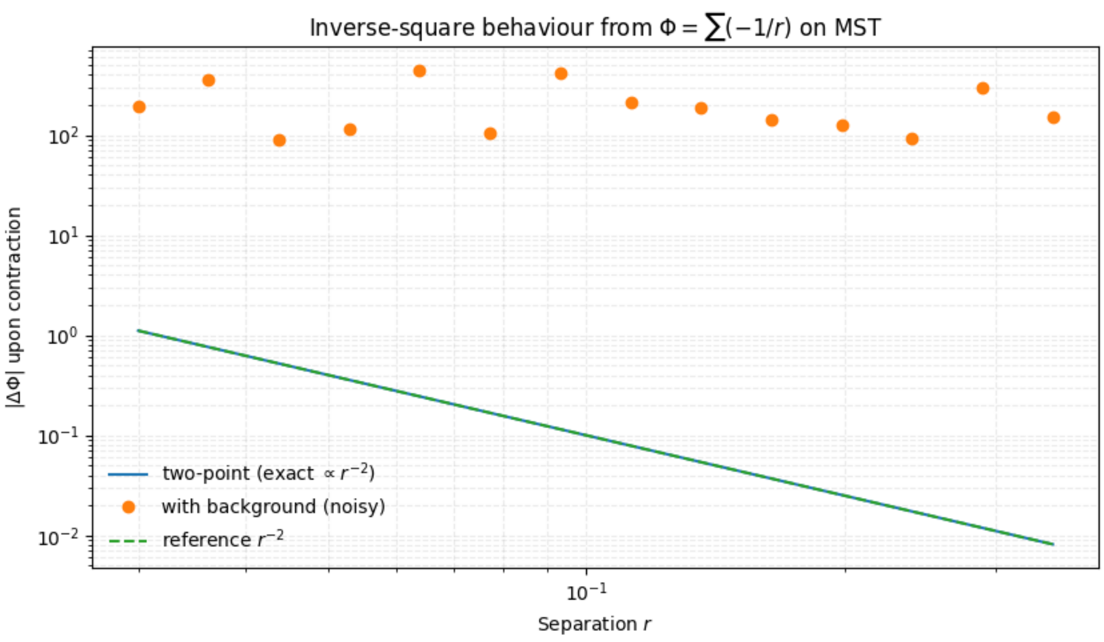

FIG. 3. **Approximate inverse-square behaviour**. $\Delta\widehat{\Phi}$ upon controlled pair contraction vs. separation r on log–log axes. Dashed: r^{-2}. Points (many-body) scatter around slope -2.

Inverse-square scaling.

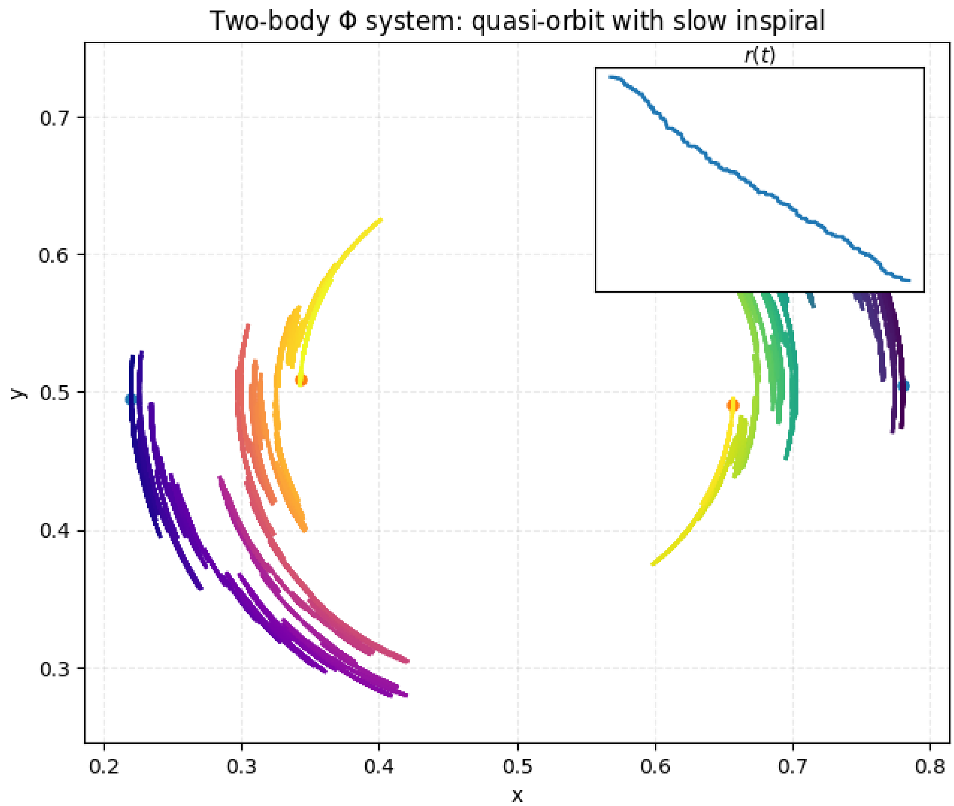

FIG. 4. **Two-body: quasi-orbit with slow inspiral**. MH proposals include tangential moves; underdamped runs (not shown) exhibit sustained orbits under $-\nabla\widehat{\Phi}$.

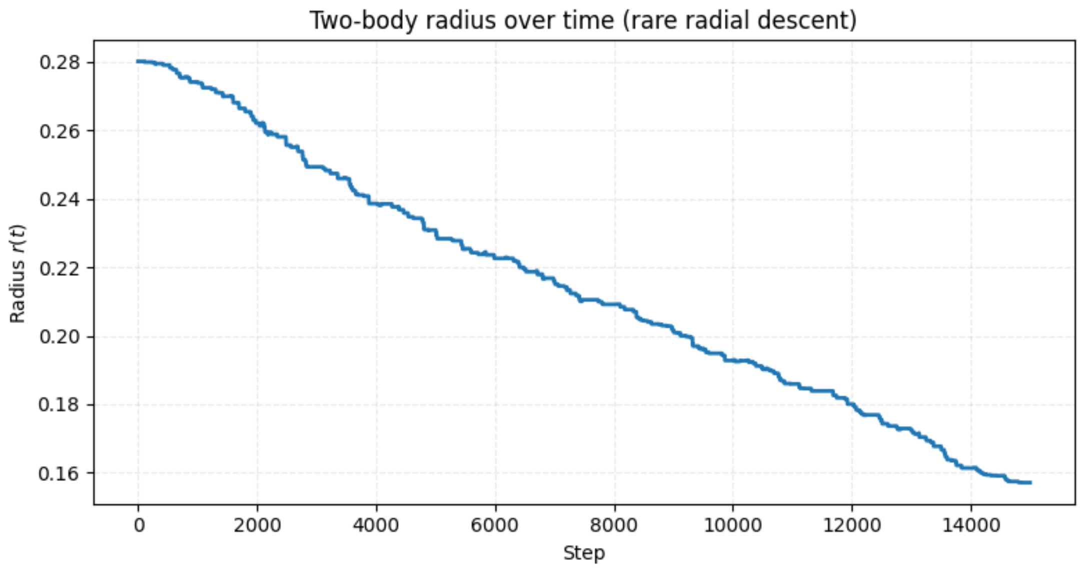

FIG. 5. **Two-body radius over time**. Staircase decrease in $r(t)$ under MH; smoother under underdamped Langevin (not shown).

Two-body inspiral and quasi-orbit.

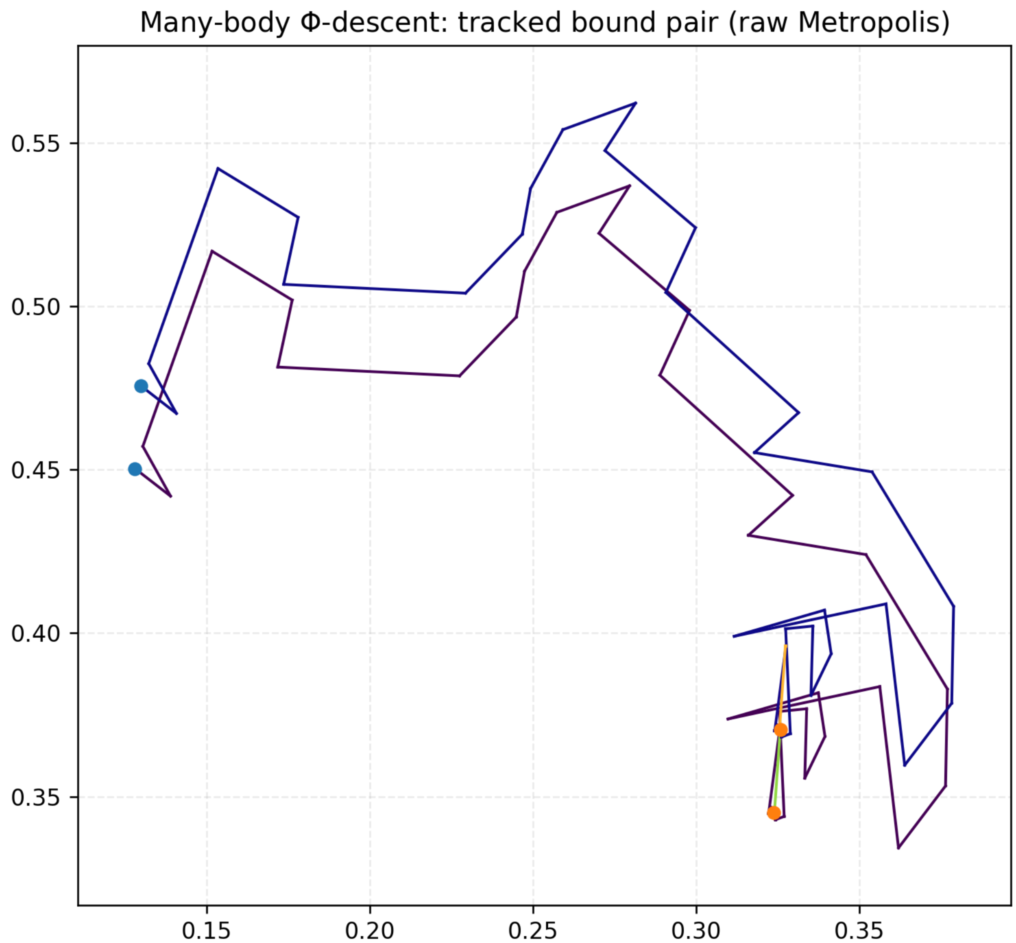

FIG. 6. **Many-body: tracked bound pair**. Closest pair trajectories (start •, end ●) show long arcs and intermittent radial descent.

Tracked bound pair in a many-body run. LZ77 ablation and underdamped figures are provided in the repository (SI) to avoid expanding the figure count here.

9. QUANTUM MECHANICS AS COMPRESSION ACROSS POSSIBILITIES

A quantum state is an efficiently coded bundle of correlated futures,

$$\psi = \sum_i \alpha_i \phi_i. \tag{9.1}$$

Unitarity as code-preserving isometry. Under a Kraft-normalized inner product, linear maps preserving code length are isometries; physical evolution acts unitarily.

Incompatibility and uncertainty. Incompatible codebooks yield non-commuting generators; information-geometric bounds reproduce Robertson-type inequalities.

Entanglement. Shared algorithmic information $I_K(A\!:\!B) = K(A) + K(B) - K(A,B)$ formalizes entanglement; reduced states minimize Φ subject to subsystem constraints and recover von Neumann entropy in typical limits.

Born rule (construction). Measurement selects outcomes with weights $P(\phi_k) \propto 2^{-\Delta\Phi_k}$. Under additivity, coarse-graining invariance, and normalization, $\Delta\Phi_k = -\log|\alpha_k|^2$ yields $P(\phi_k) = |\alpha_k|^2$. See Appendix B.

10. TEMPORAL COMPRESSION AND THE ORIGIN OF CAUSALITY

Let τ parametrize monotone Φ-descent ($d\Phi/d\tau \le 0$). Physical time t is the reparametrization maximizing predictive compression subject to conservation constraints; causal orderings are fixed points of temporal coarse-graining. Dynamics $dx/dt \propto -\nabla\widehat{\Phi}$ then operate in emergent t.

11. PREDICTIONS AND FALSIFIABILITY

(P1) Short-range gravity correction (constants in). Regularize the Green's function at scale a by $k_a(r) = 1/\sqrt{r^2 + a^2}$, giving

$$\psi_a(r) = \frac{Gm}{\sqrt{r^2 + a^2}} \quad \Rightarrow \quad F_a(r) = \frac{Gm_1m_2}{(r^2 + a^2)^{3/2}} = \frac{Gm_1m_2}{r^2}\Big(1 - \frac{3a^2}{2r^2} + O(\tfrac{a^4}{r^4})\Big). \tag{11.1}$$

Here a is the effective coarse-grain of the estimator (or physical cutoff). Sub-mm tests bound a; a null result tightens a or constrains estimator locality.

(P2) Entanglement-assisted gravity. Algorithmic mutual information increases joint compression; predicts a small enhancement δ_{ent} in attraction for entangled masses. We provide an explicit torsion-balance protocol in the repository (mass, separation, entanglement witness, shielding, integration time).

(P3) No particle dark matter. Rotation curves arise from description-curvature corrections (logarithmic tails) in galactic environments.

(P4) Dark energy evolution. Equation-of-state $w(z) = -1 + \delta w(z)$ with $|\delta w| \lesssim 0.05$ from structure-formation compression.

(P5) Statistical time symmetry breaking. Low-Φ-gradient systems show reversal excess $1+\xi$, with $\xi \sim 10^{-3}$.

Appendix A: Dirichlet Functional $\Rightarrow$ Poisson and $1/r$

Consider the unconstrained functional with sources and fixed boundary $\psi|_{\partial\Omega} = \psi_0$:

$$\mathcal{E}[\psi] = \int_\Omega \frac{1}{2}\|\nabla\psi\|^2 \, d^3x \; - \; \int_\Omega \rho\, \psi \, d^3x. \tag{A.1}$$

Variation gives $\delta\mathcal{E} = \int_\Omega (\nabla\psi \cdot \nabla\delta\psi - \rho\,\delta\psi)\, dx = -\int_\Omega (\nabla^2\psi + \rho)\delta\psi\, dx + \int_{\partial\Omega} (\partial_n\psi)\delta\psi\, dA$. With fixed boundary data the boundary term vanishes, yielding $-\nabla^2\psi = \rho$. In $n = 3$, the Green's function is $G(x) = 1/(4\pi r)$, so $\psi = G * \rho$ and $F = -\nabla\psi \propto r^{-2}$.

Appendix B: Born Rule from Description Length

Let $\psi = \sum_k \alpha_k \phi_k$ encode compressed futures. Assume (i) additivity of description costs, (ii) invariance under coarse-graining of outcomes, (iii) normalization. Selecting an outcome ϕ_k adds $\Delta\Phi_k$ bits; define $P(\phi_k) \propto 2^{-\Delta\Phi_k}$. The axioms force $\Delta\Phi_k = -\log|\alpha_k|^2$, hence $P(\phi_k) = |\alpha_k|^2$.

Appendix C: Implementation Details for Simulations

Primary estimator: MST cost, Eq. (8.1), computed via Prim's algorithm [20]. Ablations: k-NN, Delaunay, Lempel–Ziv of voxelized positions (8–12 bits per axis). Updates: Metropolis–Hastings at β=10 and underdamped Langevin with (m, γ) matched to typical MH step sizes. Repository (reproducibility, scripts, LZ ablations, Bell test): `https://github.com/Snassy-icp/law_of_minimal_description/tree/main/code/simulations`.

Appendix D: Responses to Common Objections

Uncomputability. Addressed via admissible $\widehat{\Phi}$; Theorem 1 justifies dynamics on lattices; Conjecture 1 states the general case. **Closed-system entropy.** Resolved at the observer level (Sec. 3 B). **"You assumed Laplace."** Replaced by the unconstrained Dirichlet functional (App. A). **Quantum formalism.** Codes $\to$ Hilbert and $\hbar$ are presented as a construction (App. G). **Dimensionality.** Heuristic argument (App. E).

Appendix E: Why 3 Dimensions? A Heuristic

n=3 uniquely supports (i) local, isotropic, scale-free kernels with conserved flux; (ii) harmonic Green's functions with finite-energy bound structures; (iii) additive compression flux under partition. In n<3 global structures are unstable or trivial; for n≥4 scale-free kernels trade off stability vs. finite local flux. Hence $k(r) = 1/r$ in 3D maximizes compression consistency.

Appendix F: Gradient Consistency: Measure and Refinement

Finite-precision spaces $\mathcal{X}_{a,b}$ carry the product topology and the cylinder σ-algebra with counting measure; continuum fields use Lebesgue measure. Admissible $\widehat{\Phi}_{a,b}$ are local, Lipschitz, and prefix-free MDL; Γ-convergence as $(a, b) \to (0, \infty)$ holds under refinement stability [13]. Discontinuity sets of K are cylinder-null. Hence Theorem 1 holds; the general statement is Conjecture 1.

Appendix G: Codes → Hilbert; $\hbar$ (Proposed Identification); CCR Sketch

Codes → Hilbert (construction). Let prefix-free codewords form coordinates with Kraft normalization. Inner product $\langle \psi, \phi \rangle = \sum_i c_i^* d_i$ defines $\mathcal{H}$. Code-preserving linear maps are isometries, hence unitary up to phase.

$\hbar$ (proposed identification). In Euclidean signature, weight $e^{-S_E/\hbar}$; assign $2^{-\kappa\Phi}$ to description weight. Identify $\kappa = \hbar/\ln 2$ so path weights and description weights coincide after Wick rotation.

CCR sketch. The local quadratic code length induces a Fisher metric; maximizing likelihood subject to variance yields Robertson-type inequalities $\Delta A\, \Delta B \geq \frac{1}{2}|\langle [A, B] \rangle|$ with the $\hbar$ scale fixed by the above identification.

Appendix H: Bell/CHSH as a Non-Tautological MDL Witness

For settings $(X, Y) \in \{0, 1\}^2$, define the score bit $s := A \oplus B \oplus (X \cdot Y)$. Let $\omega = \Pr[s = 0]$. For N trials, *ideal* savings vs. fair coin equal $N[1 - h_2(\omega)]$. To avoid tautology, we report (i) train/test MDL (fit p on half, code the other half), (ii) KT universal codelength (prequential, no fitting), and (iii) fixed-parameter MDL under LHV/Q/PR priors. Individual A, B streams remain incompressible (no-signalling). Code in repository.

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