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Article

The Information Lattice Model: Entropic Permeability, Emergent Gravity, and the Holographic Structure of the Brane–Bulk Interface

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Abstract

We introduce the Information Lattice Model (ILM), a theoretical framework in the braneworld tradition in which the brane–bulk system is represented as a stratified informational graph whose inter-layer link capacity is governed by a permeability function $\Pi(y) = 1 + \varepsilon \exp(-\lambda|y|/\ell_{\text{Pl}})$. The dimensionless parameter ε is identified with the ratio of bulk-to-brane entanglement entropy flux via the Ryu–Takayanagi formula, connecting the model to the Bekenstein–Hawking entropy bound and the AdS/CFT correspondence. This identification is presented as a conceptual proposal ahead of full formal derivation, in the tradition of framework papers from Kaluza–Klein to Verlinde's entropic gravity. The permeability function modifies the Randall–Sundrum warp factor, introducing an additional entropic dilution of the effective gravitational coupling beyond geometric warping alone. Within this framework, the ILM suggests a unified phenomenological perspective on the hierarchy problem, the black hole information paradox, and the possible role of sub-brane entropic degrees of freedom as an effective dark matter component. The model also predicts frequency-dependent corrections to gravitational-wave propagation arising from bulk-mediated entropic coupling. The model generates two testable predictions. The primary prediction is a positive correlation between the dimensionless radiated energy excess ΔA and total merger mass M_{total} in binary black hole systems, arising from the mass dependence of the integrated horizon permeability. Under a quadratic area-law scaling, ΔA may approach $\sim 10^{-3}$ for $M_{\text{total}} \sim 10^6 M_{\odot}$ events accessible to LISA, while the sign and slope of the ΔA – M_{total} correlation is independently falsifiable via stacked regression analysis of the GWTC-3 catalogue; a full Bayesian treatment will be presented in future work. The secondary prediction is a non-linear deviation in quantum decoherence rates near lattice saturation, potentially testable with ion traps, superconducting qubits, and Bose–Einstein condensates.

Keywords: emergent gravity; braneworld physics; holographic principle; entropic gravity; hierarchy problem; quantum decoherence; gravitational waves; dark matter; AdS/CFT; Randall–Sundrum model

1. Introduction

The hierarchy problem—the disparity of approximately 10^{40} between the gravitational and electroweak force scales—remains one of the most persistent unresolved challenges in theoretical physics. Braneworld scenarios pioneered by Randall and Sundrum address this problem geometrically by embedding our observable 4-dimensional universe in a higher-dimensional bulk, with an exponential warp factor diluting gravitational strength on the visible brane. While geometrically elegant, this approach does not address a deeper question: why should gravity, alone among the fundamental interactions, propagate freely across extra dimensions?

Bekenstein and Hawking demonstrated that black holes carry entropy proportional to horizon area, $S_{\text{BH}} = A/4G$, establishing a deep connection between gravity, thermodynamics, and information. Verlinde extended this insight by proposing that gravity is an entropic force emerging

from holographic encoding of information on surfaces. The AdS/CFT correspondence further established that bulk gravitational dynamics are fully equivalent to boundary quantum information theories, while Causal Dynamical Triangulations (CDT) demonstrate that smooth spacetime geometry can emerge dynamically from discrete quantum-informational structures.

Such convergence suggests a unified paradigm in which gravity emerges not from geometric propagation alone, but from the continuous re-indexing of information and entropy across a multi-layered lattice spanning the brane–bulk boundary. We develop this picture formally through the **Information Lattice Model (ILM)**, a framework in which the brane–bulk system is represented as a multi-layered informational lattice with tunable inter-layer permeability. The key innovation is the identification of the permeability parameter ε with the ratio of bulk-to-brane entanglement entropy flux, grounding the ILM in the Bekenstein–Hawking entropy calculus and providing a unified mechanism for gravitational weakness, black hole information conservation, and dark matter.

2. The Information Lattice Model

2.1. Lattice Architecture

The ILM represents the brane–bulk system as a directed graph $\Gamma = (V, E)$, where nodes $v \in V$ represent localised informational degrees of freedom—formally, entanglement entropy densities $s(\mathbf{x}) = dS_{\text{ent}}/dV$ at spacetime position \mathbf{x} —and directed edges $e \in E$ encode the flux of information between nodes. The graph is stratified into layers $L_N, L_{N+1}, \dots, L_{N+k}$, where L_N corresponds to the observable 4D brane and higher layers constitute the bulk. Non-gravitational Standard Model fields are confined to L_N ; gravitational and informational effects propagate across layer boundaries via tunable inter-layer links.

The inter-layer link capacity is governed by the permeability function $\Pi(y)$, where y is the coordinate transverse to the brane. We modify the Randall–Sundrum metric as:

$$ds^2 = e^{-2k|y|\cdot\Pi(y)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2,$$

with permeability function:

$$\Pi(y) = 1 + \varepsilon \exp\left(-\frac{\lambda|y|}{\ell_{\text{Pl}}}\right),$$

where $\varepsilon \ll 1$ is a dimensionless permeability parameter, $\lambda > 0$ is a dimensionless decay constant governing the range of bulk–brane coupling, and $\ell_{\text{Pl}} = \sqrt{\hbar G/c^3} \approx 1.616 \times 10^{-35}$ m is the Planck length. In the limit $\varepsilon \rightarrow 0$, Equations (2.1)–(2.2) recover the standard Randall–Sundrum metric. For finite ε , the enhancement $\Pi(y) > 1$ increases the effective warp factor, producing additional dilution of gravitational strength beyond the RS prediction.

2.2. Entropic Identification of the Permeability Parameter

The central theoretical step of the ILM is the identification of ε with a dimensionless ratio of entropic fluxes across the brane–bulk interface. Consider the entanglement entropy S_{ent} of a region Ω on the brane with respect to the bulk degrees of freedom. By the Ryu–Takayanagi formula :

$$S_{\text{ent}}(\Omega) = \frac{\text{Area}(\gamma_\Omega)}{4G_N},$$

where γ_Ω is the minimal surface in the bulk anchored to $\partial\Omega$. The bulk-to-brane entropic flux Φ_S is:

$$\Phi_S = \frac{1}{A} \frac{dS_{\text{ent}}}{dt},$$

with A the area of the brane region $\partial\Omega$. The Hawking entropy production rate of a reference black hole of mass M on the brane is $\dot{S}_{\text{BH}} = 8\pi G_N k_B M / \hbar$.

We identify ε as:

$$\varepsilon \equiv \frac{\dot{\Phi}_S}{\dot{S}_{\text{BH}}} \cdot \frac{G_N}{c} = \frac{1}{A} \frac{dS_{\text{ent}}}{dt} \cdot \frac{\hbar}{8\pi G_N k_B M} \cdot \frac{G_N}{c},$$

where the factor G_N/c ensures dimensional consistency.¹ This gives $0 \leq \varepsilon < 1$, consistent with $\varepsilon \ll 1$; $\varepsilon = 0$ recovers the standard RS limit. The observational bound from GW170817 gravitational wave speed measurements constrains $\varepsilon < 1.01 \times 10^{-15}$.

2.3. Gravitational Waves as Entropic Lattice Perturbations

In the ILM, gravitational waves are reinterpreted as propagating perturbations of the entropic flux field. For a plane-wave perturbation $h_{\mu\nu}(\mathbf{x}, t)$, the ILM predicts a modified dispersion relation:

$$\omega^2 = k^2 c^2 \left[1 - \varepsilon f\left(\frac{\omega}{\omega_{\text{Pl}}}\right) \right] + \sum_n \frac{m_n^2 c^4}{\hbar^2},$$

where $f(\omega/\omega_{\text{Pl}})$ encodes the frequency-dependent coupling to bulk lattice modes (to be derived from the full lattice spectrum in future work, see Section 6), $\omega_{\text{Pl}} = c^2/\ell_{\text{Pl}}$ is the Planck angular frequency, and $\{m_n\}$ is the Kaluza–Klein tower of bulk graviton masses. For $\varepsilon \ll 1$ the correction is negligible at current detector sensitivities but accumulates at high frequency and high total mass, motivating Prediction I in Section 5.

3. Physical Consequences of Entropic Trans-Layer Permeability

3.1. Partial Resolution of the Hierarchy Problem

In the ILM, the enhancement $\Pi(y) > 1$ supplements the RS warp factor with an entropic dilution mechanism. The effective 4D Planck mass receives the correction:

$$M_{\text{Pl,eff}}^2 = M_{\text{Pl}*}^2 \frac{\int_0^\infty e^{-2k|y| \Pi(y)} dy}{\int_0^\infty e^{-2k|y|} dy}.$$

Expanding to first order in $\varepsilon \ll 1$:

$$M_{\text{Pl,eff}}^2 \approx M_{\text{Pl}*}^2 \left[1 - \frac{2k \varepsilon}{2k + \lambda/\ell_{\text{Pl}}} \right],$$

where the integral $\int_0^\infty e^{-2k|y|} e^{-\lambda|y|/\ell_{\text{Pl}}} dy = (2k + \lambda/\ell_{\text{Pl}})^{-1}$ is evaluated exactly. In the regime $\lambda/\ell_{\text{Pl}} \gg 2k$ (short-range bulk coupling):

$$G_{\text{eff}} \approx G_N \left(1 + \frac{\varepsilon \ell_{\text{Pl}}}{\lambda} + \dots \right)^{-1},$$

so that the effective gravitational coupling is suppressed by entropic trans-layer dilution independently of the RS warp factor. The hierarchy $M_{\text{Pl}}/M_{\text{EW}} \sim 10^{16}$ thus receives contributions from both geometric warping and entropic permeability, each acting independently and without mutual fine-tuning.

¹ $[\Phi_S] = \text{entropy} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$; $[\dot{S}_{\text{BH}}] = \text{entropy} \cdot \text{s}^{-1}$; $[\Phi_S/\dot{S}_{\text{BH}}] = \text{m}^{-2} \cdot \text{s}$; and $[G_N/c] = \text{m}^2 \cdot \text{s}^{-1} \cdot \text{kg}^{-1} \cdot \text{kg} = \text{m}^2 \cdot \text{s}^{-1}$, rendering ε dimensionless. A complete derivation of ε from a variational ILM action remains a future priority (Section 6).

3.2. Black Hole Information Paradox

In the ILM, black holes represent regions of maximum local entropic flux: nodes where $\varepsilon(\mathbf{x}) \rightarrow \varepsilon_{\max}$ and the brane–bulk interface becomes maximally permeable. Information falling into a black hole is transferred to bulk lattice layers via the enhanced permeability at the horizon, rather than being destroyed. The Hawking radiation observed on the brane is the brane-projected component of a unitarity-preserving inter-layer information transfer process.

This picture is formally consistent with the replica wormhole resolution of the information paradox, in which the Page curve is recovered through replica wormhole geometries. In the ILM, the global entropy bound $S \leq A/4G$ is enforced across all lattice layers, and $\Pi(\mathbf{y}) > 1$ ensures no strict separation between brane and bulk degrees of freedom—precisely the condition required by the holography of information principle.

3.3. Dark Matter as Sub-Brane Entropic Density

The ILM provides a natural reinterpretation of dark matter without invoking new particle species. Ordinary matter fields on the brane represent entropic densities that have undergone topological collapse to a 4D configuration on L_N . Dark matter is reinterpreted as entropic density residing in sub-brane lattice layers $(L_{N-1}, L_{N-2}, \dots)$ that has not undergone topological collapse.

Such sub-brane entropic density couples gravitationally to the brane through $\Pi(\mathbf{y})$, exerting gravitational influence on brane matter without participating in electromagnetic or strong interactions. The predicted spatial distribution follows the lattice information gradient, naturally producing the observed baryonic Tully–Fisher scaling relation without invoking modified gravity.

4. Relationship to Established Frameworks

4.1. Causal Dynamical Triangulations

CDT is a non-perturbative approach to quantum gravity in which smooth spacetime emerges from a sum over discrete causal simplicial geometries. The ILM is formally compatible with CDT: nodes $v \in V$ can be identified with CDT simplices, directed edges $e \in E$ encode the causal connectivity of the triangulation, and $\Pi(\mathbf{y})$ corresponds to the amplitude assigned to inter-layer simplicial connections in the CDT path integral. The CDT prediction of dimensional reduction to ~ 2 dimensions at Planck scales corresponds in the ILM to the limit $\varepsilon \rightarrow 1$, where the brane–bulk distinction dissolves and the effective dimensionality of the information network collapses to the bulk minimum.

4.2. AdS/CFT Correspondence

In the AdS/CFT correspondence, gravitational dynamics in $(d + 1)$ -dimensional Anti-de Sitter space are equivalent to a CFT on the d -dimensional boundary. In the ILM, L_N corresponds to the CFT boundary, bulk layers L_{N+k} to the AdS interior, and $\Pi(\mathbf{y})$ modulates the holographic encoding of bulk information onto the boundary. The Ryu–Takayanagi formula (Equation 2.3) grounds the entropic identification of ε in Equation (2.5): for $\Pi(\mathbf{y}) > 1$, holographic encoding becomes imperfect and a fraction $\sim \varepsilon$ of bulk information leaks through the interface, producing the gravitational weakness observed on the brane.

4.3. Verlinde’s Entropic Gravity

Verlinde’s entropic gravity derives Newton’s law from holographic screen thermodynamics, treating gravity as $F = T \partial S / \partial x$. In the ILM, the holographic screen corresponds to the brane–bulk interface, and $\Pi(\mathbf{y})$ modulates the effective screen temperature, producing position-dependent corrections to the entropic force scaling with ε . The ILM extends Verlinde’s framework by incorporating the braneworld geometry and predicting mass-dependent corrections to gravitational wave emission; it differs from CDT in retaining the continuous brane–bulk distinction;

and it differs from the standard RS model in introducing entropic permeability as a new physical mechanism beyond geometric warping alone.

5. Falsifiable Predictions

5.1. Prediction I: Mass-Dependent Radiated Energy Excess in Binary Black Hole Mergers

The ILM predicts that binary black hole (BBH) mergers produce a systematic excess of radiated energy relative to general relativity (GR), scaling with total system mass M_{total} . The mechanism is the enhanced bulk-brane entropic coupling at high curvature: larger M_{total} produces a larger event horizon area $A_H \propto M^2$, and therefore a greater integrated permeability across the brane-bulk interface at merger. GR predicts $E_{\text{rad}}/M_{\text{total}}$ depends only on the symmetric mass ratio $\eta = m_1 m_2 / (m_1 + m_2)^2$; the ILM predicts an additional mass-dependent correction.

The natural observable is the dimensionless radiated energy excess:

$$\Delta A = \frac{E_{\text{rad,obs}} - E_{\text{rad,GR}}}{E_{\text{rad,GR}}},$$

where $E_{\text{rad,GR}} = 0.0548 \eta$ is the NR-calibrated GR prediction. The ILM specifically predicts:

1. a positive correlation between ΔA and M_{total} ;
2. systematically lower ΔA for neutron-star-containing systems, where lower compactness reduces local permeability at merger; and
3. the correlation strengthens when controlling for instrumental noise and waveform model uncertainty.

Quantitative Order-of-Magnitude Estimate

The effective permeability at merger can be parametrised as $\varepsilon_{\text{eff}} = \varepsilon_0 \xi(M_{\text{total}})$, where ε_0 is the background permeability constrained by GW170817 to $\varepsilon_0 < 1.01 \times 10^{-15}$, and $\xi(M)$ encodes the mass-dependent enhancement. Two physically motivated scaling assumptions bracket the expected signal:

Linear scaling ($\xi = M_{\text{total}}/M_{\odot}$): appropriate if the dominant contribution to ε_{eff} is proportional to the total gravitational energy available. This gives:

$$\Delta A^{(\text{lin})} \lesssim \varepsilon_0 \cdot \frac{M_{\text{total}}}{M_{\odot}} \sim 10^{-13} - 10^{-11} \quad \text{for GWTC-3 events.}$$

Quadratic (area-law) scaling ($\xi = (M_{\text{total}}/M_{\odot})^2$): motivated by the Bekenstein-Hawking entropy $S_{\text{BH}} \propto A_H \propto M^2$, since the permeability integral over the horizon surface scales as the horizon area. This gives:

$$\Delta A^{(\text{quad})} \lesssim \varepsilon_0 \cdot \left(\frac{M_{\text{total}}}{M_{\odot}} \right)^2 \sim 10^{-11} - 10^{-10} \quad \text{for GWTC-3 events.}$$

Table 1 summarises the predicted upper bounds for representative GWTC-3 events and the LISA regime.

Upper bounds on ΔA for representative events under linear and quadratic ε_{eff} scaling, using $\varepsilon_0 < 1.01 \times 10^{-15}$ from the GW170817 speed constraint. Current single-event GWTC-3 sensitivity: $\Delta A \sim 0.05 - 0.20$. LISA single-event sensitivity: $\Delta A \sim 10^{-3}$.

Table 1.

Event / Mission	$M_{\text{total}} (M_{\odot})$	$\Delta A^{(\text{lin})}$	$\Delta A^{(\text{quad})}$
GW170817 (BNS)	2.7	$< 2.8 \times 10^{-15}$	$< 7.5 \times 10^{-15}$
GW170814	56.0	$< 5.7 \times 10^{-14}$	$< 3.2 \times 10^{-12}$
GW150914	66.2	$< 6.7 \times 10^{-14}$	$< 4.4 \times 10^{-12}$
GW190521	164.3	$< 1.7 \times 10^{-13}$	$< 2.7 \times 10^{-11}$

Event / Mission	$M_{\text{total}} (M_{\odot})$	$\Delta A^{(\text{lin})}$	$\Delta A^{(\text{quad})}$
LISA $10^4 M_{\odot}$	10^4	$< 1.0 \times 10^{-11}$	$< 1.0 \times 10^{-7}$
LISA $10^5 M_{\odot}$	10^5	$< 1.0 \times 10^{-10}$	$< 1.0 \times 10^{-5}$
LISA $10^6 M_{\odot}$	10^6	$< 1.0 \times 10^{-9}$	$< 1.0 \times 10^{-3}$

Under linear scaling, $\Delta A \ll 10^{-10}$ for all current GWTC-3 events, far below the individual-event sensitivity of $\sim 10\%$. However, the predicted *positive correlation* between ΔA and M_{total} is independently falsifiable via stacked regression analysis of the full GWTC-3 catalogue ($N \approx 90$ events), where systematic trends at the $\sim 1\%$ level may become accessible. Under the quadratic (area-law) scaling, ΔA reaches $\sim 10^{-3}$ for $M_{\text{total}} = 10^6 M_{\odot}$ BBH systems—precisely at the LISA single-event sensitivity threshold—making LISA the decisive near-future test of Prediction I. The absence of a positive ΔA – M_{total} correlation in GWTC-3 data would constrain the ILM scaling exponent below unity, ruling out the area-law variant of the model. A full Bayesian treatment including waveform systematics will be presented in future work.

5.2. Secondary Prediction: Non-Linear Quantum Decoherence Anomalies near Lattice Saturation

The ILM predicts that quantum systems approaching lattice saturation exhibit non-linear deviations in decoherence rates:

$$\Gamma_{\text{ILM}} = \Gamma_0 \left[1 + \alpha \left(\frac{\rho_E}{\rho_{\text{Pl}}} \right)^2 \varepsilon \right],$$

where Γ_0 is the standard decoherence rate, $\rho_{\text{Pl}} = c^5/(\hbar G^2)$ is the Planck energy density, ρ_E is the local energy density of the quantum system, and $\alpha \sim \mathcal{O}(1)$ is a dimensionless coupling constant to be determined from the lattice mode structure. Standard quantum mechanics predicts linear dependence on environmental coupling; the ILM predicts a quadratic correction $(\rho_E/\rho_{\text{Pl}})^2$ with a non-Markovian temporal structure arising from the finite lattice relaxation time. This prediction is testable with ion traps, Bose–Einstein condensates, and superconducting qubits near their decoherence limits.

6. Discussion

The ILM bridges braneworld physics, entropic gravity, and holographic theory. By identifying ε with the ratio of bulk-to-brane information flow (Equation 2.5), the model provides a thermodynamic explanation for gravitational weakness that complements the RS mechanism: gravity’s strength is determined jointly by how spacetime is geometrically warped and how information is distributed across lattice layers.

Three limitations of the current formulation require acknowledgement. First, Equation (2.5) is a dimensional identification rather than a derivation from first principles; a complete ILM action S_{ILM} from which $\Pi(y)$ emerges dynamically from an entropic variational principle remains a future theoretical priority. Second, the function $f(\omega/\omega_{\text{Pl}})$ in Equation (2.6) has not been derived from the lattice architecture; a specific prediction for the gravitational wave spectral signature requires a complete treatment of the bulk lattice mode spectrum. Third, α in Equation (5.4) is currently unconstrained at $\mathcal{O}(1)$; deriving its value from the lattice geometry is required before the Secondary Prediction can be confronted with precision decoherence measurements.

Raju formalised the holography of information principle: in any theory of quantum gravity, a complete copy of all information is redundantly encoded near the boundary of spacetime. In the ILM, $\Pi(y) > 1$ ensures no strict brane–bulk separation, and boundary redundancy corresponds precisely to the condition that entropic flux is non-zero for finite ε . The ongoing debate between the island proposal and the holography of information principle finds a natural ILM resolution: by distinguishing local brane projections from global lattice unitarity, the ILM provides a physically explicit mechanism satisfying the holography of information within a braneworld geometry.

Future work should prioritise: (i) derivation of the ILM action and $\Pi(y)$ from an entropic variational principle; (ii) computation of the bulk lattice mode spectrum and $f(\omega/\omega_{\text{pl}})$ in Equation (2.6); (iii) a full statistical analysis of the GWTC-3 correlation predicted by Equation (5.1); and (iv) a complete treatment of the dark matter distribution predicted by the sub-brane entropic density model, including comparison with galaxy rotation curve data.

7. Conclusions

We have introduced the Information Lattice Model, a braneworld framework in which gravity emerges as the macroscopic manifestation of directed entropic flow across a permeable multi-layered lattice spanning the observable 4D brane and a higher-dimensional bulk. The central formal contribution is the identification of ε with the ratio of bulk-to-brane entanglement entropy flux (Equation 2.5), grounding the ILM in the Bekenstein–Hawking entropy calculus and connecting it formally to AdS/CFT holography, CDT, and Verlinde’s entropic gravity. The integral in Equation (3.2) demonstrates explicitly how the permeability supplements the RS warp factor in suppressing the effective gravitational coupling.

The ILM may provide a unified perspective on three open problems in theoretical physics through a single mechanism of entropic trans-layer permeability: the hierarchy problem (Section 3), the black hole information paradox, and the nature of dark matter. Two falsifiable predictions are identified: a mass-dependent excess of radiated energy in BBH mergers (Prediction I, Equation 5.1) and non-linear quantum decoherence anomalies near lattice saturation (Secondary Prediction, Equation 5.4).

The ILM suggests a possible mechanism by which the weakness of gravity reflects a thermodynamic structure rather than a fine-tuning accident: if most of the entropic flux constituting gravity leaks preferentially into bulk layers inaccessible to brane-confined observers, leaving only the fraction $\varepsilon < 10^{-15}$ coupling to the observable universe, the hierarchy problem may find a partial resolution without invoking new particles or symmetries. Dark matter is offered as a phenomenological reinterpretation in terms of non-collapsed sub-brane entropic density, a picture that remains to be developed into quantitative predictions compatible with N-body simulations and rotation curve data. If these conjectures survive further formal development, the vacuum would emerge not as a passive backdrop but as a dynamical medium with finite informational bandwidth; quantum decoherence would become a measurable window onto the entropic structure of the bulk; and gravitational waves would carry a latent record of inter-layer information transfer that future detectors may yet resolve.

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