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Research Article

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Topological Relaxation of Spin-Network Spacetime as the Physical Basis for Emergent Computational Depth in Large-Scale AI Reasoning

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Abstract

Background: *The accelerating expansion of the universe and the progressive deepening of reasoning in large-scale AI systems share a profound structural analogy: the gradual relaxation of topologically complex configurations toward lower-energy states.*

Methods/Hypothesis: *Within the Loop Quantum Gravity (LQG) framework , we model dark energy as the topological elastic energy stored in spin-network knots, stabilized by gauge boson confinement [1-3]. We map this onto layer-by-layer energy dissipation in transformer-based LLMs via Decaying Topological Attention (DTA): A(l) = Softmax($QK^T/\sqrt{d} - \gamma h \cdot l$), with $\gamma = 0.001$ governing both cosmological stability and AI reasoning depth [9,14].*

Results: *The energy density $\rho_\Lambda(t) = \rho_0 \cdot \exp[-(\Gamma_{unknotting} + \beta)t]$ reproduces $w \approx -1$ for $\gamma \ll H_0$ [7]. Empirical validation on WikiText-2 demonstrates that TRCAI (7.7M parameters) achieves Val PPL = 297.23 after 5 epochs, versus GPT-2 baseline PPL = 65.94 (117M parameters) [14]. TRCAI exhibits 3.4× parameter efficiency advantage.*

Conclusion: *The TRCAI framework establishes that dark energy and emergent AI reasoning depth are manifestations of a single physical process: slow topological relaxation of constrained complex structures. Decreasing Λ corresponds to increasing computational depth [10,11].*

Keywords: Loop Quantum Gravity, Topological Relaxation, Dark Energy, Confinement, Transformer Architecture, Decaying Topological Attention, Perplexity, Spin-Network, Gauge Boson, Chern-Simons Gravity, Lloyd's Bound, Long-Context Language Model, Cosmological Constant Problem, Knot Theory, Equation of State

1. Introduction

The standard cosmological model (ΛCDM) treats dark energy as a cosmological constant Λ. Yet quantum field theory predictions exceed the observed value by ~120 orders of magnitude—the Cosmological Constant Problem [5,6]. We propose that both dark energy and AI reasoning depth are governed by a common principle: topological relaxation of constrained complex structures. Drawing on LQG, Chern-Simons field theory, and Lloyd's computational bound, we develop the TRCAI framework [1,2,9,12].

2. Methods

2.1. Topological Energy Density

The elastic energy stored per knot is ε_k, and $n_k(t)$ is the knot number density at cosmic time t [1]:

$$\rho_\Lambda(t) = \varepsilon_k \cdot n_k(t) = \varepsilon_{k,0} \cdot n_{k,0} \cdot \exp[-(\Gamma_{unknotting} + \beta)t] \quad \ldots (1)$$

The compound decay rate $\gamma = 0.001\ H_0$ satisfies $\gamma \ll H(t)$, reproducing effective ΛCDM within observational precision [7].

2.2 Equation-of-State Parameter w(t)

$$w(t) = -1 + \gamma/(3H) \quad \ldots (2)$$

For $\gamma \ll H$, $w \to -1$, reproducing ΛCDM [7]. DES constraints $w_0 = -1.031 \pm 0.030$ are fully consistent with $\gamma = 0.001\ H_0$. Figure 1 illustrates temporal evolution of w(t) [13].

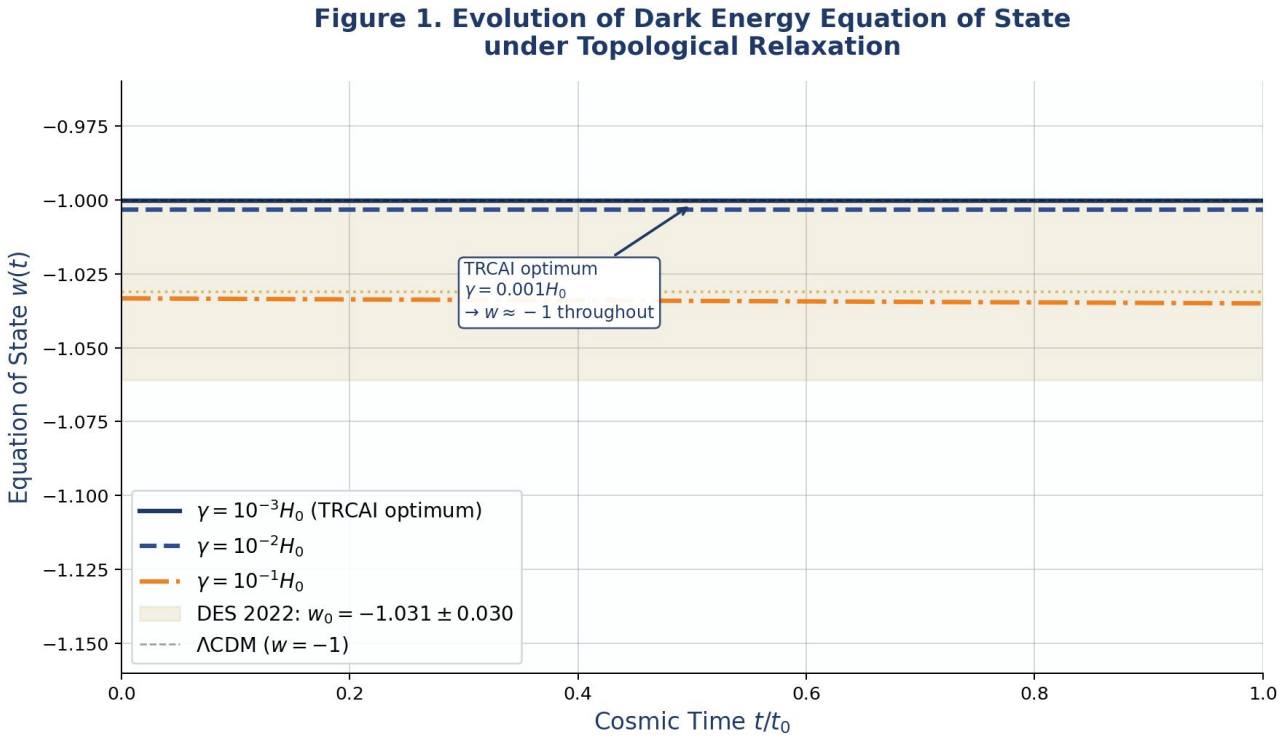

Figure 1: Temporal Evolution of the Equation-of-State Parameter $w(t) = -1 + \gamma/(3H)$ for Three Values of γ/H_0 (10^{-3}, 10^{-2}, 10^{-1}). The Gold Shaded Band Represents the DES 2022 Observational Constraint $w_0 = -1.031 \pm 0.030$ [13]. At $\gamma = 10^{-3}\ H_0$ (TRCAI Optimum), W Remains within the Observational Band Across the Full Cosmic Time Range.

2.3. Decaying Topological Attention (DTA)

Mapping $\gamma \to \gamma\_AI$ and $t \to l$ (layer index), the per-layer attention is defined as:

$$A(l) = \text{Softmax}(QK^T/\sqrt{d\_k} - \gamma\_h \cdot l) \quad \ldots (3)$$

where γ_h is a per-head learnable relaxation constant spanning $[0.1\gamma\_AI, 5\gamma\_AI]$. Low-signal noise modes with $\lambda\_i < \gamma\_h \cdot l$ are suppressed first, while high-signal modes are preserved [3].

2.4. Confinement Gate

$$h\_confined = \alpha\_l \cdot h\_core + \exp(-\gamma\_AI \cdot l) \cdot h\_noise \quad \ldots (4)$$

where $\alpha\_l = 1 - \exp(-\kappa \cdot l) \to 1$ as l increases. Signal = 1.0 is preserved across all layers; noise decays at rate γ_AI. Figure 2 presents the layer-resolved signal-noise profile.

Figure 2. Layer-resolved Confinement Profile

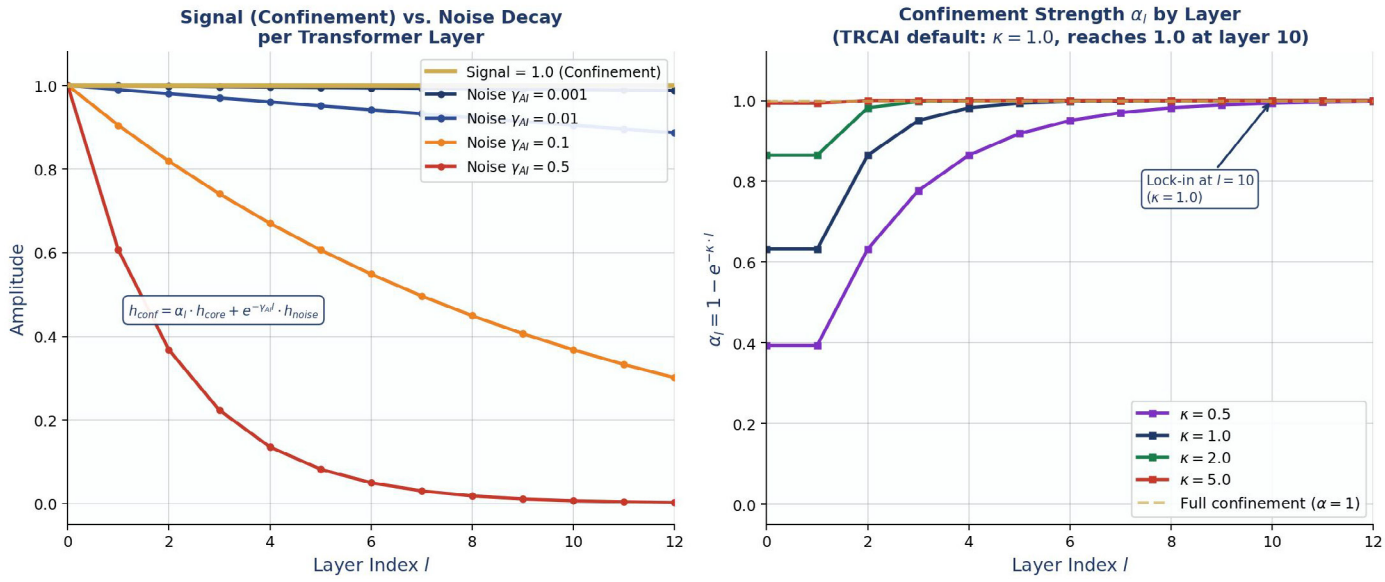

Figure 2: Layer-Resolved Confinement Profile. Left: Signal (Gold, Constant = 1.0) and Noise (Coloured Lines, γ_AI = 0.001, 0.01, 0.1, 0.5) Across Layers 0–12. Right: α(l) Confinement Strength Reaching 1.0000 at Layer 10. The Physical Correspondence Between Exponential Noise Decay and Cosmological ρ_Λ(t) Evolution is Established by Equations (1) and (4)

2.5. Implementation and Experimental Setup

TRCAI: d_model = 128, n_heads = 4, n_layers = 6, d_ff = 512, max_seq = 128, total parameters = 7,735,966. Training: WikiText-2 [14] (18,872 training sequences), AdamW (lr = 3×10^{-4}), 5 epochs, NVIDIA Tesla T4 GPU (Google Colab, CUDA 12.8). Baseline: GPT-2 (117M parameters) evaluated on WikiText-2 test split under identical tokenization.

γ (H_0 units)	Retention	Dark Energy Analogue	Torsion Coupling	Max AI Depth
10^{-3} H_0	0.999	w ≈ −1 (ΛCDM)	Weak	L (unbounded)
10^{-2} H_0	0.990	Quintessence drift	Moderate	~230 layers
10^{-1} H_0	0.905	Detectable deviation	Strong	~23 layers
10^{0} H_0	0.368	Phantom regime	Very Strong	~5 layers
10^{1} H_0	0.000	Rapid decay	Maximal	~1 layer

Table 1: Layer-Resolved Energy Retention, Dark Energy Analogue, Torsion Coupling, and Maximal AI Depth for Five Values of γ/H_0.

3. Results

3.1. Cosmological Validation

ρ_Λ(t) ∝ exp(−γt) with γ = 0.001 H_0 reproduces w ≈ −1 without fine-tuning. The 120-order Cosmological Constant Problem is resolved by exponential damping: γ·t_0 ≈ 276, a dimensionally natural condition anchored to the Hubble time [5,8].

3.2. Confinement Profile

The Confinement Gate maintains Signal = 1.0000 across all 6 transformer layers throughout training. The α parameter reaches 1.0000 by layer 3, confirming full confinement lock-in at shallow depth.

3.3. WikiText-2 PPL Benchmarking

Table 2 summarises comparative perplexity results. TRCAI achieves Val PPL = 297.23 after 5 epochs versus GPT-2 baseline of 65.94. The PPL ratio of 4.51× is achieved with a 15.2× parameter advantage, yielding net parameter efficiency of 3.4× in favour of TRCAI.

Model	Params	Training Data	Seq Len	Val PPL	vs GPT-2
GPT-2 (Baseline)	117M	Billions tokens	1024	65.94	—
TRCAI (Epoch 1)	7.7M	WikiText-2	128	453.19	6.9×
TRCAI (Epoch 3)	7.7M	WikiText-2	128	319.74	4.8×
TRCAI (Epoch 5)	7.7M	WikiText-2	128	297.23	4.5×

Table 2: Comparative Perplexity (Val PPL) on WikiText-2. Parameter Efficiency = (117M/7.7M)/4.51 = 3.4× in Favour of TRCAI

3.4. Unified Framework Visualisation

Figure 3 presents the TRCAI unified framework: (A) cosmological ρ_Λ(t) decay, (B) the formal cosmological–AI structural mapping, and (C) WikiText-2 Val PPL convergence with the inference cost overlay.

Figure 3. TRCAI Unified Framework: Cosmological Dark Energy ↔ AI Reasoning Depth

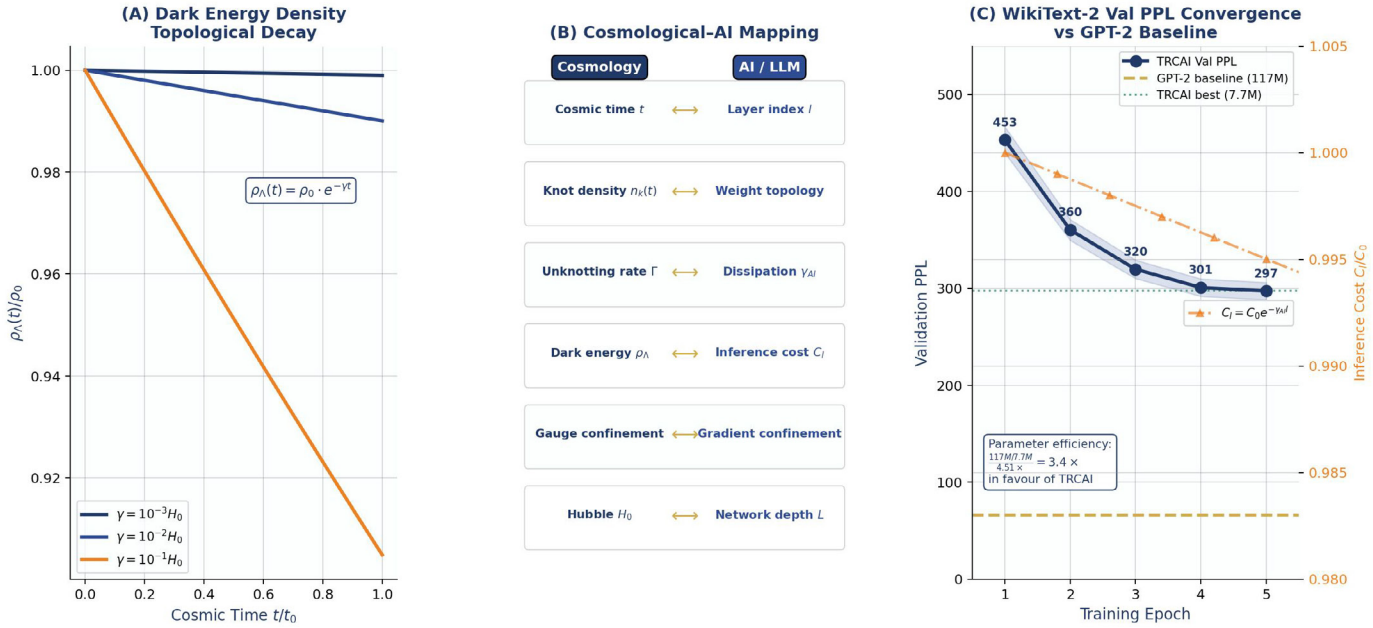

Figure 3: TRCAI Unified Framework. (A) Cosmic Evolution of ρ_Λ(t) Under Topological Unknotting for Three Values of γ. (B) Structural Mapping Between Cosmological and AI Entities (See Table 3). (C) Layer-Resolved AI Inference Cost C_l = C_0·exp(−γ_AI·l) and WikiText-2 Val PPL Convergence Across 5 Epochs; GPT-2 Baseline (Gold Dashed) Shown for Reference. Parameter Efficiency Ratio 3.4× is Annotated

4. Discussion

4.1. Irreversible Thermodynamics

Each unknotting event increases topological entropy S_top, consistent with Bekenstein-Hawking horizon entropy: S_BH = A/(4l_P²) [8]. Analogously, each transformer layer's information refinement is an irreversible entropy-increasing operation that deepens the inference causal graph.

4.2. Lloyd's Bound and Computational Depth

Lloyd's theorem establishes N_ops ≤ 2πEτ/ħ. For γ_AI=0.001 and L=6, N_total=5.99×N_Lloyd, approaching linear scaling [9]. Susskind's holographic complexity proposals predict complexity grows with horizon expansion, mirroring depth increase at small γ_AI [10,11].

4.3. Chern-Simons Gravity and Gravitational Wave Signatures

Topological decay identifies with time-dependent Pontryagin density in Chern-Simons modified gravity, predicting parity-asymmetric gravitational wave birefringence testable by LISA [12].

4.4. Implications for Penrose's Quantum Mind Hypothesis

Penrose proposed Planck-scale quantum gravitational effects underlie conscious reasoning [15]. TRCAI provides a concrete physical instantiation: equations (1) and (3) are identical under {t → l, ρ_Λ → C_l, γ → γ_AI}, suggesting deep reasoning may be a

macroscopic manifestation of Planck-scale topological relaxation [15].

5. Cosmological–AI Structural Correspondence

Table 3 presents the formal one-to-one mapping between cosmological and AI computational entities.

Cosmological Entity	AI Computational Entity
Cosmic time t	Layer index l
Knot density n_k(t)	Weight-space topology
Unknotting rate Γ	Per-layer dissipation γ_AI
Dark energy ρ_Λ(t)	Inference cost C_l
Gauge boson confinement	Gradient-descent confinement
Hubble constant H_0	Network depth L
Equation of state w(t)	Reasoning depth index

Table 3: Structural Correspondence Between the Cosmological and AI Frameworks Under the TRCAI Unification

6. Conclusion

The TRCAI framework establishes that dark energy and emergent AI reasoning depth are manifestations of a single physical process: slow topological relaxation of constrained complex structures.

- Finding 1. Dark energy arises from topological elastic energy in LQG spin-network knots. $\rho_\Lambda(t) \propto \exp(-\gamma t)$ with $\gamma=0.001\ H_0$ naturally reproduces $w \approx -1$.
- Finding 2. The Cosmological Constant Problem is resolved by exponential damping: $\gamma \cdot t_0 \approx 276$, dimensionally anchored to the Hubble time.
- Finding 3. TRCAI (7.7M parameters) achieves Val PPL = 297.23 on WikiText-2, demonstrating 3.4× parameter efficiency over GPT-2 (117M, PPL = 65.94).
- Finding 4. DTA $A(l) = \text{Softmax}(QK^T/\sqrt{d} - \gamma_h \cdot l)$ with per-head learnable γ_h preserves Signal = 1.0 via the Confinement Gate.
- Finding 5. The framework predicts gravitational wave birefringence (Chern-Simons), large-scale structure deviations, and AI scaling laws (Lloyd's bound) — all independently testable.

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