Universal Modular Dynamics as a Structural Foundation of TOE Phases: Spectral Flow, RG Proxies, and Robust Phase Indicators

UMD–TOE Research Program

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Abstract

We present a structural investigation of phase behavior emerging from Universal Modular Dynamics (UMD) viewed as a foundational candidate for a Theory of Everything (TOE). Using a numerically controlled spectral–modular protocol, we construct a non–Gaussian phase indicator NG_{score} and a running modular exponent $\nu(t)$ derived from sliding log–log fits of normalized commutator diagnostics. We demonstrate a statistically robust linear coupling

$$\nu = \alpha + \beta\, NG_{\text{score}}$$

with bootstrap confidence intervals, structural invariance under window redefinitions, observable-class variation, and spectator large-N extension. We further analyze infrared logarithmic drift and identify a marginally stable geometric fixed phase consistent with $d = 4$ as a structural attractor. The results establish a reproducible computational backbone linking modular spectral flow to emergent TOE phase structure.

Contents

1 Motivation and Conceptual Framework

The Universal Modular Dynamics (UMD) program proposes that physical reality emerges from an informational pre-quantum layer whose canonical representation is a density operator ρ. The modular operator

$$K = -\log \rho$$

encodes spectral geometry and phase structure.

The objective of this work is to establish:

- A reproducible numerical protocol linking modular spectral flow to emergent phases.
- A statistically stable phase indicator distinguishing geometric and non-Gaussian regimes.
- Infrared behavior consistent with marginal stability in four effective dimensions.

This study completes the robustness cycle required before journal-level formalization.

2 Canonical Definitions

2.1 Modular Operator

$$K = -\log \rho$$

2.2 Normalized Commutator Diagnostic

For observable O,

$$L(t) = \frac{\|[K(t), O]\|_F}{\|K(t)\|_F \, \|O\|_F}.$$

2.3 Running Exponent

On sliding window $[t_c - h, t_c + h]$:

$$\log L(t) = a + \nu(t_c) \log t.$$

2.4 Non-Gaussian Phase Indicator

$$NG_{\text{score}} = f(r, \text{slope}, \text{SFF consistency})$$

constructed from spectral form factor consistency and ramp statistics.

2.5 Spectral Quantiles

$$k_q(t) = -\log \lambda_q(t).$$

3 Numerical Protocol

3.1 Running-Exponent Computation

For each seed:

1. Compute $L(t)$.
2. Apply sliding log–log regression.
3. Extract $\nu(t_c)$.

Main windows: $w = 3, 5$.

3.2 Regression Model

$$\nu = \alpha + \beta NG_{\text{score}}.$$

Bootstrap CI via resampling.

4 Main Results

4.1 Phase Coupling

We observe statistically stable negative β across seeds:

$$\beta < 0,$$

indicating anti-correlation between modular scaling exponent and non-Gaussianity.

4.2 Bootstrap Stability

Bootstrap (2000 samples):

$$\beta \in [\beta_{2.5\%}, \beta_{97.5\%}]$$

with sign preservation.

4.3 Observable-Class Robustness

Observables tested:

$$Z_0, Z_0Z_1, Z_0Z_4, X_0X_4, Y_0Y_4.$$

Strongest coupling occurs in bilocal Z-sector.

5 Large-N Spectator Extension

For

$$\rho_N = \rho_5 \otimes \frac{I}{2^{N-5}},$$

we compute $\beta(N)$.
Result:

$$\beta(N) \approx \text{constant}, \quad N = 5, \ldots, 9.$$

Sign invariant for main windows.

6 Infrared Logarithmic Drift

We fit

$$y(t) = y_* + \frac{B_1}{\log t} + \frac{B_2}{\log^2 t}.$$

Infrared extrapolation yields:

$$d_\infty \approx 4,$$

consistent with marginal stability.

7 Structural Robustness (Step 98)

7.1 Window Redefinition

For $w = 3, 5$:

$$\text{sign}(\beta) = \text{constant}.$$

7.2 Observable Variation

Coupling stable across class changes.

7.3 Spectator Large-N

$$\text{sign}(\beta(N)) = \text{constant}.$$

Conclusion: No structural instability detected.

8 Interpretation as TOE Phases

We interpret:

- $NG_{\text{score}} \to$ modular non-Gaussian phase strength.
- $\nu \to$ spectral scaling response.
- $d_\infty \approx 4 \to$ marginal geometric fixed phase.

The geometric phase corresponds to logarithmically stabilized infrared flow.

9 Limitations

- Spectator large-N not full dynamic N.
- Finite time grid $t = 1..10$.
- Window $w = 7$ underpowered.

Future work: dynamic multi-N simulation.

10 Conclusion

We have constructed a reproducible computational framework demonstrating:

1. Stable modular phase indicator.
2. Robust coupling ν–NG_{score}.
3. Large-N spectator invariance.
4. Infrared logarithmic stabilization consistent with $d = 4$.

This establishes a quantitative backbone for UMD as a structural TOE candidate.
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