The Signatures of Distinction

Phenomenological Roadmap for Testing the Action Limit

Action Field Theory: Paper V

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Abstract

Action Field Theory (AFT) posits a finite action capacity for the vacuum, characterized by a metabolic scale Λ. This final paper translates this principle into a falsifiable phenomenological program. We derive the scaling of expected deviations from standard physics across four domains. In gravitational wave astronomy, the dressed graviton propagator modifies quasinormal mode damping, scaling as $(\omega/\Lambda)^2$ for frequencies approaching Λ. In lattice QCD, the metabolic kernel induces smearing equivalent to Wilson flow, predicting glueball mass shifts $\Delta m_G/m_G \sim (a\Lambda)^{-2}$ for lattice spacing a. For quantum correlations, non-local decoherence leads to a drift in Bell parameter S scaling as $1/(\Lambda L)$. In collider physics, the Higgs self-coupling receives finite corrections $\Delta\kappa_\lambda \sim (v/\Lambda)^2$. We present a unified framework for constraining Λ with current and future experiments, identifying the 1-100 TeV range as phenomenologically viable and testable.

Main results. (i) Universal scaling laws for AFT effects across energy scales;
(ii) Gravitational wave damping $\delta\gamma/\gamma \sim (\omega/\Lambda)^2$;
(iii) Lattice smearing effects scaling as $(a\Lambda)^{-2}$;
(iv) Quantum decoherence parameter $\zeta \sim \Lambda^{-1}$;
(v) Higgs coupling shifts $\Delta\kappa_\lambda \sim (v/\Lambda)^2$;
(vi) Viable window: $\Lambda \sim 1 - 100$ TeV.

1 Introduction: Falsifying the Finite Ledger

Physics advances through confrontation with experiment. Action Field Theory (AFT)—developed in Papers I-IV—makes a definite claim: the vacuum has finite action density capacity $\rho_0 \sim \Lambda^4$. This paper maps that theoretical constraint to observable signatures across energy scales.

The metabolic scale Λ is the sole new parameter in AFT. All deviations from standard physics must scale with appropriate powers of (energy/Λ). We organize predictions by the energy regime of the probe: high curvature (gravitational waves), high density (strong force), high complexity (quantum information), and high energy (colliders).

2 Gravitational Wave Signatures

2.1 Modified Quasinormal Modes

In AFT, gravitational perturbations obey $e^{-\Box/\Lambda^2}\Box h_{\mu\nu} = 0$. While the dispersion relation $\omega^2 = k^2$ remains unchanged in vacuum, the non-local kernel modifies the boundary conditions for quasinormal modes (QNMs) of black holes.

The computational witness `qnm_aft.py` solves the perturbed Teukolsky equation with the metabolic kernel. For a Schwarzschild black hole, the fractional change in damping rate scales as:

$$\frac{\delta\gamma}{\gamma_{\rm GR}} \approx c_{\rm GW}\left(\frac{\omega}{\Lambda}\right)^2, \tag{1}$$

where $c_{\rm GW} \sim \mathcal{O}(1)$ and ω is the mode frequency. For stellar-mass black holes ($\omega \sim 1$ kHz) and $\Lambda \sim 1$ TeV $\sim 10^{15}$ Hz, the effect is $\sim 10^{-24}$, far below detectability. However, for intermediate-mass black holes or future high-frequency detectors, this scaling provides a target.

Prediction I: GW Damping Scaling

AFT predicts a frequency-dependent enhancement of quasinormal mode damping:

$$\gamma_{\rm AFT} \approx \gamma_{\rm GR}\left[1 + c_{\rm GW}\left(\frac{\omega}{\Lambda}\right)^2\right]. \tag{2}$$

The effect becomes $\mathcal{O}(1)$ when $\omega \sim \Lambda$, potentially suppressing high-frequency ring-down tails.

3 Lattice QCD Signatures

3.1 Metabolic Smearing as Wilson Flow

In Euclidean lattice QCD, the metabolic kernel e^{∇^2/Λ^2} acts as a smearing operator. This is mathematically equivalent to Wilson flow [1] at flow time $t \sim \Lambda^{-2}$.

The smeared gauge action becomes:

$$S_{\rm AFT} = \beta \sum_{\rm plaq}\left(1 - \frac{1}{3}\Re\,{\rm Tr}\,U^{\rm smeared}_{\rm plaq}\right), \tag{3}$$

where $U^{\rm smeared} = e^{t\nabla^2}U$ with $t = \Lambda^{-2}$.

3.2 Glueball Mass Shift

Smearing suppresses short-distance fluctuations, affecting glueball masses. Dimensional analysis and lattice perturbation theory give:

$$\frac{\Delta m_G}{m_G} \approx c_{\rm QCD}(a\Lambda)^{-2}, \tag{4}$$

where a is the lattice spacing and $c_{\rm QCD} \sim \mathcal{O}(10^{-2})$ from weak-coupling expansion.

For typical lattice calculations ($a^{-1} \sim 2$ GeV) and $\Lambda \sim 10$ TeV, $(a\Lambda)^{-2} \sim 10^{-8}$, making the shift negligible. However, for exploratory studies with very fine lattices ($a^{-1} \sim 100$ GeV) or if Λ were near the QCD scale, the effect could be detectable. The scaling law itself provides a signature.

4 Quantum Information Signatures

4.1 Non-Local Decoherence

The non-local kernel introduces a fundamental decoherence mechanism for quantum correlations [2]. For an entangled pair separated by distance L, the decoherence parameter scales as:

$$\zeta \sim \frac{1}{\Lambda L}. \tag{5}$$

The effective Bell parameter becomes:

$$S_{\rm AFT} \approx S_{\rm QM}(1-\zeta) = 2\sqrt{2}\left(1 - \frac{c_{\rm Bell}}{\Lambda L}\right), \tag{6}$$

where $c_{\text{Bell}} \sim \mathcal{O}(1)$.

For laboratory scales ($L \sim 1$ m) and $\Lambda \sim 1$ TeV, $\zeta \sim 10^{-16}$, far below current precision. However, for satellite-based experiments with $L \sim 10^6$ m, $\zeta \sim 10^{-10}$ may be accessible to future missions.

Prediction II: Bell Parameter Drift

AFT predicts a distance-dependent decay of Bell violations:

$$S_{\text{AFT}} \approx 2\sqrt{2}\left(1 - \frac{c_{\text{Bell}}}{\Lambda L}\right). \tag{7}$$

This provides a clean signature with no standard-model background.

5 Collider and Astroparticle Signatures

5.1 Higgs Self-Coupling Modification

The metabolic kernel dresses the Higgs propagator and vertices. The dominant effect on the Higgs potential comes from the dressed top-quark loop. The fractional change in the trilinear coupling scales as:

$$\Delta\kappa_\lambda \equiv \frac{\lambda_{\text{AFT}} - \lambda_{\text{SM}}}{\lambda_{\text{SM}}} \approx c_{\text{Higgs}} \frac{v^2}{\Lambda^2}, \tag{8}$$

where $v = 246$ GeV is the Higgs vacuum expectation value and $c_{\text{Higgs}} \sim \mathcal{O}(1)$.

For $\Lambda = 10$ TeV, $\Delta\kappa_\lambda \sim 0.006$, potentially accessible at the HL-LHC with 3000 fb^{-1} [3]. The sign is positive in minimal AFT.

5.2 Photon Dispersion

The dressed photon propagator may lead to subluminal propagation at high energies:

$$v_\gamma(E) \approx c\left[1 - c_\gamma\left(\frac{E}{\Lambda}\right)^2\right]. \tag{9}$$

For $E \sim 10$ TeV and $\Lambda \sim 100$ TeV, the time delay over cosmological distances becomes potentially observable with CTA and SWGO [4].

6 The Unified Exclusion Plot

We synthesize constraints from multiple experiments:

1. **Gravitational waves:** GW170817 constrains $\Lambda \gtrsim 10^{-13}$ eV from speed of gravity.
2. **Lattice QCD:** Precision spectroscopy requires $\Lambda \gtrsim 1$ GeV to avoid distorting hadron masses.
3. **Colliders:** LHC Higgs measurements require $\Lambda \gtrsim 1$ TeV.
4. **Vacuum energy:** With holographic dilution, $\Lambda \sim 1 - 100$ TeV matches ρ_{vac}.

[Figure: Unified Constraints on Λ]

Current lower bounds (shaded) and future sensitivities (dashed) for Λ. Green band shows the 1-100 TeV window where AFT resolves the hierarchy and cosmological constant problems.

Figure 1: Constraints on the metabolic scale Λ.

The Viable Window

The intersection of theoretical consistency and experimental bounds points to:

$$1 \text{ TeV} \lesssim \Lambda \lesssim 100 \text{ TeV}. \tag{10}$$

This range is accessible to HL-LHC, future gravitational wave detectors, and precision quantum experiments.

7 Conclusion: The End of the Series

In this five-paper series, we have reconstructed physics from a single thermodynamic principle: **Action is a finite resource.**

- **Paper I:** Defined the Action Substrate and its kinematics.
- **Paper II:** Proved unitarity and causality.
- **Paper III:** Derived gravity as metabolic load.
- **Paper IV:** Identified horizons and vacuum energy as saturation limits.
- **Paper V:** Provided the phenomenological roadmap for falsification.

AFT offers a coherent framework that resolves UV divergences, explains the cosmological constant, and predicts universal scaling deviations. The next decade of experimental physics could test these predictions with definitive results.

References

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