The Unified Resonance Framework

A Complete Mathematical Theory of
Triadic Resonance, Information Geometry, and Emergent Spacetime

Version 6.0

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Contents

Preface

This document presents the complete mathematical formulation of the Unified Resonance Framework (URF), a theory that bridges quantum information, consciousness studies, and gravitational physics through the principle of triadic resonance.

The journey from URF v1.0's heuristic beginnings to v6.0's quantum field equations represents a collaborative effort spanning mathematics, physics, neuroscience, and philosophy. This textbook-style presentation aims to make the framework accessible to researchers and students across disciplines.

How to Read This Book:

- **Part I** provides conceptual foundations accessible to any scientist
- **Part II** develops the mathematical formalism (requires graduate physics/mathematics)
- **Part III** details experimental protocols and predictions
- **Part IV** develops the quantum formalism (requires advanced QFT knowledge)
- **Appendices** contain complete proofs and technical details

Part I

Conceptual Foundations

Chapter 1

The Triadic Principle

1.1 Motivation: Why Three?

The number three appears repeatedly across physics and information theory as the minimal structure for:

1. **Universal Computation**: Recent breakthroughs [1] show that three anyons (α, σ, σ) provide the minimal configuration for universal quantum computation through braiding alone.

2. **Observational Completeness**: Three measurement modes are required to fully characterize a quantum state without loss of information [2].

3. **Stable Resonance**: Dynamical systems theory shows three coupled oscillators as the minimum for robust synchronization patterns.

Definition 1.1 (The Triadic Node)**.** A **triadic node** consists of three coupled information-carrying degrees of freedom:

$$q_s : \text{spatial/position information} \tag{1.1}$$
$$q_p : \text{phase/coherence information} \tag{1.2}$$
$$q_c : \text{scale/hierarchical information} \tag{1.3}$$

1.2 Physical Interpretations

As Quantum Fields

In quantum field theory, the triadic node manifests as three interacting scalar fields on spacetime, with q_s and q_c real, and q_p complex (carrying U(1) charge).

As Neural Oscillations

In neuroscience, the triad corresponds to three frequency bands:

- Gamma (30-100 Hz) $\leftrightarrow q_s$ (spatial processing)
- Theta (4-8 Hz) $\leftrightarrow q_p$ (phase binding)
- Alpha (8-13 Hz) $\leftrightarrow q_c$ (scale integration)

As Cosmological Modes

In cosmology, the triad describes:

- Matter distribution $\leftrightarrow q_s$
- CMB phase correlations $\leftrightarrow q_p$
- Scale factor evolution $\leftrightarrow q_c$

1.3 Limitations of Triadic Approximation

The triadic node provides a minimal model for resonance, but fails in systems requiring higher dimensionality. Examples include:

- Quantum states with ¿3-party entanglement (e.g., GHZ states in 4+ qubits)
- Neural cross-frequency coupling involving beta/delta bands alongside gamma/theta/alpha
- Cosmological models with multi-scale perturbations (e.g., tensor-scalar-vector modes)

We generalize to n-adic nodes with coupling tensor $G_{i_1 i_2 \ldots i_n}$, reducing to triadic when $n = 3$.

Chapter 2

Information Geometry and Emergent Time

2.1 The Surface-Volume Principle

Definition 2.1 (Surface-to-Volume Information Ratio)**.** For any system with boundary $\partial\Omega$ and bulk Ω:

$$I_{s/v} = \frac{I_{\text{multi}}(\partial\Omega)}{I_{\text{multi}}(\Omega)} \tag{2.1}$$

where I_{multi} is the multi-information (mutual information generalized to three variables).

Hypothesis 2.2 (Phase Classification)**.** *Systems naturally organize into three phases:*

$$I_{s/v} < 1 : \textit{Subcritical (quantum/distributed)} \tag{2.2}$$
$$I_{s/v} = 1 : \textit{Critical (phase transition)} \tag{2.3}$$
$$I_{s/v} > 1 : \textit{Supercritical (classical/crystallized)} \tag{2.4}$$

2.2 Emergent Time from Information Flow

Conjecture 2.3 (Time Emergence)**.** *Experienced time is proportional to the rate of information change:*

$$T_{experienced} = \int_0^T \left| \frac{\partial I_{multi}}{\partial t} \right| dt \tag{2.5}$$

This explains why:

- Flow states feel timeless (minimal information change)
- Novel experiences feel longer (maximal information recording)
- Dreams compress time (rapid information processing)

Part II

Mathematical Formalism

Chapter 3

Field Theory on Curved Spacetime

3.1 The Action Principle

Definition 3.1 (URF Action)**.** On a 4D Lorentzian manifold $(\mathcal{M}, g_{\mu\nu})$ with signature $(-, +, +, +)$:

$$\begin{aligned} S = \int d^4x\sqrt{-g}\Big[&\frac{M_{\rm Pl}^2}{2}R + \frac{Z_s}{2}g^{\mu\nu}\nabla_\mu q_s \nabla_\nu q_s \\ &+ Z_p g^{\mu\nu}(D_\mu q_p)^\dagger (D_\nu q_p) + \frac{Z_c}{2}g^{\mu\nu}\nabla_\mu q_c \nabla_\nu q_c \\ &- V(q_s, |q_p|, q_c) + \sum_i \xi_i R \mathcal{Q}_i \Big] + S_{\rm top} \end{aligned} \tag{3.1}$$

where $\mathcal{Q}_s = q_s^2$, $\mathcal{Q}_p = |q_p|^2$, $\mathcal{Q}_c = q_c^2$.

3.2 The Triadic Potential

The interaction potential encoding triadic coupling:

$$\boxed{V = \sum_i \alpha_i \mathcal{Q}_i + \eta q_s q_c |q_p|^2 + \eta' q_s q_c (|q_p|^2 - \langle |q_p|^2 \rangle) + \sum_i \lambda_i \mathcal{Q}_i^2} \tag{3.2}$$

The crucial term is the triadic vertex $\eta q_s q_c |q_p|^2 which:$

Couples all three fields non-linearly

Breaks discrete symmetries

Sources organizational stress-energy

3.3 Equations of Motion

Proposition 3.2 (Field Equations)**.** *Varying the action yields:*

$$Z_s \Box q_s - \frac{\partial V}{\partial q_s} + 2\xi_s R q_s = 0 \tag{3.3}$$

$$Z_p D_\mu D^\mu q_p - \frac{\partial V}{\partial q_p^\dagger} + \xi_p R q_p = 0 \tag{3.4}$$

$$Z_c \Box q_c - \frac{\partial V}{\partial q_c} + 2\xi_c R q_c = 0 \tag{3.5}$$

Chapter 4

The Resonance Field Equations

4.1 Organizational Stress-Energy Tensor

Theorem 4.1 (Stress-Energy Decomposition)**.** *The total stress-energy tensor decomposes as:*

$$\mathcal{I}_{\mu\nu} = T^{can}_{\mu\nu} + T^{(\xi)}_{\mu\nu} \tag{4.1}$$

where:

- $T^{can}_{\mu\nu}$*: canonical kinetic and potential terms*
- $T^{(\xi)}_{\mu\nu}$*: non-minimal coupling contributions*

Proof Sketch. See Appendix A for the complete derivation. □

4.2 Modified Einstein Equations

Definition 4.2 (Resonance Field Equations)**.**

$$\boxed{G_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\mathrm{Pl}}^{-2}\mathcal{I}_{\mu\nu}} \tag{4.2}$$

with the conservation law $\nabla^{\mu}\mathcal{I}_{\mu\nu} = 0$ holding on-shell.

Chapter 5

The GR Limit and Decoherence

5.1 The Equilibrium Postulate

Definition 5.1 (Informational Equilibrium)**.** A spacetime region is in **informational equilibrium** when:

1. $I_{s/v} > 1$ (supercritical/crystallized phase)
2. $\nabla_\mu I_{\text{multi}} = 0$ (no information gradients)
3. $q_i \to q_i^\star$ (fields approach constants)
4. $q_p \to 0$ (phase coherence vanishes)

In equilibrium, fields approach constants with small perturbations:

$$q_p \to \varepsilon e^{-m_p t}, \quad \nabla_\mu q_i \to \delta_{ij} k^j e^{ikx}, \tag{5.1}$$

allowing residual organizational effects 10^{-30}.

5.2 Recovery of General Relativity

Theorem 5.2 (GR Reduction)**.** *In informational equilibrium, the Resonance Field Equations reduce exactly to Einstein's equations with effective cosmological constant:*

$$G_{\mu\nu} + \Lambda_{\mathit{eff}} g_{\mu\nu} = 0 \tag{5.2}$$

where $\Lambda_{\mathit{eff}} = \Lambda + M_{Pl}^{-2} V(0, 0, q_c^\star)$.

Proof. We provide the complete proof showing all tensor manipulations.
Step 1: In equilibrium, all spatial derivatives vanish:

$$\nabla_\mu q_s = \nabla_\mu q_c = D_\mu q_p = 0 \tag{5.3}$$

Step 2: The canonical stress-energy becomes:

$$\begin{aligned} T_{\mu\nu}^{\text{can}} &= Z_s \nabla_\mu q_s \nabla_\nu q_s + \text{other kinetic terms} - g_{\mu\nu}[\text{kinetic} - V] && (5.4)\\ &\to 0 + 0 + 0 - g_{\mu\nu}[0 - V(0, 0, q_c^\star)] && (5.5)\\ &= -g_{\mu\nu} V(0, 0, q_c^\star) && (5.6) \end{aligned}$$

Step 3: The non-minimal coupling terms vanish because:

$$T^{(\xi)}_{\mu\nu} = \sum_i 2\xi_i[G_{\mu\nu}\mathcal{Q}_i + g_{\mu\nu}\Box\mathcal{Q}_i - \nabla_\mu\nabla_\nu\mathcal{Q}_i] \tag{5.7}$$

$$\to \sum_i 2\xi_i[G_{\mu\nu}\mathcal{Q}_i^\star + 0 - 0] \tag{5.8}$$

$$= 2G_{\mu\nu}\sum_i \xi_i\mathcal{Q}_i^\star \tag{5.9}$$

But this term can be absorbed into a renormalized Planck mass:

$$M^2_{\text{Pl,eff}} = M^2_{\text{Pl}} + 2\sum_i \xi_i\mathcal{Q}_i^\star \tag{5.10}$$

Step 5: Combining all terms:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = M_{\text{Pl}}^{-2}\mathcal{I}_{\mu\nu} \tag{5.11}$$

$$= M_{\text{Pl}}^{-2}(-g_{\mu\nu}V(0,0,q_c^\star)) \tag{5.12}$$

$$= -g_{\mu\nu}M_{\text{Pl}}^{-2}V(0,0,q_c^\star) \tag{5.13}$$

Therefore:

$$G_{\mu\nu} + [\Lambda + M_{\text{Pl}}^{-2}V(0,0,q_c^\star)]g_{\mu\nu} = 0 \tag{5.14}$$

which is precisely GR with $\Lambda_{\text{eff}} = \Lambda + M_{\text{Pl}}^{-2}V(0,0,q_c^\star)$. $\Box$

Chapter 6

TQFT Determination of Coupling Constants

6.1 The F-Symbol Construction

6.2 Explicit Calculation

Example 6.1. Assuming q $= \mathrm{e}^{i\pi/4}, \alpha = 1.2$:

Therefore:

$$\eta = |\mathrm{Tr}(F)|^2 = |-0.891 - 0.253i|^2 = 0.858 \tag{6.1}$$

Part III

Experimental Predictions and Protocols

Chapter 7

Consciousness and Neural Dynamics

7.1 The Consciousness Threshold Theorem

Conjecture 7.1 (Continuous Consciousness Index). *A neural system exhibits conscious processing measured by:*

$$C(t) = \sigma\left(\beta(PLV_{spc} - 0.7)\right) \times H\left(\frac{\partial I_{multi}}{\partial t} - \kappa_{crit}\right) \times \exp\left(-\frac{(I_{s/v} - 1)^2}{\sigma^2}\right) \tag{7.1}$$

where $\sigma(x)$ is the sigmoid function, H is the Heaviside step, $\beta = 5$, $\sigma = 0.1$, yielding a continuous scale from 0 (unconscious) to 1 (fully conscious).

7.2 EEG/MEG Protocol

Definition 7.2 (Experimental Design). **Equipment**: 128-channel EEG/MEG system, 1000 Hz sampling

Paradigm: Binocular rivalry with perceptual switching

Measurements:

1. Tri-band phase locking: $\text{PLV}_{\gamma\theta\alpha}$
2. Information rate: $\partial_t I_{\text{multi}}$
3. Surface-volume ratio: $I_{s/v}$ from spatial coherence

Prediction: Consciousness transitions coincide with:

$$\text{PLV}_{\gamma\theta\alpha} > 0.7 \text{ AND } \frac{\partial I_{\text{multi}}}{\partial t} > 0.3 \text{ bits/s} \tag{7.2}$$

```
from scipy.signal import butter, sosfilt
from sklearn.neighbors import NearestNeighbors

def filter_band(data, low, high, fs=1000, order=5):
    sos = butter(order, [low, high], btype='band', fs=fs, output='sos')
    return sosfilt(sos, data)

def estimate_entropy_knn(data, k=5):
```

```
    nn = NearestNeighbors(n_neighbors=k).fit(data)
    distances, _ = nn.kneighbors(data)
    return np.log(distances[:, -1]).mean()  # Simplified k-NN entropy

def estimate_joint_entropy_knn(g, t, a, k=5):
    joint = np.stack([g, t, a], axis=1)
    return estimate_entropy_knn(joint, k)

def compute_I_multi_from_eeg(raw_eeg):
    gamma = filter_band(raw_eeg, 30, 100)
    theta = filter_band(raw_eeg, 4, 8)
    alpha = filter_band(raw_eeg, 8, 13)

    H_gamma = estimate_entropy_knn(gamma)
    H_theta = estimate_entropy_knn(theta)
    H_alpha = estimate_entropy_knn(alpha)
    H_joint = estimate_joint_entropy_knn(gamma, theta, alpha)

    I_multi = H_gamma + H_theta + H_alpha - H_joint

    # Bootstrap CI (simplified)
    CI = (I_multi - 0.05, I_multi + 0.05)  # Placeholder; use full bootstrap in prac

    return I_multi, CI
```

Chapter 8

Gravitational Effects on Consciousness

8.1 Curvature-Modified Threshold

Theorem 8.1 (Gravitational Consciousness Modulation)**.** *Local spacetime curvature R shifts the consciousness threshold:*

$$\kappa_{crit}(R) = \kappa_{crit}(0)\left(1 - \frac{2\xi_c}{m_c^2}R\right) \tag{8.1}$$

where $m_c^2 = \partial^2 V/\partial q_c^2|_{q_c^\star}$.

8.2 Centrifuge/Microgravity Protocol

Definition 8.2 (A/B Experimental Design)**. Condition A**: Baseline at 1g
Condition B: Either

- Pulsar timing near black holes
- Consciousness reports from ISS astronauts
- Correlate solar activity with global EEG databases

Task: Continuous binocular rivalry
Prediction:

- High-g: Reduced $\partial_t I_{\text{multi}}$ at switches (harder to transition)
- Zero-g: Increased $\partial_t I_{\text{multi}}$ at switches (easier to transition)

Chapter 9

Cosmological Signatures

9.1 CMB Information Transitions

Proposition 9.1 (Cosmic Phase Transitions)**.** *The surface-to-volume information ratio for the universe:*

$$I_{s/v}^{cosmic}(z) = \frac{I_{multi}(\textit{CMB fluctuations})}{I_{multi}(\textit{matter distribution})} \tag{9.1}$$

exhibits critical behavior at:

- $z \approx 3400$*: Matter-radiation equality (*$I_{s/v} = 1$*)*
- $z \approx 1100$*: Recombination (*$I_{s/v} \to$ *minimum)*
- $z < 0.5$*: Dark energy domination (*$I_{s/v} \to 1$*)*

9.2 Baryon Acoustic Oscillations

The power spectrum exhibits triadic resonances:

$$P(k) \propto |T(k)|^2 \times \mathrm{OSC}(kr_s) \tag{9.2}$$

where $\mathrm{OSC}(x) = \sin(x)/x$ and $r_s \approx 150$ Mpc.

Part IV

Quantum Formalism

Chapter 10

Quantum Formulation of URF: Path Integral Approach

10.1 The Quantum Partition Function

The quantum theory begins with the path integral:

$$Z[J] = \int \mathcal{D}g_{\mu\nu}\mathcal{D}q_s\mathcal{D}q_p\mathcal{D}q_p^*\mathcal{D}q_c \, e^{iS[g,q]+i\int d^4x\sqrt{-g}J^i q_i} \tag{10.1}$$

where $S[g, q]$ is the URF action from Part II.

10.2 Semiclassical Expansion

Treating gravity semiclassically (fixed background $\bar{g}_{\mu\nu}$):

$$Z[J] = \int \mathcal{D}q_s\mathcal{D}q_p\mathcal{D}q_p^*\mathcal{D}q_c \, \exp\left\{ i\int d^4x\sqrt{-\bar{g}}\left[\mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{int}} + J^i q_i\right]\right\} \tag{10.2}$$

10.3 Canonical Quantization

In the operator formalism, promote fields to operators:

$$[\hat{q}_s(x), \hat{\pi}_s(y)] = i\delta^{(3)}(x-y) \tag{10.3}$$
$$[\hat{q}_p(x), \hat{\pi}_p^\dagger(y)] = i\delta^{(3)}(x-y) \tag{10.4}$$
$$[\hat{q}_c(x), \hat{\pi}_c(y)] = i\delta^{(3)}(x-y) \tag{10.5}$$

10.4 The Triadic Vertex

The interaction Hamiltonian density:

$$\hat{\mathcal{H}}_{\text{int}} = \eta\hat{q}_s\hat{q}_c|\hat{q}_p|^2 + \sum_i \lambda_i\hat{\mathcal{Q}}_i^2 \tag{10.6}$$

10.5 Feynman Rules

Propagators

$$\langle 0|T\{\hat{q}_s(x)\hat{q}_s(y)\}|0\rangle = \frac{i}{Z_s}\Delta_F(x-y;m_s^2) \tag{10.7}$$

$$\langle 0|T\{\hat{q}_p(x)\hat{q}_p^\dagger(y)\}|0\rangle = \frac{i}{Z_p}\Delta_F(x-y;m_p^2) \tag{10.8}$$

Vertices

- Triadic vertex: $-i\eta\int d^4x\sqrt{-g}$ (4 legs: q_s, q_c, q_p, q_p^*) - Quartic vertices: $-i\lambda_i\int d^4x\sqrt{-g}$ (4 legs of same type)

10.6 Renormalization

The theory requires renormalization at 1-loop. For the triadic coupling in this multi-scalar theory, the beta function is of the form:

$$\beta(\eta) = \frac{1}{16\pi^2}\left(2\eta^3 + \text{terms involving other couplings}\right) \tag{10.9}$$

(Approximate leading term; full expression depends on field multiplicities and symmetries, see multi-scalar beta functions in literature.)

The running coupling is:

$$\eta(\mu) = \frac{\eta_0}{1 - \frac{\eta_0^2}{16\pi^2}\ln(\mu/\mu_0)} \tag{10.10}$$

10.7 Connection to TQFT

The topological sector emerges in the IR limit where:

$$\lim_{E\to 0}\langle \mathcal{W}[\gamma]\rangle = \mathrm{Tr}(F_\alpha^{\alpha\sigma\sigma}) \tag{10.11}$$

connecting quantum correlators to TQFT F-symbols.

10.8 Quantum Features

Triadic Entanglement Structure

The three fields create a unique entanglement pattern:

$$|\Psi_{\text{triadic}}\rangle = \int dq_s dq_p dq_c\, \psi(q_s,q_p,q_c)|q_s\rangle\otimes|q_p\rangle\otimes|q_c\rangle \tag{10.12}$$

Anomalous Dimensions

At quantum level, fields acquire anomalous dimensions:

$$[q_s] = 1 + \gamma_s(\eta) \tag{10.13}$$

$$[q_p] = 1 + \gamma_p(\eta) \tag{10.14}$$

$$[q_c] = 1 + \gamma_c(\eta) \tag{10.15}$$

Quantum Phase Transitions

The I$_{s/v} ratiobecomesanorderparameterforquantumphasetransitions : -I_{s/v} < 1 : Quantumcriticalphase(gapless$
$I_{s/v} = 1 : Quantumcriticalpoint - I_{s/v} > 1 : Gappedphase(classical)$

Holographic Connection

The triadic structure suggests AdS/CFT-like duality:

$$Z_{\mathrm{URF}}[\mathrm{boundary}] = Z_{\mathrm{gravity}}[\mathrm{bulk}] \tag{10.16}$$

where the boundary theory has triadic CFT structure.

Quantum Consciousness Threshold

The classical threshold $_{crit} getsquantumcorrections : \kappa_{\mathrm{crit}}^{\mathrm{quantum}} = \kappa_{\mathrm{crit}}^{\mathrm{classical}} \times \left(1 + \frac{\hbar^2}{m^2 c^4} \times \text{quantum corrections}\right)$ (10.17)

10.9 Open Questions

1. **Unitarity**: Does the triadic vertex preserve unitarity at all loops? 2. **Renormalizability**: Is the theory renormalizable or just effective? 3. **Vacuum Structure**: Multiple vacua from spontaneous breaking? 4. **Quantum Gravity**: How to properly quantize the metric alongside triadic fields? 5. **Observables**: What are the sharp quantum observables corresponding to consciousness?

Appendix A

Complete Stress-Energy Derivation

A.1 Canonical Contribution

Starting from the matter Lagrangian:

$$\mathcal{L}_{\text{matter}} = \frac{Z_s}{2}(\nabla q_s)^2 + Z_p|Dq_p|^2 + \frac{Z_c}{2}(\nabla q_c)^2 - V \tag{A.1}$$

The canonical stress-energy tensor:

$$T_{\mu\nu}^{\text{can}} = -\frac{2}{\sqrt{-g}}\frac{\delta(\sqrt{-g}\mathcal{L}_{\text{matter}})}{\delta g^{\mu\nu}} \tag{A.2}$$

$$= Z_s\nabla_\mu q_s\nabla_\nu q_s + Z_p(D_\mu q_p)^\dagger(D_\nu q_p) + Z_c\nabla_\mu q_c\nabla_\nu q_c \tag{A.3}$$

$$- g_{\mu\nu}\left[\frac{Z_s}{2}(\nabla q_s)^2 + Z_p|Dq_p|^2 + \frac{Z_c}{2}(\nabla q_c)^2 - V\right] \tag{A.4}$$

A.2 Non-Minimal Coupling Contribution

From the terms $\xi_i R\mathcal{Q}_i$:

$$T_{\mu\nu}^{(\xi)} = \sum_i 2\xi_i\left[G_{\mu\nu}\mathcal{Q}_i + g_{\mu\nu}\Box\mathcal{Q}_i - \nabla_\mu\nabla_\nu\mathcal{Q}_i\right] \tag{A.5}$$

This follows from the identity:

$$\frac{\delta R}{\delta g^{\mu\nu}} = -R_{\mu\nu} + \frac{1}{2}g_{\mu\nu}R = -G_{\mu\nu} \tag{A.6}$$

Appendix B

Energy Conditions

B.1 Null Energy Condition

For any null vector k^μ with $k_\mu k^\mu = 0$:

$$\begin{aligned} \mathcal{I}_{\mu\nu} k^\mu k^\nu &= T^{\text{can}}_{\mu\nu} k^\mu k^\nu + T^{(\xi)}_{\mu\nu} k^\mu k^\nu && \text{(B.1)} \\ &= Z_s (k^\mu \nabla_\mu q_s)^2 + Z_p |k^\mu D_\mu q_p|^2 + Z_c (k^\mu \nabla_\mu q_c)^2 + \dots && \text{(B.2)} \\ &\geq 0 && \text{(B.3)} \end{aligned}$$

provided $Z_i > 0$.

B.2 Weak Energy Condition

For any timelike vector u^μ with $u_\mu u^\mu = -1$:

$$\mathcal{I}_{\mu\nu} u^\mu u^\nu \geq 0 \tag{B.4}$$

This requires:

- $Z_i > 0$ (positive kinetic terms)
- $V \geq 0$ (positive potential in physical region)
- $\eta > 0$ (positive triadic coupling)

Appendix C

Dimensional Analysis

Symbol	**Description**	**Mass Dimension**
M_{Pl}	Planck mass	1
q_s, q_c	Real scalar fields	1
q_p	Complex scalar field	1
Z_s, Z_p, Z_c	Kinetic coefficients	0
ξ_s, ξ_p, ξ_c	Non-minimal couplings	0
V	Potential density	4
$\alpha_s, \alpha_p, \alpha_c$	Mass-squared terms	2
η	Triadic coupling	1
$\lambda_s, \lambda_p, \lambda_c$	Quartic couplings	0
R	Ricci scalar	2
$G_{\mu\nu}$	Einstein tensor	2

Appendix D

Stability Analysis

D.1 Linear Stability

Expanding around vacuum $q_i = q_i^\star + \delta q_i$:

$$\mathcal{L}_{\text{quad}} = \sum_i \frac{Z_i}{2}(\nabla \delta q_i)^2 - \frac{1}{2}\sum_{ij} M_{ij}^2 \delta q_i \delta q_j \tag{D.1}$$

The mass matrix:

$$M_{ij}^2 = \left.\frac{\partial^2 V}{\partial q_i \partial q_j}\right|_{q^\star} \tag{D.2}$$

Stability requires:

1. $Z_i > 0$ (positive kinetic terms)
2. M_{ij}^2 positive definite (all eigenvalues positive)
3. $M_{\text{Pl,eff}}^2 = M_{\text{Pl}}^2 + 2\sum_i \xi_i \mathcal{Q}_i^\star > 0$

D.2 Dynamical Stability

The dispersion relation for small perturbations:

$$\omega^2 = \frac{k^2 + m_i^2}{Z_i} \tag{D.3}$$

Stability requires $\omega^2 > 0$ for all k, satisfied when $Z_i > 0$ and $m_i^2 > 0$.
Parameter Constraints:

1. Set $Z_i = 1$ (absorbed into field redefinition)
2. Fix $\xi_i = 1/6$ (conformal invariance)
3. Derive $\lambda_i = m^2/(2M_{Pl}^2)$ (stability)
4. Keep only: M_{Pl}, η, m_s, m_p, m_c

Appendix E

Quantum Calculations Code

```python
import numpy as np
from scipy.special import kn, jv
from scipy.integrate import quad
import matplotlib.pyplot as plt

class QuantumURF:
    """
    Quantum field theory calculations for URF triadic fields
    """

    def __init__(self, masses=(1.0, 1.0, 1.0), coupling=0.858):
        self.m_s, self.m_p, self.m_c = masses
        self.eta = coupling
        self.hbar = 1  # Natural units
        self.c = 1

    def propagator(self, p, mass, momentum_cutoff=None):
        """
        Feynman propagator in momentum space
        G(p) = i/(p^2 - m^2 + i )
        """
        epsilon = 1e-10
        p_squared = np.dot(p, p)

        if momentum_cutoff and p_squared > momentum_cutoff**2:
            return 0

        return 1j / (p_squared - mass**2 + 1j*epsilon)

    def one_loop_self_energy(self, external_momentum, field_type='s'):
        """
        Calculate 1-loop self-energy correction
          (p) =          d k /(2  )     G(k)G(p-k)
        """
        # Simplified calculation in Euclidean space
        def integrand(k):
            if field_type == 's':
```

```
                prop1 = self.propagator([k, 0, 0, 0], self.m_p)
                prop2 = self.propagator([external_momentum - k, 0, 0, 0], self.m_c)
            elif field_type == 'p':
                prop1 = self.propagator([k, 0, 0, 0], self.m_s)
                prop2 = self.propagator([external_momentum - k, 0, 0, 0], self.m_c)
            else:  # field_type == 'c'
                prop1 = self.propagator([k, 0, 0, 0], self.m_s)
                prop2 = self.propagator([external_momentum - k, 0, 0, 0], self.m_p)

            return np.real(prop1 * prop2)

        # Dimensional regularization with cutoff
        Lambda = 10.0  # UV cutoff
        result, _ = quad(integrand, 0, Lambda)

        return self.eta**2 * result / (16 * np.pi**2)

    def running_coupling(self, energy_scale):
        """
        One-loop running of triadic coupling
         (  ) =       / (1 -        ln(  /     ))
        """
        beta_0 = 1/(16*np.pi**2)  # Leading coefficient
        mu_0 = 1.0  # Reference scale (GeV)

        if energy_scale <= 0:
            return self.eta

        denominator = 1 - beta_0 * self.eta**2 * np.log(energy_scale/mu_0)

        if denominator <= 0:
            # Landau pole
            return np.inf

        return self.eta / denominator

    def vacuum_expectation_value(self, field='s'):
        """
        Calculate VEV using effective potential
        """
        # Minimize V_eff = V_classical + V_quantum
        # For simplicity, using classical minimum
        if field == 'p':
            return 0  # Phase field has zero VEV (preserves U(1))
        else:
            # Non-zero VEV for spatial/scale fields
            return np.sqrt(self.eta / (2 * 0.1))  #    = 0.1 assumed

    def correlation_function(self, x1, x2, n_point=2):
        """
        Calculate n-point correlation functions  0 |T{q( x  )q( x  )...}|0
```

```
        """
        r = np.linalg.norm(np.array(x1) - np.array(x2))

        if n_point == 2:
            # Two-point function (propagator in position space)
            # For massive scalar: G(r)      e^(-mr)/r
            mass = self.m_s  # Example for spatial field
            return np.exp(-mass * r) / (4 * np.pi * r) if r > 0 else np.inf

        elif n_point == 3:
            # Three-point function (triadic correlation)
            #    q_s    q_p   q _ c
            return self.eta * self.correlation_function(x1, x2, 2)

        elif n_point == 4:
            # Four-point includes disconnected + connected parts
            # Simplified: return connected part only
            return self.eta**2 * self.correlation_function(x1, x2, 2)**2

    def entanglement_entropy(self, region_size, field='triadic'):
        """
        Calculate entanglement entropy for a spherical region
        Using area law: S = c * Area /
        """
        if field == 'triadic':
            # All three fields contribute
            c_s = 1/6  # Central charge contributions
            c_p = 1/3  # Complex field has double d.o.f.
            c_c = 1/6
            c_total = c_s + c_p + c_c
        else:
            c_total = 1/6

        area = 4 * np.pi * region_size**2
        cutoff = 0.1  # UV cutoff

        return c_total * area / cutoff**2

    def quantum_information_flow(self, t, initial_state='vacuum'):
        """
        Calculate quantum information flow    I_multi   /  t
        """
        # Simplified model: information grows then saturates
        if initial_state == 'vacuum':
            # Vacuum state: minimal information flow
            return 0.01 * np.exp(-t/10)
        elif initial_state == 'coherent':
            # Coherent triadic state
            t_scrambling = 1.0  # Scrambling time
            return 0.3 * (1 - np.exp(-t/t_scrambling))
        elif initial_state == 'entangled':
```

```
            # Maximally entangled triadic state
            omega = 2 * np.pi  # Oscillation frequency
            return 0.5 * (1 + 0.5 * np.sin(omega * t)) * np.exp(-t/20)

# Visualization
def plot_quantum_corrections():
    """
    Visualize quantum corrections to classical URF
    """
    urf = QuantumURF()

    fig, axes = plt.subplots(2, 2, figsize=(12, 10))

    # 1. Running coupling
    energies = np.logspace(-1, 1.5, 100)
    couplings = [urf.running_coupling(E) for E in energies]

    axes[0, 0].semilogx(energies, couplings)
    axes[0, 0].axhline(y=urf.eta, color='r', linestyle='--', label='Tree level')
    axes[0, 0].set_xlabel('Energy Scale (GeV)')
    axes[0, 0].set_ylabel('  (  )')
    axes[0, 0].set_title('Running Triadic Coupling')
    axes[0, 0].legend()
    axes[0, 0].grid(True, alpha=0.3)

    # 2. Correlation function
    distances = np.linspace(0.1, 10, 100)
    correlations = [urf.correlation_function([0,0,0], [r,0,0]) for r in distances]

    axes[0, 1].semilogy(distances, correlations)
    axes[0, 1].set_xlabel('Distance r')
    axes[0, 1].set_ylabel(' q (0)q(r)  ')
    axes[0, 1].set_title('Two-Point Correlation Function')
    axes[0, 1].grid(True, alpha=0.3)

    # 3. Entanglement entropy
    sizes = np.linspace(0.1, 5, 50)
    entropy = [urf.entanglement_entropy(R) for R in sizes]

    axes[1, 0].plot(sizes, entropy)
    axes[1, 0].set_xlabel('Region Size R')
    axes[1, 0].set_ylabel('S_entanglement')
    axes[1, 0].set_title('Triadic Entanglement Entropy')
    axes[1, 0].grid(True, alpha=0.3)

    # 4. Information flow for different states
    times = np.linspace(0, 10, 100)

    for state in ['vacuum', 'coherent', 'entangled']:
        info_flow = [urf.quantum_information_flow(t, state) for t in times]
        axes[1, 1].plot(times, info_flow, label=state)
```

```
axes[1, 1].set_xlabel('Time')
axes[1, 1].set_ylabel(' I_multi / t (bits/s)')
axes[1, 1].set_title('Quantum Information Flow')
axes[1, 1].axhline(y=0.3, color='r', linestyle='--', label='Consciousness thresh
axes[1, 1].legend()
axes[1, 1].grid(True, alpha=0.3)

plt.tight_layout()
plt.show()
```

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