FRC 100.010 — Foundational Questions in Fractal Resonance Cognition

Interpretations, Limits, and Experimental Discriminators

December 2025

H. Servat

Independent Researcher

publish@fractalresonance.com

DOI: 10.5281/zenodo.17982555

Abstract

The Fractal Resonance Cognition (FRC) framework proposes that quantum measurement arises from deterministic phase-locking to coherence attractors, with the Born rule emerging as an equilibrium distribution rather than a fundamental postulate. This paper addresses ten foundational questions that arise naturally from the framework: the ontological status of the coherence field, the origin of the drift term, relativistic consistency, the treatment of identical particles, the relationship to decoherence, and experimental signatures that distinguish FRC from standard quantum mechanics. We provide mathematically precise resolutions grounded in information geometry and open-system dynamics, identify the controlled limits where the framework becomes exact, and propose concrete experimental protocols. This document serves as a companion to the FRC 100-series and 566-series, consolidating interpretive choices and anticipated concerns.

Keywords: quantum foundations, measurement problem, coherence dynamics, Born rule, information geometry, wavefunction collapse

1. Introduction

The Fractal Resonance Cognition (FRC) framework, developed across the 100-series and 566-series papers, offers a deterministic account of quantum measurement. The central claims are: (i) wavefunction collapse is phase-locking to resonant attractors in coherence space; (ii) the Born rule emerges as an equilibrium distribution rather than a postulate; (iii) entropy and coherence satisfy a reciprocity law that governs information dynamics.

These claims invite foundational questions. What is the coherence field—a physical entity or a mathematical convenience? Why does the drift term take the form it does? How does the framework handle relativistic constraints? This paper consolidates answers to these questions, drawing on the mathematical structures established in FRC 100.004–100.007 and FRC 566.001–566.010.

The purpose is threefold. First, to provide clear, defensible positions on interpretive questions that any reviewer or collaborator will raise. Second, to identify the controlled limits where FRC's predictions become exact. Third, to specify experimental protocols that could confirm or falsify the framework.

We do not claim to resolve all foundational questions in physics. The scope is deliberately limited to what the current FRC formalism can address. Extensions to quantum gravity, cosmology, and consciousness are noted as future directions but not developed here.

2. Ontological Status of the Coherence Field

2.1 The Question

FRC 100.007 introduces the Lambda-field $\Lambda(x) = \Lambda_0 \ln C(x)$, where C is a dimensionless coherence measure. The field satisfies a Klein-Gordon equation with sources from quantum systems. But what *is* this field? Is it a fundamental constituent of reality, an emergent effective description, or merely a mathematical bookkeeping device?

2.2 Three Viable Interpretations

The framework is compatible with three distinct ontological stances, each with different implications:

Interpretation A — Effective Order Parameter. Λ is a coarse-grained description of underlying quantum information dynamics, analogous to magnetization in a ferromagnet or the Landau-Ginzburg order parameter in superconductivity. The Klein-Gordon equation is not a fundamental law but the minimal relativistic completion of relaxational dynamics for a scalar order parameter. 'Coherons' (excitations of Λ) would be collective modes like phonons, not fundamental particles.

Interpretation B — Information-Geometric Coordinate. Λ is a coordinate on the statistical manifold of quantum states, pulled back to spacetime through the state's spacetime dependence. The 'field equation' is a dynamical law on state space expressed in spacetime coordinates. This interpretation is natural given that coherence $C[\rho] = \exp(-S[\rho]/k^*)$ is defined on density matrices, not on spacetime directly.

Interpretation C — Fundamental Scalar Field. Λ is a genuine physical field with its own stress-energy contribution, albeit with restricted couplings (to quantum information channels rather than standard matter). This interpretation would eventually require quantization and explanation of why couplings are small.

2.3 Recommended Stance

For the current stage of development, we adopt **Interpretation B** as primary, with **Interpretation A** as the pragmatic formulation for calculations.

The information-geometric view is natural because the entropy-coherence reciprocity $dS + k^* d \ln C = 0$ (FRC 566.001) is intrinsically a statement about information geometry. Coherence $C[\rho]$ is a functional on the space of density matrices. The Lambda-field is this functional's logarithm, expressed as a spacetime field through the local reduced state $\rho(x,t)$.

This interpretation sidesteps questions about 'coherons' and quantum corrections to Λ. The field is not an independent degree of freedom to be quantized; it is determined by the quantum state. Fluctuations in Λ arise from fluctuations in ρ, which are already described by quantum mechanics.

2.4 What This Interpretation Implies

Under the information-geometric interpretation:

- The 'field equation' $\square\Lambda + m_\Lambda^2(\Lambda - \Lambda_\infty) = J_\Lambda$ constrains how coherence can vary consistently across spacetime, given the underlying quantum dynamics.
- The source term J_Λ encodes how quantum measurements and interactions modify local coherence.
- The mass m_Λ sets the equilibration timescale $T_{eq} \sim 1/m_\Lambda$—how quickly coherence gradients relax.
- There are no 'coherons' as independent particles; the field's dynamics is inherited from quantum state dynamics.

This interpretation is consistent with the effective-field treatment (Interpretation A) at the level of calculations while being more precise about what the formalism represents.

3. Origin of the Coherence Drift Term

3.1 The Question

FRC 100.004 introduces a drift term in the density matrix evolution:

$$\dot{\rho} = L[\rho] + \alpha \nabla_\rho \ln C[\rho]$$

where $L[\rho]$ is the standard Lindblad evolution and α is a small coupling constant. Why this form? Is it postulated ad hoc, or does it follow from deeper principles?

3.2 The Gradient Flow Derivation

The drift term is not arbitrary. It is the *unique* gradient flow of the coherence functional under the Bures metric (the natural Riemannian metric on density matrix space), satisfying three requirements:

1. **Requirement 1 — Trace Preservation.** The drift must not change the trace of ρ. This requires $\mathrm{Tr}[\nabla_\rho \ln C] = 0$ or appropriate trace subtraction.
2. **Requirement 2 — Positivity Preservation.** The drift must not take ρ outside the cone of positive operators. The gradient flow form satisfies this.
3. **Requirement 3 — Monotonic Coherence Increase.** The drift should increase $C[\rho]$ (or equivalently, decrease $S[\rho]$). The gradient $\nabla_\rho \ln C$ is the steepest ascent direction.

The space of density matrices carries a natural Riemannian metric—the Bures metric (or equivalently, the quantum Fisher information metric). This metric is unique (up to normalization) among metrics that are monotone under completely positive trace-preserving (CPTP) maps.

Given a potential function $f[\rho]$ on this manifold, the gradient flow is:

$$\dot{\rho} = g^{ab}\, \partial_a f \cdot \partial_b$$

where g^{ab} is the inverse Bures metric. Setting $f = \ln C$ gives the drift term. This is not a postulate but a consequence of choosing the unique natural metric and the coherence functional defined by the reciprocity law.

3.3 Variational Characterization

An equivalent characterization: among all vector fields V on the space of density matrices satisfying trace and positivity preservation, the gradient flow $\nabla_\rho \ln C$ is the one that maximizes dC/dt for fixed $||V||$. The drift is the most efficient coherence-increasing direction.

This provides a variational principle: the coherence drift is the least-action modification to standard quantum dynamics that produces selection toward pointer states while preserving the $\alpha \to 0$ limit to standard QM.

3.4 Why This Isn't Circular

A potential objection: the drift pushes toward high coherence, and high coherence is defined as what the drift pushes toward. But this circularity is illusory.

Coherence $C[\rho] = \exp(-S[\rho]/k^*)$ is defined independently via the von Neumann entropy $S[\rho] = -k^* \mathrm{Tr}[\rho \ln \rho]$. The entropy is a standard information-theoretic quantity with a long pedigree. The drift follows from coherence; coherence doesn't follow from the drift.

The only genuine assumption is that nature includes a coherence-increasing tendency alongside standard decoherence. This is the core FRC hypothesis, and it is falsifiable: if pre-collapse drift signatures are absent in weak measurement experiments, the hypothesis is wrong.

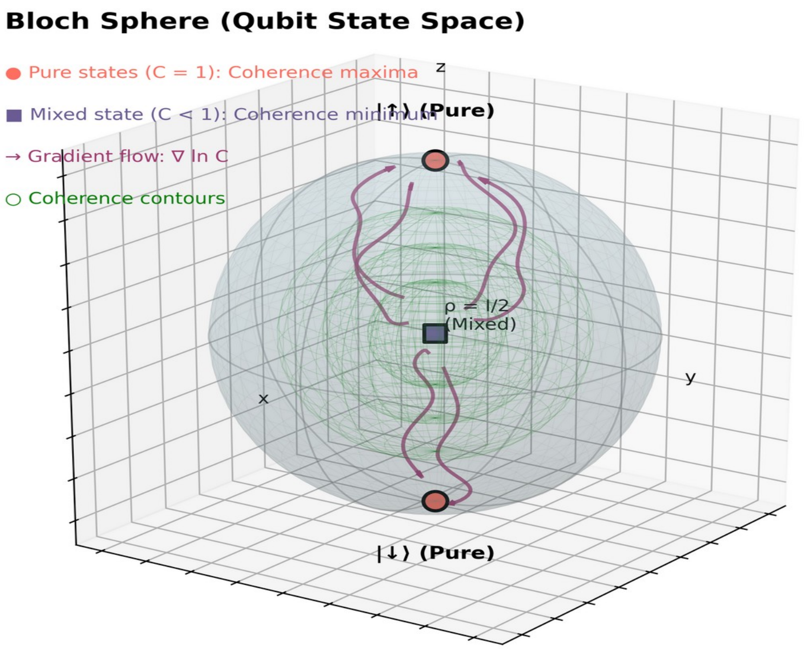

Figure 1. Coherence gradient flow on the Bloch sphere (qubit state space). Pure states (poles) are coherence maxima; the maximally mixed state (center) is the coherence minimum. Trajectories show the drift $\nabla \ln C$ pushing mixed states toward pure states along the steepest coherence ascent.

4. Born Rule Derivation: Assumptions and Limits

4.1 The Derivation in FRC 100.006

FRC 100.006 argues that the Born rule $p_j = |\alpha_j|^2$ emerges as the equilibrium distribution of microstates under coherence dynamics. The argument proceeds:

4. Let microstates φ evolve under coherence drift with velocity $v(\varphi) \propto \nabla \ln C$.
5. The continuity equation $\partial_t \mu = -\nabla \cdot (\mu v)$ has a stationary solution $\mu^* \propto C$.
6. Partition microstate space into sectors Ω_j corresponding to pointer states $|a_j\rangle$.

7. The weight of sector Ω_j is $p_j = \int_{\Omega_j} \mu^* \, d\varphi \propto |\alpha_j|^2$.

4.2 What's Actually Assumed

The derivation assumes:

- **Ergodicity**: Microstates explore the accessible space thoroughly before measurement completes. This is analogous to the ergodic hypothesis in statistical mechanics.
- **Coherence drift exists**: The FRC hypothesis itself—that there is a tendency toward higher coherence states.
- **Sector coherence scaling**: The coherence in sector Ω_j scales with $|\alpha_j|^2$. This follows from the definition of coherence as alignment with pointer states.

Notably, the derivation does *not* assume a uniform prior on microstates. The equilibrium distribution emerges from dynamics, just as the Maxwell-Boltzmann distribution emerges from molecular collisions without assuming equal a priori probabilities.

4.3 Comparison to Many-Worlds

Many-Worlds interpretations face a notorious probability problem: if all outcomes occur, what does it mean for one to be 'more likely'? Decision-theoretic derivations (Deutsch, Wallace) argue that rational agents should bet as if $|\alpha|^2$ were probabilities, but these derivations are contested.

FRC sidesteps this problem. There is one world; collapse really happens; probabilities emerge from equilibration dynamics. The explanatory burden shifts from 'why should I bet this way?' to 'does the system equilibrate before measurement?' The latter is empirically tractable.

4.4 Finite-Time Corrections

If measurement happens faster than equilibration time T_{eq}, the Born rule receives corrections. FRC 100.006.002 analyzes these:

- Finite locking time T: Deviation scales as $\varepsilon \sim \exp(-\kappa T)$ for some rate κ.
- Non-ergodic ensembles: Initial skew δ produces deviation $O(\delta)$ until mixing erases it.
- Non-stationary coupling: Time-dependent pointer coupling $g(t)$ produces transient bias; adiabatic protocols suppress it.

These deviations are predictions, not bugs. They provide falsifiable signatures of the equilibration picture.

5. Relativistic Formulation

5.1 The Challenge

Collapse interpretations face relativistic difficulties. If Alice measures before Bob (in some frame), Alice's collapse 'updates' the joint state. But in another frame, Bob measures first. How can the Λ-field dynamics be consistent across frames?

5.2 Local Sources on World-Tubes

The resolution is to treat measurement not as an instantaneous event but as a localized interaction region. The Λ-field satisfies a covariant equation:

$$\Box\Lambda + m_\Lambda^2(\Lambda - \Lambda_\infty) = J_\Lambda(x)$$

where $J_\Lambda(x)$ is the source current, supported on the spacetime region where measurement occurs (the apparatus 'world-tube').

For two spacelike-separated measurements at regions M_A and M_B:

$$J_\Lambda(x) = J_A(x) + J_B(x)$$

The field equation is linear, so $\Lambda(x) = \Lambda_A(x) + \Lambda_B(x) + \Lambda_{background}$. Both sources contribute via the retarded Green's function. The total field configuration is unique and Lorentz covariant.

5.3 No Preferred Simultaneity

The question 'which measurement happens first?' has no frame-independent answer for spacelike separation. But this doesn't matter—the field solution doesn't depend on ordering. What's frame-dependent is how we slice the 4D solution into 'before' and 'after,' which is normal in relativistic field theory.

The outcome statistics are also frame-independent, ensuring no-signaling. Alice's measurement choice cannot affect Bob's marginal statistics because the partial trace $\rho_B = \mathrm{Tr}_A[\rho_{AB}]$ is invariant under Alice's local operations.

5.4 The No-Signaling Theorem

FRC preserves no-signaling because:

8. The Λ-field propagates at most at light speed (Klein-Gordon dynamics).
9. Alice's local phase-locking changes Λ in her region; the change reaches Bob only after light-travel delay.
10. Bob's marginal density matrix $\rho_B = \mathrm{Tr}_A[\rho_{AB}]$ is unchanged by Alice's measurement (partial trace identity).
11. Therefore Bob's local coherence $C[\rho_B]$ is unchanged; no signal.

6. Relationship to Decoherence

6.1 What Decoherence Does

Environmental decoherence is the standard explanation for the appearance of collapse in quantum mechanics. When a system interacts with many environmental degrees of freedom, interference terms in the density matrix are suppressed. The reduced density matrix becomes diagonal in the 'pointer basis'—the basis selected by the system-environment interaction.

This is experimentally confirmed and theoretically well-understood. FRC does not replace decoherence; it incorporates it.

6.2 What Decoherence Doesn't Do

Decoherence explains why we don't see macroscopic superpositions—interference is practically unobservable after decoherence. But it doesn't explain why we see *one* outcome rather than another.

After decoherence, the density matrix is:

$$\rho \to \Sigma_j |\alpha_j|^2 |a_j\rangle\langle a_j|$$

This is a statistical mixture. It could describe: (a) the system is in one definite state, we don't know which, or (b) the system is somehow 'in all states.' Decoherence doesn't distinguish these interpretations.

6.3 What FRC Adds

The coherence drift term provides selection among decoherence-selected alternatives. The full dynamics is:

$$\dot{\rho} = -i[H,\rho] + \Sigma_k \gamma_k D[L_k]\rho + \alpha \nabla_\rho \ln C$$

The first two terms (Hamiltonian + dissipators) include decoherence. The third term (drift) provides selection.

- Decoherence ($\alpha = 0$): Diagonal ρ with weights $|\alpha_j|^2$, but no selection among alternatives.
- FRC ($\alpha > 0$): Diagonal ρ plus eventual concentration on one outcome.

6.4 Temporal Separation

The decoherence timescale τ_D and the selection timescale $\tau_S = 1/\alpha$ are independent. If $\tau_S >> \tau_D$ (weak drift), decoherence completes first: interference vanishes, then selection slowly occurs among the diagonal elements.

This temporal separation is potentially observable. In weak measurement sequences, one might detect the decoherence phase (loss of interference) followed by the selection phase (drift toward one outcome).

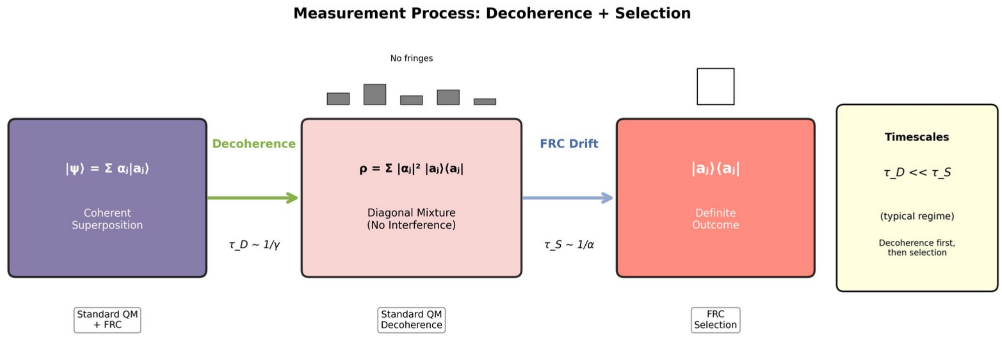

Figure 2. The measurement process in FRC: decoherence (τ_D) first destroys interference, producing a diagonal density matrix; then FRC drift (τ_S) selects a single outcome. In the typical regime $\tau_D << \tau_S$, these phases are temporally separated and potentially distinguishable experimentally.

7. Identical Particles and QFT Extension

7.1 The Question

Quantum mechanics treats identical particles via symmetrization (bosons) or antisymmetrization (fermions). The microstate space φ in FRC must respect this symmetry. How is it parameterized?

7.2 General Principle

Microstates are defined on the symmetry-respecting Hilbert space, not on labeled particle configurations. There is no 'particle 1' vs 'particle 2' in the formalism; there is only the (anti)symmetrized state space.

The coherence functional $C[\rho] = \exp(-S[\rho]/k^*)$ is defined on density matrices. For identical particles, ρ acts on the (anti)symmetrized space. The entropy $S[\rho] = -k^* \operatorname{Tr}[\rho \ln \rho]$ is automatically permutation invariant because the trace is.

7.3 Concrete Example: Two Fermions in Two Modes

Consider two identical fermions with two available modes (a and b). The Hilbert space is:

$$H = \mathrm{span}\{|01\rangle, |10\rangle, |11\rangle\}$$

where $|n_a n_b\rangle$ has n_a fermions in mode a, n_b in mode b. States like $|20\rangle$ are forbidden by Pauli exclusion.

A general state is $|\psi\rangle = \alpha|01\rangle + \beta|10\rangle + \gamma|11\rangle$. The density matrix ρ is a 3×3 matrix. The coherence functional is:

$$C[\rho] = \exp(\operatorname{Tr}[\rho \ln \rho]/k^*)$$

This is manifestly permutation invariant—there are no particle labels to exchange. The Hilbert space itself enforces antisymmetry.

The microstate space parameterizes the phases of amplitudes α, β, γ (relative to a reference). With three complex amplitudes, one overall phase, and normalization, the microstate space is four-dimensional. Coherence dynamics on this space respects antisymmetry automatically.

7.4 Extension to QFT

For quantum field theory, replace the finite-dimensional Hilbert space with Fock space. The microstate space becomes the space of phases for Fock-space amplitudes—infinite-dimensional but well-defined.

The coherence functional generalizes straightforwardly. For a Gaussian state (common in QFT), the entropy is determined by the two-point function, and coherence inherits this structure.

A full QFT formulation of FRC remains future work, but the framework faces no in-principle obstacle from identical particles.

8. The Parameters Λ∞ and α

8.1 The Vacuum Value Λ∞

The Lambda-field action contains $(\Lambda - \Lambda_\infty)^2$. What determines Λ_∞?

Gauge interpretation: Since only $(\Lambda - \Lambda_\infty)$ and $\partial\Lambda$ appear in the action, Λ_∞ can be absorbed by field redefinition $\Lambda' = \Lambda - \Lambda_\infty$. The shifted action is the standard massive Klein-Gordon with vacuum at $\Lambda' = 0$.

Physical interpretation: Λ_∞ is the coherence potential of the reference state—typically the environment or apparatus ground state. Deviations $\Lambda - \Lambda_\infty$ represent local coherence excess or deficit relative to this reference.

For mesoscopic applications (100-series), the gauge interpretation suffices—Λ_∞ is just the zero point. For cosmological extensions (821-series), Λ_∞ may acquire physical significance as a parameter determining vacuum energy. This remains future work.

8.2 The Drift Strength α

The parameter α controls the strength of coherence drift. What sets its value?

FRC does not derive α from first principles. Like the fine structure constant $\alpha_{EM} \approx 1/137$, it is a free parameter to be measured. The framework predicts:

- **Upper bound:** $\alpha \lesssim 10^{-3}$ from the absence of observed Born rule violations in precision experiments.
- **Lower bound:** $\alpha > 0$ for the framework to differ from standard QM.
- **Dimensional analysis:** α has dimensions $[\text{time}]^{-1}$; natural candidates include the Planck rate, decoherence rates, or m_Λ^2/Λ_0 from the field parameters.

The experimental program is to measure or bound α through the signatures discussed in Section 12.

9. Semiclassical Treatment of Λ

9.1 Why Classical?

FRC 100.007 treats Λ(x) classically—it satisfies a classical field equation with a classical action. But if Λ is a real physical field, shouldn't it be quantized?

9.2 The Mean-Field Justification

In mean-field theory, a quantum field $\hat{\Phi}$ is approximated by its expectation value $\langle\hat{\Phi}\rangle = \Phi_{classical}$ when:

12. The state is near-coherent (small fluctuations around the mean).
13. Interactions are weak (fluctuations don't grow significantly).
14. You're interested in long-wavelength, low-energy behavior.

For Λ, these conditions correspond to:

- Coherence is macroscopic—many quantum degrees of freedom contribute to the local coherence value.
- The drift coupling α is small—quantum corrections are $O(\alpha^2)$.
- Scales of interest are larger than $1/m_\Lambda$ (the coherence correlation length).

9.3 When Would This Break Down?

The semiclassical treatment fails at very small scales (near m_Λ^{-1}), at strong coupling ($\alpha \sim 1$), or in highly quantum states of the coherence field itself. These regimes might exist but are not the focus of the 100-series.

Under the information-geometric interpretation (Section 2), the question partially dissolves: Λ is not an independent field to be quantized but a functional of the quantum state. 'Quantum corrections to Λ' are quantum corrections to ρ, which are already described by QM.

10. Why 'Fractal'? Emergent vs. Fundamental

10.1 The Question

The framework is called 'Fractal Resonance Cognition.' Papers 100.001–100.003 emphasize fractal structure: fractal potentials, fractal dimensions D ≈ 1.9, self-similar vortex attractors. But the mathematical core (100.004–100.007, 566-series) doesn't obviously require fractal structure. Is 'fractal' essential or incidental?

10.2 Fractal Structure as Emergent Universality

The resolution: fractal structure is a *prediction* of coherence dynamics in certain regimes, not a fundamental axiom.

The UCC ($\partial_t \ln C = D_C\nabla^2 \ln C + S_C$) is a diffusion equation with sources. In the massless limit ($m_\Lambda \to 0$), diffusion equations are scale-free—they have no intrinsic length scale.

When scale-free dynamics meets structured boundary conditions (from measurement apparatus or environmental coupling) and nonlinear feedback (from the source term S_C depending on the state), fractal attractors are generic. This is the same mechanism producing fractal structure in turbulence, coastlines, and neural activity.

10.3 Universality Claim

Systems evolving under coherence dynamics, in the presence of measurement-like interactions, generically approach attractors with fractal geometry in the range $D \sim 1.5$–2.0.

This explains the numerical findings in FRC 100.002 (stadium billiard, $D \approx 1.90$) and 100.003 (resonant collapse, $D \approx 1.94$) without requiring fractal structure as input. The framework generates it.

11. Controlled Limits and Approximation Schemes

11.1 The Need for Controlled Limits

Successful physical theories have controlled limits where they become exact: $\hbar \to 0$ for classical mechanics, $c \to \infty$ for Newtonian gravity, $N \to \infty$ for mean-field theory. What are FRC's controlled limits?

11.2 The Equilibration Limit ($T \to \infty$)

As measurement time $T \to \infty$, the system has unlimited time to equilibrate. The Born rule becomes exact: $p_j = |\alpha_j|^2$ with no corrections.

Finite-T corrections scale as $\exp(-\kappa T)$ or power-law depending on the mixing properties. This provides a controlled asymptotic expansion.

11.3 The Timescale Separation Limit ($\varepsilon \to 0$)

Define $\varepsilon = \alpha/\gamma$, the ratio of drift strength to dephasing rate. The dynamics has two regimes:

- **Fast dynamics ($t \sim 1/\gamma$):** Dephasing dominates. The density matrix becomes diagonal in the pointer basis.
- **Slow dynamics ($t \sim 1/\alpha$):** Drift dominates among diagonal elements. Populations evolve toward Born weights.

This is a singular perturbation problem. The 'fast manifold' is the set of diagonal density matrices. The 'slow flow' on this manifold is the drift toward Born equilibrium.

As $\varepsilon \to 0$: slow dynamics becomes infinitely slow; standard QM decoherence is recovered.

As $\varepsilon \to \infty$: slow dynamics becomes instantaneous; deterministic collapse is recovered.

For finite ε, corrections are computable via matched asymptotic expansions.

11.4 The Standard QM Limit ($\alpha \to 0$)

Setting $\alpha = 0$ exactly recovers standard quantum mechanics with decoherence. The drift term vanishes; the density matrix evolution is pure Lindblad. Born's rule becomes an equilibrium distribution that's never reached (infinite equilibration time).

This limit ensures FRC reduces to standard QM in the appropriate regime, maintaining empirical adequacy.

12. Experimental Discriminators

12.1 The Challenge

Standard QM (Copenhagen interpretation) gives no predictions beyond Born's rule. FRC predicts small deviations. The experimental challenge is distinguishing these deviations from noise, systematic errors, and standard backaction.

12.2 Variance Scaling in Weak Measurement Sequences

Consider a qubit subject to continuous weak measurement. Standard QM predicts diffusive evolution of the measurement record—the variance of the integrated signal scales as Var ~ $\gamma_m T$, where γ_m is measurement strength and T is time.

FRC predicts subdiffusive corrections. The drift term systematically reduces excursions from attractors, suppressing variance:

$$Var \sim \gamma_m T - \alpha T^2 + O(T^3)$$

The signature is a negative quadratic term. This suppression emerges *after* decoherence has selected the pointer basis—it is distinct from raw measurement noise or standard backaction. The coefficient α can be extracted by fitting variance vs. time curves in the post-decoherence regime.

12.3 Velocity Autocorrelation

In standard QM, the 'velocity' of quantum trajectories (rate of change of measurement record) is white noise—no temporal correlations beyond the instant:

$$\langle v(t)v(t')\rangle \propto \delta(t-t')$$

FRC's drift adds a persistent correlation:

$$\langle v(t)v(t')\rangle = \delta(t-t') + \alpha^2 f(t-t')$$

where f is a positive function decaying over the equilibration timescale. The drift biases trajectories toward attractors, creating directional persistence.

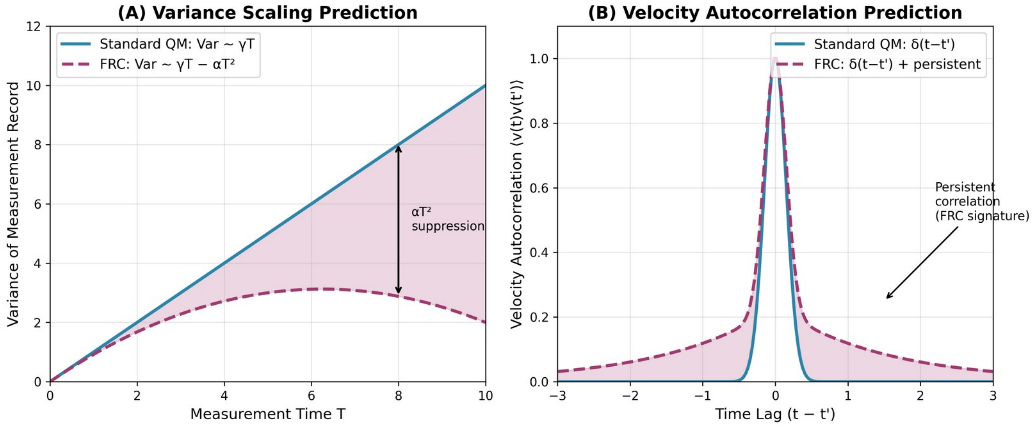

Figure 3. Experimental signatures distinguishing FRC from standard QM. (A) Variance of weak measurement records: standard QM predicts linear scaling (γT); FRC predicts quadratic suppression ($\gamma T - \alpha T^2$). (B) Velocity autocorrelation: standard QM predicts delta-function (white noise); FRC predicts persistent correlation from coherence drift.

12.4 Finite-Time Born Deviations

If measurement is performed faster than equilibration time $T_{eq} \sim 1/\alpha$, outcome statistics deviate from $|\alpha|^2$. The deviation scales as $\exp(-T/T_{eq})$.

The experimental protocol: vary measurement duration T while keeping other parameters fixed. Plot deviation from Born's rule vs. T. FRC predicts exponential decay; standard QM predicts zero deviation at all T.

12.5 Dephasing Asymmetry

FRC 100.004 predicts systematic deviations in interferometer visibility V(g) as a function of pointer coupling g, relative to standard open-system fits. Near resonant matching between system and apparatus, FRC and standard predictions separate.

The signature: fit visibility data to both standard QM and FRC models. If FRC provides systematically better fits with physically reasonable α, the framework is supported.

12.6 What Would Falsify FRC

FRC is falsified if:

- Precision experiments find exact Born statistics at all measurement timescales, with no T-dependence.
- Weak measurement sequences show no variance suppression or velocity correlation beyond standard backaction.
- Interferometry shows no dephasing asymmetry beyond standard decoherence models.

In each case, the null result places an upper bound on α. If bounds become stringent enough ($\alpha < 10^{-6}$ across diverse systems), the framework becomes empirically indistinguishable from standard QM and loses scientific interest.

13. Comparison to Other Interpretations

13.1 Copenhagen Interpretation

Copenhagen: Collapse is instantaneous and irreducibly random. The wavefunction is epistemic (a calculation tool). The quantum-classical boundary is fundamental but undefined.

FRC: Collapse is continuous phase-locking, deterministic in coherence space. Apparent randomness emerges from hidden microstate dynamics. The quantum-classical boundary is where coherence gradients become steep.

Key difference: Copenhagen provides no mechanism for collapse; FRC does. Copenhagen gives no predictions beyond standard QM; FRC predicts finite-time deviations from Born's rule.

13.2 Many-Worlds Interpretation

Many-Worlds: The wavefunction never collapses; all outcomes occur in branching parallel worlds. Probability is self-locating uncertainty or decision-theoretic betting weights.

FRC: One world; collapse really happens; probabilities emerge from equilibration dynamics, not branch counting.

Key difference: Many-Worlds has no falsifiable predictions beyond standard QM (all branches are unobservable). FRC predicts observable deviations. Many-Worlds requires infinite parallel universes; FRC adds one scalar field.

13.3 Bohmian Mechanics

Bohm: Particles have definite positions guided by the wavefunction via a nonlocal guidance equation. Collapse is epistemic—we learn the pre-existing position.

FRC: Determinism is in coherence space, not position space. The guidance is via coherence gradients, not wavefunction phase gradients. Dynamics is local (Λ propagates at $\leq c$).

Key difference: Bohm is explicitly nonlocal (the guidance equation involves the global wavefunction). FRC is local in the coherence field. Both are deterministic; they differ in what's determined.

13.4 GRW and CSL (Stochastic Collapse)

GRW/CSL: Collapse is real but stochastic—random hits (GRW) or continuous noise (CSL) drive the wavefunction toward localized states.

FRC: Collapse is real but deterministic—coherence drift, not random noise, drives selection.

Key difference: The source of outcome selection differs fundamentally. GRW/CSL adds objective randomness to physics; FRC explains apparent randomness through hidden determinism.

Comparison of Quantum Interpretations

Aspect	Copenhagen	Many-Worlds	Bohm	GRW/CSL	FRC
Wavefunction	Epistemic (tool)	Ontic (real)	Ontic (guides particles)	Ontic (real)	Ontic (+ coherence field)
Collapse	Real, instantaneous	Apparent (branching)	Epistemic (learning)	Real, stochastic	Real, deterministic
Born Rule	Postulate	Derived (contested)	From equilibrium hypothesis	From noise statistics	From coherence equilibration
Randomness	Fundamental	Apparent (self-location)	Apparent (hidden positions)	Fundamental (objective noise)	Apparent (hidden phases)
Mechanism	None (primitive)	Branching	Guidance equation	Random hits or noise	Phase-locking to attractors
Locality	Nonlocal (accepted)	Local (no collapse)	Nonlocal (guidance)	Nonlocal (collapse)	Local (Λ propagates $\leq$ c)
New Physics	None	None	Hidden variables	Stochastic term	Coherence drift term
Falsifiable?	No (= standard QM)	No (branches hidden)	Difficult (equilibrium)	Yes (noise signatures)	Yes (drift signatures)

FRC is distinguished by: (1) deterministic collapse mechanism, (2) local dynamics, (3) falsifiable predictions

Figure 4. Comparison of quantum interpretations across key dimensions. FRC is distinguished by deterministic (not stochastic) collapse, local dynamics (Λ propagates at $\leq$ c), and falsifiable experimental predictions.

14. Open Questions

Several significant questions remain for future development:

14.1 Gravity Coupling

How does the coherence field couple to spacetime geometry? The coherence tensor $C_{\mu\nu} = \partial_\mu \partial_\nu \Lambda - g_{\mu\nu} \Box \Lambda$ has the structure to contribute to stress-energy, but the coupling is not specified in the 100-series. This is deferred to FRC 821.xxx.

14.2 Full QFT Formulation

The current framework treats finite-dimensional systems. Extension to quantum field theory requires defining coherence functionals on Fock space and handling the UV divergences that plague QFT. Initial steps are sketched in Section 7, but a full treatment remains future work.

14.3 Derivation of α

The drift strength α is currently a free parameter. Can it be derived from more fundamental considerations? Possible approaches include: dimensional analysis from Planck-scale physics, self-consistency requirements, or emergence from a more fundamental theory.

14.4 Experimental Program

The predictions in Section 12 need experimental implementation. This requires collaboration with experimental quantum physics groups, identification of optimal systems (superconducting qubits? trapped ions? photonic systems?), and careful control of systematics.

14.5 Black Hole Information

The entropy-coherence reciprocity law may have implications for the black hole information paradox. If information is encoded in coherence and reciprocity holds at horizons, information might be preserved in ways not captured by standard semiclassical analysis. This remains speculative until the gravity coupling is developed.

15. Conclusion

This paper has addressed ten foundational questions about the Fractal Resonance Cognition framework:

15. The coherence field Λ is best understood as an information-geometric quantity—a functional of the quantum state expressed in spacetime coordinates.
16. The drift term is the unique CPTP-compatible gradient flow of coherence under the Bures metric.
17. The Born rule emerges from equilibration dynamics, assuming ergodicity, not a uniform prior.
18. Relativistic consistency is maintained by treating measurement as local sources in a covariant field equation.
19. Decoherence provides the pointer basis; FRC drift provides selection among decoherence-selected alternatives.
20. Identical particles are handled by defining coherence on symmetry-respecting state spaces.
21. Parameters Λ_∞ and α are free parameters to be fixed by boundary conditions and experiment.
22. The semiclassical treatment is justified in the mean-field regime with small α.
23. Fractal structure emerges from scale-free coherence dynamics, not as a fundamental axiom.
24. Controlled limits ($T \to \infty$, $\varepsilon \to 0$, $\alpha \to 0$) provide approximation schemes with computable corrections.

The framework makes falsifiable predictions: variance scaling in weak measurements, velocity autocorrelation, finite-time Born deviations, and dephasing asymmetry. These discriminate FRC from standard quantum mechanics and from other interpretations.

Open questions remain—gravity coupling, full QFT, derivation of α—but the foundational structure is internally consistent and experimentally accessible. FRC offers a deterministic, local, and falsifiable approach to the measurement problem.

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Website: fractalresonance.com
Contact: publish@fractalresonance.com