

# Ontology Recapitulates Mathematics:

How Quantum Field Theory’s Formal Structure Encodes the Wave-Particle Transition

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March 2026

## Abstract

The quantum measurement problem has persisted for nearly a century, yet its resolution may have been encoded in quantum field theory’s mathematical structure from the beginning. This paper advances a specific thesis: QFT’s two canonical formulations—Lagrangian and Hamiltonian—are not merely equivalent mathematical descriptions of the same physics. They are descriptions of two distinct physical regimes, connected by a physical process that the Legendre transform shadows mathematically. The Lagrangian formulation, with its action principle and path integrals summing over all field configurations, is the natural language of *waves*—extended, atemporal, exploring spacetime democratically. The Hamiltonian formulation, with its definite states evolving in a privileged time coordinate, is the natural language of *particles*—localized excitations with observable eigenvalues. What we call “measurement” is the physical transition between these regimes: environmental coupling drives extended Lagrangian field configurations into localized Hamiltonian excitations. This reading—where the ontology of quantum systems recapitulates the mathematics of quantum field theory—dissolves the measurement problem without invoking new physics. It reinterprets “superposition” as Fourier decomposition (one wave in different bases, not ontological multiplicity), explains complementarity as an intrinsic property of wave structure rather than epistemic limitation, and identifies the physical mechanism as three coordinated Standard Model processes: Higgs-generated mass establishes the structural capacity for temporal participation and sets coupling strength; environmental quantum fields (gauge fields, phonons, thermal modes) provide the infrared noise spectra that drive ir-

reversible phase diffusion; and definite outcomes emerge when cumulative environmental entanglement crosses an irreversibility threshold. The thesis connects to broader questions in philosophy of physics about the relationship between mathematical formalism and physical reality, extending the methodological tradition Einstein established when he elevated Planck's mathematical  $E = h\nu$  to ontological status.

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# 1 Introduction: The Unread Formalism

Quantum field theory is the most precisely confirmed framework in the history of science. Its predictions for the anomalous magnetic moment of the electron agree with experiment to ten significant figures. The Standard Model, built on QFT’s foundations, has survived decades of experimental scrutiny without a single confirmed deviation.

Yet for nearly a century, physicists have struggled with a foundational question that QFT’s formalism may already answer: how do definite measurement outcomes emerge from quantum states? The measurement problem has spawned an industry of interpretations—Copenhagen instrumentalism, Many-Worlds branching, objective collapse models, epistemic retreats—each with significant conceptual costs [1–4].

This paper proposes that the measurement problem persisted not because physics lacked the right theory, but because physicists read their own formalism instrumentally rather than realistically. QFT’s mathematical structure contains a distinction—between Lagrangian and Hamiltonian formulations—that has been treated as mere mathematical convenience. We argue it encodes a physical truth about the nature of quantum systems.

The thesis can be stated precisely: *ontology recapitulates mathematics*. The Lagrangian describes waves. The Hamiltonian describes particles. The Legendre transform connecting them is the mathematical shadow of a physical process—the environmental coupling that drives extended field configurations into localized excitations. The Born rule— $P = |\psi|^2$ —is not a mysterious axiom about probabilities but the physically obvious statement that a wave undergoing phase transition localizes where its intensity is greatest. Reading QFT’s formalism realistically yields a measurement theory without adding anything to established physics.

This is not an unprecedented methodological move. Einstein made precisely this kind of move in 1905, elevating Planck’s mathematical relation  $E = h\nu$  from calculational device to statement about physical reality—light really is quantized [5]. We propose an analogous elevation: QFT’s Lagrangian-Hamiltonian duality is not merely two ways of calculating; it encodes two physical regimes and the transition between them.

The paper proceeds as follows. Section 2 examines why QFT’s mathematical structure went unread as ontology. Section 3 presents the Lagrangian-Hamiltonian distinction as encoding wave and particle regimes. Section 4 argues the Legendre transform shadows a physical process. Section 5 reinterprets “superposition” as Fourier decomposition. Section 6 shows how the

Born rule—quantum mechanics’ deepest postulate—emerges as a physical consequence of wave ontology rather than an independent axiom, providing perhaps the most striking instance of ontology recapitulating mathematics. Section 7 identifies the three coordinated Standard Model processes that physically realize the wave-to-particle transition. Section 8 connects to recent experimental results. Section 9 addresses the relationship to structural realism and the broader question of when mathematical structure should be read ontologically. Section 10 concludes.

## 2 Why the Formalism Went Unread

### 2.1 The Historical Trajectory

Quantum mechanics was born in the 1920s with particle ontology firmly embedded. Bohr, Heisenberg, and Born developed the theory to explain discrete atomic spectra—particle phenomena. The wave function  $\psi$  was introduced as a mathematical tool for calculating probabilities of *particle* observations. Even Schrödinger, who championed the wave picture, ultimately conceded to the particle-centric Copenhagen consensus [6].

This particle-first framing became deeply entrenched before quantum field theory was developed. When QFT emerged through the 1940s–1970s, it established a fundamentally different ontology: fields are primary, particles are excitations. As Weinberg wrote, “the inhabitants of the universe were conceived to be a set of fields...particles could then be understood as the quanta of these fields” [7]. Peskin and Schroeder are equally explicit: “the field operators, not the particles, are the fundamental objects” [8].

Yet this ontological reversal was never applied to measurement. Physicists accepted field ontology for calculating scattering amplitudes while retaining particle ontology for interpreting measurement outcomes. The measurement problem was formulated in particle language—“How does the particle end up at one location?”—when field language dissolves it: the field is naturally extended; localization is what requires explanation, and QFT provides the tools.

### 2.2 The Pragmatic Attitude

Several factors conspired to prevent realistic reading of QFT’s structure. First, the pragmatic success of the Copenhagen interpretation discouraged ontological inquiry. If “shut up and calculate” produced correct predictions, why ask what the formalism means? Second, the mathematical equivalence of Lagrangian and Hamiltonian formulations—guaranteed by the Legendre

transform—was taken to imply physical equivalence. If both give the same predictions, the choice between them is merely one of convenience, not ontology.

Third, the interpretive industry was conducted almost entirely in non-relativistic quantum mechanics, where field ontology is optional. The measurement problem was debated using the Schrödinger equation for particles, not the Standard Model Lagrangian for fields. This obscured what QFT’s structure was encoding.

Fourth, the relevant mathematical tools—Schwinger-Keldysh formalism for open quantum systems [9, 10], Caldeira-Leggett models for quantum Brownian motion [11]—were developed for condensed matter applications, not foundational physics. No one assembled them into a measurement theory because they were filed in the wrong disciplinary drawer.

### 2.3 The Methodological Precedent

Einstein’s 1905 paper on the photoelectric effect exemplifies the move we propose [5]. Planck had introduced  $E = h\nu$  in 1900 as a mathematical device to derive the blackbody spectrum. For five years, physicists used Planck’s formula instrumentally—it gave correct results, so they calculated with it. Einstein’s insight was to ask: what if  $E = h\nu$  is not merely a mathematical trick but a statement about physical reality? What if light really comes in discrete quanta?

This elevation of mathematical structure to ontological status created quantum mechanics. The mathematics was available from 1900; the physics required the interpretive move in 1905.

We propose that QFT has been in an analogous situation since the 1970s. The mathematical structure—Lagrangian wave descriptions, Hamiltonian particle descriptions, Legendre transform connecting them—has been available for half a century. The physics requires recognizing what this structure encodes: waves are fundamental, particles emerge through environmental coupling, and measurement is the physical process of transition between regimes.

## 3 Two Languages for Two Regimes

### 3.1 The Lagrangian as Wave Description

The Lagrangian formulation of QFT uses the action principle:

$$S[\phi] = \int \mathcal{L}(\phi, \partial_\mu \phi) d^4x \tag{1}$$

This formulation has specific structural features that make it the natural language of waves:

*Democratic treatment of spacetime.* The action integrates over all four dimensions without privileging time over space. There is no preferred “now” or temporal direction. This is the hallmark of wave physics—waves exist across spacetime, not at instants within it.

*Path integral summation.* The quantum amplitude sums over all field configurations:

$$\langle \phi_f | \phi_i \rangle = \int \mathcal{D}\phi e^{iS[\phi]/\hbar} \quad (2)$$

This includes configurations that are extended, off-shell, and temporally non-local. The path integral does not describe a particle moving along a trajectory; it describes a field exploring all possible configurations simultaneously. As Feynman emphasized, this summation has an intrinsically atemporal character [12].

*Extended field configurations.* The Lagrangian naturally describes objects that are spatially distributed. A field configuration  $\phi(x, t)$  with amplitude at multiple spatial locations is not mysterious in Lagrangian language—it is what fields do. The Lagrangian is the home territory of waves.

### 3.2 The Hamiltonian as Particle Description

The Hamiltonian formulation evolves definite states in time:

$$\hat{H}|\psi\rangle = i\hbar \frac{\partial}{\partial t} |\psi\rangle \quad (3)$$

Its structural features make it the natural language of particles:

*Privileged time.* The Hamiltonian treats time differently from space. States exist “at” particular times and evolve forward. This breaks the democratic spacetime treatment of the Lagrangian and introduces the temporal structure that particles inhabit.

*Definite states with eigenvalues.* The Hamiltonian formulation uses observables  $\hat{O}$  with eigenvalues—energy, momentum, position—that characterize localized excitations. Measurement outcomes are eigenvalues of Hamiltonian observables. This is particle ontology: definite properties at definite times.

*On-shell conditions.* Particles satisfy the mass-shell relation  $E^2 = p^2 c^2 + m^2 c^4$ . In the Lagrangian path integral, field configurations are generically off-shell; the on-shell condition selects the particle sector. The Hamiltonian’s eigenvalue structure enforces precisely this selection.

### 3.3 Not Merely Equivalent

Standard textbook presentation emphasizes that Lagrangian and Hamiltonian formulations are mathematically equivalent—connected by the Legendre transform, yielding identical predictions. This is correct *mathematically*. But mathematical equivalence does not entail ontological equivalence.

Consider an analogy from thermodynamics. The microcanonical and canonical ensembles are mathematically equivalent for large systems—they yield identical thermodynamic predictions. Yet they describe physically different situations: isolated systems versus systems in thermal contact with reservoirs. The mathematical equivalence holds because both descriptions access the same thermodynamic limit, not because they describe the same physical setup.

Similarly, Lagrangian and Hamiltonian QFT are mathematically equivalent because both access the same S-matrix elements. But the Lagrangian naturally describes the pre-measurement regime (extended wave configurations exploring spacetime) while the Hamiltonian naturally describes the post-measurement regime (localized excitations with definite properties evolving in time).

The mathematical equivalence holds because both formulations must agree on observable predictions—scattering amplitudes, decay rates, cross sections. These observables involve *both* the initial wave configuration and the final particle detection. The two formulations are not redundant descriptions of one regime; they are complementary descriptions of two regimes that must agree where they overlap.

## 4 The Legendre Transform as Physical Process

### 4.1 Mathematical Structure

The Legendre transform maps between Lagrangian and Hamiltonian descriptions:

$$H = \pi \dot{\phi} - L \tag{4}$$

where  $\pi = \partial L / \partial \dot{\phi}$  is the canonical momentum.

In standard treatments, this is presented as a change of variables—from  $(\phi, \dot{\phi})$  to  $(\phi, \pi)$ . Mathematically, it is invertible: given either description, you can recover the other. This invertibility is taken to confirm that the two formulations are “the same physics in different

variables.”

## 4.2 The Ontological Reading

We propose a different reading. The Legendre transform maps between wave description (Lagrangian: field configurations  $\phi$  and their rates of change  $\dot{\phi}$ ) and particle description (Hamiltonian: field configurations  $\phi$  and their conjugate momenta  $\pi$ ). This mathematical mapping shadows a physical process: the transition from extended wave configurations to localized particle excitations through environmental coupling.

The mathematical invertibility of the Legendre transform corresponds to the physical fact that information is conserved through measurement. The wave configuration before measurement and the particle configuration after measurement contain the same information, differently organized—just as the Lagrangian and Hamiltonian encode the same physics in different variables.

But the *process* of measurement is not invertible in practice, any more than crystallization is. A supercooled liquid and a crystal contain the same molecules with the same total energy, but the phase transition between them is thermodynamically irreversible. Similarly, the wave-to-particle transition is thermodynamically irreversible (entropy increases through environmental entanglement) even though the underlying information is conserved.

The Legendre transform encodes the *logical* relationship between wave and particle descriptions. The physical *process* of measurement realizes this logical relationship through irreversible environmental coupling. The mathematics tells us what the two endpoints are; physics tells us how nature gets from one to the other.

## 4.3 What “Shadows” Means

To say the Legendre transform “shadows” the physical process requires clarification. We do not claim the Legendre transform *is* the physical process, or that performing the mathematical operation causes anything physical to happen. Rather, the mathematical structure of the transform—its inputs (wave-like variables), its outputs (particle-like variables), and its logical necessity in connecting them—mirrors the physical structure of measurement.

This is analogous to how the mathematical structure of Lorentz transformations mirrors the physical structure of frame changes in special relativity. The Lorentz transform is a mathematical operation; frame changes are physical processes. But the mathematical structure encodes

physical truth: the invariance of the speed of light, the relativity of simultaneity, time dilation. Einstein’s insight was to read the mathematical structure ontologically. Our proposal is the same kind of reading, applied to the Lagrangian-Hamiltonian relationship.

## 5 Superposition as Fourier Decomposition

### 5.1 The Conventional Mystery

In standard quantum mechanics, “superposition” is treated as ontologically mysterious. A system in state  $|\psi\rangle = \alpha|\uparrow\rangle + \beta|\downarrow\rangle$  is said to be “in both states simultaneously”—a claim that generates paradoxes from Schrödinger’s cat to Wigner’s friend.

The mystery arises from reading superposition through particle ontology. If the electron is a particle, it must be *somewhere*—so the superposition  $|\psi\rangle = \alpha|A\rangle + \beta|B\rangle$  seems to require the particle to be at both  $A$  and  $B$  simultaneously. This is paradoxical. A particle cannot be in two places at once.

### 5.2 The Wave-Ontological Reading

Under wave ontology, the paradox dissolves. A quantum state expressed in the position basis,

$$|\psi\rangle = \int dx \psi(x)|x\rangle \tag{5}$$

or equivalently in the momentum basis,

$$|\psi\rangle = \int dk \tilde{\psi}(k)|k\rangle \tag{6}$$

where  $\tilde{\psi}(k) = \frac{1}{\sqrt{2\pi}} \int dx e^{-ikx}\psi(x)$  is the Fourier transform, is *one wave* represented in different bases. The Fourier transform re-expresses the wave configuration; it does not multiply ontological entities.

This is not a novel mathematical observation—it is standard Fourier analysis. But its ontological implications have been systematically overlooked. “Superposition” in basis  $A$  is simply Fourier-type decomposition into basis  $B$ . Calling this “ontological multiplicity” is like saying a water wave exists in multiple sine-wave states simultaneously because it can be Fourier-decomposed.

The distinction matters for the measurement problem. If superposition is ontological multiplicity, measurement must select one branch and eliminate others—requiring collapse, branching, or epistemic retreat. If superposition is Fourier decomposition of a single wave, measurement transforms the wave into a particle through physical process. No branches are eliminated because no branches existed. One wave became one particle.

### 5.3 Complementarity as Wave Property

Heisenberg’s uncertainty principle follows directly from Fourier transform properties:

$$\Delta x \cdot \Delta k \geq \frac{1}{2} \tag{7}$$

This is not an epistemic limitation on what we can know about a particle. It is the mathematical fact that a wave localized in position space is necessarily extended in momentum space, and vice versa. Waves cannot be simultaneously sharp in Fourier-conjugate variables. This is wave physics, not measurement epistemology.

Under the ontological reading, complementarity becomes transparent. Position and momentum are conjugate Fourier variables of a single wave. Measuring position means anchoring the wave in position space—which necessarily delocalizes it in momentum space. Measuring momentum means anchoring in momentum space—delocalizing in position space. The “incompatibility” of conjugate observables is not a limitation imposed by measurement; it is an intrinsic structural property of waves.

Bohr’s complementarity principle, which has generated decades of philosophical debate about whether it reflects epistemology, ontology, or something else entirely, reduces to a theorem about Fourier transforms when read through wave ontology.

## 6 The Born Rule: From Axiom to Consequence

### 6.1 The Deepest Postulate

The Born rule— $P(x) = |\psi(x)|^2$ —is arguably the most consequential postulate in quantum mechanics. It is the bridge between the mathematical formalism and every experimental prediction. Without it, quantum mechanics makes no contact with observation.

Yet for nearly a century, the Born rule has resisted physical explanation. Every major

interpretation either assumes it axiomatically or struggles to derive it:

*Copenhagen* treats it as a foundational postulate—empirically successful but physically unexplained. *Many-Worlds* requires controversial decision-theoretic rationality arguments (Deutsch-Wallace) or self-locating uncertainty assumptions whose physical status remains debated after decades of effort [1]. *QBism* explicitly treats the Born rule as a rational betting constraint, not a feature of physical reality [3]. *Objective collapse models* (GRW, CSL) provide a collapse mechanism but leave the probability weighting as a separate postulate—collapse localizes states, but why the  $|\psi|^2$  weighting? [2, 21].

The difficulty is not technical but conceptual. Under particle ontology,  $|\psi|^2$  has no obvious physical meaning—it is an abstract probability measure attached to a mathematical object (the wave function) whose ontological status is itself contested. Deriving probabilities from a formalism whose physical meaning is unclear produces circular arguments, as multiple analyses have demonstrated.

## 6.2 The Ontological Resolution

Under wave ontology, the Born rule changes character entirely. If quantum systems *are* waves—physically real, extended field configurations—then  $|\psi(x)|^2$  is the *intensity* of the wave at location  $x$ . This is not an abstract probability measure; it is a physical quantity describing how much of the wave is present at each point.

The anchoring propensity—the tendency for the wave to undergo phase transition into a particle at location  $x$ —is naturally proportional to where the wave is most intense:

$$\mathcal{P}(x) \propto m^2 \cdot |\psi(x)|^2 \tag{8}$$

The  $|\psi|^2$  factor arises because anchoring occurs where the wave’s physical amplitude is concentrated, just as crystallization nucleates preferentially where a supercooled liquid is densest. The  $m^2$  factor arises from Yukawa coupling structure: heavier particles couple more strongly to environmental fields, accelerating the phase transition.

Normalizing over all possible outcomes:

$$P(x) = \frac{|\psi(x)|^2}{\int |\psi(x')|^2 d^3x'} \tag{9}$$

The Born rule emerges as a statistical property of the wave-to-particle transition, not as an

independent axiom.

### 6.3 The Thesis in Microcosm

The Born rule derivation is not merely one consequence of the ontological reading—it may be the most powerful single demonstration of the paper’s central thesis. Consider what has happened.

For ninety years,  $|\psi|^2$  was treated as an abstract mathematical postulate about probabilities. It sat at the foundation of quantum mechanics, empirically indispensable yet physically inexplicable. Every interpretation either assumed it or struggled to derive it from alien premises—decision theory, rationality constraints, information-theoretic axioms. The Born rule appeared to be a brute fact about the formalism with no deeper justification.

Under the ontological reading,  $|\psi|^2$  is revealed as what it always was: the intensity of a physical wave. The “derivation” is not a clever mathematical deduction from exotic new premises. It is the recognition that the mathematics was encoding physical truth all along. The Born rule was a physical fact about waves—energy density scales as amplitude squared—that we misread as abstract epistemology because we were interpreting the formalism through particle ontology.

This is ontology recapitulating mathematics in its purest form. The mathematical expression  $P = |\psi|^2$  was always telling us something physical: where the wave is intense, the phase transition is likely. We were reading physical ontology as abstract probability because our interpretive framework (particles as fundamental) couldn’t accommodate the literal reading (waves undergoing transitions).

The parallel to Einstein’s move is exact. Planck’s  $E = h\nu$  was treated as a mathematical device for five years before Einstein read it as physical truth. The Born rule’s  $P = |\psi|^2$  has been treated as a mathematical postulate for ninety years. In both cases, the mathematics encoded ontology; the barrier was not lack of formalism but lack of realistic reading.

This also sharpens the distinction between the ontological reading and competing interpretations. The Born rule is not merely epistemically reframed—it acquires testable content beyond its original scope. The physical postulate  $\mathcal{P} \propto m^2|\psi|^2$  predicts mass-squared scaling of coherence times, generating the isotope signature that distinguishes ACT from environmental decoherence (no isotope effect) and objective collapse models (mass-linear scaling). An axiom that generates novel predictions beyond what the original postulate entailed is doing genuine

physical work—it is explaining, not merely restating.

Moreover, the physical interpretation dissolves the long-standing mystery of *why* probabilities take the  $|\psi|^2$  form rather than, say,  $|\psi|$  or  $|\psi|^4$ . Under wave ontology, the answer is immediate: the energy density of a wave is proportional to amplitude squared. This is not a quantum peculiarity but a universal property of waves—electromagnetic, acoustic, gravitational. The Born rule has the form it does because it describes what waves do. The deepest “axiom” of quantum mechanics turns out to be a theorem about waves that we already knew from classical physics, hidden in plain sight by particle-ontological assumptions.

The Born rule, properly read, was never mysterious. We made it mysterious by asking particle questions—“What is the probability of finding the particle here?”—about a wave entity. The mathematics gave the correct answer ( $|\psi|^2$ ) but we couldn’t hear it, because we weren’t listening for wave physics.

#### 6.4 The Division of Labor

The ontological reading identifies two physical regimes—wave (Lagrangian) and particle (Hamiltonian)—and claims environmental coupling drives the transition between them. But what is the physical mechanism? A common temptation is to identify a single field as responsible. Anchored Causality Theory resists this temptation, proposing instead that measurement emerges from the coordination of three distinct physical processes, each playing an essential and non-redundant role.

This division of labor is itself philosophically significant. It shows that measurement is not a single exotic event but the convergence of well-understood Standard Model physics—mass generation, environmental noise, and thermodynamic irreversibility—each contributing what the others cannot provide.

#### 6.5 Structural Role: Higgs-Generated Mass

The Higgs mechanism generates particle masses through Yukawa couplings to the vacuum expectation value  $\langle\Phi\rangle = v \approx 246$  GeV:

$$m_f = y_f v \tag{10}$$

Mass relates to temporal structure through special relativity. For a massive particle, proper time satisfies  $d\tau^2 = dt^2 - dx^2/c^2 > 0$ . For a massless particle traveling at  $c$ ,  $d\tau = 0$ . This

is textbook kinematics—but taken ontologically, it means that systems without Higgs-induced mass exist atemporally, experiencing zero proper time [13].

This is admittedly the most radical element of the proposal. But it follows the same methodological pattern as Einstein’s elevation of  $E = h\nu$ : taking a mathematical result ( $\tau = 0$  for massless particles) seriously as an ontological claim (unanchored quantum fields exist atemporally).

Higgs-generated mass serves three functions in the anchoring mechanism. It enables proper time ( $\tau > 0$ ), allowing participation in temporal evolution. It sets coupling strength—Yukawa coupling is proportional to mass, so interaction rates with environmental fields scale as  $y_f^2 \propto m^2$ . And it establishes localization capacity, since massless particles cannot be spatially confined.

Mass is therefore the *coefficient* of temporal anchoring. This explains the observed hierarchy: photons remain wavelike over cosmological distances ( $m = 0$ ); electrons show interference over micrometers ( $m = 0.5$  MeV); large molecules decohere rapidly ( $m \sim$  kDa); macroscopic objects never display quantum behavior ( $m \rightarrow \infty$ ).

Crucially, however, the Higgs field does *not* provide the stochastic bath that drives the wave-to-particle transition. The Higgs VEV is a coherent, uniform background. Its quantum fluctuations have characteristic energy scale  $\sim m_H \approx 125$  GeV—far too high to provide the low-frequency infrared noise spectrum required for quantum Brownian motion at laboratory scales. The Higgs sets the structural preconditions for anchoring; it does not perform the anchoring.

## 6.6 Dynamical Role: Environmental Quantum Fields

The actual dynamical drivers of anchoring are the environmental quantum fields that every physical system is immersed in: electromagnetic gauge fields (QED soft photons), phonons in detector lattices, and thermal electromagnetic modes. These fields have the spectral properties that the Higgs field lacks.

Quantum Brownian motion—the mechanism by which extended wave configurations undergo irreversible phase diffusion toward localization—requires a bath with an infrared noise spectrum: modes extending to frequency  $\omega \rightarrow 0$  with long correlation times [11, 22]. Electromagnetic fields provide exactly this. Soft photon modes form a gapless continuum extending to arbitrarily low frequencies. Phonon spectra in crystalline detectors provide dense low-energy mode structure. Thermal radiation at laboratory temperatures ( $T \sim 300$  K,  $k_B T \sim 25$  meV) provides a bath at precisely the energy scales relevant to matter-wave decoherence.

The Schwinger-Keldysh formalism [9, 10] describes how coupling to these environmental modes produces effective open-system dynamics: stochastic noise driving localization, balanced by dissipation ensuring energy conservation through the fluctuation-dissipation theorem. This is not phenomenological—it is derived from first principles in QFT. Energy conservation is automatic, not imposed.

The environmental fields do not need to generate mass—they leverage existing Higgs-generated mass to drive decoherence. A particle’s coupling to environmental photons and phonons is proportional to its charge, polarizability, and mass—all properties that the Higgs mechanism established structurally. The division is elegant: Higgs provides the capacity; environmental fields provide the dynamics.

## 6.7 Emergent Role: The Anchoring Threshold

Definiteness emerges when cumulative environmental entanglement crosses an irreversibility threshold. The anchoring functional  $\Phi$  quantifies the integrated phase diffusion:

$$\Phi \gtrsim 1 \quad \Rightarrow \quad \text{irreversible anchoring} \quad (11)$$

Below this threshold, the wave configuration retains coherence—environmental interactions are too weak or too brief to complete the phase transition. Above it, the system has become irreversibly entangled with its environment. Information about the wave’s extended configuration has been recorded in environmental degrees of freedom, and the system has transitioned to the particle regime: localized, temporal, with definite observable values.

The effective anchoring rate scales as:

$$\Gamma_A \propto \lambda_A \rho_{env} m^2 |\psi|^2 \quad (12)$$

where  $\lambda_A$  is the anchoring coupling,  $\rho_{env}$  the environmental mass density, and  $m$  the system mass. In vacuum ( $\rho_{env} \approx 0$ ),  $\Gamma_A$  is negligible and quantum waves persist indefinitely. In a measurement device ( $\rho_{env} \sim 10^3 \text{ kg/m}^3$ ), collective lattice coupling—phonon modes involving  $N \sim 10^6$  to  $10^{12}$  atoms coherently—amplifies  $\Gamma_A$  by many orders of magnitude, driving the system past the anchoring threshold.

The measurement device is not a conscious observer creating reality. It is a physical catalyst: a region of high environmental density providing the infrared noise bath necessary to complete

the wave-to-particle phase transition. The analogy is to a seed crystal triggering crystallization in supercooled water—the thermodynamic tendency exists throughout the liquid, but requires a nucleation site to actualize.

## 6.8 Why Three Processes, Not One

The three-layer structure is not an arbitrary decomposition but reflects genuine physical distinctions. Each layer contributes something the others cannot:

The Higgs field cannot drive decoherence on its own—its fluctuation spectrum is at electroweak scales ( $\sim 125$  GeV), not the infrared scales ( $\sim$  meV) where laboratory decoherence operates. Environmental fields cannot generate mass or establish the coupling hierarchy—without Higgs-generated Yukawa structure, there would be no mass-dependent anchoring rate. And neither structural mass nor dynamical noise produces definite outcomes without crossing the irreversibility threshold where the phase transition completes.

This coordination is itself an instance of ontology recapitulating mathematics. The Standard Model Lagrangian contains the Higgs sector, the gauge sector, and their interactions as distinct mathematical structures. The ontological reading recognizes these as playing distinct physical roles in the measurement process—just as QFT’s formalism would suggest.

## 6.9 Completing the Decoherence Program

This three-process framework extends rather than replaces the decoherence program [4, 14]. Decoherence theory successfully explains *when* and *what* decoheres—how environmental monitoring suppresses interference between macroscopically distinct states on extremely short timescales. But decoherence leaves open the “hard problem”: why does environmental entanglement produce definite outcomes rather than merely creating ignorance about correlations?

The ontological reading provides an answer. Decoherence describes the dynamics of coherence suppression—correctly identifying environmental coupling as the driver. The three-process framework identifies the specific physical layers: Higgs-generated mass establishing coupling strength, environmental gauge fields and phonons providing the actual bath dynamics, and the anchoring threshold marking irreversible transition to definiteness. Decoherence identifies *when* and *what*; the ontological reading proposes *how* and *why*.

The relationship parallels statistical mechanics and thermodynamics. Statistical mechanics describes molecular dynamics and successfully predicts thermodynamic behavior. But it

doesn't identify what temperature *is* ontologically (mean kinetic energy of microscopic constituents). Decoherence describes measurement dynamics; the ontological reading provides the measurement ontology.

## 7 Empirical Standing

Philosophy of physics benefits from testability. The ontological reading of QFT's formalism is not merely an interpretive gloss—it generates a framework that is already validated by existing experiments, supported by suggestive anomalies, and decisively testable through proposed measurements.

### 7.1 Already Validated

A framework's credibility depends first on whether it accounts for what is already known. ACT's formalism—quantum Brownian motion with mass-dependent coupling to environmental fields—reproduces all observed decoherence phenomena. This is not trivial: the framework was not constructed to fit these results but derives them from the ontological reading of QFT's structure.

*Progressive decoherence.* Matter-wave interferometry consistently shows exponential decay of coherence:  $\rho(t) \propto e^{-\Gamma t}$ . Under the ontological reading, this is phase diffusion—the wave gradually losing coherence as environmental entanglement accumulates. The functional form  $e^{-\Phi(t)}$  emerges directly from quantum Brownian motion dynamics [15, 23].

*Mass dependence.* Heavier particles decohere faster—dramatically so. C<sub>60</sub> fullerenes (720 amu) show measurably shorter coherence than lighter molecules in the same apparatus. This mass scaling is the signature of Yukawa coupling structure: anchoring rate scales as  $m^2$  because heavier particles couple more strongly to environmental fields through their Higgs-generated mass [15, 17].

*Temperature scaling.* Decoherence rates increase with temperature, following  $\Gamma \propto T$  for Ohmic coupling. This is the fluctuation-dissipation theorem in action: thermal bath modes drive faster phase diffusion at higher temperatures. Observed in levitated nanoparticle experiments and cavity QED [11].

*Pressure dependence.* Decoherence rates scale with background gas pressure—more environmental matter means faster anchoring. This is the  $\rho_{env}$  dependence in the anchoring rate,

confirmed across ultra-high vacuum to atmospheric measurements [23].

*Observable-specific rates.* Position decoheres faster than momentum in every experimental platform tested—ion traps, matter-wave interferometers, cavity QED. Under the ontological reading, this follows from spectral density structure: position couples to Ohmic environmental noise (rapid anchoring), while momentum couples to super-Ohmic noise (slower anchoring). One mechanism, different spectral couplings, matching observed rates.

*Zero-temperature persistence.* Decoherence persists even at cryogenic temperatures approaching absolute zero. Vacuum fluctuations—zero-point energy of environmental fields—continue to drive phase diffusion even when thermal modes are frozen out. This is precisely what quantum Brownian motion predicts: the bath has a zero-point spectrum that never vanishes.

These six categories of validated predictions establish that the ontological reading’s mathematical framework—quantum Brownian motion with mass-dependent environmental coupling—is not speculative. It reproduces the full phenomenology of decoherence using established physics. The framework was not tuned to match these results; they emerge from the same Schwinger-Keldysh formalism that describes open quantum systems throughout condensed matter physics.

## 7.2 Suggestive Anomaly: Excess Decoherence

Beyond mere consistency, there is a suggestive pattern in the data. Schlosshauer’s systematic review of decoherence experiments across platforms reveals that measured decoherence rates are consistently *faster* than predictions from identified environmental sources alone [23]. Large molecules in matter-wave interferometers lose coherence faster than blackbody radiation, residual gas collisions, and other known environmental effects can account for.

Standard models handle this by introducing ad hoc parameters. The ontological reading offers a physical explanation: the “excess” decoherence is intrinsic anchoring driven by environmental quantum field coupling (soft photons, phonon modes) beyond the conventionally identified sources. The mass-squared scaling naturally produces stronger effects for heavier molecules, consistent with the observed trend.

This is suggestive rather than decisive—excess decoherence could have mundane explanations (unidentified environmental sources, systematic errors). But it is the pattern the ontological reading predicts, and it appears consistently across experimental platforms.

### 7.3 Decisive Test: The Isotope Mass Dependence

The mass-squared scaling in the anchoring rate ( $\Gamma_A \propto m^2$ ) produces a unique, falsifiable signature. Consider two molecules differing only in isotopic composition—for example, large organic molecules with  $^{12}\text{C}$  versus  $^{13}\text{C}$  substitution. Their electronic structure is essentially identical, so environmental decoherence effects are the same. But the mass difference affects intrinsic anchoring rate:

$$\frac{\tau_{coh}(^{12}\text{C})}{\tau_{coh}(^{13}\text{C})} \approx \left(\frac{13.003}{12.000}\right)^2 \approx 1.17 \quad (13)$$

This 15–20% predicted difference cleanly discriminates three frameworks: standard quantum mechanics with environmental decoherence (predicts 0% isotope effect—the environment cannot distinguish isotopes), objective collapse models like CSL with mass-linear scaling (predicts  $\sim 8\%$ ), and the ontological reading with mass-squared scaling (predicts  $\sim 17\%$ ). A single precision experiment in matter-wave interferometry could discriminate among them [15, 16].

### 7.4 Independent Support: Bright and Dark States

Recent work by Villas-Bôas et al. (2025) in Physical Review Letters provides independent support for the wave-first ontology [18]. They demonstrated that in classical interference patterns, photons are physically present in “dark” regions where classical theory predicts no light—existing in quantum “dark states” where amplitudes for detector excitation cancel perfectly. Which-path detection doesn’t disturb a trajectory; it transforms the underlying quantum state from dark to bright configuration.

This finding resonates with the ontological reading. Something real persists where classical particle ontology sees nothing—because the entity is a wave, not a particle. Measurement transforms the wave’s state rather than disturbing a particle’s trajectory. Their “dark states” are wave configurations where photon coupling to the detector doesn’t trigger anchoring; “bright states” are where it does. Villas-Bôas et al. work entirely within standard quantum mechanics (new decomposition of existing states); the ontological reading proposes the physical mechanism underlying these observations.

### 7.5 The Three-Tier Structure

The evidence forms a natural hierarchy: validated (existing experiments already confirm the framework’s predictions), suggestive (excess decoherence anomaly matches the pattern the

framework predicts), and decisive (isotope mass dependence would uniquely confirm or falsify the mass-squared scaling). This three-tier structure—not just “here is a prediction”—gives the ontological reading the empirical standing of a framework already grounded in data, not merely awaiting future tests.

## 8 Structural Realism and the Interpretation of Formalism

### 8.1 When Should Mathematics Be Read Ontologically?

The thesis “ontology recapitulates mathematics” raises a foundational question in philosophy of science: when is mathematical structure a reliable guide to ontology?

Not always. Ptolemaic epicycles were mathematically successful but ontologically misleading. Virtual particles in Feynman diagrams are calculational tools, not persistent entities. Mathematical surplus structure is real and must be distinguished from physically significant structure.

But sometimes mathematical structure reveals physical truth. The Lorentz group structure of special relativity encodes genuine features of spacetime. The fiber bundle structure of gauge theories reflects actual physical symmetries. The Riemannian geometry of general relativity describes real spacetime curvature.

What distinguishes reliable from unreliable mathematical guides to ontology? We suggest three criteria:

*Structural persistence.* When the same mathematical distinction appears across multiple formulations and cannot be eliminated by change of variables, it likely encodes something physical. The Lagrangian-Hamiltonian distinction persists across all formulations of QFT—it is not an artifact of a particular mathematical representation.

*Physical correlates.* When mathematical structures map onto independently observable physical differences, the mapping is reliable. Waves and particles are not mathematical abstractions—they correspond to different experimental regimes (interference patterns versus detector clicks) with different physical characteristics (extension versus localization, coherence versus definiteness).

*Predictive consequences.* When ontological reading of mathematical structure generates novel testable predictions, it earns credibility. The mass-squared scaling prediction ( $\Gamma_A \propto m^2$ ) is a consequence of reading the Lagrangian-Hamiltonian structure ontologically. If confirmed,

it would strongly support the reading; if falsified, it would undermine it.

All three criteria are satisfied for the Lagrangian-Hamiltonian duality: the distinction persists structurally, maps onto observable physical differences, and generates testable predictions.

## 8.2 Relation to Structural Realism

The thesis has natural connections to structural realism—the view that scientific theories capture the world’s structure rather than its intrinsic nature [19, 20]. Ontic structural realists hold that structure is all there is; epistemic structural realists hold that structure is all we can know.

The ontological reading of QFT’s formalism is compatible with both variants but goes further than either typically does. Standard structural realism identifies mathematical structures (symmetry groups, fiber bundles) as reflecting physical structure. The ontological reading identifies a *duality* within the mathematical structure—two complementary descriptions connected by a transform—as reflecting a *process*: the physical transition between the regimes each description naturally captures.

This is a stronger claim than typical structural realism. It says not only that QFT’s mathematical structure reflects physical reality, but that the *internal organization* of QFT’s mathematics—its division into Lagrangian and Hamiltonian languages—reflects the internal organization of physical reality into wave and particle regimes. The mathematics doesn’t just describe the world’s structure; its own structure encodes how the world transitions between configurations.

## 8.3 Against Underdetermination

A standard objection to realist interpretation of quantum mechanics is underdetermination: multiple interpretations yield the same predictions, so empirical evidence cannot distinguish them. This objection assumes interpretive equivalence.

The ontological reading breaks this assumption. By reading QFT’s mathematical structure ontologically, it generates predictions (mass-squared scaling) that differ from other interpretations (mass-linear for CSL, no intrinsic effect for Copenhagen + decoherence). The interpretation is not empirically equivalent to alternatives. It is testable, and potentially falsifiable, through specific experiments.

This illustrates a general point: interpretive questions in quantum mechanics are sometimes treated as empirically inert, matters of taste rather than fact. The ontological reading shows

this need not be so. Taking mathematical structure seriously as ontological guide can generate empirically distinguishable consequences. Philosophy of physics can do more than catalog interpretive options; it can identify testable commitments that distinguish them.

## 9 Conclusion: Reading the Formalism

The measurement problem has persisted for nearly a century. During that time, physicists developed quantum field theory—a framework whose mathematical structure, we argue, already contains the solution.

The evidence is structural. The Lagrangian formulation describes waves: extended field configurations exploring spacetime democratically through path integral summation. The Hamiltonian formulation describes particles: localized excitations with definite properties evolving in a privileged time coordinate. The Legendre transform connecting them is not merely a change of variables but the mathematical shadow of a physical process: environmental coupling driving extended wave configurations into localized particle excitations.

The evidence is also axiomatic. The Born rule—quantum mechanics’ most consequential and most mysterious postulate—loses its mystery under wave ontology.  $|\psi|^2$  is not an abstract probability measure but the intensity of a physical wave. Measurement probabilities track where the wave is most intense because that is where the phase transition preferentially occurs. The deepest “axiom” of quantum mechanics turns out to be a theorem about waves, encoded in the formalism from the beginning.

“Superposition” is Fourier decomposition—one wave in different bases, not ontological multiplicity. Complementarity is the inherent structure of waves, not epistemic limitation. The measurement mechanism emerges from three coordinated Standard Model processes: Higgs-generated mass establishes the structural capacity for anchoring, environmental quantum fields (gauge fields, phonons) provide the infrared noise that drives phase diffusion, and definite outcomes emerge when cumulative entanglement crosses an irreversibility threshold. No new physics is required—only realistic reading of existing physics.

This reading—ontology recapitulates mathematics—follows the methodological tradition Einstein established when he elevated  $E = h\nu$  from mathematical device to physical reality. The mathematics of QFT has been telling us what quantum systems are and how measurement works. The Lagrangian-Hamiltonian duality encodes wave-particle regimes. The Born rule

encodes wave intensity physics. The Legendre transform encodes the transition process. We needed only to read what was written.

The proposal is testable. The mass-squared scaling of coherence times produces predictions distinguishable from environmental decoherence (no isotope effect) and objective collapse models (mass-linear scaling). Matter-wave interferometry experiments, feasible with current technology, could confirm or falsify the central prediction within the coming years [15, 16].

If confirmed, the implications extend beyond quantum foundations. They suggest that the relationship between mathematical formalism and physical reality is deeper than instrumentalism allows—that mathematical structure, carefully read, reveals not just patterns in data but the architecture of the world. The measurement problem would be resolved not by adding new physics to QFT but by finally reading what QFT has been saying all along.

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