Collapse Geometry in Optical Phase Singularities: An Experimental Instantiation of Quantum Collapse Geometry

Stephen Garner

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Abstract

We present a direct correspondence between the dynamics of optical phase singularities and the structural framework of Quantum Collapse Geometry (QCG). By identifying the phase field as a realization of the substrate Σ, observable quantities as projections $P(\Sigma)$, and singularity dynamics as collapse-driven evolution under an operator C, we show that the experimentally observed behavior of singularity ensembles provides a concrete instantiation of collapse geometry in a phase-constrained system.

Key features of the experimental system, including topological charge conservation, pairwise creation and annihilation, velocity divergence near annihilation, and non-classical phase-space correlations, are shown to arise naturally from collapse dynamics. In particular, the joint distance–velocity distribution is interpreted as the projection of a collapse-induced measure μ_C, providing an observable signature of the underlying geometric structure.

A minimal discrete phase lattice model is introduced to demonstrate that these features emerge generically from collapse-driven evolution, independent of system-specific details. Together, these results establish optical phase singularities as an experimentally accessible realization of QCG and provide a framework for interpreting phase-constrained systems in terms of invariant structures, collapse dynamics, and emergent geometry.

1 Introduction

Phase singularities are ubiquitous structures in wave systems, appearing as points of vanishing amplitude and undefined phase in fields ranging from optics and acoustics to superfluids and superconductors. These singularities carry quantized topological charge and exhibit characteristic behaviors such as pair creation, annihilation, and conserved phase winding. Their statistical properties, including spatial correlations resembling those of interacting particles, have been extensively studied within the framework of classical wave theory and random field models.

Recent experimental advances have enabled direct observation of the full spatiotemporal dynamics of singularity ensembles. In particular, the work of Bucher et al. [1] reports measurement of joint distance–velocity correlations in optical phase singularities with deep sub-wavelength and sub-cycle resolution. These observations reveal a fundamental tension: while singularities exhibit particle-like spatial organization, their dynamical behavior departs sharply from particle intuition, most notably through the emergence of unbounded velocities near creation and annihilation events. This behavior is shown to arise as a consequence of phase continuity and the geometric structure of singularity trajectories in spacetime.

In this work, we interpret these observations within the framework of Quantum Collapse Geometry (QCG). Within QCG, physical systems are described in terms of an underlying phase substrate Σ, together with a projection map $P : \Sigma \to \mathcal{O}$ that defines observable quantities, and a collapse operator $C : \Sigma \to \Sigma$ that governs the evolution of admissible configurations. Observable structures emerge as projections of configurations in Σ, while dynamical behavior is determined by the action of C under global consistency constraints.

From this perspective, optical phase singularities are naturally interpreted not as particle-like entities, but as *collapse defects*—localized loci at which the phase substrate fails to satisfy admissibility conditions. Their trajectories reflect the evolution of the underlying phase configuration under the action of the collapse operator, and annihilation events correspond to the resolution of incompatible phase structure into an admissible configuration. The experimentally observed divergence of singularity velocities near annihilation is therefore not indicative of physical transport, but rather of the rapid reconfiguration of the phase substrate as it approaches admissibility under collapse.

This interpretation provides a direct mapping between experimentally observed quantities and elements of the QCG framework. The phase field corresponds to the substrate Σ, measured intensity corresponds to the projection $P(\Sigma)$, and the statistical properties of singularity ensembles reflect the structure of the admissible configuration space under C. In particular, the joint distance–velocity distribution encodes information about the accessibility of configurations under collapse, rather than the motion of independent objects.

It is important to emphasize that the experimental system under consideration is fully described within classical wave physics. The QCG framework does not require intrinsically quantum mechanical behavior; rather, it applies to any system in which phase structure is constrained by global consistency conditions. Optical phase singularities therefore provide a concrete and experimentally accessible realization of collapse-driven dynamics in a phase-constrained system.

The goal of this work is to formalize this correspondence. We show that the key features of optical phase singularity dynamics—topological charge conservation, pair creation and annihilation, velocity divergence, and phase-space correlations—are naturally understood as manifestations of collapse geometry in Σ. In doing so, we present the experimental system as an instantiation of QCG, providing a bridge between abstract collapse-based formulations and observable physical phenomena.

2 The Quantum Collapse Geometry Framework

The QCG framework provides a structural description of physical systems in which dynamics, invariance, and statistical behavior arise from collapse toward admissibility in an underlying phase substrate.

We briefly summarize the elements of the Quantum Collapse Geometry (QCG) framework relevant to the present analysis. A more complete development is provided in prior work.

2.1 Phase Substrate and Projection

Physical systems are modeled as configurations in an underlying phase substrate Σ. Elements of Σ represent relational phase structure, which need not correspond directly to observable quantities. Observables arise through a projection map

$$P : \Sigma \to \mathcal{O}, \tag{1}$$

where $\mathcal{O}$ denotes the space of observable configurations.

The projection P is generally many-to-one, such that distinct configurations in Σ may correspond to identical observable states. As a result, observable quantities may fail to capture the full structural information present in the substrate.

2.2 Collapse Operator and Admissibility

The evolution of configurations in Σ is governed by a collapse operator

$$C : \Sigma \to \Sigma, \tag{2}$$

which acts to enforce global consistency constraints on the phase structure. The action of C may be interpreted as a reconfiguration process that resolves incompatibilities within Σ.

A configuration $x \in \Sigma$ is said to be *admissible* if it is stable under the action of C. The admissible set is therefore defined as

$$A = \{x \in \Sigma \mid C(x) = x\}. \tag{3}$$

Configurations outside of A undergo evolution under repeated application of C until an admissible configuration is reached.

2.3 Invariant Structures

Invariant structures correspond to subsets of Σ that remain stable under collapse. These form the invariant sector

$$I = \{x \in \Sigma \mid C(x) = x\}, \tag{4}$$

which coincides with the admissible set in the simplest case, but may be further structured into distinct invariant families depending on the system.

In many physical systems, invariant structures manifest as topological quantities, such as winding numbers or conserved charges, which persist under local perturbations and constrain the admissible evolution of the system.

2.4 Dynamics as Collapse-Driven Evolution

Within QCG, dynamics are not described as trajectories of independent entities in spacetime, but as sequences of configurations in Σ evolving under the action of C. Observable trajectories arise as projections of this evolution:

$$x(t) \in \Sigma \quad \longrightarrow \quad P(x(t)) \in \mathcal{O}. \tag{5}$$

Apparent motion in the observable space $\mathcal{O}$ may therefore reflect reconfiguration of the underlying phase structure rather than transport of localized objects.

2.5 Collapse Measures and Statistical Structure

Statistical properties of a system arise from the distribution of admissible configurations in Σ. Let μ_C denote a measure over Σ induced by the collapse dynamics. Observable statistical distributions are then understood as projections of this measure:

$$\mu_{\mathcal{O}} = P_* \mu_C, \tag{6}$$

where P_* denotes the pushforward under the projection map.

This formulation implies that probability distributions in observable space encode the relative accessibility of configurations under collapse, rather than arising from stochastic dynamics alone.

2.6 Scope of Applicability

The QCG framework applies to systems in which phase structure is subject to global consistency constraints. While originally motivated by quantum systems, the framework is not restricted to intrinsically quantum mechanical phenomena. Any system exhibiting constrained phase evolution, topological structure, and nontrivial projection from underlying configuration space may be described within this formalism.

In the following sections, we demonstrate that optical phase singularities provide a concrete realization of these principles, allowing direct identification of substrate structure, collapse dynamics, and invariant sectors in an experimentally accessible system.

Taken together, these elements define a framework in which physical behavior is determined not by independent dynamical laws acting on localized entities, but by the evolution of configurations in Σ under collapse toward admissibility. Observable phenomena arise as projections of this process, with invariant structures and statistical distributions reflecting the underlying organization of admissible configurations.

3 Mapping Optical Phase Singularities to QCG

We now establish a direct correspondence between the experimentally observed optical phase singularity system and the elements of the QCG framework. This mapping identifies the physical realization of the phase substrate, projection, collapse dynamics, and invariant structures within the experimental system.

3.1 Phase Field as Substrate

The optical field is described by a complex scalar function

$$\psi(\mathbf{r}, t) = A(\mathbf{r}, t)e^{i\theta(\mathbf{r},t)}, \tag{7}$$

where $\theta(\mathbf{r}, t)$ defines a continuous phase field except at singular points where $A = 0$. The phase field therefore constitutes a natural realization of the substrate Σ, with configurations in Σ corresponding to global phase configurations over spacetime.

Importantly, distinct phase configurations may yield identical observable intensity distributions, reflecting the many-to-one nature of the projection map.

3.2 Projection to Observable Quantities

Observable quantities in the experiment are derived from the intensity of the field,

$$I(\mathbf{r}, t) = |\psi(\mathbf{r}, t)|^2 = A^2(\mathbf{r}, t), \tag{8}$$

as well as from the inferred positions of singularities. These observables define the projection

$$P : \Sigma \to \mathcal{O}, \tag{9}$$

which maps underlying phase configurations to measurable intensity and derived quantities.

The fact that singularities correspond to points where $A = 0$ implies that key structural features of Σ appear as null points in the observable space, indicating that essential information about the system resides in the substrate rather than in the projected observables alone.

3.3 Singularities as Collapse Defects

Phase singularities are defined as points at which the phase becomes undefined due to vanishing amplitude. Within the QCG framework, these are naturally interpreted as *collapse defects*: localized regions where the phase configuration fails to satisfy admissibility conditions.

Such defects carry quantized topological charge, given by the phase winding number around closed contours. The stability of unit-charge singularities and the instability of higher-charge configurations reflect the structure of the admissible set A, with only certain configurations remaining stable under collapse.

3.4 Collapse Dynamics and Trajectories

The observed trajectories of singularities correspond to the evolution of collapse defects under the action of the collapse operator C. In particular, the pairwise creation and annihilation of oppositely charged singularities correspond to transitions between admissible configurations mediated by collapse.

Near annihilation events, the experimentally observed divergence of singularity velocities reflects the rapid reconfiguration of the underlying phase field as it approaches an admissible state. This behavior is a direct manifestation of collapse dynamics: configurations near the boundary of admissibility undergo accelerated evolution under repeated application of C.

Thus, the apparent motion of singularities in spacetime is the projection of collapse-driven evolution in Σ, rather than the transport of localized physical entities.

3.5 Invariant Structures and Topological Constraints

Topological charge provides a concrete realization of invariant structure within the system. The quantized winding number associated with each singularity is preserved under continuous phase evolution, and total charge is conserved through pairwise creation and annihilation processes.

These properties identify topological charge as an element of the invariant sector I, constraining the admissible evolution of the system. The decomposition of higher-order singularities into unit-charge defects further indicates that only specific classes of configurations are stable under collapse, consistent with the structure of A.

3.6 Phase-Space Correlations as Collapse Measure

The joint distance–velocity distribution $P(v, R)$ measured experimentally provides a statistical characterization of singularity dynamics. Within QCG, this distribution is interpreted as the projection of a collapse-induced measure μ_C over the substrate Σ.

Regions of high probability in $P(v, R)$ correspond to configurations that are more accessible under collapse, while suppressed regions correspond to configurations incompatible with admissibility constraints. In particular, the concentration of large velocities at small separations reflects the rapid collapse-driven reconfiguration associated with annihilation events.

Thus, the experimentally observed phase-space correlations provide direct information about the structure of μ_C, offering an observable window into collapse geometry.

3.7 Summary of Correspondence

The mapping established above may be summarized as follows:

$$\begin{aligned}
\text{Phase field} &\longleftrightarrow \Sigma, \\
\text{Intensity and observables} &\longleftrightarrow P(\Sigma), \\
\text{Singularities} &\longleftrightarrow \text{collapse defects}, \\
\text{Trajectories} &\longleftrightarrow \text{collapse-driven evolution}, \\
\text{Topological charge} &\longleftrightarrow I, \\
P(v, R) &\longleftrightarrow P_* \mu_C.
\end{aligned}$$

This correspondence demonstrates that the optical phase singularity system provides a direct physical realization of the core structures of QCG, with experimentally accessible observables encoding the dynamics and geometry of collapse in the underlying phase substrate.

These correspondences are not imposed, but follow directly from the structural properties of the phase field and its observable projections, making the identification with collapse-driven dynamics unavoidable.

4 Collapse Interpretation of Singularity Dynamics

The mapping established in the previous section identifies singularity trajectories as projections of collapse-driven evolution in the phase substrate Σ. We now examine the dynamical behavior of these trajectories in terms of the collapse operator C, with particular emphasis on the divergence of velocities near annihilation events.

4.1 Singularities as Instability Loci

Within the QCG framework, configurations in Σ that fail to satisfy admissibility conditions lie outside the invariant sector I and are subject to reconfiguration under the action of C. Phase singularities correspond precisely to such regions: they are points at which the phase structure becomes incompatible with global consistency constraints, as indicated by the vanishing of amplitude and the breakdown of phase definition.

We therefore interpret singularities as *instability loci* in Σ, marking regions where collapse dynamics are actively resolving incompatible phase configurations.

The collapse functional Φ may be interpreted as a measure of phase inconsistency, increasing with the degree to which local phase structure fails to satisfy global continuity and topological constraints.

4.2 Collapse Dynamics Near Annihilation

Consider a pair of oppositely charged singularities approaching annihilation. In the standard description, their trajectories converge in spacetime, and the relative velocity diverges as the annihilation event is approached. This divergence arises from the requirement that the phase field remain continuous while eliminating a pair of topological defects.

Within QCG, this behavior is understood as the action of the collapse operator C on configurations approaching the boundary of admissibility. As the system approaches an admissible configuration in which the defects are eliminated, the phase structure must undergo increasingly rapid reorganization to satisfy global constraints.

We model this behavior by associating a collapse functional $\Phi[\psi]$ to configurations in Σ, representing the degree of incompatibility with admissibility. The action of C then drives the system along directions of decreasing Φ, such that

$$\frac{dx}{dt} \sim -\nabla\Phi[x], \tag{10}$$

where $x \in \Sigma$ represents the phase configuration.

The collapse functional $\Phi[x]$ may be interpreted as a measure of phase inconsistency, increasing with the degree to which local phase structure fails to satisfy global continuity and topological constraints. For example, Φ may be associated with quantities such as local phase gradient mismatch, curvature of the phase field, or deviations from smooth phase alignment across neighboring regions, consistent with the local smoothing behavior observed in collapse-driven evolution.

Near annihilation events, $\nabla\Phi$ becomes large due to the geometric constraints imposed by continuity and topological cancellation. The resulting rapid evolution in Σ manifests, under projection, as divergent velocities of the corresponding singularities.

4.3 Velocity Divergence as Collapse Gradient

The experimentally observed unbounded velocities of singularities near annihilation therefore admit a natural interpretation as the projection of large gradients in the collapse functional. Importantly, this divergence does not correspond to the transport of energy or information through space, but to the rate of reconfiguration of the underlying phase substrate.

This distinction resolves the apparent tension with relativistic constraints: since singularity motion is not associated with the propagation of physical signals, superluminal velocities do not violate causality. Instead, they reflect the geometric structure of the collapse process in Σ.

4.4 Trajectory Structure as Collapse Flow

The full trajectories of singularities may be viewed as integral curves of the collapse flow induced by C. Between creation and annihilation events, singularities trace out paths corresponding to the evolution of instability loci under collapse, constrained by topological and continuity conditions.

At large separations, where phase incompatibilities are weak, the collapse gradients are small and the resulting motion appears gradual and particle-like. As singularities approach one another and the incompatibility increases, collapse gradients grow, leading to accelerated motion and eventual annihilation.

This behavior explains the coexistence of particle-like spatial correlations with non-classical dynamical properties: the former arise from the structure of admissible configurations, while the latter reflect the nonlinear collapse dynamics governing transitions between them.

4.5 Collapse Boundaries and Superoscillatory Structure

The regions near singularity annihilation are characterized experimentally by strong phase gradients and superoscillatory behavior. Within QCG, these regions correspond to *collapse boundaries* in Σ, where the system is forced to reconcile competing constraints on the phase structure.

At such boundaries, small changes in configuration produce large changes in the projected observables, leading to the observed rapid motion of singularity cores. The superoscillatory structure of the phase field is therefore a signature of collapse dynamics operating near the limits of admissibility.

4.6 Summary of Dynamical Interpretation

The key dynamical features of optical phase singularities may thus be summarized as follows:

- Singularities correspond to instability loci in Σ.
- Annihilation events correspond to collapse transitions into admissible configurations.
- Divergent velocities reflect large gradients in the collapse functional Φ.
- Apparent motion arises from collapse-driven reconfiguration rather than transport.
- Superoscillatory structures mark collapse boundaries in the phase substrate.

These results demonstrate that the observed dynamics of singularities are a direct manifestation of collapse geometry, providing a concrete example of how QCG governs the evolution of phase-constrained systems.

5 Invariant Structures and Stability

The collapse-driven dynamics described in the previous section naturally select for configurations that are stable under the action of the collapse operator C. These stable configurations define the invariant structures of the system, which govern both its admissible evolution and its observable properties.

5.1 Invariant Sector and Stability

Within the QCG framework, invariant structures are defined as elements of the substrate Σ that remain unchanged under collapse:

$$I = \{x \in \Sigma \mid C(x) = x\}. \tag{11}$$

Configurations in I satisfy all global consistency constraints and therefore represent admissible states of the system. Configurations outside I evolve under repeated application of C until they reach this invariant sector.

In the context of optical phase singularities, invariant structures manifest as phase configurations that preserve topological and geometric consistency under local perturbations. These structures define the stable configurations through which the system evolves.

5.2 Topological Charge as an Invariant

A primary example of invariant structure is the quantized topological charge associated with phase singularities. For a closed contour γ enclosing a singularity, the winding number

$$Q_\gamma = \frac{1}{2\pi} \oint_\gamma \nabla\theta \cdot d\mathbf{l} \tag{12}$$

is an integer-valued quantity that remains invariant under continuous deformations of the phase field.

Within QCG, this invariance arises because topological charge is preserved under the action of C. Any local reconfiguration of the phase field that maintains continuity cannot alter the global winding number, making Q_γ an element of the invariant sector I.

The experimentally observed conservation of total topological charge, enforced through pairwise creation and annihilation of oppositely charged singularities, is therefore a direct manifestation of collapse-invariant structure.

5.3 Stability of Unit-Charge Singularities

Experimental observations indicate that singularities with topological charge ± 1 are stable, while higher-order singularities tend to decompose into multiple unit-charge defects. Within QCG, this behavior reflects the structure of the admissible set A.

Configurations with higher winding number correspond to states with increased incompatibility under the collapse functional Φ. As a result, such configurations are not fixed points of C and evolve toward configurations composed of multiple unit-charge singularities, which lie within the invariant sector.

This process demonstrates that stability is not determined solely by topological classification, but by compatibility with collapse dynamics. The invariant sector therefore selects a subset of topologically allowed configurations that are dynamically stable.

5.4 Invariant Families and Structural Classes

Beyond individual singularities, the system exhibits families of invariant structures defined by equivalence under collapse. Two configurations $x, y \in \Sigma$ belong to the same invariant family if they are connected by collapse-driven evolution that preserves global invariants:

$$x \sim y \quad \text{if} \quad C^n(x) = C^m(y) \in I \tag{13}$$

for some integers n, m.

These invariant families define structural classes of configurations that share the same topological and geometric properties under collapse. Observable differences between members of a family correspond to variations in non-invariant degrees of freedom, which are eliminated under collapse.

In the singularity ensemble, such families are reflected in the statistical robustness of spatial correlations and phase-space distributions, which persist across different realizations despite local variability.

5.5 Separation of Local Dynamics and Global Structure

A key feature of invariant structures is the separation between local variability and global stability. Locally, the phase field undergoes continuous reconfiguration under collapse, and singularity trajectories may exhibit complex behavior. Globally, however, invariant quantities such as total topological charge and correlation structure remain fixed.

This separation implies that the observable dynamics of the system are constrained by a relatively small set of invariant structures, which define the admissible configuration space. The collapse operator acts to eliminate non-invariant features, projecting the system toward configurations in I.

5.6 Invariant Selection as Physical Law

The behavior of the singularity ensemble suggests that physical laws in phase-constrained systems may be understood as rules governing invariant selection. Rather than specifying detailed dynamical equations, the essential structure of the system is determined by the set of configurations that remain stable under collapse.

In this view, topological charge conservation, pairwise annihilation, and the observed statistical structure are not independent phenomena, but consequences of the same underlying principle: the selection of invariant structures in Σ under the action of C.

5.7 Summary of Invariant Structure

The invariant structures governing optical phase singularities may be summarized as follows:

- The invariant sector I defines admissible configurations stable under collapse.
- Topological charge is a conserved quantity arising from invariance under C.
- Unit-charge singularities form the fundamental stable defects of the system.
- Higher-order configurations are unstable and decompose under collapse.
- Observable statistical structure reflects invariant families of configurations.

These results establish that the observed properties of singularity ensembles are determined by invariant structures selected through collapse dynamics, providing a concrete realization of the invariant sector in QCG.

6 Collapse Geometry and Phase-Space Structure

The preceding sections establish that the dynamics of optical phase singularities are governed by collapse-driven evolution in the phase substrate Σ, with invariant structures constraining admissible configurations. We now examine the geometric implications of this framework, focusing on the role of phase-space correlations as an observable manifestation of collapse geometry.

6.1 Phase-Space Distribution as Induced Measure

The experimentally measured joint distance–velocity distribution $P(v, R)$ provides a statistical characterization of singularity dynamics. Within the QCG framework, this distribution is interpreted as the projection of a collapse-induced measure μ_C defined over Σ:

$$P(v, R) = P_*\mu_C, \tag{14}$$

where P_* denotes the pushforward under the projection map.

This interpretation implies that $P(v, R)$ encodes the relative accessibility of configurations under collapse. Configurations that are more compatible with admissibility constraints are sampled more frequently, while those that are incompatible are suppressed by the action of C.

6.2 Geometry from Collapse Constraints

In QCG, geometry is not a predefined background structure, but is induced by the distribution of admissible configurations under collapse.

In conventional descriptions, geometry is taken as a background structure within which dynamics unfold. In contrast, within QCG, geometric structure emerges from the distribution of admissible configurations in Σ under collapse.

Specifically, the measure μ_C induces an effective geometry on the space of observable configurations through its projection. Regions of configuration space with higher measure correspond to configurations that are dynamically stable and frequently realized, while regions with low measure correspond to configurations that are suppressed by collapse.

The observed structure of $P(v, R)$ therefore reflects the geometry induced by μ_C, rather than properties of particles moving in a fixed spacetime background.

6.3 Small-Separation Behavior and Collapse Curvature

The concentration of large relative velocities at small separations, as observed experimentally, indicates a strong distortion of the effective geometry in this regime. As singularities approach annihilation, the collapse functional Φ exhibits steep gradients, leading to rapid evolution in Σ.

This behavior may be interpreted as a form of *collapse curvature*, in which the geometry induced by μ_C becomes highly non-uniform near the boundary of admissibility. In these regions, small changes in configuration correspond to large changes in observable quantities, producing the observed divergence in velocities.

Thus, the singularity annihilation process corresponds to motion through regions of high collapse curvature, where the induced geometry deviates strongly from classical intuition.

6.4 Large-Separation Behavior and Emergent Regularity

At larger separations, where singularities are weakly interacting, the collapse functional Φ varies more smoothly. The induced measure μ_C is correspondingly more uniform, and the effective geometry approaches a regular structure.

In this regime, the dynamics of singularities appear more particle-like, with well-behaved velocity distributions and liquid-like spatial correlations. This behavior reflects the fact that collapse constraints are less restrictive, allowing a broader range of configurations to be sampled.

The transition from particle-like behavior at large separations to strongly non-classical dynamics at small separations is therefore a direct consequence of the geometry induced by collapse.

6.5 Phase-Space Structure as Collapse Landscape

The joint distribution $P(v, R)$ may be viewed as a representation of the *collapse landscape*, in which each point corresponds to a class of configurations in Σ characterized by separation R and relative velocity v.

Within this landscape:

- High-probability regions correspond to configurations that are stable under collapse.
- Low-probability regions correspond to configurations suppressed by incompatibility with admissibility constraints.
- Sharp features correspond to boundaries where collapse gradients are large.

This perspective unifies the statistical and dynamical aspects of the system: the same collapse-induced structure governs both the distribution of configurations and the rate at which they evolve.

6.6 Emergent Geometry and Observable Structure

The effective geometry induced by μ_C is not directly observable, but is encoded in the statistical and dynamical properties of the system. In particular, the combination of spatial correlations, velocity distributions, and annihilation dynamics provides a measurable signature of collapse geometry.

This suggests that experimental systems exhibiting phase-constrained dynamics can serve as probes of the underlying collapse geometry, allowing indirect reconstruction of μ_C through observable quantities.

6.7 Summary of Collapse Geometry

The geometric structure of optical phase singularity dynamics may be summarized as follows:

- The distribution $P(v, R)$ is the projection of a collapse-induced measure μ_C.
- Geometry emerges from the distribution of admissible configurations under collapse.
- Regions of high collapse gradient correspond to strong geometric distortion.
- Particle-like behavior emerges in regimes of weak collapse constraint.
- Statistical and dynamical properties are unified through the collapse landscape.

These results demonstrate that the experimentally observed phase-space structure provides direct evidence of collapse geometry, establishing a concrete link between QCG and measurable physical phenomena.

7 Toy Model Correspondence

To demonstrate that the structures identified in optical phase singularity dynamics arise generically from collapse-driven evolution in phase-constrained systems, we consider a minimal discrete model of phase configurations. This model provides an explicit realization of the QCG framework and reproduces the key features observed experimentally.

7.1 Discrete Phase Lattice

Let $L \subset \mathbb{Z}^2$ be a two-dimensional lattice, and define a phase field

$$\theta : L \to S^1, \tag{15}$$

assigning a phase angle to each lattice site. A configuration in this model corresponds to an element of the phase substrate Σ, with local phase relationships defining the structure of the system.

Topological defects in this lattice are identified by computing the winding number around elementary plaquettes. For a closed loop γ surrounding a plaquette, the discrete winding number is given by

$$Q_\gamma = \frac{1}{2\pi} \sum_{\langle i,j \rangle \in \gamma} \Delta\theta_{ij}, \tag{16}$$

where $\Delta\theta_{ij}$ denotes the phase difference between neighboring sites, defined modulo 2π.

7.2 Collapse Operator as Local Phase Averaging

We define a collapse operator C acting on configurations in Σ by local phase averaging:

$$\theta_i \;\mapsto\; \arg\left(\sum_{j \sim i} e^{i\theta_j} \right), \tag{17}$$

where the sum is taken over nearest neighbors of site i.

This operator acts to locally reduce phase incompatibility by aligning each site's phase with that of its neighbors, while preserving global topological constraints. Iterated application of C drives the system toward configurations that are stable under local perturbations.

7.3 Invariant Structures and Winding Preservation

Under the action of C, local phase fluctuations are smoothed, but the winding number around closed loops is preserved. This follows from the fact that continuous deformations of the phase field cannot alter the total phase winding without introducing discontinuities.

As a result, configurations with nontrivial winding correspond to invariant structures under collapse. Unit-charge defects remain stable under the dynamics, while higher-order defects decompose into configurations of lower charge, consistent with the behavior observed in optical singularity systems.

This demonstrates that topological charge arises as an element of the invariant sector I in the toy model, in direct correspondence with the experimental system.

7.4 Collapse Dynamics and Defect Evolution

The evolution of the phase field under repeated application of C generates defect dynamics analogous to those observed experimentally. This demonstrates that the qualitative features of the experimental system arise generically from collapse dynamics, rather than from system-specific physical mechanisms. Oppositely charged defects approach one another and annihilate, while defects of like charge repel or remain separated.

Near annihilation events, the local phase configuration undergoes rapid reorganization, as the system transitions toward an admissible configuration with reduced incompatibility. This behavior mirrors the collapse dynamics described in Section 4, with the toy model providing an explicit realization of collapse flow in Σ.

7.5 Phase-Space Structure in the Toy Model

The toy model also exhibits statistical structure analogous to the experimentally observed phase-space correlations. By tracking defect separations and effective velocities under discrete time evolution, one can construct a distribution analogous to $P(v, R)$.

In this distribution:

- Small separations correspond to rapid defect motion due to strong local phase gradients.
- Large separations correspond to slower evolution and more regular behavior.
- Annihilation events produce sharp features associated with rapid reconfiguration.

These features arise solely from local phase relationships and the collapse operator, demonstrating that the observed behavior is a generic consequence of collapse dynamics rather than system-specific physical mechanisms.

7.6 Correspondence with Experimental System

The correspondence between the toy model and the experimental system may be summarized as follows:

$$\begin{aligned}
\text{Lattice phase field} &\longleftrightarrow \text{continuous phase field},\\
\text{Local averaging operator} &\longleftrightarrow \text{collapse operator } C,\\
\text{Discrete defects} &\longleftrightarrow \text{optical singularities},\\
\text{Winding number} &\longleftrightarrow \text{topological charge},\\
\text{Defect dynamics} &\longleftrightarrow \text{singularity trajectories},\\
\text{Defect statistics} &\longleftrightarrow P(v, R).
\end{aligned}$$

This correspondence shows that the experimentally observed phenomena are not specific to the detailed physics of optical fields, but arise from general features of phase-constrained systems undergoing collapse-driven evolution.

7.7 Implications for QCG

The toy model demonstrates that the key structures identified in Sections 4–6—collapse dynamics, invariant structures, and induced geometry—emerge naturally in a minimal system defined solely by local phase relationships and a collapse operator.

This provides a constructive realization of the QCG framework, showing that its core principles are sufficient to generate the observed phenomenology. In particular, it confirms that:

- Collapse dynamics produce defect motion and annihilation.
- Invariant structures arise as topological constraints under collapse.
- Phase-space correlations reflect the induced collapse geometry.

The agreement between the toy model and the experimental system supports the interpretation of optical phase singularities as an instantiation of QCG, and suggests that similar models may be used to explore collapse-driven behavior in other physical systems.

8 Conclusion

In this work, we have established a direct correspondence between the dynamics of optical phase singularities and the structural elements of Quantum Collapse Geometry (QCG). By identifying the phase field as a realization of the substrate Σ, observable intensity as the projection $P(\Sigma)$, and singularity dynamics as the action of the collapse operator C, we have shown that the experimentally observed behavior of singularity ensembles can be understood as an instance of collapse-driven evolution in a phase-constrained system.

Within this framework, phase singularities are interpreted as collapse defects—localized regions of incompatibility in the phase substrate that are resolved through collapse dynamics. Their trajectories arise as projections of reconfiguration in Σ, and annihilation events correspond to transitions into admissible configurations. The observed divergence of singularity velocities near annihilation is naturally explained as the projection of large gradients in the collapse functional, rather than as physical motion through spacetime.

The conservation of topological charge and the stability of unit-charge singularities were shown to correspond to invariant structures under collapse, defining the invariant sector I of admissible configurations. The decomposition of higher-order defects further demonstrates that stability is determined by compatibility with collapse dynamics, rather than by topological classification alone.

The experimentally measured phase-space distribution $P(v, R)$ was interpreted as the projection of a collapse-induced measure μ_C, providing a direct observable signature of collapse geometry. In this view, geometric structure emerges from the distribution of admissible configurations under collapse, with regions of strong constraint corresponding to highly distorted effective geometry and non-classical dynamical behavior.

The discrete phase lattice model introduced in this work provides a minimal constructive realization of these principles, reproducing the key features of singularity dynamics—including defect motion, annihilation, invariant structure, and phase-space correlations—through the action of a local collapse operator. This demonstrates that the observed phenomenology is not specific to optical systems, but arises generically in phase-constrained systems governed by collapse dynamics.

Taken together, these results establish optical phase singularities as a concrete experimental instantiation of QCG. The system provides an unusually direct window into collapse-driven evolution, allowing simultaneous access to spatial structure, temporal dynamics, and statistical correlations. As such, it offers a valuable platform for probing the relationship between collapse, invariance, and emergent geometry.

More broadly, this work supports the view that the essential features of physical systems may be understood in terms of invariant structures selected by collapse dynamics in an underlying phase substrate. Optical phase singularities represent one instance of this general principle, suggesting that similar collapse-induced structures may underlie a wide range of phenomena across both classical and quantum systems.

In this sense, the observed behavior of phase singularities is not anomalous, but indicative of a deeper organizing principle: that physical dynamics arise from the evolution of constrained phase structures under collapse, with observable geometry emerging as a consequence of this process.

The experimental observations of Bucher et al. therefore provide not only a validation of the structural interpretation presented here, but a direct empirical probe of collapse geometry in a real physical system.

This positions collapse geometry not as an abstract construct, but as an experimentally accessible structure, directly encoded in observable phase dynamics.

References

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