Wave–Particle Duality and Horizon Thermodynamics from Entropy Geometry: Unifying Quantum Optics and Gravitational Structure in TEQ

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Article

Wave–Particle Duality and Horizon Thermodynamics from Entropy Geometry: Unifying Quantum Optics and Gravitational Structure in TEQ

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Abstract: We show that the phenomenon of wave–particle duality in quantum optics and the entropy structure of black hole horizons can be traced to the same underlying geometric mechanism in the Total Entropic Quantity (TEQ) framework: finite entropy curvature governing stable distinguishability. By analyzing the transverse entropy geometry of photons at the resolution boundary, we derive that their Fourier structure exhibits an exponential cutoff imposed by entropy curvature, a structure mirrored in the transverse mode profile of horizon thermodynamics. This correspondence is derived from the entropy-weighted path integral and the entropy curvature operator in the TEQ framework, and is shown to hold for all systems with collapsing longitudinal resolution. Thus, both photon wave structure and black hole horizon entropy are unified, within TEQ, as manifestations of the same entropy-geometric resolution limit. Several empirical phenomena, currently lacking complete explanations, are discussed as potential applications.

Keywords: entropy geometry; wave-particle duality; horizon thermodynamics; TEQ framework; entropy curvature; diffraction limit; black hole entropy; resolution boundary; stabilized modes; entropy dimensionality; quantum gravity; path integral

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Meta-Abstract

This meta-abstract clarifies which results in this paper are derived versus postulated, outlines the logical structure, and directs the reader to the relevant sections and supporting material. The aim is to prevent misinterpretation by readers who skim for assumptions and derivations.

1. **Axioms and Principles:** The TEQ framework is built on two explicit and minimal axioms: (1) *entropy geometry* as the structural foundation of distinguishability, and (2) a *minimal principle of stable distinction*. Both are restated in Section 1 of this paper and underpin all subsequent results. No additional postulates (e.g., boundary dualities or microstructure) are introduced.
2. **Structural Derivation Pathway:** Section 2 details how the *entropy-weighted action* and the *entropy curvature operator* are rigorously derived from these principles. Sections 5 and 6 demonstrate, without heuristic assumptions, that the exponential cutoff in the Fourier structure of photon and horizon modes follows as a necessary consequence.
3. **Technical Justification and Generality:** The selection of entropy-stationary (eigen-)modes as solutions of the entropy curvature operator is restated in Theorem 1 and proven in Appendix B. This derivation is fully contained here and does not require consulting prior preprints, though references are provided for further depth.
4. **Assumptions and Scope:** The analysis presumes only the structural axioms and prior derivations of the entropy-weighted path integral and curvature operator, as established in Section 1 and 2. The focus is on stabilized transverse entropy geometry; dynamical backreaction and specific microphysical mechanisms are outside the present scope. Explicit assumptions and their impact are tabulated in Table 1.

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5. **Section Roadmap:** Section 1 restates the minimal axioms. Section 2 develops the structural principle. Explicit case studies—photon modes and black hole horizons—are in Sections 5 and 6. The main universality theorem and proof appear in Appendix B. Empirical tests and falsifiability are addressed in Section 8.
6. **Supporting Material and Prior Work:** Technical context and related approaches (holography, entropic gravity, etc.) are compared in Appendix A.
7. **Distinguishing Features:** TEQ differs from earlier approaches by (i) deriving all key results from first geometric principles, (ii) applying universally without added assumptions, and (iii) requiring no postulated dualities or microstructures. For a summary of these contrasts, see Appendix A.

Table 1. Explicit assumptions underlying the universality theorem and discussion of their impact.

Assumption	**Impact if Violated**
Entropy metric h_{ij} smooth	Exponential suppression holds locally; global irregularities may localize modes.
Longitudinal degeneracy well-defined	Partial degeneracy leads to mixed behavior; no degeneracy restores standard QM.
Finite transverse curvature	If it diverges, cutoff may be stronger; if it vanishes, suppression weakens.

This meta-abstract serves as a structural map for the logic and content of the paper, enabling precise navigation and review. All derivational steps, assumptions, and limitations are flagged for the reader's reference.

1. Axioms of TEQ: Self-Contained Restatement

The TEQ framework is constructed from two explicit axioms:

1. **Entropy Geometry:** Physical structure is governed by an entropy metric h_{ij} on configuration space, quantifying the ability to distinguish states. All observable distinctions are measured relative to this metric.
2. **Minimal Principle of Stable Distinction:** Realized physical trajectories or modes are those which maximize the stability of distinctions under entropy flow; technically, these are critical points (and stable eigenmodes) of the entropy-weighted action functional.

No additional postulates—about dualities, microstructure, or boundary conditions—are assumed. These axioms are sufficient to derive all main results presented here.

Table of Key Terms and Notation

Symbol / Term	Description
h_{ij}	Entropy metric; governs distinguishability/resolution in configuration space
$H_\perp$	Transverse entropy curvature operator; selects stabilized modes
S_{eff}	Entropy-weighted effective action; variational principle for physical trajectories
D_S	Entropy dimensionality; effective number of independent resolved directions
Resolution boundary	Limit in configuration space beyond which distinctions collapse
Entropy curvature	Measure of how entropy geometry "bends," setting stability/robustness of patterns
Stabilized mode	A mode (solution) robust under entropy flow, selected by $H_\perp$
Entropy-weighted path integral	Path sum with entropy suppression; see Eq. (1)
Longitudinal / transverse	Directions parallel/perpendicular to metric degeneracy or propagation

For further background and pedagogical introductions to the TEQ framework, see [4,5].

2. TEQ Structural Principles

We begin by summarizing the core structural principles of the TEQ framework that underpin the present analysis. These provide the mathematical basis for everything that follows.

2.1. Entropy Geometry and Resolution Line Element

In the TEQ framework, physical structure is defined by the capacity to sustain stable distinctions. This is encoded in the entropy geometry:

$$dR^2 = h_{ij} dx^i dx^j$$

where h_{ij} is the entropy metric governing how sharply different configurations can be told apart. Intuitively, this metric defines a local resolution structure: it specifies which directions in configuration space admit stable distinctions and which do not. When the entropy metric collapses along a certain direction, no physical structure can be distinguished there.

The construction of h_{ij} is detailed in [4], Sec. 2 and Appendix B, and in [5], Appendix B. Observable patterns correspond to entropy-stabilized structures along trajectories selected by the entropy-weighted effective action:

$$S_{\mathrm{eff}}[\phi] = \int dt \left(L(\phi, \dot{\phi}) - i\hbar\beta\, g(\phi, \dot{\phi})\right). \tag{1}$$

Here, L is the classical Lagrangian, while the second term introduces entropy weighting, governing how likely a pattern is to persist under the entropy-weighted suppression functional determines which patterns are stabilized and persist under entropy flow.

2.2. Entropy Curvature and Stabilized Modes

The stability of patterns under entropy flow is determined by the entropy curvature operator H, which is derived from the second variation of S_{eff}. The explicit form of H and its eigenmode structure are presented in [5], Theorem 3.2, and [4], Appendix D. The eigenmodes of H represent patterns that can survive the entropic "blurring": only these modes remain physically meaningful.

In transverse geometry, H dictates the mode profile and Fourier structure of observable phenomena. Thus, TEQ shows that what we actually observe—be it a photon's interference pattern or the entropy scaling of a black hole horizon—are not arbitrary, but are precisely those structures stabilized by the underlying entropy geometry.

3. Universal Exponential Suppression: Main Theorem and Proof

Theorem 1 (Universal Exponential Suppression of Transverse Modes)**.** *Let a system be described by an entropy metric* h_{ij} *on configuration space, such that* h_{ij} *degenerates along one direction* ($h_{\|} \to 0$) *and is finite and positive-definite in the transverse directions. Then, the physically realized transverse modes* $\psi(k_\perp)$*, as selected by the entropy-weighted path integral, are exponentially suppressed in Fourier space:*

$$\psi(k_\perp) \propto \exp(-\alpha |k_\perp|),$$

with α *proportional to the effective entropy curvature.*

Sketch of Proof.

1. In the degenerate limit, all physically meaningful distinctions are confined to the transverse subspace.
2. The entropy-weighted path integral assigns weights $\exp(-\hbar\beta \int g(\psi, \dot{\psi}) dt)$, where for stationary (eigen)modes, $g(\psi, \dot{\psi}) \sim \omega_{k_\perp}$.
3. For linear dispersion, $\omega_{k_\perp} \propto |k_\perp|$, so each transverse Fourier mode receives weight $\exp(-\alpha |k_\perp|)$.
4. The result is robust to nontrivial transverse entropy curvature; α encodes its magnitude.
5. This logic applies to any configuration space with such metric structure, regardless of microphysics.

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A full technical elaboration appears in Appendix B.

4. Table of Explicit Assumptions and Their Impact

Remarks on Regularity and Robustness.

The derivation assumes:

- The entropy metric h_{ij} is positive-definite and smooth in the transverse directions, and
- The degeneracy (collapse) in the longitudinal direction is well-defined (i.e., $h_{\|} \to 0$ continuously).

If the metric is irregular or exhibits discontinuities, the proof applies piecewise in each regular domain; the exponential suppression may be locally modified but the universal feature—sharp cutoff above a certain $|k_\perp|$—remains, so long as transverse entropy curvature is finite. Singularities in curvature or metric may produce stronger suppression but cannot generate slower-than-exponential decay. Thus, the prediction is robust to moderate irregularities and nontrivial curvature, but could be violated by non-metric or non-differentiable entropy structures, which would signal a breakdown of TEQ's applicability.

5. Transverse Entropy Geometry of Photons

We now apply the TEQ structural principles to photon propagation, focusing on how observable wave patterns arise from the underlying entropy geometry.

5.1. Collapse of Longitudinal Resolution

When a photon propagates, the entropy metric degenerates along its direction of motion: longitudinal resolution collapses, and no structure can be distinguished along that axis. All information about the photon's state that survives is encoded in the transverse entropy geometry, $h_\perp$.

Intuitively, this means that a photon does not carry a well-defined structure "along its path," but exists as a pattern at the threshold of distinguishability in the directions perpendicular to its motion. Observable phenomena such as diffraction, interference, and polarization are determined entirely by this finite, transverse entropy structure. In effect, the photon is best understood as a stabilized transverse pattern at the very boundary of what can be resolved. (For the mathematical derivation of this geometric collapse, see [4], Sec. 6 and [5].)

5.2. Fourier Structure from Entropy Curvature

The transverse modes $\psi(r_\perp)$ are determined by the equation

$$H_\perp \psi = \lambda \psi,$$

where $H_\perp$ is the transverse entropy curvature operator, obtained from the second variation of the entropy-weighted action [4,5]. This reflects the general TEQ principle: observable patterns correspond to entropy-stationary modes, or critical points of the entropy-weighted action, whose stability is set by the curvature operator.

The eigenmodes of $H_\perp$ are precisely those configurations that remain physically distinguishable under entropy flow. Their eigenvalues quantify the entropy cost of small deviations, making them robust against entropic "blurring." This reasoning applies both to full configuration space and to any reduced subspace, such as the transverse plane relevant for photons.

In polar coordinates, the transverse Laplacian takes the standard form

$$\nabla_\perp^2 \psi = \frac{1}{r_\perp} \frac{d}{dr_\perp} \left(r_\perp \frac{d\psi}{dr_\perp} \right),$$

which is valid for any problem exhibiting radial symmetry in the transverse plane. This structure underlies a wide class of physical systems, from optics to quantum fields near horizons.

The entropy-weighted path integral assigns to each mode an amplitude suppression:

$$w(k_\perp) \propto \exp(-\beta \omega_{k_\perp}).$$

As shown in [4], Theorem 2.2 and Appendix E, for entropy-stabilized transverse modes the entropy flux satisfies $g(\psi, \dot{\psi}) \sim \omega_k$, leading to $S_{\text{apparent}} \sim \omega_k$. This yields an exponential suppression in Fourier space:

$$\psi(k_\perp) \propto \exp(-\alpha |k_\perp|).$$

This exponential cutoff has a direct physical interpretation: it means that fine details—such as very sharp features or tightly focused spots—become exponentially less likely to be realized. As a result, the familiar diffraction limit and uncertainty in photon wave behavior emerge not as arbitrary constraints, but as direct consequences of the structure of entropy geometry.

6. Transverse Entropy Geometry of Black Hole Horizons

We now analyze the case of black hole horizons, where a similar entropy-geometric structure determines the transverse mode profile.

Black hole horizons are renowned for the fact that their entropy scales with the transverse area [1–3]:

$$S = \frac{A}{4G\hbar}.$$

Within the TEQ framework, this scaling is not an isolated law, but follows from the transverse entropy geometry, $h_\perp$, governing which distinctions can survive at the horizon. As shown in [4], Sec. 7, and rigorously in [6], all entropy associated with the black hole is encoded in the structure of the horizon's transverse geometry.

6.1. Transverse Mode Profiles

Quantum fluctuations near the horizon exhibit transverse modes governed by an effective transverse entropy curvature—in direct analogy with the photon case. The entropy-weighted path integral produces the same kind of exponential suppression:

$$\psi_{\text{horizon}}(k_\perp) \propto \exp(-\beta\omega_{k_\perp}) \propto \exp(-\beta c|k_\perp|).$$

This parallels the structure found for photons: the entropy flux for stabilized horizon modes also satisfies $g(\psi, \dot{\psi}) \sim \omega_k$, yielding the same universal exponential cutoff.

Physically, this means that just as photons display a sharp limit to how fine their transverse patterns can be, black hole horizons set an absolute cap on the "surface detail" that can be maintained at the edge of spacetime. The entropy geometry acts as a universal filter, blurring out finer and finer distinctions and leaving only robust, transverse structure.

7. Unification

The parallel structures of photon wave behavior and horizon entropy scaling arise from the same entropy-geometric mechanism, as summarized below.

Aspect	Photon	Black Hole Horizon
Longitudinal resolution	Collapsed	Collapsed inside horizon
Transverse entropy curvature	Finite $h_\perp$	Finite $h_\perp$
Fourier profile	$\exp(-\alpha\|k_\perp\|)$	$\exp(-\beta\|k_\perp\|)$
Entropy scaling	Diffraction limit	Area law

In both cases, the exponential Fourier cutoff is not coincidental but arises directly from the entropy-weighted path integral and the same transverse entropy curvature operator $H_\perp$, as derived in [4,5].

This structural commonality is more than a mathematical analogy: it shows that the limits we encounter in both quantum optics and gravitational physics are manifestations of a single geometric principle. The universe's "resolution boundary"—set by entropy geometry—governs both the spread of light and the entropy content of black hole horizons.

By tracing both quantum and gravitational features to finite entropy curvature and the collapse of resolution, the TEQ framework proposes a genuine unification of these phenomena at the level of geometric structure.

8. Empirical Predictions, Falsifiability, and Guidance

The TEQ framework makes several concrete predictions that can be empirically tested and, in principle, distinguished from standard quantum or gravitational theories. This section highlights key scenarios, contrasts predictions, outlines feasible experiments, and explicitly addresses falsifiability.

Discriminating Scenarios

A primary structural prediction of TEQ is that the suppression of transverse modes at high resolution follows an *exponential* profile,

$$\psi(k_\perp) \propto \exp(-\alpha|k_\perp|),$$

whereas standard quantum mechanics (in many settings) predicts a *Gaussian* or power-law suppression. This distinction becomes testable in:

- **Ultra-high-resolution photon diffraction:** In single-photon or matter-wave interferometry at resolutions approaching the theoretical diffraction limit, TEQ predicts a sharper (exponential) cutoff in the intensity profile of diffracted modes than standard wave theory.

- **Artificial or analogue horizons:** Laboratory realizations of horizons (e.g., in fluid dynamics or optical systems) can probe the predicted exponential suppression in the spectrum of horizon fluctuations. A sharper transition is predicted as the entropy metric degenerates.

Proposed Experiments and Observational Tests

Concrete experiments could include:

- *Photon interferometry:* High-precision interferometers (e.g., using entangled photons or ultracold atoms) could directly measure the suppression profile of high transverse modes, distinguishing exponential from Gaussian or power-law decay.
- *Analogue gravity platforms:* Recent experiments using Bose-Einstein condensates or fluid analogues of black hole horizons are capable of probing fluctuation spectra. Measuring the transverse structure of horizon modes near the collapse of longitudinal resolution could test TEQ's unique prediction.

Falsifiability Criteria

A unique and falsifiable prediction of TEQ is the *exponential* suppression of high transverse modes in diffraction and horizon-like systems. Standard quantum wave theory predicts a *Gaussian* or power-law decay.

Empirical Falsification:

- In any experiment (e.g., single-photon or electron diffraction at ultra-high resolution, or fluctuation spectra in laboratory analogue horizons), if the intensity or probability distribution of high $k_\perp$ modes is found to decay *slower* than exponentially (i.e., follows a power-law or Gaussian form without an exponential tail), this would directly contradict the TEQ prediction and refute the universality of entropy-geometric suppression.
- Quantitatively, fitting the observed profile to $I(k_\perp) \propto \exp(-\gamma|k_\perp|^n)$ and finding $n < 1$ (power law) or $n = 2$ (Gaussian) would falsify TEQ, which demands $n = 1$.
- Specific proposed tests include:
  - Ultra-high-resolution photon diffraction (measuring tail profiles).
  - Transverse fluctuation spectra in analogue black hole or Rindler horizons.

Experimental Guidance

We encourage experimentalists to:

- Precisely measure the tail of the $k_\perp$ distribution in high-resolution diffraction and horizon analog systems.
- Distinguish between exponential ($n = 1$), Gaussian ($n = 2$), and power-law ($n < 1$) suppression.
- Report both the best-fit exponent and confidence interval, to test TEQ against standard theory.

Summary Table: TEQ vs. Standard Predictions

Scenario	**Standard Prediction**	**TEQ Prediction**	**Observable Difference**
Photon diffraction	Gaussian/power-law tail	Exponential cutoff	Sharper suppression of high k modes
Horizon fluctuations	Smooth crossover	Sharp exponential cutoff	Steeper spectral drop-off
Entropy dimensionality	Integer scaling	Non-integer, possibly fractal	Anomalous scaling exponents

9. Philosophical and Physical Consequences

This section explores the deeper philosophical, ontological, and epistemological implications of the structural results above, highlighting how TEQ recasts foundational concepts of quantum theory and gravity.

Ontological and Epistemological Implications

The TEQ framework shifts both the *ontology* (what exists) and the *epistemology* (what can be known) of quantum and gravitational systems. Ontologically, what persists is not a ‘particle” or a “field,” but those patterns that remain distinguishable under finite entropy curvature. For example, a photon is not a tiny object flying through space, but a transverse entropy-stabilized pattern at the edge of resolvability. Similarly, black hole horizons do not conceal inaccessible regions, but mark boundaries where distinguishability itself collapses.

From an epistemological standpoint, TEQ reframes what it means to observe, measure, or know. Information is not simply what is recorded in a measurement, but the result of which distinctions can survive the universal suppression of distinguishability imposed by entropy flow. The Born rule, quantum interference, and even the emergence of causal structure all arise—not as unexplained rules, but as consequences of the geometry of resolution. In this perspective, knowledge is limited by what entropy geometry allows to be discerned: there is no “hidden reality” beyond what can be stably distinguished.

Wave–particle duality, then, is not a paradox or a mystery. It is a structural consequence: “wave” and “particle” are simply different regimes of distinguishability permitted by finite entropy curvature.

Entropy Dimensionality and the Structure of Distinction

A rigorous definition of entropy dimensionality (D_S) within TEQ remains an open challenge, but its conceptual role provides a new way to connect the photon and the black hole horizon.

For photons, the entropy metric collapses longitudinally ($h_{\|} \to 0$), so all structure is confined to the transverse directions. The effective entropy dimensionality is reduced, potentially even fractal in character, reflecting the scale-free nature of interference and polarization patterns.

In black holes, the horizon acts as a transverse entropy boundary: entropy dimension collapses radially, and the area law expresses the fact that all surviving distinction is transverse. In both cases, collapse of entropy dimensionality gives rise to the same exponential cutoff in Fourier space.

This suggests that entropy dimensionality, even if non-integer or locally defined, offers a unifying language for discernibility in quantum gravity. The photon and the horizon are both best understood as entropy-stabilized patterns at the boundary of what can be resolved.

While not yet formalized, D_S may be connected to existing notions such as the information dimension in fractal geometry, the effective number of distinguishable microstates in coarse-grained statistical mechanics, or the scaling behavior of entropy-weighted measures in information geometry. A promising direction is to define D_S via the local scaling of the entropy measure under coarse-graining:

$$\mu(\epsilon) \sim \epsilon^{D_S}$$

where $\mu(\epsilon)$ counts the number of resolvable distinctions at resolution scale ϵ. Such a definition would provide a geometric, observer-independent account of dimensionality based on entropy structure, consistent with the TEQ principle that all physical observables arise from stable distinctions under entropy flow.

Philosophical Summary Statement

What is usually called “wave–particle duality” is not a mysterious dualism, but the signature of entropy geometry at the resolution boundary. A photon is a transverse entropy-stabilized pattern whose finite entropy curvature dictates its observable wave-like properties. The unity of wave and

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horizon phenomena is not just a formal resemblance, but a natural consequence of the same entropy-geometric constraint.

10. Unexplained Observations and Potential Applications

While this paper focuses on deriving structural results within the TEQ framework, it is worth noting that several empirical phenomena, currently lacking fully satisfactory explanations, may find a natural structural account in the results presented here.

We emphasize that the following connections are *suggested* by the formal results but are not yet rigorously derived in full within the TEQ framework. Future work is required to formalize these connections explicitly.

- **Universality of the diffraction limit:** The derived exponential suppression of transverse modes (Sections 5–6, Appendix B) offers a structural explanation for the universal character of diffraction and resolution limits observed across different quantum systems. The TEQ framework suggests that such behavior is a geometric consequence of entropy structure, rather than an artifact of specific wave equations.
- **Horizon entropy area law:** The TEQ derivation of the area law scaling for horizons (Section 6) provides a non-microstructural explanation for this universal feature of gravitational systems. This may shed light on why the area law holds so generally, even beyond regimes where a detailed microscopic model is known.
- **Unruh radiation and accelerated horizons:** The universality theorem proved in Appendix B suggests that any entropy-degenerate system should exhibit similar exponential suppression of transverse modes. This raises the possibility that observed features of Unruh radiation and analog gravity systems may be structurally explained within the TEQ framework. A full derivation of this connection is a subject for future work.
- **Entropy-dimensionality effects:** The conceptual role of entropy dimensionality D_S introduced in Section 9 suggests new avenues for explaining scaling behavior in systems where effective dimensionality changes near critical surfaces (e.g., horizons, confinement boundaries, condensed matter analogues). Formalizing this connection within TEQ remains an open challenge.

We present these connections not as proven results, but as structurally motivated avenues for further investigation. They point to the potential explanatory power of the TEQ framework beyond the specific derivations presented here.

11. Future Work

While this paper establishes a rigorous structural unification of photon wave behavior and horizon entropy scaling under the TEQ framework, several promising directions remain open for further investigation and formalization.

Entropy Dimensionality

Future work will aim to formalize entropy dimensionality D_S within the TEQ framework, potentially revealing fractal and non-integer structures of discernibility that further unify quantum, gravitational, and informational phenomena. The role of entropy dimensionality in determining the scaling behavior of observable degrees of freedom remains a key question for both theoretical development and empirical testing.

New Phenomena and Predictions

Building on the universality result proven in Appendix B, the TEQ framework suggests several avenues where new physical phenomena may be predicted or existing unexplained observations structurally accounted for:

- **Universal exponential cutoff prediction:** TEQ predicts that in any system where the entropy metric becomes degenerate along one direction, the surviving transverse structure will exhibit exponential suppression in Fourier space. This could be tested in:
  - analog gravity systems (e.g., fluid horizons, optical analogues),
  - condensed matter systems with entropy flow constraints,
  - high-precision photon or matter-wave diffraction experiments.
- **Entropy-dimensionality effects:** TEQ suggests that when entropy dimensionality collapses (non-integer D_S), physical systems will display novel scaling of their observable degrees of freedom. This could lead to new predictions in:
  - near-horizon physics,
  - fractal optical systems,
  - cosmological horizon studies.
- **Entropy curvature as a control parameter:** TEQ further suggests that manipulating the effective entropy curvature—through environment, boundary conditions, or flow control—could alter observable wave behavior. This opens possible new directions in:
  - quantum control,
  - optical design,
  - thermodynamic engineering of quantum systems.

These directions represent structural consequences of the TEQ framework that, while not yet fully developed, point toward broad potential explanatory and predictive power. Formalizing these connections and testing their predictions will be a priority in future work.

12. Conclusions

We have shown that wave–particle duality in quantum optics and horizon entropy scaling in gravitational systems both arise from a single structural principle in the TEQ framework: finite transverse entropy curvature governing which distinctions can be stably maintained.

The explicit exponential suppression observed in both photon diffraction and horizon mode profiles follows directly from the entropy-weighted variational principle. This extends the TEQ-based unification of quantum and gravitational structure, offering a structural explanation for phenomena that were previously linked only by analogy.

By recognizing that the same entropy geometry governs both photon wave behavior and black hole horizon entropy, this work provides a unified structural explanation for both domains. The limits set by entropy curvature are not arbitrary but reflect a universal principle about what the universe allows to be resolved, whether at the smallest scales of quantum optics or the largest boundaries of spacetime.

Several empirical phenomena, currently lacking complete explanations, appear structurally compatible with this result and are discussed as potential applications. Finally, the derivation presented here suggests that this exponential suppression of high-frequency transverse modes is a general structural consequence of entropy geometry whenever longitudinal resolution collapses. To make this universality explicit, Appendix B provides the general proof that in any system where the entropy metric degenerates along one direction, the surviving observable structure exhibits the same exponential Fourier cutoff derived here.

Acknowledgments: This work was carried out independently during a period of cognitive and physical rehabilitation following a brain hemorrhage. It reflects part of a personal recovery process rather than a formal research program. ChatGPT was used for language refinement and structural organization; all theoretical content is the author's own.

Appendix A. Relation to Prior Work and Distinctive Features of TEQ

A variety of frameworks have explored structural limits in quantum and gravitational systems, including the holographic principle [9], entropic gravity [11], and microstate-based black hole thermodynamics [1,2]. These approaches often postulate boundary–bulk correspondences, entropic forces, or specific microphysical models to account for observed phenomena.

The TEQ framework departs fundamentally from such approaches in three key respects:

- **Structural derivation:** In TEQ, all central results—such as resolution boundaries, entropy scaling, and the exponential suppression of high-frequency modes—are not assumed, but rigorously derived as necessary consequences of finite entropy curvature within a unified geometric framework.
- **Universality:** These results hold for any system in which the entropy metric degenerates, regardless of the underlying microphysics, boundary dualities, or information-theoretic assumptions. This universality extends the applicability of TEQ across quantum, gravitational, and potentially condensed matter systems.
- **No additional assumptions:** Unlike previous frameworks that introduce new postulates (such as boundary duality or emergent gravity conjectures), TEQ relies solely on two core structural principles: entropy geometry and the minimal principle of stable distinction. No ad hoc axioms or supplemental conjectures are required.

Importantly, the emergence of boundary-like or “holographic-like” features in TEQ is not a foundational postulate but a necessary outcome of entropy geometry applied to systems with degenerate resolution. This unified approach both clarifies and simplifies the explanation of phenomena previously regarded as unrelated or as requiring specialized assumptions. The exponential suppression of high-resolution modes and the unification of quantum and gravitational limits are distinctive features of TEQ.

Clarifying Scope and Focus. While there exist other approaches—such as holography, loop quantum gravity, causal set theory, and entropic gravity—that aim to explain structural features of spacetime and information limits, the TEQ framework does not rely on interpretive postulates or microstructural conjectures. Its focus is strictly geometric and deductive: all results are derived from two minimal principles—entropy geometry and stable distinction—without invoking dualities, emergent spacetime scenarios, or speculative information-theoretic assumptions.

For this reason, we deliberately avoid interpretive commitments associated with ongoing debates about holography, entropy bounds, or spacetime emergence. The TEQ derivation of exponential suppression and resolution collapse proceeds from internal structure alone, and the appearance of “holographic-like” behavior emerges as a structural consequence—not as a guiding hypothesis.

Similarities and Differences Table

Approach	**Foundational Assumption**	**TEQ Difference**
Holographic principle	Boundary–bulk encoding postulated	Boundary-like effects derived from entropy geometry
Entropic gravity	Gravity as emergent from entropy	Entropy geometry unifies quantum and gravity structure
Standard QFT	Microstates/postulates for scaling	No microstructure: structure from geometric stability
Loop quantum gravity / causal sets	Quantum geometry or discrete structure postulated	Continuous entropy geometry governs resolution

For comprehensive reviews of related approaches, see [14–16].

Appendix B. General Proof of Universal Transverse Exponential Suppression

This Appendix provides a general derivation showing that in any system where the entropy metric degenerates along one direction (longitudinal collapse), the surviving observable transverse structure must exhibit exponential suppression

in Fourier space. This generalizes the results obtained explicitly for photons (Section 5) and black hole horizons (Section 6).

Appendix B.1. Setup

Consider a configuration manifold with coordinates $x^{\mu} = (x^{\parallel}, x_i^{\perp})$, where the entropy metric has the structure

$$dR^2 = h_{ij}^{\perp} dx_i^{\perp} dx_j^{\perp} + \epsilon\, h_{\parallel} dx^{\parallel} dx^{\parallel},$$

with $\epsilon \to 0$. That is, the longitudinal direction becomes entropy-degenerate.

Observable patterns must then be fully encoded in the transverse subspace $x_i^{\perp}$, with entropy geometry governed by $h_{ij}^{\perp}$.

Appendix B.2. Entropy-Weighted Path Integral

The entropy-weighted path integral is constructed as

$$\int \mathcal{D}[\psi] \, \exp\left(iS[\psi] - \hbar\beta \int dt \, g(\psi, \dot{\psi}) \right).$$

For entropy-stabilized modes, the entropy flux satisfies

$$g(\psi, \dot{\psi}) \sim \omega_k,$$

as proven in the main text and prior references.

Appendix B.3. Entropy Curvature Operator

From the second variation of S_{eff}, the entropy curvature operator $H_{\perp}$ in the transverse directions has eigenmodes ψ_k defined by

$$H_{\perp} \psi_k = \lambda_k \psi_k,$$

with corresponding entropy flux $g(\psi_k, \dot{\psi}_k) \sim \omega_k$.

Appendix B.4. Fourier-Space Suppression

In Fourier space, this leads to a weight assigned to each transverse mode:

$$w(k_{\perp}) \propto \exp(-\beta \omega_{k_{\perp}}).$$

Since for generic linear dispersion relations $\omega_{k_{\perp}} \propto |k_{\perp}|$, this yields the universal exponential suppression:

$$\psi(k_{\perp}) \propto \exp(-\alpha |k_{\perp}|),$$

with $\alpha = \beta\, c_{\text{eff}}$, where c_{eff} depends on the transverse entropy curvature $h_{ij}^{\perp}$.

Appendix B.5. Universality Statement

The above reasoning relies only on:

- Degeneracy of the entropy metric along one direction ($h_{\parallel} \to 0$);
- Finite positive-definite transverse entropy curvature ($h_{ij}^{\perp}$);

- Entropy-weighted path integral structure.

Therefore, the result holds generally: *any physical system in which longitudinal entropy resolution collapses will exhibit exponential suppression of observable transverse modes in Fourier space*.

This general result explains and subsumes the specific examples of photon diffraction (Section 5) and horizon entropy structure (Section 6), and predicts the same behavior in any system with longitudinal entropy collapse.

Appendix B.6. Conclusion

The exponential Fourier cutoff is thus a **general structural consequence** of entropy geometry in the TEQ framework, not a peculiarity of photons or black hole horizons. This Appendix formally generalizes the results of Sections 5 and 6.

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