Reconstruction of a Minimal Six-Dimensional Light Null Entity with Mutual Base Space-Fiber Method

Tingfang Yi

Centiver Ltd, 85 Bolton Street, Cambridge, MA 20140 USA

Abstract

We propose a unified minimal six-dimensional (6D) light null entity, where the fundamental properties of light are reinterpreted as intrinsic degrees of freedom within a singular closed manifold. This 6D structure integrates a two-dimensional null propagation geometry with four intrinsic 1D degrees of freedom: optical phase, polarization, frequency, and orientation relative to the null momentum generator. In this framework, conventional four-dimensional (4D) spacetime optical, electromagnetic, and quantum phenomena arise as lower-dimensional projection or section measurements of this structure, while preserving consistency with established theories at the level of current observations. Spacetime coordinates and photon internal degrees of freedom may be geometrically equivalent components of a higher-dimensional manifold.

Introduction- Light occupies a unique and paradoxical position in fundamental physics. While it serves as the universal constant for spacetime measurement, its own intrinsic nature remains fragmented under the standard four-dimensional (4D) Minkowski framework. Propagating at an invariant speed c without a rest frame or proper time, light exhibits properties (such as phase, polarization, and frequency) that appear as external parameters rather than geometric necessities. In the 4D spacetime observer's frame, these properties often manifest as mutually incompatible or gauge-dependent variables. For instance, null propagation precludes the existence of a rest length,

yet polarization is strictly transverse; frequency is defined only through an external temporal parameter, while discrete photon detections contrast sharply with continuous field evolution. These light features are traditionally accommodated within separate theoretical or hypothetical frameworks-classical electrodynamics [1-3], special and general relativity [4,5], and quantum electrodynamics (QED) [6-8]-whose individual consistency is operational but conceptually fragmented. While QED provides an accurate predictive framework, it does not provide an intrinsic geometric ontology beyond 4D section.

We propose that spacetime coordinates and intrinsic photon degrees of freedom are mutually interchangeable components of a higher-dimensional null manifold. In this view, 4D observables-phase, polarization, frequency, and propagation orientation-emerge as projections of a continuous 6D entity. This base-fiber symmetry naturally resolves apparent paradoxes of light, such as wave-particle duality and independent internal freedoms, establishing a minimal, self-consistent high-dimensional ontology for the photon. The 4D incompatibilities are artifacts of dimensional reduction. By reconstructing light as a minimal 6D null entity. We show that these observed phenomena emerge naturally from the intrinsic geometry of a higher-dimensional null manifold, offering a more complete and coherent ontology of the photon. Using mutual base space-fiber geometric reconstruction method, we reconstruct a minimal 6D light null entity with intrinsic light freedoms: null propagation, optical phase, polarization, frequency, and orientation along the null momentum generator. These intrinsic dimensions are not extended spatial directions, but as the observable physical attributes of light themselves, thereby bypassing the conceptual hurdles of dimensional compactification or unobservability. Subsequently, longstanding paradoxes of light arise not from intrinsic indeterminacy, but from dimensional reduction under measurement. By

transcending the unidirectional governance of the base space over the fiber in classical bundle theory, the framework of mutual base space-fiber introduces a fundamental duality where base and fiber may interchange roles, establishing a mathematical symmetry and connectivity for reconstructing higher-dimensional entities from their reciprocal geometric projections. Importantly, QED remains fully compatible with the 6D light null entity projections/sectional measurements at the level of all existing 4D predictions. The observations of high-dimensional entity projection demonstrate that, under some conditions, when a continuous higher-dimensional entity is projected onto a space lower by at least two dimensions (N→N-2), the original topological connectivity is "sheared", resulting in apparent discreteness and point-like behavior. A 4D photonic quantum point is not a stochastic dot, but a compressed cross-section of a 6D light entity with compressed unit of information. The present work formulates the structural framework basis of a minimal 6D light null entity, and detailed dynamical development and quantitative implications will be followed in subsequent studies/reports.

Minimal Intrinsic Geometry of Light with Six Intrinsic Degrees of Freedom-The intrinsic state of a light entity (**Table S1**) is specified by

$$\mathcal{L} = (\hat{\mathbf{n}}, \phi, \theta_P, \nu, \sigma),$$

Where

$\hat{\mathbf{n}} \in S^2$ is the null propagation direction (2D),

$\phi \in$ S1 is the optical phase (1D),

$\theta_P \in$ S1 parameterizes polarization (1D),

$\nu \in \mathbb{R}^+$ is the frequency (1D),

$\sigma \in \{+,-\}$ labels orientation along the null momentum generator (1D).

These define the minimal intrinsic manifold

$$\mathcal{M}_6 = S^2 \times S^1_\phi \times S^1_P \times \mathbb{R}^+_\nu \times \mathbb{Z}_2$$

which is the smallest closed structure capable of encoding irreducible, incompatible and established native properties of light (**Table S1**). These internal degrees of freedom are not extended spatiotemporal coordinates, but intrinsic attributes of a null physical entity. Their apparent separability in 4D descriptions arises solely upon projection/sectional measurement. Frequency labels null generator scaling class and cannot be intrinsically reduced to a phase derivative without reintroducing an external time parameter. Orientation along the null momentum generator, to distinguish forward- and backward-directed null propagation while preserving nullity, therefore constitutes an independent intrinsic binary degree of freedom.

The propagation geometry of light is intrinsically two-dimensional, corresponding to the space of null directions. Because a null entity admits no rest frame, no proper time, and no intrinsic transverse localization, its evolution cannot be parameterized internally by a time-like coordinate. Spacetime trajectories emerge only upon projection/section into observer-defined coordinates.

The null condition is identically satisfied,

$$p^\mu p_\mu = 0$$

with

$$E=h\nu, \qquad |\mathbf{p}| = \frac{h\nu}{c}$$

Energy and momentum arise from frequency and null orientation, without invoking rest mass or intrinsic temporal evolution. The generator orientation σ enforces the positive-energy condition and distinguishes forward and backward null propagation.

Field Representation and 4D Section-A sectioned/projected single-photon state may be written as

$$\Psi(\hat{\mathbf{n}}, \phi, \theta_P, \nu) = A\,\mathbf{e}(\theta_P)\,e^{i\phi}, \qquad \mathbf{e}\cdot\hat{\mathbf{n}} = 0$$

Classical electromagnetic fields arise as coherent superposition or ensemble limits of such sectioned/projected states. Maxwell's equations emerge as consistency conditions enforcing transversality, gauge invariance, and null propagation within the section/projection space [1-3].

Quantum phase phenomena, including interference and Berry phases [9], correspond to holonomies in the phase-polarization fiber induced by section/projection along null propagation. Discrete photon detection reflects the intersection of a 4D detector worldvolume with an extended 6D null entity, rather than the existence of a localized particle point. Within this framework, wave-particle duality, photon identity, and measurement collapse are not intrinsic features of light, but structural consequences of dimensional reduction (**Table S2**). A photonic quantum point is not a mere dot or numerical value, but a compressed unit of information. It represents a locally compressed cross-section of a higher-dimensional tensor structure. The observed number, distribution, spacing, and coupling patterns of 4D light/photon quantum dots encode features consistent with the proposed 6D light null entity, providing a quantifiable map of high-dimensional information. This paradigm shift redefines the once-perceived stochastic noise of 4D light quantum dots as a deterministic characteristic spectrum map of 6D light entities, which may serve as solid supporting evidences for the existence of the 6D light entity and a spectrum for decoding intrinsic features of the 6D light null entity.

Consistency With Established Physics-Special Relativity: Lorentz invariance is preserved through the intrinsic null structure. No preferred frame or superluminal dynamics is introduced, as all observable propagation occurs along null directions consistent with c. General Relativity: In curved spacetime, the null direction follows geodesics, while phase and polarization undergo geometric transport, reproducing gravitational redshift and known polarization holonomies [5]. Quantum Electrodynamics: All experimentally accessible QED predictions arise as sections/projections of the 6D null entity. Scattering amplitudes, vacuum polarization, radiative corrections, and standard optical observables remain unchanged at the level of 4D measurable physics [6-8].

Decisive Experimental Test -In standard quantum optics, interference visibility V and which-path distinguishability D obey the complementarity bound

$$V^2 + D^2 \leq 1$$

which holds even for weak measurements and partial path marking. Any continuous modulation of visibility in the presence of path distinguishability is constrained by this inequality and cannot exceed it within conventional quantum electrodynamics. The six-dimensional null entity framework predicts a controlled and repeatable violation of this bound under specific internal degree-of-freedom manipulations, while preserving single-photon statistics and without invoking post-selection or erasure. Experimental Configuration: A Mach-Zehnder interferometer is configured with the following elements: 1) Single-photon source: heralded single photons via spontaneous parametric down-conversion (SPDC). 2) Path marking: a calibrated birefringent

element introducing a fixed, measurable path distinguishability $D > 0$, verified independently by polarization-resolved detection. 3) Internal holonomy module (key element): a closed-loop phase-polarization coupling device inserted in one arm, implementing a nontrivial geometric transformation in the (ϕ, θ_P) internal fiber without altering path distinguishability. 4) Detectors: polarization-insensitive single-photon avalanche photodiodes (SPADs). Crucially, the internal holonomy module is designed such that path information remains available in principle, and no which-path erasure is performed. Predictions*:* Conventional quantum electrodynamics: Visibility is bounded by the complementarity inequality,

$$V_{\mathrm{QED}} \leq \sqrt{1 - D^2}$$

and internal polarization manipulations cannot increase V once D is fixed. Six-dimensional null entity framework: Interference visibility depends on the internal geometric holonomy accumulated along the null entity's propagation and is given by

$$V_{\mathrm{6D}} = \sqrt{1 - D^2} + \kappa\, \mathcal{H}(\phi, \theta_P)$$

where $\mathcal{H}$ is a closed-loop holonomy functional determined by the phase–polarization fiber geometry, and κ is a coupling constant fixed by the birefringent strength.

For sufficiently small but finite κ, the theory predicts

$$V_{\mathrm{6D}}^2 + D^2 > 1$$

representing subtle deviation in specific holonomy-controlled regime. Falsifiability Criterion: Observation of $V^2 + D^2 \leq 1$ under all internal holonomy manipulations falsifies the six-dimensional null entity model. Observation of a reproducible violation $V^2 + D^2 > 1$ under fixed, independently verified D constitutes decisive evidence for intrinsic internal structure beyond four-dimensional projection. This experiment therefore provides a sharp, unambiguous distinction between the proposed framework and standard quantum electrodynamics.

Discussion-Our reconstruction of 6D light null entity may open avenues of understanding higher dimensional light entity. The intrinsic six dimensions of null propagation, optical phase, polarization, frequency, and orientation along the null momentum generator and their inherent connectivity in 6D light null entity may expand the understandings of nature properties of light. The transition from viewing 4D light/photon quantum dots as stochastic noise to a deterministic characteristic spectrum constitutes a foundational proof of the 6D light entity. The recurring geometric regularities and coupling matrices within these discrete points function as the intrinsic topological signatures of a higher-dimensional entity. A key conceptual advance of this work is the elevation of the internal degrees of freedom of the photon to geometric parity with spacetime coordinates within a unified high-dimensional manifold. Unlike traditional fiber bundle approaches, where spacetime acts as the base and internal structure is relegated to the fiber, here spacetime itself emerges as merely one projection of the total geometric entity. This reconceptualization dissolves the hierarchical distinction between base and fiber, allowing a truly covariant treatment of light's intrinsic properties, and providing a natural framework to encode polarization, phase, frequency, and orientation on equal footing with null propagation. Such a perspective shifts the paradigm from a spacetime-centric view to a manifold-centric view, wherein the photon's full structure is realized only in the higher-dimensional embedding.

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References

1. J. D. Jackson, *Classical Electrodynamics* (Wiley, 3rd Ed., 1999).
2. D. J. Griffiths, *Introduction to Electrodynamics* (Pearson, 2017).
3. R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics, Vol. II* (Addison-Wesley, 1964).

4. A. Einstein, *Annalen der Physik* **17**, 891 (1905).
5. B. F. Schutz, *A First Course in General Relativity* (Cambridge Univ. Press, 2009).
6. C. Itzykson and J.-B. Zuber, *Quantum Field Theory* (McGraw-Hill, 1980).
7. W. Greiner and J. Reinhardt, *Quantum Electrodynamics* (Springer, 2009).
8. S. Weinberg, *The Quantum Theory of Fields, Vol. I* (Cambridge Univ. Press, 1995).
9. M. V. Berry, *Proc. R. Soc. Lond. A* **392**, 45 (1984).
10. M. O. Scully and K. Drühl, *Phys. Rev. A* **25**, 2208 (1982).
11. P. G. Kwiat et al., *Phys. Rev. Lett.* **74**, 4763 (1995).
12. W. P. Schleich, *Quantum Optics in Phase Space* (Wiley-VCH, 2001).
13. T. J. Weinhold et al., *Optics Lett.* **38**, 1239 (2013).

Supplementary Material

Reconstruction of a Minimal Six-Dimensional Light Null Entity

Tingfang Yi

Centiver Ltd, 85 Bolton Street, Cambridge, MA 20140 USA

This supplementary section provides a simple geometric illustration to clarify a general structural point underlying the main text: a single higher-dimensional (3D) physical entity may admit multiple lower-dimensional projections/sections that appear mutually incompatible, while remaining fully self-consistent at the intrinsic level. The illustration is not intended as evidence for

the six-dimensional (6D) light null entity itself, but as an explicit example demonstrating how mutual base space-fiber reconstruction operates in an ordinary geometric entity system. A 3D helical spring, though embedded in three-dimensional space, is intrinsically a one-dimensional parametric curve whose minimal structural parameters generate multiple physically interpretable properties such as rotation, phase, and chirality. Its lower-dimensional projections, while lossy, preserve structured signatures sufficient for constrained reconstruction. Analogously, the intrinsic degrees of freedom of a 6D light entity may form a minimal irreducible structure within the six-dimensional null manifold, whose 4D manifestations represent structured projections that partially encode the underlying geometry in a logically, geometrically, and physically consistent manner.

Discreteness and dot appearances of at least 2-dimensinal (2D) projection reduction of a continuous higher-dimensional entity- The projection of a 3D helical spring entity in vertical direction on 1D straight line space appears two separated dots at the same time (with the projection dot distance equal to the diameter of the spring's circle). The projection of the same 3D spring entity in horizonal direction on 1D straight line space appear multiple separated dots at the same time (with the projection dot number equal to the number of spiral turns, and the neighboring projection dot distance equal to the pitch of the helix).

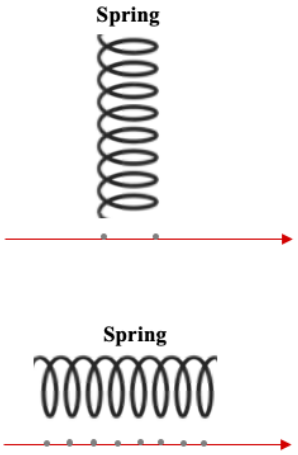

Figure S1. Discreteness and dot appearances with at least 2-dimensinal (2D) projection reduction. Discreteness and dot appearances of a single static 3D helical spring entity's one projection on 1D straight line space. One projection of the same 3D spring entity (in vertical or horizonal directions) appears two or multiple separated dots (in gray dot) at the same time on 1D straight line space, respectively.

The discreteness and dot appearances of a 3D spring entity on 1D (with 2D reduction) straight line space projection demonstrate that the original 3D helical spring topological connectivity is "sheared" in 1D straight line space, resulting in apparent discreteness and point-like behavior. The paradox of discreteness and multiple separated dot appearance of 1D projections of a single 3D spring entity at the same time in 1D line space are compatible and with intrinsic connectivity in the 3D helical spring entity. These observations suggest that, at least under some conditions, when a continuous higher-dimensional entity is projected onto a space lower by at least two dimensions (N→ N-2), the original entity topological connectivity is "sheared", resulting in separated point-like activity and discreteness. Although very limited, loss of connectivity, and very fragmental and

incomplete, these discrete dots/projections/sectional measurements at lower (N-2) dimension do encode residual fiber data of the parent structure of the higher-dimensional (N) entity, which are not as a consequence of stochastic fragmentation, but as a deterministic reduction of a continuous higher-dimensional geometry. In this formulation, apparent quantum discreteness reflects a geometrically constrained projection with information preserved in compressed form. In an inverse view, the discreteness and multiple or many separated dot appearance/detections/ descriptions at the same time of a single known object/entity in an N-dimensional space may indicate that these appearance/detections/ descriptions maybe a projection of an at least N+2 dimension-object/entity in N-dimension space. It is difficult to reconstruct a 3D spring entity only with the separated dot projections in 1D due to the too much topological connectivity loss during the 2-dimensional reduction.

Decomposition and Reconstruction of a 3D Helical Spring Entity with Mutual Base Space -Fiber-

Consider a three-dimensional helical spring embedded in Euclidean space, parametrized by

$$\mathbf{r}(s) = \left(R\cos s,\ R\sin s,\ Ps\right)$$

where R is the radius, P is the pitch $s \in \mathbb{R}$ parameter, and is an intrinsic parameter along the curve. XY-plane: a circle $x^2+y^2 = R^2$; XZ-plane: a sine wave $y = R \sin (z/h)$, and YZ-plane cosine wave $x = R \cos (z/h)$. This curve admits a natural base-fiber decomposition: the axial direction defines a one-dimensional base, the angular coordinate defines a one-dimensional fiber, the full entity is not reducible to either alone. Importantly, the helix exists as a single, well-defined geometric object independent of any projection/section. Different projections in the orthogonal 2D planes (circle, sine wave, cosine wave) of the same helical entity yield qualitatively distinct curves.

Each projection is internally consistent, yet the three descriptions are mutually incompatible within 2D planes. Each projection captures a genuine aspect of the helical spring, yet none alone uniquely specifies the full 3D structure.

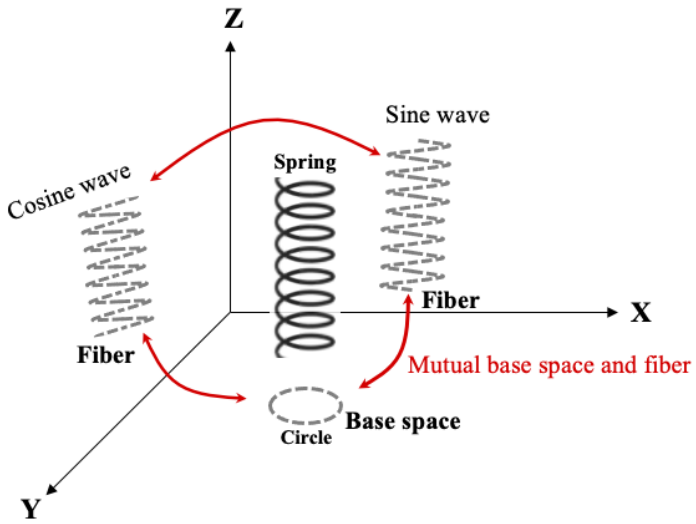

Figure S2. Decomposition and reconstruction of a 3D helical spring entity. Decomposition of a 3D helical spring entity in 2D XY-plane, XZ-plane and YZ-plane with three mutually incompatible projections of a circle, a sine wave, and a cosine wave, respectively. Reconstruction of these three 2D mutually irreducible and incompatible projections by mutual base space-fiber reestablish a sole geometric 3D helical spring entity.

While individual projections are incomplete, the combination of mutual base and fiber parameters of the three 3D projections of circle, sine wave, cosine wave uniquely reconstructs the original helix spring entity. The apparent incompatibility among the projected curves arises solely from dimensional reduction, not from any ambiguity or inconsistency in the underlying object. This (**Fig.S1**) illustrates a general principle: projection multiplicity does not imply ontological multiplicity. Three principles of the mutual base space-fiber 3D entity geometry reconstruction are:

1) irreducible and mutually incompatible 2D descriptions of the 3D entity, 2) no single lower-dimension description is ontologically privileged, 3) intrinsic connectivity of all mutual base space-fibers. The number of three of the mutually irreducible and incompatible 2D descriptions in the three orthogonal planes is equal to the minimal dimension number of three of a helical spring entity. This 3D entity geometric reconstruction method with mutual base space-fiber reconstructions of irreducible and mutually incompatible 2D descriptions and their intrinsic connectivity may extend to other high dimensional (N+1) geometric entity reconstruction from mutually incompatible lower-dimensional (N) descriptions with 1D difference. It may be inefficient to use the mutual base space-fiber reconstruction method for higher-dimensional reconstruction with 2D difference due to the loss of too much connectivity information during 2D reduction. The number of mutually irreducible and incompatible lower-dimensional descriptions (projections/sections) of a higher-dimensional entity are related to the minimal dimension number of the higher-dimensional entity.

In standard fiber-bundle geometry, the base space and the associated projection are fixed a priori, which implicitly assumes the existence of a preferred decomposition of the system. This assumption is appropriate when the physical object itself distinguishes external coordinates from internal degrees of freedom. However, it already encodes a choice of projection and therefore cannot be regarded as an intrinsic property of a genuinely higher-dimensional object.

While standard 4D physics describes light as a gauge field quantum, it treats the phenomenon as a foundational limit, yet it remains ontologically silent-much like a 2D projection of a 3D spring entity that appears irreducible within a 2D plane. However, if the 4D light we observe is merely a

low-dimensional shadow/section measurement, its true substance remains invisible in our 4D geometry. This raises a profound possibility: can the ontological essence of light only be answered by stepping into the higher dimensions from which it originates?

Relation to the Six-Dimensional Light Null Entity- The mutually incompatible observations in 2D projections or cross-sections of a 3D helical spring-such as top-view circular projections versus side-view sinusoidal profiles-cannot be reconciled within any single 2D theoretical framework, yet they are naturally unified in the full 3D structure, indicating that the 2D observations are projections of a higher-dimensional entity. Analogously, the paradoxical phenomena observed of light in 4D-including the coexistence of discrete quanta and continuous fields, and the independent behavior of polarization, phase, and propagation orientation-cannot be fully explained within conventional 4D theories. These 4D contradictions similarly suggest that the observed phenomena are projections/sections of a higher-dimensional light entity, whose intrinsic structure can reconcile these apparent paradoxes in a self-consistent manner.

Even when low-dimensional theories provide self-consistent explanations for observed phenomena, the existence of higher-dimensional structures can remain necessary to resolve apparent paradoxes. For example, in condensed-matter physics, the quantized Hall conductance in the integer quantum Hall effect cannot be fully explained by semiclassical 2D electron models; only by invoking the underlying topological invariants does one obtain a unified, self-consistent description. Similarly, in high-energy physics, the Kaluza-Klein framework demonstrates that the electromagnetic field can be interpreted as a manifestation of 5D spacetime geometry, a higher-dimensional structure that naturally unifies interactions otherwise treated independently in 4D. By

analogy, the mutually incompatible observations of light in 4D discrete quanta versus continuous fields, and independent polarization, phase, and propagation orientation-may be interpreted as projections of a higher-dimensional light entity, whose intrinsic structure reconciles these low-dimensional paradoxes in a self-consistent manner beyond the explanatory reach of conventional 4D theories.

The six-dimensional structure of the light null entity arises naturally from the intrinsic geometry of null propagation geometry, optical phase, polarization, frequency, and orientation along the null momentum generator. By allowing base space and fiber roles to exchange among these five components, each acquires full geometric status, rather than being treated as an auxiliary or dependent degree of freedom. This mutual base space-fiber relation ensures that all projections are mutually consistent and fully capture the underlying higher-dimensional object. Any attempt to reduce the dimensionality would collapse this internal consistency, while any additional dimensions would lack intrinsic constraints or observable necessity. Therefore, six dimensions represent the minimal and complete geometric description of the light null entity, uniquely determined by its projection/section-consistent structure.

Reconstruction of a Minimal 5D Light Manifold as Evidence for the 6D Light Null Entity-
Numerous experiments have revealed couplings among propagation, polarization, phase, and frequency. While these phenomena are well described within conventional frameworks, their persistent geometric interdependence suggests the possibility that these degrees of freedom may arise as projections of a higher-dimensional unified structure. There are five pair-couplings: propagation-polarization (spin Hall of light), propagation-phase (Berry phase), polarization-phase (Pancharatnam phase), polarization-frequency (optical activity dispersion), phase-

frequency(chirped pulses), and three triple-couplings: propagation-polarization-phase (geometric phase transport), polarization-frequency-phase (ultrafast polarization dynamics), propagation-polarization-frequency (spin-dependent dispersion). Orientation, as an implicit degree of freedom, dictates the embedding of the propagation geometry. This implies that these couplings represent different projections of a single unified structure-5D light manifold. Based on the above abroad light freedom coupling and intrinsic connectivity, we construct a minimal 5D light manifold $\mathsf{M5}$ as an intermediate structure between 4D photon and 6D light null entity capturing both the observable 4D null propagation dynamics and an additional hidden degree of freedom. This manifold is formalized as a fiber bundle $\pi : \mathsf{M5} \to \mathsf{B4}$ where $\mathsf{B4}$ is the 4D base spacetime and the 1D fiber encodes internal optical orientation or phase. Coupling compatibility equations are imposed to ensure consistency between the 4D observable dynamics and the internal fiber degrees of freedom, guaranteeing that the manifold is dynamically admissible.

The reconstruction theorem establishes that, given the 4D light dynamics and the coupling constraints, there exists a unique minimal 5D manifold (up to gauge equivalence) that recovers the 4D observations while incorporating the hidden degree of freedom. This minimality condition ensures that no extraneous degrees of freedom are included beyond what is necessary to satisfy the coupling relations.

The existence of the 5D intermediate manifold, along with its well-defined fiber structure and compatibility relations, provides indirect evidence for the 6D entity: 1) Projection relationship, the 5D manifold represents the natural compression of the 6D null entity into a lower-dimensional intermediate while retaining essential internal degrees of freedom; 2) Coupling compatibility, the

internal fiber of the 5D manifold encodes interactions between observable and hidden DOFs, reflecting the intrinsic couplings expected in the 6D entity; 3) Uniqueness, the reconstruction theorem implies that the minimal 5D manifold is the only structure consistent with the 4D dynamics and the imposed couplings, suggesting that it is not arbitrary but emerges from a higher-dimensional parent; 4) Compression mapping, in this framework, the 5D manifold can be regarded as a faithful projection or "shadow" of the 6D light null entity, so its presence supports the existence of the higher-dimensional structure. Thus, the minimal 5D light manifold serves both as a rigorous reconstruction framework and as a theoretical bridge, providing a concrete link between observable 4D light dynamics and the hypothesized 6D light null entity.

Minimality and Dimensional Necessity of the Six-Dimensional Null Structure-We now show that the six-dimensional structure proposed here is forced by internal consistency requirements. Any intrinsic description of light with fewer than six independent degrees of freedom fails to reproduce at least one empirically established native property of light without introducing observer-dependent or non-geometric postulates.

Consider a general intrinsic description of light as a null entity characterized by a propagation geometry and a set of internal degrees of freedom $\{\chi i\}$. Empirically, a physical realization of light simultaneously exhibits:

1. null propagation with invariant speed c,
2. well-defined optical phase supporting interference,
3. frequency determining energy and momentum,
4. polarization with helicity structure,

5. a definite orientation along the null momentum generator.

Next, we examine the consequences of attempting to eliminate any one of the four internal degrees of freedom (ϕ, v, θ_P, σ), which are irreducible and mutually incompatible descriptions in 4D observations.

(i) Absence of intrinsic phase (ϕ).

Without an intrinsic phase variable, interference phenomena must be defined entirely through external time parameters. This renders phase observer-dependent and incompatible with the existence of geometric (Berry-type) phases observed under cyclic polarization transport. A null entity admitting no proper time cannot generate phase evolution intrinsically unless phase is an independent internal coordinate.

(ii) Absence of intrinsic frequency (v).

If frequency is not an independent intrinsic degree of freedom, energy must be introduced externally via observer-defined temporal slicing. This violates Lorentz invariance at the intrinsic level and obstructs the invariant null energy-momentum relation $E=hv$. Frequency therefore cannot be derived from phase alone without reintroducing an external time parameter, which a null entity lacks.

(iii) Absence of intrinsic polarization (θ_P).

Polarization cannot be reconstructed from phase, frequency, or propagation geometry. Attempts to treat polarization as a derived gauge artifact fail to reproduce helicity conservation and polarization-dependent geometric transport in curved spacetime. The empirical independence of polarization thus requires a distinct intrinsic dimension.

(iv) Absence of generator orientation (σ).

Eliminating orientation along the null generator removes the ability to distinguish forward- and backward-directed null propagation while preserving nullity. This leads to an ambiguity in the sign of energy and obstructs the enforcement of the physical positive-energy condition. Orientation therefore constitutes an independent intrinsic binary degree of freedom.

The above analyses suggest the minimal dimension number of a higher-dimensional light entity can be the number of irreducible and mutually incompatible descriptions/freedoms of null propagation (2), optical phase (1), frequency (1), polarization (1), and orientation along the null momentum generator (1): 2 +1+1+1+1= 6. Therefore, a minimum 6-dimensional null entity of light can manifest these 5 native, irreducible and mutually incompatible properties/freedoms in 4D detections (observations, descriptions, projections, or sections), which matches the 4D photon quantum observations related at least 2D more in higher-dimensional continuous entity. Any Lorentz-invariant intrinsic description of a massless spin-1 null entity encoding phase interference, polarization helicity, frequency-defined energy, and orientation along null generator requires dimension ≥ 6. The minimal 6D light null entity is uniquely determined by the six mutually incompatible degrees of freedom observed in 4D; it is compelled by logical, geometric, and physical consistency, realizing a triple consistency of structure, projection, and intrinsic physical properties.

These four internal degrees of freedom are mutually irreducible and cannot be generated from one another without violating Lorentz invariance, null structure, or empirical polarization and phase

phenomena. Together with the intrinsically two-dimensional null propagation geometry, they form a six-dimensional minimal closed manifold. Any intrinsic description with fewer than six dimensions necessarily fails to encode at least one empirically observed property of light without introducing external observer-dependent structures. Conversely, any extension beyond six dimensions introduces unconstrained degrees of freedom lacking empirical necessity. The six-dimensional null entity is therefore both minimal and complete, uniquely determined by consistency rather than choice.

A single 6D light null entity can manifest through many mutually incompatible 4D projections, sections, or experimental observations, which may individually appear paradoxical or contradictory. These 4D observations point to the existence of a higher-dimensional entity, which may provide an alternative intrinsic geometric description consistent with existing data. In both 3D spring and 6D light entities, the lower-dimensional projections or measurements do not by themselves determine the existence, correctness, or complete structure of the higher-dimensional entity, but all projections must be consistent with the underlying geometry.

Intrinsic degrees of freedom as high-dimensional manifolds: The four intrinsic 1D degrees of freedom detected in 4D-optical phase, polarization, frequency, and orientation, are actually projections of 3D topological structures within the 6D entity. What we measure as linear parameters are the "shadows" of complex rotational and helical behaviors in the hidden 2D subspace. Invariance of light speed: The invariant light speed c is redefined as the intrinsic propagation velocity of the 6D fluid medium. Because 4D observations are merely cross-sections of this global 6D state, the perceived speed remains constant regardless of the observer's relative

4D velocity. Single photon interference: The "interference" may be the self-interaction of the 6D manifold's geometry, which only appears as "divided" when viewed through restricted 4D window.

In 4D spacetime, the 6D light entity manifests in a state that is neither truly wave nor truly particle. Its observed interference patterns and discrete detection events are projections/sections of its higher-dimensional fluid manifold. Conventional terms like "wave" and "particle" are only approximate descriptors, but do not capture the true 6D nature of light. This duality of “wave-like, particle-like" state is not a physical paradox but a geometric necessity, arising from the information compression and topological constraints imposed when a continuous 6D entity is mapped onto the restricted dimensions of observable reality. Consequently, quantization is interpreted not as an intrinsic fragmentation of the entity, but as a topological consequence of 6D-to-4D dimensional reduction.

The 6D light null entity differs fundamentally from Kaluza-Klein, Twistor, and conventional multi-dimensional light field approaches. In this framework, the additional dimensions correspond directly to intrinsic photon degrees of freedom-optical phase, polarization, frequency, and orientation along the null momentum generator-rather than to abstract spatial or complex coordinates. This construction defines a minimal, closed manifold that unifies all empirically established photon properties within a single coherent geometric structure.

By expanding the dimensionality of light to a minimal 6D manifold, we may bridge the gap between continuous field theory and discrete quantum mechanics in a geometric reinterpretation. The "quantum" is revealed not as a fundamental graininess of nature, but as a topological 2D

reduction consequence of observing a 6D null entity from a 4D perspective. This reconstruction suggests that the four fundamental properties of light are intrinsically coupled within a higher-dimensional geometry, awaiting a unified mathematical description. Projecting a 6D light entity onto 4D spacetime is analogous to projecting a 3D helical spring onto a 1D line space with 2D reduction: most internal couplings/connectivity are sheared or averaged out, leaving only residual information that manifests as tiny phase shifts or visibility perturbations, which become observable only under specific conditions such as path marking or weak measurement, making the experimental detection of 6D corrections in 4D a highly constrained task. A critical inquiry arises as to whether the two dimensions 'lost' of 6D light null entity in the 4D projection correspond to the non-commutativity of quantum operators, potentially revealing a direct geometric mapping between the intrinsic manifold's extra-degrees of freedom and the complex structure of Hilbert Space.

Experimental observations of mixed topologies in light, such as spin-orbit coupling, vector beams with spatially structured polarization, and knotted optical vortices (Hopfions) exhibiting nonzero Hopf invariants, strongly suggest that the photon's internal degrees of freedom are interwoven in a higher-dimensional manifold, providing compelling indirect evidences for the existence of a 6D light entity beyond conventional 4D spacetime. Hopfions are known topological solutions of the 4D Maxwell equations, yet the 6D light entity framework naturally explains why photons can carry such topological invariants during free propagation. As indirect evidence, the existence and stability of Hopfion topology indicate that the photon's internal degrees of freedom are far richer than predicted by standard Maxwell theory, and this stability is naturally accounted for within the 6D model. Fragmentary experimental evidence suggests the possible existence of a phase-

polarization-frequency Hopf-type coupling in light. Observations such as frequency-dependent spin-orbit effects, wideband vector beams with subtle polarization-phase correlations, and structured optical frequency combs hint that these internal degrees of freedom may be interwoven in a topologically nontrivial way. While a direct measurement of the full Hopf linking across all three degrees of freedom has not yet been realized, these indications point toward the potential presence of a higher-dimensional internal geometry consistent with the proposed 6D light entity.

What was previously dismissed as random, chaotic light/photon quantum dots is now revealed to be a highly structured information map of the 6D light entity. The distribution, spacing, and coupling of these dots encode reproducible features of the underlying higher-dimensional structure. This recognition constitutes a conceptual leap, transforming formerly overlooked fragments into a valuable spectral blueprint for probing the internal architecture of light. Much like discrete points on a 1D line can reveal the precise pitch and diameter of a 3D helix, the spatial intervals and coupling variances of these 4D fragments provide a structured mapping of high-dimensional dynamics. By decoding the distribution matrices of these formerly dismissed residues, we transition from observing random probability to reconstructing the 6D geometric reality, unlocking the precise cryptographic key to the internal architecture of light.

Table S1: Mutually irreducible and incompatible properties of light and structural relations.

This table analyzes light properties which are mutually irreducible and cannot be generated from one another within a 4D intrinsic framework, and reach the minimal set (in bold) of independent intrinsic degrees of freedom required to encode known optical and quantum phenomena of light.

	Light property	Empirically established	Defined intrinsically in 4D?	Reducible from other properties?	Mutually incompatible with	Candidate intrinsic dimension
1	Null propagation speed c	Yes	Yes	No	Proper time, rest frame	**Null base geometry (2D)**
2	Absence of rest mass	Yes	Yes	No	Proper length, localization	Null constraint
3	Optical phase ϕ	Yes	No (requires time parameter)	No	Discrete detection	**Phase fiber (1D)**
4	Frequency v	Yes	No (observer-dependent)	No	Null proper time	**Frequency fiber (1D)**
5	Polarization	Yes	Gauge-dependent	No	Scalar wave description	**Polarization fiber (1D)**
6	Transversality	Yes	Constraint-based	Derived	Longitudinal modes	Projection constraint
7	Discrete detection events	Yes	No	No	Continuous fields	Projection effect
8	Wave-particle duality	Yes	No	No	Classical ontology	Projection effect
9	Photon identity indistinguishability	Yes	No	No	Particle localization	Intrinsic nonlocality
10	Zero proper time	Yes	Yes	No	Internal clock	Null geometry
11	Energy–momentum relation $E = pc$	Yes	Yes	Derived	Rest mass	Frequency + null orientation
12	Handedness / helicity (spin-1)	Yes	Yes	No	Scalar waves	**Generator orientation (1D)**

Experimentally established properties of light most notably optical phase, frequency, polarization, and helicity-cannot be derived from one another, nor from null propagation alone, within a 4D intrinsic description. At the same time, these properties are observed to coexist in every physical realization of light. The table highlights that these properties are: empirically independent, structurally incompatible as intrinsic 4D variables, and yet simultaneously realized.

The six-dimensional null light entity proposed in the main text introduces the minimal number of intrinsic degrees of freedom required to encode all entries in Table S1 without redundancy. Observable 4D electromagnetic and quantum phenomena arise as sections/projections that selectively access subsets of these intrinsic variables. The table therefore provides a compact structural summary of the physical motivation for the intrinsic dimensionality adopted in the theory.

Table S2. Selected 4D observations and paradoxes that may be naturally interpreted through a six-dimensional (6D) light null entity.

	4D Observation / Theory	Paradox / Incompatibility	6D Light Null Entity Interpretation
1	Quantum Electrodynamics (QED)	Vacuum fluctuations, wave-particle duality, photon self-energy divergences	2D reduction projection results in discreteness, dot-like behavior and quantum observations. Separation of 2D null propagation and 4D internal DOFs (phase, polarization, frequency, orientation) provides a geometric basis for quantization and avoids singularities.
2	Quantum Mechanics	Discrete quanta vs continuous wavefunction	Discrete observables arise from intrinsic 4D fiber, preserving continuity in propagation without ad hoc collapse.
3	Maxwell Electromagnetism	Polarization, phase, and orientation treated independently; cannot capture discrete-continuous duality	Internal DOFs along 6D null path unify field and particle descriptions, allowing simultaneous discrete-continuous behavior.
4	Gravitational lensing of light	Classical EM predicts deflection but ignores internal quantum degree of freedoms (DOFs)	6D propagation along null geodesic with evolving internal DOFs predicts subtle polarization- or frequency-dependent lensing effects.
5	Photon entanglement	Nonlocal correlations appear “spooky” in 4D	Correlated internal DOFs (phase/polarization/frequency) are naturally linked in 6D, offering a local geometric interpretation.
6	Coherence / decoherence phenomena	Loss of phase information in standard 4D treatment	Phase and orientation as intrinsic 6D dimensions may enable natural tracking of coherence in complex systems.

Observers restricted to low-dimensional subspaces perceive only fragments of higher-dimensional entity structures, giving rise to observable contradictory phenomena. By reconstructing light’s behavior from its low-dimensional projections/sections, we show that spin-1 characteristics, and polarization naturally emerge from a six-dimensional geometric framework of a minimal 6D light null entity. This approach predicts specific correlations between polarization, helicity, and

momentum that are directly testable in controlled optical experiments. Our results suggest that many “intrinsic” properties of light are in fact observer-dependent projections/sections of a higher-dimensional structure, providing a pathway to experimentally probe the underlying six-dimensional ontology and revealing new high-dimensional signatures in light-matter interactions.