Effective Geometric Modulation of Photon Propagation by Local Space-Time Structure: A Falsifiable Laboratory Framework

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Abstract

We propose a minimal phenomenological framework in which local space-time structure acts as an active geometric background for photon propagation. Rather than relying on astrophysical anomalies, the model reduces this coupling to a falsifiable laboratory prediction: a direction-dependent phase or frequency shift in precision interferometers or cavity resonators. The predicted signal exhibits a characteristic second-harmonic rotational dependence, $\cos(2(\theta - \theta_0))$, and scales linearly with the effective path length. We also relate the ansatz to photon-sector searches in the Standard-Model Extension (SME), note the associated sidereal signatures, and use existing terrestrial cavity bounds as an empirical benchmark for the effective scale $\varepsilon\chi$. By specifying lock-in extraction, null channels, blind analysis, and fixed detection thresholds, the framework turns a geometric postulate into a decisive experimental test to be confirmed or excluded by measurement.

1 Introduction

The present work is formulated as a minimal phenomenological framework rather than a microscopic theory of quantum gravity. Its central assumption is that space-time may admit an effective local structure whose physical consequences become observable in precision measurements of photon propagation. The purpose of the model is therefore not to derive this structure from first principles, but to encode its leading measurable consequences in a form that is experimentally falsifiable.

Accordingly, the framework introduces only the minimal set of ingredients required for such a test. First, the relevant space-time structure is assumed to be local rather than globally fixed. Second, its influence is represented at the phenomenological level by an effective structural parameter, χ, and an associated preferred axis in the laboratory frame. Third, the model is constructed so as not to require any *a priori* assumption of fundamental Lorentz violation at the microscopic level. Any anisotropy appears only as an effective low-energy signature of the local structure under investigation. At the same time, any viable leading-order realization must be confronted with the established language and bounds of photon-sector tests in the Standard-Model Extension (SME) [1, 2, 3].

2 Geometrical Framework

Within this framework, space-time is not treated as a passive kinematic background that merely hosts fields and particles. Instead, it is modeled as an active geometric structure whose local organization can modify the propagation properties of physical excitations. The relevant claim is modest but precise: if such a structure exists, then its observable role must appear as a controlled modulation of measurable quantities rather than as an abstract geometric reinterpretation alone.

This viewpoint shifts the emphasis from geometry as description to geometry as interaction. In the minimal model, the effect of the underlying structure is not introduced through a full metric reconstruction or a microscopic dynamical theory, but through its effective influence on a selected probe sector. The operational question is therefore not whether a nontrivial geometry can be postulated, but whether it generates a reproducible experimental signature distinguishable from known backgrounds.

The minimal model further assumes that the local space-time structure may define a preferred orientation in the measurement frame. This orientation is parameterized by an axis θ_0, understood not as a universal direction of nature, but as the effective laboratory-frame imprint of the local geometric organization. The appearance of such an axis is the minimal ingredient required to translate the structural hypothesis into a direction-dependent observable.

At the phenomenological level, the associated anisotropy is assumed to be even under reversal of the apparatus orientation by π, which leads naturally to a second-harmonic angular dependence in the measurable signal. This symmetry assumption is not imposed for mathematical convenience alone; it is the simplest nontrivial realization of a local directional structure compatible with the null-test logic developed below. More elaborate angular dependences are possible in extended models, but the present work restricts attention to the minimal $\cos(2\theta)$ sector needed for a clean falsifiable prediction.

The electromagnetic field is adopted as the primary probe of the proposed structure because photon propagation offers direct access to phase, coherence, and resonance observables with exceptionally high precision. In this sense, the photon is not singled out by speculative ontology, but by experimental suitability: small effective modifications of propagation can be accumulated over long paths L, compared interferometrically, or resolved spectroscopically in cavity configurations.

The relevant object is the local vacuum environment experienced by the photon, understood operationally as the effective propagation medium generated by the underlying space-time structure. In the present minimal framework, this environment is not derived microscopically. Rather, it is represented through a modified effective wave vector and its associated observables.

A geometric proposal of this type remains physically incomplete unless it produces a concrete observable together with a protocol for falsification. The next step is therefore to specify how the assumed space-time structure couples to the local photon environment, how this coupling enters an interferometric or resonant observable, and under which null tests and statistical criteria such a signal could be established or excluded.

3 Experimental Signature and Detection Protocol

3.1 Space-Time–Quantum Coupling

To translate the geometrical framework into a measurable signature, we model the space-time–quantum coupling as a direct physical back-reaction onto the electromagnetic field. We assume that structural modifications or local anisotropies of the dynamic space-time geometry directly modulate quantum transition amplitudes within the photon's local vacuum environment.

Crucially, to ensure strict experimental consistency, this imprint cannot manifest as generic noise. The model requires the coupling to yield a specific, functionally determined shift in the photon's propagation characteristics—such as an alteration in emission frequency, directional phase accumulation, or vacuum coherence—that is fundamentally distinguishable from thermal fluctuations or standard quantum electrodynamical (QED) vacuum polarization.

3.2 Laboratory Measurement Architecture

To isolate this predicted space-time–quantum coupling, the physical signature must be extracted within a highly controlled measurement geometry. We advocate for a laboratory-scale approach, specifically utilizing high-precision interferometry or dual-mode cavity resonators, as the primary testbed. Unlike astrophysical or cosmological observations—which are inevitably convoluted by complex source physics, interstellar plasma, and limited control parameters—a terrestrial laboratory architecture provides the necessary degrees of freedom to perform rigorous null tests.

Within an interferometric setup or a resonant cavity, a structure-sensitive optical path can be directly compared against a common-mode reference signal. This differential measurement strategy suppresses shared environmental noise sources and isolates the purely geometry-induced phase or frequency difference. The observable of interest is therefore not the mere presence of an anomaly, but its reproducible functional dependence on controlled parameters: the optical path length L, the orientation angle θ relative to the laboratory frame, and the effective coupling strength.

3.3 Mathematical Form of the Signature

To render the proposed coupling experimentally testable, the geometric effect must be expressed as an explicit modulation of photon propagation. In the minimal phenomenological model, this is encoded as a small orientation-dependent correction to the effective wave vector,

$$k_{\text{eff}}(\omega,\theta,\chi)=\frac{\omega}{c}\left[1+\varepsilon\chi\cos\bigl(2(\theta-\theta_0)\bigr)\right], \tag{1}$$

where ε denotes a dimensionless coupling strength, χ is an effective structural parameter characterizing the local amplitude of the underlying space-time geometry, and θ_0 defines the preferred axis of that structure in the laboratory frame. This parametrization is deliberately minimal: it introduces an anisotropic propagation law without presupposing a fundamental violation of Lorentz invariance at the microscopic level.

For an interferometric path of length L, the leading observable consequence is an accumulated geometric phase shift,

$$\Delta\phi_{\text{geo}}\approx\frac{\omega L}{c}\,\varepsilon\chi\cos\bigl(2(\theta-\theta_0)\bigr). \tag{2}$$

The central prediction is therefore unambiguous. The signal scales linearly with the effective propagation length L, exhibits a characteristic π-periodic modulation under controlled rotation of the apparatus, and vanishes under angular averaging or in the limit $\chi\to 0$. In a cavity implementation, the same structure may equivalently appear as a direction-dependent frequency splitting or resonance shift. To leading order, the corresponding fractional cavity signal is of order

$$\frac{\delta\nu}{\nu}\sim\varepsilon\chi\cos\bigl(2(\theta-\theta_0)\bigr), \tag{3}$$

which provides the natural dimensionless quantity for comparison with existing precision searches.

3.4 Relation to SME, Sidereal Modulation, and Practical Scale

The ansatz in Eq. (1) is phenomenologically close to the orientation-dependent photon-sector signals sought in SME analyses of resonator and Michelson-Morley-type experiments [2, 4, 5, 6, 7]. The present work does not claim a complete operator-level mapping onto a specific SME coefficient set. Nonetheless, if the leading-order signal projects onto the standard nondispersive cavity channels, then existing terrestrial searches already provide an empirical scale for the admissible magnitude of $\varepsilon\chi$.

In particular, current cavity-based tests constrain relevant orientation-dependent fractional frequency shifts at least at the 10^{-17} to 10^{-18} class, depending on the channel and experimental realization [5, 6, 3]. Equation (3) should therefore be read not only as a formal observable, but also as a practical benchmark: any viable leading-order realization of the minimal model must either lie below existing terrestrial sensitivity or differ from the standard SME channels in a clearly specified way.

A further consequence concerns time dependence. If the preferred axis θ_0 is effectively fixed in a Sun-centered inertial frame, then Earth rotation generates sidereal sidebands in addition to any actively imposed laboratory rotation, exactly as in standard SME search strategies [2, 4, 7]. If instead the relevant structure is purely laboratory locked, active rotation remains the primary discriminator. In either case, sidereal analysis provides an additional and experimentally standard cross-check rather than an optional embellishment.

3.5 Systematics, Null Tests, and Error Budget

Any claim of a geometry-induced signal is contingent on its quantitative separation from known instrumental and environmental systematics. In practice, the dominant backgrounds are expected to arise from thermal drifts of optical path lengths, mechanical stress and vibration coupling, magnetic-field-induced perturbations, laser-frequency instability, and electronic offsets in the readout chain. The observation of a raw phase or frequency excursion alone is therefore physically meaningless unless it can be tied to the specific symmetry structure predicted by the model.

The analysis should accordingly be performed in a harmonic decomposition of the rotation-dependent data stream, with particular emphasis on lock-in extraction of the second angular harmonic. Because the model predicts a signal proportional to $\cos(2(\theta - \theta_0))$, the relevant observable is not broadband excess noise, but a stable and reproducible 2θ component with the correct phase structure. This provides a direct discriminator against generic drift mechanisms, which typically populate low-frequency backgrounds or different angular harmonics and do not reproduce the predicted geometric scaling with L.

A viable measurement protocol therefore requires explicit null channels and control configurations. These include a common-mode reference path, a symmetry-restored or effectively decoupled geometry corresponding to $\chi \to 0$, continuous monitoring of environmental parameters, and blind scans of orientation to suppress analysis bias. A candidate signal is only meaningful if the extracted 2θ component is absent in the null channels, scales with the path length as predicted, and remains phase-stable under controlled reversal or reorientation of the apparatus.

3.6 Detection Criteria and Statistical Protocol

To prevent confirmation bias and observer-induced selection effects, the experimental protocol mandates a strict blind analysis. All significance thresholds, null-channel definitions, and data-selection cuts must be finalized prior to unblinding the dataset. The hypothesis test is exclusively restricted to the pre-defined second angular harmonic of the rotation data, parameterized as

$$S(\theta) = A_2 \cos(2\theta) + B_2 \sin(2\theta) + \text{backgrounds}, \tag{4}$$

with extracted amplitude

$$R_2 = \sqrt{A_2^2 + B_2^2}. \tag{5}$$

The corresponding phase provides an independent consistency check.

The model establishes a two-tiered detection threshold based on standard frequentist criteria. Evidence for the space-time–quantum coupling is defined as a statistically significant extraction of the 2θ amplitude at a level of $R_2/\sigma_{R_2} \geq 3$, provided that all concurrent null channels remain consistent with zero within their respective uncertainties. A formal discovery claim requires the signal to reach the $R_2/\sigma_{R_2} \geq 5$ threshold, alongside confirmed linear scaling with L, reproducible phase stability under rotation, and independent replication in a modified setup.

While complementary Bayesian model comparison may be reported as a secondary robustness check, the primary arbiter remains the frequentist threshold. The model is considered rigorously falsified if, given sufficient instrumental sensitivity to resolve the predicted $\varepsilon\chi$ parameter space, the experiment yields a null result for the 2θ harmonic, or if an observed signal fails the geometric scaling and reversibility tests.

4 Secondary Consistency Checks

Long-baseline astrophysical channels may eventually provide supplementary consistency information, since even tiny anisotropic propagation effects can accumulate over large distances. In the present paper, however, such channels are intentionally not used as primary evidence. Their interpretation is entangled with source modeling, plasma propagation, environmental inhomogeneities, and the absence of controlled null rotations. For the minimal framework developed here, astrophysical data are therefore best treated as secondary cross-checks on any laboratory-motivated parameter range rather than as standalone discovery channels [3].

5 Discussion

The main strength of the present minimal model is not microscopic completeness, but experimental sharpness. Rather than proposing a purely geometric reinterpretation of photon propagation, the framework reduces the hypothesis to a specific measurable signature, a constrained angular harmonic, explicit null tests, and a predefined statistical decision rule. In this sense, the model is constructed to fail clearly if nature does not realize the proposed coupling.

At the same time, the scope of the model is deliberately limited. The parameter χ has been introduced as an effective structural parameter summarizing the local amplitude of the underlying space-time organization, but it has not been derived from a microscopic geometric theory. Likewise, the coupling strength ε is treated phenomenologically, and the present work does not attempt a first-principles estimate of the combined scale $\varepsilon\chi$. The benchmark discussion above is therefore empirical rather than derived: it places the model in the landscape of existing searches without claiming microscopic closure.

A second limitation is the restriction to the nondispersive minimal sector. The present analysis focuses on the cleanest anisotropic signature, namely a $\cos(2(\theta - \theta_0))$ modulation of the effective propagation law. More elaborate frequency dependence, additional angular harmonics, or coupling to other probe sectors may be explored in extended models, but would enlarge the parameter space and weaken the immediate falsifiability of the first test. The present strategy is therefore to establish the simplest nontrivial laboratory target before considering broader generalizations.

The natural next step is accordingly twofold. On the theoretical side, one would seek either an explicit mapping of the present ansatz onto SME operator classes or a precise demonstration of how it departs from them, together with a microscopic derivation of χ in terms of geometric invariants. On the experimental side, one would translate the present protocol into a sensitivity forecast for specific interferometric or cavity platforms, including realistic systematics, sidereal demodulation channels, and achievable lock-in performance. These developments belong to a follow-up study; they are not prerequisites for the logical consistency of the minimal falsifiability framework established here.

6 Conclusion

We have formulated a minimal phenomenological framework in which an effective local space-time structure modulates photon propagation and thereby generates a directly testable laboratory signature. The model reduces this idea to a concrete prediction: a direction-dependent phase or frequency shift with a characteristic second-harmonic rotational structure, linear scaling with propagation length, and strict disappearance in predefined null configurations. By combining an explicit observable, a controlled laboratory architecture, a systematic error budget, blind analysis, and fixed evidence and discovery thresholds, the framework converts a geometric postulate into a falsifiable experimental program.

The significance of the present work lies precisely in this reduction. It does not claim a complete microscopic theory of space-time, nor does it rely on astrophysical anomalies as primary evidence. Instead, it identifies the minimal laboratory conditions under which the proposed coupling can be established or excluded, and it places the leading-order signal in direct contact with the established SME search program and existing cavity bounds. If no such signal is observed within the relevant sensitivity window, the model fails. If the predicted harmonic, scaling, and reversibility structure is observed and replicated, the hypothesis acquires a concrete empirical footing. In either case, the framework is designed to be decided by measurement rather than interpretation.

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