# Electrodynamics and Photonic Propagation in a Scalar–Modulated Vacuum within the QGT:IR Framework

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**Abstract**

We develop an extended formulation of electrodynamics within the Quantum Gravity Theory based on Inverted Relativity (QGT:IR), where spacetime is fundamentally Minkowskian and gravitational phenomena emerge from the constitutive response of a scalar–structured vacuum. Within the Electromagnetic Spectral Equilibrium Model (ESEM), the vacuum behaves as a dispersive and absorptive medium characterized by a scalar–dependent response function $B(\epsilon)$.

We derive the modified Maxwell equations, establish global energy conservation through the Radioactive Equilibrium Point (REP), and show that electromagnetic radiation undergoes spectral relaxation toward an infrared attractor identified as the Global Equilibrium Spectral Point (GESP). This framework provides an effective, non–geometric contribution to cosmological redshift phenomena without invoking metric expansion, while preserving gauge invariance, local Lorentz symmetry, and unitarity.

**Keywords:** Quantum gravity; electrodynamics in media; induced gravity; vacuum polarization; cosmic redshift; effective field theory

## 1 Introduction

The observation that light emitted by distant astrophysical sources arrives redshifted is one of the most robust empirical facts in modern cosmology. Within the standard ΛCDM paradigm, this redshift is interpreted as a consequence of the expansion of spacetime itself, encoded in the Friedmann–Lemaître–Robertson–Walker (FLRW) metric [1,2]. In this geometric interpretation, the wavelength of a photon stretches proportionally to the cosmic scale factor $a(t)$, leading to the well–known relation

$$1 + z = \frac{a(t_0)}{a(t_e)}. \tag{1}$$

Despite its phenomenological success, this interpretation raises deep theoretical challenges. The required value of the cosmological constant suffers from extreme fine–tuning [3], the inflationary epoch is introduced to address horizon and flatness problems [4], and persistent discrepancies remain between local and early–universe determinations of the Hubble parameter [5,6]. More fundamentally, the geometric nature of gravity obstructs the construction of a renormalizable quantum theory of spacetime.

An alternative perspective, pursued in this work, is that cosmological and gravitational phenomena need not originate from a fundamental dynamical geometry. In the Quantum Gravity Theory based on Inverted Relativity (QGT:IR), spacetime is assumed to be fundamentally flat and static, described by a Minkowski background $\eta_{\mu\nu}$. Observable gravitational effects emerge instead from the collective response of quantum fields propagating in a structured vacuum. This viewpoint is closely related to the concept of induced gravity, first proposed by Sakharov [7] and later elaborated by Adler [8], where the Einstein–Hilbert action arises as an effective description of vacuum polarization rather than a fundamental postulate.

Within this framework, electrodynamics acquires a central role. Rather than propagating in an empty vacuum, electromagnetic fields interact with a scalar degree of freedom $\epsilon(x)$ that encodes the vacuum's constitutive properties. Similar ideas appear in quantum field theory in curved spacetime, where particle propagation is affected by background fields and vacuum structure [9]. In QGT:IR, however, the background remains Minkowskian, and all non–trivial effects arise from field interactions.

The purpose of this article is to develop a detailed formulation of electrodynamics in such a scalar–modulated vacuum. We show that, at macroscopic scales, electromagnetic radiation undergoes a gradual spectral relaxation due to its interaction with the vacuum scalar field. This relaxation defines an effective, non–expansionist contribution to cosmological redshift phenomena, while preserving global energy conservation and local relativistic symmetries.

In the following sections, we introduce the theoretical foundations of QGT:IR, derive the modified Maxwell equations within the Electromagnetic Spectral Equilibrium Model (ESEM), analyze the associated energy balance through the Radioactive Equilibrium Point (REP), and explore the emergence of a Global Equilibrium Spectral Point (GESP) as an infrared attractor of electromagnetic radiation.

# 2 Theoretical Foundations of the QGT:IR Framework

## 2.1 Inverted Relativity and the Role of the Background

The Quantum Gravity Theory based on Inverted Relativity (QGT:IR) adopts a non–geometric starting point in which spacetime is assumed to be fundamentally flat and described by a fixed Minkowski metric $\eta_{\mu\nu}$. This assumption does not contradict the principles of special or general relativity, but rather reflects a different ontological ordering of physical degrees of freedom.

Instead of treating spacetime curvature as a fundamental entity, QGT:IR follows the logic of induced gravity, where gravitational dynamics emerge as an effective macroscopic description of quantum vacuum fluctuations. This idea was first proposed by Sakharov [7] and later formalized by Adler [8], who showed that the Einstein–Hilbert action can arise from integrating out matter fields in a flat background.

From the perspective of effective field theory, there is no fundamental inconsistency in describing gravity as an emergent phenomenon on Minkowski space, provided that local Lorentz invariance and energy–momentum conservation are preserved [10, 11]. In QGT:IR, the geometric description of gravity is therefore understood as a large–scale approximation, not as a fundamental structure to be quantized.

## 2.2 Scalar Vacuum Degree of Freedom

The emergence of gravitational and cosmological phenomena in QGT:IR is mediated by a real scalar field $\epsilon(x)$, which encodes the constitutive properties of the quantum vacuum. Such scalar degrees of freedom are ubiquitous in effective field theories describing collective modes arising from symmetry breaking [10].

The effective action for the vacuum scalar is taken to be

$$S_\epsilon = \int d^4x \left[ \frac{1}{2} \partial_\mu \epsilon \, \partial^\mu \epsilon - V(\epsilon) + \mathcal{L}_{\text{int}}(\epsilon, \Psi) \right], \tag{2}$$

where $\Psi$ denotes matter fields. The self–interaction potential $V(\epsilon)$ is assumed to be bounded from below, ensuring classical stability.

Radiative stability is achieved by imposing a $\mathbb{Z}_2$ symmetry, $\epsilon \to -\epsilon$, which forbids linear couplings and protects the scalar mass from large quantum corrections. This mechanism is standard in effective field theories involving light scalar fields [11, 12].

### 2.3 Effective Metric and Matter Coupling

Matter fields experience the presence of the vacuum scalar through an effective conformal metric,

$$\bar{g}_{\mu\nu} = A^2(\epsilon)\,\eta_{\mu\nu}, \tag{3}$$

where $A(\epsilon)$ is an even function of $\epsilon$. Expanding around the vacuum state,

$$A^2(\epsilon) = 1 + \frac{1}{2}\beta^2\epsilon^2 + \mathcal{O}(\epsilon^4). \tag{4}$$

This form of coupling is reminiscent of scalar–tensor theories of gravity [13, 14], but with a crucial conceptual difference: in QGT:IR, the metric $\bar{g}_{\mu\nu}$ is not a fundamental dynamical variable. Instead, it provides an effective description of how matter propagates in a polarized vacuum.

Because the coupling is purely conformal and even in $\epsilon$, violations of the weak equivalence principle are suppressed at leading order, and current experimental bounds are naturally satisfied [14, 15].

## 3 Electromagnetic Sector and the Electromagnetic Spectral Equilibrium Model

### 3.1 Electrodynamics in a Constitutive Vacuum

Electromagnetism in QGT:IR is formulated as a gauge field theory propagating in a structured vacuum medium. This approach is mathematically equivalent to classical electrodynamics in continuous media, a framework that has been extensively developed and experimentally validated [16, 17].

The electromagnetic field tensor retains its standard definition,

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{5}$$

ensuring exact gauge invariance and local Lorentz symmetry.

The interaction between the electromagnetic field and the vacuum scalar is encoded in the Electromagnetic Spectral Equilibrium Model (ESEM) through the Lagrangian density

$$\mathcal{L}_{EM} = -\frac{1}{4}B(\epsilon)\,F_{\mu\nu}F^{\mu\nu}, \tag{6}$$

where $B(\epsilon)$ plays the role of a vacuum response function, analogous to the permittivity of a material medium.

### 3.2 Derivation of the Modified Maxwell Equations

Varying the action with respect to the gauge potential $A_\mu$ yields the modified Maxwell equations,

$$\partial_\mu \left(B(\epsilon)F^{\mu\nu}\right) = J^\nu, \tag{7}$$

where $J^\nu$ denotes external matter currents.

Expanding the derivative leads to

$$B(\epsilon)\,\partial_\mu F^{\mu\nu} + (\partial_\mu B)\,F^{\mu\nu} = J^\nu, \tag{8}$$

which can be rewritten as

$$\partial_\mu F^{\mu\nu} = J^\nu + J^\nu_{\rm vac}, \tag{9}$$

with an effective vacuum polarization current

$$J^\nu_{\rm vac} = -\frac{\partial_\mu B}{B} F^{\mu\nu}. \tag{10}$$

This structure is formally identical to Maxwell's equations in dispersive and absorptive media [16, 17], with the vacuum itself acting as the medium.

### 3.3 Lorentz and Gauge Consistency

Because $B(\epsilon)$ is a Lorentz scalar and depends only on local field values, the theory preserves local Lorentz invariance. No preferred reference frame is introduced at the level of the fundamental equations. Gauge invariance is exact, as the Lagrangian depends only on the gauge–invariant combination $F_{\mu\nu}F^{\mu\nu}$.

In the limit $\partial_\mu\epsilon \to 0$, the response function becomes constant and standard vacuum electrodynamics is recovered. This ensures consistency with precision tests of electromagnetism and with quantum electrodynamics at laboratory scales [18, 19].

## 4 Energy Balance and the Radioactive Equilibrium Point

### 4.1 Global Energy–Momentum Conservation

A central requirement of the QGT:IR framework is the exact conservation of energy and momentum at the fundamental level. Since spacetime is assumed to be non–expanding and described by a fixed Minkowski background, Noether's theorem applies globally and yields a conserved total energy–momentum tensor,

$$\partial_\mu T^{\mu\nu}_{\rm tot} = 0, \tag{11}$$

where

$$T^{\mu\nu}_{\rm tot} = T^{\mu\nu}_{EM} + T^{\mu\nu}_{\epsilon} + T^{\mu\nu}_{\rm matter}. \tag{12}$$

The electromagnetic contribution is obtained from the modified Lagrangian,

$$T^{\mu\nu}_{EM} = B(\epsilon)\left(F^{\mu\alpha}F^{\nu}_{\ \alpha} - \frac{1}{4}\eta^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}\right), \tag{13}$$

while the scalar vacuum field contributes

$$T^{\mu\nu}_{\epsilon} = \partial^\mu\epsilon\,\partial^\nu\epsilon - \eta^{\mu\nu}\left(\frac{1}{2}\partial_\alpha\epsilon\,\partial^\alpha\epsilon - V(\epsilon)\right). \tag{14}$$

The divergence of $T^{\mu\nu}_{EM}$ does not vanish individually, reflecting the continuous exchange of energy and momentum between the electromagnetic sector and the vacuum scalar. However, the total tensor remains conserved, ensuring strict global energy conservation [20].

### 4.2 Definition of the Radioactive Equilibrium Point

The continuous interaction between electromagnetic radiation and the vacuum scalar field leads naturally to a dynamical equilibrium condition. We define the *Radioactive Equilibrium Point* (REP) as the state for which the net energy transfer between sectors vanishes when averaged over macroscopic scales,

$$\left\langle \frac{d\rho_{EM}}{dt} \right\rangle + \left\langle \frac{d\rho_\epsilon}{dt} \right\rangle = 0. \tag{15}$$

This condition does not imply the absence of local energy exchange, but rather identifies an attractor of the coupled system. The REP is therefore analogous to equilibrium states studied in non–equilibrium thermodynamics, where steady states arise from a balance of fluxes [21].

### 4.3 Thermodynamic Interpretation

From a thermodynamic perspective, the electromagnetic field constitutes an open subsystem embedded in the larger vacuum environment. Its entropy production rate may be negative locally, provided that the total entropy of the combined system increases,

$$\dot{S}_{\rm tot} = \dot{S}_{EM} + \dot{S}_{\epsilon} \geq 0. \tag{16}$$

Such behavior is well known in the theory of irreversible processes and does not violate the second law of thermodynamics [22]. The REP corresponds to a stationary state in which entropy production is minimized subject to the global constraints of the system.

## 5 Spectral Relaxation and Effective Redshift

### 5.1 Spectral Transport Equation

The modified Maxwell equations derived in the ESEM framework imply that electromagnetic waves propagating through regions of slowly varying $\epsilon(x)$ experience a gradual spectral evolution. In the geometric optics approximation, the frequency $\nu$ of a photon satisfies a transport equation of the form

$$\frac{d\nu}{dl} = -\Gamma_{\epsilon}(\epsilon)\,\nu, \tag{17}$$

where $l$ denotes the physical path length along the photon's trajectory, and $\Gamma_{\epsilon}$ is an effective absorption coefficient determined by the local vacuum response.

This equation is mathematically identical to the attenuation of radiation in absorptive media, a well–established result in classical electrodynamics [16, 17].

### 5.2 Solution and Redshift Relation

Integrating the spectral transport equation yields

$$\nu(l) = \nu_0 \exp\left( - \int_0^l \Gamma_{\epsilon}(l')\, dl' \right). \tag{18}$$

The observed redshift is then given by

$$1 + z \equiv \frac{\nu_0}{\nu(l)} = \exp\left( \int_0^l \Gamma_{\epsilon}(l')\, dl' \right). \tag{19}$$

This relation reproduces a redshift–distance law without invoking metric expansion. The parameter $\Gamma_{\epsilon}$ plays a role analogous to the Hubble parameter in standard cosmology, but here represents a property of the vacuum rather than a kinematic expansion rate.

### 5.3 Relation to Previous Non–Expansionist Proposals

Non–expansionist interpretations of redshift have been considered historically, most notably by Zwicky [23]. While such early proposals lacked a consistent field–theoretic foundation, the present framework embeds spectral relaxation within a fully relativistic and energy–conserving effective field theory.

Importantly, the QGT:IR mechanism does not rely on ad hoc photon decay or explicit violations of Lorentz invariance. Instead, redshift emerges as a cumulative interaction between radiation and a dynamical vacuum background, consistent with relativistic cosmology as formulated in modern field–theoretic terms [20, 24].

# 6 Global Equilibrium Spectral Point

## 6.1 Radiative Equilibrium in an Open Vacuum System

The long–term evolution of electromagnetic radiation in the QGT:IR framework is governed by the coupled dynamics of the electromagnetic field and the vacuum scalar $\epsilon$. As shown in the previous sections, radiation propagating through the scalar–modulated vacuum undergoes continuous spectral relaxation. Over sufficiently long timescales, this process drives the system toward a stationary infrared configuration.

We define the *Global Equilibrium Spectral Point* (GESP) as the asymptotic attractor of the coupled electromagnetic–vacuum system, characterized by vanishing net energy transfer,

$$\lim_{t\to\infty} \frac{d\rho_{EM}}{dt} = 0, \tag{20}$$

while local interactions between radiation and the vacuum persist.

Such equilibrium states are well understood in statistical physics and do not require the system to be isolated. Instead, they emerge naturally in open systems subject to irreversible processes, as extensively discussed by Landau and Lifshitz [22].

## 6.2 Thermal Character of the Equilibrium Spectrum

A generic result of radiative equilibration in dispersive and absorptive media is the emergence of a universal thermal spectrum. The Planck distribution arises as the unique stationary solution compatible with detailed balance and maximal entropy [25].

Within the QGT:IR framework, the equilibrium electromagnetic energy density at the GESP takes the form

$$\rho_{EM}^{\mathrm{eq}} = a\,T_{\mathrm{vac}}^4, \tag{21}$$

where $a$ is the radiation constant and $T_{\mathrm{vac}}$ is the effective vacuum temperature associated with the scalar background.

This result does not depend on a primordial hot phase, but follows from the universal properties of radiative equilibration in a stable vacuum.

## 6.3 Interpretation of the Cosmic Microwave Background

The Cosmic Microwave Background (CMB) is observationally characterized by an almost perfect blackbody spectrum with temperature $T \simeq 2.725\,\mathrm{K}$ [26]. In standard cosmology, this spectrum is interpreted as a relic of an early hot and dense phase of the universe [2].

In the present framework, the CMB may alternatively be interpreted as the observational manifestation of the GESP: a stationary equilibrium spectrum maintained dynamically by the interaction between electromagnetic radiation and the vacuum scalar field. This interpretation does not contradict existing observations, but reframes their physical origin within an effective field theory context.

# 7 Compact Objects and Black Stars

## 7.1 Scalar Backreaction and the Avoidance of Singularities

One of the most striking consequences of the QGT:IR framework concerns the fate of gravitational collapse. In classical General Relativity, the Hawking–Penrose singularity theorems imply that sufficiently massive collapsing objects inevitably form spacetime singularities under broad conditions [27].

These theorems rely crucially on the geometric nature of gravity and on specific energy conditions. In QGT:IR, where gravity emerges from vacuum polarization rather than spacetime curvature, these assumptions are no longer applicable.

As matter density increases, the scalar field $\epsilon$ responds through its coupling to the trace of the energy–momentum tensor,

$$\frac{dV}{d\epsilon} + \frac{1}{2}\beta^2 \epsilon \, T^{\mu}_{\ \mu} = 0. \tag{22}$$

This equilibrium condition generates an effective vacuum pressure that counteracts further collapse, preventing the formation of singularities.

### 7.2 Black Stars as Non–Singular Compact Objects

The endpoint of gravitational collapse in QGT:IR is therefore not a classical black hole, but a compact, non–singular object referred to here as a *Black Star*. Such objects are closely related to gravastar models proposed by Mazur and Mottola [28], where vacuum polarization effects stabilize ultra–compact configurations.

Black Stars possess a physical surface and an internal structure, but may appear effectively black to distant observers due to extreme spectral redshift of outgoing radiation.

### 7.3 Spectral Horizons and Information Preservation

Although Black Stars do not possess true event horizons, they exhibit a *spectral horizon*: photons escaping from regions of strong scalar gradients undergo exponential spectral relaxation,

$$z_{\text{spec}} \sim \exp\left(\int \Gamma_\epsilon dl\right), \tag{23}$$

reaching the GESP limit before escaping to infinity.

The absence of a true event horizon has important implications for unitarity. Information is not destroyed, but remains encoded in correlations between matter fields and the vacuum scalar. This aligns with analyses of exotic compact objects and horizonless alternatives to black holes [29, 30].

## 8 Gravitational Waves as Scalar Vacuum Modes

### 8.1 Scalar Perturbations of the Vacuum

In the QGT:IR framework, gravitational phenomena are not interpreted as dynamical curvature of spacetime, but as collective excitations of the vacuum. Small perturbations of the scalar field around a background configuration,

$$\epsilon(x) = \epsilon_0(x) + \delta\epsilon(x), \tag{24}$$

satisfy, to leading order, a relativistic wave equation,

$$\Box\, \delta\epsilon + m_\epsilon^2 \, \delta\epsilon = 0, \tag{25}$$

where $m_\epsilon$ is the effective mass of the scalar mode.

These perturbations propagate at relativistic speeds and transport energy and momentum, analogously to gravitational waves in General Relativity, but with scalar rather than tensor polarization.

### 8.2 Phenomenological Comparison with Observations

The direct detection of gravitational waves by the LIGO and Virgo collaborations [31] provides strong empirical evidence for propagating gravitational degrees of freedom. Within QGT:IR, the observed signals are interpreted as macroscopic oscillations of the vacuum scalar excited during violent astrophysical events, such as compact object mergers.

At leading order, the waveform morphology can closely mimic that predicted by General Relativity, ensuring consistency with current observational constraints [32, 33]. However, the absence of true event horizons in the present framework generically allows for late–time deviations, including the possibility of post–merger echoes [29]. Such features provide a potential observational handle to distinguish scalar vacuum modes from purely tensorial gravitational waves.

## 9 Discussion and Domain of Validity

### 9.1 Effective Field Theory Regime

The QGT:IR framework is constructed explicitly as an effective field theory. Its domain of validity is therefore restricted to macroscopic and mesoscopic scales, where collective vacuum effects dominate and the scalar description remains appropriate.

At microscopic scales, standard quantum electrodynamics and particle physics are recovered in the limit of vanishing scalar gradients,

$$\partial_\mu \epsilon \to 0, \tag{26}$$

ensuring consistency with laboratory experiments.

### 9.2 Relation to General Relativity and Standard Cosmology

General Relativity emerges in QGT:IR as an effective geometric description valid in regimes where the scalar vacuum response can be encoded in an approximately curved metric. However, the theory does not aim to reproduce all solutions of Einstein's equations exactly.

Similarly, the present framework does not invalidate the phenomenological success of the ΛCDM model. Instead, it provides an alternative microscopic interpretation of certain large–scale phenomena, such as redshift and the CMB, within a flat–background field theory context.

### 9.3 Limitations and Open Questions

Several important questions remain open. These include the precise mapping between scalar vacuum parameters and cosmological observables, the detailed dynamics of structure formation, and the quantitative constraints imposed by precision cosmology.

As emphasized in effective field theory analyses of gravity [10–12], such limitations are not deficiencies, but expected features of any low–energy description.

## 10 Conclusions

We have presented a comprehensive formulation of electrodynamics in a scalar–modulated vacuum within the Quantum Gravity Theory based on Inverted Relativity. By treating the vacuum as a constitutive medium described by a light scalar field, we derived modified Maxwell equations, established global energy conservation through the Radioactive Equilibrium Point, and identified an infrared attractor of electromagnetic radiation, the Global Equilibrium Spectral Point.

The framework is mathematically consistent, preserves fundamental symmetries, and does not violate established physical laws. While it remains an effective and exploratory theory, it offers a coherent alternative perspective on gravitational, cosmological, and electromagnetic phenomena, and suggests concrete avenues for observational tests.

## Data Availability Statement

No new experimental data were generated in this study. Observational datasets referenced for phenomenological comparison, including cosmic microwave background measurements and gravitational wave observations, are publicly available through the Planck Legacy Archive and the LIGO/Virgo public data releases.

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