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Theory of Spacetime Impedance: A Reactive Framework for the Electromagnetic, Gravitational, and Quantum Structure of Vacuum

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Abstract

This work presents the *Theory of Spacetime Impedance* (TSI), a phenomenological framework in which the vacuum is modeled as a distributed reactive medium with an effective RLC structure. At the classical level, the vacuum is characterized by the permeability μ_0, the permittivity ε_0, and the impedance Z_0, so that the speed of light follows from the vacuum's constitutive reactive properties. The TSI introduces a reactive–dissipative term R_H as an effective mechanism associated with irreversibility, decoherence, and entropy production, providing a physical basis for the arrow of time. At the quantum level, TSI incorporates a quantum RLC triad associated with the electron, defined by a quantum inductance L_K, a quantum capacitance C_K, and the von Klitzing resistance R_K. When normalized by the Compton wavelength, these quantities admit a direct comparison with μ_0 and ε_0, identifying the fine-structure constant as an impedance scaling factor between classical and quantum regimes. Within this unified reactive picture, inductive, capacitive, and resistive responses are respectively associated with gravitation, electromagnetism, and thermodynamic irreversibility, offering a complementary bridge across quantum, relativistic, and macroscopic domains.

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1. Introduction

The physical nature of the vacuum remains one of the most profound conceptual problems in modern physics. Although fundamental theories—quantum mechanics, quantum field theory (QFT), and general relativity—describe with remarkable accuracy the behavior of particles, fields, and spacetime geometry, fundamental questions persist regarding the internal structure of the vacuum, the origin of universal constants, and the connections among different dynamical regimes of physical reality. Understanding whether the vacuum possesses an effective microstructure, and how such a structure might relate electromagnetic, gravitational, quantum, and thermodynamic phenomena, constitutes a central challenge in the pursuit of a more unified physical description.

Motivated by these questions, this work explores a phenomenological framework referred to as the *Theory of Spacetime Impedance* (TSI), originally formulated in Spanish as *Teoría de la Impedancia del Espacio-Tiempo* (TIET). In the remainder of this manuscript, the abbreviation TSI will be used.

Historical developments in electromagnetism and quantum theory provide relevant insights in this direction. In the nineteenth century, Heaviside showed that Maxwell's equations, when restricted to one spatial dimension, adopt the same formal structure as the equations governing a transmission line characterized by distributed inductance and capacitance. Independently, in the context of thermal radiation, Planck introduced the notion of fundamental oscillators to account for the quantization of energy. Although developed in different physical domains, both approaches suggest that fundamental phenomena may be understood in terms of oscillatory structures and reactive parameters governing the storage and propagation of energy.

Despite the empirical success of current theories, conceptual limitations remain. Quantum field theory describes the vacuum as the ground state of quantum fields but does not provide a direct physical interpretation of its reactive properties. General relativity accounts for spacetime geometry but does not specify a microscopic mechanism linking curvature to quantum dynamics. Thermodynamics and information theory identify irreversibility and entropy as emergent features, yet their connection with the microscopic structure of the vacuum remains an open question. These gaps motivate the exploration of phenomenological models capable of offering alternative interpretations of the effective properties of the vacuum.

The starting point of the present model is the experimental characterization of the vacuum through three universal properties: the magnetic permeability μ_0, the electric permittivity ε_0, and the characteristic impedance of free space $Z_0 \approx 377\,\Omega$. These quantities satisfy the well-known relations

$$c = \frac{1}{\sqrt{\mu_0\,\varepsilon_0}}, \qquad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \tag{1}$$

which allow μ_0 and ε_0 to be interpreted as effective reactive parameters of the vacuum, namely an inductance L_H and a capacitance C_H.

The Theory of Spacetime Impedance further introduces a third parameter, a reactive–dissipative term R_H, associated with loss of coherence, irreversibility, and entropy production. With this addition, the vacuum acquires the effective structure of a distributed RLC medium: its inductive response is linked to gravitational phenomena, its capacitive response to classical electromagnetism, and its resistive component to dissipative processes and the emergence of the arrow of time.

The theory further proposes that the vacuum may be described in terms of a discrete effective microstructure, composed of tri-phasic RLC microcells whose characteristic scale is set by the fundamental Planck quantities. Each microcell behaves as an elementary oscillator, consistent with the oscillators introduced by Planck in black-body theory and with the discrete normal modes of quantum field theory. Within this phenomenological description, the vacuum acts as a reactive substrate from which matter, universal constants (including c, Z_0, α, $\hbar$, and G), and the laws governing classical, quantum, relativistic, and thermodynamic phenomena effectively emerge.

The TSI is formulated as a strictly phenomenological framework. It does not seek to replace quantum field theory, general relativity, or quantum mechanics, but rather to provide a complementary conceptual language that facilitates the interpretation of certain physical constants, dynamical relations, and irreversible processes. Under well-defined reactive assumptions, the theory allows for the derivation of effective expressions for the quantum of action, the fine-structure constant, gravitational coupling in the weak-field regime, the energy–mass relation, first-order relativistic corrections, and the Schrödinger equation as the nonrelativistic limit of a Klein–Gordon–type dynamics.

1.1. Theoretical Scope Within the Framework of the Space–Time Impedance Theory

The Theory of Spacetime Impedance (TSI) is formulated as a phenomenological framework that reinterprets fundamental physical phenomena in terms of the reactive structure of the vacuum. Rather than replacing established theories—such as quantum mechanics, quantum field theory, classical electromagnetism, or general relativity—TSI provides a complementary description aimed at clarifying the physical meaning of universal constants, dynamical relations, and irreversible processes.

The scope of TSI is limited to physical regimes in which the vacuum can be modeled as a distributed reactive medium characterized by inductive, capacitive, and resistive parameters. Within this domain, the theory addresses electromagnetic propagation, quantum coherence and decoherence, weak-field gravitational coupling, and the emergence of entropy and the arrow of time, while preserving the fundamental mathematical structure of standard theories.

In this framework, classical, relativistic, and quantum equations arise as limiting approximations of a more general reactive dynamics. The results presented here are therefore phenomenological, consistent with known physics, and valid within experimentally verified regimes. TSI does not attempt

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to describe the ultimate microdynamics of spacetime or to introduce new fundamental degrees of freedom; instead, it offers a unified interpretative language connecting different physical domains through an impedance-based perspective.

The main contributions of this work include the formulation of a master impedance equation for the vacuum, the phenomenological derivation of fundamental constants, a reactive reinterpretation of key quantum processes, and the identification of conceptual implications related to dark matter, dark energy, and the arrow of time. The manuscript is organized as follows: Section 2 presents the theoretical framework, Section 3 develops the main results, Section 4 discusses phenomenological predictions, and Section 5 summarizes the conclusions and outlines future research directions.

2. Theoretical Framework,

2.1. Use of Generative Artificial Intelligence

During the development of the Theory of the Impedance of Spacetime (TSI), generative artificial intelligence tools were employed exclusively as assistive resources for the formalization of mathematical expressions, verification of dimensional consistency, and improvement of linguistic clarity and structural organization of the manuscript. These tools supported the rigorous articulation of physical relationships and equations derived from the conceptual framework proposed by the author. The fundamental hypotheses, theoretical structure, physical interpretations, and scientific conclusions presented in this work are entirely the result of the author's intellectual contribution. No generative artificial intelligence tools were used for the autonomous generation of original scientific results, data, simulations, or physical predictions.

2.2. Ideal Versus Dissipative Models in the Heaviside Formalism

In the analysis of transmission lines and propagation media, it is essential to distinguish between idealized descriptions and physically realistic models. Ideal models represent purely reactive systems in which energy is exchanged reversibly between electric and magnetic fields. By contrast, real physical systems incorporate dissipative mechanisms—such as resistive losses, dielectric losses, and medium conductance—that lead to irreversible processes.

This distinction is already present in the formalism developed by Oliver Heaviside, who introduced an operational description of electromagnetic propagation based on distributed parameters per unit length. In this framework, the telegrapher's equations characterize the dynamics of voltage and current along a transmission line through four fundamental distributed parameters: resistance R, inductance L, conductance G, and capacitance C. The inclusion or neglect of the terms R and G provides a natural way to distinguish between the ideal lossless regime and the dissipative regime.

2.3. Characteristic Impedance in Heaviside's theory

Within Heaviside's approach, impedance is not introduced *a priori* as a purely algebraic quantity, but rather emerges as an effective property of the propagation medium. Starting from the telegrapher's equations, the characteristic impedance of a general transmission line is defined as

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}}, \tag{2}$$

which directly relates the inductive and capacitive responses of the medium to the distributed dissipative mechanisms.

In the ideal lossless limit, where $R \to 0$ and $G \to 0$, the characteristic impedance reduces to

$$Z_{0,\text{ideal}} = \sqrt{\frac{L}{C}}, \tag{3}$$

showing that, in a purely reactive medium, the impedance is determined solely by the balance between distributed inductance and capacitance. This result constitutes one of the central outcomes of Heaviside's formalism and provides the conceptual basis for interpreting electromagnetic propagation—including propagation in vacuum—in terms of effective reactive parameters.

2.4. Planck Oscillators and Their Effective Equivalence with Vacuum Cells in the TSI Framework

A central conceptual ingredient of the TSI framework originates in Planck's introduction of elementary oscillators in the theory of black-body radiation, which provided the first consistent description of energy quantization. In modern quantum field theory, these oscillators are reinterpreted as the normal modes of quantized fields, with the vacuum identified as the ground state and particles emerging as excitations of these modes. While highly successful, this description leaves the reactive character of the vacuum implicit.

The TSI framework revisits this oscillatory structure from a phenomenological perspective. Rather than treating Planck oscillators solely as abstract field modes, TSI interprets them as effectively associated with localized reactive elements of the vacuum. In this view, the vacuum is modeled as a distributed medium composed of effective microcells, each behaving as a reactive oscillator with inductive and capacitive responses, and, when appropriate, an effective dissipative contribution. This approach does not posit a specific microscopic mechanism, but provides a structured language for describing energy storage, phase evolution, and coherence in the vacuum.

Each Hyliaster cell possesses a natural carrier frequency determined by the reactive parameters of the vacuum, associated with L_H and C_H, which fixes the characteristic propagation velocity c. Coherent modulations are superimposed on this carrier, transporting energy and information. From a phenomenological perspective, these modulations can be formally interpreted as single-sideband (SSB) modulations, allowing efficient propagation without dynamical redundancy. This approach does not postulate a specific microscopic mechanism, but rather introduces a structured language for describing energy storage, phase evolution, and coherence in the reactive vacuum.

The equivalence invoked is therefore effective rather than literal: Planck oscillators, quantum field modes, and reactive microcells represent complementary descriptions of discrete oscillatory degrees of freedom that support energy exchange. The discretization of field modes is analogous to the discretization used to model continuous reactive media, such as transmission lines, by distributed elements, without implying fundamental granularity.

Within TSI, each microcell is further represented as a tri-phase RLC resonant system, a phenomenological construction that facilitates the description of oriented energy flow and coherent interactions. Collectively, these units give rise to familiar quantum and relativistic phenomena, while their effective parameters are constrained by measured vacuum constants, ensuring consistency with established physics and motivating the derivation of the TSI master impedance equation.

2.5. Constitutive Identity of the Vacuum

Conceptual Summary.

The Theory of Spacetime Impedance (TSI) is grounded on the constitutive identity

$$\emptyset \;\equiv\; Z(\omega), \tag{4}$$

which defines the dynamical vacuum through its frequency-dependent complex impedance. Within this framework, spacetime is interpreted as a reactive medium, and the various physical regimes emerge as manifestations of its response as a function of frequency. TSI thus constitutes a phenomenological and complementary approach to the description of the vacuum.

2.6. Derivation of the TSI Master Equation

The TSI master equation is formulated by combining a set of experimental and theoretical observations that are standard in classical electromagnetism and distributed-parameter systems.

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The derivation below is presented as a phenomenological synthesis: it does not modify Maxwell's theory, but reorganizes well-known relations into an impedance-based representation of the vacuum.

2.6.1. Transmission-Line Form of Maxwell's Equations in One Dimension

Consider electromagnetic propagation in vacuum restricted to a single spatial coordinate x. In this one-dimensional reduction, Maxwell's equations can be written in a form mathematically equivalent to a lossless distributed-parameter transmission line, in which a voltage-like quantity $V(x,t)$ and a current-like quantity $I(x,t)$ satisfy

$$\frac{\partial V}{\partial x} = -\,L_s\,\frac{\partial I}{\partial t}, \tag{5}$$

$$\frac{\partial I}{\partial x} = -\,C_t\,\frac{\partial V}{\partial t}. \tag{6}$$

Here L_s and C_t denote effective distributed parameters associated with the vacuum within this formal mapping. Importantly, Equations (5)–(6) should be understood as a structural analogy based on a one-dimensional reduction; no claim is made that the electromagnetic field in vacuum is literally a circuit variable.

2.6.2. Propagation Speed and the Product L_sC_t

Combining Equations (5)–(6) yields a wave equation for V (and similarly for I) with propagation speed

$$v = \frac{1}{\sqrt{L_s\,C_t}}. \tag{7}$$

Requiring consistency with the experimentally observed propagation speed in vacuum, $v = c$, fixes the product of the effective parameters:

$$L_s\,C_t = \frac{1}{c^2}. \tag{8}$$

2.6.3. Characteristic Impedance and the Ratio L_s/C_t

For a lossless distributed-parameter medium, the characteristic impedance is

$$Z_0 = \sqrt{\frac{L_s}{C_t}}. \tag{9}$$

Using the experimentally measured free-space impedance Z_0, Eq. (9) provides an independent relation fixing the ratio of the effective parameters:

$$\frac{L_s}{C_t} = Z_0^2. \tag{10}$$

Together, Equations (8) and (10) determine L_s and C_t in terms of c and Z_0, establishing a consistent reactive parameterization of the vacuum within the transmission-line analogy.

2.6.4. Universal Impedance Form of Reactive Media

A general linear medium exhibiting both reactive storage and dissipation admits a complex impedance representation of the form

$$Z(\omega) = R + j\left(\omega L - \frac{1}{\omega C}\right), \tag{11}$$

where L and C describe inductive and capacitive responses, respectively, and R accounts phenomenologically for dissipative effects. In standard circuit and wave-propagation contexts, such a term represents losses, finite conductivity, or irreversible energy conversion. In the TSI interpretation, the same functional structure is adopted as an effective description of vacuum response, where R is introduced as a phenomenological measure of decoherence and irreversibility rather than material friction.

2.6.5. Synthesis: The Master Impedance Equation of TSI

In the Theory of Spacetime Impedance (TSI), the dynamic vacuum is operationally defined through its constitutive identity,

$$\emptyset \equiv Z(\omega), \tag{12}$$

which establishes that the physical properties of spacetime can be fully characterized by a complex, frequency-dependent impedance.

By identifying the effective vacuum parameters as

$$L = L_s, \qquad C = C_t, \qquad R = R_t, \tag{13}$$

the effective impedance of the vacuum takes the form

$$Z(\omega) = R_t + j\left(\omega L_s - \frac{1}{\omega C_t}\right). \tag{14}$$

Equation (14) is referred to as the *TSI master impedance equation*. It simultaneously encodes: (i) the transmission-line structure obtained from the one-dimensional reduction of Maxwell's equations; (ii) the constraint imposed by the speed of light c through the product $L_s C_t$; (iii) the experimentally measured impedance of free space Z_0 through the ratio L_s/C_t; and (iv) the universal reactive–dissipative form of linear media via the inclusion of the resistive term R_t.

In this formulation, the vacuum parameters (L_s, C_t, Z_0) are treated as effective reactive descriptors linked to experimentally established constants, while the additional term R_t introduces a phenomenological channel through which loss of coherence and entropy production can be modeled within a unified impedance-based language. Although this formal structure is already present in the mathematics of classical physics, the TSI adopts and reinterprets it to describe the vacuum as a reactive medium. The following sections develop the physical consequences of this approach.

2.7. Reactive Interpretation of the Bronstein Cube

The Bronstein cube organizes modern physical theories according to the role of three fundamental constants: the speed of light c, Planck's constant $\hbar$, and the gravitational constant G. In the conventional interpretation, each vertex of the cube corresponds to a distinct theoretical regime, while the simultaneous inclusion of all three constants is associated with the unresolved problem of quantum gravity.

Within the framework of the Theory of Spacetime Impedance (TSI), this structure admits a different and more unified interpretation. Rather than treating c, $\hbar$, and G as independent fundamental inputs, the TSI framework describes them as emergent quantities arising from the reactive properties of the vacuum, characterized by the effective parameters (L_H, C_H, R_H). In this sense, the Bronstein cube is not viewed as a classification of separate theories, but as a projection of different reactive regimes of a single physical substrate: the reactive vacuum (Hyliaster).

Specifically, the relativistic limit associated with c corresponds to the capacitive–inductive propagation condition of the vacuum, $c = 1/\sqrt{L_H C_H}$. Quantum behavior governed by $\hbar$ emerges from phase quantization and resonance conditions of the microcellular reactive structure. Gravitational effects encoded in G arise as a collective inductive response of the vacuum to energy density. The simultaneous presence of c, $\hbar$, and G thus reflects the full activation of the reactive degrees of freedom of the Hyliaster, rather than the coexistence of conceptually disconnected principles.

From this perspective, the domain commonly referred to as "quantum gravity" does not require the introduction of additional fundamental entities, but is interpreted as a regime in which the inductive, capacitive, and phase-coherent responses of the reactive vacuum are simultaneously relevant. The Bronstein cube therefore acquires a structural interpretation within the TSI framework, highlighting the role of vacuum impedance as a unifying element across classical, relativistic, and quantum domains.

2.8. Reactive Microstructure of the Vacuum: The Hyliaster

Once the master impedance equation of the vacuum has been established, it is natural to inquire whether such a reactive description admits an effective microstructural interpretation. In distributed physical systems, macroscopic impedance relations typically emerge from the collective behavior of elementary units rather than from a continuous substance devoid of internal structure. Within the phenomenological scope of the Theory of Spacetime Impedance (TSI), this observation motivates the introduction of an effective microstructure of the reactive vacuum, referred to as the *Hyliaster*.

The Hyliaster is defined as the minimal reactive substrate capable of storing, transmitting, and modulating energy, phase, and information in spacetime. It is not introduced as a new fundamental entity, but as a phenomenological representation of the vacuum consistent with the master impedance equation. Specifically, the Hyliaster provides a microstructural interpretation of a vacuum characterized by distributed inductive, capacitive, and resistive responses.

In this framework, the vacuum is modeled as a network of discrete reactive microcells whose characteristic scale is set by fundamental Planck quantities. Each microcell behaves as a *distributed triphase RLC resonator*, rather than as a lumped element, reflecting the intrinsically extended nature of spacetime. The inductive component encodes the inertial and gravitational response of the medium, the capacitive component governs its electromagnetic response, and the resistive component accounts for irreversible processes such as decoherence and entropy production.

This representation is consistent with several established physical concepts. First, it aligns with the oscillators introduced by Planck in his theory of black-body radiation, which represent the minimal units capable of exchanging quantized energy. Second, it is compatible with the discrete normal modes of quantum field theory, where fields are decomposed into harmonic oscillators associated with each mode. Third, it reflects the well-known behavior of distributed reactive media—such as transmission lines and waveguides—where continuous propagation emerges from an underlying distributed reactive structure.

Within the Hyliaster description, the characteristic relations of the vacuum,

$$c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}}, \qquad Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}, \tag{15}$$

are understood as emergent macroscopic parameters arising from the collective response of the reactive microcells. In this sense, the speed of light and the vacuum impedance do not appear as independent postulates, but as effective propagation and stability conditions of the reactive medium.

Importantly, the Hyliaster should be regarded as a phenomenological construct. It does not imply a literal granular structure of spacetime, nor does it postulate new microscopic degrees of freedom beyond those already encoded in established theories. Rather, it serves as a conceptual and mathematical bridge linking the distributed reactive description of the vacuum with observable physical constants and dynamical regimes.

From this perspective, matter, fundamental constants (including c, Z_0, α, $\hbar$, and G), and the laws governing classical, quantum, and relativistic dynamics emerge as effective manifestations of the inductive, capacitive, and resistive responses of the Hyliaster. The resistive component, in particular, provides a natural phenomenological basis for irreversibility, decoherence, and the thermodynamic arrow of time.

In summary, the Hyliaster represents the reactive microstructural substrate of spacetime implied by the TSI framework. It encapsulates, in a unified and internally consistent manner, the inductive, capacitive, and resistive responses of the vacuum, thereby providing a coherent foundation from which diverse physical phenomena can be interpreted as different operational regimes of a single underlying reactive medium.

2.9. Propagation as State Reconfiguration in a Discrete Medium

In distributed physical systems, the propagation of an excitation does not necessarily involve the material displacement of the supporting substrate, but rather the sequential reconfiguration of local states. This principle is well established in various physical contexts, such as the propagation of mechanical waves in elastic media, electrical pulses in transmission lines, and phonons in crystalline lattices, where the constituents of the medium remain essentially fixed and what is transmitted is a dynamical configuration of energy and phase.

From this perspective, the Theory of Spacetime Impedance (TSI) interprets the propagation of particles and waves not as the transport of matter through a passive vacuum, but as the coherent transfer of states between cells of the reactive vacuum (the Hyliaster). These cells do not move; they act as locally stationary elements whose internal configuration adjusts in response to coupling with neighboring cells, enabling the continuous reconstruction of a dynamical pattern.

A contemporary technological example illustrating this principle is a high-resolution digital display. In a 4K screen, millions of pixels remain fixed in space, each composed of an RGB triad. The apparent motion of an image or a luminous point does not occur because the pixels move, but because their internal states are reconfigured sequentially and synchronously. Visual information thus propagates as a temporal pattern over a discrete and immobile spatial support.

Analogously, within TSI, the reactive vacuum neither moves nor flows. The propagation of a quantum or classical excitation corresponds to the modulation of the fundamental carrier frequency of the vacuum, locally reconstructed in each Hyliaster cell. The physical identity of a particle or wave is preserved not by the transport of a material object, but by the continuity of phase, energy, and information patterns across the reactive network of the vacuum.

Throughout the history of physics, from Maxwell and Heaviside to modern quantum field theory, multiple theoretical frameworks and experimental results converge on a common idea: what propagates is not matter as a substantial entity, but dynamical configurations of an underlying substrate. formalizes this intuition by identifying that substrate with a reactive vacuum of RLC structure, in which particles and waves emerge as coherent patterns of reconfiguration rather than as objects moving through space. This interpretation provides a coherent unification of wave propagation, effective particle localization, and the absence of substantial transport of the medium, offering a clear phenomenological basis for describing spacetime as a distributed reactive system.

2.10. Scope of the TSI Equation

The master equation of the Theory of the Impedance of Spacetime (TSI) is proposed to be valid across both microscopic and macroscopic scales, describing physical behavior that extends from the microphysical domain to the universal macroscopic regime.

2.10.1. Physical Starting Point: What the TSI Equation Describes

TSI Master Equation

$$Z(\omega) = R_H + j\left(\omega L_H - \frac{1}{\omega C_H}\right) \tag{16}$$

This expression does not describe an elementary particle, a fundamental force, or an abstract geometry. Rather, within a theoretical–phenomenological framework, it describes how spacetime responds to a dynamical perturbation. From this perspective, the universe is not conceived as a passive stage, but as a physical reactive medium, analogous to a transmission line with distributed parameters, an RLC resonator, or an antenna characterized by a specific impedance, extended from microscopic scales to the macroscopic scale of the universe. Within this framework, different physical phenomena emerge as particular response regimes of a single underlying reactive medium.

2.10.2. Gravitation — the Inductive Term (ωL_H)

In classical physics, inductance represents resistance to changes in current.

Within TSI, the inductive term represents resistance to changes in temporal flux. This property manifests as gravitational inertia:

- mass does not "attract" in the Newtonian sense;
- mass hinders variations of local time;
- spacetime responds with a dynamical delay to changes, which manifests as temporal curvature.

Thus, gravitation is not interpreted as a fundamental force, but as an inductive effect of the reactive medium itself: reactive spacetime.

For this reason, gravity:

- is universal,
- couples to all forms of energy,
- and propagates with a finite limiting velocity.

Gravitation therefore emerges as an inductive response of the reactive vacuum.

2.10.3. Electromagnetism — the Capacitive Term $(1/\omega C_H)$

Capacitance measures the ability to store a potential difference.

Within TSI, the capacitive term represents:

- spatial coupling,
- polarization of the medium,
- charge separation.

These effects correspond directly to electromagnetic phenomena:

- electric fields as energy storage,
- magnetic fields as dynamical redistribution,
- electromagnetic waves as inductive–capacitive oscillations of the medium.

In this context, spacetime does not transport geometry alone, but also physical electric potential.

As a result:

- light propagates,
- atoms possess structure,
- electric charge exists.

Electromagnetism thus emerges as a capacitive response of the reactive vacuum.

2.10.4. Quantum Mechanics: $j = \sqrt{-1}$, Resonant Regime and Phase

In the expression for the complex impedance of the reactive vacuum, the imaginary factor $j = \sqrt{-1}$ has a precise physical meaning and does not constitute a mathematical artifact. In wave physics and circuit theory, the imaginary term represents a $\pi/2$ phase rotation between conjugate variables, indicating reversible energy storage and coherent phase evolution.

Within the TSI framework, the imaginary part of Z_H encodes the coherent oscillatory dynamics of the Hyliaster, while the real term R_H introduces irreversible processes associated with dissipation, decoherence, and entropy production. This separation naturally reflects the distinction between quantum dynamics and classical irreversible processes.

A formally analogous structure appears in the Schrödinger equation,

$$i\hbar \frac{\partial}{\partial t}\psi = \hat{H}\psi, \tag{17}$$

where the imaginary unit guarantees unitary evolution of the quantum state. Similarly, in TSI the factor j ensures phase coherence of vacuum excitations, allowing stable resonances and quantization of modes.

Consequently, Planck's constant $\hbar$ is interpreted as the parameter that sets the minimum action scale associated with these coherent oscillations of the reactive vacuum. Quantum mechanics thus emerges as the resonant regime of the Hyliaster, while quantum decoherence is associated with the action of the resistive term R_H.

2.10.5. Relativity — Medium Structure and Propagation Limit

Relativity is incorporated without introducing additional postulates.

Every reactive medium possesses a maximum propagation velocity determined by its constitutive parameters.

Within TSI:

- this velocity arises from L_H and C_H,
- and coincides with the speed of light.

As a consequence:

- time dilates,
- lengths contract,
- and causality is preserved.

Relativity is therefore not interpreted here as a purely geometric construction, but as an emergent electromagnetic property of the medium. In this sense, Einstein's formulation is fully respected.

2.10.6. Thermodynamics — the Resistive Term (R_H)

Resistance is the only term that:

- breaks time-reversal symmetry,
- dissipates energy,
- destroys coherence.

Within TSI:

- R_H constitutes the source of entropy,
- defines the arrow of time,
- and gives rise to irreversibility.

When $R_H \approx 0$:

- behavior is quantum,
- reversible,
- and coherent.

When $R_H > 0$:

- decoherence emerges,
- effective collapse appears,
- and classical thermodynamics manifests.

Thermodynamics is therefore not introduced as an external element, but is already contained in the equation from its initial formulation.

2.10.7. Physical Unification (Without Forcing)

Unification arises because:

- the fundamental equation is not modified,
- no new fields are introduced,
- no additional forces are postulated.

Only the dominant regime of the same constitutive expression changes.

Dominant term regime	Emergent phenomenon
Inductive dominance	Gravitation
Capacitive dominance	Electromagnetism
Inductive = capacitive	Quantum mechanics
Full structure	Relativity
Resistive $\neq 0$	Thermodynamics

This correspondence constitutes a functional unification rather than a formal imposition.

Final Conclusion

When interpreted through its own structure, the spacetime impedance equation contains:

- gravitation,
- electromagnetism,
- quantum mechanics,
- relativity,
- and thermodynamics,

as manifestations of a single reactive medium. TSI does not compete with existing theories, but rather contains them as natural limiting cases.

2.11. Methodological Summary and Falsification Criteria

The master equation of the Theory of Spacetime Impedance (TSI),

$$Z_H(\omega) = R_H + j\left(\omega L_H - \frac{1}{\omega C_H}\right), \tag{18}$$

is interpreted as an effective constitutive relation of spacetime in the frequency domain. Its physical consistency and predictive scope are determined by the following key elements.

From a dimensional standpoint, the resistive term R_H has the dimensions of impedance $[\Omega]$ and represents irreversible processes associated with dissipation and entropy production. The inductive parameter L_H, with dimensions of inductance [H], quantifies the temporal inertia of the medium, while the capacitive parameter C_H, with dimensions of capacitance [F], characterizes the ability of spacetime to store potential energy. The combination of the reactive terms defines a natural frequency $\omega_0 = 1/\sqrt{L_H C_H}$, characteristic of an effective resonant model.

The validity of the TSI equation is restricted to the linear-response regime, under small dynamical perturbations, where the constitutive parameters may be treated as effective constants and modal superposition applies. Within this framework, spacetime is modeled as a resonator with lumped parameters, and the dynamics are adequately described in the harmonic or quasi-harmonic domain.

As a direct consequence of its structure, TSI predicts the existence of a characteristic resonant scale of the reactive vacuum, manifested as a maximal dynamic response near the frequency ω_0. It further anticipates transitions between coherent and incoherent regimes governed by the resistive term R_H, leading to universal bounds on quantum coherence and to a constitutive link between irreversibility and the structure of spacetime.

The theory is experimentally falsifiable if no resonant scale attributable to the vacuum is identified, if no dynamical effects associated with an effective complex impedance are observed, or if fundamentally irreversible processes are demonstrated to exist in the absence of any dissipative contribution. These criteria establish a clear framework for empirical testing, distinguishing TSI as a physically verifiable proposal.

3. Results

The results presented in this section are phenomenological in nature. They do not constitute a derivation of fundamental physical constants from first principles, nor the formulation of an underlying microscopic theory. Instead, they are obtained through a coherent reinterpretation of empirically established quantities within the framework of the Theory of Space–Time Impedance (TSI).

In this context, the equations and relations presented here should be understood as effective expressions that characterize the reactive and resistive response of the vacuum when treated as a physical medium. From this perspective, quantities such as the vacuum impedance, the quantum Hall resistance, and the fine-structure constant emerge as structural parameters associated with energy storage, electromagnetic propagation, and the stability conditions of the reactive vacuum.

3.1. Quantum RLC Structure of the Vacuum

A central result of the Theory of the Impedance of Spacetime (TSI) is the emergence of a complete quantum RLC structure associated with the vacuum. This result follows from the consistent application of Planck's quantization principle to the three fundamental modes that characterize a linear reactive medium: capacitive, inductive, and resistive responses.

In classical electrodynamics, the vacuum already exhibits nontrivial constitutive properties, described by the electric permittivity ε_0 and the magnetic permeability μ_0. These constants define the characteristic impedance of free space,

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 376.73\ \Omega, \tag{19}$$

which governs electromagnetic wave propagation and indicates that the vacuum can be described as a medium capable of storing electric and magnetic energy. In this sense, the vacuum possesses an intrinsically reactive character.

Within the TSI framework, the vacuum is modeled as an effective medium in which the inductive and capacitive responses admit quantum analogues associated with the electron. These are described by a quantum inductance L_K and a quantum capacitance C_K. When normalized by the electron Compton wavelength λ_C, the quantities L_K/λ_C and C_K/λ_C acquire the same dimensional character as μ_0 and ε_0, allowing for a direct comparison between the classical and quantum descriptions.

Table 1. Comparison between the classical vacuum parameters and the quantum parameters associated with the electron within the TSI framework. Quantum quantities are normalized by the electron Compton wavelength λ_C.

Parameter	Classical vacuum	Quantum (electron)	Scaling factor
Characteristic impedance	$Z_0 = \sqrt{\mu_0/\varepsilon_0} \approx 376.73\ \Omega$	$R_K = h/e^2 \approx 25.813\ \mathrm{k\Omega}$	$R_K/Z_0 = 1/(2\alpha)$
Inductance per unit length	$\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H/m}$	$L_K/\lambda_C \approx 8.60 \times 10^{-5}\ \mathrm{H/m}$	$(L_K/\lambda_C)/\mu_0 = 1/(2\alpha)$
Capacitance per unit length	$\varepsilon_0 = 8.854 \times 10^{-12}\ \mathrm{F/m}$	$C_K/\lambda_C \approx 1.29 \times 10^{-13}\ \mathrm{F/m}$	$(C_K/\lambda_C)/\varepsilon_0 = 2\alpha$

The third element completing the RLC structure is the von Klitzing quantum resistance,

$$R_K = \frac{h}{e^2} \approx 25.813\ \mathrm{k\Omega}, \tag{20}$$

experimentally established in the context of the quantum Hall effect. Unlike a classical dissipative resistance, R_K represents a fundamental quantum scale of impedance, fixed by the quantization of charge and action. Within the TSI framework, R_K is interpreted as the characteristic resistive element associated with electron–vacuum coupling, rather than as a source of thermal dissipation.

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In direct analogy with the classical expression for the vacuum impedance, the quantum resistance may be written as an effective characteristic impedance determined by the ratio of the quantum inductive and capacitive responses,

$$R_K \equiv Z_K = \sqrt{\frac{L_K}{C_K}} = \sqrt{\frac{L_K/\lambda_C}{C_K/\lambda_C}}. \tag{21}$$

The comparison between classical and quantum impedances leads to a fundamental scaling relation governed by the fine-structure constant α,

$$\frac{R_K}{Z_0} = \frac{1}{2\alpha} \approx 68.5. \tag{22}$$

Equivalently, the following impedance identity establishes a direct bridge between the classical and quantum descriptions of the vacuum:

$$\boxed{\sqrt{\frac{L_K}{C_K}} = \frac{1}{2\alpha}\sqrt{\frac{\mu_0}{\varepsilon_0}}}. \tag{23}$$

Within the TSI framework, the fine-structure constant admits a direct impedancial interpretation. In particular, the ratio between the von Klitzing quantum resistance and the vacuum impedance satisfies

$$\frac{R_K}{Z_0} = \frac{1}{2\alpha}, \tag{24}$$

showing that α quantifies the mismatch between the electromagnetic impedance of free space and the structural resistance associated with the oscillators of the reactive vacuum. In this sense, the strength of the electromagnetic coupling is encoded in the quantum RLC response of the vacuum.

3.1.1. Quantum Origin of the RLC Structure

It should be emphasized that the expressions introduced for the quantum inductance L_K and the quantum capacitance C_K are specific to the framework of the Theory of Space–Time Impedance (TSI). These quantities do not belong to the standard formulation of quantum electrodynamics, nor are they derived from microscopic first principles. Instead, they are introduced as effective parameters designed to describe the minimal reactive response of the vacuum in the quantum regime. In this sense, L_K and C_K constitute original relations within the TSI and represent a phenomenological extension of the classical constitutive properties of the vacuum.

Starting from the quantization of energy $E = \hbar\omega$ and from the classical expressions for energy storage and dissipation in electrical elements, a minimal quantum response can be associated with each component of the RLC structure.

In the capacitive sector, the minimum stored energy $E_C = Q^2/(2C)$, with $Q = e$, leads to a quantum capacitance

$$C_Q = \frac{e^2}{2\hbar c}, \tag{25}$$

which represents the minimal polarization response of the vacuum.

Analogously, in the inductive sector, the energy $E_L = LI^2/2$, considering a quantum current $I = e\omega$, leads to a quantum inductance

$$L_Q = \frac{2\hbar}{e^2 c}, \tag{26}$$

which may be interpreted as the minimal unit of temporal memory or phase delay supported by the vacuum.

Finally, in the dissipative sector, the energy lost per cycle in a resistive element, $E_R = I^2 R/\omega$, leads to a quantum resistance

$$R_Q = \frac{\hbar}{e^2}, \tag{27}$$

which coincides, up to conventional factors of 2π, with the quantum Hall resistance discovered experimentally by von Klitzing. Within the TSI framework, this observed resistance is interpreted as the resistive sector of a more general quantum RLC structure of the vacuum.

Remarkably, these three quantities satisfy the exact relations

$$L_Q\, C_Q = \frac{1}{c^2}, \qquad \frac{L_Q}{C_Q} = R_Q^2, \tag{28}$$

which reproduce the classical propagation and impedance conditions of the vacuum. This result shows that the speed of light and the impedance of free space emerge naturally as invariants of the quantum reactive structure, rather than as independent postulates.

The expressions obtained for the quantum inductance and capacitance are intrinsic to the TSI framework and characterize the effective response of the vacuum.

3.1.2. Physical Interpretation

From this perspective, the quantum Hall resistance represents only one vertex of a deeper triadic structure. The TSI framework predicts that the vacuum supports complementary quantum capacitive and inductive responses, which have already found partial realizations in low-dimensional systems and nanostructures.

Taken together, these results suggest that the vacuum can be coherently modeled as a quantum reactive medium whose fundamental properties are encoded in a unified RLC structure. Wave–particle duality then emerges as an effective property of the coupled electron–vacuum system, rather than as an intrinsic dichotomy of the particle considered in isolation.

3.2. Derivation of Quantum Inductance and Capacitance from α, μ_0, ε_0, and λ_C

Within the framework of the Theory of Space–Time Impedance (TSI), the quantum inductance and capacitance associated with the electron can be expressed directly in terms of well-established physical constants. In particular, the fine-structure constant α, the vacuum permeability μ_0, the vacuum permittivity ε_0, and the electron Compton wavelength λ_C allow for an unambiguous determination of the quantum scales L_K and C_K.

Starting from the correspondence between the classical vacuum parameters and their quantum counterparts normalized by λ_C, the following scaling relations are obtained:

$$\frac{L_K/\lambda_C}{\mu_0} = \frac{1}{2\alpha}, \qquad \frac{C_K/\lambda_C}{\varepsilon_0} = 2\alpha. \tag{29}$$

These relations immediately yield

$$\frac{L_K}{\lambda_C} = \frac{\mu_0}{2\alpha}, \qquad \frac{C_K}{\lambda_C} = 2\alpha\, \varepsilon_0, \tag{30}$$

and therefore the explicit expressions for the quantum inductance and capacitance:

$$\boxed{L_K = \frac{\mu_0\, \lambda_C}{2\alpha}, \qquad C_K = 2\alpha\, \varepsilon_0\, \lambda_C.} \tag{31}$$

These expressions satisfy a set of nontrivial consistency checks, reinforcing the interpretation of the quantum RLC triad as a natural extension of the constitutive properties of the classical vacuum.

First, the product of L_K and C_K is given by

$$L_K C_K = \left(\frac{\mu_0\,\lambda_C}{2\alpha}\right)(2\alpha\,\varepsilon_0\,\lambda_C) = \mu_0\varepsilon_0\,\lambda_C^2. \tag{32}$$

Since $\mu_0\varepsilon_0 = 1/c^2$, one obtains

$$\boxed{L_K C_K = \frac{\lambda_C^2}{c^2},} \tag{33}$$

showing that the product of the quantum inductance and capacitance fixes a natural temporal scale associated with the electron Compton wavelength.

Second, the ratio between L_K and C_K directly defines a characteristic quantum impedance:

$$\frac{L_K}{C_K} = \frac{\mu_0}{\varepsilon_0}\,\frac{1}{(2\alpha)^2}. \tag{34}$$

Taking the square root yields

$$\boxed{\sqrt{\frac{L_K}{C_K}} = \frac{1}{2\alpha}\sqrt{\frac{\mu_0}{\varepsilon_0}} = \frac{Z_0}{2\alpha},} \tag{35}$$

where $Z_0 = \sqrt{\mu_0/\varepsilon_0}$ is the characteristic impedance of the classical vacuum.

These results demonstrate that the quantum inductance and capacitance are not independent parameters, but are fully determined by the electromagnetic structure of the vacuum, the fine-structure constant, and the Compton length scale. Within the TSI framework, this dimensional and structural coherence supports the interpretation of the vacuum as a quantum reactive medium endowed with a well-defined RLC triad, whose characteristic impedance governs electromagnetic propagation, quantization, and dynamical stability.

Naturally, the pair formed by the quantum inductance L_K and the quantum capacitance C_K defines a characteristic impedance associated with an elementary reactive vacuum cell or quantum oscillator. Explicitly, their ratio fixes a quantum impedance

$$Z_K \equiv \sqrt{\frac{L_K}{C_K}}, \tag{36}$$

which coincides, up to conventional numerical factors, with the von Klitzing quantum resistance $R_K = h/e^2$. Within the TSI, this identification allows R_K to be interpreted not as a dissipative parameter, but as the fundamental impedance governing reactive coupling and quantized dynamics in each vacuum cell, or *Hyliaster*, thereby completing the quantum RLC triad (R_K, L_K, C_K).

This interpretation establishes a bridge between Planck-scale oscillatory models and physical phenomena described within the TSI. By grounding the concept of the Planck oscillator in the reactive properties of the vacuum, the TSI provides a unified and operational description in which the frequency of light, the quantum of action, the fine-structure constant, and the impedance of free space emerge from a single underlying RLC dynamics of the reactive vacuum.

3.3. The Quantum RLC Triad and the Physical Interpretation of Planck Oscillators

Within the framework of the Theory of Space–Time Impedance (TSI), the quantum RLC triad provides a concrete physical interpretation of the oscillatory structures traditionally known as Planck oscillators. While in conventional formulations such oscillators are often introduced as formal or statistical constructs, TSI identifies them as effective physical entities emerging from the reactive structure of the vacuum.

The inductive, capacitive, and resistive elements of the quantum RLC triad correspond directly to the parameters that determine the characteristic frequency of electromagnetic propagation. In

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particular, the balance between quantum inductance and quantum capacitance fixes a natural angular frequency,

$$\omega_0 = \frac{1}{\sqrt{L_H C_H}}, \tag{37}$$

which coincides with the frequency scale associated with the propagation of light in the reactive vacuum. This correspondence establishes that the oscillatory modes underlying electromagnetic phenomena are not mere mathematical abstractions, but physical modes supported by the vacuum itself.

From this perspective, Planck oscillators emerge as manifestations of elementary reactive units of the vacuum, each characterized by a well-defined quantum RLC structure. These units admit stable oscillatory dynamics governed by the same parameters that define the vacuum impedance and the speed of light. The presence of the resistive element ensures that such oscillations are regulated by quantization conditions, rather than by uncontrolled dissipative processes.

In TSI, these elementary oscillatory units are referred to as *reactive vacuum cells*, embedded in the *Hyliaster* substrate. A cell does not constitute a particle in the conventional sense, but rather an effective vacuum oscillator capable of storing, exchanging, and coupling energy through its intrinsic quantum RLC structure. The collective behavior of these cells gives rise to macroscopic electromagnetic propagation, quantum stability, and the emergence of fundamental constants such as c, Z_0, $\hbar$, G, and α.

3.4. Visualization of the Origin of the Quantum of Action in the TSI

Within the framework of the Theory of Space–Time Impedance (TSI), no new quantum of action is introduced, nor is the fundamental status of the reduced Planck constant $\hbar$ modified. The purpose of this subsection is solely to visualize its effective physical origin from the reactive structure of the vacuum described by the quantum RLC triad.

The quantum inductance L_K and quantum capacitance C_K associated with the reactive vacuum naturally define a characteristic frequency,

$$\omega_0 = \frac{1}{\sqrt{L_K C_K}} = \frac{c}{\lambda_C}, \tag{38}$$

which coincides with the electron Compton frequency. This temporal scale emerges directly from the reactive properties of the vacuum and does not require additional postulates.

Complementarily, the same pair (L_K, C_K) defines a characteristic quantum impedance,

$$Z_K = \sqrt{\frac{L_K}{C_K}} = \frac{Z_0}{2\alpha}, \tag{39}$$

which coincides, up to conventional numerical factors, with the von Klitzing quantum resistance. This impedance sets the scale of reactive coupling of the vacuum at the quantum level.

By combining the temporal scale fixed by the characteristic frequency of the reactive vacuum,

$$\omega_0 = \frac{1}{\sqrt{L_K C_K}} = \frac{c}{\lambda_C}, \tag{40}$$

with the impedancial scale determined by the quantum triad,

$$Z_K = \sqrt{\frac{L_K}{C_K}} = \frac{Z_0}{2\alpha}, \tag{41}$$

one obtains a complete characterization of the elementary dynamics of the reactive vacuum.

In this context, a natural quantity with dimensions of action is given by the ratio between a characteristic energy and the angular frequency,

$$\mathcal{A} \sim \frac{E}{\omega_0}. \tag{42}$$

Since the elementary reactive energy associated with a vacuum cell can be expressed in terms of the impedancial coupling Z_K, the action associated with a minimal reactive cycle is fixed by the combination of ω_0 and Z_K. This scale is phenomenologically identified with the quantum of action $\hbar$.

In this way, the reduced Planck constant does not appear as an independent postulate, but as the invariant that relates the temporal and impedancial scales of the RLC dynamics of the reactive vacuum.

3.5. Fine-Structure Constant from the Quantum RLC Triad

Within the TSI framework, the quantum response of the vacuum is characterized by a triad of elementary quantities (R_Q, L_Q, C_Q) associated with the minimal dissipative, inductive, and capacitive sectors of the vacuum. This triad is constrained by two exact structural relations, analogous to the classical vacuum conditions:

$$L_Q\, C_Q = \frac{1}{c^2}, \qquad \frac{L_Q}{C_Q} = R_Q^2. \tag{43}$$

Equation (43) fixes both the propagation scale (c) and the internal impedance scale (R_Q) of the quantum vacuum.

To connect this triad with the strength of electromagnetic coupling, we introduce the vacuum impedance Z_0, operationally defined as the ratio between electric and magnetic field amplitudes in free space. In the transmission-line representation, the impedance is determined by the inductive–capacitive ratio. Accordingly, at the level of the effective vacuum response one has

$$Z_0 = \sqrt{\frac{L}{C}}, \tag{44}$$

and the TSI triad suggests the corresponding quantum ratio

$$\sqrt{\frac{L_Q}{C_Q}} = R_Q. \tag{45}$$

Thus, R_Q is identified as the intrinsic impedance scale associated with the minimal quantum RLC response.

The fine-structure constant α is defined in SI units as

$$\alpha \equiv \frac{e^2}{4\pi\varepsilon_0 \hbar c}. \tag{46}$$

Using $Z_0 = 1/(\varepsilon_0 c)$ and the reduced quantum resistance $R_Q \equiv \hbar/e^2$, Equation (46) can be rewritten as

$$\alpha = \frac{1}{4\pi}\,\frac{Z_0}{R_Q}. \tag{47}$$

Finally, substituting the triad relation (45), one obtains a TSI expression in which α is determined by the ratio between the classical vacuum impedance and the minimal quantum impedance scale of the vacuum itself:

$$\boxed{\alpha = \frac{1}{4\pi}\,\frac{Z_0}{\sqrt{L_Q/C_Q}}} \tag{48}$$

This derivation does not redefine α; rather, it shows that within the TSI framework the electromagnetic coupling constant can be interpreted as a dimensionless measure of how the classical vacuum impedance compares with the minimal quantum RLC impedance encoded by the vacuum triad.

3.5.1. Emergence of the Speed of Light and the Vacuum Impedance

Within the TSI framework, the vacuum is modeled as an effective reactive medium characterized by an intrinsic inductance L_H and capacitance C_H, analogous to the distributed parameters of a transmission line. In such a medium, the propagation speed of disturbances is determined by the balance between the inductive and capacitive responses, which naturally leads to the relation

$$c = \frac{1}{\sqrt{L_H C_H}}. \tag{49}$$

By identifying these parameters with the electromagnetic constants of the vacuum, μ_0 and ε_0, the standard expression for the speed of light is recovered, showing that its invariance emerges as a structural property of the reactive vacuum.

In a complementary manner, the vacuum exhibits a characteristic impedance associated with the ratio between its inductive and capacitive responses,

$$Z_0 = \sqrt{\frac{L_H}{C_H}} = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 377\ \Omega. \tag{50}$$

From this perspective, the vacuum impedance is not an arbitrary constant, but a stability condition that fixes the relationship between the reactive responses of the medium. Consequently, both the speed of light and the vacuum impedance emerge coherently from the same underlying reactive structure.

3.6. Gravitational Constant from the Quantum RLC Triad (TSI Ansatz)

In TSI, gravitation is associated with the *inductive* (longitudinal) sector of the vacuum response. The vacuum is modeled as a reactive medium whose quantum response admits a minimal RLC triad (R_Q, L_Q, C_Q) satisfying the structural relations

$$L_Q\, C_Q = \frac{1}{c^2}, \qquad \frac{L_Q}{C_Q} = R_Q^2. \tag{51}$$

These relations fix the propagation scale (c) and the intrinsic quantum impedance scale ($R_Q = \sqrt{L_Q/C_Q}$) of the vacuum.

Weak-field identification.

In the Newtonian limit of general relativity, the gravitational potential Φ governs time dilation as

$$\frac{\delta\tau}{\tau} \simeq \frac{\Phi}{c^2}, \tag{52}$$

and satisfies Poisson's equation

$$\nabla^2\Phi = 4\pi G\,\rho. \tag{53}$$

TSI interprets Φ/c^2 as a *phase-delay* (time-delay) field induced by inductive loading of the vacuum. Operationally, we encode this by allowing the effective inductive parameter of the vacuum to depend on the local energy density $u = \rho c^2$,

$$L_{\text{eff}} = L_s[1 + \chi_L\, u], \tag{54}$$

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where χ_L is a longitudinal susceptibility (vacuum compliance) with dimensions $[\chi_L] = \mathrm{m}^3/\mathrm{J}$. Since the propagation constraint reads $L_s C_t = 1/c^2$, a local perturbation δL implies a local perturbation in the time-delay field. Matching Equations (52)–(53) yields the identification

$$\boxed{G \equiv \frac{c^4}{8\pi}\,\chi_L.} \tag{55}$$

Triad-based parametrization of χ_L.

To connect χ_L to the quantum triad, TSI introduces a minimal vacuum energy exchange scale per cell via Planck quantization, $E = \hbar\omega$, and a characteristic cell length $\ell = c/\omega$ (phenomenological coarse-graining). This defines an energy-density scale

$$u(\omega) = \frac{\hbar\omega}{\ell^3} = \frac{\hbar\omega^4}{c^3}. \tag{56}$$

The inductive susceptibility is then parametrized as the ratio between a quantum reactive scale and the energy-density scale,

$$\chi_L(\omega) = \frac{\eta}{u(\omega)}, \qquad \eta \equiv \frac{Z_0}{R_Q}, \tag{57}$$

where η is a dimensionless measure of how the classical vacuum impedance compares to the intrinsic quantum impedance scale of the triad. Substituting Equations (56)–(57) into Eq. (55) gives the TSI expression

$$\boxed{G(\omega) = \frac{c^4}{8\pi}\,\frac{Z_0/R_Q}{\hbar\omega^4/c^3} = \frac{c^7}{8\pi\hbar}\,\frac{Z_0}{R_Q}\,\omega^{-4}.} \tag{58}$$

Equation (58) should be read as a *structural* derivation: within TSI, G emerges as the coupling scale that converts longitudinal vacuum compliance (inductive loading) into the Newtonian time-delay field. A complete numerical prediction requires fixing the coarse-graining frequency ω from an independent, empirically anchored condition (e.g., a crossover scale where reactive and dissipative sectors become comparable).

3.7. TSI (R_K, L_K, C_K) Relation for the Vacuum Energy Density

Within the Theory of the Impedance of Spacetime (TSI), the introduction of a (R_K, L_K, C_K) relation for the vacuum energy density is not intended as a first-principles derivation of the cosmological constant, but rather as the formulation of an expression that is consistent with the reactive-vacuum principles adopted in this work and compatible with the standard definitions of general relativity and electromagnetism.

Standard identification.

In the ΛCDM cosmological model, the cosmological constant is commonly rewritten in terms of an effective vacuum energy density,

$$\rho_{\mathrm{vac}} = \frac{\Lambda c^2}{8\pi G}, \qquad P_{\mathrm{vac}} = -\rho_{\mathrm{vac}}\, c^2, \tag{59}$$

such that Λ corresponds to a constant negative pressure with equation of state $w = -1$.

TSI principle: vacuum response at cosmological scales.

In TSI, the vacuum is modeled as a reactive medium whose response depends on the characteristic frequency at which it is excited. At cosmological scales, the natural angular frequency scale is set by the expansion rate,

$$\omega_{\mathrm{cos}} \sim H, \tag{60}$$

where H is the Hubble parameter. A central construct of TSI is that the vacuum contribution relevant for cosmological dynamics corresponds to an effective response evaluated at $\omega \sim \omega_{\text{cos}}$, rather than to a sum over ultraviolet modes.

Quantum reactive microstructure.

The quantum RLC triad introduced in this work associates to the reactive vacuum a characteristic microscopic frequency determined by the quantum inductance and capacitance,

$$\omega_0 = \frac{1}{\sqrt{L_K C_K}} = \frac{c}{\lambda_C}, \tag{61}$$

as well as a characteristic quantum impedance,

$$Z_K = \sqrt{\frac{L_K}{C_K}} = \frac{Z_0}{2\alpha}, \tag{62}$$

where λ_C is the electron Compton wavelength, Z_0 is the vacuum impedance, and α is the fine-structure constant.

Closure ansatz.

Guided by the TSI description of the vacuum as a reactive medium with quantized microstructure, a phenomenological closure relation is introduced in which the vacuum energy density relevant at cosmological scales is suppressed by the ratio between the cosmological frequency scale and the microscopic reactive scale. A compact and dimensionally consistent form is

$$\boxed{\rho_{\text{vac}}^{(\text{TSI})} = \kappa_\Lambda \frac{1}{\alpha^2} \frac{\hbar}{c^3} \omega_0^3 H} \tag{63}$$

where κ_Λ is a dimensionless calibration parameter expected to be of order unity. Using Equation (61), this expression may be written equivalently as

$$\boxed{\rho_{\text{vac}}^{(\text{TSI})} = \kappa_\Lambda \frac{1}{\alpha^2} \frac{\hbar H}{\lambda_C^3}} \tag{64}$$

which makes explicit that the cosmological contribution of the vacuum is controlled by a microscopic density set by λ_C and by the cosmological time scale H^{-1}.

Effective cosmological constant.

Substituting into the standard relation of Equation (59), one obtains an effective cosmological constant compatible with the usual relativistic identification,

$$\boxed{\Lambda_{\text{eff}}^{(\text{TSI})} = \frac{8\pi G}{c^2} \rho_{\text{vac}}^{(\text{TSI})} = \kappa_\Lambda \frac{8\pi G}{c^2} \frac{1}{\alpha^2} \frac{\hbar}{c^3} \omega_0^3 H} \tag{65}$$

Interpretation.

Equations (63)–(65) should be interpreted as a closure relation within the TSI framework, rather than as a microscopic derivation. The vacuum energy density entering cosmological dynamics is described as an effective reactive response of the vacuum evaluated at the cosmological frequency $\omega \sim H$, while the quantum triad (R_K, L_K, C_K) fixes the fundamental reactive scales through ω_0 and Z_K. The only free parameter, κ_Λ, captures the residual model dependence without compromising the structural coherence of the approach.

- Within TSI, the cosmological-constant equation of the standard model is understood as describing a reactive behavior of the vacuum;
- the cosmological constant Λ corresponds to a dominantly capacitive regime;
- the factor c^2 connects this response to the constitutive electromagnetic structure of the vacuum;
- the factor π reflects the oscillatory and distributed character of the spacetime medium;
- the quantity P_{vac} represents the effective reactive pressure associated with vacuum energy storage.

3.8. Quantum Gravity in the TSI Framework

Within the phenomenological scope of the Theory of Spacetime Impedance (TSI), quantum gravity is not conceived as an independent theory based on the direct quantization of the gravitational field or of spacetime geometry. Instead, it is understood as a limiting regime of the same reactive vacuum dynamics that underlies electromagnetism, quantum coherence, and thermodynamic irreversibility.

In the TSI framework, spacetime is modeled as a reactive medium characterized by effective inductive, capacitive, and resistive responses. Gravitational phenomena arise from the inductive sector of this medium, which encodes the resistance of the vacuum to variations in temporal flow and energy transport. In the classical limit, this inductive response reproduces the geometric description of gravity embodied in general relativity. In the quantum regime, however, the same inductive structure supports coherent phase dynamics that are already present in quantum field theory.

From this perspective, quantum gravity does not require the introduction of gravitons as fundamental particles or the postulation of a discrete microscopic geometry. Instead, it emerges as a regime in which inductive vacuum responses become phase-coherent at quantum scales, interacting with the capacitive (electromagnetic) and resistive (dissipative) sectors of the vacuum. The quantization of gravitational effects is therefore not imposed *ab initio*, but follows from the same phase-coherence conditions that govern quantum mechanics.

Crucially, within the phenomenological reach of the TSI, quantum gravity is understood not as a separate theory of quantized gravitational fields, but as a *limiting regime* of the unified reactive dynamics that also governs electromagnetism, quantum coherence, and thermodynamic irreversibility. In this view, gravity, quantum behavior, and the arrow of time are different expressions of a single physical substrate—the reactive vacuum—operating under different frequency and coupling regimes.

This interpretation naturally reconciles the conceptual tension between general relativity and quantum mechanics. Gravity remains universal and geometric at macroscopic scales, while its quantum aspects appear as coherent inductive responses of the vacuum at microscopic scales, without violating causality or requiring fundamentally new entities. As such, the TSI provides a coherent and economical conceptual framework in which quantum gravity is not an isolated problem, but an emergent aspect of the same reactive structure that underlies all known fundamental interactions.

3.9. Reactive Structure of Matter and Waves in the TSI Framework

3.9.1. The Atom as an Effective RLC System in the TSI Framework

Within the Theory of Spacetime Impedance (TSI), the atom is interpreted phenomenologically as a stable configuration of the reactive vacuum (Hyliaster), characterized by the coexistence of three effective responses: inductive, capacitive, and resistive. This triad constitutes a minimal stability condition for a bounded physical structure. The capacitive response accounts for electric energy storage and potential separation, the inductive response encodes phase inertia associated with effective currents and moments, and the resistive term parametrizes dissipative coupling, fixing the local arrow of time through decoherence and entropy production.

At an effective level, the atomic state may be represented by a frequency-dependent impedance,

$$Z_{\text{atom}}(\omega) = R_{\text{a}} + j\left(\omega L_{\text{a}} - \frac{1}{\omega C_{\text{a}}}\right), \tag{66}$$

where $(L_\mathrm{a}, C_\mathrm{a}, R_\mathrm{a})$ denote effective parameters summarizing the net reactive response of the system. Spectral stability is associated with the presence of characteristic frequencies, consistent with a quasi-resonant regime. In the low-loss limit ($R_\mathrm{a} \to 0$), maximal phase coherence is achieved, allowing for quasi-stationary modes. In the TSI interpretation, the atom does not act upon an inert vacuum; rather, it emerges as a coherent configuration of the reactive vacuum itself.

3.9.2. The Electron as a Modulated Excitation of the Hyliaster

In the TSI framework, the electron is described as a coherent excitation of the Hyliaster. It is not interpreted as an object transporting a material substrate, but as a propagating pattern of phase and energy sustained by local reconfigurations of reactive microcells. Operationally, the electron corresponds to a modulation superimposed on a reactive carrier of the vacuum: the microcells do not move, but their phase state is sequentially reconfigured along an effective trajectory.

This picture is consistent with the use of complex amplitudes and phase relations in coherent regimes. When the excitation is dominated by inductive and capacitive responses, phase coherence is preserved and the behavior is wave-like. When an effective resistive coupling increases, for example due to environmental interaction or measurement, coherence is lost and localization emerges. The electron is thus understood as a continuous transition between: (i) a coherent propagation regime dominated by reactive responses, and (ii) a localized regime induced by resistive coupling.

From this perspective, the quantized character of the electron is linked to the minimal phase coherence supported by the microstructure of the reactive vacuum, together with the existence of effective invariants, such as the quantum of action, which constrain elementary exchanges of energy and phase.

3.9.3. Electromagnetic Waves as an RLC Triad: Electric, Magnetic, and Irreversible Components

A classical electromagnetic wave exhibits two field components in phase quadrature: the electric field **E** and the magnetic field **B**. In the TSI framework, this structure is interpreted directly in terms of reactive energy storage. The electric component corresponds to capacitive energy storage, while the magnetic component corresponds to inductive energy storage. The 90° phase shift reflects the alternating exchange between capacitive and inductive energy in a reactive medium.

The TSI extends this description by incorporating an effective resistive component associated with irreversibility. Even in near-ideal propagation, the reactive vacuum admits a resistive term R_H, representing coherence loss, effective dissipation, and entropy production. Consequently, the complete phenomenological description of a wave in the Hyliaster is organized as an RLC triad:

$$\text{Capacitive } (C_H) \leftrightarrow \mathbf{E}, \qquad \text{Inductive } (L_H) \leftrightarrow \mathbf{B}, \qquad \text{Resistive } (R_H) \leftrightarrow \text{irreversibility}. \tag{67}$$

Within this interpretation, wave propagation does not require the physical transport of vacuum cells. Instead, propagation is understood as a sequential phase coupling among microcells, formally analogous to signal transmission in a distributed transmission line. The reactive components determine coherence and propagation speed, while the resistive component sets a universal bound on coherence and its degradation. Thus, in TSI, electromagnetic waves are the macroscopic manifestation of the same RLC architecture that, at the microcellular level, supports quantum excitations.

3.10. Structural Similarity Between Newton and Coulomb Laws

Within the TSI framework, and strictly at a phenomenological level, inverse-square interactions can be represented as limiting behaviors of the reactive model. This analogy does not imply a physical derivation of Newton's or Coulomb's laws, nor an ontological interpretation of the reactive vacuum, but rather a formal correspondence between reactive scales of the medium and the constants characterizing these interactions.

- **Capacitive regime** (C_H dominant):
$$F_E = \frac{1}{4\pi\varepsilon_0}\frac{q_1 q_2}{r^2}, \tag{68}$$
interpreted as the effective form associated with the capacitive mode of the phenomenological model.
- **Inductive regime** (L_H dominant):
$$F_G = G\frac{m_1 m_2}{r^2}, \tag{69}$$
interpreted as an analogous coupling within the inductive reactive mode.

In both cases, a common formal structure appears:

$$F = \frac{K_{\text{react}}\, X_1 X_2}{r^2}, \tag{70}$$

where, in a purely phenomenological sense,

$$K_{\text{react}} = \begin{cases} \dfrac{1}{4\pi\varepsilon_0}, & \text{capacitive (electric) regime,} \\ G, & \text{inductive (gravitational) regime.} \end{cases} \tag{71}$$

This correspondence reflects a structural similarity between inverse-square interactions within the distributed RLC model, without attributing fundamental physical character to the reactive vacuum or deriving the constants G or $1/(4\pi\varepsilon_0)$ from the TSI scheme.

3.11. Entanglement, No–Cloning, and Bell Correlations Within the TSI Framework

Within the framework of the Theory of the Impedance of Spacetime (TSI), quantum entanglement is interpreted as the persistence of a single reactive configuration of the vacuum (Hyliaster) that admits multiple observable spatial projections. Two excitations are considered entangled if, and only if, they share the same effective reactive impedance and a non-factorizable phase structure, even when their spatial manifestations appear separated in classical spacetime.

From this perspective, entanglement does not involve the transmission of energy, signals, or superluminal information between subsystems. Instead, it reflects the existence of a common reactive mode that the vacuum does not distinguish as independent entities. Spatial separation does not break entanglement as long as the shared reactive configuration remains intact.

The no–cloning theorem is interpreted in TSI as a direct consequence of the uniqueness of reactive configurations of the Hyliaster. An exact duplication of a quantum state would require the coexistence of two identical reactive impedances occupying the same fundamental vacuum mode, which is physically inconsistent. Accordingly, the reactive vacuum does not admit copies of a complete configuration, but only multiple projections associated with a single excitation pattern.

The act of measurement introduces a local resistive coupling between the quantum excitation and the measuring apparatus, producing an impedance discontinuity. This coupling breaks the phase coherence of the shared mode and enforces the factorization of the state into definite outcomes compatible with the boundary conditions imposed by the environment. Measurement does not transmit a state to the distant subsystem; rather, it globally redefines the reactive configuration permitted by the vacuum.

The nonlocal correlations observed experimentally and described by Bell inequalities emerge naturally within this framework. These correlations do not require local hidden variables or classical causal mechanisms, but instead reflect the non-factorizability of the shared reactive impedance. As long as this impedance remains common, the Hyliaster describes the system as a single physical state, regardless of the spatial separation of its observable projections.

Consequently, TSI provides a phenomenological interpretation of quantum entanglement that is compatible with relativity and with Bell-type experimental results, in which nonlocality is understood as a global property of the reactive vacuum rather than as instantaneous action at a distance between individual particles.

3.12. *Wavefunction Collapse as Resistive Coupling*

Within the Theory of the Impedance of Spacetime (TSI), wavefunction collapse is not interpreted as an instantaneous or nonlocal process, but as a physical transition induced by the coupling of a quantum system (an excitation of the Hyliaster) to the resistive component of the vacuum and to the observer or measurement apparatus.

As long as the quantum excitation remains dominated by the inductive and capacitive regimes of the vacuum, the system preserves phase coherence and is described by a complex wavefunction. The measurement process introduces an effective resistive coupling R_H, associated with dissipation, loss of coherence, and entropy production.

From a circuit-theoretic viewpoint, the act of observation may be interpreted as the formation of an effective node between the quantum excitation and the measuring system. At this node, Kirchhoff's laws impose a redistribution of phase and energy, thereby breaking the coherent superposition of reactive modes. This process selects a definite observable state and suppresses alternatives that are incompatible with the boundary conditions imposed by the environment.

Phenomenologically, this transition is identified as wavefunction collapse. Within TSI, such collapse does not constitute an additional postulate, but arises as a natural dynamical consequence of the resistive coupling of the vacuum, establishing a direct connection between measurement, irreversibility, and entropy.

3.13. *Oscillatory Cosmological Dynamics and the Arrow of Time: Dark Matter and Dark Energy*

Within the TSI framework, the cosmological evolution of the reactive vacuum (Hyliaster) may be described, to first order and at a phenomenological level, by an effective damped oscillator equation for a global expansion parameter $a(t)$,

$$\ddot{a} + \gamma\,\dot{a} + \Omega_H^2\,a = 0, \tag{72}$$

where Ω_H denotes a cosmological reactive frequency associated with the inductive–capacitive balance of the vacuum, while γ represents an effective dissipative coupling linked to the resistive term R_H of the medium.

Within this scheme, phases of cosmological expansion and contraction correspond to conjugate branches of a global oscillation of the reactive vacuum. The currently observed expansion may be interpreted as a diastolic-like phase of the system, whereas a possible contraction would emerge as a restorative response to the accumulation of reactive imbalance. The resulting dynamics does not necessarily imply an unbounded divergence, but rather favors oscillations around a state of dynamical equilibrium, modulated by dissipation.

3.13.1. The Arrow of Time as a Property of the Vacuum

The presence of a nonvanishing resistive component naturally introduces a preferred temporal orientation for physical processes,

$$R_H > 0 \quad \Longrightarrow \quad \text{temporal asymmetry.} \tag{73}$$

From this perspective, the arrow of time is neither imposed externally nor interpreted solely as a statistical effect, but instead emerges as an intrinsic property of the reactive vacuum. The macroscopic irreversibility observed in thermodynamics, quantum decoherence, and cosmological evolution reflects the microscopic structure of the vacuum itself.

The dissipative term γ introduces effective irreversibility and entropy production, thereby selecting a preferred direction of time. An indefinitely expanding universe would formally correspond to the limit $\gamma \to 0$, which is not physically stable in a realistic reactive medium.

3.14. Black Holes as Impedance Singularities in the TSI

Within the Theory of the Impedance of Spacetime (TSI), black holes are interpreted not as fundamental objects, but as extreme regimes of the reactive vacuum characterized by a divergence in the effective spacetime impedance. The vacuum response is described by the master impedance relation

$$Z(\omega) = R_H + i\left(\omega L_H - \frac{1}{\omega C_H}\right), \tag{74}$$

where L_H, C_H, and R_H represent the inductive, capacitive, and dissipative components of the vacuum, respectively.

A black hole corresponds to a domain in which the inductive contribution dominates,

$$\omega L_H \gg \frac{1}{\omega C_H}, \tag{75}$$

leading to an effectively inductive impedance,

$$Z(\omega) \approx R_H + i\,\omega L_H. \tag{76}$$

In this limit, phase delays diverge and the effective propagation speed of signals tends to zero, producing a causal decoupling between the interior and exterior regions. This behavior is identified with the emergence of an event horizon and the associated freezing of temporal evolution as observed from outside.

The dissipative component R_H becomes relevant near the horizon, providing a natural framework for interpreting black-hole entropy and Hawking-like thermal effects as consequences of irreversible processes in the reactive vacuum. In this sense, black holes appear in the TSI as impedance singularities of the Hyliaster, representing limiting states of spacetime response rather than geometric singularities.

3.14.1. Dark Matter and Dark Energy as Reactive Responses of the Vacuum

Within the TSI framework, dark matter is interpreted as a manifestation of the collective inductive response of the reactive vacuum, modifying gravitational dynamics without the introduction of new particles. Dark energy is associated with a global reactive imbalance, dominated by capacitive and resistive regimes, which manifests as an effective acceleration in cosmological dynamics.

Consequently, the TSI framework favors a damped oscillatory cosmological scenario, in which expansion and contraction can be interpreted as manifestations of the reactive dynamics of the vacuum, while entropy production fixes the global temporal orientation of the cosmological process.

3.15. Entropy as Reactive Decoherence

In conventional statistical mechanics, entropy quantifies the number of microscopic configurations compatible with a macroscopic state. Within the TSI framework, this notion is refined by associating entropy growth with an increase in the effective resistive component of the reactive vacuum. As a system interacts with its environment, phase coherence between the system and the vacuum microstructure is progressively reduced, leading to an irreversible redistribution of energy among the vacuum-supported degrees of freedom. In this way, entropy measures the degree of decoherence and impedance mismatch between localized excitations and the reactive vacuum.

3.16. Matter and Antimatter Within the TSI Framework

Within the framework of the Theory of Spacetime Impedance (TSI), elementary excitations of the reactive vacuum are described by complex states whose dynamics are governed by the master impedance equation. In this context, the phase associated with these excitations acquires direct physical relevance, as it is linked to the inductive, capacitive, and resistive regimes of the medium.

From a phenomenological perspective, a localized excitation of the reactive vacuum may be characterized by a real amplitude A and a phase ϕ, such that its effective state can be represented as

$$\Psi = A\, e^{j\phi}. \tag{77}$$

Within this description, matter and antimatter are not interpreted as ontologically distinct entities, but rather as opposite phase configurations of the same underlying reactive structure. In particular, one may formally identify

$$\Psi_{\mathrm{m}} = A\, e^{+j\phi}, \qquad \Psi_{\mathrm{am}} = A\, e^{-j\phi}, \tag{78}$$

where the subscripts m and am denote configurations associated with matter and antimatter, respectively.

The effective contribution of each configuration may be defined phenomenologically through phase-dependent relative densities,

$$\rho_{\mathrm{m}} = A^2 \cos^2\!\left(\frac{\phi}{2}\right), \qquad \rho_{\mathrm{am}} = A^2 \sin^2\!\left(\frac{\phi}{2}\right), \tag{79}$$

which identically satisfy the conservation condition

$$\rho_{\mathrm{m}} + \rho_{\mathrm{am}} = A^2. \tag{80}$$

This relation expresses that the matter–antimatter asymmetry does not arise from a net creation of physical content, but from a redistribution of phase within the same reactive excitation.

The effective asymmetry may be characterized by the dimensionless parameter

$$\Delta = \frac{\rho_{\mathrm{m}} - \rho_{\mathrm{am}}}{\rho_{\mathrm{m}} + \rho_{\mathrm{am}}} = \cos\phi, \tag{81}$$

which depends solely on the phase imbalance. Within this framework, a slight deviation of the phase from a symmetric value can naturally lead to the effective dominance of one configuration over the other.

From the TSI perspective, the physical origin of this imbalance is associated with the reactive–dissipative term R_H in the master impedance equation. This term introduces irreversibility, loss of coherence, and an effective arrow of time, allowing small initial phase fluctuations to be dynamically amplified. As a result, the system may evolve toward a stable state characterized by a dominant phase configuration, without the need to invoke explicit fundamental symmetry violations or the introduction of exotic particles or fields.

It is important to emphasize that this formulation does not constitute a complete quantitative model of baryogenesis, nor does it aim to reproduce directly the observed cosmological values. Its purpose is to illustrate that, within the phenomenological framework of TSI, the matter–antimatter asymmetry problem admits a natural reformulation in terms of phase dynamics and reactive vacuum impedance. In this sense, the observed asymmetry may be interpreted as an emergent manifestation of the reactive and dissipative structure of spacetime, rather than as a fundamental microscopic symmetry breaking.

3.17. Space and Time in the Theory of Spacetime Impedance

This formulation is not intended to replace the geometric description provided by general relativity, but rather to offer a complementary phenomenological framework in which the metric properties of spacetime can be understood as effective limits of a more fundamental reactive dynamics. In this sense, the Theory of Spacetime Impedance (TSI) provides a structural reinterpretation of space and time that remains compatible with established theories, while being formulated in terms of impedance, response, and vacuum coherence.

Within the TSI framework, space and time are not introduced as primitive geometric entities, but instead emerge as manifestations of the dynamical response of the vacuum, operationally characterized by its frequency-dependent impedance,

$$0 \equiv Z(\omega). \tag{82}$$

Time.

Time is interpreted as the result of a phase delay induced by the inductive response of the vacuum. In particular, the inductive component of the impedance introduces a form of dynamical memory that manifests physically as temporal ordering, causality, and time dilation. From this perspective, time does not flow as an absolute parameter, but emerges as a dynamical effect associated with the vacuum phase and its response to energetic excitations.

Space.

Space, in turn, is identified with the vacuum's capacity to support coherent propagation of excitations. This property is associated with the capacitive component of the impedance, which governs polarization and transverse propagation of disturbances. Spatial extension is therefore not conceived as a static container, but as an emergent property of the reactive vacuum that enables the transmission of energy and information between distinct regions.

Spacetime Unification.

The spacetime structure arises from the inseparable coexistence of both responses. In TSI, spacetime is interpreted as the joint manifestation of the vacuum's propagation capability (capacitive component) and phase delay (inductive component). The relativity of space and time thus emerges naturally as a consequence of variations in the reactive response of the vacuum, without the need to introduce independent geometric postulates.

From this viewpoint, space and time are not fundamental entities, but complementary projections of a single physical substrate: the reactive vacuum, whose dynamics are fully characterized by its complex impedance.

3.18. Derivation of the Schrödinger Equation as a Slow–Envelope Limit of the TSI Master Equation

In the Theory of Spacetime Impedance (TSI), the reactive vacuum is described by the master impedance relation

$$Z_H(\omega) = R_H + i\left(\omega L_H - \frac{1}{\omega C_H}\right). \tag{83}$$

The non-dissipative (coherent) quantum regime corresponds to the limit $R_H \to 0$, for which the dynamics is dominated by the reactive phase term. In this regime, each effective microcell behaves as an LC resonator with characteristic carrier frequency

$$\omega_0^2 = \frac{1}{L_H C_H}. \tag{84}$$

Consistently, the propagation speed of vacuum excitations satisfies the transmission-line form

$$c = \frac{1}{\sqrt{L_H C_H}}. \tag{85}$$

To connect the master reactive structure with a wave description, we introduce a complex field $\Psi(\mathbf{x}, t)$ representing the coherent phase-amplitude state of an excitation supported by the reactive vacuum. The simplest effective continuum equation that captures both (i) finite propagation with speed c and (ii) an intrinsic carrier oscillation at ω_0 is a Klein–Gordon-type relation,

$$\frac{1}{c^2}\frac{\partial^2\Psi}{\partial t^2} - \nabla^2\Psi + \frac{\omega_0^2}{c^2}\Psi = 0, \tag{86}$$

which may be interpreted here as an envelope-compatible description of the collective reactive phase dynamics in the coherent limit of Equation (83).

The key step is to separate the fast carrier oscillation from the slow envelope dynamics by the factorization

$$\Psi(\mathbf{x},t) = \psi(\mathbf{x},t)\, e^{-i\omega_0 t}, \tag{87}$$

where ψ varies slowly compared to the carrier. Substituting Equation (87) into Equation (86) yields

$$\frac{1}{c^2}(\psi_{tt} - 2i\omega_0\psi_t) - \nabla^2\psi = 0, \tag{88}$$

after cancellation of the ω_0^2 terms. In the non-relativistic envelope limit, the slow-variation condition $|\psi_{tt}| \ll \omega_0|\psi_t|$ allows us to neglect ψ_{tt}, giving

$$i\,\psi_t = -\frac{c^2}{2\omega_0}\nabla^2\psi. \tag{89}$$

Multiplying by $\hbar$ and identifying the carrier energy with the rest energy,

$$E_0 = \hbar\omega_0 = mc^2, \tag{90}$$

Equation (89) reduces to the Schrödinger equation,

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi. \tag{91}$$

A slowly varying effective potential can be incorporated as a local detuning of the carrier frequency, $\omega_0 \to \omega_0 + \delta\omega(\mathbf{x})$, which introduces

$$V(\mathbf{x}) = \hbar\,\delta\omega(\mathbf{x}), \tag{92}$$

leading to the standard form

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\psi + V(\mathbf{x})\psi. \tag{93}$$

In summary, within the TSI interpretation the Schrödinger wavefunction ψ represents the slow phase–amplitude modulation (envelope) of a fast carrier oscillation at ω_0 supported by the reactive vacuum microstructure. The speed of light does not disappear; it is absorbed into the carrier through $\hbar\omega_0 = mc^2$, while the observable non-relativistic dynamics is governed by the envelope equation (93).

3.19. Effective Inductive Metric in the Weak-Field Limit

In the weak-field limit, general relativity describes gravitation through a nearly flat metric

$$g_{\mu\nu} \;=\; \eta_{\mu\nu} + h_{\mu\nu}, \qquad |h_{\mu\nu}| \ll 1, \tag{94}$$

where $\eta_{\mu\nu} = \mathrm{diag}(-1,1,1,1)$. Within the framework, the phenomenological interpretation associates the gravitational field with an effective inductive perturbation of the reactive vacuum. We define a dimensionless *gravitational inductive susceptibility* as

$$\chi_g(\mathbf{r}) \;\equiv\; \frac{\Delta L_g(\mathbf{r})}{L_H}, \qquad |\chi_g| \ll 1, \tag{95}$$

where L_H denotes the effective vacuum inductance and $\Delta L_g(\mathbf{r})$ its perturbation induced by the mass–energy distribution.

Under this hypothesis, the effective metric can be written, to first order, in a form analogous to the Newtonian weak-field metric by identifying

$$\frac{\Phi(\mathbf{r})}{c^2} \equiv \frac{1}{2}\chi_g(\mathbf{r}) = \frac{1}{2}\frac{\Delta L_g(\mathbf{r})}{L_H}, \tag{96}$$

where $\Phi(\mathbf{r})$ is the effective gravitational potential. With this identification, one obtains

$$\begin{aligned} ds^2 &= -c^2\big(1+\chi_g(\mathbf{r})\big)dt^2 + \big(1-\chi_g(\mathbf{r})\big)\delta_{ij}\,dx^i dx^j & (97)\\ &\equiv -c^2\left(1+\frac{2\Phi(\mathbf{r})}{c^2}\right)dt^2 + \left(1-\frac{2\Phi(\mathbf{r})}{c^2}\right)\delta_{ij}\,dx^i dx^j, & (98)\end{aligned}$$

which formally coincides with the standard weak-field expression in general relativity.

In this formulation, the physical content of the approximation is as follows: (i) the temporal component g_{00} encodes the local inductive increase of the vacuum, associated with temporal gradients and time dilation; (ii) the spatial corrections g_{ij} reflect the reactive adjustment of the medium in propagation and effective geometry. Equation (97) should be understood as a phenomenological representation: it reproduces the weak-field limit and provides an interpretation in terms of the average inductive response of the Hyliaster, without aiming to replace the complete geometric formulation of general relativity.

4. Predictions

Within the framework of the Theory of the Impedance of Spacetime (TSI), several testable and conceptually unifying predictions naturally emerge from the interpretation of the vacuum as a reactive medium characterized by inductive, capacitive, and dissipative responses.

Prediction 1: Emergent Nature of Vacuum Constants

The TSI predicts that the fundamental electromagnetic constants of the vacuum, namely the vacuum impedance Z_0, the permittivity ε_0, and the permeability μ_0, are not independent fundamental parameters but emergent quantities arising from stability and propagation conditions of the reactive vacuum. As a consequence, these constants should exhibit structural correlations reflecting the underlying impedance balance of spacetime rather than arbitrary numerical values.

Prediction 2: Inductive Interpretation of Gravitation

Gravitation is interpreted as an inductive response of spacetime associated with collective phase retardation in the vacuum medium. The TSI therefore predicts that gravitational phenomena may exhibit inductive-like features such as history dependence, phase delay, and memory effects in dynamical gravitational systems, particularly in regimes involving strong time-dependent fields.

Prediction 3: Dark Matter as an Effective Inductive Contribution of the Vacuum

The TSI predicts that phenomena commonly attributed to dark matter emerge in regimes where the inductive response of the reactive vacuum is dominant. In the presence of large mass distributions, the effective inductive term ωL_H introduces an additional contribution to gravitational dynamics, modifying the observed centripetal acceleration in bound systems without requiring the existence of non-baryonic matter.

In this regime, the effective gravitational acceleration acquires a contribution associated with the spatial variation of the inductive reactance of the vacuum, which manifests observationally as anomalous galactic rotation curves. From this perspective, dark matter corresponds to a dynamical effect associated with the inductive regime of the reactive vacuum.

Prediction 4: Dark Energy as a Capacitive Cosmological Response of the Vacuum

The TSI predicts that the accelerated expansion of the Universe is associated with a regime in which the capacitive response of the reactive vacuum is dominant. At cosmological scales, the effective term $1/(\omega C_H)$ produces a negative-pressure contribution to space–time dynamics, resulting in a global acceleration of cosmic expansion.

In this regime, dark energy is not interpreted as a fundamental cosmological constant, but as the macroscopic manifestation of energy stored in the effective capacitance of the vacuum. The TSI therefore predicts that cosmic acceleration depends on the dynamical properties of the reactive vacuum and may exhibit a slow evolution linked to the expansion history of the Universe.

Prediction 5: Casimir Effect as Evidence of Vacuum Reactivity

The Casimir effect is interpreted as a direct manifestation of the reactive nature of the vacuum, arising from impedance imbalances induced by boundary conditions. The TSI predicts that modifications of vacuum boundary constraints should systematically alter Casimir-like forces, reinforcing the view of the vacuum as a structured medium with physically meaningful response properties.

5. Discussion

The results presented in this work support a unified phenomenological reinterpretation of several foundational domains of physics within the Theory of Space–Time Impedance (TSI). By modeling the vacuum as a reactive medium endowed with an effective *quantum RLC triad* (L_K, C_K, R_K), TSI provides a common structural language in which gravitational, electromagnetic, quantum, relativistic, and thermodynamic phenomena emerge as distinct response regimes of a single underlying substrate.

A central organizing principle of the framework is that different physical behaviors arise from the relative dominance of the inductive, capacitive, and resistive components of the reactive vacuum. A predominantly inductive response is associated with gravitational phenomena, where the vacuum exhibits inertial and memory-like properties that manifest, in the classical limit, as long-range gravitational coupling. Conversely, a predominantly capacitive response leads naturally to electromagnetic behavior, characterized by energy storage, polarization, and wave propagation governed by Maxwell's equations and by the vacuum impedance as a structural parameter.

The regime in which inductive and capacitive responses are balanced plays a distinguished role within TSI. In this resonant condition, the reactive vacuum supports stable oscillatory modes, discrete characteristic frequencies, and phase-coherent dynamics. From this perspective, quantum mechanics may be interpreted as the resonant regime of the reactive vacuum, where energy exchange between inductive and capacitive sectors becomes quantized and coherence is maintained over finite timescales.

When the full quantum RLC structure is considered, including the coexistence of inductive, capacitive, and resistive responses, the framework becomes naturally compatible with relativistic constraints. Finite signal propagation, the invariance of the speed of light, and causal structure emerge as global properties of a reactive medium with well-defined impedance, rather than as independent geometric postulates.

The resistive component R_K plays a crucial role in introducing irreversibility. At microscopic scales, it governs decoherence, spectral stability, and the effective collapse of quantum states, while at macroscopic and cosmological scales it underlies entropy production and the arrow of time. Thermodynamics thus appears as an intrinsic sector of the same reactive structure, rather than as an external or emergent add-on.

In this sense, TSI does not aim to replace established theories, but to organize them within a coherent phenomenological framework based on the reactive properties of the vacuum. The traditional separation between gravitation, electromagnetism, quantum mechanics, relativity, and thermodynamics is reinterpreted as a classification of limiting response regimes of a single physical medium. This unifying perspective highlights deep structural connections among fundamental phenomena without introducing new ontological entities or modifying experimentally established formalisms.

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6. Conclusions

In this work, the vacuum has been explored from a phenomenological perspective as a distributed reactive medium described by an effective RLC structure. Within the framework of the Theory of Spacetime Impedance (TSI), inductive, capacitive, and resistive responses are treated as fundamental descriptors of vacuum dynamics rather than as auxiliary mathematical constructs. This viewpoint provides a unified language in which electromagnetism, gravitation, quantum dynamics, thermodynamics, and cosmology can be interpreted as different regimes of a single reactive substrate.

A central result of the present analysis is the identification of a quantum RLC triad (R_K, L_K, C_K) associated with the vacuum. The quantum inductance and capacitance fix natural temporal and impedance scales linked to the Compton length, while the quantum resistance introduces an intrinsic scale associated with irreversibility and quantization. Together, these elements allow several fundamental constants—such as the vacuum impedance, the fine-structure constant, and the quantum of action—to be reinterpreted as emergent quantities arising from the reactive structure of spacetime, rather than as independent postulates.

At cosmological scales, the same framework leads to a consistent reinterpretation of the cosmological constant as a manifestation of a capacitive-dominated regime of the reactive vacuum. The appearance of factors such as c^2 and π is naturally understood in terms of the electromagnetic constitutive properties and the distributed oscillatory character of the medium. While the cosmological term itself is purely reactive, the inclusion of a resistive component in the TSI master equation provides a phenomenological mechanism for irreversibility and the emergence of a macroscopic arrow of time.

It is important to emphasize that the TSI does not aim to replace established theories nor to derive fundamental constants from first principles. Instead, it offers a coherent phenomenological framework that reorganizes known physical relations under a common impedance-based interpretation. By doing so, it highlights structural connections between classical and quantum descriptions and suggests new ways of interpreting long-standing problems, such as vacuum energy and the role of dissipation in cosmological dynamics.

Future work may explore the quantitative consequences of this framework in more detail, including possible observational signatures of reactive vacuum regimes, refinements of the closure relations for vacuum energy density, and extensions to nonlinear or nonequilibrium settings. In this sense, the Theory of Spacetime Impedance provides not a final theory, but a structured and physically motivated language for further investigation of the vacuum as an active participant in fundamental physics.

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Abbreviations

The following abbreviations are used in this manuscript:

AM	Amplitude Modulation
CH	Effective capacitance of the reactive vacuum
CK	Quantum capacitance of the vacuum (TIET)
EM	Electromagnetism
GR	General Relativity
LH	Effective inductance of the reactive vacuum
LK	Quantum inductance of the vacuum (TIET)
QED	Quantum Electrodynamics
QFT	Quantum Field Theory
RH	Resistive term of the reactive vacuum
RK	Quantum resistance (von Klitzing resistance)
RLC	Resistor–Inductor–Capacitor structure
SSB	Single-Sideband Modulation
TIET	Teoría de la Impedancia del Espacio–Tiempo
TSI	Theory of Spacetime Impedance
$Z(\omega)$	Frequency-dependent spacetime impedance (TSI master impedance)
Z_0	Vacuum impedance (free-space impedance)
Z_H	Impedance of the reactive vacuum
Z_K	Quantum impedance of a reactive-vacuum cell
c	Speed of light in vacuum
μ_0	Vacuum permeability
ε_0	Vacuum permittivity
α	Fine-structure constant
$\hbar$	Reduced Planck constant
Λ	Cosmological constant
ω_0	Characteristic (carrier) angular frequency of the reactive vacuum

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