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Article

Gravitational-Wave–Induced Coherence Effects in Extreme Regimes: A Phenomenological Exploration

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Abstract

This work presents a phenomenological exploration of coherence-related effects induced by intense gravitational-wave environments within the framework of the Unified Theory of Informational Spin (TGU). Rather than claiming observational detection or confirmed matter creation, the study investigates a hypothetical mechanism by which strong, non-linear spacetime perturbations may drive localized departures from linear gravitational regimes, giving rise to effective coherence gradients. A simplified toy model is introduced to describe how extreme gravitational-wave excitation could correlate with geometric indicators of regime validity, without modifying gravitational-wave propagation or source dynamics. The analysis is explicitly limited to exploratory regimes and does not assert direct correspondence with current gravitational-wave detections. Instead, it aims to assess internal consistency, qualitative behavior, and limiting properties of coherence-based diagnostics under sustained non-linearity. The framework is constructed to converge exactly to General Relativity in weak-field and linear regimes, while allowing controlled deviations only at the level of regime characterization. In this context, coherence indicators are shown to act as diagnostic tools that may signal inference degeneracies when standard linearized gravitational-wave templates are applied beyond their domain of validity. The phenomenological descriptors employed in this study are not introduced as independent model parameters, but are inherited as diagnostic proxies from the broader geometric framework of the Unified Theory of Informational Spin, where coherence-related quantities arise from fixed normalization conditions and vanish identically in linear gravitational regimes. The results motivate future, fully reproducible studies using public gravitational-wave datasets and provide a structured phenomenological basis for exploring regime-aware inference methods, without introducing exotic matter fields, modifying propagation laws, or violating established conservation principles (LIGO–Virgo–KAGRA Collaboration, 2023) [2].

Keywords: gravitational waves; matter creation; informational coherence; TGU; dark matter; spin network

Statement of Changes from Version v1

This manuscript represents a substantial conceptual and epistemological revision relative to Version v1 of this work. Earlier exploratory formulations investigated the speculative possibility that extreme gravitational-wave environments could catalyze matter-generation mechanisms within the Unified Theory of Informational Spin (TGU). While that hypothesis served as an initial motivation, it was not supported by sufficient observational, numerical, or theoretical constraints to justify causal claims.

In the present version, the scope has been deliberately narrowed and reformulated. The focus is shifted away from matter creation or particle genesis and toward a conservative, phenomenological analysis of regime-dependent inference effects in gravitational-wave physics. Coherence-related quantities are no longer treated as dynamical agents but as geometric diagnostic descriptors indicating departures from linear perturbative regimes.

Key changes include:

- Removal of claims regarding gravitational-wave-induced matter creation or particle genesis.
- Reinterpretation of coherence as an operational, geometry-based proxy rather than a physical field or source of new degrees of freedom.
- Explicit enforcement of convergence with General Relativity in all linear and weak-field regimes.
- Emphasis on diagnostic inference degeneracies, such as amplitude and polarization biases, rather than on direct physical observables.
- Clarification that phenomenological parameters (e.g., α) are inherited from the geometric normalization of the broader TGU framework and are not introduced as free or fitted quantities within this study. (Matuchaki, 2025) [6].

These revisions position the present work as a conservative, falsifiable exploration of regime awareness in gravitational-wave analysis, fully compatible with null observational outcomes and without asserting new physics beyond established gravitational theory.

1. Introduction

The observation of gravitational waves has provided direct access to dynamical regimes of space-time characterized by strong curvature, rapid temporal variation, and intrinsically non-linear behavior. While General Relativity (GR) has demonstrated remarkable predictive power in describing both the generation and propagation of gravitational waves, most observational analyses rely fundamentally on linearized or perturbative formulations defined over a background geometry (Abbott et al., 2016) [1].

This reliance is fully justified in the regimes currently probed by gravitational-wave detectors, where spacetime perturbations remain small at asymptotic distances and the separation between background and fluctuation is well defined. However, from a theoretical standpoint, the question of how to characterize the boundaries of validity of linearized descriptions in extreme gravitational environments remains open. This question does not challenge the correctness of GR itself, but rather concerns the applicability of specific approximation schemes within it.[2]

The present work addresses this issue by introducing a geometrically grounded, operational descriptor designed to quantify the degree to which spacetime dynamics admit a stable linearized representation. This descriptor, referred to here as *coherence*, is not proposed as a new physical field, interaction, or conserved quantity. Instead, it functions as a scalar indicator of regime validity, measuring the relative dominance of perturbative dynamics versus intrinsic spacetime curvature.

Within this framework, coherence does not modify Einstein's equations, nor does it alter gravitational-wave propagation. Rather, it provides a compact and invariant way to characterize transitions between regimes where linear perturbation theory is sufficient and regimes where non-linear geometric effects become non-negligible. In this sense, coherence plays a role analogous to dimensionless parameters used elsewhere in physics to demarcate the limits of approximation schemes, such as Reynolds numbers in fluid dynamics or Knudsen numbers in kinetic theory.

The conceptual motivation for this approach is aligned with the broader Unified Theory of Informational Spin (TGU), in which coherence appears as an emergent organizational descriptor across gravitational, quantum, and cosmological systems. In the present article, however, coherence is employed in a strictly conservative and geometric sense. No assumptions are made regarding microscopic informational substrates, discrete spacetime structure, or new degrees of freedom. All constructions remain fully embedded within classical General Relativity(Matuchaki, 2025) [6].

A central objective of this work is therefore not to predict new observables, but to assess internal consistency and limiting behavior. Specifically, we investigate whether intense and sustained gravitational-wave excitation could, in principle, be associated with localized departures from the regime where linearized gravitational dynamics provide an adequate description. Any such departures are interpreted purely as indicators of approximation breakdown, not as physical instabilities, matter creation mechanisms, or violations of conservation laws.

To explore this question, we introduce a phenomenological but geometrically defined coherence proxy derived from curvature invariants and perturbative gradients. A simplified toy model is then employed to examine qualitative behavior under idealized extreme conditions. The model is explicitly restricted to exploratory purposes and is not calibrated against observational data.

Crucially, the framework is constructed to converge exactly to standard General Relativity in weak-field and linear regimes. All coherence-related effects vanish smoothly as curvature invariants decrease, ensuring full compatibility with the extensive body of experimental and observational tests supporting GR.

The structure of this paper is as follows. Section 2 reviews the standard gravitational-wave formalism in General Relativity, establishing the baseline against which regime validity is assessed. Section 3 introduces the geometric definition of coherence and its interpretation as a measure of linearization validity. Section 4 presents illustrative results demonstrating qualitative behavior in extreme strain environments. Section 5 discusses limitations, falsifiability, and observational outlook, emphasizing the conservative and non-assertive nature of the approach.

By maintaining a strict separation between geometry, phenomenology, and interpretation, this work aims to clarify how coherence-based descriptors may serve as useful analytical tools for probing the boundaries of linear gravitational dynamics—without proposing new physics, modifying General Relativity, or asserting observational claims beyond current empirical reach.

2. Gravitational-Wave Background in General Relativity

In General Relativity, gravitational waves arise as propagating perturbations of the spacetime metric around a background geometry that satisfies Einstein's field equations. In regimes where spacetime curvature explains the dominant dynamics and perturbations remain small, the metric can be expressed as

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu},$$

where $g_{\mu\nu}^{(0)}$ denotes a background solution and $h_{\mu\nu}$ represents a weak perturbation.[1]

Under the linearized approximation and in the absence of strong backreaction, the perturbations satisfy a wave equation on the background spacetime. In vacuum and in transverse-traceless gauge, this reduces to a set of propagating tensor modes traveling at the speed of light. This framework has been extensively validated by gravitational-wave observations and forms the operational baseline for all analyses presented in this work. [1,2]

It is important to emphasize that this linearized treatment remains valid only as long as the perturbations do not induce sustained non-linear deformation of the background geometry. In astrophysical scenarios involving compact binaries observed at asymptotic distances, this condition is well satisfied, and General Relativity provides an accurate and complete description of the observed signals.

However, in environments characterized by persistent and intense spacetime strain, such as regions of prolonged gravitational-wave interaction or strong coupling with matter fields, the separation between background and perturbation may become less sharply defined. While General Relativity itself remains valid, additional effective descriptions may become useful to characterize emergent structural behavior without modifying the underlying theory.

The present study does not seek to alter the gravitational-wave formalism of General Relativity. Instead, it adopts the standard GR description as a reference framework against which phenomenological coherence-related effects are evaluated. Any deviation discussed in subsequent sections is constructed to vanish smoothly in the weak-field and linear limits, ensuring exact convergence with GR where its applicability is empirically established.

This section therefore serves solely to define the conventional gravitational-wave baseline and the regime of linear validity, providing a consistent point of comparison for the exploratory phenomenological model introduced in the following section.

3. Phenomenological Coherence Model

Within the Unified Theory of Informational Spin (TGU), coherence is treated as an effective organizational property that characterizes the degree to which a physical system admits a stable, approximately linear description. In this work, coherence is not introduced as a fundamental field or conserved quantity, but rather as an operational proxy used to parameterize departures from linear gravitational behavior under extreme conditions (Matuchaki, 2025) [6].

To explore this idea in the context of intense gravitational-wave environments, we introduce a simplified phenomenological model designed to capture qualitative trends rather than quantitative predictions. The model is explicitly restricted to exploratory purposes and is not derived from first principles. Its primary role is to assess internal consistency, regime dependence, and limiting behavior within a coherence-based extension of gravitational dynamics.

We define an operational coherence proxy $\mathcal{C}$, which characterizes the effective stability of space-time dynamics in a given region. In linear and weak-field regimes, $\mathcal{C}$ remains close to a reference value corresponding to standard General Relativity. Under sustained non-linear excitation, however, $\mathcal{C}$ may experience localized reductions, hereafter referred to as coherence deficits. These deficits do not imply negative energy densities or violations of conservation laws, but rather signal the breakdown of a purely linear approximation.

To model the spatial response of coherence under extreme gravitational-wave excitation, we adopt a simple attenuation ansatz of the form

$$\mathcal{C}(r) = \mathcal{C}_0 \exp(-\alpha r^2),$$

where r denotes a characteristic distance from the region of maximum strain, $\mathcal{C}_0$ is the reference coherence level, and α is a phenomenological parameter controlling the spatial extent of coherence loss. This functional form is not unique and should be interpreted as a coarse-grained description analogous to diffusive or decoherence processes in effective media (Zurek, 2003) [5].

The parameter α is treated as phenomenological and environment-dependent. No claim is made regarding its universality or microscopic origin. Importantly, the model is constructed such that coherence deficits remain localized and vanish smoothly as the system approaches the linear regime, ensuring exact convergence with General Relativity in weak-field conditions.

In this framework, coherence deficits act as indicators of regime transition rather than as sources of new fundamental interactions. The model does not predict the creation of real particles or matter fields, nor does it introduce additional degrees of freedom beyond those already present in the gravitational-wave background. Any effective instability discussed in subsequent sections should therefore be interpreted as a transient, phenomenological feature associated with sustained non-linearity.

This phenomenological approach aligns with the broader structure of the TGU, in which coherence-related effects emerge selectively when systems depart from linear behavior and remain suppressed elsewhere. The following section applies this model illustratively to extreme gravitational-wave scenarios, emphasizing qualitative behavior and consistency with established physical limits. [6]

4. Geometric Definition of Coherence and Regime Validity

In the present work, the concept of coherence is not introduced as a fundamental physical field, nor as an independent dynamical degree of freedom. Instead, coherence is defined operationally as a geometric indicator of the local validity of linearized gravitational dynamics. This definition is motivated by the observation that General Relativity admits multiple equivalent descriptions depending on whether spacetime dynamics are treated in linearized or fully non-linear form.

In standard gravitational-wave analyses, the metric is decomposed as

$$g_{\mu\nu} = g_{\mu\nu}^{(0)} + h_{\mu\nu},$$

where $g_{\mu\nu}^{(0)}$ is a background solution and $h_{\mu\nu}$ represents perturbative deviations. This separation is well defined only as long as the perturbations remain small compared to the geometric curvature scales of the background. When this condition is violated, the linear approximation ceases to provide an adequate description, even though the underlying theory of General Relativity remains valid.[1]

Within this context, coherence is introduced as a scalar, dimensionless measure of the degree to which spacetime dynamics admit a stable linearized representation.[5]

4.1. Coherence as a Measure of Linearization Validity

We define the operational coherence proxy $\mathcal{C}(x)$ at a spacetime point x as an inverse measure of the relative dominance of non-linear curvature effects over perturbative dynamics:

$$\mathcal{C}(x) \equiv \left(\frac{\|\nabla^2 h_{\mu\nu}(x)\|}{\|R_{\mu\nu\rho\sigma}(x)\|} \right)^{-1}$$

where $\nabla^2 h_{\mu\nu}$ characterizes second-order variations of the perturbative metric components and $R_{\mu\nu\rho\sigma}$ is the Riemann curvature tensor associated with the full spacetime geometry. Norms are taken in an invariant, coordinate-independent manner.

This definition assigns high coherence ($\mathcal{C} \gg 1$) to regions where perturbative dynamics dominate and the linearized description is robust, and low coherence ($\mathcal{C} \lesssim 1$) to regions where background curvature effects become comparable to or exceed perturbative contributions. Importantly, this definition does not introduce new physical fields, nor does it alter Einstein's equations; it merely quantifies the regime of applicability of linearized General Relativity.[1]

4.2. Geometric Origin of Spatial Coherence Profiles

In strongly curved but approximately isotropic environments, such as localized regions near extreme gravitational-wave sources, the spatial variation of curvature invariants can be expanded to second order around a point of maximal strain. Under these conditions, the leading-order solution of the corresponding geometric attenuation equation admits a Gaussian profile:

$$\mathcal{C}(r) \approx \mathcal{C}_0 \exp\left(-\frac{r^2}{\ell_c^2}\right),$$

where r is a characteristic radial distance from the region of maximal curvature and ℓ_c is a coherence length scale defined by curvature invariants,

$$\ell_c^{-2} \sim \langle R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \rangle.$$

In this formulation, the Gaussian form is not postulated as a fundamental law but arises as an effective description of coherence attenuation in regimes where curvature gradients are smooth and localized. The parameter governing the decay is therefore not arbitrary, but is directly tied to invariant geometric quantities of the spacetime.

4.3. Absence of Circularity and Physical Interpretation

It is crucial to emphasize that coherence is not defined by stability, nor is instability defined by coherence loss. Instead, coherence quantifies the degree to which a perturbative, linearized description remains geometrically valid. Instability, in this framework, refers to the breakdown of a specific approximation scheme, not to the emergence of new physical processes, matter creation, or violations of conservation laws.

Accordingly, coherence deficits should be interpreted as markers of regime transition rather than as physical instabilities or sources of new dynamics. The underlying spacetime continues to obey Einstein's equations at all times.

4.4. Limiting Behavior and Convergence with General Relativity

By construction, the coherence proxy satisfies

$$\lim_{\|R_{\mu\nu\rho\sigma}\| \rightarrow 0} \mathcal{C}(x) \rightarrow \infty,$$

ensuring exact convergence with linearized General Relativity in weak-field regimes. Conversely, in regions where curvature invariants grow large, coherence decreases smoothly without exhibiting singular or divergent behavior.

This guarantees that the framework does not introduce discontinuities, exotic fields, or ad hoc modifications to gravitational-wave propagation. Instead, it provides a controlled and geometrically grounded way to characterize the boundaries between linear and strongly non-linear gravitational regimes.

4.5. Relation to the Unified Theory of Informational Spin

Within the broader context of the Unified Theory of Informational Spin, coherence is interpreted as an emergent organizational descriptor that appears consistently across gravitational, quantum, and cosmological systems. In the present work, however, coherence is employed in a strictly operational and geometric sense, without invoking microscopic informational substrates or ontological claims.[6]

This restrained usage ensures compatibility with conservative physical interpretations while remaining aligned with the structural principles of the TGU, in which coherence-related effects emerge selectively and remain suppressed in regimes where standard theories provide accurate descriptions.

4.6. Relation to the Unified Theory of Informational Spin

The phenomenological constructions employed in the present work are not introduced as independent or ad hoc modifications of gravitational dynamics. Instead, they should be understood as a restricted, diagnostic application of concepts already established within the broader framework of the Unified Theory of Informational Spin (TGU).

In the TGU, coherence is not postulated as a new physical field, nor as an additional dynamical degree of freedom. Rather, it emerges as an effective geometric descriptor associated with the stability of linearized representations of spacetime dynamics. Within that framework, deviations from linear behavior are parameterized through dimensionless geometric efficiency factors derived from the normalization of a three-dimensional coherent spin field.

In particular, the coherence attenuation parameter commonly denoted by α in the present work is not a freely adjustable quantity. In the foundational formulation of the TGU, this parameter arises from geometric considerations and is expressed as

$$\alpha = 1 + k \cdot \frac{e}{a},$$

where e and a denote orbital eccentricity and semi-major axis, respectively, and $k \approx 0.0881$ is a dimensionless geometric constant (the Matuchaki parameter) fixed by normalization conditions of the coherent spin structure. This construction ensures that coherence-related effects vanish smoothly in the limit of circular or weakly perturbed systems, guaranteeing exact convergence with General Relativity in linear regimes.[6]

Here, the parameter α is treated phenomenologically within the scope of this work, acting as an effective geometric indicator of regime departure, while its underlying normalization and geometric origin are defined in the broader TGU framework.

In the context of the present gravitational-wave study, α is not employed as a dynamical coupling or correction to the propagation equations. Instead, it is treated as an effective diagnostic proxy, inherited from the TGU framework, whose role is to characterize the proximity of a given system to the breakdown of linearized inference assumptions. No claim is made that α modifies the generation, propagation, or polarization content of gravitational waves themselves.

Accordingly, the use of coherence-related descriptors in this work should be interpreted as a regime-aware diagnostic tool rather than as a proposal for new gravitational physics. The phenomenological models introduced here are designed to explore internal consistency, limiting behavior, and inference robustness under extreme curvature conditions, while remaining fully compatible with the established predictions of General Relativity.

This restricted application preserves the conceptual separation between the broader ontological program of the TGU and the narrowly defined goals of the present study. Acceptance of the results presented here does not require endorsement of the full TGU framework; conversely, the validity of the TGU does not depend on the phenomenological constructions explored in this article.

5. Phenomenological Modeling of Coherence Response

5.1. Operational Coherence Modulation

In the present framework, gravitational-wave propagation itself is not modified with respect to the predictions of General Relativity. Instead, we introduce a phenomenological description of how an operational coherence proxy associated with the surrounding environment may respond to sustained spacetime strain.

To illustrate this response, we consider a simplified spatial modulation of the coherence proxy in the form

$$\mathcal{C}(r, t) = \mathcal{C}_0 \cos\left(\frac{2\pi r}{\lambda} - \omega t\right) \exp(-\alpha r^2),$$

where $\mathcal{C}_0$ denotes a reference coherence level, λ and ω characterize the dominant length and time scales of the excitation, and α is a phenomenological parameter controlling the spatial extent of coherence attenuation.

This expression does not represent a physical decay of the gravitational-wave amplitude. Rather, it serves as a toy ansatz describing how coherence-related descriptors may become spatially localized in extreme, non-linear environments. The exponential factor is introduced as a coarse-grained representation of coherence loss analogous to diffusive or decoherence processes in effective media (Zurek, 2003) [5].

5.2. Effective Stability Indicator

Within this phenomenological context, it is useful to define an effective stability indicator Σ_{eff} associated with the coherence proxy,

$$\Sigma_{\text{eff}}(r) = \Sigma_0 \exp(-\alpha r^2),$$

where Σ_0 represents a reference stability level in the linear regime. This quantity does not correspond to an energy density or to any conserved physical field. Instead, it functions as an operational marker indicating the degree to which a local region admits a stable, approximately linear description.

Threshold values of Σ_{eff} are not interpreted as physical phase transitions or particle-creation conditions. Rather, they are employed illustratively to delineate the boundary between linear and strongly non-linear regimes within the model. No claim is made regarding the generation of real matter, violation of conservation laws, or emergence of new degrees of freedom.

5.3. Model Parameters and Scope

The parameters α , λ , and ω appearing in the model are treated as phenomenological descriptors without assumed universality. They are not derived from first principles and are not calibrated against observational gravitational-wave data in this work. Their role is limited to exploring qualitative behavior and regime dependence under controlled, idealized conditions.

Any future attempt to constrain such parameters would require fully reproducible analyses based on public datasets and explicit environmental modeling. The present study deliberately refrains from such calibration in order to preserve its exploratory and conservative character.

Overall, this phenomenological modeling approach is constructed to ensure exact convergence with General Relativity in linear regimes while allowing coherence-related descriptors to become relevant only in environments characterized by sustained non-linearity. The model is therefore intended as a qualitative tool for investigating regime transitions rather than as a source of quantitative predictions.

It is emphasized that the phenomenological use of α in this section does not imply an adjustable or fitted parameter, but a diagnostic proxy inherited from the geometric structure of the TGU and employed here without calibration to observational data.

6. Illustrative Results and Qualitative Behavior

In this section, we present illustrative results obtained from the phenomenological coherence model introduced above. These results are not intended to provide quantitative predictions or to establish observational correspondence with existing gravitational-wave detections. Instead, they serve to highlight qualitative trends, limiting behavior, and internal consistency under extreme spacetime strain.

The analysis considers idealized gravitational-wave environments characterized by sustained non-linear excitation over a localized region. Such conditions are not representative of typical gravitational-wave observations at asymptotic distances, but are introduced here as controlled scenarios to probe the response of the operational coherence proxy defined in Section 3.

Within this setting, the coherence proxy $\mathcal{C}(r)$ exhibits localized reductions in regions of maximal strain, with the spatial profile governed by the phenomenological attenuation parameter α . For small values of α , corresponding to weak or transient non-linearity, coherence remains effectively uniform and indistinguishable from the linear General Relativity baseline. As α increases, coherence deficits become more pronounced but remain spatially confined.

A key feature of the model is the absence of runaway behavior. Even in highly strained scenarios, coherence deficits saturate rather than diverge, and the system smoothly returns to the linear regime once the excitation is removed. This behavior reflects the construction of the model, which enforces convergence with General Relativity in the weak-field limit and prohibits unbounded deviations.

The qualitative response of the coherence proxy suggests that any coherence-related effects, if present, would manifest indirectly through transient structural reorganization rather than through direct modification of gravitational-wave propagation. In particular, no alteration of wave speed, polarization content, or asymptotic waveform structure is predicted within the regime of validity of the model.

It is important to stress that these illustrative results do not imply the creation of real matter or the emergence of new particle degrees of freedom. Instead, they indicate the possibility of temporary departures from linear stability in extreme environments, which may be interpreted as phenomenological markers of regime transition rather than as physical instabilities.

The results further reinforce a recurring pattern observed across applications of the TGU framework: coherence-related effects remain suppressed in linear and weakly perturbed regimes and emerge only when sustained non-linearity is present. This selective activation distinguishes the model from generic modifications of gravity and ensures compatibility with existing observational constraints. [6,7]

The implications of these qualitative trends, along with their limitations and potential avenues for falsification, are discussed in the following section.

7. Limitations, Falsifiability, and Observational Outlook

The phenomenological nature of the present study imposes clear and intentional limitations. The coherence model introduced in this work is not derived from a microscopic theory, nor does it attempt to replace or modify the fundamental structure of General Relativity. Its scope is restricted to exploring qualitative behavior in regimes characterized by sustained non-linearity and extreme spacetime strain.

A primary limitation of the model is the absence of direct observational calibration. The operational coherence proxy and its associated parameters are introduced solely as descriptive tools to investigate regime dependence and limiting behavior. As such, no quantitative predictions or parameter constraints are claimed, and no correspondence with specific gravitational-wave events is asserted. The results should therefore be interpreted as illustrative rather than predictive.

Despite these limitations, the framework admits clear avenues for falsifiability. First, the model predicts strict convergence to General Relativity in linear and weak-field regimes. Any empirical indication of coherence-related effects in domains where General Relativity is known to apply with high precision would directly falsify the phenomenological assumptions adopted here. Conversely, the absence of any coherence signatures in extreme non-linear environments would constrain the relevance or parameter space of the model. Within this phenomenological analysis, variations in α should be interpreted as reflecting changes in geometric regime rather than new physical degrees of freedom, and any physically meaningful determination of its value lies outside the scope of the present work.

Second, the model predicts that coherence-related effects, if present, should manifest indirectly through transient structural organization rather than through modifications of gravitational-wave propagation itself. Observational strategies aimed at detecting changes in wave speed, polarization content, or asymptotic waveform structure would therefore not be expected to reveal such effects. Instead, potential signatures would be confined to environments characterized by prolonged interaction, strong coupling with matter, or persistent non-linearity.

Future observational efforts could explore these possibilities using fully reproducible analyses of public gravitational-wave datasets, combined with environmental modeling of extreme astrophysical systems. High-signal-to-noise events, long-duration signals, or systems embedded in dense or highly dynamical media may provide suitable testbeds for probing regime transitions beyond linear approximations.[2]

It is emphasized that the absence of any detected coherence-related effects in such studies would not conflict with established gravitational physics. Rather, it would reinforce the interpretation of coherence as a selectively activated, phenomenological descriptor with limited applicability. In this sense, the present work is designed to be falsifiable not by demanding confirmation, but by remaining compatible with null results.

Overall, this section underscores that the value of the present study lies not in advancing specific observational claims, but in clarifying the conditions under which coherence-based extensions of gravitational dynamics may or may not become relevant. By delineating explicit limitations and testable boundaries, the framework aims to support future investigations without challenging the empirical foundations of General Relativity.

8. Conceptual Context and Relation to the Unified Theory of Informational Spin

The present study is conceptually situated within the broader framework of the Unified Theory of Informational Spin (TGU), which provides a coherence-based phenomenological perspective on gravitational and cosmological phenomena. It is emphasized, however, that this work does not aim to develop, extend, or formalize the foundational structure of the TGU itself. Instead, it explores a specific qualitative mechanism that is consistent with the general principles of the framework while remaining operationally and epistemologically limited.[6]

Within the TGU, coherence is interpreted as an effective descriptor of how physical systems admit stable, approximately linear representations across scales. A central feature of the framework is its strict convergence to established theories—such as General Relativity and the Standard Model—in regimes where linearity and weak coupling apply. Coherence-related effects are not assumed to be universal or continuously active, but rather to emerge selectively when systems are driven into sustained non-linear regimes.

In this context, the coherence proxy introduced in this work should be understood as an operational parameterization of regime transition rather than as a fundamental physical field. No assumptions are made regarding the microscopic composition of spacetime, the existence of elementary informational units, or the ontological status of coherence. The model is constructed to remain agnostic about underlying mechanisms and to avoid introducing new degrees of freedom beyond those already present in the gravitational-wave background.

The role of the TGU in this article is therefore purely contextual. It provides a guiding principle—namely, that coherence-related descriptors may become relevant only when linear approximations cease to be sufficient—without imposing specific structural or dynamical claims. This approach mirrors other phenomenological applications of the TGU, where coherence serves as an organizing concept across disparate regimes while remaining suppressed in domains governed accurately by conventional theories (Matuchaki, 2025) [6].

Accordingly, the results presented here should be interpreted as illustrative consistency checks within a coherence-based phenomenological perspective, rather than as confirmations of the TGU or as evidence for new fundamental processes. The present work is complementary to more comprehensive treatments of the TGU available elsewhere and is designed to remain fully compatible with conservative interpretations and null observational outcomes.

9. Simulations and Observational Outlook

9.1. Illustrative Computational Modeling

To explore the qualitative behavior of the phenomenological coherence model, we implemented simplified numerical simulations designed for illustrative purposes only. These simulations do not represent physical models of spacetime microstructure, nor do they attempt to reproduce gravitational-wave observations. Their sole objective is to visualize regime transitions associated with sustained non-linearity.[5]

The simulations consider an idealized spatial grid subjected to a time-dependent excitation that mimics localized, oscillatory spacetime strain. An operational coherence proxy, as defined in previous sections, is evaluated across the grid to identify regions where linear approximations become increasingly inadequate. No assumptions are made regarding the existence of elementary spin units or physical lattices.

Regions exhibiting reduced coherence are highlighted as markers of extreme regime conditions. These markers should not be interpreted as particle formation, matter generation, or physical instabilities. Instead, they serve as qualitative indicators of localized departures from linear behavior within the phenomenological framework.

9.2. Visualization of Regime Transitions

Three-dimensional visualizations were produced using VPython to provide an intuitive representation of coherence modulation under idealized excitation. The visual output illustrates the coexistence of wave-like behavior and localized coherence deficits in a controlled environment.

Threshold values employed in the visualization are arbitrary and chosen solely to enhance contrast. They do not correspond to physical phase transitions, critical phenomena, or observable quantities. The simulations are therefore illustrative rather than predictive and are not intended to support quantitative inference.

9.3. Observational Perspective

The present study does not perform a comparison with existing gravitational-wave datasets, nor does it claim consistency with specific events observed by current detectors. Any attempt to relate coherence-based descriptors to observational data would require a fully documented, reproducible analysis pipeline based on public datasets and explicit environmental modeling.

Future observational studies could investigate whether extreme, long-duration, or strongly coupled astrophysical systems exhibit signatures consistent with regime transitions beyond linear approximations. Importantly, the absence of any such signatures would constitute a valid and informative outcome, constraining the applicability of coherence-based phenomenological descriptors.

Accordingly, the simulations presented here are intended as conceptual tools to guide future inquiry rather than as evidence for new physical processes.

9.4. *Experimental Outlook and Exploratory Proposals*

The phenomenological nature of the present study implies that any potential experimental relevance must be approached with caution. The purpose of the following proposals is not to validate the Unified Theory of Informational Spin as a whole, nor to assert the existence of new physical entities, but to outline possible avenues for exploring the limits of applicability of coherence-based descriptors in extreme regimes.

- **Observation of Extreme Gravitational-Wave Environments.** Future gravitational-wave observations of systems characterized by prolonged non-linearity and high spacetime strain, such as massive binary black hole mergers or neutron star–black hole interactions, may provide suitable environments for testing whether linear approximations remain fully sufficient. The absence of any coherence-related signatures in such events would place meaningful constraints on phenomenological extensions (Planck Collaboration, 2020) [3].
- **Multi-Messenger Contextual Studies.** Rather than searching for direct particle creation, correlated observations across gravitational, electromagnetic, and neutrino channels could be used to examine whether extreme gravitational environments exhibit unexpected environmental or structural features. Any such studies must remain consistent with standard astrophysical processes and should be interpreted conservatively.
- **Large-Scale Correlative Analyses.** Statistical comparisons between maps of gravitational-wave source distributions and large-scale cosmological surveys may be used to explore whether regions associated with extreme gravitational activity exhibit non-trivial correlations. Such analyses would not constitute evidence for new matter components, but could help delimit the regime of validity of coherence-based descriptors.
- **Polarization and Precision Measurements.** Continued improvements in detector sensitivity, including future space-based observatories, may enable more precise measurements of gravitational-wave polarization content. Within the present framework, no deviation from General Relativity is expected in linear regimes; therefore, any detected anomalies would require careful scrutiny and independent confirmation.
- **Computational and Data-Driven Exploration.** Advanced simulations and data-analysis techniques, including machine learning methods, may assist in identifying subtle patterns or regime transitions in large datasets. Such approaches should be regarded as exploratory tools and must be accompanied by transparent methodology and reproducibility.

It is emphasized that null results across these exploratory avenues would be fully consistent with the conservative assumptions adopted in this work. The value of such investigations lies not in confirming a specific theoretical framework, but in clarifying the boundaries between linear gravitational behavior and regimes where additional phenomenological descriptors may or may not become relevant.

10. **Comparative Considerations: Coherence-Based Descriptors and Gravitational Scattering**

This section examines whether phenomenological features that could, in principle, be associated with coherence-based descriptors might also arise from well-established gravitational propagation effects, such as gravitational lensing or scattering. The purpose of this comparison is not to exclude conventional mechanisms, but to clarify the qualitative distinctions between different classes of effects.

10.1. Gravitational Lensing as a Reference Framework

Gravitational lensing is known to affect the propagation of gravitational waves, particularly in the presence of massive intervening structures. Existing models predict frequency-dependent amplification and phase modulation, typically characterized by symmetric and alignment-dependent patterns. These effects have been extensively studied and provide a well-understood reference against which alternative phenomenological descriptors may be compared (Planck Collaboration, 2020) [3]. .

Importantly, lensing-induced modulations are expected to depend primarily on the mass distribution along the line of sight and on source–lens–observer alignment, and they do not generically introduce intrinsic angular asymmetries in the polarization content of the signal.

10.2. Qualitative Distinctions in Symmetry Structure

Within coherence-based phenomenological perspectives, any potential modulation would be expected to arise not from intervening mass distributions, but from the internal dynamical regime of the gravitational system itself. As a result, such effects—if they exist—would be characterized by symmetry properties distinct from those of gravitational lensing.

Specifically, coherence-related descriptors would not be tied to external alignment conditions and would therefore not be expected to reproduce the characteristic symmetric amplification templates associated with lensing. This distinction is qualitative and does not imply the presence of observable deviations in existing data.

10.3. Interpretive Scope and Limitations

The considerations presented here are purely illustrative. No claim is made that current gravitational-wave observations exhibit statistically significant modulations beyond those expected from established propagation effects. Likewise, the absence of obvious lensing signatures along a given line of sight cannot be taken as evidence for alternative mechanisms.

The value of this comparison lies in delineating the types of symmetry patterns that different physical mechanisms would produce, should deviations ever be observed in future high-precision datasets. Any such observations would require careful statistical treatment, independent confirmation, and conservative interpretation.

In this sense, the present discussion serves to clarify conceptual boundaries rather than to advance claims of detection or exclusion. Conventional gravitational scattering and lensing remain fully sufficient to explain all currently available observations.

11. Future Work

The present work is intentionally framed as a phenomenological and diagnostic exploration. While the internal consistency of the framework has been established, several important research directions remain open and are deferred to future studies. We outline them here to clarify scope and guide subsequent development.

11.1. Operational Definition of the Regime Indicator ϵ

A central open problem is the formulation of an operationally independent definition of the regime indicator ϵ . In the current framework, ϵ functions as a diagnostic label for the validity domain of a linear inference map and is not treated as a physical parameter inferred from waveform amplitude or detection statistics.

Future work should formalize independent proxies for ϵ , potentially based on geometric, coherence-related, or environmental indicators (e.g., curvature scales, phase-coherence measures, or external astrophysical context), thereby avoiding circular dependence on the same parameters it is meant to qualify.

11.2. Explicit Construction of a Nonlinear Inference Map

The present study highlights the implicit assumption of a universal linear mapping between recovered waveform amplitudes and extrinsic parameters such as luminosity distance and inclination. It does not attempt to derive an explicit nonlinear alternative.

A natural next step is the construction of an explicit nonlinear inference map,

$$\theta = F_{\text{nonlinear}}^{-1}(h, \epsilon), \quad (1)$$

and a systematic comparison with the standard linear mapping. Such a development would require careful modeling choices and lies beyond the scope of the current phenomenological treatment.

11.3. Bayesian Inference and Model Comparison

To connect the diagnostic framework with observational practice, future studies should implement Bayesian inference pipelines that allow comparison between linear and regime-aware inference models. This includes evaluating evidences of the form

$$P(D | M_{\text{linear}}) \quad \text{vs.} \quad P(D | M_{\text{nonlinear}}), \quad (2)$$

using nested sampling or related techniques.

Such analyses would clarify whether regime-aware inference provides statistically meaningful improvements for specific events or detector sensitivities, without modifying waveform generation or propagation.

11.4. Astrophysical and Detector Regimes of Interest

The present work deliberately refrains from asserting specific astrophysical thresholds at which $\epsilon \neq 1$ must occur. Identifying physical or observational regimes where linear inference assumptions may become unreliable remains an open question.

Future investigations may explore scenarios involving extreme curvature environments, strong gravitational lensing, multi-path propagation, or next-generation detectors probing deeper cosmological distances, where regime-aware diagnostics could become relevant.

11.5. Relation to Existing Waveform Modeling

Finally, it will be important to further clarify the relationship between the proposed diagnostic framework and state-of-the-art GR waveform modeling. The present approach is complementary rather than competitive: it does not replace accurate waveform templates, but instead interrogates the robustness of the inverse mapping from recovered waveforms to inferred extrinsic parameters.

A systematic integration with existing inference pipelines would help delineate the precise conceptual and practical role of regime-aware diagnostics within gravitational-wave astronomy.

12. Conclusion

This work has explored a limited phenomenological extension of gravitational-wave physics motivated by coherence-based considerations associated with the Unified Theory of Informational Spin (TGU) (Matuchaki, 2025) [6]. Rather than proposing new fundamental fields or modifying General Relativity, the analysis focused on whether coherence-related descriptors may serve as effective indicators of regime transitions when gravitational systems are driven far beyond linear approximations. [1,6]

By construction, the framework presented here reproduces the predictions of General Relativity in all regimes where current observations are well described by linear or weakly non-linear dynamics. No deviations are expected, nor required, in such domains. The coherence proxy introduced in this study becomes potentially relevant only in extreme environments characterized by sustained non-linearity, high strain, or prolonged departures from equilibrium.

The results should therefore be interpreted as illustrative and exploratory. They do not constitute evidence for new physical processes, matter generation mechanisms, or modifications of gravitational-wave propagation. Instead, they demonstrate internal consistency with a broader coherence-based perspective while remaining fully compatible with conservative interpretations and null observational outcomes.

An important implication of this approach is the emphasis on transversal regime consistency. The same organizing principle—coherence as an effective descriptor—appears suppressed in linear regimes, marginal in moderately non-linear systems, and potentially relevant only in extreme conditions. This pattern, rather than any specific numerical prediction, represents the primary contribution of the present work.

Future observational advances may further clarify whether coherence-based descriptors provide additional explanatory value in extreme gravitational environments or whether standard frameworks remain sufficient across all accessible regimes. In either case, the methodology adopted here offers a structured and falsifiable way to delineate the boundaries of applicability between established theories and phenomenological extensions.

Accordingly, the present study should be viewed not as a test of the TGU itself, but as a conservative probe of how coherence-oriented concepts may—or may not—emerge as useful tools in the analysis of gravitational phenomena beyond the linear domain.

An indirect implication of this analysis is that previously proposed hypotheses involving gravitational-wave-induced matter creation cannot be meaningfully assessed without an intermediate regime-diagnostic step. While the present work makes no claims regarding particle genesis or mass generation, it demonstrates that any causal interpretation of extreme gravitational-wave environments requires prior identification of the breakdown of linear inference regimes. Thus, the hypothesis of matter creation is not ruled out a priori, but shown to be logically subordinate to regime-aware diagnostics.

Within the broader Unified Theory of Informational Spin, mechanisms for the emergence of matter from coherence collapse are formulated at a fundamental level. The present work does not address these mechanisms directly. Instead, it establishes that any causal application of such processes—whether related to matter generation or other non-linear phenomena—requires a prior, regime-aware diagnostic ensuring the validity of physical inference. In this sense, the present analysis constitutes a necessary, though not sufficient, step toward physically meaningful causal interpretations within the TGU framework.

Appendix A Consistency and Regime-Diagnostic Tests

This appendix presents a set of internal consistency and regime-diagnostic tests associated with the phenomenological coherence framework introduced in the main text. All tests reported here are explicitly *non-empirical* and are intended to assess mathematical consistency, limiting behavior, numerical stability, and inference robustness.

Throughout this appendix, all detector-level signals are standard General Relativity (GR) waveforms. No modification of gravitational-wave generation, propagation, polarization, or dispersion is introduced.

Appendix B Convergence with General Relativity in the Weak-Field Limit

We first verify that the coherence diagnostic introduced in Eq. (7) remains compatible with GR in the weak-field limit. The diagnostic quantity is defined as

$$C \equiv \frac{\|\nabla^2 h\|}{\|R\|}, \quad (\text{A3})$$

where h is the metric perturbation and R is the Ricci scalar associated with the background geometry.

As $R \rightarrow 0$, the ratio diverges formally, reflecting the vanishing of curvature information in flat spacetime. This behavior is expected by construction and confirms that the diagnostic does not introduce spurious structure in the GR limit.

This test constitutes a consistency check of limiting behavior, not a physical prediction.

Appendix C Regime-Dependent Inference Degeneracy (Clarified)

This section addresses a potential inference-level degeneracy arising from the universal application of a linear-regime inference map across distinct geometric or coherence regimes.

Key Clarifications

The detector-level gravitational-wave signal always satisfies

$$h_{\text{obs}} = h_{\text{GR}}. \quad (\text{A4})$$

Consequently, the matched-filter detection signal-to-noise ratio (SNR), in the standard LIGO/Virgo sense, is strictly identical to that predicted by GR.

No physical attenuation, amplification, or distortion of the waveform is introduced by the framework.

Appendix C.1 Role of the Diagnostic Factor ϵ

The parameter $\epsilon \in (0, 1]$ is introduced purely as a *diagnostic indicator of regime validity*. It does not represent a physical propagation effect, nor does it modify the strain, waveform morphology, or noise-weighted inner product.

Instead, ϵ labels the applicability of a linear inference map that translates recovered amplitudes and polarization ratios into extrinsic parameters such as luminosity distance and inclination.

Appendix C.2 Nature of the Degeneracy

If one assumes $\epsilon = 1$ (linear regime) while geometric or coherence indicators suggest $\epsilon < 1$, then:

- The matched-filter SNR remains unchanged.
- The recovered waveform remains GR-consistent.
- The mapping from amplitude to extrinsic parameters becomes ill-conditioned.

This produces an amplitude or distance inference bias, not an observable SNR deviation. Any apparent “SNR bias” should therefore be understood strictly as a parameter-inference degeneracy, not a modification of detection statistics or signal propagation.

Appendix D Gaussian Profile Consistency Test

We test the diagnostic response against a Gaussian strain profile of the form

$$h(t) \propto \exp\left(-\frac{t^2}{2\sigma^2}\right). \quad (\text{A5})$$

The diagnostic reproduces the expected Gaussian structure with vanishing residuals. This test is tautological by design and serves exclusively as a numerical sanity check, verifying correct normalization and implementation.

Appendix E Application to GW150914

The framework is applied to the GW150914 event using standard GR strain amplitudes and published source parameters.

For reasonable diagnostic parameter choices, the inferred regime remains close to the linear limit ($\epsilon \approx 1$), indicating:

- No deviation from GR propagation,
- No anomaly in detection SNR,
- No special coherence signature for this event.

This confirms that the diagnostic framework does not artificially flag standard GR events as anomalous.

Appendix F Stability Bounds of the Diagnostic Kernel

The coherence kernel includes bounded trigonometric and exponential components of the form

$$K(r) = |\cos(\theta)| e^{-ar^2}. \quad (\text{A6})$$

By construction,

$$0 \leq K(r) \leq 1, \quad (\text{A7})$$

ensuring numerical stability and preventing unphysical amplification.

This test verifies boundedness and stability properties only.

Appendix G Explicit Equivalence with GR Propagation

Finally, we emphasize that the framework enforces

$$h_{\text{coherence}} = h_{\text{GR}} \quad (\text{A8})$$

for all detector-level observables.

The coherence formalism introduces no modification to gravitational-wave generation, propagation, polarization, or dispersion. Its sole purpose is to provide a regime-aware diagnostic layer for inference robustness, identifying where linear assumptions may become unreliable without predicting new physics in the signal itself.

Appendix H Appendix Summary

All tests presented in this appendix are consistency and diagnostic checks rather than empirical validation. No observable deviations from GR are predicted, no physical SNR modification occurs, and any degeneracy arises exclusively at the level of parameter inference.

References

1. B. P. Abbott et al., "Observation of Gravitational Waves from a Binary Black Hole Merger," *Phys. Rev. Lett.*, vol. 116, no. 6, 061102 (2016). <https://doi.org/10.1103/PhysRevLett.116.061102>
2. LIGO–Virgo–KAGRA Collaboration, "O4 Run Preliminary Data Release," Gravitational Wave Open Science Center (GWOSC), 2023. Available at: <https://www.gw-openscience.org/O4/>
3. Planck Collaboration, "Planck 2018 results. VI. Cosmological parameters," *Astron. Astrophys.*, vol. 641, A6 (2020). <https://doi.org/10.1051/0004-6361/201833910>
4. G. Bertone, D. Hooper, and J. Silk, "Particle Dark Matter: Evidence, Candidates and Constraints," *Phys. Rep.*, vol. 405, no. 5–6, pp. 279–390 (2005). <https://doi.org/10.1016/j.physrep.2004.08.031>
5. W. H. Zurek, "Decoherence, Einselection, and the Quantum Origins of the Classical," *Rev. Mod. Phys.*, vol. 75, pp. 715–775 (2003). <https://doi.org/10.1103/RevModPhys.75.715>
6. H. Matuchaki, "The Unified Theory of Informational Spin: A Coherence-Based Framework for Gravitation, Cosmology, Quantum Systems," *Preprints* (2025). <https://doi.org/10.20944/preprints202502.0514.v5>
7. H. Matuchaki, "Gravitational Wave Polarization and Informational Coherence in a Phenomenological Framework," *Preprints* (2025). <https://doi.org/10.20944/preprints202503.1613.v1>

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