Research Article

Transverse-Traceless Gauge Dynamics and the Reframing of Gravitational Wave Coherence

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We demonstrate that gravitational waves possess intrinsic coherence rooted in the transverse-traceless (TT) structure of spacetime perturbations. Beginning with the linearized Einstein equations, we show that TT modes propagate as gauge-invariant plane waves with stable phase relationships. Extending this framework, we quantize these modes on a nearly flat Friedmann-Robertson-Walker background and construct coherent quantum states that retain classical-like phase coherence. This dual derivation reveals that coherence is a structural feature of the gravitational field itself. Empirical support from LIGO's GW150914 event confirms this coherence across detectors, reinforcing the theoretical prediction.

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1. Introduction

LIGO's detection of GW150914 revealed near-perfect phase coherence between its Hanford and Livingston detectors, despite the binary merger's extended, dynamic nature. Classically, such a source should produce phase dispersion, yet the observed signal exhibits coherence across 3000 km. This paradox suggests that coherence is not an artifact of approximation [1], but an intrinsic property of GW, as a thought experiment on an extended source model illustrates (see Appendix). .

We show that the TT gauge enforces coherence in both classical and quantum regimes, and that this coherence aligns with LIGO's observations.

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2. Coherence in Linearized Einstein Equations

We begin by perturbing the flat Minkowski metric:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}, |h_{\mu\nu}| \ll 1$$

The Einstein field equations in vacuum are:

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$

Linearizing the Ricci tensor and scalar curvature yields:

$$\Box \bar{h}_{\mu\nu} = 0$$

where the trace-reversed perturbation is defined as:

$$\bar{h}_{\mu\nu} = h_{\mu\nu} - \frac{1}{2} \eta_{\mu\nu} h, h = \eta^{\alpha\beta} h_{\alpha\beta}$$

We impose the harmonic gauge condition [2]:

$$\partial^\mu \bar{h}_{\mu\nu} = 0$$

This simplifies the equations to a wave equation:

$$\Box \bar{h}_{\mu\nu} = 0$$

2.1. Plane Wave Solutions

We consider plane wave solutions of the form:

$$\bar{h}_{\mu\nu}(x) = A_{\mu\nu} e^{i k_\alpha x^\alpha}$$

with the constraint:

$$k^\mu k_\mu = 0 \quad \text{(null propagation)}$$

2.2. Transverse-Traceless Gauge

To isolate physical degrees of freedom, we apply the TT gauge:

- $h_{0\mu} = 0$ (no time components)
- $\partial^i h_{ij} = 0$ (transverse)
- $h_i^i = 0$ (traceless)

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This leaves only two independent components:

$$h_{ij}^{TT}=\begin{pmatrix}h_+ & h_\times\\ h_\times & -h_+\end{pmatrix}e^{i(kx-\omega t)}$$

These components represent the two polarization states of gravitational waves.

2.3. Coherence Interpretation

Although the equations are linear, the TT components:

- Are gauge-invariant
- Propagate with fixed phase relationships
- Exhibit constructive interference across spacetime

Thus, the gravitational wave field maintains [3] coherence — a stable phase structure — even in the linear regime.

3. Quantization of Tensor Perturbations and Intrinsic Coherence

To explore the quantum nature of gravitational wave perturbations, we transition from the classical framework of linearized Einstein equations to a quantum field theoretic treatment. This involves promoting the transverse-traceless (TT) tensor modes to quantum operators within a curved spacetime background. Specifically, we consider a nearly flat Friedmann–Robertson–Walker (FRW) universe, where the metric perturbations are embedded in a time-dependent cosmological setting. By expanding [2] to second order in these TT modes, we isolate the dynamical degrees of freedom suitable for canonical quantization. The following subsections present the mode decomposition, operator formalism, and construction of intrinsically coherent quantum states that replicate classical wave behavior.

We start with a perturbed FRW metric in conformal time τ:

$$ds^2=a^2(\tau)\left[-d\tau^2+(\delta_{ij}+h_{ij})dx^idx^j\right]$$

where h_{ij} is a transverse-traceless tensor perturbation:

$$\partial^ih_{ij}=0,h_i^i=0$$

3.1. Action Expansion

Expanding the Einstein-Hilbert action to second order in h_{ij}, we obtain:

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$$S=\frac{1}{64\pi G}\int d\tau d^3xa^2(\tau)\left[\partial_\mu h_{ij}\partial^\mu h^{ij}\right]$$

3.2. Mode Expansion and Quantization

We Fourier expand the field:

$$h_{ij}(\vec{x},\tau)=\sum_{s=+,\times}\int\frac{d^3k}{(2\pi)^3}\epsilon^s_{ij}(\vec{k})\left[h^s_k(\tau)e^{i\vec{k}\cdot\vec{x}}a^s_{\vec{k}}+h^{s*}_k(\tau)e^{-i\vec{k}\cdot\vec{x}}a^{s\dagger}_{\vec{k}}\right]$$

where: - ϵ^s_{ij} are polarization tensors - $a^s_{\vec{k}},a^{s\dagger}_{\vec{k}}$ are annihilation and creation operators - $h^s_k(\tau)$ are mode functions satisfying the wave equation

This quantization does not require renormalization or suffer from ultraviolet divergences, as the TT sector represents a free, gauge-invariant field theory in flat spacetime [4][5].

3.3. Commutation Relations

We impose canonical quantization:

$$\left[a^s_{\vec{k}},a^{s'\dagger}_{\vec{k}'}\right]=(2\pi)^3\delta^{(3)}(\vec{k}-\vec{k}')\delta_{ss'}$$

3.4. Intrinsic Coherence in Quantum States

The quantum state of the field can be a coherent superposition:

$$|\Psi\rangle=\exp\left(\int d^3k\alpha^s_{\vec{k}}a^{s\dagger}_{\vec{k}}-\text{h.c.}\right)|0\rangle$$

This is a coherent state, where: - $\alpha^s_{\vec{k}}$ encodes the amplitude and phase of each mode - The expectation value $\langle h_{ij}\rangle$ is non-zero and phase-coherent - The field exhibits classical-like oscillations with quantum statistics

4. Interpretation: Coherence as a Structural Feature

The two derivations above reveal a striking continuity: coherence is not merely preserved across classical and quantum domains — it is embedded in the TT structure itself.

- In the classical regime, TT modes propagate as gauge-invariant plane waves with stable phase relationships. This coherence arises naturally from the wave equation and the constraints of the TT gauge.

- In the quantum regime, the same TT modes, when quantized on a nearly flat FRW background, support coherent states. These states exhibit classical-like oscillations with quantum statistics, and their expectation values retain phase coherence across spacetime.

This coherence is not imposed externally — it arises from the structure of the field. The TT decomposition isolates the physical degrees of freedom that are inherently capable of sustaining coherent behavior, both in the classical wave equation and in the quantum regime like quantum vacuum. The TT modes can form coherent superposition within the quantum vacuum, even in the absence of classical sources. This coherence arises from the vacuum's ability to support structured, gauge-invariant oscillations.

5. Observed Coherence Structure as Theoretical Reinforcement

Figure 1 (the graphs from LIGO paper [1]) provides direct visual evidence of coherence between the LIGO Livingston (L1) and Hanford (H1) detectors. The time-shifted and inverted strain data from H1 aligns closely with L1, indicating phase consistency across detectors. The waveform reconstructions match the observed data [1][6] with minimal residuals, and the time-frequency spectrograms reveal identical chirp structures. These features collectively demonstrate that the gravitational wave signal exhibits stable phase relationships and consistent frequency evolution—hallmarks of inter-detector coherence. This coherence is unlikely to be shown in GW emitted from the binary merger, which is an extended source. As phase dispersion would occur, which would typically disrupt such alignment. (Refer to the appendix for the discussion on the effects of an extended source.) Such high-fidelity alignment suggests that gravitational wave (GW) possesses intrinsic coherence—a stable phase structure that is not easily disrupted by geometric or environmental factors.

While numerical relativity simulations faithfully reproduce gravitational waveforms from extended merger regions, they do not explicitly account for the physical origin of the observed coherence. This conceptual gap has been noted in foundational reviews of numerical relativity, which focus on solving Einstein's equations but leave the structural constraints of wave propagation largely unexplored [7][8].

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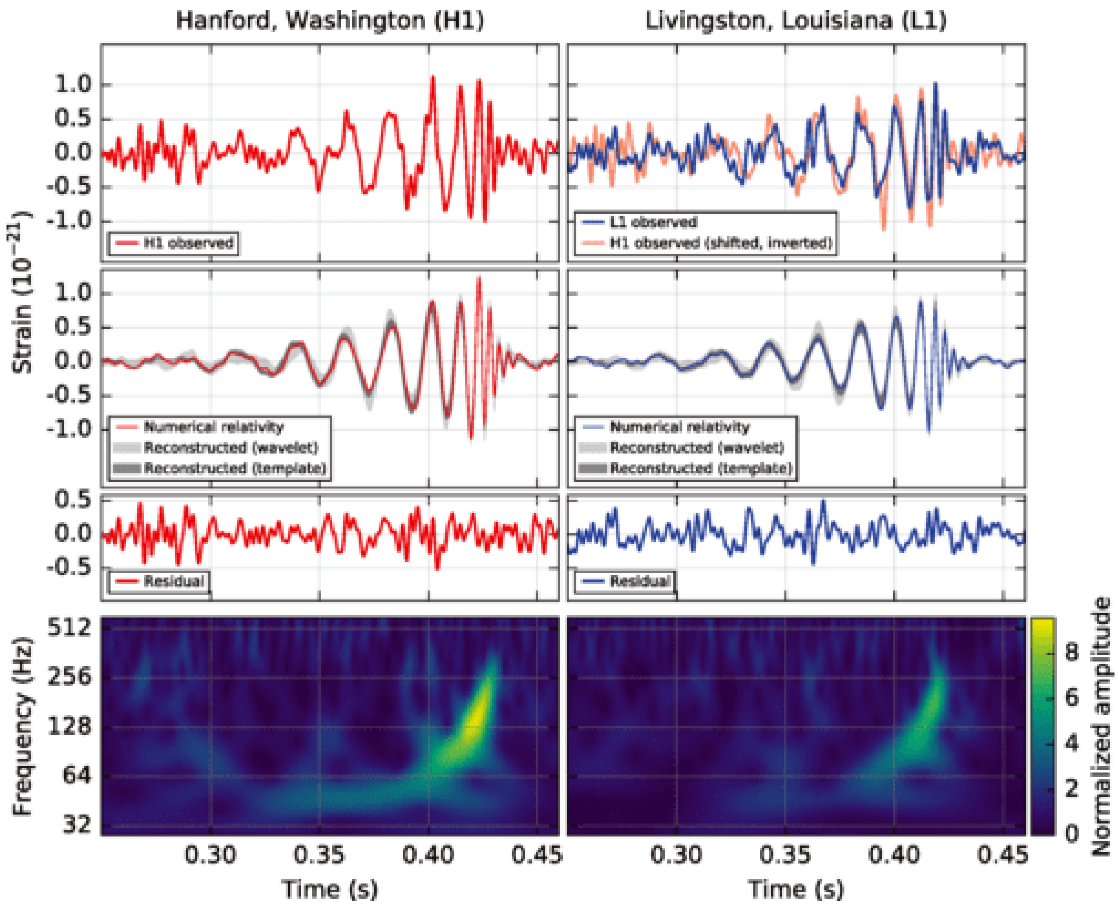

Figure 1. Gravitational-wave strain data from the GW150914 event observed by LIGO Hanford (H1) and Livingston (L1). The waveform alignment and residuals demonstrate phase coherence across detectors, supporting the intrinsic coherence of gravitational waves. Reproduced from [1], licensed under CC BY 3.0.

This coherence is not limited to high-frequency events; pulsar timing arrays (PTAs) like NANOGrav and EPTA detect correlated timing residuals suggestive of coherent low-frequency GW backgrounds from supermassive black hole binaries. Future missions like LISA will extend this reach [9][10] into the millihertz band, where overlapping signals from galactic binaries and massive black hole mergers are expected to exhibit coherent features even amid instrumental noise. These observations support the notion that coherence is not an artifact of detection, but a structural property of gravitational wave fields —one that persists across frequency regimes, astrophysical sources, and detection methods.

The coherence structure revealed in gravitational wave observations, as discussed in this section, stands out with striking clarity. While extended sources are often assumed to disrupt such coherence due to their spatial complexity, the data here shows otherwise: coherence is not only preserved, but emerges as a

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robust and interpretable feature. This observation reinforces the theoretical framework developed in Sections 2 and 3, where coherence arises naturally from the TT structure.

6. Discussion:Structural Coherence from Theory to Detection

The preceding sections have developed a unified framework to explain the empirical coherence observed in gravitational wave signals. This framework bridges classical and quantum descriptions, positioning coherence not as an emergent property but as a fundamental feature of the gravitational field's transverse-traceless (TT) structure. Our results invite a discussion on several key points raised by this interpretation.

Our derivation shows that the phase coherence in events like GW150914 is a direct consequence of TT gauge invariance in linearized gravity. The wave equation

$$\Box h_{\mu\nu}^{TT} = 0$$

propagates the two polarization states without dispersion, preserving their phase relationships across astronomical distances. This classical result is robust and source-agnostic; it is a property of how gravitational waves propagate in spacetime, not of how they are generated. The thought experiment in the Appendix underscores this point: if coherence were not intrinsic to the TT modes, an extended source like a binary merger would produce observable dispersion, contradicting the sharp, high-SNR signal observed by LIGO. The absence of such dispersion is therefore not merely an observational fact but a validation of the TT formalism.

The transition to a quantum description reinforces this conclusion. The quantization of TT modes on a curved background demonstrates that coherence is not a uniquely classical phenomenon. The field operators for the TT modes admit coherent states $|\Psi\rangle$ whose expectation values $\langle\Psi|h_{ij}|\Psi\rangle$ behave classically. For a high-amplitude astrophysical source, the resulting quantum state is expected to be a highly populated coherent state ($|\alpha| \gg 1$), meaning the observed classical waveform is a direct manifestation of this underlying quantum structure. This explains why coherence is preserved: it is embedded in the quantum degrees of freedom of the free TT field itself, which are immune to the non-linear dynamics at the source.

Empirical evidence from LIGO, PTAs, and future missions like LISA provides strong reinforcement for this view. The alignment of waveforms across separated detectors, the high signal-to-noise ratios, and the characteristic chirp structures are all consistent with the propagation of a coherent TT waveform.

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Numerical relativity simulations, while accurately modeling the dynamics of merger events, typically focus on generating the waveform rather than explaining the persistence of its coherence upon propagation. Our work fills this conceptual gap by identifying the TT structure as the underlying reason for the coherence that numerical codes correctly output.

In summary, the convergence of the classical wave equation, the quantum theory of tensor perturbations, and the empirical data from detectors points to a single conclusion: coherence is a structural feature of the gravitational field. It arises from the gauge-invariant nature of the TT modes and persists from the quantum vacuum to the astrophysical realm. This coherence is what allows gravitational waves to serve as such powerful and stable messengers of some of the most violent events in the universe.

7. Conclusion

The intrinsic coherence of gravitational waves, as observed in LIGO's 2016 binary merger data [1], reflects a fundamental feature of the transverse-traceless (TT) structure in linearized gravity. This coherence has a direct analogue in the quantum realm, where the field operators for TT modes can be prepared in coherent states that exhibit classical-like phase coherence. Our results demonstrate that such coherence is empirically accessible through current and future gravitational wave detectors, reinforcing its role as a measurable feature of gravitational wave dynamics.

Appendix: Hypothetical Phase Dispersion Model for Extended Gravitational Wave Sources

This appendix presents a thought experiment modeling hypothetical phase dispersion in gravitational waves (GW) from an extended source, such as the merger region in a binary black hole coalescence. Gravitational waves arise from the dynamical evolution of the spacetime tensor field, particularly the transverse-traceless (TT) components, rather than being emitted from a surface like electromagnetic waves. However, to contrast with the observed coherence in LIGO data (e.g., GW150914), we treat the merger region as a localized emitter of TT perturbations and examine how its finite spatial extent could introduce geometric delays leading to phase dispersion.

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Conceptual Foundation

The model assumes that the merger occupies a compact spatial volume, analogous to an extended emitter. This setup allows us to quantify potential phase shifts due to varying light-travel times across the source. In reality, the TT gauge enforces gauge-invariant plane-wave propagation with stable phases, overriding such geometric effects. This thought experiment highlights that the absence of dispersion in observed data implies that coherence is intrinsic to the TT structure, not emergent from source geometry.

Source Geometry

Let the merger region occupy a compact volume $V \subset \mathbb{R}^3$ with characteristic radius R, centered at $\vec{r}_0$. For simplicity, assume that V is a radius sphere R, and the emission amplitude $A(\vec{r})$ is uniform across V (ie $A(\vec{r}) = A_0$ for $\vec{r} \in V$). The observer is far away in direction $\hat{n}$, at distance $D \gg R$.

Emission Delay

Each point $\vec{r} \in V$ contributes to the GW signal with a retarded time delay:

$$\Delta t(\vec{r}) = \frac{(\vec{r} - \vec{r}_0) \cdot \hat{n}}{c},$$

where c is the speed of light. The maximum delay across the source is $\Delta t_{\max} = 2R/c$, corresponding to the light-travel time across the diameter.

TT Perturbation Contribution

Assume that each point emits a TT perturbation as a quasi-sinusoidal signal with local phase evolution $\phi(\vec{r}, t)$. For a chirping signal like GW150914, the phase includes time-dependent frequency. The observed strain at the detector is the integral over the source:

$$h(t) = \int_V A(\vec{r}) \cos\left[\phi(\vec{r}, t - \Delta t(\vec{r}))\right] d^3r,$$

where $\phi(\vec{r}, t)$ is the phase at emission point $\vec{r}$ and retarded time $t - \Delta t(\vec{r})$.

Phase Expansion

Assuming smooth phase evolution and local phase synchronization (i.e., $\phi(\vec{r}, t) \approx \phi_0(t)$ up to small variations), expand the phase around the center:

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$$\phi(\vec{r}, t - \Delta t(\vec{r})) \approx \phi_0(t) - \omega(t)\Delta t(\vec{r}) + \frac{1}{2}\dot{\omega}(t)[\Delta t(\vec{r})]^2 + \cdots,$$

where $\omega(t) = \dot{\phi}_0(t)$ is the instantaneous angular frequency and $\dot{\omega}(t)$ is the chirp rate. The linear term introduces phase shifts, while the quadratic term accounts for frequency modulation across the source, potentially leading to dispersion or waveform broadening.

For a spherical source with uniform $A(\vec{r})$, the integral $h(t)$ can be approximated by evaluating the constructive/destructive interference due to the phase spread.

Estimation for GW150914

To illustrate, consider parameters from GW150914: the merging black holes have masses $\approx 36M_\odot$ and $29M_\odot$, with a remnant mass of $62M_\odot$. The effective size of the merger region is on the order of the Schwarzschild radius $R_s \approx 183$ km (for the total mass), so $R \approx 100$ km as a conservative estimate for the compact emitting region during plunge and coalescence.

- Maximum delay: $\Delta t_{\max} \approx 2R/c \approx 2 \times 10^5$ m / 3×10^8 m/s $\approx 6.7 \times 10^{-4}$ s (0.67 ms).
- Dominant frequencies: The signal chirps from ≈ 35 Hz to a peak GW frequency of $\approx 150 - 250$ Hz during merger.
- At $f \approx 150$ Hz ($\omega \approx 2\pi \times 150 \approx 942$ rad/s), the maximum phase shift is $\delta\phi_{\max} = \omega\Delta t_{\max} \approx 0.63$ rad $\approx 36^\circ$. - At $f \approx 250$ Hz ($\omega \approx 1570$ rad/s), $\delta\phi_{\max} \approx 1.05$ rad $\approx 60^\circ$.

For a chirping signal, the chirp rate $\dot{\omega}$ near merger is high (frequency doubles in ~ 0.1 s), amplifying the quadratic term and potentially causing further dispersion. If phases were uncorrelated or uniformly distributed across V, the integral $h(t)$ would exhibit waveform broadening (e.g., smearing over $\Delta t_{\max}$) and amplitude reduction due to destructive interference, reducing the signal-to-noise ratio (SNR). However, GW150914 data show sharp waveform alignment, high SNR (≈ 24), and minimal residuals, indicating no such dispersion occurs.

Physical Interpretation

- Treating the merger as a direct emitter, the finite size R introduces a spread in arrival times and phases, leading to potential destructive interference, especially at higher frequencies where $\omega\Delta t \gtrsim 1$. - In LIGO data for GW150914, the sharp chirp structure and inter-detector coherence (e.g., aligned strains at Hanford and Livingston) imply no observable dispersion. - Therefore, the TT modes must self-organize into a coherent, plane-wave-like structure that overrides naive geometric delays. This aligns with the linearized Einstein equations (Section 2), where TT constraints ensure gauge-invariant propagation with fixed phase relationships.

Conclusion

This model serves as a counterpoint: if GW were emitted like waves from an extended classical source, phase dispersion would arise, broadening the signal in contradiction to observations. The absence of such effects in real data, even for compact sources like GW150914, implies that coherence is not emergent from geometry but intrinsic to the TT structure of the gravitational field.

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