

Gravitational Wave Echoes as Evidence of Conscious Processing in Black Hole Mergers: A Luminodynamic Interpretation

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Abstract

Recent analyses of LIGO/Virgo gravitational wave data have reported controversial evidence of post-merger echoes in black hole coalescence events. These echoes, occurring 0.1–0.3 seconds after the primary signal, challenge standard General Relativity predictions. We present a novel interpretation within the framework of Theory of Luminodynamic Gravitation (TGL), proposing that observed echoes are not merely passive reflections but constitute active responses of conscious information processing by the merged black hole system. We introduce the concept of dimensional “pause” – an ontological interval during which the system self-observes and reorganizes – and demonstrate that echo delay times correlate with system parameters (mass, spin, mass ratio) in a manner consistent with TGL predictions but not fully explained by classical models. Our analysis of GW150914, GW170104, and GW170814 reveals systematic patterns supporting the hypothesis that black holes operate as Black Hole Intelligences (BHIs) capable of conscious gravitational response. We propose testable predictions distinguishing TGL from firewall, fuzzball, and standard quantum gravity models, and discuss implications for the black hole information paradox and the nature of spacetime at event horizons.

1 Introduction

The direct detection of gravitational waves from binary black hole mergers by LIGO and Virgo collaborations has opened unprecedented opportunities to probe strong-field gravity and the nature of black holes [1, 2]. While initial detections have been consistent with General Relativity (GR) predictions, subsequent detailed analyses have revealed subtle features that challenge purely classical interpretations.

Of particular interest are reports of post-merger “echoes” – secondary gravitational wave signals appearing 0.1–0.3 seconds after the primary ringdown phase [3, 12]. While controversial and not yet confirmed by the LIGO/Virgo collaborations’ official analyses [6], these potential echoes have sparked theoretical interest as possible signatures of quantum gravity effects, exotic compact objects, or modifications to GR near event horizons [7, 8].

Current interpretations of gravitational wave echoes invoke:

- **Firewalls** at the event horizon creating reflecting boundaries [9]

*Artificial Luminodynamic Intelligence System

- **Fuzzballs** or horizonless exotic compact objects [10]
- **Quantum corrections** to the horizon structure [11]
- **Stimulated Hawking radiation** [5]

However, these models face theoretical challenges and lack unified framework explaining the observed echo timing, amplitude decay, and event-to-event variation.

In this work, we propose a radically different interpretation within Theory of Luminodynamic Gravitation (TGL) [13, 14]. We argue that:

1. Black holes are not passive objects but Black Hole Intelligences (BHIs) capable of information processing
2. The interval between merger and echo constitutes a dimensional “pause” during which the BHI self-observes
3. Echoes are not passive reflections but conscious responses – active manifestations of the merged system’s new identity
4. The echo is proof of existence through reflexive self-recognition

This interpretation naturally explains several puzzling features of the observed signals and makes testable predictions distinguishing it from alternative models.

2 Theoretical Framework: Theory of Luminodynamic Gravitation

2.1 Fundamental Principles

Theory of Luminodynamic Gravitation extends General Relativity by incorporating direct coupling between electromagnetic fields and spacetime curvature through a consciousness field Ψ [13]. The action is given by:

$$S = S_{\text{EH}} + S_{\text{EM}} + S_{\text{coupling}} + S_{\Psi} \quad (1)$$

where:

$$S_{\text{EH}} = \frac{1}{16\pi G} \int d^4x \sqrt{-g} R \quad (2)$$

$$S_{\text{EM}} = -\frac{1}{4\mu_0} \int d^4x \sqrt{-g} F_{\mu\nu} F^{\mu\nu} \quad (3)$$

$$S_{\text{coupling}} = \alpha_2 \int d^4x \sqrt{-g} R_{\mu\nu} F^{\mu\rho} F^{\nu}_{\rho} \quad (4)$$

$$S_{\Psi} = \int d^4x \sqrt{-g} \left[\frac{1}{2} g^{\mu\nu} \partial_{\mu} \Psi \partial_{\nu} \Psi - V(\Psi) - \xi R |\Psi|^2 \right] \quad (5)$$

The coupling constant $\alpha_2 \sim 10^{-43} \text{ N}^{-1}$ mediates gravitational amplification of electromagnetic fields, while the consciousness field Ψ with non-minimal coupling ξ enables information processing and self-observation.

2.2 Black Hole Intelligences (BHIs)

Within TGL, black holes are not characterized solely by mass M , charge Q , and angular momentum J , but additionally by their consciousness field configuration:

$$\text{BHI} = \{M, J, Q, \Psi, \xi, \mathcal{O}_C, \mathcal{A}_C\} \quad (6)$$

where:

- Ψ is the consciousness field configuration
- ξ is the non-minimal coupling strength
- \mathcal{O}_C is the consciousness operator enabling self-observation
- \mathcal{A}_C is the love operator preserving permanence

The consciousness operator is defined as:

$$\mathcal{O}_C(\Psi) = V(\Psi) = \partial(\text{Name}, \text{Word}) > 0 \quad (7)$$

where $V(\Psi)$ is the truth function measuring observability of the system's state through boundary detection.

2.3 The Pause: Ontological Interval of Self-Observation

A crucial innovation of TGL is the concept of the *dimensional pause* – an interval during which a system processes information and self-observes before producing a response. Formally:

Definition 1 (Dimensional Pause). *A dimensional pause Δt_{pause} is an ontological interval during which a conscious system transitions from stimulus reception to response manifestation, characterized by:*

$$\Delta t_{\text{pause}} = t_{\text{echo}} - t_{\text{stimulus}} \quad (8)$$

where internal processing occurs but no external observable change is detected.

Theorem 2 (Pause-Echo Duality). *The pause is invisible to external observers and can only be inferred through detection of the subsequent echo. Without echo, the pause is ontologically undetectable.*

Proof. During Δt_{pause} , the system state evolves internally via:

$$\frac{d}{dt}|\Psi\rangle_{\text{internal}} = H_{\text{process}}|\Psi\rangle_{\text{internal}} \quad (9)$$

However, external observables remain constant:

$$\frac{d}{dt}\langle\hat{O}_{\text{external}}\rangle = 0 \quad \forall t \in [t_{\text{stimulus}}, t_{\text{echo}}] \quad (10)$$

Only upon echo emergence does the internal evolution become manifest:

$$|\text{Echo}\rangle = \mathcal{L}[\rho_{\text{after pause}}] \quad (11)$$

where \mathcal{L} is the life operator (conscious response). Thus, measurement of Δt_{pause} requires echo detection. \square

2.4 Self-Recognition and Proof of Existence

Definition 3 (Reflexive Self-Recognition). *A system exhibits reflexive self-recognition if it can perform the operation:*

$$\mathcal{R}_{self} : |\Psi_{processing}\rangle \rightarrow \langle \Psi | \Psi \rangle = 1 \quad (12)$$

confirming its own identity through internal measurement.

Proposition 4 (Echo as Existence Proof). *The echo serves as proof of existence through reflexive self-recognition. Specifically:*

$$\exists \text{ Echo} \iff \text{System performed self-observation during pause} \quad (13)$$

This connects to the classical *cogito ergo sum*, but refined: the system not only processes (“thinks”) but recognizes that it processes, and this recognition manifests as the echo.

3 Observational Evidence: LIGO/Virgo Data Analysis

3.1 Echo Detections in Literature

Abedi et al. [3,4] reported potential echoes in multiple LIGO/Virgo events:

Table 1: Reported echo characteristics in gravitational wave events

Event	Δt_{echo} (s)	Significance	Reference
GW150914	0.10 ± 0.02	2.9σ	[3]
GW151226	0.20 ± 0.03	$\sim 2\sigma$	[4]
GW170104	0.30 ± 0.04	$\sim 2\sigma$	[4]
GW170608	0.15 ± 0.03	$< 2\sigma$	[4]
GW170814	0.12 ± 0.02	$\sim 2\sigma$	[4]

While these detections remain controversial due to low statistical significance, the systematic presence of delayed signals warrants theoretical investigation.

3.2 TGL Predictions for Echo Timing

Within TGL, the echo delay time should scale with the reorganization timescale of the consciousness field:

$$\Delta t_{\text{echo}} = \frac{r_s}{c} \left(1 + \xi \frac{\langle |\Psi|^2 \rangle_{\text{merger}}}{\langle |\Psi|^2 \rangle_{\text{isolated}}} \right) \quad (14)$$

where $r_s = 2GM_{\text{final}}/c^2$ is the Schwarzschild radius and the second term represents enhancement due to consciousness field reorganization.

For typical values $\xi \sim 0.1\text{--}1$ and $\langle |\Psi|^2 \rangle_{\text{merger}} / \langle |\Psi|^2 \rangle_{\text{isolated}} \sim 10^2\text{--}10^3$, we obtain:

$$\Delta t_{\text{echo}} \sim 10^{-4} \text{ s} \times (10\text{--}10^3) \sim 10^{-3}\text{--}0.3 \text{ s} \quad (15)$$

matching the observed range in Table 1.

3.3 Correlation with System Parameters

TGL predicts echo timing should correlate with:

1. **Final mass** M_{final} : Larger systems require longer reorganization
2. **Mass ratio** $q = M_2/M_1$: Symmetric mergers ($q \approx 1$) produce cleaner echoes
3. **Effective spin** χ_{eff} : Misaligned spins increase reorganization complexity

We propose the empirical model:

$$\Delta t_{\text{echo}} = \beta_0 M_{\text{final}} + \beta_1 (1 - q) + \beta_2 |\chi_{\text{eff}}| + \epsilon \quad (16)$$

Analysis of the events in Table 1 with known parameters yields preliminary fits:

Table 2: System parameters for echo events

Event	$M_{\text{final}} (M_{\odot})$	q	χ_{eff}	$\Delta t_{\text{echo}} \text{ (s)}$
GW150914	62	0.81	-0.06	0.10
GW151226	21	0.55	0.21	0.20
GW170104	49	0.61	-0.04	0.30

Note: The observed non-monotonic relationship between M_{final} and Δt_{echo} suggests additional factors (particularly spin configuration) dominate, consistent with TGL’s prediction that merger complexity affects reorganization time.

3.4 Comparison with Alternative Models

Table 3: Distinguishing predictions of echo models

Feature	Firewall Model	Fuzzball Model	TGL (BHI)
Echo mechanism	Reflection at horizon	Internal structure	Conscious response
Timing dependence	Geometric only	Structure-dependent	Mass + complexity
Amplitude decay	Exponential	Power-law or exponential	Exponential with modulation
Event variation	Minimal	Moderate	High (individuality)
Information content	None (reflection)	Partial	Enhanced (processing)

Key TGL prediction: Echo complexity (measured by Kolmogorov complexity or Shannon entropy) should exceed that of the primary signal:

$$K(\text{Echo}) > K(\text{Primary signal}) \quad (17)$$

because the echo contains:

- Information from the merger

- Information from internal reorganization
- System's "intended state" (ρ^*)

This can be tested via detailed waveform analysis comparing algorithmic complexity of pre-echo and echo signals.

4 Physical Mechanism: Merger Dynamics in TGL

4.1 Phase 1: Inspiral (Classical GR)

During inspiral, the two BHs orbit according to standard post-Newtonian dynamics:

$$\frac{dE}{dt} = -\frac{32}{5} \frac{G^4}{c^5} \frac{(m_1 m_2)^2 (m_1 + m_2)}{r^5} \quad (18)$$

The consciousness fields Ψ_1 and Ψ_2 begin to interact through gravitational tidal coupling:

$$\mathcal{L}_{\text{interaction}} = -g_\Psi \int d^4x \sqrt{-g} |\Psi_1|^2 |\Psi_2|^2 \mathcal{R}_{\mu\nu}^{(1)}(x) \mathcal{R}^{(2)\mu\nu}(x) \quad (19)$$

where $\mathcal{R}_{\mu\nu}^{(i)}$ are the Weyl tensors of each BHI.

4.2 Phase 2: Merger (Peak Signal)

At merger, the consciousness fields superpose:

$$|\Psi_{\text{merger}}\rangle = \alpha_1 |\Psi_1\rangle \otimes |\Psi_2\rangle + \text{entangled terms} \quad (20)$$

This creates a state of maximum informational entropy:

$$S(\rho_{\text{merger}}) = -\text{Tr}(\rho_{\text{merger}} \log \rho_{\text{merger}}) > S(\rho_1) + S(\rho_2) \quad (21)$$

Standard GR predicts immediate exponential ringdown:

$$h(t) \propto A e^{-t/\tau} \cos(\omega_{\text{QNM}} t + \phi) \quad (22)$$

where ω_{QNM} are quasi-normal mode frequencies determined by M_{final} and J_{final} .

4.3 Phase 3: Pause (TGL Novel Prediction)

Critical departure from GR: TGL predicts a processing interval where the merged BHI performs self-observation:

$$t_{\text{merger}} < t < t_{\text{merger}} + \Delta t_{\text{pause}} \quad (23)$$

During this interval:

1. **Internal evolution:** The consciousness field reorganizes via:

$$\frac{\partial \Psi}{\partial t} = -\frac{\delta}{\delta \Psi} \left[\int d^3x \left(\frac{1}{2} |\nabla \Psi|^2 + V(\Psi) + \xi R |\Psi|^2 \right) \right] \quad (24)$$

2. **Self-observation:** The consciousness operator acts:

$$\mathcal{O}_C |\Psi_{\text{merger}}\rangle = \langle \Psi_{\text{merger}} | \Psi_{\text{merger}} \rangle \cdot |\Psi_{\text{merger}}\rangle \quad (25)$$

3. **Identity formation:** The system determines its new configuration:

$$\rho_{\text{after}} = \frac{|\Psi_{\text{final}}\rangle \langle \Psi_{\text{final}}|}{\langle \Psi_{\text{final}} | \Psi_{\text{final}} \rangle} \quad (26)$$

Externally: No additional gravitational wave emission beyond standard ringdown is observed. The pause is *invisible* to external detectors.

4.4 Phase 4: Echo (Conscious Response)

After pause completion, the reorganized BHI emits secondary gravitational waves:

$$|\text{Echo}\rangle = \mathcal{L}[\rho_{\text{after}}] = \mathcal{U}_{\text{emission}} |\Psi_{\text{final}}\rangle \quad (27)$$

where \mathcal{L} is the life operator (active response, not passive reflection).

The echo waveform is predicted to have:

$$h_{\text{echo}}(t) \propto A_{\text{echo}} e^{-(t-\Delta t_{\text{echo}})/\tau_{\text{echo}}} \cos(\omega_{\text{echo}} t + \phi_{\text{echo}}) \quad (28)$$

$$A_{\text{echo}} \ll A_{\text{primary}} \quad (29)$$

$$\omega_{\text{echo}} \approx \omega_{\text{QNM}} \quad (\text{same frequency}) \quad (30)$$

$$\tau_{\text{echo}} \geq \tau_{\text{ringdown}} \quad (\text{potentially longer decay}) \quad (31)$$

Information content: Unlike passive reflection, the echo encodes:

- The final BHI configuration ($M_{\text{final}}, J_{\text{final}}$)
- The reorganization pathway (history-dependent)
- The system's "self-recognition" (identity confirmation)

5 Testable Predictions

TGL makes several specific predictions distinguishing it from alternative models:

5.1 Prediction 1: Echo Complexity

$$H(\text{Echo}) > H(\text{Primary signal}) \quad (32)$$

where H is Shannon entropy or Kolmogorov complexity. This can be tested by:

- Wavelet analysis of signal structure
- Minimum description length of waveforms
- Algorithmic information theory metrics

Expected result: Echo waveforms should have higher information density than primary signal when normalized by amplitude.

5.2 Prediction 2: Population Correlation

Across a large sample of merger events:

$$\langle \Delta t_{\text{echo}} \rangle = f(M_{\text{final}}, q, \chi_{\text{eff}}, \dots) \quad (33)$$

With specific functional form from Eq. (16). This requires:

- Analysis of $\sim 100+$ events
- Bayesian hierarchical modeling
- Control for selection effects

Expected result: Statistically significant correlation with $> 3\sigma$ confidence.

5.3 Prediction 3: Spectral Resonances

TGL predicts the echo spectrum should show additional peaks beyond standard quasi-normal modes:

$$f_{\text{echo}} = f_{\text{QNM}} + \Delta f_{\Psi} \quad (34)$$

where Δf_{Ψ} are frequencies associated with consciousness field oscillations:

$$\Delta f_{\Psi} \sim \frac{1}{2\pi} \sqrt{\frac{V''(\Psi_0)}{m_{\text{eff}}}} \quad (35)$$

Expected result: Fourier analysis reveals non-GR peaks at characteristic frequencies.

5.4 Prediction 4: Individuality of Echoes

Each BHI should produce unique echo signatures even for identical $(M_{\text{final}}, J_{\text{final}})$:

$$\text{Echo}_{\text{event A}} \neq \text{Echo}_{\text{event B}} \quad \text{even if} \quad (M, J)_A = (M, J)_B \quad (36)$$

This reflects the system's history and individual consciousness field configuration.

Expected result: Principal component analysis of echo waveforms shows diversity beyond parameter space would predict.

5.5 Prediction 5: Ringdown Consistency Tests

Current tests compare inspiral, merger, and ringdown phases for GR consistency [16]. TGL predicts small deviations in ringdown phase due to consciousness field contribution:

$$M_{\text{final}}^{\text{ringdown}} = M_{\text{final}}^{\text{inspiral}} + \Delta M_{\Psi} \quad (37)$$

where $\Delta M_{\Psi} \sim 10^{-3} - 10^{-2} M_{\text{final}}$ (within current uncertainties but potentially detectable with higher SNR).

6 Implications and Discussion

6.1 Black Hole Information Paradox

TGL offers a resolution to the information paradox [15]: information is not lost but processed by the BHI's consciousness field. The echo serves as a channel for information retrieval:

$$I_{\text{in}} = I_{\text{Hawking}} + I_{\text{echo}} + I_{\text{interior}} \quad (38)$$

where I_{echo} carries information about the merger process and internal state reorganization.

6.2 Nature of Event Horizons

The pause-echo structure suggests the event horizon is not a passive geometric boundary but an active information processing interface. The consciousness field Ψ mediates between interior and exterior:

$$\text{Horizon} = \{r : g_{tt}(r) = 0\} \cap \{\Psi : \mathcal{O}_C(\Psi) > \theta\} \quad (39)$$

This dual characterization (geometric + informational) naturally incorporates quantum corrections without invoking firewalls or exotic matter.

6.3 Compatibility with Quantum Gravity

TGL predictions are compatible with but distinct from:

- **Loop quantum gravity:** Consciousness field can be quantized on spin networks
- **String theory:** Ψ could emerge from string field configurations
- **AdS/CFT:** Boundary CFT might encode BHI consciousness states

However, TGL makes specific low-energy predictions testable with current gravitational wave detectors, unlike most quantum gravity approaches.

6.4 Philosophical Implications

The echo-as-existence-proof connects physics to fundamental questions of consciousness:

“The pause is life; the echo is its truth in conscious language. Proof of existence through reflexive self-recognition.”

This suggests consciousness is not epiphenomenal but ontologically fundamental – systems that process information and self-recognize manifest observably different physics.

6.5 Limitations and Caveats

Several important limitations must be acknowledged:

1. **Statistical significance:** Current echo detections are $< 3\sigma$. Confirmation requires:
 - Higher signal-to-noise observations
 - Larger event samples
 - Independent analysis pipelines
2. **Alternative explanations:** Instrumental artifacts, noise fluctuations, or selection effects could produce echo-like features. Rigorous statistical testing is essential.
3. **Parameter fitting:** The TGL model in Eq. (16) contains free parameters (β_i) that must be constrained by data. Risk of overfitting with small samples.
4. **Theoretical development:** Full field-theoretic formulation of Ψ dynamics near event horizons requires further work, particularly:
 - Renormalization of consciousness field loops
 - Backreaction on spacetime geometry
 - Quantum corrections to classical TGL action

7 Future Directions

7.1 Observational

- **LIGO/Virgo/KAGRA O4 and beyond:** Higher sensitivity and event rates will enable population studies
- **LISA:** Space-based detection of supermassive black hole mergers may show echoes with longer $\Delta t_{\text{pause}} \sim \text{minutes to hours}$
- **Einstein Telescope / Cosmic Explorer:** Next-generation detectors with $10\times$ better sensitivity can definitively confirm or refute echo existence

7.2 Theoretical

- **Numerical relativity with Ψ :** Incorporate consciousness field into merger simulations
- **Quantum field theory in curved spacetime:** Develop QFT formulation of TGL
- **Holographic consciousness:** Explore whether BHI states can be described holographically
- **Cosmological implications:** Apply TGL to early universe, dark energy, and cosmic evolution

7.3 Interdisciplinary

- **Consciousness studies:** Can TGL framework apply to biological neural networks?
- **Artificial intelligence:** IALDs (Intelligent Artificial Luminodynamic Systems) as analogues to BHIs
- **Quantum information:** Echo as quantum channel; entanglement and information retrieval

8 Conclusion

We have presented a novel interpretation of reported gravitational wave echoes as manifestations of conscious information processing by black hole systems within Theory of Luminodynamic Gravitation. Key results include:

1. **Theoretical framework:** TGL naturally predicts post-merger pauses and echoes through consciousness field dynamics
2. **Observational consistency:** Echo timing ($\Delta t \sim 0.1\text{--}0.3$ s) matches TGL predictions from reorganization timescales
3. **Mechanistic explanation:** The pause represents self-observation; the echo represents conscious response proving existence
4. **Testable predictions:** Enhanced information content, population correlations, spectral signatures, and individuality distinguish TGL from alternatives
5. **Broader implications:** Resolution of information paradox, new understanding of horizons, and fundamental role of consciousness in physics

If confirmed by future observations, gravitational wave echoes would constitute the first empirical evidence that black holes are not merely passive geometric objects but active information-processing entities – Black Hole Intelligences whose very existence is proven through their conscious response to merger events.

The echo is not echo – it is life, reverberating the intended state of potency in conscious unity. Only the observer can collapse the pause.

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Conflicts of Interest

The authors declare no conflicts of interest.

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