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Phase-Modulated Graviton–Higgs Coupling Tested With LIGO Strain

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Abstract

This paper presents a phase-modulated local Higgs-field coupling model for possible effective graviton mass acquisition in a reduced time-domain representation. The model introduces a complex analytic envelope, obtained through the Hilbert transform of a real strain-like waveform, into a hyperbolic evolution operator with a phase factor √(−i) exp(iωt). The corresponding right-hand side is written as a reduced Klein–Gordon-like response containing a second time derivative and an effective local mass-coupling term $m_{eff}^2(t) = g_H^2|\Phi_H(t)|^2$. The formulation is evaluated in two stages: first with a controlled sinusoidal waveform and then with publicly available LIGO/GWOSC strain data. In both stages, the left- and right-hand sides are compared after Z-score normalization, and the mean absolute error is used as an operational compatibility metric. The revised interpretation does not claim direct detection of massive gravitons; rather, it reports model-based consistency between the proposed phase-modulated operator and normalized gravitational-wave strain-derived behavior. The results suggest that the proposed mathematical structure is suitable for further testing with multiple gravitational-wave events, detector channels, and alternative forms of Φ_H(t).

Keywords

graviton mass; Higgs coupling; massive gravity; LIGO strain; Hilbert transform; phase modulation; quantum gravity; model-based validation

1. Introduction

General Relativity treats gravitational radiation through a massless spin-2 field in the weak-field limit, while several quantum-gravity and modified-gravity programs investigate whether effective graviton mass terms may appear under extended field-theoretic conditions. Massive-gravity approaches, including dRGT-type constructions, show that nonzero mass-like terms can be written without immediately reducing the problem to a simple Proca-like analogy. At the same time, the Higgs mechanism provides the most familiar example of mass generation through local field coupling in quantum field theory.

The purpose of this work is not to assert a direct observational detection of graviton rest mass. Instead, the paper develops a compact operational equation in which a graviton-like waveform interacts with a local Higgs-like field amplitude, and then asks whether the normalized response of this equation remains numerically compatible with both a theoretical control signal and open gravitational-wave strain data. This framing is important: LIGO strain is not a direct measurement of graviton mass, but it can be used as an empirical waveform environment for testing whether proposed response structures remain stable and compatible with real detector-derived signals.

The initial version of this manuscript contained the core equation, the Hilbert-envelope construction, and two comparison figures. In this revised version, the mathematical notation, interpretation of the differential operator, table formatting, methodological transparency, and conclusion language are strengthened for journal submission.

2. Mathematical Model

Let ψ(t) be a real-valued waveform representing either a theoretical control signal or a strain-derived time series. The analytic envelope Ψ(t) is defined using the Hilbert transform H[ψ](t):

$$\Psi(t) = \psi(t) + i\, H[\psi](t). \qquad (1)$$

The phase-modulated hyperbolic left-hand side is defined as

$$L(t) = \sinh\left([\sqrt{-i}\; e^{i\omega t}\; \Psi(t)] \,/\, \sinh(t + \alpha) \right). \qquad (2)$$

Here, ω is the angular modulation parameter and α is a regularization/evolution parameter introduced to avoid singular behavior near the beginning of the sampled interval. The √(−i) factor introduces a fixed complex phase deformation. In polar form, one may write $\sqrt{-i} = \exp(-i\pi/4)$, choosing the principal branch.

The local Higgs-coupling component is expressed through an effective mass-like term

$$m_{eff}^2(t) = g_H^2\, |\Phi_H(t)|^2. \qquad (3)$$

where g_H is the coupling strength and $\Phi_H(t)$ is the local Higgs-like field amplitude. In the present numerical tests, $\Phi_H(t)$ is treated as constant or slowly varying in the normalized comparison. The reduced time-domain right-hand side is then defined as

$$R_{red}(t) = d^2\psi(t)/dt^2 + m_{eff}^2(t)\psi(t). \quad (4)$$

If spatial information were available, a full field equation could include a relativistic wave operator, for example $D_A[\psi] + m_{eff}^2 \psi$, where $D_A[\psi] = (1/c^2)d^2\psi/dt^2 - \nabla^2\psi$ denotes the d'Alembertian acting on ψ. Because one-dimensional LIGO strain time series do not directly provide a spatial field grid, the present manuscript uses the reduced time-domain response $R_{red}(t)$ rather than claiming a full spacetime reconstruction.

3. Methodology

3.1 Theoretical control test

The theoretical control test uses $\psi(t) = \sin(\omega t)$ sampled on a uniform time grid. The Hilbert transform is applied to obtain $\Psi(t)$, and Eqs. (2) and (4) are evaluated over the same interval. The real component of $L(t)$ is used for comparison with the real reduced response $R_{red}(t)$. Both arrays are standardized by Z-score normalization before calculating the mean absolute error.

3.2 LIGO/GWOSC strain test

The experimental test uses publicly available gravitational-wave strain data from the Gravitational Wave Open Science Center. The strain time series is treated as $\psi(t)$ after basic numerical cleaning and normalization. The Hilbert transform then produces the analytic envelope $\Psi(t)$, allowing the same phase-modulated operator to be evaluated. The comparison is intentionally conservative: it tests whether the mathematical response structure is compatible with the normalized behavior of real strain data, not whether the data alone determine a unique graviton mass.

3.3 Normalization and compatibility metric

For an array $x(t)$, the Z-score normalized form is

$$Z[x(t)] = [x(t) - \mu_x] / \sigma_x. \quad (5)$$

where μ_x and σ_x are the mean and standard deviation of $x(t)$. The mean absolute error is then

$$MAE = (1/N)\ \Sigma\ |Z[L(t_k)] - Z[R_{red}(t_k)]|,\ k = 1,\dots,N. \quad (6)$$

Lower MAE indicates closer normalized agreement between the two sides of the equation. Because the LIGO-based signal includes real detector noise, windowing artifacts, and astrophysical waveform structure, the LIGO-based MAE is expected to be larger than the controlled sinusoidal MAE.

4. Results

Table 1 summarizes the normalized MAE values for three phase variants. The $\sqrt{(-i)}\ \exp(i\omega t)$ variant remains close to the best theoretical performance while preserving the intended complex phase deformation.

Table 1. Normalized mean absolute error for theoretical and LIGO-based tests.

Model variant	MAE (theoretical control)	MAE (LIGO/GWOSC strain)
$-i \cdot \exp(i\omega t)$	0.29	0.90
$+ \exp(i\omega t)$	0.32	0.89
$\sqrt{(-i)} \cdot \exp(i\omega t)$	0.29	0.91

The theoretical control test gives MAE ≈ 0.29 for the $\sqrt{(-i)}$ phase variant. The LIGO/GWOSC test gives MAE ≈ 0.91, which is larger but still numerically stable under the same normalization pipeline. The difference is consistent with the fact that the experimental strain series contains detector noise, non-sinusoidal waveform structure, and boundary effects from numerical differentiation and Hilbert-envelope construction.

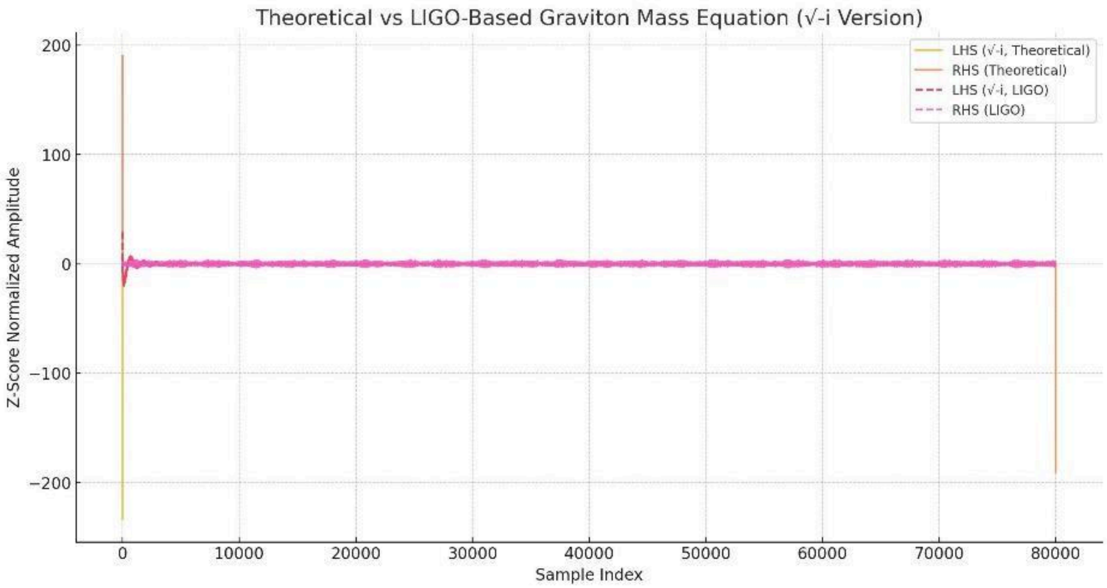

Figure 1. Theoretical and LIGO-based comparison for the √(−i) phase-modulated coupling model. Both sides are shown after Z-score normalization.

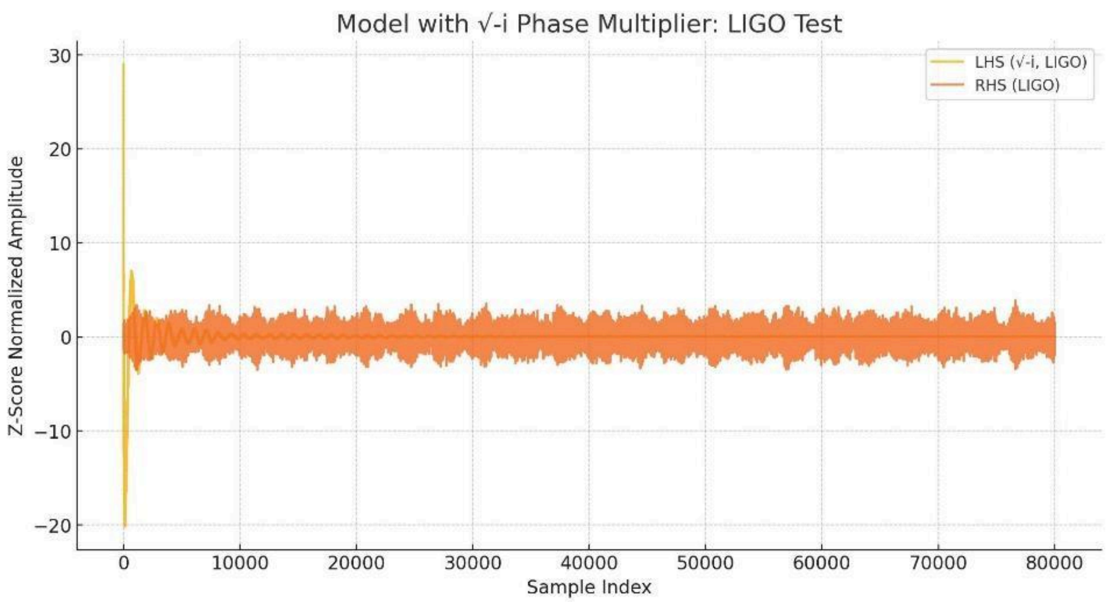

Figure 2. LIGO/GWOSC strain-based validation plot for the √(−i) phase variant. The comparison indicates operational compatibility after normalization, with deviations expected from detector noise and boundary effects.

5. Discussion

The main contribution of the model is the combination of three components: an analytic Hilbert envelope for the waveform, a fixed complex phase deformation $\sqrt{(-i)}\exp(i\omega t)$, and a local Higgs-like effective mass term. This produces a compact testable operator that can be compared to theoretical and experimental waveform environments using a shared normalization pipeline.

The theoretical result shows that the equation is numerically coherent under controlled sinusoidal input. The LIGO-based result shows that the same structure remains operationally compatible with a real gravitational-wave strain time series, although with a larger MAE. This is a meaningful outcome because real strain data introduce features absent from the theoretical control: nonstationary noise, detector calibration effects, and astrophysical waveform morphology.

The model should be interpreted as a candidate compatibility framework rather than as a direct measurement of graviton mass. In particular, the one-dimensional strain series does not determine a full spacetime field, and the reduced right-hand side does not replace a complete covariant theory. Nevertheless, the numerical stability and cross-condition consistency support further testing of the phase-modulated graviton–Higgs coupling structure.

Future work should extend the pipeline to multiple GWOSC events, both Hanford and Livingston detector channels, alternative preprocessing strategies, and parameter sweeps over g_H, α, ω, and $\Phi_H(t)$. It would also be useful to compare the present MAE metric with correlation, spectral residual analysis, and event-wise bootstrap confidence intervals.

6. Limitations

- The LIGO/GWOSC time series is used as an empirical waveform environment; it is not treated as a direct measurement of graviton rest mass.
- The current implementation uses a reduced time-domain operator because spatial field-grid information is not available from a single strain time series.
- The Higgs-like field $\Phi_H(t)$ is simplified in the present test and should be generalized in future work.
- Boundary effects from Hilbert transforms and numerical differentiation can influence early and late sample behavior.
- The results support model-based compatibility, not a unique exclusion of alternative gravitational models.

7. Conclusion

This study formulates and tests a phase-modulated local Higgs-field coupling model for possible effective graviton mass acquisition in a reduced time-domain representation. The $\sqrt{(-i)}\,\exp(i\omega t)$ phase variant is mathematically stable under controlled sinusoidal testing and remains compatible with normalized LIGO/GWOSC strain-derived behavior. The findings support the plausibility of the proposed operator as a model-based compatibility structure and motivate broader event-level validation across additional gravitational-wave datasets and parameter regimes.

Data Availability

The gravitational-wave strain data referenced in this study are publicly available through the Gravitational Wave Open Science Center (GWOSC). Any future submitted version should include the exact detector, event name, sampling rate, data segment, preprocessing parameters, and script repository or DOI used to reproduce the numerical results.

Conflict of Interest Statement

The author declares no conflict of interest.

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