Bridging Quantum and Classical Gravity via Synchronization: A Computational Diagnostic

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Abstract

We present a computational diagnostic that explores the compatibility of two gravitationally induced entanglement (GIE) mechanisms. Rather than treating quantum mediator proposals (Marletto–Vedral / Bose *et al.*) and classical-gravity-with-QFT-matter claims (Aziz–Howl) as mutually exclusive, we build an *adaptive bridge* driven by a synchronization module. A driven, lossy quantum dimer (Model C_q) exhibits a dressed-mode spectral *doublet*, while a matched classical surrogate (Model C_c) does not. The doublet confidence $D_c \in [0, 1]$ modulates the bridge weight between faithful implementations of the two proposals (Models A and B). We emphasize this does *not* adjudicate whether gravity must be quantum; it provides an evidence-aggregation workflow and a tunable test-bed that reproduces the observed doublet under transparent "plumbing" (QRT, DC removal, two-port sum).

1 Introduction

Entanglement-based witnesses for quantum gravity were proposed in [1, 2]. Aziz and Howl have argued that classical gravity with quantum matter can also yield entanglement via virtual-matter processes, prompting rebuttals that their construction imports effective nonlocality [3, 4]. We treat these as limiting mechanisms within a shared parameter space and define a synchronization "bridge" whose weighting is informed by an independently measurable spectral feature (a dressed-mode doublet).

Notation and units

Time/frequency in the dimer are reported in arbitrary simulation units; we compare *predicted* vs *measured relative* splittings, avoiding unit ambiguity.

2 Model implementations

2.1 Model A: Quantum mediator (MV/Bose)

Two masses (here $m_1 = m_2 = m$) in spatial superposition interact gravitationally, accumulating branch-dependent phases

$$\phi_{ij} = \frac{Gm^2\tau}{\hbar\, d_{ij}}, \qquad (i, j) \in \{L, R\}^2, \tag{1}$$

with $d_{LL} = d_{RR} = d$, $d_{LR} = d + \Delta x$, $d_{RL} = d - \Delta x$. Relative phases

$$\Delta\phi_{LR} = \frac{Gm^2\tau}{\hbar}\left(\frac{1}{d + \Delta x} - \frac{1}{d}\right), \quad \Delta\phi_{RL} = \frac{Gm^2\tau}{\hbar}\left(\frac{1}{d - \Delta x} - \frac{1}{d}\right), \tag{2}$$

enter the recombined spin state; we quantify entanglement by negativity N_A (for two-qubit pure states $N_A = \frac{1}{2}$ concurrence).

2.2 Model B: Classical gravity with QFT matter (Aziz–Howl)

A classical metric perturbation $h_{\mu\nu}$ couples to quantum matter,

$$H_{\text{int}} = -\tfrac{1}{2}\int d^3x \; h_{\mu\nu}(x)\, \hat{T}^{\mu\nu}(x), \tag{3}$$

and higher-order processes involving virtual matter propagators generate branch-dependent phases/amplitudes. In our implementation we follow the *paper-faithful preset* to reproduce their *scaling* in a sphere+test-particle geometry (e.g. the dominant RL branch scales like $\propto G\, m\, M^2 R^2 t/(\hbar\, d_{RL}^3)$ in the far-field).[1] The resulting entanglement proxy is reported as N_B.

2.3 Model C: Synchronization bridge

We use two linearly coupled, driven oscillators (annihilators $a_{1,2}$),

$$H = \omega_1 a_1^\dagger a_1 + \omega_2 a_2^\dagger a_2 + g(a_1^\dagger a_2 + a_1 a_2^\dagger) + \Omega_1(a_1 + a_1^\dagger) + \Omega_2(a_2 + a_2^\dagger), \tag{4}$$

with losses $\kappa_{1,2}$ and tiny pure dephasing γ_ϕ. Normal modes split by

$$\Delta\omega \;=\; 2\sqrt{g^2 + (\Delta/2)^2}, \quad \Delta = \omega_2 - \omega_1. \tag{5}$$

Spectrum method (plumbing). We compute the emission PSD via QRT from the *time-evolved* steady state (robust to nullspace issues), subtract the coherent DC pedestal, and *sum both leakage ports* to avoid dark modes. A small drive asymmetry ($\Omega_1 \neq \Omega_2$) plus $\gamma_\phi > 0$ keeps lines visible. The *doublet confidence* D_c (0–1) is extracted from peak count, separation, and balance within a band around the mean mode frequency.

3 Bridge mechanism

3.1 Adaptive coupling

We define

$$\lambda \;=\; (1 - D_\text{c})\,\frac{N_A}{N_A + N_B} \;+\; D_\text{c} \cdot \tfrac{1}{2}, \tag{6}$$

recovering evidence-weighting when $D_\text{c} \to 0$ and equal weighting when a strong doublet ($D_\text{c} \to 1$) suggests dressed-state hybridization.

3.2 Unified score

$$S \;=\; \lambda\, N_A + (1 - \lambda)\, N_B + \gamma\, D_\text{c}\, \sqrt{N_A N_B}, \qquad \gamma \approx 0.5, \tag{7}$$

where the geometric-mean term heuristically captures coherent co-contribution. We label regimes by $(N_A, N_B, D_\text{c}, \lambda)$: quantum-mediator dominant, classical+QFT dominant, and *bridge (dressed-state)* when $D_\text{c} \gtrsim 0.25$.

4 Results

We adopt the "paper" preset used in code and report JSON-derived metrics.

Parameters (C_q baseline)

ω_1=1.00, ω_2=1.14, g=0.38, κ_1=κ_2=0.015, γ_ϕ=0.003, Ω_1=0.06, Ω_2=0.02, N=5, dt=0.01, T_run=70.

[1] We treat B as a parametric surrogate for the claimed effect, not as an endorsement of any disputed nonlocal elements.

Predicted vs measured split

$$\Delta f_{\text{pred}} = \frac{2\sqrt{g^2 + (\Delta/2)^2}}{2\pi} \quad \Rightarrow \quad \Delta f_{\text{pred}} \approx 0.123.$$

From the run: $D_c = 0.599$, peak count $= 2$, measured split $\Delta f_{\text{meas}} \approx 0.12143$ (relative error $\sim$1.3%). The bridge weight is $\lambda = 0.682$ (*A-lean, dressed-state*).

Quantity	Value	Notes
N_A (Model A negativity)	0.038864	from MV/Bose module
N_B (Model B negativity)	0.001860	Aziz–Howl preset
D_c (doublet confidence)	0.598900	quantum dimer only
Δf_{meas}	0.121429	PSD peak spacing
Δf_{pred}	0.122990	from g, Δ
λ	0.682232	bridge label: A-lean

Table 1: Key synchronization and bridge metrics from the reported run.

Control ($\mathbf{C_c}$). The matched classical surrogate yields a single dominant spectral line (peak count $= 0$ under the same detector), consistent with no resolvable doublet.

5 Discussion

Complementarity. The two mechanisms need not be mutually exclusive: small masses/long τ enhance Model A; large masses/short t can enhance virtual-matter scaling in Model B; intermediate regimes produce dressed-state hybridization diagnosable via D_c.

Caveat on Model B. Nonlocality concerns in [3] remain contested [4]. We therefore use B *as a parametric surrogate* to test bridge behavior, not as a claim of physical completeness.

Methodological point. The observed doublet depends critically on using the *time-evolved* steady state for QRT, subtracting the DC pedestal, and aggregating both ports; omitting these can bury the doublet despite identical physics.

6 Limitations and next steps

Finite Fock truncation (N=5) trades speed and accuracy; larger N yields consistent splits. Thresholds in peak detection and window length affect D_c; we report these alongside raw PSDs. Future work will map $(M, t, \Delta x)$ against (N_A, N_B, D_c), include realistic decoherence, and target experiments that sit inside the bridge regime.

References

[1] C. Marletto and V. Vedral, "Gravitationally induced entanglement between two massive particles is sufficient evidence of quantum effects in gravity," *Phys. Rev. Lett.* **119**, 240402 (2017).

[2] S. Bose *et al.*, "Spin entanglement witness for quantum gravity," *Phys. Rev. Lett.* **119**, 240401 (2017).

[3] J. Aziz and R. Howl, "Classical theories of gravity produce entanglement," *Nature* **646**, 813–817 (2025).

[4] C. Marletto and V. Vedral, “Classical gravity cannot mediate entanglement by local means,” arXiv:2510.19969 (2025).