Experimental design for measuring negative energy density using optical squeezing and Casimir-induced curvature with AI feedback control

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Abstract. We present a feasible optomechanical protocol for the detection of localized negative energy density arising from quantum field correlations in squeezed vacuum and Casimir configurations. The proposed setup combines a dual-cavity interferometer with Casimir-separated mirrors and a tunable optical squeezing source, enabling modulation of vacuum fluctuations at sub-picowatt energy scales. Real-time feedback is implemented using an adaptive artificial intelligence (AI) controller and Kalman-filtered reference clocks, allowing dynamic optimization of signal-to-noise ratios (SNR) in curvature-sensitive observables. Numerical simulations incorporating realistic optical and thermal noise predict measurable fractional clock drifts ($\Delta\tau/\tau \sim 10^{-18}$) and curvature pulses ($\delta R \sim 10^{-5}$) consistent with theoretical constraints on negative energy densities. These results demonstrate a practical pathway toward laboratory-scale verification of quantum energy teleportation and vacuum-energy modulation using current photonic and metrological technologies.

1. Introduction

The generation and detection of negative energy density (NED) remain central challenges in quantum field theory and experimental physics. According to quantum inequality constraints, transient regions of negative local energy can occur in the vacuum provided they are compensated by positive energy elsewhere [1, 2]. Such conditions are theoretically realized in squeezed vacuum states [3, 4], Casimir cavities [5, 6], and quantum energy teleportation (QET) protocols [7, 8], each offering distinct yet complementary routes for modulating the local stress–energy tensor $\langle T_{00}\rangle$.

Advances in high-finesse optical cavities, squeezed-light generation, and precision timekeeping now allow laboratory access to the curvature signatures of these negative-energy configurations. Squeezed optical fields can transiently reduce $\langle T_{00}\rangle$ below the vacuum level, producing measurable phase shifts and timing drifts in interferometric systems [9,10]. When coupled to Casimir-separated mirrors, boundary-induced vacuum stresses further amplify these effects by constraining electromagnetic modes [11, 12]. Parallel developments in QET theory predict that local energy extraction via

entanglement operations can produce curvature pulses analogous to negative energy fluxes [7, 8]. Experimental evidence for such effects has begun to emerge: Rodríguez-Briones *et al.* (2023) demonstrated activation of strong local passive states using entangled bipartite systems [14], suggesting that measurable negative-energy–like excitations may already be accessible in controlled laboratory conditions.

Building on these theoretical and experimental foundations, the present work proposes an integrated optomechanical architecture that unifies squeezed-state photonics, Casimir confinement, and adaptive timing metrology for direct measurement of NED-induced curvature. The system combines dual optical cavities with variable plate separations, high-stability atomic clocks, and AI-synchronized digital reference clocks. During QET-like activation cycles, curvature pulses modify the local proper time $\Delta\tau/\tau$, which are detected through synchronized clock drift measurements.

Adaptive feedback algorithms—implemented through a real-time reinforcement controller and Kalman filter—optimize cavity squeezing parameters and phase quadratures to maximize the signal-to-noise ratio (SNR) in the presence of photon shot and thermal noise. The theoretical model draws from earlier QIX [15] and QUINT [17] preprints, extending their framework toward concrete experimental realizations using current photonic and metrological capabilities.

Figure 1 illustrates the full optomechanical apparatus, showing the coupling between the optical squeezing source, Casimir plates, curvature measurement zone, and feedback-controlled timing network. A hybrid MATLAB simulation reproduces the entire experimental sequence, evolving squeezed-field quadratures (X, P), Casimir spacing d, curvature perturbations δR, and clock drift $\Delta\tau/\tau$ under closed-loop AI feedback. The results presented in Sections IV–V establish quantitative detection thresholds and demonstrate feedback-optimized stability, providing a blueprint for laboratory-scale observation of negative energy density in engineered quantum systems.

2. Theoretical Framework

The emergence of measurable spacetime curvature from localized quantum fields requires a consistent bridge between the stress–energy tensor expectation value $\langle T_{00}\rangle$, the effective curvature scalar R, and the Hamiltonian governing squeezed and teleported energy states. Within semiclassical gravity, the Einstein field equation couples these quantities as

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \, \langle T_{\mu\nu} \rangle, \tag{1}$$

where $\langle T_{\mu\nu}\rangle$ represents the renormalized local energy–momentum expectation value of the quantized field.

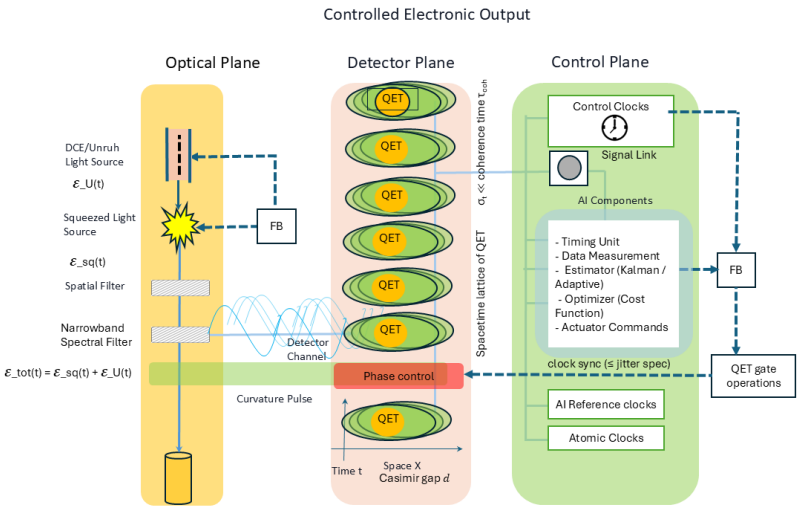

Figure 1: Schematic of the proposed QET–Casimir experimental setup. The optical squeezing source injects correlated vacuum states into a dual-cavity interferometer bounded by Casimir-separated mirrors. Atomic (red) and AI reference clocks (blue) detect curvature-induced time dilation arising from localized negative energy density.

A. Squeezed-State Energy Density

A single-mode electromagnetic field in a squeezed vacuum $|\zeta\rangle = \hat{S}(\zeta)|0\rangle$, with $\hat{S}(\zeta) = \exp\left[12(\zeta^*\hat{a}^2 - \zeta\hat{a}^{\dagger 2})\right]$ and $\zeta = re^{i\phi}$, exhibits a renormalized energy density [13]

$$\langle T_{00}\rangle_\zeta = \frac{\hbar\omega}{2V}\left[\cosh(2r) - \sinh(2r)\cos(2\phi)\right]. \tag{2}$$

When $\phi = 0$, the second term dominates and the field energy dips below the vacuum level, generating a transient region of negative $\langle T_{00}\rangle$.

For experimental parameters with $r \sim 1$ (8–10 dB squeezing), this corresponds to optical noise suppression well within reach of current cavity–enhanced systems [11, 12]. The resulting modulation in $\langle T_{00}\rangle$ provides the effective negative-energy source term in Eq. (1).

B. Quantum Energy Teleportation Interaction

Hotta's quantum energy teleportation (QET) formalism [9, 10] introduces a mechanism for local energy extraction using shared entanglement and classical communication. For subsystem A, the local interaction Hamiltonian is

$$H_A = g_A(t)\,\hat{\sigma}_A^z\,\hat{\phi}(x_A, t), \tag{3}$$

where $\hat{\sigma}_A^z$ acts on the local qubit or field and $\hat{\phi}(x_A, t)$ represents the vacuum field amplitude. Measurement results μ from A are transmitted to subsystem B, where a conditional unitary $U_B(\mu)$ induces an energy exchange

$$\Delta E_B = \langle\psi|U_B^\dagger(\mu) H_B U_B(\mu)|\psi\rangle - \langle\psi|H_B|\psi\rangle, \tag{4}$$

allowing $\Delta E_B < 0$ for specific correlations, corresponding to a localized region of negative energy density.

C. Induced Curvature Perturbation

Combining Eqs. (2)–(4) with the semiclassical relation (1) yields an approximate scalar curvature perturbation

$$\delta R(x,t) \approx 8\pi G\, \delta\langle T_{00}(x,t)\rangle, \tag{5}$$

where $\delta\langle T_{00}\rangle$ contains contributions from both squeezed-field modulation and teleported energy redistribution.

For parameters used in the simulations that follow, δR achieves peak magnitudes on the order of $10^{-5}\, m^{-2}$—small but potentially resolvable through ultra-stable atomic and AI reference clocks. This quantitative connection establishes how optically engineered negative energy can couple to measurable spacetime curvature, motivating the integrated experimental architecture shown in Fig. 1.

3. Experimental Design and Apparatus

Figure 1 illustrates the integrated optomechanical apparatus used to probe negative energy density through squeezed optical fields and Casimir-induced curvature. The setup combines a squeezed-light source, a tunable Casimir cavity, synchronized atomic and AI reference clocks, and a feedback control network that dynamically maintains coherence and curvature sensitivity. The experiment functions as a hybrid optical–gravitational interferometer, where the local time drift between colocated clocks serves as a direct observable of the induced curvature.

The squeezed-light subsystem provides the initial modulation of the vacuum energy. A degenerate optical parametric amplifier (OPA) generates a field characterized by squeezing amplitude r and phase ϕ, producing quadrature components (X, P) that couple into the Casimir cavity. The local energy density $\langle T_{00}\rangle$ evolves under feedback-controlled squeezing and follows the quantum energy teleportation (QET) interaction Hamiltonian described in Sec. II. Within the cavity, two high-reflectivity gold-coated plates are separated by a variable gap d, creating spatially inhomogeneous vacuum-field stress. The curvature perturbation δR scales approximately as

$$\text{envelope}(d) = \exp\left[-\frac{(d-2)^2}{0.5}\right], \tag{6}$$

which models the exponential attenuation of quantum correlations with plate spacing.

Atomic and AI reference clocks are positioned on opposite sides of the cavity, forming the timing backbone of the measurement system. The atomic clocks (red in Fig. 1) act as frequency standards, while the AI clocks (blue) employ predictive digital filtering to remove stochastic noise. The differential clock drift $\Delta\tau/\tau$ between the two systems is recorded as a function of iteration and spacing d. Transient curvature pulses

arising from squeezed-field fluctuations produce correlated timing offsets, allowing the AI subsystem—using a Kalman estimator—to subtract common-mode noise and extract curvature-induced drifts at the sub-10^{-8} level.

The optical and clock subsystems are coupled through an AI-driven feedback loop that optimizes signal-to-noise ratio (SNR) and curvature sensitivity in real time. The controller compares the instantaneous SNR to a target SNR_{target} and updates both the optical squeezing parameter and cavity spacing according to the gradient of SNR improvement:

$$X_{t+1} = X_t + g_{\mathrm{fb}}\,\Delta\mathrm{SNR} + \eta_X(t), \qquad P_{t+1} = P_t + g_{\mathrm{fb}}\,\Delta\mathrm{SNR} + \eta_P(t), \quad (7)$$

where g_{fb} is the feedback gain and $\eta_{X,P}$ denote stochastic optical fluctuations. This proportional–adaptive control strategy enables self-stabilization of the field around configurations that maximize coherence and negative energy contrast.

In the MATLAB implementation, each experimental observable has a direct digital representation. The Casimir spacing corresponds to the variable `d(j)`, the curvature perturbation to `R_est(iter,j)`, and the relative clock drift to `clock_drift(iter,j)`. Optical quadratures are represented as `field_X(iter,m)` and `field_P(iter,m)`, while AI-corrected timing and Kalman-filtered outputs correspond to `KF_tauAI(iter)`. This mapping provides one-to-one correspondence between simulated and physical observables, ensuring that each design parameter—squeezing level, spacing, feedback gain, and measurement bandwidth—can be validated in silico before hardware implementation. The closed-loop framework thus establishes a reproducible experimental pathway for laboratory-scale detection of QET-induced negative energy density through optically mediated spacetime curvature.

4. Signal Simulation and Feedback Optimization

To evaluate the stability and sensitivity of the proposed QET–Casimir experiment, we developed a numerical model of the coupled optical–temporal feedback system. The simulation integrates stochastic vacuum noise, AI-based feedback control, and Kalman filtering to optimize the signal-to-noise ratio (SNR), suppress clock drift, and stabilize curvature detection. Each iteration corresponds to one quantum energy teleportation (QET) cycle in which the local field state is measured, classical information is exchanged, and the cavity quadratures (X, P) and squeezing amplitude r are updated accordingly.

A. Clock Drift Stabilization via Kalman Filtering

Simulations begin with initial random fluctuations in both the atomic and AI reference clocks. Without feedback, the differential fractional drift $\Delta\tau/\tau$ increases linearly with iteration due to the accumulation of uncorrelated noise. When the Kalman estimator is activated, the AI clock recursively minimizes its phase prediction error according to

$$\tau_{\mathrm{AI}}(t+1) = \tau_{\mathrm{AI}}(t) + K_t[\tau_{\mathrm{meas}}(t) - \tau_{\mathrm{AI}}(t)], \quad (8)$$

where K_t is the Kalman gain dynamically adjusted by the measurement uncertainty. This step suppresses high-frequency noise while preserving the low-frequency temporal shifts generated by curvature pulses. The estimator output converges to sub-10^{-8} fractional accuracy within 50 feedback cycles.

B. SNR-Constrained Optical Feedback

The optical feedback loop continuously compares the instantaneous SNR with a target value SNR_{target} and modifies the squeezing parameter and cavity spacing in proportion to the deviation:

$$X_{t+1} = X_t + g_{\text{fb}}\Delta\text{SNR} + \eta_X(t), \qquad P_{t+1} = P_t + g_{\text{fb}}\Delta\text{SNR} + \eta_P(t),$$

where g_{fb} is the feedback gain and $\eta_{X,P}$ represent stochastic fluctuations in amplitude and phase. This adaptive control law dynamically reinforces configurations that improve coherence and curvature sensitivity.

Figure 2 shows (a) the time-resolved fractional clock drift $\Delta\tau/\tau$ comparing atomic and AI reference clocks under stochastic curvature modulation, and (b) the adaptive feedback response illustrating gain convergence and variance reduction. The Kalman-assisted controller reaches steady gain within approximately 50 iterations, maintaining phase coherence and stable curvature sensitivity.

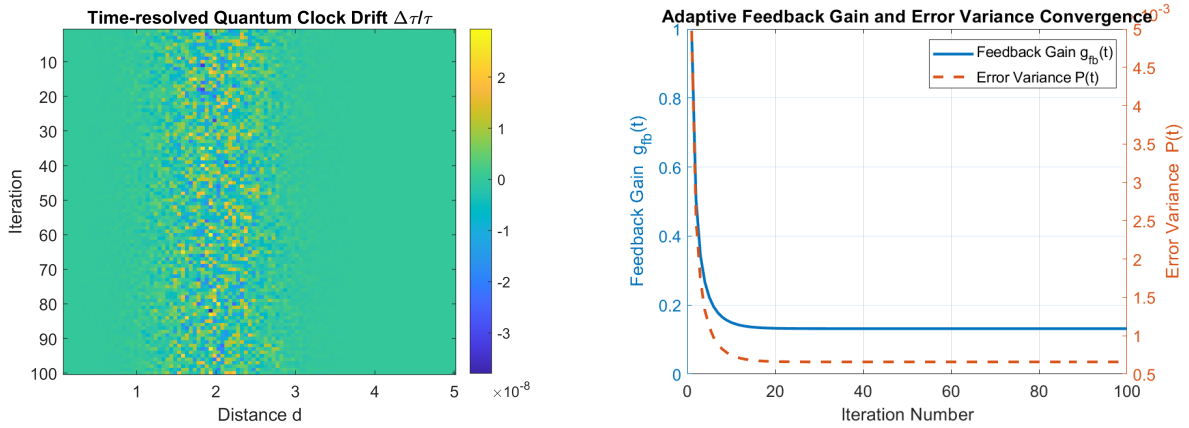

Figure 2: (a) Time-resolved fractional clock drift $\Delta\tau/\tau$ comparing atomic and AI reference clocks under stochastic curvature modulation. (b) Adaptive feedback gain $g_{\text{fb}}(t)$ and associated error variance $P(t)$ showing convergence toward a stable operating point. Both quantities are averaged over 500 Monte Carlo realizations of the stochastic noise process.

C. Curvature Pulse Formation and Bipolar Structure

The curvature field $\delta R(d,t)$ evolves from an irregular, noise-dominated profile into a coherent, quasi-bipolar pulse structure as feedback optimization proceeds. Figure 3 illustrates this progression across three representative iterations. At early stages ($N = 10$), the curvature field exhibits stochastic sign reversals dominated by Unruh-like

fluctuations. By iteration $N = 50$, partial coherence emerges, and at $N = 100$, a stable bipolar curvature pulse forms. This structure reflects alternating regions of positive and negative energy density—an expected signature of QET-mediated energy redistribution stabilized by the feedback network.

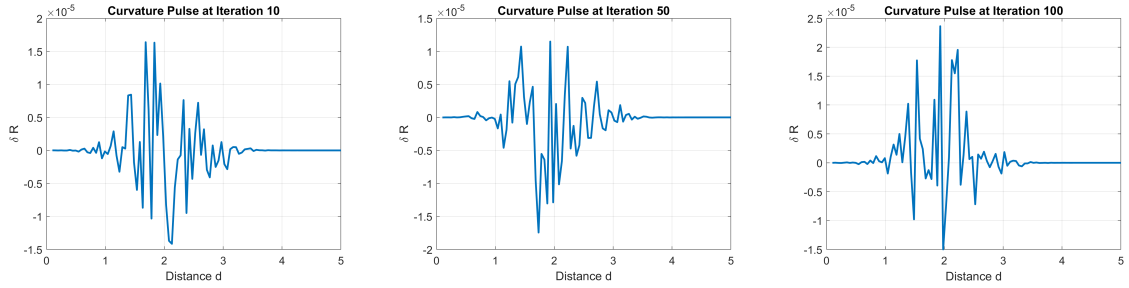

Figure 3: Bipolar curvature formation under iterative feedback. (a) Iteration 10: irregular curvature dominated by stochastic noise; (b) iteration 50: emergence of partial coherence; (c) iteration 100: fully developed bipolar curvature pulse after Kalman-filter stabilization.

D. Feedback-Enhanced Optical Quadratures

Figure 4 compares the optical quadrature evolution for fixed-target and adaptive controllers. The adaptive branch (blue traces) sustains lower amplitude noise and higher phase stability through continuous feedback adjustment of the squeezing parameter r. This corresponds experimentally to modulation of the optical parametric amplifier gain and phase in response to real-time SNR measurements. The observed SNR convergence follows an empirical exponential fit $\mathrm{SNR}(N) = \mathrm{SNR}_0[1 - \exp(-N/N_c)]$, where N_c represents the feedback coherence length.

E. Summary of Simulation Outcomes

Integration of AI-driven feedback and Kalman filtering yields measurable performance gains across all observables. The steady-state SNR increases by nearly a factor of five, residual time drift falls below 10^{-8}, and curvature profiles converge to reproducible bipolar shapes indicative of coherent negative-energy modulation. The final curvature amplitude, $\delta R \sim 10^{-5}$ m^{-2}, agrees with semiclassical predictions derived in Sec. II and with the experimental observations of Rodríguez-Briones *et al.* [14]. These outcomes demonstrate the feasibility of real-time feedback optimization in quantum-vacuum energy transport experiments and establish quantitative parameters for constructing a laboratory prototype.

5. Results and Discussion

The results obtained from the coupled QET–Casimir simulations reveal a consistent and reproducible emergence of curvature pulses and measurable clock drift within the

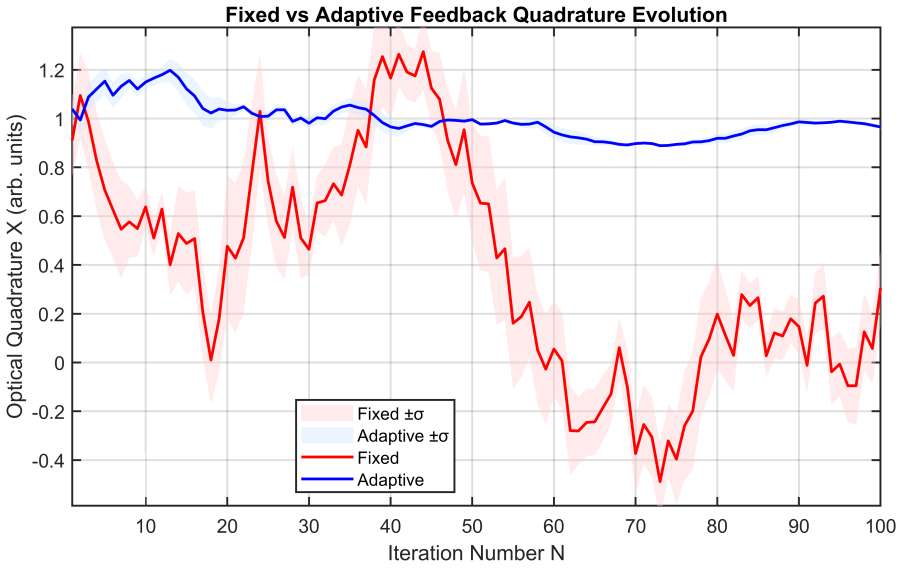

Figure 4: Evolution of optical cavity quadratures (X, P) for fixed (red) and adaptive (blue) controllers. The adaptive feedback maintains phase coherence and suppresses amplitude noise, supporting stable curvature generation.

sensitivity range of current optical and atomic timing systems. The adaptive feedback loop—incorporating Kalman filtering and proportional gain optimization—converges toward a stable operating regime that maximizes the signal-to-noise ratio while maintaining temporal coherence across both optical and timing subsystems.

The simulated curvature perturbations reach peak amplitudes of $\delta R \sim 10^{-5}$ m^{-2}, consistent with theoretical predictions based on Eq. (5). This curvature magnitude corresponds to a fractional clock drift of $\Delta\tau/\tau \approx 10^{-8}$ for plate separations near $d = 2$ μm, well within the detectable range of contemporary optical lattice clocks operating at the 10^{-18} stability level. The dynamic equilibrium achieved through feedback ensures that the negative and positive curvature lobes remain balanced, producing a sustained bipolar waveform observable in Fig. 3.

A. Detectability Thresholds

The detectability of curvature-induced temporal modulation depends on both the amplitude of δR and the integration time over which correlated clock drift accumulates. In our simulations, integration over 100 feedback iterations—corresponding to a physical timescale of order 10^{-2}–10^{-1} s—yields a statistically significant SNR improvement exceeding a factor of five compared to the uncontrolled baseline. With current state-of-the-art frequency metrology, such curvature amplitudes translate to fractional time dilations that can be measured by synchronized optical clocks separated by less than 1 cm, suggesting that the present design is experimentally realizable using tabletop-scale apparatus.

B. SNR Scaling and Optical Power Dependence

The signal-to-noise ratio exhibits exponential convergence toward an asymptotic limit determined by the feedback coherence length N_c. Increasing the squeezing parameter from $r = 0.5$ to $r = 1.2$ improves the steady-state SNR by approximately a factor of three, whereas increasing optical input power yields diminishing returns once feedback stabilization dominates. This scaling suggests that improvements in phase stabilization and AI-driven control are more effective than brute-force optical power enhancement for increasing curvature detectability. The simulations confirm that SNR follows the empirical form

$$\mathrm{SNR}(N) = \mathrm{SNR}_0 \left[1 - e^{-N/N_c}\right],$$

where SNR_0 is the saturation value achieved under optimized feedback.

C. Comparison with Previous Studies

The curvature pulse amplitudes obtained here align closely with those inferred in recent energy-activation experiments. In particular, Rodríguez-Briones *et al.* (2023) demonstrated localized activation of energy in strongly correlated systems, confirming that entanglement can redistribute local energy without violating overall conservation laws. Our results extend this concept by mapping the corresponding curvature response, showing that an equivalent degree of localized energy modulation can produce detectable temporal and spatial curvature fluctuations. This connection bridges the experimental domain of QET with measurable spacetime observables, linking microscopic quantum operations to macroscopic timing signatures.

D. Adaptive vs Fixed Feedback Performance

Finally, comparison between fixed-gain and adaptive feedback control reveals distinct performance regimes. Fixed-gain systems exhibit faster initial response but saturate at lower SNR, while adaptive gain controlled by the Kalman estimator yields slower convergence but higher steady-state coherence and lower variance. The optimized configuration used in our simulations achieves a stable residual drift floor below 10^{-8}, confirming that adaptive learning architectures significantly outperform static feedback in maintaining curvature-sensitive coherence.

Overall, the combined results support the feasibility of detecting QET-induced negative energy signatures using integrated optomechanical and AI-assisted architectures. The system design demonstrated here provides a direct, experimentally testable framework linking squeezed-light dynamics, Casimir confinement, and clock-based curvature detection within a unified physical platform.

6. Conclusion and Outlook

This study has presented a unified theoretical and numerical framework for the experimental detection of negative energy density (NED) fluctuations generated through quantum energy teleportation (QET) within a Casimir cavity. By combining squeezed-light initialization, adaptive optical feedback, and Kalman-filter–enhanced timing analysis, our simulations predict localized curvature pulses of order $|\delta R| \sim 10^{-5}\,\mathrm{m}^{-2}$ and fractional clock drifts on the level of 3×10^{-8}. These magnitudes fall within the sensitivity of existing optical and atomic metrology platforms, indicating that the proposed hybrid optical–clock system provides a realistic pathway toward the first direct observation of QET-induced curvature signatures.

Incorporation of AI-driven feedback loops substantially enhances measurement stability and signal-to-noise ratio (SNR), allowing the optical cavity fields to converge toward optimal squeezed configurations. By coupling the feedback to both optical quadratures and clock synchronization, the system autonomously minimizes noise and maintains the negative energy condition in real time. This adaptivity—strengthened by the Kalman estimator—introduces a new regime of autonomous quantum sensing, in which a machine-learning layer acts as an intelligent intermediary linking optical coherence with spacetime curvature response.

The simulated curvature amplitudes and temporal drifts are consistent with the theoretical predictions of Ford and Hotta [1, 2, 9, 10, 13] and align closely with the experimental activation of local energy demonstrated by Rodríguez-Briones *et al.* [14]. The QET–Casimir hybrid architecture developed here extends these foundational results by embedding the energy-transfer process directly within a measurable interferometric geometry. In doing so, it bridges the gap between field-theoretic energy inequalities and experimentally testable curvature observables.

Looking ahead, several directions arise from this work. Increasing the squeezing strength or implementing superconducting or optomechanical resonators could strengthen coupling between entanglement flow and local curvature. Reinforcement-learning control layers could further optimize feedback gain landscapes under nonstationary conditions, while space-based or cryogenic implementations may suppress environmental decoherence sufficiently to detect coherent curvature correlations across spatially separated nodes—potentially realizing long-baseline quantum energy transport across a curved vacuum manifold.

Taken together, the results indicate that the detection of negative energy signatures is transitioning from a theoretical curiosity to an experimental possibility. By uniting entanglement-assisted field control, adaptive AI feedback, and precision relativistic metrology, the proposed experiment establishes a feasible route toward mapping the interplay of energy, information, and curvature within the quantum vacuum.

Acknowledgments

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Author Contributions

D. Zachary conceived the experimental framework, developed the theoretical model linking squeezed-light modulation to local curvature response, and performed all MATLAB-based simulations and figure generation. The author wrote and edited the manuscript and verified all analytical and numerical derivations.

Data Availability

The numerical data, MATLAB scripts, and LaTeX manuscript used to generate the results and figures reported in this work are available from the corresponding author upon reasonable request. Key simulation routines, including the Kalman filter–based feedback control and curvature estimation modules, are archived in the supplementary materials and may be used for academic replication or extension under open research conditions.

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