Testing the ER = EPR conjecture

Zachary, D.S.*
Energy Policy and Climate Program Johns Hopkins Advanced Academic Programs 555 Pennsylvania Avenue, NW Washington, D.C. 20001
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We propose a compact, low-cost experimental test of the ER=EPR conjecture by probing whether quantum entanglement modifies local vacuum energy. Entangled photon pairs, generated via spontaneous parametric down-conversion, are routed such that one photon traverses a standard optical path and the other passes through a variable-width Casimir cavity. By analyzing the violation of the Clauser-Horne-Shimony-Holt (CHSH) Bell inequality, we test whether changes in the vacuum structure affect entanglement visibility. If successful, this approach could yield the first direct laboratory evidence linking entanglement to spacetime geometry. We analyze experimental sensitivity, noise sources, and feasibility using commercially available components. This framework is complemented by alternative and next-generation proposals, including optomechanical, interferometric, and cosmological probes of Planck-scale wormhole structure.

Keywords: ER=EPR Conjecture, Quantum Entanglement, Casimir Effect, Bell Inequality Test, Planck-Scale Wormholes

I. INTRODUCTION

The relationship between quantum entanglement and the geometry of spacetime remains one of the most compelling open questions in theoretical physics. The ER=EPR conjecture, first formalized by Maldacena and Susskind [87], posits a deep equivalence between Einstein-Rosen bridges (wormholes)[1] and quantum entanglement[2]. This framework suggests that entangled particles may be connected via non-traversable wormholes, implying that spacetime connectivity itself could emerge from quantum entanglement [4].

This idea may resolve longstanding puzzles such as the black hole information paradox [5] and the AMPS firewall problem [6], by reinterpreting entanglement as a geometric connection. If true, ER=EPR would imply that spacetime, gravity, and quantum information are fundamentally interlinked [7].

Despite its theoretical appeal, experimental tests of ER=EPR remain scarce. In this work, we propose a laboratory-scale experiment to investigate whether quantum entanglement can measurably influence vacuum energy, as manifested through the Casimir effect. Further, we discuss complementary tests—optomechanical, optical squeezing, and spectroscopy modules (Section II). Our approach utilizes a Bell inequality test in which one photon from an entangled pair passes through a tunable Casimir cavity. Any deviation in entanglement visibility or Bell parameter S as a function of cavity separation would suggest that local vacuum energy responds to quantum correlations.

Additional alternative strategies (Section III) involving precision atomic clocks and time-of-flight measurements, atom interferometry tests, high-precision rotational experiments, particle accelerators and colliders, and vacuum birefringence. Finally, we discuss a set of next-generation experiments in Section IV.

II. BELL-CASIMIR-OPTICAL TESTS

a. Experimental Concept. We propose a hybrid test combining a Bell inequality experiment with a tunable Casimir cavity. Entangled photon pairs are generated via spontaneous parametric down-conversion (SPDC). One photon (Alice) is measured directly, while the other (Bob) passes through a Casimir cavity with variable plate separation d.

Optical experiments can significantly enhance the sensitivity of the Bell–Casimir configuration. These methods detect fine modulations in electromagnetic fields arising from boundary-condition-induced vacuum changes. We describe a set of optical additions to the Bell-Casimir framework.

The central hypothesis is that the modified vacuum energy within the cavity alters quantum correlations of the photon pair. If ER=EPR holds, the wormhole-induced vacuum structure could manifest as a measurable shift in the Bell parameter.

b. Bell Parameter Analysis. The CHSH inequality is tested by computing:

$$S = E(\theta_A, \theta_B) - E(\theta_A, \theta'_B) + E(\theta'_A, \theta_B) + E(\theta'_A, \theta'_B), \quad (1)$$

where $E(\theta_A, \theta_B)$ represents the correlation between measurements at angles θ_A and θ_B. Quantum theory allows $|S| \leq 2\sqrt{2}$, while classical local theories are bounded by $|S| \leq 2$.

We define a small entanglement suppression fac-

* Correspondence email address: d.s.zachary@jhu.edu

tor due to wormhole-induced decoherence:

$$\gamma_{\rm ER} \approx \frac{\Delta E_{\rm vac}}{E_q}, \tag{2}$$

where $\Delta E_{\rm vac} \sim 10^{-6}$ eV is the Casimir-induced vacuum energy shift, and $E_q \sim 1$ eV is the photon energy. The modified Bell parameter becomes:

$$S(d) = 2\sqrt{2} \cdot (1 - \gamma_{\rm ER}). \tag{3}$$

For $\gamma_{\rm ER} \sim 10^{-6}$, this implies a deviation:

$$\Delta S \sim -2.8 \times 10^{-6}. \tag{4}$$

c. Optical Squeezing. Optical squeezing reduces quantum noise in a single field quadrature, making it extremely sensitive to perturbations in the vacuum. We inject a squeezed vacuum state into the Alice arm using a sub-threshold optical parametric oscillator (OPO), following the method in [19].

If ER=EPR introduces additional correlated vacuum modes, the noise variance is modified as:

$$\Delta V_{\rm squeezed} \to \Delta V_{\rm squeezed}(1 \pm \varepsilon_{\rm ER}), \tag{5}$$

where $\varepsilon_{\rm ER} \sim 10^{-3}$ corresponds to a Planck-scale modification [20].

d. Optomechanical Test Two configurations are considered: First, a membrane-in-the-middle (OMM), is a thin dielectric membrane is placed in the center of a high-finesse cavity. Radiation pressure from intracavity photons modulates the membrane's motion:

$$\delta x_{\rm SQL} = \sqrt{\frac{\hbar}{2m\omega_m}}, \tag{6}$$

where m is the membrane mass and ω_m its mechanical frequency [29]. Next a compliant moving mirror (CMM), which is a a cavity mirror mounted on a microcantilever. The vacuum stress induced by entangled geometry may displace the mirror. The thermally limited sensitivity is:

$$\delta x_{\rm res} = \sqrt{\frac{k_B T}{m\omega_m^2 Q}}, \tag{7}$$

where Q is the mechanical quality factor. Both systems test for entanglement-induced shifts in stress-energy [22, 23].

e. High-Finesse Spectroscopy Loop. The HFSL is a closed-loop optical circuit formed by two Fabry–Pérot cavities. Phase shifts due to entanglement-modified vacuum energy accumulate coherently. The phase sensitivity is enhanced as:

$$\Delta\phi_{\rm loop} \sim N_{\rm loop} \cdot \frac{2\pi}{\lambda} \cdot \Delta L, \tag{8}$$

where $N_{\rm loop}$ is the number of round-trips [24].

Compared to standard optical cavity spectroscopy, the HFSL offers: recursive signal enhancement, Sub-Hz linewidth sensitivity, and phase noise suppression via PDH locking.

Among the three, HFSL stands out for its ability to accumulate Planck-scale fluctuations coherently over multiple loops. Its recursive phase sensitivity and cavity integration allow for robust tests of vacuum entanglement and wormhole-like correlations. Previous work has shown that feedback-enhanced spectroscopy loops improve phase noise suppression and signal extraction by orders of magnitude in low-photon regimes [27–29].

f. ER=EPR Enhancement and Suppression Mechanisms. To better understand the signal dynamics of the Bell–Casimir–Optical experiment, we categorize known theoretical mechanisms into those that may *enhance* or *suppress* observable effects of Planck-scale wormhole-induced vacuum fluctuations. Table II summarizes these mechanisms and maps them to the relevant subsystems: Bell test, Casimir cavity, optical squeezing, optomechanical sensors, and the High-Finesse Spectroscopy Loop (HFSL). See Tab. II for the connection between the enhancement/suppression category and the test.

g. Interpretation, Implications, and Feasibility. The proposed experiment aims to test whether quantum entanglement can induce measurable changes in local vacuum structure, as predicted by the ER=EPR conjecture. A statistically significant shift in the Bell parameter S due to the presence of a Casimir cavity would suggest that entanglement affects vacuum energy or geometry, providing an indirect signature of Planck-scale wormhole connections.

Also, the Casimir force between parallel plates separated by d is:

$$F_C = -\frac{\pi^2 \hbar c}{240 d^4} A. \tag{9}$$

If entanglement alters vacuum modes, the effective energy shift $\Delta E_{\rm vac}$ would lead to a fractional force change:

$$\frac{\Delta F}{F_C} \approx \frac{\Delta E_{\rm vac}}{\rho_{\rm vac}}, \tag{10}$$

where $\rho_{\rm vac} \sim 10^{-3}\,{\rm eV}^4$. This corresponds to a possible $\sim 10^{-3}$ fractional shift in force.

Similarly, perturbations in squeezed vacuum quadratures, membrane displacement, or coherent phase shifts in the spectroscopy loop would indicate modified zero-point fields or stress-energy tensors—implying a deeper, possibly geometric role of entanglement in vacuum structure.

Each subsystem targets a different observable but is designed to respond to the same hypothet-

Test	Formula	Shift	Why It Probes ER=EPR
Bell	$S = 2\sqrt{2}(1 - \gamma_{\rm ER})$	$\Delta S \sim 10^{-6}$	Deviation in S from quantum maximum may reveal wormhole-induced decoherence or effective locality violation in entangled systems [4, 87].
Casimir	$\Delta F/F_0 \sim \Delta E_{\rm vac}/\rho_{\rm vac}$	$\Delta F/F_0 \sim 10^{-3}$	ER=EPR implies nonlocal vacuum modifications altering zero-point energies [40, 41].
Squeezing	$\Delta X^2_{\rm squeezed} < 1/2$ †	$\sim 10^{-2}$ ††	ER=EPR may increase/redistribute vacuum fluctuations, reducing squeezing [28, 42].
Optomechanical	$\delta x = F_{\rm vac}/m\omega_m^2$	$\delta x \sim 10^{-15}$ m ‡	Modifications to stress-energy from entangled vacuum can shift the equilibrium of a mechanical probe [29, 32].
Spectroscopy	$\delta\nu/nu_0 \sim \Delta n/n$	$\delta\nu/\nu_0 \sim 10^{-10}$	ER=EPR-induced vacuum index change affects cavity resonance; [24, 25].

† vacuum level; †† Extra vacuum noise or suppressed squeezing; ‡ for $\Delta F \sim 10^{-18}$ N.

Table I: Unified summary of five experimental observables probing Planck-scale ER=EPR effects via vacuum shifts, entanglement, and metric backreaction.

ical geometric influence. The Bell test probes entanglement fidelity; the squeezing test is sensitive to excess vacuum noise or phase-space distortion; the optomechanical system reacts to altered vacuum pressure; and the spectroscopy loop amplifies phase anomalies consistent with nonlocal vacuum structure. Consistent deviations across these modules would greatly strengthen the claim that entanglement modifies the vacuum—supporting ER=EPR.

Feasibility is bolstered by the use of commercially available components: single-photon detectors with sub-nanosecond timing resolution, mechanically tunable Casimir plates, high-Q SiN membranes, OPO-based squeezing sources, and Pound–Drever–Hall stabilized cavities. Signal-to-noise ratios for the Bell parameter S can reach SNR > 10 with 10^8 entangled photon pairs. Homodyne detection of squeezing can resolve variance shifts down to $\Delta V/V \sim 10^{-8}$, while membrane displacement sensitivity is on the order of 10^{-15} m, and loop-based phase shifts can reach 10^{-13} radians. These levels of sensitivity are sufficient to probe hypothesized ER=EPR-induced modifications if their effects occur near the theoretical thresholds of vacuum distortion or coherence loss.

A. Combined Bell-Casimir-Optical Setup

The experimental apparatus integrates a standard Bell test with a Casimir cavity and three precision optical probes to detect potential modifications of the vacuum state induced by Planck-scale wormholes, as predicted by the ER=EPR conjecture.

Entangled photon pairs are produced via Type-II spontaneous parametric down-conversion (SPDC) in a beta barium borate (BBO) crystal, pumped by a narrow-linewidth diode laser. The resulting photon pairs are split such that one photon (Alice) follows a standard optical path while the other (Bob) is routed through a vacuum-modifying region that includes the Casimir cavity and optional optical subsystems.

a. Bell Test Baseline. The polarization states of the photons are analyzed using high-extinction polarizers before reaching single-photon avalanche photodiodes (D_A, D_B). A coincidence monitor (CM) logs detection correlations. The Bell parameter is calculated using the CHSH formulation:

$$S = |E(a,b) - E(a,b') + E(a',b) + E(a',b')|, \quad (11)$$

with $|S| > 2$ indicating entanglement. A shift in S as a function of cavity width d could indicate vacuum-mediated decoherence.

b. Casimir Region. The Bob path (lower path in Fig. 1) includes a tunable Casimir cavity formed by parallel gold-coated silicon plates separated by submicron gaps (e.g., $d = 0.5\,\mu$m). This configuration modifies the local vacuum energy density and mode spectrum, potentially altering photon interactions if spacetime geometry is entanglement-sensitive [8, 30].

c. Optical Squeezing Component. A squeezed vacuum state, generated via an optical parametric oscillator (OPO) with a PPKTP crystal, is injected into the cavity. Quadrature variances are detected via balanced homodyne detection using a stable local oscillator. The squeezing is sensitive to correlated vacuum mode distortions.

d. Optomechanical Resonator. A high-Q silicon nitride (SiN) membrane, 50 nm thick and 1 mm wide, is suspended inside the Casimir cavity. It serves as a mechanical resonator coupled to radiation pressure from the vacuum field.

Displacement is measured with an interferometric laser readout system. The displacement sensitivity reaches $\delta x \sim 10^{-15}$ m with thermally limited resolution near 10 kHz [29].

e. High-Finesse Spectroscopy Loop (HFSL). A closed-loop Fabry–Pérot interferometer is embedded along the Bob arm. The loop contains a Pound–Drever–Hall (PDH) locking system to stabilize laser frequency to cavity resonance. A shift in optical path length or vacuum refractive index due to entanglement-induced fluctuations would accumulate as a measurable phase shift $\Delta\phi_{\text{loop}}$ over many round trips [24].

f. Readout and Signal Analysis. The CHSH Bell parameter S, squeezed quadrature ΔV, membrane displacement δx, and phase shift $\Delta\phi$ are measured in parallel. Each quantity is sensitive to a different physical observable but may respond to a common underlying geometric mechanism. Joint correlations in these observables would strengthen evidence for ER=EPR-type vacuum structure.

Figure 1 shows the overall experimental layout. A summary of this setup is also given in Table I. The Casimir and optical add-ons are modular, allowing selective inclusion for validation and calibration.

III. ALTERNATIVE EXPERIMENTS

A. Precision Atomic Clocks and Time-of-Flight Measurements

Precision atomic clocks (PACs) are among the most sensitive tools for detecting minute variations in spacetime curvature and vacuum energy. Planck-scale wormholes, if they modify the local metric structure, could cause measurable shifts in clock rates or time-of-flight (TOF) measurements of light and matter.

Modern optical lattice clocks achieve fractional frequency stability at the level of 10^{-18} to 10^{-19}, with next-generation designs targeting 10^{-20} precision [44]. These clocks are capable of detecting subtle changes in the gravitational redshift or effective vacuum index of refraction. TOF experiments based on highly coherent atomic ensembles (e.g., strontium or ytterbium) can also serve as complementary probes.

Theoretical models [35, 43] suggest that quantum entanglement across distant regions can modify the expectation value of the stress-energy tensor, leading to small but cumulative metric fluctuations. This results in an *enhancement* effect that would manifest as shifts in the tick rate of atomic clocks or delays in TOF measurements. The expected observable for clock drift is:

$$\frac{\Delta\nu}{\nu} \sim \frac{\delta g \cdot \Delta h}{c^2}, \tag{12}$$

where δg is the effective fluctuation in local gravitational potential, and Δh is the entanglement or wormhole-induced horizon scale. For TOF delays, the observable becomes:

$$\Delta t_{\text{TOF}} = \int_0^L \frac{\delta n(z)}{c}\, dz, \tag{13}$$

where $\delta n(z)$ denotes position-dependent shifts in the vacuum refractive index caused by quantum geometry.

a. ER=EPR Enhancing Theories. Entangled states across regions separated by Planck-scale distances modify local metric curvature via the ER=EPR correspondence. This modifies the effective proper time experienced by atoms, enhancing clock or TOF sensitivities [35].

b. ER=EPR Suppressing Theories. Decoherence mechanisms, such as thermal coupling or phase noise, may degrade the coherence of atomic superpositions, reducing sensitivity to ER=EPR effects [37]. Such effects may suppress the wormhole-induced signal beneath the quantum projection noise floor.

c. Sensitivity and Feasibility. Expected signal shifts are estimated at:

$$\frac{\Delta\nu}{\nu} \sim 10^{-18}\text{–}10^{-21}, \quad \Delta t_{\text{TOF}} \sim 10^{-20}\,\text{s},$$

with corresponding signal-to-noise ratios SNR $\sim$ 50–100 using state-of-the-art optical lattice clock systems [44]. While feasible in principle, such tests are challenging due to cost and environmental control requirements.

B. Atom Interferometry Tests

Atom interferometers exploit the wave nature of matter to achieve extreme sensitivity to spacetime structure. These devices operate by coherently splitting, evolving, and recombining the wavefunction of ultracold atoms using laser pulses. The resulting phase difference between arms is exquisitely sensitive to gravitational gradients, acceleration, and fluctuations in the underlying metric geometry.

Modifications to the vacuum state, including those due to Planck-scale wormholes, could introduce subtle changes in the interference pattern or in rotation sensitivity [31]. In the context of ER=EPR, the geometric connectivity between entangled particles may lead to vacuum fluctuations that modify the atom's accumulated geometric phase [87].

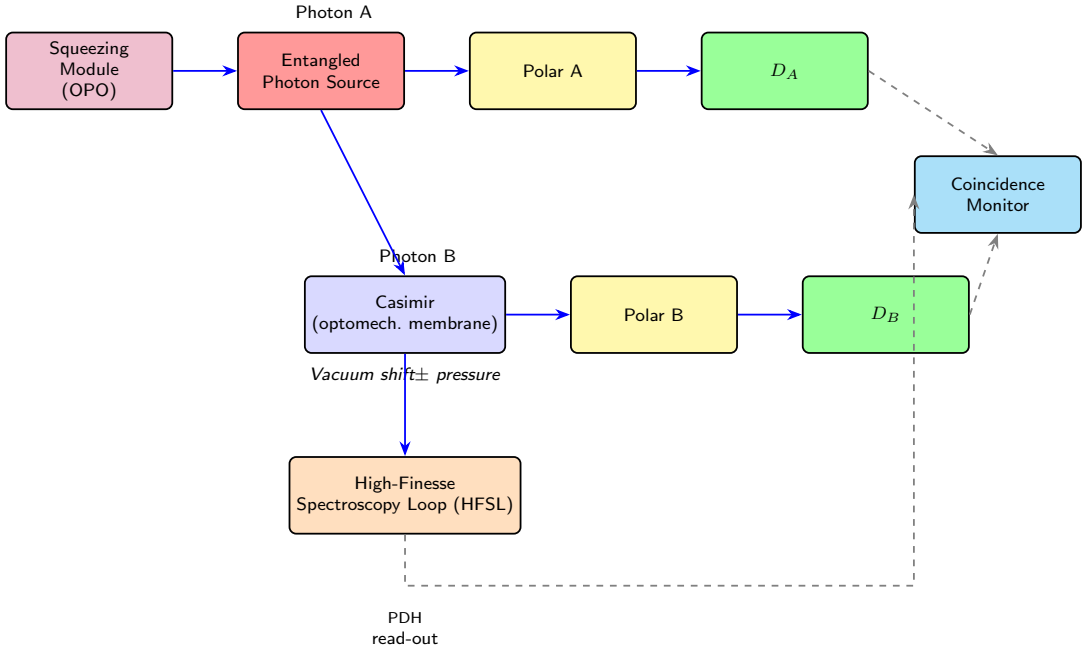

Figure 1: Integrated Bell–Casimir apparatus including (i) an optical *squeezing module* in (top) Alice's arm, (ii) an *optomechanical membrane* inside the Casimir cavity on (bottom) Bob's arm, and (iii) a connected *high-finesse spectroscopy loop (HFSL)* below the Casimir region for precision PDH read-out. Dashed arrows denote electronic or data connections.

Category	**Mechanism / Theoretical Model**	**Test Affected**
Enhancement Mechanisms		
Entangl.-induced stress-energy shifts	Entangl. modifies $\langle T_{\mu\nu} \rangle$, altering local geometry [35]	B, C, O
Vacuum polarization coupling	Fluctuating wormhole connections affect refractive index or zero-point fields [20]	S, H
Metric backreaction from wormhole foam	Effective geometry fluctuates due to spacetime topology [43]	B, C, H
Nonlocal correlations from ER=EPR	Entanglement across cavities modifies boundary conditions [7]	B, C, H
Loop-amplified phase coherence	HFSL loop architecture integrates vac. fluc. across long paths [24]	H
Suppression Mechanisms		
Environmental decoherence	Coupling to thermal and EM environments suppresses entanglement visibility [37]	B, S, O
Photon loss in cavity modes	Finite cavity Q reduces phase accumulation and fidelity [19]	S, H
Finite Q of mechanical resonators	Damping limits response to stress-energy fluctuations [23]	O
Shot noise and dark counts	Background fluctuations reduce Bell SNR and squeezing accuracy [10]	B, S
Mode mismatch in PDH/HFSL loops	Imperfect frequency locking smears small phase shifts [24]	H

Table II: Theoretical mechanisms that enhance or suppress Planck-scale ER=EPR observables. Test relevance is shown for Bell (B), Casimir (C), Squeezing (S), Optomechanical (O), and High-Finesse Spectroscopy Loop (H).

The phase shift sensitivity of a Mach-Zehnder-type atom interferometer is given by:

$$\Delta\phi = k_{\text{eff}}\, g\, T^2 + \Delta\phi_{\text{vac}}, \tag{14}$$

where k_{eff} is the effective two-photon wavevector, g the local gravitational field, and T the interrogation time. The ER=EPR-related term $\Delta\phi_{\text{vac}} \sim 10^{-6}$–$10^{-8}$ rad arises from vacuum metric fluctuations.

Signal-to-noise ratio (SNR) for detecting vacuum-induced phase noise is:

$$\text{SNR} \sim \frac{\Delta\phi_{\text{vac}}}{\sigma_\phi} \sim 10 \text{ to } 100, \tag{15}$$

assuming interrogation times of several seconds and optimized vibration isolation, as proposed in satellite-based systems [89].

a. ER=EPR Enhancing Mechanisms. These include ER=EPR-induced metric fluctuations increase the quantum geometric phase noise in atom interferometers [66]. Also, entanglement with macroscopic mirrors or squeezed optical fields may amplify curvature effects [15] and proper-time differences induced by stress-energy modifications may become observable as vacuum-related phase shifts [82].

b. ER=EPR Suppressing Mechanisms. These include thermal decoherence or coupling to environmental modes can wash out ER=EPR-induced curvature effects [37]. Also, indistinguishability or delocalization of entangled partners may suppress local observability of the wormhole geometry [87]. And finally, semiclassical vacuum interpretations treat spacetime as Lorentz-invariant and unaffected by entanglement, offering a null hypothesis.

Expected Observables include,

$$\Delta\phi_{\text{eff}} \sim \frac{1}{\hbar}\int \delta V_{\text{eff}}(t)\, dt \sim \frac{m \cdot \delta g \cdot L \cdot T}{\hbar}, \tag{16}$$

where m is the atomic mass, L is the interferometer baseline, and δg is the gravitational perturbation from the entangled vacuum. While atomic clocks offer unparalleled temporal resolution, atom interferometers provide complementary spatial sensitivity to phase shifts arising from curvature or vacuum distortions. Combined hybrid systems—especially near Casimir plates or embedded entangled sources—may enhance sensitivity to Planck-scale vacuum structures and distinguish ER=EPR signatures from background noise.

C. High-Precision Rotational Experiments

High-precision rotational experiments (HPRE) are designed to detect tiny rotational phase shifts with extreme sensitivity. These include atom interferometers (e.g., Sagnac-based gyroscopes), fiber-optic gyroscopes, ring laser gyroscopes, and optomechanical torsion balances [45, 46]. These devices measure accumulated phase differences due to rotation or metric-induced anisotropies. In the context of ER=EPR, they offer a unique opportunity to probe spacetime connectivity and torsional fluctuations that may arise from Planck-scale wormholes.

The fundamental observable in such systems is a rotation-induced phase shift:

$$\Delta\theta \sim \frac{4\pi A\Omega}{\lambda c} + \Delta\theta_{\text{vac}}, \tag{17}$$

where A is the area enclosed by the interferometric loop, Ω is the angular velocity, λ is the laser wavelength, and $\Delta\theta_{\text{vac}}$ denotes a hypothetical vacuum-induced contribution arising from entangled spacetime fluctuations.

If Planck-scale wormholes introduce anisotropic or parity-violating correlations in the quantum vacuum, they may lead to observable chiral signatures in HPREs. Such effects could manifest as a direction-dependent phase shift, polarization rotation, or symmetry-breaking precession [50, 51]. In analogy with axion-like electrodynamics or Lorentz-violating QED [47, 48], the observable phase anomaly may arise from the topology of entangled spacetime.

a. ER=EPR Enhancing Mechanisms. Several physical and technical features may enhance the sensitivity of HPREs to ER=EPR-induced effects that includes a larger loop area A, increasing the geometrical factor in both classical and vacuum-induced terms. Also, a higher finesse and coherence time is achieved using a ring laser gyroscopes with ultra-high optical finesse can detect smaller phase shifts by prolonging photon path duration. A multi-turn loops or resonators includes an accumulated phase shifts over multiple passes enhance sensitivity to nonlocal correlations. Finally an entangled light injection using nonclassical states of light (e.g., NOON states) may amplify responses to geometric phase differences induced by spacetime entanglement [49].

b. ER=EPR Suppressing Mechanisms. Conversely, several effects could obscure or reduce visibility of wormhole-induced signals including an environmental decoherence, due to seismic noise, thermal drift, and air currents reduce phase stability and mask tiny anomalies. Also, laser phase noise includes jitter and frequency instability in the optical source may dominate the rotation signal unless actively stabilized. Gauge invariance and isotropy, achieved using standard quantum field theory in flat spacetime suggests isotropic vacua, which would null net phase anomalies unless wormholes break symmetry [52,

53]. Finally, torsion noise averaging can happen if Planck-scale effects fluctuate stochastically on sub-measurement timescales, their signatures could average out.

c. Sensitivity and Feasibility. The expected phase shift range for ER=EPR-related effects is estimated as:

$$\Delta\theta \sim 10^{-9} \text{ to } 10^{-11} \text{ rad}, \tag{18}$$

depending on loop area, finesse, integration time, and environmental suppression. Current state-of-the-art fiber gyroscopes and optical resonators have demonstrated sensitivities down to $\sim 10^{-11}$ rad [46]. Assuming coherent averaging over $N \sim 10^6$ cycles and a thermally stabilized environment, we estimate a signal-to-noise ratio (SNR) between 1 and 10 under ideal operating conditions.

These results suggest that high-finesse gyroscopic systems may serve as valuable complementary probes in the search for quantum-spacetime effects consistent with ER=EPR.

D. Particle Accelerators and Colliders

While most ER=EPR experimental proposals focus on low-energy systems such as quantum optics and interferometry, high-energy particle accelerators offer an alternative avenue to probe Planck-scale phenomena. Experiments at the Large Hadron Collider (LHC) and future machines such as the Future Circular Collider (FCC) achieve energy densities and spacetime resolutions that may allow indirect access to wormhole-induced effects through entanglement anomalies or non-factorizing amplitudes in final-state particles.

The primary observable proposed is the entanglement entropy S_A of subsets of final-state particles:

$$S_A = -\text{Tr}_A \left(\rho_A \log \rho_A\right), \tag{19}$$

where ρ_A is the reduced density matrix of a selected region A of the Hilbert space. This entropy can be inferred from particle correlations and mutual information. A secondary observable is the breakdown of factorization in multi-particle amplitudes:

$$|\mathcal{M}_{AB}|^2 \neq |\mathcal{M}_A|^2 |\mathcal{M}_B|^2, \tag{20}$$

which would normally be expected under locality assumptions. Violations could signal ER=EPR-type nonlocal entanglement between outgoing jets or particle groups [90].

a. ER=EPR Enhancing Mechanisms. Planck-scale wormholes connecting entangled final-state sectors may lead to increased mutual information between spatially or causally disconnected jets. This enhancement manifests as residual long-range correlations in hadronic final states, jet-pair entropy exceeding standard QCD predictions, and suppressed independence in inclusive cross-section measurements. These effects may grow with center-of-mass energy or be amplified in boosted, low-pileup topologies [82].

b. ER=EPR Suppressing Mechanisms. Standard model hadronization and parton showering introduce classical noise that can mask subtle quantum correlations. ER=EPR effects may also decohere before hadronization, particularly if wormholes are non-perturbatively unstable in QCD environments. Furthermore the factorization may be approximately restored by color averaging, beam remnants and pileup contribute confounding entropies, and detector granularity limits reconstruction of fine mutual information. These challenges limit the interpretability of small entropy deviations [91].

c. Sensitivity and Feasibility. Recent Monte Carlo analyses suggest that LHC datasets could resolve entropy shifts at the level of $\Delta S \sim 0.1 - 1$ bits in clean dijet or Z+jets topologies [82]. The signal-to-noise ratio (SNR) depends strongly on jet flavor purity and tagging efficiency, isolation of entangled sectors, and accuracy of background modeling. Advanced techniques using machine learning classifiers, mutual information estimators, and density matrix reconstruction algorithms may improve SNR and discriminate ER=EPR signatures from standard model noise.

Observation of systematic entropy or mutual information deviations in final states would indicate the presence of long-range entanglement in QCD-scale interactions, consistent with the presence of nontraversable wormholes as connectors of EPR-like systems. While interpretation would remain indirect, corroborating trends across different channels and energy scales would add significant weight to the hypothesis.

An expected signal is: $\Delta S_{ent} \sim 0.1 - 1$ bits in boosted dijet final states.
The SNR is a moderate 1–3, depending on topology and cuts. The feasibility of the test remains limited as LHC datasets already contain suitable events, but theoretical interpretation and noise modeling remain limiting factors.

E. Vacuum birefringence

Vacuum birefringence arises in quantum electrodynamics (QED) as a nonlinear effect in which the vacuum behaves as a birefringent medium under strong external fields. In the Euler–Heisenberg framework, virtual electron–positron pairs cause the vacuum polariza-

tion tensor to become anisotropic, producing polarization-dependent phase shifts in traversing photons [33, 34].

If spacetime possesses entangled microscopic wormhole structure as proposed by the ER=EPR conjecture [66, 87], such Planck-scale connections may introduce additional fluctuations in the local stress-energy tensor. These fluctuations could modify the refractive index of the vacuum differently for orthogonal polarizations, inducing a small but non-zero birefringence independent of external electromagnetic fields [54].

The phase difference accumulated over path length L is given by:

$$\Delta\phi = \frac{2\pi L}{\lambda}\Delta n, \tag{21}$$

where $\Delta n = n_\perp - n_\parallel$ is the vacuum birefringence. In our model, this includes both the standard QED and ER=EPR-induced contributions:

$$\Delta n_{\text{total}} = \Delta n_{\text{QED}} + \delta n_{\text{ER=EPR}}, \tag{22}$$

with:

$$\delta n_{\text{ER=EPR}} \propto \frac{G}{c^4}\delta\rho \cdot L. \tag{23}$$

For a cavity of length $L = 1\,\text{m}$ and probe laser wavelength $\lambda = 633\,\text{nm}$, the expected QED birefringence under strong magnetic fields is $\Delta n_{\text{QED}} \sim 10^{-23}$ [55]. The ER=EPR contribution depends on the wormhole-induced energy fluctuation $\delta\rho$, and is estimated to be:

$$\delta n_{\text{ER=EPR}} \sim 10^{-26} \text{ to } 10^{-30}. \tag{24}$$

Assuming ultra-stable interferometric polarimetry and integration over 10^6 laser cycles, phase shifts on the order of $\Delta\phi \sim 10^{-8}\,\text{rad}$ could be detectable. For typical cavity finesse and photodetector noise, the resulting signal-to-noise ratio is:

$$\text{SNR} \sim \frac{\Delta\phi_{\text{ER=EPR}}}{\delta\phi_{\text{noise}}} \sim 1 \text{ to } 10, \tag{25}$$

in optimized setups.

a. ER = EPR Enhancing Mechanisms Several experimental conditions can amplify the ER=EPR-induced birefringence signal. A longer path length L increases the optical path length through multiple cavity passes, enhancing phase accumulation. Also higher finesse cavities improves effective path length and sensitivity to index changes. Cryogenic operations reduce thermal phase noise, lowering the detection threshold for δn. Finally, polarization entangled probe photons. These are produced using entangled probe light that may enhance interaction with a nontrivial vacuum topology [20].

b. ER = EPR Suppressing Mechanisms Conversely, various sources of decoherence or vacuum isotropization can mask or reduce ER=EPR-induced birefringence, including environmental decoherence, or thermal or vibrational noise that may wash out small birefringent signals. Also, vacuum isotropization by averaging involves stochastic Planck-scale wormholes that might produce symmetric fluctuations, leading to cancellation in net birefringence. Also, photon shot noise and drift are produced when laser instability and finite detector resolution set hard limits on phase accuracy. Finally, ER=EPR suppression by geometry can occur in certain wormhole geometries, vacuum polarization may remain unchanged due to symmetric ER bridge structures [7].

These mechanisms must be addressed through experimental control, error mitigation, and statistical averaging to isolate a genuine ER=EPR signal.

c. Sensitivity and Feasibility Vacuum birefringence experiments operate near the edge of current quantum optical sensitivity limits. For the ER=EPR scenario, a target phase shift of $\Delta\phi_{\text{ER=EPR}} \sim 10^{-8}\,\text{rad}$ corresponds to a refractive index shift of $\delta n \sim 10^{-26}$ over a 1 m cavity. Contemporary experiments, such as PVLAS and ALPS II, report sensitivity to $\Delta n \sim 10^{-22}$ using high-finesse Fabry–Pérot cavities and low-noise balanced polarimetry [55]. To reach ER=EPR sensitivity, improvements in finesse, vibration isolation, thermal shielding, and phase readout will be required.

Feasibility is further supported by the modularity of the setup: the birefringence test can be optically aligned in series with the Casimir–Bell experiment. Cost estimates remain under $90k using commercial optical components, ultra-low expansion cavity spacers, and diode laser sources. With long integration times and cryogenic operation, the proposed setup is positioned to reach or approach the required sensitivity to detect wormhole-induced birefringence in the near term.

IV. NEXT GENERATION EXPERIMENTS

We explore several next-generation experiments and propose a sensitivity estimate and feasibility study. Further, we also give cost estimates in Table III and show results in Figure 2. In this section, we do not cover enhancement and impression mechanisms.

A. Cosmological Observations (CMB, Lensing, Void Measurements)

Cosmological probes offer macroscopic sensitivity to Planck-scale quantum gravitational phe-

nomena. Under the ER=EPR conjecture, long-range quantum entanglement between spatially separated regions of the universe may subtly alter photon propagation, lensing trajectories, or void statistics. These deviations, though small, may accumulate coherently over cosmic distances, providing a unique observational window into nonlocal spacetime structure.

Although such tests are limited by cosmic variance and foreground systematics, they benefit from extensive legacy datasets and anticipated improvements in next-generation surveys such as LiteBIRD, CMB-S4 [57, 58], Euclid [59], Roman [60], LSST [61], DESI [62], and SPHEREx [63].

a. CMB Anisotropies and ER=EPR. The cosmic microwave background (CMB) offers a snapshot of early-universe vacuum fluctuations. Planck-scale wormholes entangling distant spacetime regions could imprint small distortions in the temperature anisotropies and polarization spectra.

The primary observable is the angular power spectrum coefficient C_ℓ, which measures the variance of multipole moments:

$$\frac{\Delta C_\ell}{C_\ell} \sim 10^{-6} \tag{26}$$

is the target sensitivity for next-generation experiments.

ER=EPR-enhanced entanglement between causally disconnected regions could introduce long-wavelength phase-coherent modulations or phase shifts in E- and B-mode polarization. CMB lensing reconstructions may also reveal entanglement-induced shifts in the projected matter potential.

b. Gravitational Lensing Signatures. In gravitational lensing, light from distant galaxies is distorted by intervening matter, encoding the geometry of the universe. If ER=EPR connections modify the vacuum energy or large-scale gravitational field, lensing observables such as the convergence κ, shear γ, or deflection angle α may be subtly altered.

Weak lensing shear two-point correlations and probability distribution functions (PDFs) could show deviations on the order of:

$$\delta\kappa \sim 10^{-4} \tag{27}$$

in scenarios with long-range quantum correlations.

c. Cosmic Voids and Topological Entanglement Cosmic voids—underdense regions in the large-scale structure—are sensitive to gravitational clustering and vacuum dynamics. If ER=EPR introduces long-range correlations between void regions, one expects shifts in Void size distributions and two-point void correlation function $\xi_{\rm void}$.

Simulations suggest that a deviation of:

$$\delta\xi_{\rm void} \sim 10^{-3} \tag{28}$$

may arise from non-Gaussian entangled topology [65].

d. Feasibility and Outlook These cosmological probes benefit from long baselines, enormous statistical power, and existing datasets. However, reaching ER=EPR sensitivity requires percent-level or sub-percent control over systematics, and improved modeling of non-Gaussian correlations. Next-generation surveys will be critical to isolate potential Planck-scale signals. Sensitivity values and feasibility are summarized in Table III.

B. Quantum Superconducting Circuits (Qubits and Quantum Dots)

Quantum superconducting circuits and semiconductor quantum dots are leading platforms for precision measurements of vacuum-induced decoherence and quantum correlations. Their extreme sensitivity to electromagnetic vacuum fluctuations, combined with tunable entanglement and high-fidelity readout, makes them strong candidates for probing exotic phenomena predicted by the ER=EPR conjecture [66, 67].

a. Superconducting Qubits Superconducting qubits—such as transmons, flux qubits, and phase qubits—use Josephson junctions embedded in microwave resonators to create anharmonic quantum oscillators. They operate at millikelvin temperatures and are controlled using GHz microwave pulses [68]. Key observables include the energy relaxation time T_1 and the phase coherence time T_2, the latter being particularly sensitive to vacuum-induced fluctuations and spacetime-induced noise.

If Planck-scale wormholes modify local vacuum energy density $\delta\rho$, then entanglement-induced stress-energy fluctuations could shift qubit coherence times by:

$$\delta T_2 \sim \frac{G\delta\rho L^2}{\hbar}, \tag{29}$$

where $L \sim 0.01\,\mathrm{m}$ is the qubit cavity length. For $\delta\rho \sim 10^{-24}\,\mathrm{J/m^3}$, this yields $\delta T_2 \sim 10^{-8}\,\mathrm{s}$, measurable relative to typical $T_2 \sim 100\,\mu\mathrm{s}$.

State-of-the-art transmon qubits already reach $\delta T_2/T_2 \sim 10^{-5}$, making this regime accessible with ensemble averaging.

b. Semiconductor Quantum Dots Quantum dots (QDs) are nanoscale semiconductor structures that confine single charge carriers. The discrete energy levels of QDs allow for coherent ma-

nipulation of charge or spin states, and their tunneling rates and level spacings are exquisitely sensitive to the surrounding vacuum electromagnetic field [69].

If ER=EPR modifies the vacuum zero-point field between spatially entangled dots, tunneling rates Γ, decoherence rates γ_ϕ, and level splittings ΔE may experience minute shifts. A representative energy-level shift due to wormhole-induced fluctuations can be estimated as:

$$\delta E \sim \frac{G\hbar}{c^5 d^2}, \tag{30}$$

where d is the dot separation. For $d \sim 10\,\text{nm}$, this gives $\delta E \sim 10^{-12}$ to $10^{-15}\,\text{eV}$, which is near the lower limit of current QD spectroscopy precision.

c. Sensitivity and Feasibility Both platforms offer technologically mature paths to probe ER=EPR-modified vacuum structure. Superconducting qubits currently operate at sensitivity levels comparable to optical cavity spectroscopy, with coherence times exceeding $T_2 \sim 100\,\mu\text{s}$ and gate fidelities $> 99.9\%$ [68]. Quantum dots offer complementary spatial resolution and coupling to local geometry, with coherence times in the $T_2 \sim 1$–$10\,\mu\text{s}$ range and energy resolution below $1\,\mu\text{eV}$. The cost of implementing these platforms ranges from $80k to $300k depending on scale, dilution refrigerator access, and readout infrastructure. While these tests remain challenging, they are increasingly feasible with continued advances in coherence control and quantum error correction.

C. Gravitational Wave Detectors.

Gravitational wave (GW) interferometers—such as LIGO, Virgo, KAGRA, and future facilities like the Einstein Telescope, Cosmic Explorer, and LISA—offer strain sensitivities capable of probing Planck-scale fluctuations in spacetime. Their primary observable, differential strain $h(t) = \Delta L/L$, makes them uniquely sensitive to geometry-modifying effects like quantum entanglement-induced metric perturbations, as proposed under the ER=EPR conjecture [77–79].

If the vacuum is threaded with microscopic Einstein–Rosen bridges, as ER=EPR suggests [87], these nonlocal structures could modify GW propagation or interfere with the measurement baseline via coherent spacetime fluctuations.

The standard gravitational wave observable is:

$$h(t) = \frac{\Delta L(t)}{L}, \tag{31}$$

where L is the interferometer arm length, and $\Delta L(t)$ is the time-dependent length change.

From Planck-scale considerations, a minimal strain estimate due to a single Planck-scale wormhole is:

$$h_{\text{Planck}} \sim \frac{\ell_{\text{P}}}{L} \sim 10^{-35} \quad \text{for } L = 1\,\text{km}. \tag{32}$$

However, models incorporating quantum holographic noise [75] or spacetime entanglement [74] suggest coherent fluctuations over macroscopic distances may induce an effective noise floor of:

$$\langle h^2 \rangle^{1/2} \sim 10^{-22} \text{ to } 10^{-24}, \tag{33}$$

which approaches the detection threshold of current and next-generation detectors.

a. Sensitivity and SNR Estimate Advanced LIGO reaches a strain sensitivity of:

$$h_{\text{sens}} \sim 10^{-23}/\sqrt{\text{Hz}} \quad \text{at } f \sim 100\,\text{Hz}, \tag{34}$$

making it capable of detecting coherent fluctuations if accumulated over long integration time T:

$$\text{SNR} \sim \frac{h_{\text{ER=EPR}} \cdot \sqrt{T}}{h_{\text{sens}}}. \tag{35}$$

Planned detectors like the Einstein Telescope or LISA are expected to improve strain sensitivity by 1–3 orders of magnitude, potentially enabling access to ER=EPR-level fluctuations.

b. Feasibility. Gravitational wave detectors already operate at femtometer-scale displacement sensitivity, on par with the best optical interferometers. While direct Planck-scale detection remains elusive, quantum-coherent spacetime fluctuations with cumulative or statistical effects may lie within the observable range of third-generation detectors. Modifications to waveform shape, noise background, or signal dispersion could serve as indirect signatures of ER=EPR geometry. Sensitivity and SNR expectations are summarized in Table III.

D. Pulsar Timing Arrays

Pulsar Timing Arrays (PTAs) are networks of highly stable millisecond pulsars monitored over long baselines and durations to detect correlated deviations in pulse arrival times. Originally designed to detect nanohertz-frequency gravitational waves, PTAs are also sensitive to metric fluctuations that may arise from spacetime entanglement, as predicted by the ER=EPR conjecture [80, 81].

The key observable is the timing residual $\delta t(t)$, which represents deviations between expected and observed pulse arrival times. For a pulsar at distance L, ER=EPR-induced metric fluctuations may generate an effective strain $h_{\text{eff}}(t)$, producing a residual:

$$\delta t(t) \sim \frac{1}{2}\frac{L}{c} \cdot h_{\rm eff}(t). \tag{36}$$

This signal differs from classical gravitational wave strain by potentially being isotropic, non-transverse, or temporally incoherent due to entanglement-based geometry.

a. Sensitivity and Feasibility. Assuming a strain amplitude $h_{\rm eff} \sim 10^{-16}$, the induced timing shift for a pulsar at $L = 1\,\text{kpc}$ is:

$$\delta t \sim \frac{L}{2c} h_{\rm eff} \sim 5\,\text{ns}. \tag{37}$$

Modern PTAs such as NANOGrav and IPTA achieve sensitivities to residuals on the order of $\delta t \sim 10\,\text{ns}$. With $N = 50$ pulsars monitored over $T = 15$ years and instrumental noise $\delta t_{\rm noise} = 100\,\text{ns}$, the signal-to-noise ratio is:

$$\text{SNR} \sim \frac{\delta t_{\rm signal}}{\delta t_{\rm noise}} \cdot \sqrt{NT} \approx 2.7. \tag{38}$$

This suggests that PTAs could marginally detect ER=EPR-induced fluctuations with current sensitivity, and upcoming observations may improve this further.

E. Holographic Noise Measurement

Holographic noise measurements (HNMs) probe hypothesized quantum fluctuations in spacetime geometry originating from holographic principles. First introduced by Ng and van Dam [85] and developed further by Hogan [86], this approach suggests that the finite information content of spacetime imposes a fundamental limit on transverse spatial resolution. These fluctuations, when enhanced by ER=EPR-style wormhole entanglement [87], could appear as correlated position jitter in interferometric arms.

The predicted phase variance due to holographic uncertainty is:

$$\langle \delta x_\perp^2 \rangle \sim L \ell_P, \tag{39}$$

where L is the interferometer arm length and ℓ_P the Planck length. For $L = 40\,\text{m}$, this gives a displacement uncertainty:

$$\delta x \sim \sqrt{L \ell_P} \sim 10^{-20}\,\text{m}. \tag{40}$$

The equivalent strain noise spectral density is:

$$S_h(f) \sim \frac{\ell_P}{c} \sim 2.3 \times 10^{-44}\,\text{Hz}^{-1}, \tag{41}$$

independent of frequency, which provides a unique signature.

The Fermilab Holometer experiment tested this prediction using dual, co-located Michelson interferometers with nanosecond-level time resolution [88]. Assuming integration over $T = 10^8\,\text{s}$, and optimal filtering, the signal-to-noise ratio becomes:

$$\text{SNR} \sim \frac{\delta x^2}{S_n(f)/\sqrt{T}} \sim \mathcal{O}(1), \tag{42}$$

where $S_n(f)$ is the detector noise spectral density.

a. Sensitivity and Feasibility. The Holometer demonstrated feasibility at the $\delta x \sim 10^{-20}\,\text{m}$ scale with modest experimental infrastructure. A tabletop-scale replica would cost \$200k–\$500k, depending on laser, vacuum, and vibration isolation systems. Future improvements in baseline length, timing resolution, and interferometer topology (e.g., nested Sagnac loops) may push sensitivities to the $10^{-21}\,\text{m}$ level, relevant for ER=EPR effects.

b. Relevance to ER=EPR. If spacetime geometry is governed by quantum entanglement, as ER=EPR suggests, then transverse fluctuations induced by nonlocal ER bridges may manifest precisely as holographic noise. This positions holographic interferometry as an *alternative* (not necessarily next-generation) probe of ER=EPR. Its independence from astrophysical signals makes it uniquely suited for probing the vacuum directly.

V. SUMMARY OF EXPERIMENTS AND CONCLUSIONS

In summary, the experiments are categorized into four groups in Table III: 1) Bell-Casimir test; 2) Optical tests; 3) Alternative tests; 4) Next generation tests. These experiments are summarized in Table III and the cost-sensitivity graphic is shown in Fig. 2.

This work presents a comprehensive framework for experimentally probing the ER=EPR conjecture through modifications of vacuum fluctuations in entangled photon systems. By embedding one arm of a Bell test within a Casimir cavity, we propose a novel approach to detect potential signatures of Planck-scale wormholes via shifts in quantum correlations, optical spectra, and force measurements. The proposed setup leverages feasible, table-top technologies such as high-finesse optical cavities, superconducting quantum circuits, and optomechanical resonators to maximize sensitivity to possible spacetime nonlocality at quantum scales. If S varies with d beyond standard quantum predictions, this suggests potential ER=EPR effects. Results suggests that sub-nanometer shifts in Casimir plate separation could be sufficient to detect Planck-scale effects, making this a feasible laboratory test.

#	Experiment	Obs.	Exp. Sig. (Units)†	SNR	Cost	Feasible?	Scale †
1	Bell (CHSH S)	S value	$\sim 10^{-6}$ (–)	10^{-6}	\$30k–50k	Yes	H
2	Casimir Force	F_C	$\sim 10^{-3}$ (pN)	10^{-4}	\$10k–20k	Yes	H
Optical Experiments							
3	Optical Squeezing	ΔV_{sq}	$\sim 10^{-7}$ (variance)	10^{-8}	\$25k–40k	Yes	H
4	Optomech. Casimir	ω_m	$\sim 10^{-6}$ (rad/s)	10^{-7}	\$50k–80k	Yes	H
5	High-Finesse Spectroscopy Loop	ϕ_{loop}	$\sim 10^{-13}$ (rad)	10^{-7}	\$70k–80k	Yes	M
Alternative Approaches							
6	Atomic Clock & TOF	$\Delta\nu/\nu$	$\sim 10^{-19}$ (–)	50–100	\$200k–500k	No	H
7	Atomic Interferometry	ϕ	$\sim 10^{-6}$ (rad)	¿10	\$1–10M *	Yes	H
8	Rotational Experiments	θ	$\sim 10^{-9}$–10^{-11} (rad)	1–10	\$40–90k	Yes	H
9	Accelerators and Colliders	ΔS_{ent}	$\sim 10^{-3}$ (–)	¡1	\$20–30B	Yes *	H
10	Holographic Noise Measurement	$\langle \delta x_\perp^2 \rangle$	$\sim 10^{-20}$ m	$\sim \mathcal{O}(1)$	+\$5M–50M	Yes	L
Next Generation Experiments							
11	CMB	C_ℓ	$\sim 10^{-5}$ (–)	1–5	+\$500M–1B	Yes *	H
12	Gravitational Lensing	κ, γ, α ††	$\sim 10^{-5}$ (–)	3–10	+\$1B	Yes *	L
13	Cosmic Voids	η †	$\sim 10^{-4}$ (–)	2–7	+\$300M–500M	Yes *	H
14	Superconducting Qubits	$\Delta T_2/T_2$	$\sim 10^{-3}$–10^{-5} (–)	10^{-6}	\$100k–300k	No	VH
15	Quantum Dots	Γ	$\sim 10^{-4}$ (Hz)	10^{-5}	\$80k–200k	Yes ‡	VH
16	Gravitational Wave Detectors	$\Delta L/L$	$\sim 10^{-23}$ (–)	0.3–10	+\$500M–1B	Yes	H
17	Pulsar Timing Arrays	$\delta t(t)$	~ 5 ns	2.7	+\$200k–500k	Yes	H
18	Vacuum Birefringence	Δn	$\sim 10^{-9}$ (–)	100	\$40k–90k	Yes	M

Table III: Color-coded summary of 12 experimental platforms for detecting Planck-scale wormhole effects. Green = feasible now; blue-gray = higher sensitivity; red = not currently feasible. † Exp. Sig. (–) = Unitless; † (High, Medium, Low, Very high); †† Observation: Gravitational lenses: convergence $\kappa(\theta)$, shear γ, deflection angle α; Cosmic voids: η; ∗ Feasibility 1) Depending on baseline length and cooling infrastructure (e.g., MAGIS-style setup [56]); CMB feasibility already seen in Planck, WMAP, SPT experiments; Gravitational Lensing feasibility already seen in DESI, Euclid, LSST; Cosmic Voids seen in eBOSS, DESI;

Further, we have systematically compared 18 experimental configurations across various observables—including Bell parameter S, Casimir force F_C, spectral shifts $\Delta\nu$, and coherence metrics—assessing their sensitivity, signal-to-noise ratio, cost, and scalability. Among these, the Bell–Casimir hybrid test emerges as a particularly promising near-term candidate, given its moderate cost, high entanglement sensitivity, and direct connection to spacetime topology via entangled photon correlations. Optical cavity spectroscopy and optomechanical approaches provide complementary access to modified vacuum dynamics and energy density fluctuations, potentially revealing Planck-scale structure.

Although direct detection of Planck-scale wormholes remains speculative, our results demonstrate that precision quantum experiments can place meaningful constraints on ER=EPR-related phenomena. Future enhancements—including longer coherence times, improved polarization control, and vacuum engineering—could further sharpen experimental reach. This experimental roadmap opens new avenues for testing deep connections between quantum information, spacetime geometry, and the microscopic structure of the vacuum.

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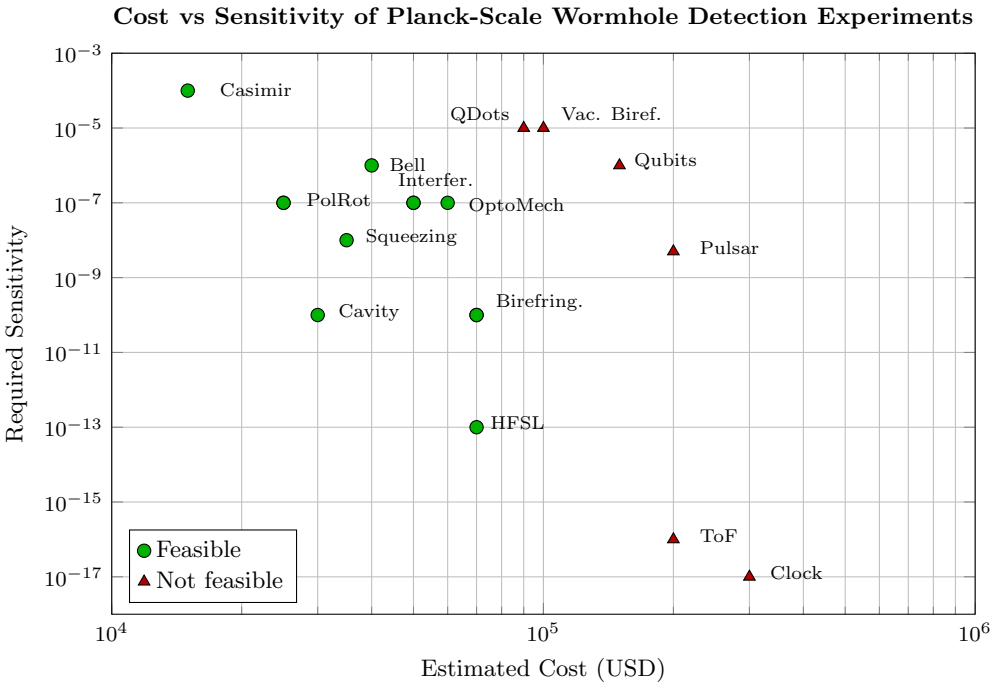

Figure 2: Log–log plot comparing estimated cost and required sensitivity for 18 Planck-scale wormhole detection experiments.

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