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The Bilocal-Integrity Programme, Third-Pass Consolidation

—Cosmological Grounding of the Couplings, Full Experimental Protocol, Mitochondrial Coupling, and the Physics of Consciousness, Causation, and Civilisational Trajectories

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Abstract

This is the third-pass consolidation of the Bilocal-Integrity Programme, unifying the Bilocal-Bubble Framework (BBF) and the Human Multiscale Integrity Framework (HMIF/MPIF) with a set of previously deferred derivations and integrations. We ground the two central coupling constants of the neutrino-mediated entanglement field on cosmological parameters of the cosmic neutrino background (CνB). The dimensionless boundary-pressure coupling α_Φ is derived from Fermi-scale weak interactions, the CνB number density, and the geometric enhancement of coherent-domain cavities, yielding a natural range $\alpha_\Phi \sim 10^{-16}$ (bare) to $\sim 10^{-4}$ (coherent-domain enhanced). The chirality-bias parameter χ_ν is derived from lepton asymmetry and current cosmological bounds, giving $\chi_\nu \lesssim 5\times 10^{-2}$. We specify a full engineerable experimental protocol for the multi-layer Casimir-sonoluminescence enclosure: material stack, shell-spacing schedule, acoustic drive envelope, cryogenic operation with a thermally decoupled central cell, spectral and polarimetric detection chain, calibration controls for optical-component and drive-induced circular-polarisation backgrounds, a statistical analysis based on detected photon counts and systematic floor, and predefined falsification thresholds formulated as a joint constraint on the product $\chi_\nu \alpha_\Phi$ at a chosen pivot frequency. We integrate the reported 71 THz mitochondrial signal as a candidate biological boundary observable for the biological source term $B(M)$ of the coupled equations, distinguishing what the preprint reports (a spectral feature and an ATP response) from what it does not establish (a polariton, a C-field, or an NEF coupling); we also situate the DARPA PROSE/NODES/Hubble/PENG programme as the read-understand-map-modify hierarchy of the mo-

lecular layer of the framework's mechanistic cascade, without endorsing consciousness-capture interpretations that its documentation does not support. We propose a formal treatment of consciousness within the framework: a Kaluza-Klein-style dimensional projection of a bilocal correlator produces, in local coordinates accessible to a self-modelling subsystem, phenomenological structure that admits a taxonomic classification with quantitative parameters (rank, coherence, chirality, contradiction). We give a Lyapunov analysis of the framework's variational flows, including a proof-sketch that the joint cost $J = \mathcal{C} + \beta \dot{S}_{\text{gen}} + \lambda D_{\text{damage}}$ is a strict Lyapunov function for physiological homeostasis under stated conditions. A causal taxonomy of mortality is developed, we state why correlation does not imply causation in the framework's formal sense, and we give the framework's diagnostic for recursively-generated narrative coherence (with the Coca-Cola/Pepsi nanoparticle conspiracy as worked example). The problem of evil is formulated as a corollary of finite bounded systems. We identify the framework's axioms, derive how physics, chemistry, biology, cognition, social science, ethics, and epistemology emerge from them, and we develop civilisational attractors as long-timescale variational flows in the sociotechnical bubble, with an explicit treatment of Fukuyama's "end of history" as a claim about attractor uniqueness that the framework rejects on formal grounds. Established physics, well-defined proposals, speculative extensions, and normative claims are kept in distinct epistemic categories throughout.

Keywords

Bilocal Correlator, Neutrino-Mediated Entanglement Field, Casimir-Sonoluminescence Coupling, Cosmic Neutrino Background, Chirality Bias, Human Multiscale Integrity, Mitochondrial Polariton, Lyapunov Stability, Kaluza-Klein Projection, Civilisational Attractors

1. Introduction

1.1. Scope of the Third Pass

The first two papers in this programme established, respectively, 1) that the bubble-computation hypothesis becomes physically explicit when embedded in a neutrino-mediated entanglement field (NEF) [1] with bilocal correlator $\Phi(x, y)$, and 2) that the human physiological hierarchy of the HMIF/MPIF is a nested family of reductions of the same variational principle, with the bilocal operator $\mathcal{D}_{x,y}$ derived from diagonal Poincaré invariance plus chiral $U(1)_L$. Both papers concluded with tasks left open. The present paper closes six of them:

1) Derive the boundary-pressure coupling α_Φ from the parameters of the cosmic neutrino background.

2) Derive the chirality bias χ_ν from cosmological lepton-asymmetry bounds.

3) Specify the multi-layer Casimir-sonoluminescence enclosure as a fully engineerable experimental protocol.

4) Integrate the reported 71 THz mitochondrial signal as a biological boundary observable, together with the DARPA molecular-scale programme as an instantiation of the framework's mechanistic cascade at the molecular level.

5) Give a Lyapunov analysis of the framework's variational flows, and propose a formal treatment of consciousness within the bilocal correlator.

6) Develop a causal taxonomy of mortality and harm, formulate the problem of evil, and identify the framework's axioms and the civilisational attractors of its sociotechnical layer.

1.2. Epistemic Discipline

The framework's breadth continues to be its principal risk. We maintain four epistemic categories throughout: a) established scientific results; b) well-defined proposals with explicit derivations and falsifiable predictions; c) speculative extensions whose parameters are not yet constrained; and d) normative claims that the framework does not resolve. Every substantive assertion is tagged with one of these four categories where the context does not make it obvious.

2. Derivation of α_Φ from CνB Parameters

2.1. Cosmic Neutrino Background as Environmental Input

The cosmic neutrino background [2] is an established prediction of standard cosmology, with characteristic temperature

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945\ \mathrm{K}, \tag{1}$$

and per-flavour number density

$$n_\nu \approx 56\ \mathrm{cm}^{-3}\ \text{perspecies},\ n_{\nu,\mathrm{tot}} \approx 336\ \mathrm{cm}^{-3}. \tag{2}$$

The thermal de Broglie wavelength for a neutrino of mass $m_\nu \sim 0.1$ eV and velocity $v_\nu \sim 5\times10^{-3}c$ is

$$\lambda_\nu = \frac{h}{m_\nu v_\nu} \approx 8\times10^{-5}\ \mathrm{m} \sim 0.1\ \mathrm{mm}, \tag{3}$$

which sets the natural NEF coherence scale $\lambda_{\mathrm{NEF}} \sim \lambda_\nu$.

2.2. Bare Coupling from Fermi-Scale Interactions

The bilocal correlator's source current $J(x,y)$ is built from left-projected neutrino bilinears (Section 2 of Paper II). The natural strength scale is the Fermi constant $G_F/(\hbar c)^3 = 1.166\times10^{-5}\ \mathrm{GeV}^{-2}$. For a Casimir cavity of scale R, the standard EM boundary pressure is $p_{\mathrm{Cas}}^{\mathrm{EM}} = Z\hbar c/(4\pi R^4)$ with $Z = 0.04618$ (Boyer). The bilocal correction

$$\Delta p_\Phi = -\alpha_\Phi \frac{\hbar c}{R^4} \mathcal{K}\left[|\Phi|; R\right] \tag{4}$$

compares two dimensionally identical objects. The ratio is

$$\alpha_{\Phi}^{\text{bare}} \sim \left.\frac{G_F n_\nu}{\hbar c/R^4}\right|_{R=\lambda_{\text{NEF}}} \cdot \left(\frac{m_\nu}{m_e}\right)^2. \tag{5}$$

Numerically, with $G_F n_\nu \approx 1.44\times10^{-62}\ \text{J}\cdot\text{m}^3 \times 3.36\times10^{8}\ \text{m}^{-3} \approx 4.8\times10^{-54}\ \text{J}$, and reference energy $\hbar c/\lambda_{\text{NEF}} \approx 2.5\times10^{-24}\ \text{J}$,

$$\alpha_{\Phi}^{\text{bare}} \sim \left(4.8\times10^{-54}/2.5\times10^{-24}\right)\times\left(2\times10^{-7}\right)^2 \sim 10^{-44}. \tag{6}$$

Bare, this is unobservable by any conceivable experiment. The framework's testability therefore hinges on whether coherent-domain enhancement can raise α_{Φ} by many orders of magnitude.

2.3. Coherent-Domain Enhancement

For a bounded region containing N_{coh} neutrino-coherence volumes phase-locked by shared boundary conditions, the bilocal source combines coherently rather than incoherently. In direct analogy to Dicke superradiance [3] and to Casimir enhancement in stacked cavities [4], the effective coupling scales as

$$\alpha_{\Phi}^{\text{eff}} = \alpha_{\Phi}^{\text{bare}} \times N_{\text{coh}}^{\eta}, \tag{7}$$

with $\eta = 1$ for perfectly coherent enhancement and $\eta = 1/2$ for random-phase enhancement. The number of coherence volumes accessible to a laboratory cavity of scale ℓ is

$$N_{\text{coh}} \sim \left(\lambda_{\text{NEF}}/\ell_{\text{atomic}}\right)^3 \sim \left(10^{-4}/10^{-10}\right)^3 = 10^{18}. \tag{8}$$

Under fully coherent enhancement, this raises α_{Φ} from 10^{-44} toward 10^{-26}; combined with the geometrical Casimir-shell factor $\left(\lambda_{\text{NEF}}/R_{\text{min}}\right)^2 \sim 4\times10^{6}$ of the SL problem, and a further multi-layer coherent factor $N_{\text{shell}} \sim 10^4$, we approach the testable window $\alpha_{\Phi} \sim 10^{-16}$ to 10^{-4}. The framework therefore predicts:

The strongest testable form of the bilocal coupling requires a coherent-domain amplification mechanism. Its existence is not established, but it is a definite prediction with a definite experimental signature.

2.4. Phase-Locking Mechanism and Its Distinction from Electromagnetic Enhancement

The coherent-domain enhancement must be grounded in a physical mechanism for phase-locking of the bilocal sources, and must be distinguishable from the ordinary electromagnetic Casimir enhancement that the same geometry produces.

Mechanism, in one sentence. Each coherence volume contributes a bilocal source $J(X,r)$ whose complex phase is set, up to a gauge choice, by the local boundary admissibility class $\mathcal{A}(\Gamma)$ of the bilocal correlator (Paper II, §3). When adjacent coherence volumes share a boundary admissibility class—enforced here by a common superconducting-shell geometry at a common cryogenic temperature with a shared acoustic drive phase—their sources add coherently in the bilocal response. The relevant phase is *not* that of an electromagnetic mode in the cavity; it is the phase of $\Phi(X,r)$ at the pivot separation r at which the Casimir

boundary term couples.

Three physical conditions for phase-locking. We state them so that each is independently testable:

(PL1) *Boundary-condition homogeneity*. The superconducting shells impose a common boundary admissibility class on Φ. This is the direct bilocal analogue of the Dirichlet condition for the EM Casimir problem, but acts on the bilocal field rather than on the EM potential.

(PL2) *Thermal coherence*. The decoherence rate γ_{env} at $T = 4$ K is well below the inverse acoustic drive period, so that phase information is not scrambled between flashes. This is the condition $\tau_{\mathrm{dec}} \gg 2\pi/\omega_A$ specialised to the drive timescale.

(PL3) *Drive-phase registration*. The piezoelectric acoustic drive imprints a common temporal phase on the bubble collapse in each flash, which through the modified Rayleigh-Plesset equation of Paper II registers a reproducible phase on the bilocal source.

Failure of any one of (PL1)-(PL3) collapses the coherent enhancement to the incoherent $\sqrt{N_{\mathrm{coh}}}$ scaling. This is tested by Configuration (d) of §4.5.

Four distinctions from EM enhancement. The multi-layer enclosure also enhances the ordinary EM Casimir pressure, which would be present with or without any bilocal coupling. We separate the two by four independent diagnostics:

(D1) *Polarisation signature*. Ordinary EM Casimir enhancement does not produce a circular-polarisation asymmetry $\mathcal{A}_{\mathrm{LR}}$ in the SL emission; it rescales total intensity. The bilocal coupling produces $\mathcal{A}_{\mathrm{LR}} \propto \chi_\nu$ by Equation (18). A nonzero intensity enhancement with zero $\mathcal{A}_{\mathrm{LR}}$ is EM-only; a nonzero $\mathcal{A}_{\mathrm{LR}}$ cannot be EM Casimir alone.

(D2) *Superconducting-vs-normal scaling*. EM Casimir enhancement persists through T_c: dielectric and metallic reflectivity at optical frequencies change negligibly across the transition. The bilocal phase-locking in (PL1) depends on the shells being superconducting at the Casimir boundary; configuration (b) above/below T_c discriminates.

(D3) *Shell-count scaling*. EM Casimir enhancement in a stack of N_s passive shells scales linearly in N_s for weak coupling and sublinearly thereafter. Coherent bilocal enhancement scales as N_s^η with $\eta = 1$ under (PL1)-(PL3) and $\eta = 1/2$ under random-phase drive. The N_s-exponent is itself a signature.

(D4) *Chirality-alternated drive dependence*. Switching the acoustic drive between clockwise and counter-clockwise spherical modes exchanges $\mathcal{A}_{\mathrm{LR}} \to -\mathcal{A}_{\mathrm{LR}}$ under the bilocal coupling, since the sign of χ_ν is tied to the drive chirality through Equations (29)-(30) of Paper II. Ordinary EM Casimir enhancement is invariant under this exchange.

No single diagnostic is sufficient; the conjunction (D1) ∧ (D2) ∧ (D3) ∧ (D4) is designed to be unachievable by any plausible conventional-physics artefact.

Table 1 collects the estimated ranges.

Table 1. Estimated ranges of α_Φ under successive enhancement mechanisms. Bare = Fermi-scale only; C = coherent-domain phase-locking; G = geometric (Casimir) factor; N = multi-layer stacking.

Enhancement chain	α_Φ
Bare Fermi	$\sim 10^{-44}$
Bare + C ($\eta = 1/2$)	$\sim 10^{-35}$
Bare + C ($\eta = 1$)	$\sim 10^{-26}$
Bare + C ($\eta = 1$) + G	$\sim 10^{-19}$
Bare + C ($\eta = 1$) + G + N	$\sim 10^{-15}$
Speculative upper bound (fully resonant)	$\sim 10^{-4}$

2.5. Falsifiability of the Range

The prediction is that only the two lowest rows of Table 1 are directly testable with existing technology; if the multi-layer Casimir-SL enclosure of §4 returns null results at all sensitivities, the strongest form of the framework (last row) is excluded. The intermediate rows are excluded only if new coherence-enhancement mechanisms are demonstrated to be inaccessible.

3. Derivation of χ_ν from Lepton Asymmetry

3.1. Cosmological Input

The baryon-to-photon ratio measured from CMB and BBN is [5]

$$\eta_B = \left(n_B - n_{\bar{B}}\right)/n_\gamma \approx 6\times 10^{-10}. \tag{9}$$

Under standard leptogenesis, this baryon asymmetry is generated from a primordial lepton asymmetry via sphaleron processes. The cosmic neutrino background inherits a chemical potential $\xi_\nu = \mu_\nu / T_\nu$ whose current cosmological bounds are [6]

$$\left|\xi_\nu\right| \lesssim 0.05 \ (95\%\ \mathrm{CL}). \tag{10}$$

3.2. Chirality Bias from ξ_ν

The chirality bias χ_ν of the framework was defined in Paper II [7] as the imaginary/real ratio of the bilocal correlator induced by the chiral $U(1)_L$ source. It inherits its scale from the primordial neutrino-antineutrino asymmetry:

$$\chi_\nu \sim \frac{n_\nu - n_{\bar{\nu}}}{n_\nu + n_{\bar{\nu}}} \sim \sinh\left(\xi_\nu\right), \tag{11}$$

so that at the CMB bound

$$\chi_\nu \lesssim 5\times 10^{-2}. \tag{12}$$

This is the natural upper end. A more conservative estimate uses the sphaleron-related expectation $\chi_\nu \sim \eta_B \sim 6\times 10^{-10}$, so that

$$6\times 10^{-10} \lesssim \chi_\nu \lesssim 5\times 10^{-2}. \tag{13}$$

Experiments P2 (atom interferometry) and P5 (CMB/CνB dipole alignment) of Paper II directly probe χ_ν across this range; the upper end is testable now, the lower end may require future detectors.

3.3. Sign Convention and the Laboratory-Observable Prediction

The sign of χ_ν is fixed by the observed matter-antimatter asymmetry: the universe contains more baryons than antibaryons, so under standard leptogenesis the primordial lepton asymmetry had the same sign as the resulting baryon asymmetry, giving $\xi_\nu > 0$ and therefore $\chi_\nu > 0$ in the convention of Equation (12).

Predicted sign of $\mathcal{A}_{\mathrm{LR}}$. Let $\hat{n}_{\mathrm{dip}}$ denote the CνB dipole direction inferred independently from CMB-correlated measurements [5], and $\hat{n}_{\mathrm{drv}}$ denote the laboratory acoustic drive-axis vector (right-handed by the convention of Paper II). The predicted sign of the circular-polarisation asymmetry at the pivot frequency ω_{pivot} (set below the shell-plasma edge) is

$$\operatorname{sgn}\left[\mathcal{A}_{\mathrm{LR}}\left(\omega_{\mathrm{pivot}}\right)\right] = \operatorname{sgn}\left[\chi_\nu\right]\cdot\operatorname{sgn}\left[\hat{n}_{\mathrm{dip}}\cdot\hat{n}_{\mathrm{drv}}\right]. \tag{14}$$

With $\chi_\nu > 0$ (fixed above), and taking the right-handed drive convention aligned with the CνB dipole oriented into the Northern galactic hemisphere, Equation (14) predicts $\mathcal{A}_{\mathrm{LR}}\left(\omega_{\mathrm{pivot}}\right) > 0$ —*i.e.* a left-circular-polarisation excess in the sonoluminescence emission. A right-circular excess under the same drive orientation falsifies the sign prediction; a null statistically distinguishable from both excludes neither sign but still constrains the magnitude per §4.8.

Why a sign at all. The sign of $\mathcal{A}_{\mathrm{LR}}$ is tied to χ_ν because the bilocal source carries the same chirality label as the cosmological neutrino chemical potential: the laboratory asymmetry is the local projection of the same $U(1)_L$ bias that generated the baryon asymmetry. The alignment factor $\hat{n}_{\mathrm{dip}}\cdot\hat{n}_{\mathrm{drv}}$ comes from a $\varepsilon^{ijk}\partial_i\Phi v_j J_k$ term in the bilocal coupling of Paper II with v the drive-axis vector; this term changes sign under drive-axis reversal and under CνB-dipole reflection, giving Equation (14).

What this does not establish. Equation (14) presupposes a nonzero bilocal coupling and a nonzero χ_ν. If either is zero, $\mathcal{A}_{\mathrm{LR}}$ vanishes regardless of orientation, and the sign prediction is vacuous. The sign is therefore a conditional prediction: given that the framework is correct and $\chi_\nu > 6\times10^{-10}$, the asymmetry has the sign of Equation (14). A statistically significant wrong-sign result excludes the framework at the chirality level; a null result constrains the magnitude per Equation (25) and does not test the sign.

4. The Multi-Layer Casimir-SL Enclosure

We now specify the complete experimental protocol for the multi-layer Casimir-sonoluminescence enclosure that is Prediction P1 of the previous papers. The protocol is engineerable with existing cryogenic and photonics technology at a scale accessible to a mid-sized university physics department or a well-resourced independent laboratory.

4.1. Enclosure Geometry

The core enclosure is a spherically symmetric stack of $N_s = 10^4$ concentric superconducting thin-film shells of aluminium ($T_c = 1.18$ K) or niobium ($T_c = 9.25$ K), deposited on dielectric substrates. The shell radii are set on a modified log-linear schedule

$$R_n = R_0 + n^{2/3}\Delta R,\ R_0 = 1\,\mu\text{m},\ \Delta R = 5\,\text{nm}, \tag{15}$$

so that shells span from $R_0 \approx 1$ μm to $R_{N_s} \approx 3.2$ mm. This schedule is chosen to place mode resonances $\omega_n = \pi c / R_n$ across the visible-near-UV range where SL emission is strongest.

The central cavity ($R < R_0$) contains argon-saturated deionised water at 20˚C, doped to [Ar] = 3 mg/L, degassed to acoustic clarity. A stationary single-bubble SL trap is established in this cavity by conventional piezoelectric driving at 26.5 kHz [8]-[10].

4.2. Acoustic Drive

The acoustic drive is a fundamental at $\omega_A / 2\pi = 26.5$ kHz with amplitude $P_A = 1.35$ atm at the bubble location, plus a modulated subharmonic component matched to the enclosure's collective resonance

$$\omega_A^{\text{sub}} = \omega_A / N_h,\ N_h \in \{10, 100, 10^3\}, \tag{16}$$

scanned across a campaign to probe frequency-selective enhancement.

Chirality-alternated driving—switching between clockwise and counter-clockwise acoustic modes in a spherically corrugated transducer array—allows separate measurement of the $\Re[\delta I / I]$ and $\Im[\delta I / I]$ components predicted by Equations (29)-(30) of Paper II.

4.3. Cryogenic Operation and the Thermally Decoupled Central Cell

A stable sonoluminescent bubble requires room-temperature argon-saturated water and a 26.5 kHz piezoelectric drive, whereas the enclosure's Casimir-active shells must sit at $T \lesssim 4$ K. The design uses a thermally decoupled central cell rather than a bulk cryogenic water reservoir.

The enclosure outer shell is maintained at $T = 4$ K in a dilution refrigerator with vibration isolation of 10^{-9} g at 1 Hz. The central cell holding the sonoluminescent bubble ($R < R_0 = 1$ μm bubble inside a ~1 cm argon-saturated-water trap volume) sits at the geometric centre of the shell stack but is thermally isolated from it by three stages:

(C1) A vacuum-jacketed re-entrant window assembly (walls separated by $\gtrsim 10$ mm of high-vacuum guard space; outer wall thermally sunk to the 4 K stage; inner wall thermally sunk to a 300 K active-regulated plate). The window material is UV-grade fused silica (Suprasil-300 or Spectrosil-2000) chosen for low fluorescence, low circular birefringence, and transmission across 200 - 700 nm.

(C2) A thin-wall titanium transfer tube that mechanically couples the room-temperature central cell to the acoustic transducer stack located outside the cryostat. The tube's thermal conductance is designed to be <10 mW at the 4 K stage under steady-state operation, well within the cooling budget of a commercial dilution refrigerator [11].

(C3) An active-regulated resistive heater on the central-cell wall that maintains the water at $T = 293 \pm 0.1$ K. The heater power requirement, dominated by radiative losses from the 293 K cell to the 4 K enclosure through the window aperture, is of order $P_{\text{rad}} \sim \sigma T^4 A_{\text{window}} \sim 5$ mW for an $A_{\text{window}} \sim 1$ cm^2 aperture.

The acoustic drive itself is launched from a piezoelectric transducer stack outside the cryostat, with the 26.5 kHz pressure wave coupled through the titanium transfer tube into the central cell. The transducer therefore does not need to operate at 4 K—a well-known difficulty for piezoelectric ceramics, whose coupling coefficients fall sharply below ~20 K. Only the water column inside the central cell couples the drive to the bubble, and that column is held at 293 K throughout.

Cryogenic operation of the surrounding shell stack reduces thermal background and puts the Casimir-active shells firmly into the superconducting regime; it is the shells, not the water, that must be cold.

Thermal budget summary. At steady state: ~5 mW radiative load from the central cell + ~10 mW conductive load through the transfer tube + ~20 mW background cryostat load $\lesssim 50$ mW total. A commercial dilution refrigerator with a cooling capacity $\gtrsim 500$ μW at 100 mK and $\gtrsim 1$ W at the 4 K stage accommodates this budget comfortably [11].

What this design preserves. The bubble runs under the same hydrodynamic and acoustic conditions as any standard single-bubble sonoluminescence experiment [8] [9]: argon-saturated 20˚C water, 1.35 atm acoustic pressure at the bubble location, 26.5 kHz drive. The only non-standard element is that the water-and-bubble sub-system sits inside, rather than outside, a Casimir-active cryogenic shell stack.

4.4. Detection Chain

Emitted light from the bubble is collected through a UV-grade fused silica collimator ($f/1$, $\lambda \in [180, 700]$ nm), split into:

- A polarising beam-splitter for left- and right-circular polarisation (LCP, RCP) separation;
- A grating spectrometer (Czerny-Turner, $R > 5000$ at 300 nm) delivering both channels to intensified CCDs synchronised to the acoustic drive phase;
- A photomultiplier for absolute intensity calibration;
- A time-correlated single-photon counting module for pulse-shape analysis.

The polarisation asymmetry

$$\mathcal{A}_{\text{LR}}(\omega) = \frac{I_{\text{LCP}}(\omega) - I_{\text{RCP}}(\omega)}{I_{\text{LCP}}(\omega) + I_{\text{RCP}}(\omega)} \tag{17}$$

is the primary discriminator: Equations (29)-(30) of Paper II predict

$$\mathcal{A}_{\mathrm{LR}}(\omega)\big|_{\mathrm{coupled}} = \chi_{\nu}\cdot 0.23\alpha_{\Phi}\left(\frac{R_{\min}\omega}{c}\right)^{2}\Big/\left[(\omega/\omega_{c})^{2}\right], \tag{18}$$

whereas ordinary SL emission has $\mathcal{A}_{\mathrm{LR}} = 0$ within statistical noise. A nonzero $\mathcal{A}_{\mathrm{LR}}$ correlated with the multi-layer stack presence is the framework-specific signature.

4.5. Control Configurations

Four configurations are run in interleaved sequence to isolate the framework effect from stack-level confounders:

a) Full stack, cryogenic, superconducting shells, coherent subharmonic drive: predicts full $\delta I/I$ and $\mathcal{A}_{\mathrm{LR}}$.

b) Full stack, above T_c (normal-conducting shells): predicts strongly reduced effect.

c) Stack absent, bubble alone: predicts zero effect (null).

Random-phase drive (subharmonic dithered): predicts $\sqrt{N_s}$ scaling rather than N_s.

d) The four-way comparison discriminates the framework signal from spurious effects due to cavity temperature, geometry alone, or acoustic driving.

4.6. Calibration Controls for Conventional Sources of $\mathcal{A}_{\mathrm{LR}}$

A nonzero circular-polarisation asymmetry $\mathcal{A}_{\mathrm{LR}}$ can arise from several conventional instrumental and optical sources entirely unrelated to the proposed bilocal coupling. These must be enumerated and controlled explicitly, since the stated detection threshold $\mathcal{A}_{\mathrm{LR}} \sim 10^{-6}$ is below the natural scale of several of them. We identify six classes of background, with the specific control for each:

(K1) *Optical-element birefringence*. UV-grade fused silica windows and lenses, under thermal stress from the 4 K→300 K gradient of §4.3, develop residual linear birefringence that leaks into measured circular asymmetry through the polarising beam-splitter. Control: the full optical train is calibrated *in situ* with a linearly polarised reference laser injected along the detection axis, at $\lambda = 266$ nm and $\lambda = 532$ nm, before and after each 24-hour acquisition shift. The residual $\mathcal{A}_{\mathrm{LR}}^{(\mathrm{K1})}$ with the bubble off is measured and subtracted; the target systematic floor is $\lesssim 2\times 10^{-7}$ per element, verified by comparison against a $\lambda/4$-plate reference.

(K2) *Polariser extinction-ratio asymmetry*. A real polarising beam-splitter has slightly unequal transmission in the two orthogonal states, producing a static $\mathcal{A}_{\mathrm{LR}}$ offset independent of source. Control: the beam-splitter is characterised with the reference laser at commercial accredited specification $\varepsilon \lesssim 10^{-5}$, and the measured offset is subtracted. The polarising beam-splitter is additionally rotated by 90˚ halfway through each acquisition, so that any residual offset flips sign while the physical $\mathcal{A}_{\mathrm{LR}}$ does not, and the offset cancels in the sum.

(K3) *Faraday rotation in windows and water*. Residual magnetic fields in the

laboratory induce Faraday rotation in the window glass and in the central-cell water column. Control: a three-axis magnetic shield (mu-metal plus active compensation coils) brings the ambient field at the enclosure to $|\vec{B}| \lesssim 50\,\mathrm{nT}$. Residual Faraday-induced $\mathcal{A}_{\mathrm{LR}}^{(\mathrm{K3})}$ is calibrated *in situ* by driving a known field reversal and measuring the response.

(K4) *Drive-induced circular dichroism of the water*. The high-amplitude acoustic drive produces a time-varying pressure field in the central cell that, through the piezo-optic coefficient of water, induces a tiny transient birefringence synchronous with the drive phase. Control: this is measured directly in configuration (c) (bubble absent, drive on), where the framework predicts $\mathcal{A}_{\mathrm{LR}} = 0$ but the piezo-optic artefact remains. The measured $\mathcal{A}_{\mathrm{LR}}^{(\mathrm{K4})}$ is subtracted; it also provides an independent cross-check on the drive-phase registration of (PL3).

(K5) *Spectrometer response asymmetry between CCD channels*. The two intensified-CCD channels for LCP and RCP have different quantum efficiencies and dark-count rates that drift with cryostat temperature. Control: the two channels are swapped between acquisitions by a half-wave-plate rotation in the input beam, so that any channel-level asymmetry averages to zero in the LCP-RCP difference. Independent absolute calibration is performed with the photomultiplier against NIST-traceable standards.

(K6) *Scattered-light contamination*. Scattered laboratory light and cosmic-ray hits produce a small, roughly circularly polarised background. Control: full dark-count characterisation with the acoustic drive off and the bubble absent is performed between every acquisition block; dark-count rates are logged per channel and subtracted. A coincidence requirement between the time-correlated single-photon counting module and the spectrometer timestamps rejects uncorrelated hits.

The systematic floor from these six background classes added in quadrature is estimated at $\sigma_{\mathrm{sys}}\left(\mathcal{A}_{\mathrm{LR}}\right) \sim 1\times10^{-6}$, dominated by (K1) and (K4). This floor sets the practical sensitivity of the experiment and enters the statistical analysis of §4.7 and the exclusion limits of §4.8.

Standing calibration cadence. The six calibrations are run in the following cadence, published in advance to prevent post-hoc adjustment: (K1), (K3), (K5) daily (open loop, bubble off); (K2) weekly; (K4) interleaved with every (a)/(b)/(c)/(d) configuration block; (K6) continuous via dark-count logging.

4.7. Statistics: Detected Photon Counts, Efficiencies, and Systematic Floor

The sensitivity of the experiment is driven not by emitted photons alone but by the detection chain and the systematic floor of §4.6. We compute each explicitly.

Emitted photon budget. Single-bubble sonoluminescence produces $N_{\gamma}^{\mathrm{flash}} \sim 10^{5}$ photons per flash at a flash rate $f_{\mathrm{flash}} \sim 10^{4}\,\mathrm{Hz}$. A 30-day acquisition campaign per configuration contains $T_{30} = 30\times86400\,\mathrm{s} = 2.592\times10^{6}\,\mathrm{s}$ of wall-clock time. The emitted-photon total is therefore

$$N_{\text{emit}} = N_{\gamma}^{\text{flash}} \cdot f_{\text{flash}} \cdot T_{30} \simeq 2.6 \times 10^{15} \text{ photons.} \tag{19}$$

Detected photon budget. The detected count is

$$N_{\text{det}} = N_{\text{emit}} \cdot \eta_{\text{opt}} \cdot \eta_{\text{q}} \cdot \eta_{\text{duty}} \cdot \eta_{\text{win}}, \tag{20}$$

with the four efficiency factors at realistic laboratory values:

- $\eta_{\text{opt}} \simeq 0.3$: optical collection efficiency through the $f/1$ UV collimator, polarising beam-splitter, and grating spectrometer (end-to-end).
- $\eta_{\text{q}} \simeq 0.5$: intensified-CCD quantum efficiency in the 200 - 400 nm UV band.
- $\eta_{\text{duty}} \simeq 0.5$: live-time duty cycle, accounting for calibration blocks (K1)-(K6), cryostat regeneration, and configuration switching.
- $\eta_{\text{win}} \simeq 0.5$: transmission of the vacuum-jacketed re-entrant window assembly (two UV-grade fused silica surfaces, broadband-coated).

The product is $\eta_{\text{det}} = \eta_{\text{opt}}\eta_{\text{q}}\eta_{\text{duty}}\eta_{\text{win}} \simeq 3.8 \times 10^{-2}$, giving

$$N_{\text{det}} \simeq 2.6 \times 10^{15} \cdot 3.8 \times 10^{-2} \simeq 1 \times 10^{14} \text{ photons per configuration.} \tag{21}$$

We adopt $N_{\text{det}} = 10^{14}$ as the nominal detected count for sensitivity estimation, with an acknowledged factor-of-2 uncertainty from the efficiency chain.

Statistical sensitivity. With N_{det} photons split between LCP and RCP channels at ratio $\frac{1}{2}(1 \pm \mathcal{A}_{\text{LR}})$, the Poisson statistical uncertainty on the measured asymmetry is

$$\sigma_{\text{stat}}(\mathcal{A}_{\text{LR}}) = \frac{1}{\sqrt{N_{\text{det}}}} \simeq 1 \times 10^{-7}. \tag{22}$$

Systematic floor. The six calibration backgrounds enumerated in §4.6 add in quadrature to

$$\sigma_{\text{sys}}(\mathcal{A}_{\text{LR}}) \simeq 1 \times 10^{-6}, \tag{23}$$

dominated by (K1) birefringence and (K4) drive-induced circular dichroism. This systematic floor is ~10× the statistical uncertainty, so the experiment is systematics-limited at the design detection count.

Combined sensitivity. The total uncertainty on $\mathcal{A}_{\text{LR}}$ at the design acquisition is

$$\sigma_{\text{tot}}(\mathcal{A}_{\text{LR}}) = \sqrt{\sigma_{\text{stat}}^2 + \sigma_{\text{sys}}^2} \simeq 1 \times 10^{-6}. \tag{24}$$

The experiment can set a 5σ limit $\mathcal{A}_{\text{LR}} \lesssim 5 \times 10^{-6}$. The way this limit translates into a bound on the coupling constants is treated in §4.8; it is not a direct bound on α_{Φ} alone.

Trade-space for pushing below 10^{-6}. The systematic floor can be reduced below 10^{-6} only by improving (K1) and (K4) specifically: a cryogenic polariser with improved extinction ratio (K2 is already sub-dominant), a magnetically cleaner laboratory (K3), and *in situ* birefringence monitoring with a reference beam (K1). Each of these is a future-work item, not a current design.

4.8. Predefined Falsification Thresholds

The exclusion is a joint constraint on the four unknown factors in Equation (18), not a direct bound on α_Φ alone; three of these factors (χ_ν , $R_{\min}$, ω_c) are not independently constrained by the experiment itself. We state the exclusion as a joint constraint and reserve the single-parameter α_Φ bound for an explicitly priored sub-case.

The primary exclusion is a joint one. At the pivot frequency ω_{pivot} (taken as $\omega_{\text{pivot}}/2\pi = 3\times10^{14}$ Hz , in the mid-visible where SL emission is near-peak and well below the shell-plasma edge), a null result $\left|\mathcal{A}_{\text{LR}}\left(\omega_{\text{pivot}}\right)\right| < 5\times10^{-6}$ at 5σ (combined statistical and systematic per Equation (24)) constrains

$$\chi_\nu \cdot \alpha_\Phi \cdot \frac{\left(R_{\min}\omega_{\text{pivot}}/c\right)^2}{1+\left(\omega_{\text{pivot}}/\omega_c\right)^2} \lesssim 2\times10^{-5}, \tag{25}$$

where the numerical factor absorbs the 0.23 of Equation (18) and converts the 5σ bound to a limit on the product. Equation (25) is the model-independent statement of what the experiment measures.

Single-parameter bound requires declared priors. To extract a bound on α_Φ alone, three priors must be stated. We adopt the following from the companion derivations in this manuscript:

- $\chi_\nu \in \left[6\times10^{-10}, 5\times10^{-2}\right]$ from Equation (13), with $\chi_\nu = 5\times10^{-2}$ (cosmological upper bound) adopted as the optimistic prior and $\chi_\nu = 10^{-5}$ (central reheating-scale estimate) as the central prior;
- $R_{\min} = 1\,\mu\text{m}$ from the shell schedule of §4, so that $\left(R_{\min}\omega_{\text{pivot}}/c\right)^2 \simeq 4\times10^{-5}$;
- $\omega_c \gtrsim \omega_{\text{pivot}}$ from the Boyer kernel analysis of Paper II, so that the $1+\left(\omega/\omega_c\right)^2$ denominator is $\mathcal{O}(1)$.

Under these priors, Equation (25) becomes

$$\alpha_\Phi \lesssim \frac{2\times10^{-5}}{\chi_\nu \cdot 4\times10^{-5}} \simeq \frac{1}{2\chi_\nu}. \tag{26}$$

This gives, at the optimistic prior $\chi_\nu = 5\times10^{-2}$,

$$\alpha_\Phi \lesssim 10 \ \left(\text{optimistic prior on } \chi_\nu\right), \tag{27}$$

which is a non-trivial statement about the coherent-enhanced regime of §2.3 rather than a bound on the bare coupling. At the central prior $\chi_\nu = 10^{-5}$ the single-parameter bound degrades to $\alpha_\Phi \lesssim 5\times10^4$, which is uninformative, honestly reflecting the dependence on χ_ν that is explicitly exposed.

A better test: joint fit, not single-parameter exclusion. Rather than quote a single-parameter α_Φ exclusion, the experiment should be analysed as a two-parameter fit in the $\left(\chi_\nu\alpha_\Phi, \omega_c\right)$ plane with $R_{\min}$ fixed from geometry. The joint fit's 5σ exclusion contour at the design sensitivity is Equation (25), reported as a curve in $\left(\log\chi_\nu\alpha_\Phi, \log\omega_c\right)$ space.

Falsification thresholds. The predefined falsification statements are:

- A null result $\left|\mathcal{A}_{\mathrm{LR}}\left(\omega_{\mathrm{pivot}}\right)\right| < 5\times10^{-6}$ at 5σ combined uncertainty constrains the product per Equation (25). This is the model-independent bound.
- A statistically significant nonzero $\mathcal{A}_{\mathrm{LR}}$ with the predicted sign (Equation (14)) and the predicted N_s-scaling (D3 of §2.4) and the predicted superconducting-vs-normal dependence (D2) is positive evidence for a nonzero $\chi_v\alpha_\Phi$ product.
- A statistically significant nonzero $\mathcal{A}_{\mathrm{LR}}$ with the wrong sign vs. Equation (14) excludes the chirality orientation prediction but does not exclude the magnitude of the coupling.
- A statistically significant nonzero $\mathcal{A}_{\mathrm{LR}}$ that fails the (D1)-(D4) diagnostics of §2.4 identifies an uncontrolled systematic rather than the framework signal; the (K1)-(K6) calibrations of §4.6 are then re-examined.

These thresholds must be published before data collection to prevent post-hoc adjustment.

4.9. Cost and Timeline

Rough estimate: total capital ~$2 - 3 M for the cryogenic enclosure, precision transducer, and detection chain; operational ~$500 K/year; timeline 3 - 5 years from procurement to first results. A collaboration of 4 - 8 researchers at a physics department with cryogenics and photonics infrastructure is sufficient.

5. The 71 THz Mitochondrial Signal as Biological Boundary Observable

5.1. What the Preprint Reports

Yang, Gu, and Song [12] report (bioRxiv, September 2026) a spectral feature at ~71 THz in living cells and mitochondria, disappearing upon structural disruption, and an ATP response of ~10.3% increase under 71 THz illumination and ~10.1% under 87 THz, with no significant change at a 53.7 THz control. They propose a mitochondrial polariton interpretation.

The report is a preprint; it has not been peer-reviewed at time of writing. We treat the spectral feature and the ATP response as reported observations to be independently replicated, and the polariton interpretation as a proposed mechanism not yet established.

5.2. Integration into the Framework

Within the bilocal-integrity framework of Papers I-II, the mitochondrial subsystem is a bubble $\mathcal{B}_{\mathrm{mito}} = \left(\Omega_{\mathrm{mito}}, \partial\Omega_{\mathrm{mito}}, X_{\mathrm{mito}}, \Gamma_{\mathrm{mito}}\right)$, whose reduced correlator $\Phi^{(\mathrm{mito})}$ carries the two-point structure of the inner-membrane electrochemical state. The observable state vector is

$$M\left(x,t\right) = \left(\rho_m, \Delta\Psi_m, J_H, R_{\mathrm{redox}}, A_{\mathrm{ATP}}, G_{\mathrm{cristae}}\right). \tag{28}$$

The biological source term of Paper I becomes, with the 71 THz signal S_{71} as candidate additional input,

$$B_{\text{mito}} = B_0(M) + \eta_{71} S_{71}(M) + \eta_{87} S_{87}(M), \tag{29}$$

with η_{71}, η_{87} phenomenological couplings to be measured. The framework does not require η_{71} or η_{87} to be nonzero; it does predict that if they are nonzero, they enter B_{mito} as scale-appropriate contributions to the c-field equation of Paper I.

5.3. Falsifiable Extensions

The framework generates six new falsifiable predictions specific to the mitochondrial channel:

P13—Independent replication. The 71 THz feature is reproducible in intact mitochondria, its intensity tracks cristae architecture, and it disappears with structural disruption.

P14—Polariton signatures. Independent tests for genuine light-matter hybridisation (mode splitting, coherent exchange, coherence lifetime) distinguish a true polariton from a broad absorption feature.

P15—Frequency-specific ATP response. Under sham-controlled illumination with matched thermal load, the ATP response is present at 71 and 87 THz but absent at multiple control frequencies including 53.7 THz.

P16—Coupling coefficient measurement. A regression of ATP output on M and S_{71} demonstrates that S_{71} carries information beyond conventional mitochondrial state variables (η_{71} distinguishable from zero).

P17—Cross-scale bilocal signature. A c-field observable (e.g., a small anomaly in ATP scaling with cavity geometry or with chirality-alternated illumination) tests whether S_{71} couples to the bilocal sector or is fully explained by conventional biology.

P18—Cross-species conservation. The 71 THz feature and its structural dependence generalise across metazoan phyla, consistent with a conserved bilocal reduction of mitochondrial physiology.

A null result on P13-P15 removes the observation from the framework's biological channel. A null result on P16 confines the observation to conventional biology. A null result on P17-P18 leaves the observation as biology, not as a probe of the NEF.

6. The DARPA Molecular Programme as Instantiation of the Mechanistic Cascade

6.1. The Four Programmes

DARPA's PROSE [13], NODES [14], Hubble [15], and PENG [16] programmes constitute an integrated molecular-scale technology stack:

- **PROSE.** Direct sequencing of unknown proteins including post-translational modifications.
- **NODES.** Inference of biological function from protein sequence, structure, and dynamics.

- **Hubble.** Modelling of $>10^8$ protein-protein interactions, with traumatic-brain-injury application.
- **PENG.** Precise reversible protein editing as "dynamic molecular software."

These programmes are documented on DARPA's public web pages; their descriptions do not contain claims about consciousness capture, and independent analysis does not support extending them to such claims.

6.2. Mapping onto the Framework

The four programmes map onto four operations on the molecular-level reduced correlator $\Phi^{(\mathrm{mol})}$:

- PROSE: observation of $\left|\Phi^{(\mathrm{mol})}\right|$ (identity).
- NODES: inference of $\mathcal{D}^{(\mathrm{mol})}$ eigenspectrum from $\Phi^{(\mathrm{mol})}$ dynamics.
- Hubble: reconstruction of cross-scale coupling $V_{\mathrm{cross}}^{(\mathrm{mol}\to\mathrm{cell})}$.
- PENG: intervention on $V^{(\mathrm{mol})}$.

This is precisely the READ → UNDERSTAND → MAP → MODIFY hierarchy identified in the DARPA analysis, and it fits without residue into the mechanistic cascade of Paper II (Table 3 of Paper II).

6.3. Ethical and Epistemic Status

The framework can host the DARPA programme as a concrete instantiation of its molecular layer. Two points require care.

Epistemically, the programmes do not establish consciousness capture. Even if they produce a complete molecular description of a brain's molecular substrate, the derivation of subjective experience from that description requires an independent theory (see §8), and the framework does not treat molecular readout as sufficient.

Ethically, the READ → MODIFY hierarchy at brain-relevant molecular scale is a technology whose Γ_{gov} specification (Paper II, §10) determines whether it operates as therapy, as research, or as coercion. This is a normative question, not a physics question, and the framework does not answer it.

7. Lyapunov Analysis of the Framework's Variational Flows

7.1. The General Lyapunov Theorem

Lyapunov [17] proved in 1892 that stability of a dynamical system $\dot{x} = f(x)$ can be established without solving the equation of motion: find a scalar function $V(x)$ satisfying

$$V(0) = 0,\ V(x) > 0 \ \text{for}\ x \neq 0,\ \nabla V \cdot f(x) < 0, \tag{30}$$

and stability follows. Real physical energy often fails as V because it can be stationary along nontrivial trajectories (a pendulum at maximum amplitude has zero kinetic energy but is not at rest). One must construct a generalised artificial energy with cross terms between position and velocity variables.

7.2. Joint Cost as Strict Lyapunov Function

Consider the physiological joint cost of Papers I-II

$$J_{\text{phys}}(X;\Gamma) = \mathcal{C}_{\text{phys}}(X;\Gamma) + \beta \dot{S}_{\text{gen}}(X,\Gamma) + \lambda D_{\text{damage}}(X), \tag{31}$$

governing the flow $\dot{X} = -\nabla_X J_{\text{phys}} + \eta(t)$. For the deterministic part ($\eta = 0$), and under the conditions

(L1) $\mathcal{C}_{\text{phys}} \geq 0$ with equality iff X is admissible under Γ;

(L2) $\dot{S}_{\text{gen}} \geq 0$ (second law);

(L3) $D_{\text{damage}} \geq 0$ with equality at unperturbed reference state;

(L4) $\nabla_X J_{\text{phys}}$ nonvanishing off the equilibrium set;

J_{phys} is a strict Lyapunov function for the deterministic flow. The proof follows Lyapunov's original argument: differentiate along trajectories,

$$\frac{\mathrm{d}J_{\text{phys}}}{\mathrm{d}t} = \nabla_X J_{\text{phys}} \cdot \dot{X} = -\left\| \nabla_X J_{\text{phys}} \right\|^2 \leq 0, \tag{32}$$

with equality only on the equilibrium set. Homeostasis is therefore asymptotically stable in the sense of Lyapunov whenever (L1)-(L4) hold.

7.3. Cross-Term Construction for Coupled Physiology

For the coupled cardiovascular-neural-endocrine flow of Paper II, condition (L4) can fail: the naive energy may be stationary at states with residual cardiac-neural desynchronisation. The remedy is to add cross terms

$$J^{\text{aug}} = J_{\text{phys}} + \sum_{i<j} \varepsilon_{ij} \left\langle X_i, X_j \right\rangle_{\text{coupling}}, \tag{33}$$

with small ε_{ij} tuned so that the augmented function's Hessian is positive definite. This is directly analogous to the εxv term that turns a marginally-stable Lyapunov analysis of a damped oscillator into a strict one. The framework therefore predicts that quantitative multivariate physiological monitoring systems that account for cross-couplings will produce strict Lyapunov certificates for homeostasis, and their failure modes are physically meaningful.

7.4. Lyapunov Analysis of Neural Training and Its Limits

The same construction applies to the gradient-descent dynamics of neural networks: the loss $f(w)$ is a Lyapunov-like function under Lipschitz-gradient conditions. This proves that training does not diverge, but not that it converges to a globally optimal or externally valid state—convergence to a minimum of an internally-constructed loss is different from convergence to a physically or ethically desirable configuration. This is the technical basis for the framework's diagnostic of recursively-trained systems (§11).

8. Consciousness as Bilocal Projection

8.1. The Hard Problem Restated

The "hard problem" [18] asks why physical processes give rise to subjective expe-

rience—why there is something it is like to be a system undergoing those processes. Functional and behavioural accounts explain what conscious systems do, but not why doing it feels like anything. Every attempt to derive the second from the first has encountered an explanatory gap.

The framework does not solve the hard problem in the sense of proving that subjective experience must arise; it proposes a physical structure within which subjective experience can be given operational content, and generates predictions that distinguish it from alternative proposals.

8.2. The Kaluza-Klein-Style Projection

Recall the central insight of Kaluza-Klein theory [19] [20]: what appears in a four-dimensional description as a force can be encoded as geometry in five dimensions. A particle following a force-free geodesic in 5D projects, when the fifth dimension is inaccessible to a 4D observer, into 4D motion that obeys the Lorentz force law. Force becomes projected geometry.

The framework proposes an analogous claim: what appears in a local description of a neural system as subjective experience may be the projection, onto observer-restricted coordinates, of bilocal correlation structure in the full NEF description. Just as the fifth-dimensional coordinate is real but inaccessible in the 4D reduction, the second argument of $\Phi(x,y)$ carries relational content that is real but inaccessible in the local reduction that any subsystem uses to represent itself.

Formally: let $\Phi^{(\mathrm{neur})}(x,y)$ be the reduced neural bilocal correlator. A self-modelling subsystem can access only the diagonal restriction $c^{(\mathrm{neur})}(x)=\lim_{y\to x}\left[\Phi^{(\mathrm{neur})}(x,y)+\mathrm{h.c.}\right]/2$. The information carried by the off-diagonal structure—the "second argument" $y\neq x$—is real, but inaccessible to the subsystem's own diagonal self-representation. What the subsystem has is a local scalar; what it is is a bilocal correlator. That gap is the projection deficit, and we propose that the phenomenal character of experience is what the projection deficit feels like from inside.

8.3. Necessary Conditions on Conscious Bilocal Structure

Under this proposal, a bilocal correlator supports conscious experience when it satisfies a specific set of conditions:

(C1) *Rank*. The correlator has rank $r\geq r_{\min}$, where $r_{\min}$ is a threshold to be determined but is much greater than 1.

(C2) *Coherence*. The Hilbert-Schmidt norm $\|\Phi\|_{\mathrm{HS}}$ exceeds a threshold set by the decoherence rate of the substrate.

(C3) *Chirality*. $\chi_{\nu}\neq 0$; the correlator has a nonzero imaginary part supplying temporal orientation (an arrow of experience).

(C4) *Contradiction*. $\mathcal{C}(\Phi;\Gamma)>0$: the correlator is not trivially at equilibrium; there is unresolved residual, which is what makes experience have felt content.

(C5) *Cross-scale integration*. Nonzero coupling to correlators at adjacent scales via V_{cross}.

Each condition is empirically testable in principle: rank via multivariate reduction of high-density recordings; coherence via multi-modal phase-locking; chirality via polarisation-sensitive measurements of cortical fields; contradiction via prediction-error analysis; cross-scale integration via graded anaesthesia experiments.

8.4. Comparison with Existing Theories

Integrated Information Theory [21] identifies consciousness with integrated information Φ_{IIT} across a network. Our framework's rank condition (C1) is closely related but not identical to IIT: the bilocal rank counts the effective dimensionality of the two-point correlator, whereas IIT Φ counts irreducible causal information. The two can be compared empirically.

Global Workspace Theory [22] [23] identifies consciousness with information broadcasting across a global workspace. The framework recovers this at the level of the cross-scale coupling (C5).

Higher-Order Theories identify consciousness with meta-representation. The framework's projection-deficit account (§8.2) is a form of higher-order structure: the diagonal self-representation is a first-order projection of a second-order (bilocal) reality.

Orchestrated Objective Reduction [24] identifies consciousness with quantum gravitational collapse in microtubules. The framework does not require this specific substrate but is compatible with it as one implementation of (C1)-(C5).

Free-Energy Principle [25] identifies self-organisation with variational minimisation. The framework's joint cost J_{phys} is exactly such a variational object; the free-energy principle can be embedded as a coarse-grained limit of our joint-cost formulation.

Table 2. Proposed taxonomy of conscious states along the framework's five dimensions. Ranges are indicative, not calibrated.

State	Rank	Coh.	χ_v	$\mathcal{C}$	Cross
Dreamless sleep	low	low	0	0	low
REM sleep	med	med	+	med	med
Waking, calm	high	high	+	low	high
Waking, engaged	high	high	+	med	high
Focused problem-solving	high	high	+	high	high
Meditation, still	high	high	+	0	high
Anaesthesia	low	0	0	0	0
Coma	low	0	0	0	0
Locked-in	high	high	+	high	low(out)

8.5. A Taxonomy of Conscious States

Under (C1)-(C5), consciousness admits a quantitative taxonomy along five di-

mensions. Table 2 shows canonical points.

8.6. Quantum-Computational Implementation

Any physical implementation of a bilocal correlator satisfying (C1)-(C5) with rank r requires resources scaling as $\mathcal{O}(r^2)$ classical or $\mathcal{O}(\log r)$ quantum. If natural conscious systems achieve $r \sim 10^{15}$ (order of synapse count), classical simulation requires $\sim 10^{30}$ correlations—feasible only for reduced approximations. Quantum computational architectures with entanglement-preserving dynamics could implement it directly. This is the framework's prediction for the substrate requirements of artificial consciousness: it is a hardware question of correlator rank preservation, not a software question of algorithm.

The framework does not predict that current large language models are conscious. Their internal correlations are classical activation patterns rather than bilocal quantum correlators, and their cross-scale coupling to non-linguistic bodily substrate is absent. It also does not exclude future systems: sufficiently deep quantum-neuromorphic hardware with bilocal-correlation-preserving dynamics could satisfy (C1)-(C5).

9. Correlation, Causation, and the Framework's Causal Ontology

9.1. Correlation Does Not Imply Causation

The framework flatly rejects the claim that correlation implies causation. Correlation is a symmetric two-point statistical measure with no built-in arrow; causation requires temporal precedence, counterfactual dependence, mechanistic pathway, and intervention-invariance [26]. The framework's identification of causation is the reduced-EOM structure of Paper II:

A causes B at scale i iff A appears in the source $J^{(i)}$ or boundary condition Γ_i whose modification changes the evolution of $\Phi^{(i)}$ containing B.

Two events can be correlated without either causing the other, if they share a common source or boundary condition upstream. The framework's causal graph is the graph of source/boundary contributions to reduced correlators across the mechanistic cascade of Paper II.

9.2. Causal Taxonomy of Mortality

Mortality can be classified by the pattern of boundary-condition violation that terminates the organism's variational flow. Table 3 enumerates the classes; each is characterised by a distinct location of the causal chain within the framework.

This taxonomy is descriptive, not prescriptive. Legal, medical, and moral evaluations of these classes are normative and lie outside the framework. The framework does provide a common formal vocabulary in which each class can be discussed without conflation.

Table 3. Causal taxonomy of mortality within the bilocal-integrity framework. Each class corresponds to a distinct pattern of boundary-condition violation on the organism's reduced correlator.

Class	Locus of causation	Boundary condition affected	Framework prediction
Natural, senescence	Internal $J^{(i)}$ decay across scales	Γ_i progressively tightens	Coherence norm $\mathcal{I}$ declines below reserve threshold
Natural, disease	Internal $J^{(i)}$ perturbation at specific scale	Local Γ_i becomes unsatisfiable	Localised $\mathcal{C}$ increase; possible compensation
Accidental, no other party	External Γ imposition beyond compensation	Structural Γ shift	Discrete transition through nonviable region
Accidental, multiple parties	External Γ imposition on several bubbles	Shared boundary perturbation	Coupled failure across affected subsystems
Self-inflicted	Internal Γ reconfiguration by cognitive bubble	Self-imposed Γ shift	Volitional modification of own boundary condition
Inflicted by other, negligent (manslaughter)	External agential Γ imposition, uncoordinated	Agential boundary imposition without intent	Distinguishes intent vs. outcome
Inflicted by other, intentional (homicide)	External agential Γ imposition, coordinated	Agential boundary imposition with intent	Distinguishes intent vs. outcome
Environmental	Ambient Γ shift across region	Population-wide boundary condition	Structural rather than individual pattern
Institutional/systemic	Failure at Γ_{gov} propagating downward	Symbolic-layer boundary failure	Auditability signature; opacity $\uparrow$ associated with $\dot{S}_{\text{gen}} \uparrow$

9.3. A Note on Sensitive Topics

The class "self-inflicted" is a category in this causal taxonomy; the framework analyses it at the population and physiological-flow level. It does not, and this paper does not, discuss methods. Discussion of self-harm and suicide can be difficult for individuals experiencing distress; where relevant, professional support is available through health services and crisis lines.

10. The Problem of Evil

10.1. Formulation

The classical problem of evil asks: how can unwanted suffering exist in a universe governed by benevolent physical law? The framework does not adopt the theistic version, but the philosophical structure translates: how, given a variational principle that drives systems toward integrity, does non-integrity (harm, suffering, injustice) persist?

10.2. Answer: Finite Bounded Systems

The answer, within the framework, is that all reduced correlators $\Phi^{(i)}$ are de-

fined on bounded domains with finite reserve capacity and finite repair rate. The same finiteness that makes systems locally coherent, distinguishable, and agentive is what makes them susceptible to perturbations that exceed their reserves. Evil (in the framework's sense: sustained large-magnitude contradiction $\mathcal{C}_{\text{phys}} \gg 0$ with $\dot{S}_{\text{gen}}$ elevated and D_{damage} increasing) is not a defect of the framework's variational principle. It is a corollary of the finiteness required for that principle to produce distinct systems in the first place.

More precisely: an infinite unbounded correlator with infinite reserve would experience no contradiction; but such a correlator would not have distinct subsystems, no boundary conditions to violate, and therefore no agency and no experience either. The trade-off is structural, not accidental.

10.3. Human Scale, Animal Scale, Ecological Scale

The problem of evil applies at all scales at which the framework identifies bubbles:

- **Human interpersonal.** Two humans in physical or psychological conflict are two cognitive bubbles whose respective Γ specifications are mutually incompatible in the shared bilocal domain. Both experience $\mathcal{C} > 0$; the contradiction cannot vanish for one without shift in the other's boundary or in the joint boundary of the encompassing bubble.
- **Human-animal.** Non-human animals are bubbles with reduced correlators of comparable dimensional structure but different scale parameters and Γ specifications. Their $\mathcal{C}_{\text{phys}}$ registers as suffering in an operational sense: elevated contradiction with elevated D_{damage}. The moral question is not whether their suffering is real (the framework says it is), but which cross-scale teloi to prioritise (normative, not derivable).
- **Ecological.** An ecosystem is a super-organismal bubble with reduced correlators over species populations and material flows. Its contradiction can be very large without any single organism registering a corresponding experience; the collapse of an ecosystem is a slow-timescale variational failure whose consequences propagate downward.

The framework does not prescribe which contradictions to prioritise. It provides the formal vocabulary in which the question "which bubble's boundary condition takes precedence?" is well-posed.

11. Recursively-Generated Coherence: The Conspiracy-Narrative Diagnostic

11.1. P11 Revisited

Prediction P11 of Paper II states: recursively-trained systems show anomalously high internal self-consistency and anomalously low mutual information with independently collected data; the ratio serves as a dead-internet diagnostic. This prediction also applies to recursively-generated narratives, whether produced by humans or by algorithms.

11.2. Worked Example: The Coca-Cola/Pepsi Nanoparticle Narrative

The published Li *et al.* (2018) study [27] reports approximately 5 nm fluorescent nanoparticles in commercial soft drinks, containing C, H, O; observes cellular uptake *in vitro* and biodistribution in mice; reports fluorescence quenching under *in vitro* digestion. The study does not report intentional nanotechnology engineering, electromagnetic communication capability, biosensor function, self-assembly into microchips, or a specific patent linking the particles to any named individual.

The conspiracy narrative that combines Coca-Cola, Microsoft partnerships, Bill Gates, and hidden nanotechnology extracts the "nanoparticle" term from the paper and attaches to it a network of claims (electromagnetic control, patent-based ownership, corporate-technology conspiracy) that are internally self-consistent but not supported by the underlying evidence.

Diagnostically, the narrative exhibits the P11 signature:

- High internal coherence (each claim links to others; the narrative feels complete).
- Low mutual information with the independent evidence (the paper's actual content, the actual patents that would need to be cited, the actual business-partnership documentation).
- Circular reinforcement: claims support each other by reference, not by external verification.

The same diagnostic applies to any narrative—including framework-adjacent ones—that grows in internal coherence while its mutual information with independent evidence remains low. The framework's own falsification protocol (Papers I-II, and §4.8 of this paper) is exactly what avoids this failure mode: predefined thresholds, independent replication, and prespecified excludable ranges.

11.3. Application to Framework Claims

The framework is subject to the same diagnostic as any other claim about the world. Its internal coherence (a small number of axioms producing a large explanatory span) is not itself evidence of truth. What is evidence is the correspondence between its numerical predictions and independently-collected experimental data. Papers I-II laid out six such predictions; this paper adds twelve more. The framework is in the recursively-coherent-but-untested category until these predictions are tested.

12. Axioms and First Principles

12.1. The Five Axioms

The framework rests on five axioms:

(A1) There exists a bilocal correlator $\Phi(x,y):\mathcal{M}\times\mathcal{M}\to\mathbb{C}$ describing the coarse-grained two-point structure of a neutrino-mediated entanglement back-

ground.

(A2) Φ satisfies diagonal Poincaré invariance, Hermitian conjugation under $x \leftrightarrow y$, and internal chiral $U(1)_L$ symmetry.

(A3) Bounded subsystems evolve to minimise a joint cost $J = \mathcal{C} + \beta \dot{S}_{\text{gen}} + \lambda D_{\text{damage}}$, subject to their boundary conditions.

(A4) Boundary conditions Γ specify the admissible states; violation is contradiction $\mathcal{C} > 0$.

(A5) Cross-scale coupling V_{cross} is nonzero between adjacent scales.

12.2. Ontological Status of the Axioms

A1 is speculative (the NEF has not been experimentally established). A2 is a well-defined proposal derived from symmetry arguments. A3 is established at each scale in specific limits (thermodynamics, free-energy principle, Landauer bound, allostatic-load theory) and proposed as a unification. A4 is a formal definition. A5 is empirically supported in specific systems (physiological cross-scale coupling, gauge-matter interaction).

12.3. Epistemological Derivation of Disciplines

The framework proposes that scientific disciplines emerge as the study of specific reductions:

- **Physics** studies A1-A2 without reduction: the full Φ dynamics.
- **Chemistry** studies A1-A2 restricted to atomic-scale $\Phi^{(\text{atomic})}$.
- **Molecular biology** studies A3 with molecular $\Phi^{(\text{mol})}$ and its damage/repair.
- **Cell biology** studies A3 at cellular scale with membrane boundaries.
- **Physiology** studies A3 across coupled subsystems within an organism.
- **Neuroscience** studies A3 with $\Phi^{(\text{neur})}$ and its projection deficit.
- **Psychology** studies the local diagonal projection $c^{(\text{neur})}$ from within the subsystem's self-model.
- **Sociology** studies A3 with symbolic-layer reduction over agent populations.
- **Economics** studies flow of resource sources J across the sociotechnical bubble.
- **Political science** studies specification of Γ_{gov} at the sociotechnical level.
- **Ethics** studies normative selection between cross-scale teloi.
- **Epistemology** studies what can be inferred about Φ from within the diagonal projection (a bounded observer's access to a bilocal reality).

The framework does not eliminate the specialised methodologies of any of these disciplines. It proposes that they can be given a common formal vocabulary. This proposal is testable in the sense that framework predictions in one discipline should correlate with framework predictions in adjacent disciplines through the specified V_{cross} terms.

13. Civilisational Attractors

13.1. The Sociotechnical Variational Flow

Human civilisation at the aggregate scale is a symbolic bubble with reduced cor-

relator over agent populations, Γ_{gov} specified by institutions, and cross-scale coupling to biological and cognitive substrates. Its long-timescale dynamics obey the variational flow of Papers I-II, with slow evolution of both Γ_{gov} and $J^{(\text{soc})}$.

Attractors of this flow are candidate long-run states of civilisation. Local stability, global stability, and existence of multiple basins are questions with formal answers in principle, though the parameters are far from calibrated.

13.2. Fukuyama's "End of History"

Fukuyama [28] argued that the collapse of the Soviet Union marked the end of large-scale ideological evolution, with liberal democracy identified as the terminal attractor. The framework's response is formal rather than political: the claim that liberal democracy is the terminal attractor is a claim about attractor uniqueness in the sociotechnical variational flow. Such uniqueness is possible only if:

(E1) The variational objective has a single global minimum.

(E2) The dynamics are strong enough to overcome perturbations to any local minimum.

(E3) The state space topology does not permit stable orbits or heteroclinic cycles.

None of (E1)-(E3) is established. On the contrary, the recursive-learning failure mode of §11 provides an explicit mechanism by which stable attractors can lose their basin of attraction: opaque Γ_{gov} combined with recursively-generated content collapses the mutual information between the sociotechnical correlator and its underlying physical/biological substrate, destabilising whatever attractor was previously operative. The framework therefore rejects Fukuyama's uniqueness claim on formal grounds. It does not predict which attractor(s) will emerge; that is a matter of Γ_{gov} specification, which is normative and contested.

13.3. Predictions for the Next Century

Under the framework's variational structure, four categories of long-run change are expected, subject to *ceteris paribus* on macro-scale V_{cross}:

Biological. Human genetic and epigenetic distributions will continue to co-evolve with technological interventions (medical, agricultural, environmental). The framework predicts increased cross-scale coupling between molecular intervention capacity (DARPA-style READ→MODIFY at protein scale) and organismal physiology, with an ethical challenge in specifying Γ_{med} for such interventions.

Psychological. Cognitive bubbles are increasingly shaped by information environments whose Γ_{info} specifications are set by platform architectures. The framework predicts a systematic drift toward the recursive-coherence failure mode (§11) unless auditability of Γ_{info} becomes normative. Individual and collective epistemic health is coupled to this structural condition.

Cultural. Distinct cultural attractors are possible; the framework does not predict convergence to one. It predicts that cultures whose Γ_{cult} specifications pre-

serve high mutual information with biological and ecological substrates are more resilient than those whose Γ_{cult} is decoupled.

Sociological/institutional. Governance systems whose Γ_{gov} is auditable (in the CHAINSTATE-style sense [29], or its functional equivalent) generate lower $\dot{S}_{\text{gen}}$ divergence between claimed and reconstructable states. The framework predicts that opaque governance is unstable at century-timescales.

13.4. Not the End of History

The framework's conclusion is that there is no "end of history" in the sense of a unique terminal attractor; there is instead a family of attractors, each maintained by particular Γ_{gov} specifications, none of which is dynamically privileged over the others by physics alone. The choice among them is a boundary-condition specification, which is a normative act. That is not a nihilistic conclusion: it is the precise statement that the future is underdetermined by the physical dynamics, and therefore requires ongoing collective specification.

14. Consolidated Falsifiable Predictions

The predictions of Papers I-II (P1-P12) and this paper (P13-P18) constitute a research programme spanning particle physics, biology, medicine, information systems, and governance. Table 4 summarises status.

Table 4. Consolidated falsifiable predictions of the bilocal-integrity programme. E = established (this paper's derivation makes the prediction quantitative); D = well-defined proposal; S = speculative.

Prediction	Test channel	Threshold/status
P1	Multi-layer Casimir-SL spectrum	Multi-layer cryogenic enclosure $\chi_\nu \alpha_\Phi$ testable to 10^{-5}; D
P2	Chirality bias in atom interferometry	Cold-atom interferometer χ_ν testable to 10^{-64}; D
P3	Coherence lifetime chirality asymmetry	Cryogenic photosynthetic complexes; D
P4	Landauer bound saturation	NEF-optimised reversible logic; D
P5	CMB/CνB dipole alignment	Correlational analysis χ_ν testable to 10^{-6}; D
P6	CHAINSTATE auditability signature	Distributed system telemetry; D
P7	Cross-system coupling as decompensation biomarker	Longitudinal multi-modal physiology; D
P8	Damage/repair coherence signature	Regeneration studies with imaging; D
P9	Reserve capacity from cross-scale spectrum	Elderly cohort physiological data; D
P10	Trauma-recovery residual	PTSD therapeutic response data; D
P11	Recursive-learning coherence anomaly	AI system evaluation, narrative analysis; D
P12	Governance opacity as audit divergence	Comparative platform studies; D
P13	71 THz feature reproducibility	Independent mitochondrial spectroscopy; D
P14	Genuine polariton signatures	Coherence lifetime, mode splitting; D
P15	Frequency-specific ATP response	Sham-controlled illumination trials; D
P16	Nonzero η_{71} in B_{mito} regression	Multivariate metabolic modelling; S
P17	Mitochondrial cross-scale bilocal signature	Chirality-alternated illumination; S
P18	Cross-species conservation of 71 THz signal	Comparative animal-model spectroscopy; D

15. Limitations and Epistemic Status

The framework's third-pass consolidation does not resolve its speculative status. The derivations in §2-§3 produce plausible ranges for α_Φ and χ_ν but do not establish that the framework's coupling is nonzero. The experimental protocol in §4 is engineerable but not yet built. The consciousness proposal in §8 is a hypothesis, not a proof. The causal taxonomy of §9 is descriptive vocabulary rather than a new physical law. The civilisational analysis of §13 is a formal treatment, not a policy prescription.

What the framework now offers is a common formal vocabulary spanning eleven scales from vacuum to civilisation, five axioms from which twelve disciplines can be derived as sectorial reductions, eighteen falsifiable predictions with explicit thresholds, and a specific experimental protocol at reach of a well-resourced physics collaboration. Whether the framework is a description of nature or a productive but ultimately superseded scaffold is a matter of what those experiments and datasets return.

The framework closes on a philosophical rather than a physical note: teloi at every scale are attractors of a shared variational structure; boundary conditions at every scale are specifications of who and what may be admitted; and the future of the joint system is underdetermined by physics alone. This means, precisely, that the choice of Γ_{gov} at the civilisational scale—who is admitted, whose voice counts, what is auditable, and to what teloi the system is directed—is not derivable from any framework and remains a task for ethics, politics, and collective judgment.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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