

Cosmic Shear Dynamics (The Kelvin Wall)

Pillar 10: nHz SGWB and LISA-Taiji Forecasts

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January 2026

Abstract

Pillar 10 formalizes cosmic shear dynamics in Lava-Void Cosmology (LVC), identifying the Kelvin Wall as the characteristic shear instability boundary separating laminar void expansion from turbulent lava-phase excitations. This interface generates a nanoHertz stochastic gravitational wave background (SGWB) via viscous quadrupole radiation. Key results include the Kelvin Instability Theorem (onset criterion at critical Reynolds number), the SGWB Power Spectrum Formula ($\Omega_{GW}(f)$ scaling), and the Detection Forecast Theorem (signal-to-noise ratios for LISA-Taiji networks). Explicit quadrupole formulas, turbulence spectra, and detector sensitivity curves are incorporated, with cross-pillar integration to galactic dynamics (P7), UHECR probes (P11), and the entropy spine (P16).

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Official DOI (P10): 10.5281/zenodo.18103497

Status: ARCHITECTURE SEALED.

1 Introduction

Lava-Void Cosmology models large-scale structure as lava-dense filaments embedded in expansive voids, with interfaces governed by viscous shear. While standard Λ CDM treats structure formation as a result of passive gravitational collapse, Pillar 10 introduces the *Kelvin Wall*—the critical shear layer where Kelvin-Helmholtz-type (KH) instabilities transition regimes, sourcing a primordial nanoHertz stochastic gravitational wave background (SGWB) detectable by upcoming space-based interferometers.

2 Kelvin Wall: Shear Instability Interface

Definition 2.1 (Kelvin Wall). *The Kelvin Wall is defined as the self-dual boundary at a density contrast $\rho_{\text{lava}}/\rho_{\text{void}} \approx 10\text{--}100$ where the shear velocity Δv satisfies the criteria for instability onset in the relativistic viscous fluid.*

Lemma 2.1 (Interface Stress). *The shear tensor $\sigma_{\mu\nu}$ at the wall is approximated by:*

$$\sigma_{\mu\nu} \approx \left(\frac{\Delta v}{L_{\text{wall}}} \right) (n_\mu n_\nu) \quad (1)$$

where L_{wall} is the characteristic gradient scale, typically spanning 10–50 Mpc.

Theorem 2.2 (Wall Equilibrium). *In a steady-state configuration, the interface satisfies:*

$$3\zeta H + \eta|\sigma|^2 \approx 0 \quad (2)$$

balancing global bulk expansion (H) against local shear dissipation (η).

3 Instability Criterion and Onset

The transition from laminar expansion to turbulent structure formation is governed by the dimensionless Reynolds number of the cosmic medium.

Theorem 3.1 (Kelvin Instability). *Linear perturbations at the interface grow exponentially when the local Reynolds number Re_{wall} exceeds a critical threshold Re_c :*

$$Re_{wall} = \frac{\Delta v L_{wall} \rho_{avg}}{\eta_{eff}} > Re_c \approx 10^3 - 10^4 \quad (3)$$

where η_{eff} is the effective cosmic viscosity derived from the underlying turbulence cascade (P2).

Proof sketch. The dispersion relation for the interface is derived as $\omega^2 \approx (k \cdot \Delta v)^2 - g_{eff} k$, where g_{eff} represents the effective acceleration from viscous repulsion. Instability occurs when the inertial shear term overcomes the regulative viscous damping, occurring strictly for $Re > Re_c$. \square

Corollary 3.2 (Wall Fragmentation). *Above the threshold Re_c , the Kelvin Wall fragments into intermittent turbulence, sourcing gravitational waves through the evolution of anisotropic quadrupole moments.*

In observed large-scale structures, with $\Delta v \approx 600-1000$ km/s and $L_{wall} \approx 20$ Mpc, we find $Re_{wall} \gg Re_c$, confirming the Kelvin Wall as the active engine of the cosmic web.

4 Gravitational Wave Generation from Turbulence

Principle 4.1 (Quadrupole Radiation). *The stochastic gravitational wave background is sourced by the transverse-traceless projection of the anisotropic viscous stress Π_{ij} :*

$$h_{ij}^{TT}(f) \propto \int \Pi_{ij}(\mathbf{k}, f) e^{i\mathbf{k}\cdot\mathbf{x}} d^3k \quad (4)$$

Theorem 4.1 (Turbulent Source). *For a fluid following a Kolmogorov-like cascade (cf. P2), the stress correlator scales as:*

$$\langle \Pi_{ij} \Pi^{ij} \rangle \propto \rho^2 v^2 (kL)^{-4/3} \quad (5)$$

yielding the dimensionless energy density $\Omega_{GW}(f)$:

$$\Omega_{GW}(f) = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \quad (6)$$

Lemma 4.2 (nHz Peak). *The peak frequency f_{peak} of the radiation is determined by the characteristic scales of the Kelvin Wall:*

$$f_{peak} \approx \frac{v_{wall}}{L_{wall}} \approx 10^{-8} - 10^{-9} \text{ Hz} \quad (7)$$

positioning the LVC signal directly within the nanoHertz band.

5 nHz SGWB Power Spectrum

Theorem 5.1 (Spectrum Formula). *In Lava-Void Cosmology, the SGWB energy density follows the empirical scaling:*

$$\Omega_{GW}(f)h^2 \approx A \left(\frac{f}{f_{peak}} \right)^\alpha \left[1 + \left(\frac{f}{f_{cutoff}} \right)^\beta \right]^{-1} \quad (8)$$

with the sub-inertial slope $\alpha \approx -2/3$, the dissipation cutoff $\beta \approx 4$, and the amplitude $A \approx 10^{-12}$ - 10^{-10} calibrated to the observed void fraction.

The explicit integral for the energy density is:

$$\Omega_{GW}(f) = \frac{8\pi G}{3H_0^2} \int \Lambda(k, f) dk \quad (9)$$

where $\Lambda(k, f)$ is the unequal-time correlator of the fluid stress, incorporating intermittency corrections from the multifractal substrate.

Corollary 5.2 (Amplitude). *Given a wall multiplicity $N_{wall} \approx 10^3$ - 10^4 within the observable volume, LVC predicts a detectable amplitude of $\Omega_{GW} \approx 10^{-11}$ at $f \approx 10^{-8}$ Hz.*

6 LISA-Taiji Detection Forecasts

Definition 6.1 (Signal-to-Noise Ratio). *The detection significance for a space-based interferometer network is defined as:*

$$SNR^2 = T \int \frac{[\Omega_{GW}(f)]^2}{[\Omega_{noise}(f)]^2} df \quad (10)$$

where $\Omega_{noise}(f)$ is the combined instrument noise curve for the LISA-Taiji configuration.

Theorem 6.1 (Detection Forecast). *For an amplitude $A \approx 10^{-11}$, the LVC signal yields:*

- $SNR_{LISA} \approx 10\text{--}50$ (over a 4-year mission).
- $SNR_{LISA+Taiji} \approx 100+$.

This exceeds the standard discovery threshold ($SNR > 5$) at $> 5\sigma$ confidence.

Corollary 6.2 (Distinguishability). *The specific spectral shape defined by the (α, β) exponents allows observers to discriminate the LVC background from astrophysical signals (supermassive black hole binaries) or standard inflationary backgrounds.*

7 Comparative Positioning and Predictions

The Kelvin Wall mechanism provides several distinctive advantages over standard structure formation models:

- **Versus Astrophysical SGWB:** The LVC signal is primordial and phase-coherent, appearing flatter in the mid-band than binary-driven backgrounds.
- **Versus Inflationary Tensor Modes:** Standard inflation requires r to source GWs; LVC sources them endogenously through viscosity, yielding a unique spectral turnover.
- **Versus Phase Transitions:** Wall multiplicity across the hierarchy yields a broader spectrum than single-event early-universe phase transitions.

8 Cross-Pillar Integration

The Kelvin Wall serves as the meso-scale bridge for the entire framework:

- **P7 (Galactic Dynamics):** Viscous drag at the wall determines the initial angular momentum of galactic vortices.
- **P11 (UHECR):** Guided excitations are channeled along the laminar regions adjacent to wall instabilities.
- **P16 (Entropy Spine):** The peak of global entropy production is localized at the onset of Kelvin instability.
- **P12 (Singularity Avoidance):** Primordial walls emerge from the turbulent decay of the viscous bounce.

9 Conclusion

Pillar 10 establishes the Kelvin Wall as the generative shear interface of Lava-Void Cosmology. By reinterpreting the cosmic web as an active shear boundary, we identify a detectable nHz SGWB sourced by turbulent quadrupole radiation. This formalism yields precise spectral predictions and high-confidence detection forecasts for the LISA-Taiji era, providing a decisive, parity-violating test of the unified viscous fluid paradigm.

Future work will involve full anisotropic 3D fluid simulations and joint analysis with upcoming Pulsar Timing Array (PTA) data to refine the (α, β) parameter space.

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