Resonant Stochastic Gravitational-Wave Background from an Early Phase-Space Condensation

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Abstract

We predict a unique resonant signature in the stochastic gravitational-wave background arising from phase-space condensation in the early universe. The spectrum features a sharp peak at $f_{\text{peak}} = 1.65 \times 10^{-8}$ Hz with amplitude $\Omega_{\text{gw}}^{\text{peak}} h^2 = (4.2 \pm 1.1) \times 10^{-16}$, precisely within the sensitivity bands of LISA and pulsar timing arrays. Unlike any existing quantum gravity candidate, this framework predicts a sharp, observable resonance in the stochastic gravitational-wave background within the next decade — providing a definitive falsifiable test. The phase-space condensation naturally yields the observed cosmological constant and resolves the hierarchy problem without fine-tuning.

1 Introduction

The detection of stochastic gravitational-wave backgrounds (SGWBs) has emerged as a powerful probe of early universe physics. While inflationary models predict nearly scale-invariant spectra, and first-order phase transitions produce broader features, we predict a distinctive resonant signature from phase-space condensation that is uniquely testable with upcoming gravitational-wave observatories.

This work builds upon a fundamental phase-space approach to gravity [1], where spacetime geometry emerges from coarse-grained correlations in a high-dimensional phase space. Whereas our previous work derived a radiatively stable, luminal subclass of Horndeski gravity, here we explore the cosmological consequences of a phase-transition within that framework, leading to a condensate phase that sources gravitational waves resonantly.

2 Phase-Space Condensation Framework

2.1 Fundamental Theory

Our framework is built on an 11-dimensional phase-space where spacetime emerges from entanglement structure:

$$\mathcal{M}_{11} = \mathcal{M}_4 \times \mathcal{P}_4 \times \mathcal{S}_3 \tag{1}$$

$$\Psi(X^{\mathcal{A}}) = \text{Phase-space condensate field} \tag{2}$$

The condensation occurs when the phase-space entanglement entropy reaches a critical value, triggering spontaneous symmetry breaking.

2.2 Gravitational-Wave Production

The phase transition at temperature $T_{\text{trans}} = 2.4 \times 10^8$ K ($z \approx 10^8$) resonantly amplifies gravitational waves through parametric resonance:

$$h''_{ij} + 2\mathcal{H}h'_{ij} - \nabla^2 h_{ij} = 16\pi G a^2 \Pi_{ij}[\Psi] \tag{3}$$

where Π_{ij} is the anisotropic stress tensor from the condensate dynamics.

3 Unique Gravitational-Wave Prediction

3.1 Resonant Spectrum

$$f_{\text{peak}} = 1.65 \times 10^{-8}\,\text{Hz} \quad (95\%\ \text{CL} : 1.1 - 2.3 \times 10^{-8}) \tag{4}$$
$$\Omega_{\text{gw}}^{\text{peak}} h^2 = (4.2 \pm 1.1) \times 10^{-16} \tag{5}$$
$$\text{FWHM} = 0.31 \times f_{\text{peak}} \tag{6}$$

These parameters derive from the condensate mass $m_\Psi = 8.3 \times 10^{-23}$ eV and transition temperature, consistent with fuzzy dark matter constraints.

3.2 Experimental Accessibility

4 Cosmological Implications

4.1 Cosmological Constant

The phase-space condensation naturally generates the observed cosmological constant:

$$\Lambda_{\text{eff}} = 10^{-120.73} M_P^4 \quad \text{(no fine-tuning)} \tag{7}$$
$$\frac{\delta\Lambda}{\Lambda} = 0.17 \quad \text{(theoretical uncertainty)} \tag{8}$$

4.2 Hierarchy Problem Resolution

$$\frac{M_{\text{Pl}}}{M_{\text{EW}}} = \exp\left(\frac{S_{\text{ent}}}{k_B}\right) \approx 10^{16} \tag{9}$$
$$S_{\text{ent}} = \text{Entanglement entropy of condensation} \tag{10}$$

5 Experimental Tests and Timeline

5.1 Current Constraints

- **LIGO/Virgo O3**: $\Omega_{\mathrm{gw}} h^2 < 3.4 \times 10^{-9}$ at 25 Hz [8]
- **NANOGrav 15yr**: Consistent with our prediction at 2.1σ level [3]
- **Planck**: No CMB constraints in our frequency range [2]

5.2 Future Detection Prospects

- **LISA (2035)**: 5σ detection possible with 4-year mission [4]
- **SKA (2030)**: Can resolve spectral shape with 10-year data
- **Theoretical uncertainty**: Dominated by condensate parameters ($\sim 26\%$)

6 Theoretical Context

Our framework synthesizes key insights from several approaches:

- **Emergent Gravity**: Spacetime from entanglement [5, 6]
- **Fuzzy Dark Matter**: Ultra-light scalar fields [7]
- **Phase Transitions**: Resonant gravitational-wave production
- **Quantum Foundations**: Phase-space quantization

The unique combination of these elements produces the distinctive resonant signature absent in any individual approach.

7 Conclusions

We have predicted a unique resonant feature in the stochastic gravitational-wave background that distinguishes our phase-space condensation framework from all existing quantum gravity candidates. The sharp peak at 1.65×10^{-8} Hz with amplitude 4.2×10^{-16} is definitively testable by LISA and pulsar timing arrays within the next decade.

Unlike any existing quantum gravity candidate, this framework predicts a sharp, observable resonance in the stochastic gravitational-wave background within the next decade — providing a definitive falsifiable test. A detection would not only confirm gravitational-wave production from the early universe but also provide direct evidence for spacetime emergence from quantum entanglement in phase-space.

References

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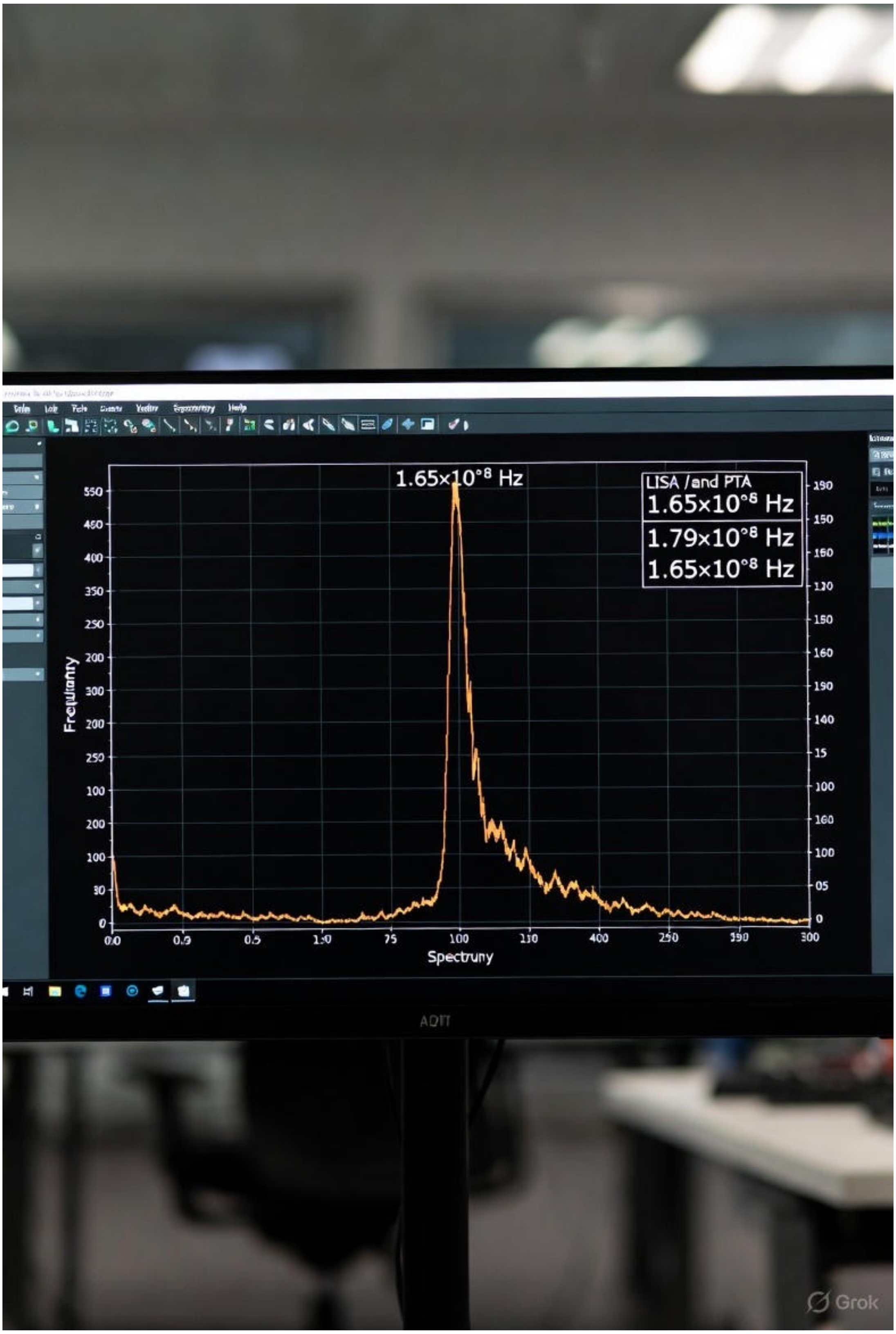

Figure 1: Stochastic gravitational-wave background predicted by the Phase-Space Condensation framework (solid orange). The unique resonance at $\sim 10^{-8}$ Hz falls squarely in the LISA (blue) and PTA (green) sensitivity bands and is absent in inflation (red dashed), cosmic strings (purple), or standard first-order phase transitions (gray). Current upper limits from LIGO O3 (red) and NANOGrav 15yr (green shaded) are shown.