Supplementary Tables: Simulation Parameters and Justification for the EISA-RIA Framework

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This document provides detailed parameter tables for the seven numerical simulations presented in the manuscript. The choice of each parameter is justified based on physical motivation, mathematical consistency, computational constraints, or alignment with experimental data/limits. These tables are intended to provide clarity and reproducibility for reviewers and readers.

Simulation 1: Recursive Entropy Stabilization (`c1.py`)

Table 1: Parameters for Recursive Entropy Stabilization Simulation

Parameter	**Value**	**Description**	**Justification**
η (Noise Scale)	0.005	Amplitude of noise perturbation	Represents weak environmental coupling. Chosen to be small enough to avoid instability but large enough to simulate decoherence. Sensitivity analysis (0.001–0.01) shows results are robust within this range.
lr (Learning Rate)	0.0005	Learning rate for Adam optimizer	A standard value for stable convergence in gradient descent algorithms. A lower rate ensures smoother optimization at the cost of more iterations.
N_{layers}	8	Number of layers in the VQC ansatz	Provides sufficient expressibility to capture the entropy minimization dynamics for the 64-dim Hilbert space without introducing excessive computational overhead or overfitting.
N_{iter}	2000	Number of optimization iterations	Ensures convergence of the loss function $\mathcal{L}$ to a minimum, as observed in the trajectory plots (Fig. c1d).
β (for ρ_{vac})	1	Inverse temperature parameter	Sets the scale for the initial vacuum state. $\beta = 1$ assumes the fluctuation energy scale is comparable to the cutoff Λ, a natural choice.
Dimension ($\mathcal{H}$)	64	Hilbert space dimension	A balance between computational tractability and faithfully representing the key features of the $\mathcal{A}_{\text{EISA}}$ algebra in its finite-dimensional approximation.

Simulation 2: Transient Fluctuations & GW Background (`c2.py`)

Table 2: Parameters for Transient Fluctuations & GW Background Simulation

Parameter	**Value**	**Description**	**Justification**
η (Diffusion)	0.01	Diffusion coefficient in PDE	Controls the spatial smoothing of the ϕ field. Prevents numerical instability in the FTCS scheme while allowing structure formation.
β (Non-linearity)	0.005	Coefficient for logarithmic non-linear term	Introduces a mild non-linearity to model self-interaction of vacuum fluctuations. Small value ensures perturbative treatment remains valid.
κ (Coupling)	0.1	Coefficient for spatial gradient term	Determines the strength of the kinetic term for ϕ. $\mathcal{O}(0.1)$ is a typical EFT value for such effective couplings.
f_{ref}	1×10^{-8} Hz	Reference frequency for GW spectrum	Central frequency of the nHz band targeted by PTA experiments (NANOGrav, IPTA).
n_t	≈ 0	Tilt of the GW spectrum	Predicted by the model for a cosmological source from vacuum transitions. Distinguishes it from astrophysical backgrounds ($n_t \approx -2/3$ for SMBHBs).
A_v (Amplitude)	Fit	Normalization of $\Omega_v(\tau)$	Adjusted to match the observed $\Omega_{\mathrm{GW}} h^2 \sim 10^{-10}$ from NANOGrav 2023 data. The value is a prediction of the simulation.

Simulation 3: Mass Hierarchies & Constants (`c3.py`)

Table 3: Parameters for Mass Hierarchies & Constants Simulation

Parameter	**Value**	**Description**	**Justification**
μ^2	-1	Mass parameter in potential $V(\Phi)$	Negative mass squared triggers spontaneous symmetry breaking, leading to a non-zero VEV $\langle\Phi\rangle$.
λ	0.1	Quartic coupling in potential $V(\Phi)$	Positive value ensures potential is bounded from below. $\mathcal{O}(0.1)$ is a reasonable perturbative coupling strength.
κ (Grav-Scalar)	0.1	Non-minimal coupling to curvature R	Represents the strength of the interaction between the condensate Φ and gravity. $\mathcal{O}(0.1)$ is a typical value in scalar-tensor theories.
N	3	Number of generations/flavors	Matches the known number of particle generations in the Standard Model.
y_i (Yukawa)	Fit	Yukawa couplings for fermions	Adjusted to reproduce the observed fermion mass ratios, which are outputs of the Casimir invariants of $\mathcal{A}_{\text{EISA}}$ and the minimization process.

Simulation 4: Cosmic Evolution (`c4.py`)

Table 4: Parameters for Cosmic Evolution Simulation

Parameter	**Value**	**Description**	**Justification**
η (Perturbation)	0.01	Amplitude of initial perturbation	Seeds the evolution of the transient vacuum energy component. Small value consistent with CMB constraints on primordial fluctuations.
τ_{decay}	Fit	Decay timescale of $\Omega_v(\tau)$	Determines the redshift at which the transient vacuum energy decays. Adjusted to provide a $\Delta H_0 \sim 3\,\text{km/s}$ increase, mitigating the Hubble tension.
$\tau_{\text{crackling}}$	Fit	Onset time for cascade steps	Sets the cosmological time for phase transitions within the cascade mechanism. Chosen to avoid conflict with BBN and CMB epochs.
$\Omega_m, \Omega_r, \Omega_\Lambda$	ΛCDM	Standard cosmological parameters	Fixed to Planck 2018 best-fit values to isolate the effect of the new $\Omega_v(\tau)$ component.

Simulation 5: Algebra Verification & Bayes (`c5.py`)

Table 5: Parameters for Algebra Verification & Bayesian Evidence Simulation

Parameter	**Value**	**Description**	**Justification**
$\text{fluct}_{\text{amp}}$	8×10^{-4}	Amplitude of fluctuation prior	Represents the expected level of residual fluctuations in the low-energy vacuum state. A small value consistent with the notion of a stable, low-entropy vacuum.
H_0 (EISA-RIA)	67.4	Hubble constant (base value)	The ΛCDM value from Planck. The model adds ΔH_0 from Ω_v to reach ~ 70 km/s/Mpc.
κ (EISA-RIA)	0.31 ± 0.01	Grav-scalar coupling (MCMC result)	Posterior value from fitting the model to cosmological data. Determines the strength of the vacuum energy contribution.
Tolerance	10^{-10}	Numerical tolerance for Jacobi identity	Stringent tolerance ensures the algebraic closure of $\mathcal{A}_{\text{EISA}}$ is verified to machine precision, confirming mathematical consistency.

Simulation 6: Universe Simulator (`c6.py`)

Table 6: Parameters for EISA Universe Simulator

Parameter	Value	Description	Justification
Δt	1×10^{-36} s	Simulation time step	Extremely small step is necessary to resolve the Planck-scale dynamics of the field evolution while maintaining numerical stability.
M_{Pl}	1.22×10^{19} GeV	Planck mass	Fundamental constant. Sets the scale for gravitational interactions.
θ	$(1.616 \times 10^{-35})^2$	Initial condition parameter	Related to the Planck length squared. Sets the initial scale for quantum fluctuations.
Grid Size	64	Lattice points per dimension	Computational compromise: large enough to capture essential dynamics, small enough for numerical feasibility.

Simulation 7: CMB Power Spectrum (`c7.py`)

Table 7: Parameters for CMB Power Spectrum Analysis

Parameter	Value	Description	Justification
κ	0.31 ± 0.01	Grav-scalar coupling (MCMC)	Central posterior value from the fit. Primarily determines the amplitude of the CMB power spectrum modification.
n	7 ± 1	Spectral index parameter (MCMC)	Related to the scaling properties of the vacuum fluctuations. An integer value near 7 emerges from the algebraic structure.
A_v	$(2.1 \pm 0.5) \times 10^{-9}$	Fluctuation amplitude (MCMC)	Sets the overall normalization of the vacuum energy contribution to the CMB perturbations.
τ_{decay}	Fit	Decay time of fluctuations	Adjusted so that the modifications primarily affect large angular scales (low-ℓ), as suggested by the model.