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Numerical Study of the Modal Dynamics of a Quantum Scalar Field in de Sitter Spacetime

In a curved, time-dependent spacetime there is no unique notion of vacuum or particle, since the expansion of the geometry exchanges energy with the quantum fields propagating on it. De Sitter space, the reference geometry for cosmological inflation, admits analytical treatment thanks to its high symmetry. However, a numerical approach allows a systematic exploration of how the solutions change with the physical parameters of the field and provides a methodology that can be extended to less symmetric expansion histories.

We study a free, real scalar field with mass m and coupling ξ to the spacetime curvature, acting as a spectator (no backreaction) on a de Sitter background with flat spatial sections ($\kappa = 0$), whose curvature arises from the expansion. After a Fourier decomposition, the dynamics reduces to a parametric oscillator equation, $\chi_k''(\eta) + \omega_k^2(\eta)\,\chi_k(\eta) = 0$, which is integrated numerically in Python with adiabatic initial conditions. The numerical mode functions are compared with the known analytical solution in terms of Hankel functions (Bunch–Davies vacuum), and their dependence on m/H and ξ is explored.

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