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Dynamical nonlinear tails in black hole ringdown

Nonlinear tails in black hole perturbations, arising from second-order effects, present a distinct departure from the well-known Price tail of linear theory. We present an analytical derivation of the power law indices and amplitudes for nonlinear tails stemming from outgoing sources, and validate these predictions to percent-level accuracy with numerical simulations. We then perform a perturbative analysis on the dynamical formation of nonlinear tails in a self-interacting scalar field model, wherein the nonlinear tails are sourced by a $\lambda\Phi^3$ cubic coupling. Due to cascading mode excitations and back-reactions, nonlinear tails with t^{-l-1} power law are sourced in each harmonic mode, dominating the late time behavior of the scalar perturbations. In verification, we conducted numerical simulations of the self-interacting scalar model, including all real spherical harmonic (RSH) with $l \leq 4$ and their respective nonlinear couplings. We find general agreement between the predicted and numerical power law indices and amplitudes for the nonlinear tails, with the exception of $l = 4$ modes, which display t^{-4} power law instead of the predicted t^{-5}. This discrepancy is due to distortion in the source of the tails, which is caused by another nonlinear effect. These results establish nonlinear tails as universal features of black hole dynamics, with implications for gravitational wave astronomy: they may imprint observable signatures in merger remnants, offering novel probes of strong-field gravity and nonlinear mode couplings.

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