

Thermal production of gravitational waves in the early universe

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In this work, we systematically study gravitational wave (GW) production during both the inflationary and post-inflationary epochs. While inflationary GWs can be readily derived from tensor perturbations during inflation, post-inflationary GWs arise from a variety of processes during reheating and require detailed treatment for quantitative analysis. We consider four distinct production channels: (i) pure inflaton annihilation, (ii) graviton bremsstrahlung from inflaton decay, (iii) radiation-catalyzed inflaton-graviton conversion, and (iv) scattering among fully thermalized radiation particles. For each channel, we solve the corresponding Boltzmann equation to obtain the GW spectrum and derive a simple yet accurate analytical expression for it. By employing a consistent treatment of all production channels, our analysis yields for the first time the full spectrum of GWs produced during the inflationary and post-inflationary epochs. We find that, while inflationary GWs dominate at low frequencies, post-inflationary processes generally produce high-frequency GWs with considerably high energy densities that may significantly exceed that of inflationary GWs.

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