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Modern Computational Approaches to Post-Inflationary Reheating and Dark Matter Production

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While analytical methods remain fundamental in physics, many phenomena require computational approaches to be fully understood. In early universe cosmology, this necessity becomes paramount: understanding post-inflationary dynamics—including resonant particle production, backreaction, and rescattering—demands numerical solutions beyond perturbative methods.
We employ lattice simulations on high-performance computing (HPC) systems to study non-linear inflaton dynamics and subsequent matter production. Recent advances in HPC accessibility enable us to explore previously intractable parameter spaces, particularly for models that connect inflation to dark matter production through mechanisms such as gravitational particle creation or inflaton decay chains.
However, fully simulating the thermal universe remains a significant challenge for future work. Current simulation tools are optimized for the very short timescales of initial particle production, making it computationally prohibitive to evolve the system through the entire thermalization process. Additionally, these lattice simulations, being semiclassical, struggle to capture quantum effects crucial for complete thermalization. Fortunately, strongly-interacting turbulent thermalization systems exhibit universal scaling behaviors during the energy redistribution phase. We are leveraging machine learning techniques to exploit this universality and develop predictive models for the thermalization process. By combining these learned patterns with subsequent Boltzmann calculations, we aim to develop a comprehensive framework that bridges the gap between early-time particle production and the eventual thermal equilibrium of the universe.

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