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The Big Bang in the Lab: Table-top Experiments of Reheating After Inflation

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In inflationary cosmology, the Universe must transition from a state dominated by the nearly homogeneous inflaton condensate, into a state dominated by a hot bath of Standard Model particles, a process known as reheating. Detailed modelling of this transition often reveals the presence of exponentially growing instabilities, whose dynamics is typically referred to as preheating. A common example occurs when the inflaton undergoes oscillations around a potential minimum shortly after the inflationary phase ends. Linear fluctuations of either the inflaton or fields coupled to it then obey a wave equation with an oscillating mass, leading to exponential growth of certain bands of wavenumbers. Eventually these growing modes become large enough to undergo strong mode-mode coupling, leading to a fracturing of the inflaton and a breakdown of the assumption of homogeneity. Depending on the specific model, the resulting complex medium can display a range of interesting properties, including: the emergence of scaling regimes dominated by log-normal density fluctuation, the production of topological defects, and the creation of long-lived approximate solitary waves. This nonlinear stage can only be studied using semiclassical lattice simulations. While these lattice simulations are believed to provide a good approximation to the full quantum dynamics, they have never been tested with experiments leaving the possibility for novel quantum phenomena.

I will show how we can emulate end-of-inflation dynamics in the lab using two coupled dilute gas Bose-Einstein condensates (BECs), providing the exciting opportunity to experimentally study the end-of-inflation. First, I will explain the connection between the (nonrelativistic) BEC dynamics and relativistic scalar field relevant to cosmology. In particular, by appropriately tuning parameters, the evolution of the relative phase of the BECs is well described by the relativistic sine-Gordon model. To study preheating, we begin with two nearly homogeneous BECs and imprint an initial relative phase between them. The relative phase then undergoes oscillations analogous to a rigid pendulum. Of course, quantum mechanics ensures that the condensates cannot be perfectly homogeneous, and small quantum fluctuations must be present initially. In the sine-Gordon theory, there is a single band of linearly unstable modes which grow exponentially in the presence of a homogeneous oscillating background. As a first step, I will demonstrate that the cold atom system replicates the linear instability of the sine-Gordon model. I will also quantify the deviations from the pure sine-Gordon limit, showing they are small. I then use lattice simulations of the BECs to study the full nonlinear evolution of the condensates. I will show that once the fluctuations enter the nonlinear regime, the relative phase fractures into a collection of localized oscillating field configurations, known as oscillons. This behaviour matches that seen in simulations of the pure sine-Gordon model.

Time permitting, I will briefly comment on possible applications to the emergence of domain wall networks and to relaxion dynamics. The former occurs when we start the condensates π out of phase with each other, while the latter occurs when we allow the relative phase to undergo full rotations thus scanning many minima of the effective sinusoidal potential. More generally, since the effective relativistic field is a phase variable, these BEC systems may be useful to experimentally study a broad class of axions relevant to cosmology.

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