Nonlinear Physics at the End of Inflation

Eva H. Nesbit and John T. Giblin, Jr.

Department of Physics, Kenyon College

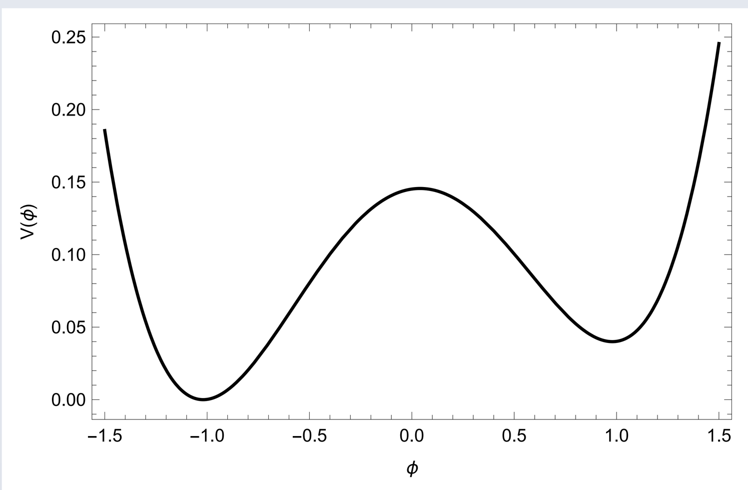
Abstract

The theory of inflation attempts to answer some of the most pressing questions in cosmology: why is the Universe so homogeneous and flat? As it turns out, initializing this period of accelerated expansion is relatively easy; however, ending inflation is a harder obstacle to overcome. This research investigates two theoretical ends to inflation through two different models. We use lattice simulations to generate gravitational wave signals produced through a first order phase transition that could end inflation. We use one field to describe the phase transition and couple it to the gravitational field. High-resolution lattice simulations can produce the spectra of the gravitational waves. This information can then be used at observatories, e.g. LIGO, to help search for gravitational waves and to put constraints on our model. The detection and study of gravitational waves and their signals is a path toward a deeper understanding of gravity and high-energy physics. In our second model, we end inflation through high-order nonlinear interactions with other fields. These interactions produce resonant phenomena that could alternatively describe the end of inflation.

Gravitational Waves from Reheating

We use two different C++ programs that evolve scalar fields over an expanding background: LatticeEasy and GABE (the Grid and Bubble Evolver). Using LatticeEasy, written by Gary Felder and Igor Tkachev, and a Gravitational Wave package for LatticeEasy, written by John T. Giblin, Jr., we model the production of Gravitational Waves and plot their spectra. To do this, we first define a two-minima potential,

$$V = \frac{1}{8}\lambda\phi^4 - \frac{1}{4}\lambda\phi^2\phi_0^2 + \epsilon\lambda\phi_0^3\phi + \lambda\phi_0^4\Gamma^4$$



where Phi is the scalar field driving inflation, the inflaton field. In this model, the inflaton begins by oscillating about one minima then tunnels to the other. We call this quantum tunneling event a phase transition. Both LatticeEasy and GABE describe the evolution and interaction of these scalar fields by the Klein-Gordon equation,

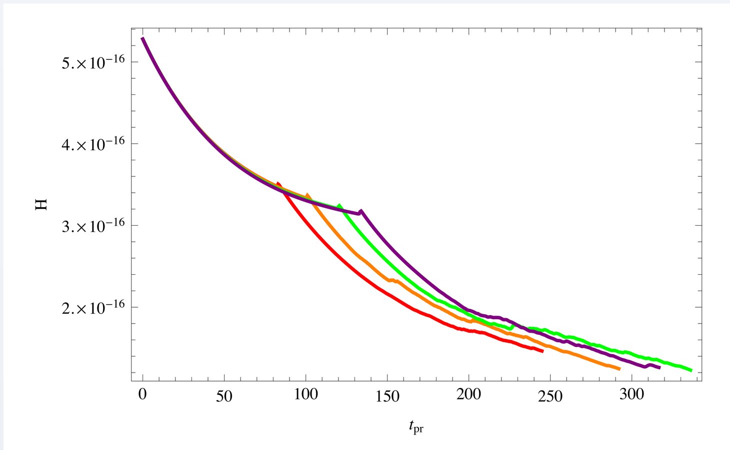
$$\ddot{\phi} - \frac{\nabla^2\phi}{a^2} + 3\frac{\dot{a}}{a}\dot{\phi} = -\frac{\delta V}{\delta\phi}.$$

We implement our two-minima model into the Klein-Gordon equation and couple it to the gravitational field,

$$\ddot{h}_{ij} - \frac{\nabla^2}{a^2}h_{ij} + 3H\dot{h}_{ij} = 16\pi G\Pi_{ij}^{TT}.$$

Inflation ends when the potential energy of the inflaton field is no longer dominant. We investigate this special moment in time by calculating the Hubble parameter. When we plot this parameter, we see that there is a change in slope at this transition.

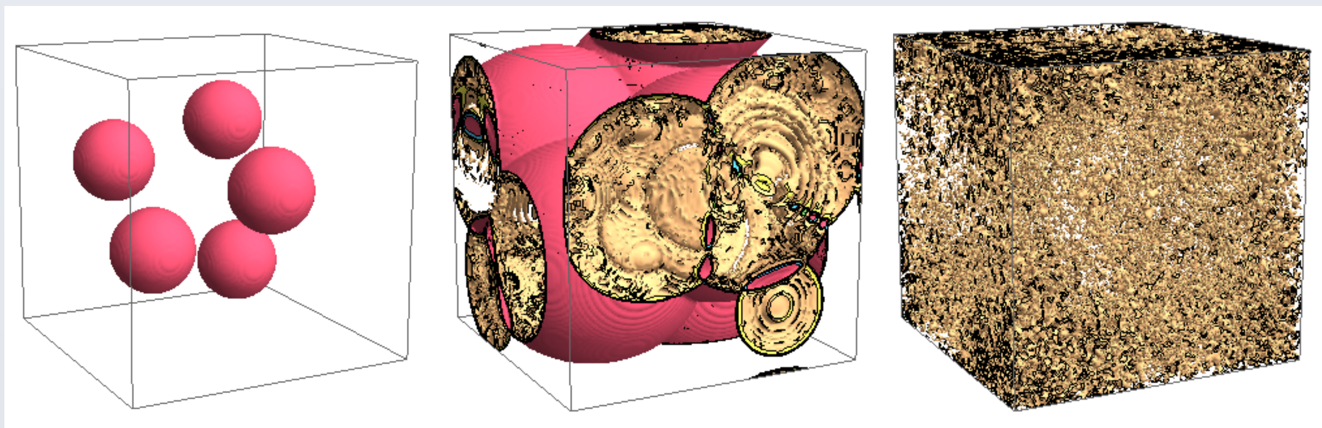
By performing numerous simulations and probing varying box sizes (subsequently probing varying values for x, a variable we defined to be the number of e-folds during the phase transition), we determined that decreasing the number of bubbles per Hubble volume leads to a later end to inflation. Below is a plot of the Hubble parameter with varying values of box density and therefore varying values of x.



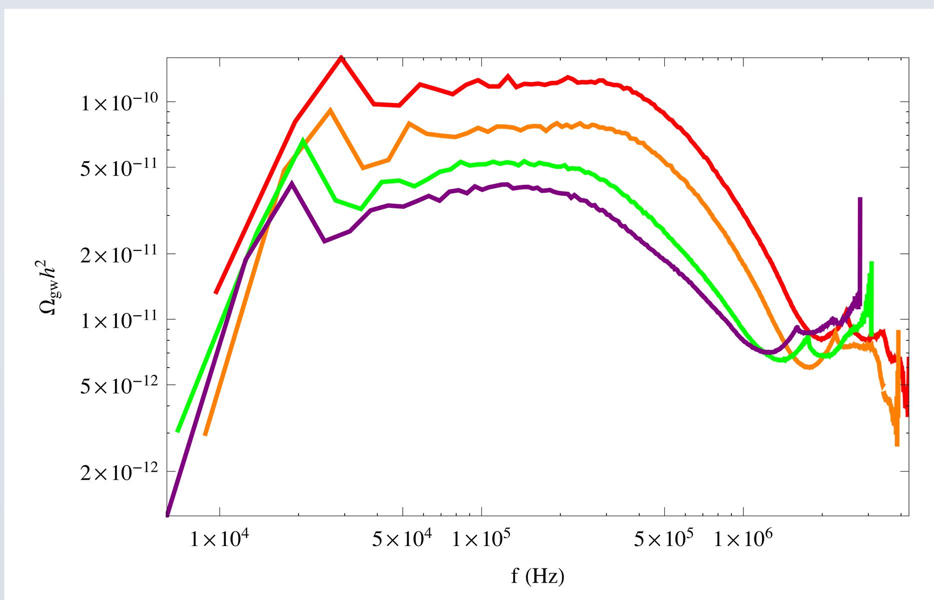
Red: x = **0.875**, **Orange:** x = **0.894**
Green: x = **1.011**, **Purple:** x = **1.108**

Gravitational Wave Production

The potential defined in our Gravitational Wave model contains two minima: a meta-stable minima and a stable minima. These two minima correspond to two possible states of the Universe: false vacuum and true vacuum, respectively. We model these two states and the transition between them by, first, randomly initializing a system of bubbles of true vacuum surrounded by space in false vacuum. The phase transition begins when the bubbles collide and finishes when the Universe is entirely in the stable, true vacuum state.



This phase transition produces large amounts of energy, some of which is the source for gravitational waves. We can tell exactly how much energy these waves have by plotting their spectra. Below shows the peak Gravitational Wave spectra for four different simulations with varying values of x.



Red: x = **0.875**, **Orange:** x = **0.894**
Green: x = **1.011**, **Purple:** x = **1.108**

LIGO is able to probe at frequencies on the order of 10^4 Hz—very close to the frequencies we recovered from our simulations.

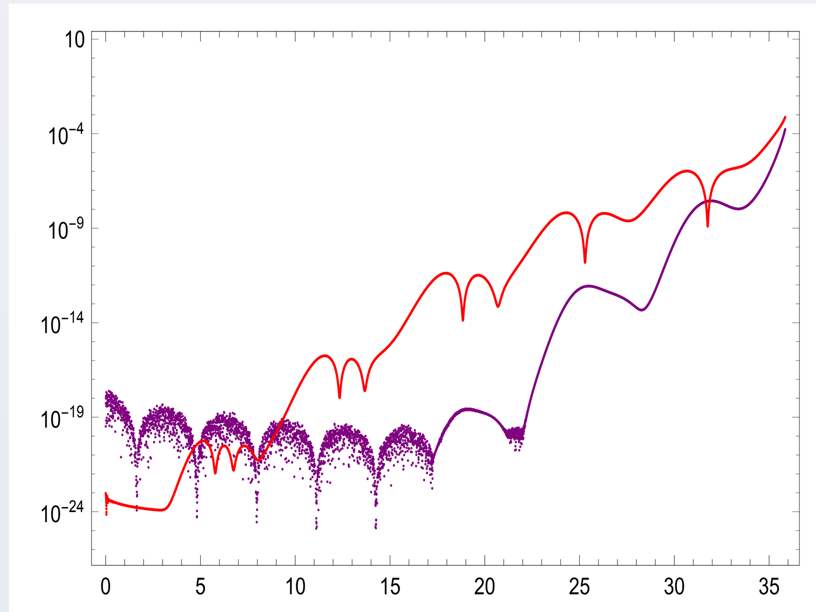
High-Order Nonlinear Field Interactions

We use GABE, written by John T. Giblin, Jr. and two Kenyon alumni, Hillary L. Child and J. Tate Deskins, to model the evolution of two fields, Phi and Chi, with high-order coupling terms added to the potential function. The Phi field represents the inflaton field, the Chi field a generic field. The couplings allow the energy stored in the inflaton to parametrically amplify modes of the coupled fields, which represent the matter in the Universe. We probed two models of this kind, having two different potential energy functions,

$$V = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}m_\chi^2\chi^2 + \frac{cm^2}{\Lambda}\phi\chi^2$$

$$V = \frac{1}{2}m_\phi^2\phi^2 + \frac{1}{2}m_\chi^2\chi^2 + \frac{c}{\Lambda}\phi\chi^4.$$

We can plot the variance, a proxy for particle production, of each field:



The variance of the Phi and Chi field for the $\phi\chi^4$ coupling
Purple: variance of the Phi field
Red: variance of the Chi field

The increased variance of the fields over time corresponds to energy from the inflaton field being released and subsequently converted into matter. However, these new interactions are very violent and introduce new technological challenges (i.e. GABE crashes!)

References

1) A. Lopez and K. Freese, "First Test of Gravity Waves from Inflation using ADVANCED LIGO," arXiv:1305.5855 [astro-ph.HE].
2) GABE, cosmo.kenyon.edu/gabe.html
3) G. N. Felder and I. Tkachev, "LATTICEEASY: A Program for lattice simulations of scalar fields in an expand- ing universe," Comput. Phys. Commun. 178, 929 (2008) [hep-ph/0011159].
4) H. L. Child and J. T. Giblin, Jr., "Gravitational Radiation from First-Order Phase Transitions," JCAP 1210, 001 (2012) [arXiv:1207.6408 [astro-ph.CO]].
5) R. Easther, R. Galvez, O. Ozsoy and S. Watson, "Supersymmetry, Nonthermal Dark Matter and Pre- cision Cosmology," Phys. Rev. D 89, 023522 (2014) [arXiv:1307.2453 [hep-ph]].

Acknowledgements

The National Science Foundation, PHY-1068080 and Kenyon Summer Science Scholars provided the funding for this research. I would like to thank my advisor, Tom Giblin, for his knowledge, support and guidance. Additionally, I would like to thank our collaborators Katherine Freese (Michigan Center for Theoretical Physics, University of Michigan), Alejandro López-Suárez (Michigan Center for Theoretical Physics, University of Michigan) and Scott Watson (Dept. of Physics, Syracuse University).