Artifacts in the Wake of a First-Order Phase Transition

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Abstract

The early Universe had different properties than it does today. The change of a system’s properties—from one phase to another—is the definition of a phase transition. It is possible that the Universe underwent a first order phase transition that brought the metastable inflaton field to its true minimum. First-order phase transitions are defined by bubble nucleation in which parts of a field tunnel into the true minimum state. The bubbles then expand, collide, and coalesce until the rest of the field is brought to its true minimum state. Cosmologically, this can be modeled using the Coleman-De Luccia bounce, which gives the profile of a field coupled to gravity.

These bubbles can be modeled using GABE; our software that is developed to study early-universe physics. There was also a modification added into GABE that allows for the calculation of the gravitational wave signature produced by the bubble collisions. The simulations showed that oscillons were produced from this potential, and also show that the bubble collisions have a significant effect on the gravitational wave background of the universe.

Phase Transitions

At the GUT scale ($1{\times}10^{25}$ eV), the strong, weak, and electromagnetic forces are unified. As the universe cooled, the symmetries that unified these forces broke down and the electroweak force decomposed into the weak and electromagnetic forces. In order to break the symmetry of this symmetry, a phase transition is required.

A common type of phase transition is first-order, where the transition from one state to another takes place through bubble nucleation. Parts of the true vacuum state nucleate into the classically stable local minima. These bubbles then begin to expand due to a pressure difference and then collide and coalesce, which brings the system into the global minima, or the true vacuum state, as shown in below.

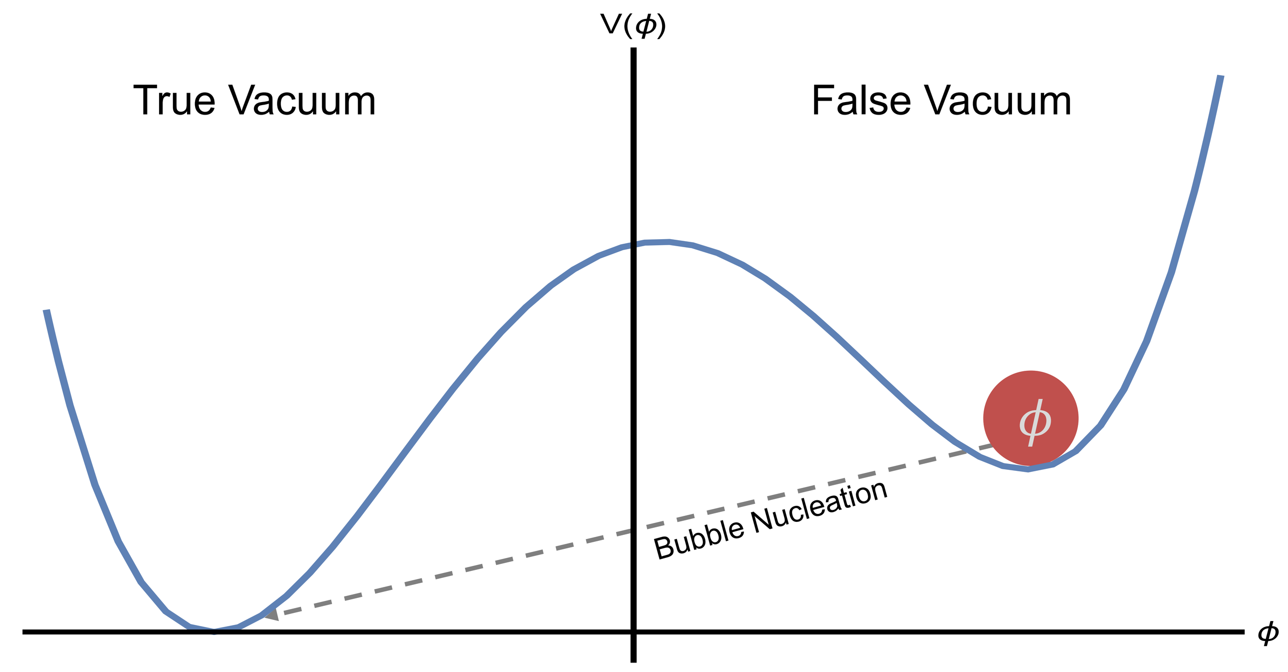

Fig. 1 – A classically stable system nucleates into the true vacuum state

Coleman-De Luccia Bounce

Fields with false minima energy states occur in grand unified theories and electroweak theories. This physically motivates vacuum decay, which can be modelled with bubble nucleation. Coleman and De Luccia made the first calculations on false minima decay, where they solved for the instanton profile, $\phi(\vec{x})$ which describes what the bubbles in the field look like. The bubbles have a thin-wall that separate the different vacuum states in the form of a according to the following.

$$\phi = \phi_0 \tanh\left(\frac{\phi_0\sqrt{\lambda}}{2}(r - r_*)\right)$$

Modelling Bubble Nucleation

The Grid and Bubble Evolver (GABE) software was used to evolve the bubbles over time. The initial radius of the bubbles is set by the constraints of the parameters chosen for the following two hill potential where λ and ϵ are free parameters, ϕ_0 is set by physical constraints, and μ sets the energy of at the true minimum to be exactly zero. Bubbles are assigned a center on the lattice and are then evolved over time.

$$V(\phi) = \frac{\lambda}{8}(\phi^2 - \phi_0^2)^2 + \epsilon\lambda\phi_0^3(\phi + \phi_0) + \mu^4$$

Oscillons after a First-Order Phase Transition

Oscillons are massive, localized in space, and long-living non-topological structures that many non-linear equations of motion generate. The potential used will lead to non-linear equations of motion, and the bubble collisions should produce areas of over-densities. By plotting and animating the proportional energy density of the universe, it is seen that oscillons are produced in this model of a first-order phase transition, as seen in figure 3.

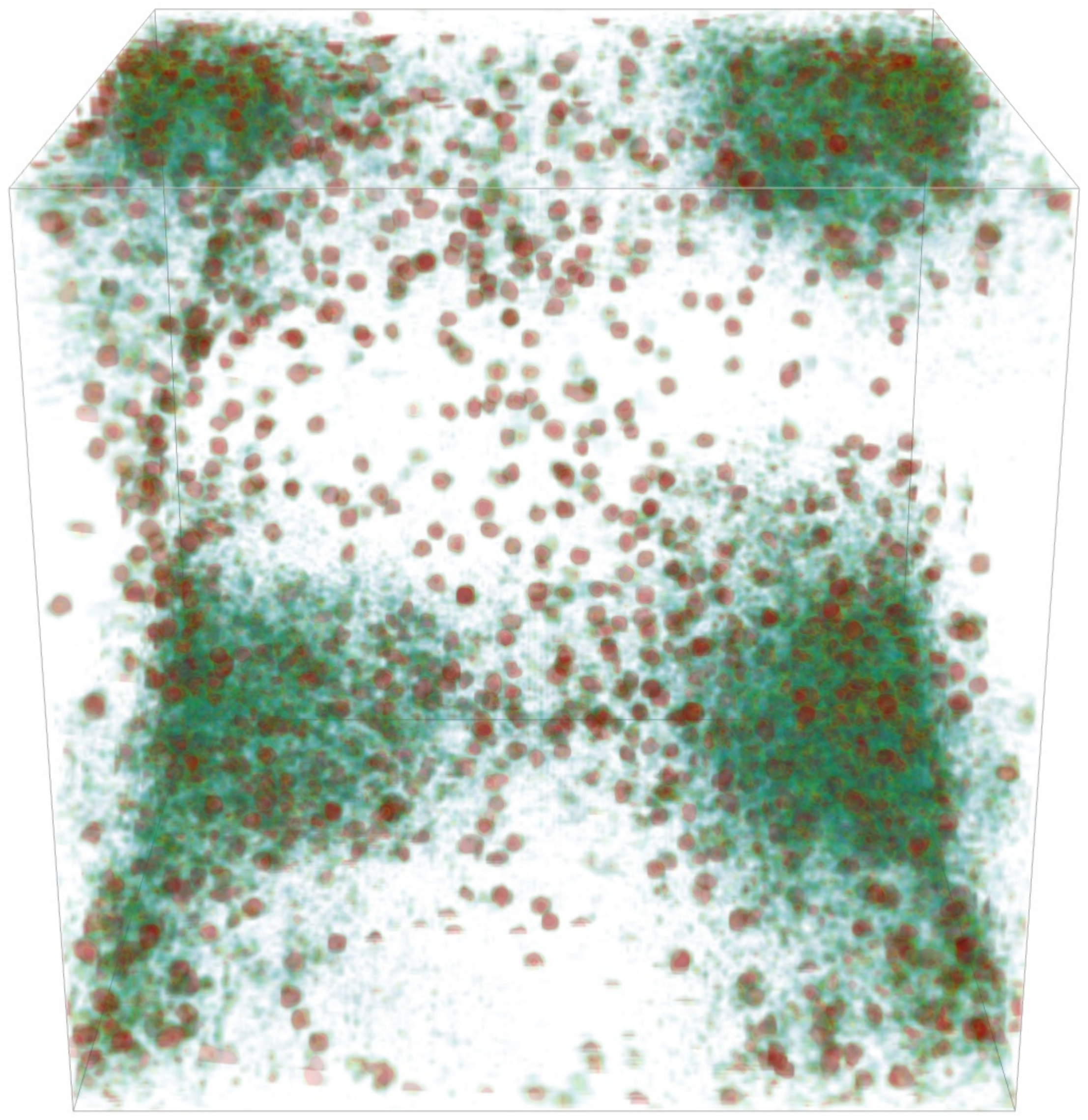

Fig. 3 – A plot of the energy density of the universe after bubble collision where oscillons form

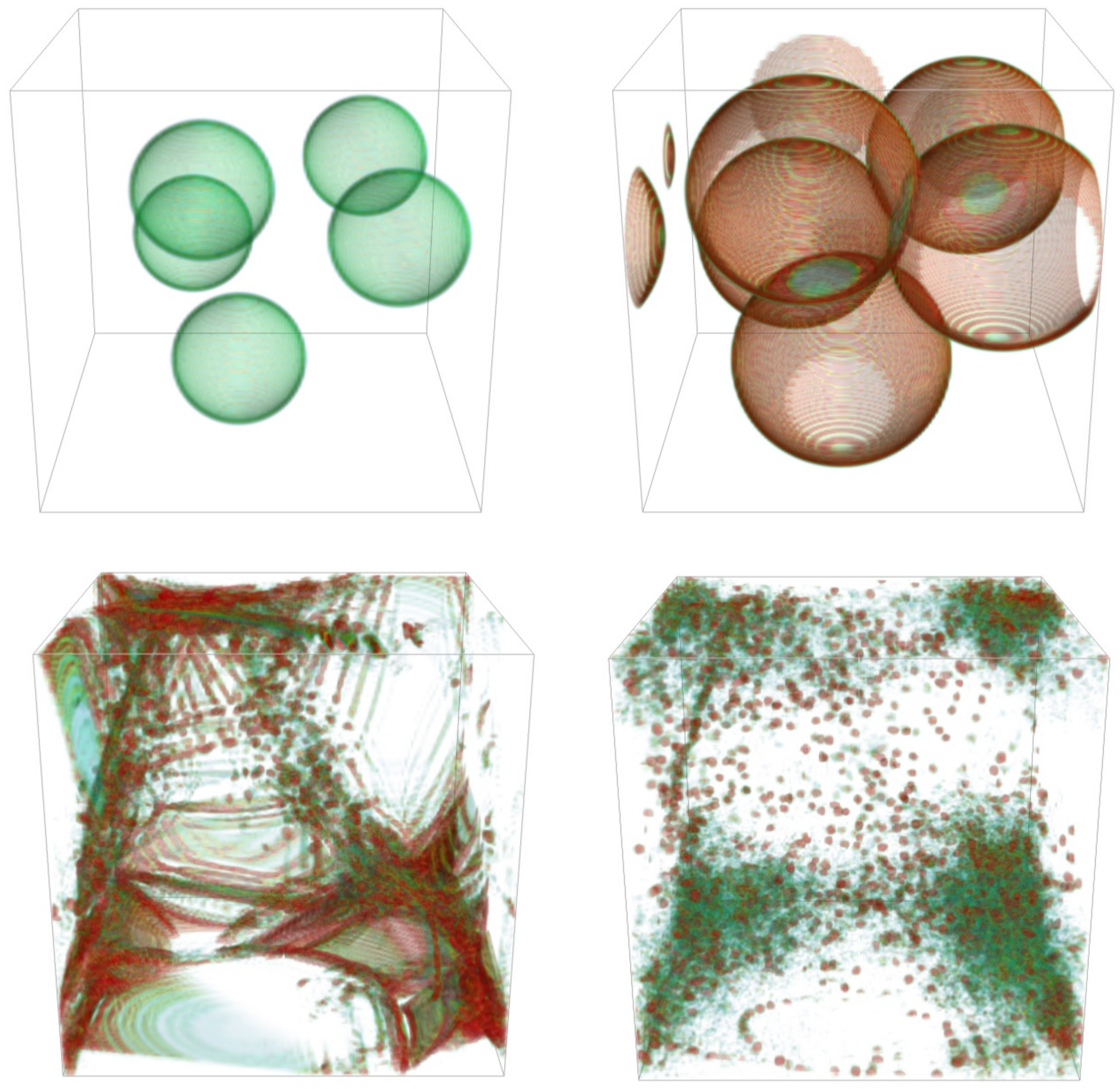

Fig. 2 – Frames of an animation of the energy density of the universe from the simulations

Gravitational Effects

Another possible observable from a first-order phase transition would be gravitational radiation. The emission of gravitational waves from astrophysical sources can create a stochastic background of gravitational radiation. Once instruments are sensitive enough, the simulated the gravitational wave signature can be compared to observation to determine if a phase transition occurred.

In order to evolve metric perturbations, a modified version of GABE was used. The anisotropic stress tensor is calculated in momentum space which is then projected onto the transverse plane to evolve h_{ij} according to the equation below. From the simulations, we get the following gravitational wave spectra.

$$\ddot{h}_{ij} + 3\frac{\dot{a}}{a}\dot{h}_{ij} - \frac{1}{a}\nabla^2 h_{ij} = \frac{16\pi G}{a^2}\delta S_{ij}^{TT}$$

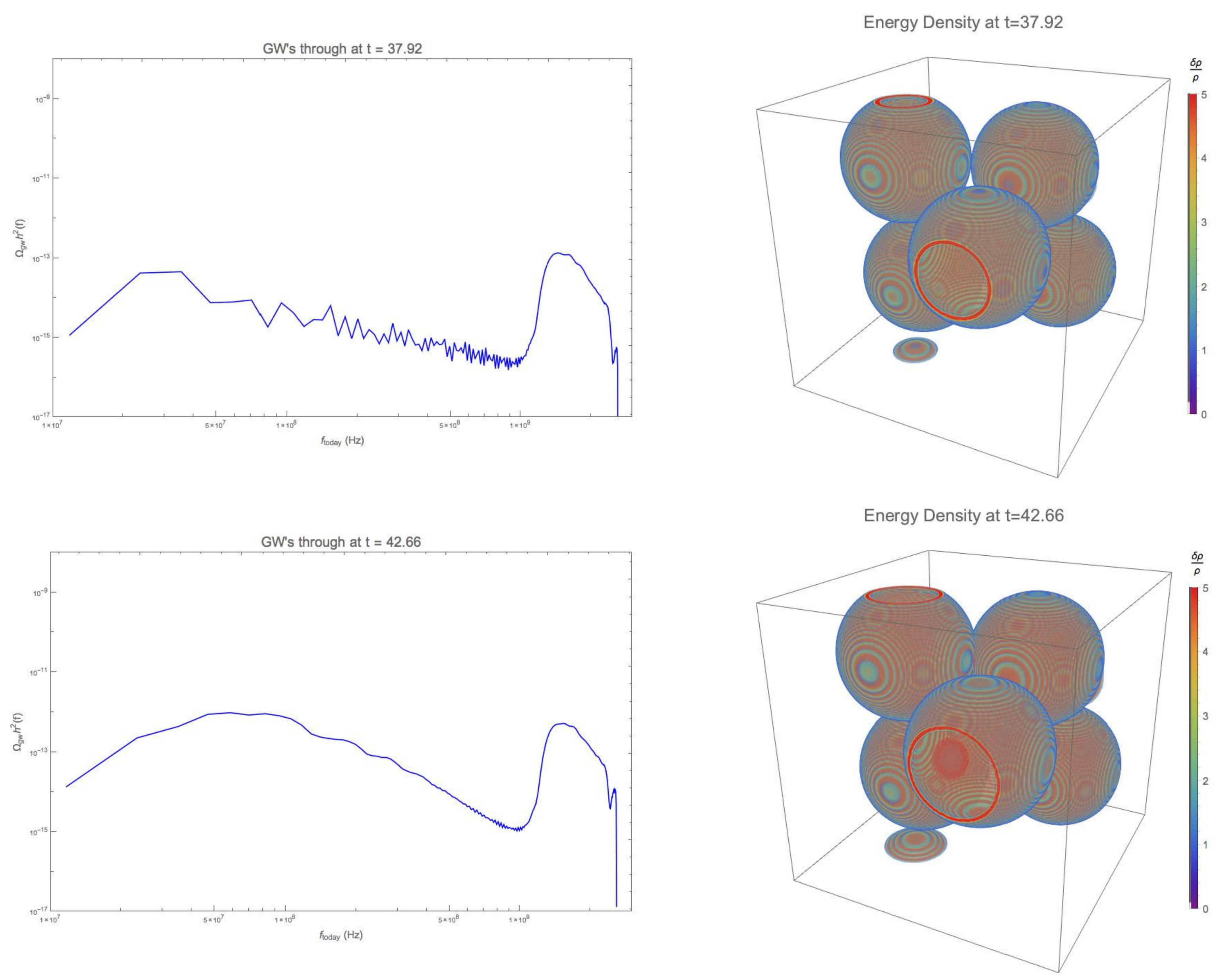

Fig. 4 – The gravitational wave signature before and after bubble collisions.

Conclusions

Using the instanton profile found by Coleman and De Luccia, simulations of first-order phase transitions in the early universe were modeled on an expanding lattice background. From the coalescence of the nucleated bubbles, oscillons are created. As found in previous research, it is known that oscillons form in many models of preheating due to nonlinear equations of motion. From these simulations, we see that oscillons may also form during first-order phase transitions. This creates a matter-dominated phase of the universe, which affects the dynamics that dictate its evolution.

The gravitational wave signature for a first-order phase transition was also modelled in lattice simulations. After the bubbles collide, the gravitational wave signature’s middle frequencies increase in amplitude. The high frequency tail seen in figures is a numerical artifact. The small resolution of the run created numerical artifacts at the high frequency tail. This can be fixed with a higher resolution run. The magnitude of the gravitational waves did not reach a detectable frequency by A-LIGO. Next steps include initializing bubbles with quantum fluctuations, including a coupled matter field, and exploring new potentials.

References and Acknowledgments

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Thank you to Professor Tom Giblin for incredible support, motivation, and pizza. Additionally, I would like to thank my labmates for support inside and outside of the lab, as well as developing a unique and extensive lab culture.