The Decay and Gravitational Effects of Non-Topological Structures After Inflation

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Abstract

In a self-resonant model of the inflaton field, there is the potential for generating an oscillon-dominated phase of the universe. An oscillon is a non-topological structure that is massive, localized, and long-lived. These structures are semi-stable due to the fact that they slowly lose energy over time through scalar radiation.

Using the axion monodromy potential, oscillons were produced in a lattice simulation. Under the assumption that oscillons are approximately 1 m^{-1} in width, the simulation was not accurate for long enough to see oscillons decay. By adding a canonical scalar field coupling term, $\frac{1}{2}\phi^2\chi$^2, where χ is a scalar matter field, there is another channel for oscillons to lose energy.

Again, due to the constraint of considering oscillons to be approximately 1m^{-1}, the simulation is not accurate long enough to see them decay. Using results from the simulations, a more accurate approximation of the size of oscillons was found. They are closer to 10 m^{-1}, which would allow for simulations ten times longer than done here.

In order to understand the gravitational effects of these structures, the simulation code was modified to include linear perturbations in the ψ field (which perturbs the gravitational field). Although the oscillons are very energy dense (over 20 times the average energy density of the universe), the perturbations of ψ never grew large enough for perturbation theory to break down.

Introduction

Early in the universe’s timeline, there was an extremely short period of time where the universe expanded by an incredible amount. This period is called inflation and was mechanized by the theoretical inflaton field. This rapid expansion caused the universe to cool down significantly. There’s one problem though – the temperature of the universe after inflation is much warmer than expected. Therefore, there must have been a process that reheated the universe.

Oscillons are massive, localized in space, and long-living. Potentially, these structures could have taken part in reheating the universe. Today, however, there is no evidence of their existence. This means that oscillons must have eventually decayed for them to be undetectable today. Additionally, because they are so massive, they should also have had considerable gravitational effects.

Non-linear Potentials

Oscillons are produced by non-linear potentials where the potential is shallower than quadratic near the minimum. Non-linear potentials allow for self-resonance, which will be stronger than any resonances due to a coupling. The model used for the following simulations is the axion monodromy potential, $V(\phi) = M^2m^2\left[\sqrt{1+\left(\frac{\phi}{M}\right)^2} - 1\right]$. M, m, ϕ_0, and $\dot{\phi}_0$ are parameters based off of Mustafa Amin’s research on oscillons. They satisfy the slow roll conditions of inflation and will allow for self-resonance.

Grid and Bubble Evolver (GABE)

A common method of simulating the evolution of the early universe is to use a lattice simulation. These simulations use coupled differential equations to calculate the value of a field at each point on a three dimensional grid. For the oscillon simulations, the Grid and Bubble Evolver (or GABE), developed by Hillary Child, Tate Deskins, and Tom Giblin in 2013, was used to evolve the inflaton field on an expanding background. The code was edited to use the axion monodromy potential so that oscillons could be produced.

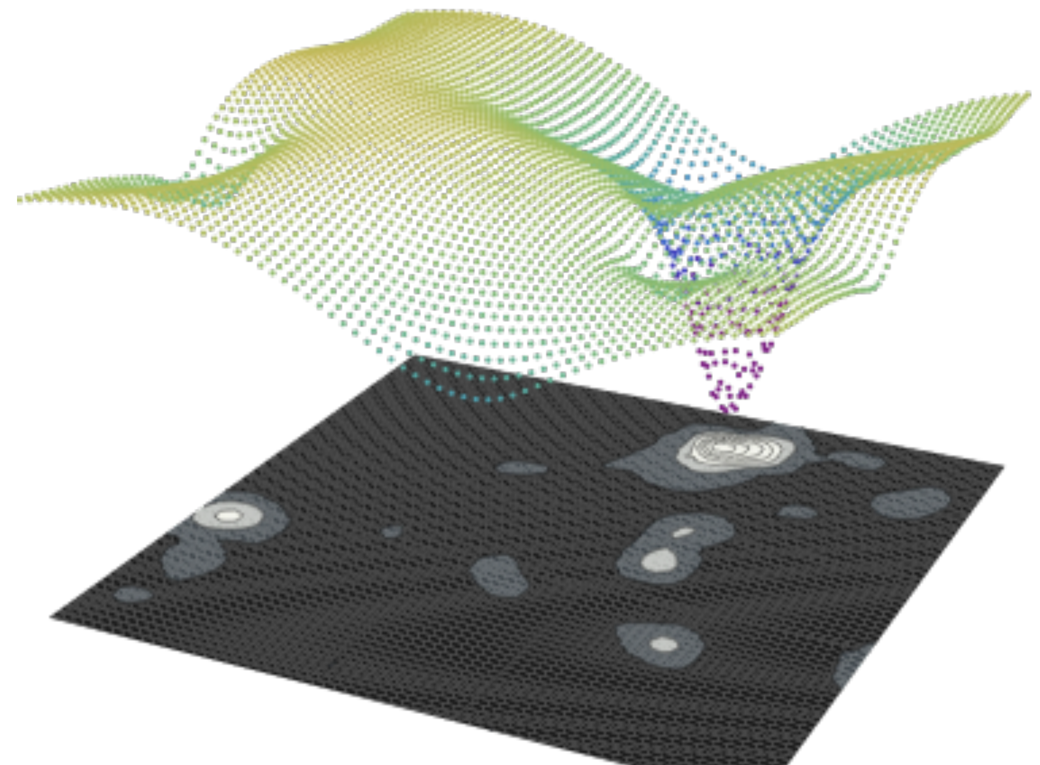


Fig. 5

Oscillon Decay

These are the results of the simulation for an uncoupled inflaton field. As shown in Figure 1, variance increases by several orders of magnitude. This is due to the oscillations of the oscillons creating large variances in the once homogeneous field.

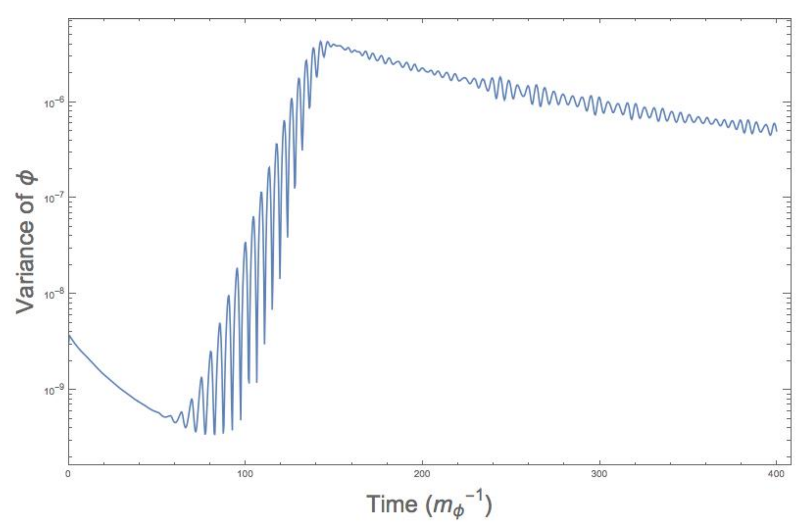


Fig. 1 – The log of the variance of the inflaton field over time for the axion monodromy potential

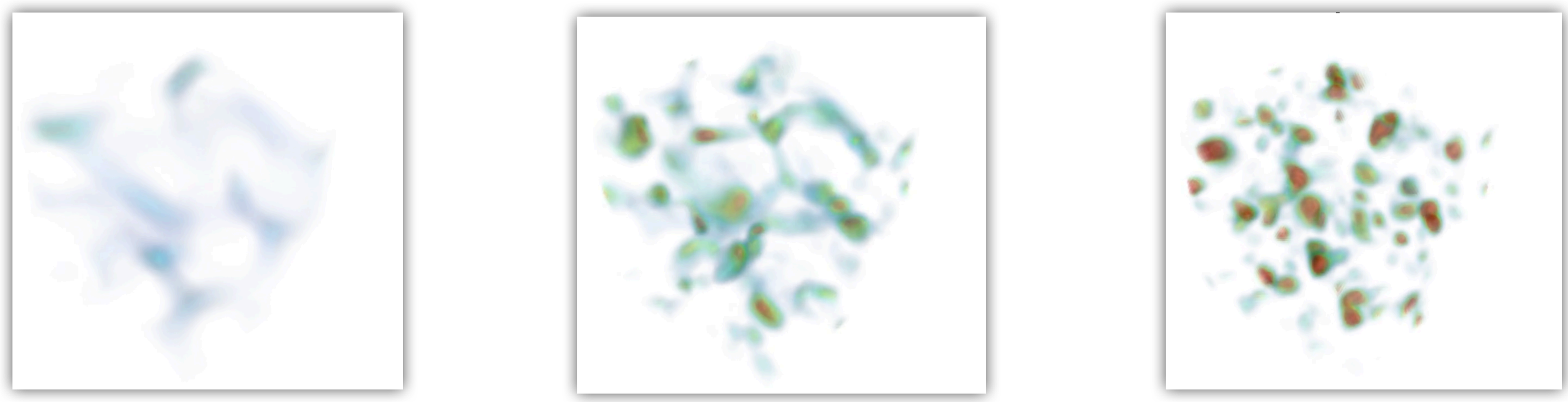
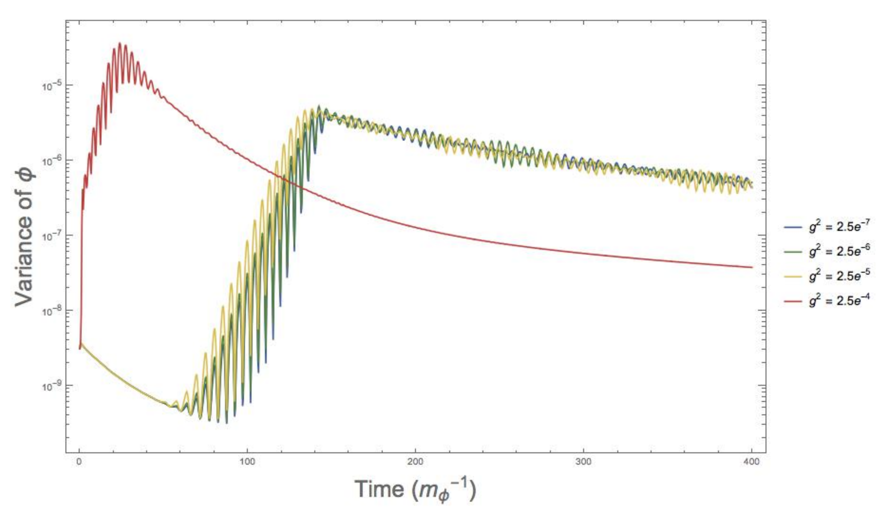


Fig. 2 – Frames of an animation of the energy density of the universe. In the third frame, oscillons have formed.

As evidenced by the variance plot and the animation, oscillons were produced using this potential. The oscillons, however, did not decay – the simulation did not run long enough. The limitations on how long the simulation can run accurately is determined by the approximate size of the oscillons. They are assumed to be around 1 m_ϕ^{-1}. Once the scale factor a(t) is larger than 12, the simulation does not accurately capture the dynamics of oscillons.

So, the oscillons did not decay quick enough. One solution is to add a canonical scalar field coupling term, $\frac{1}{2}\phi^2\chi$^2, to the axion monodromy potential. Here, χ is a scalar matter field. This gives the oscillons another channel to loose energy via scalar radiation.



For minimally coupled fields, oscillons are produced. When the coupling term, g, is too large, they system becomes unphysical. Again, animations show that the oscillons did not decay within the time of the simulation.

Fig. 3 – The log of the variance of the inflaton field for several values of g.

Gravitational Effects

The previous simulations used the FLRW metric, an equation that determines how a homogeneous and isotropic universe expands over time. This metric does not take into consideration local gravity. Oscillons are massive structures and therefore will lead to areas of stronger gravitational potential.

Consider the perturbed metric,

$$ds^2 = -(1+2\psi)dt^2 + a^2(t)(1-2\psi)[dx^2+dy^2+dz^2]$$

Here, ψ is the Newtonian potential – a field that characterizes local gravity. Simulations ran with this new metric also produced oscillons. Did oscillons have any affect on the ψ field?

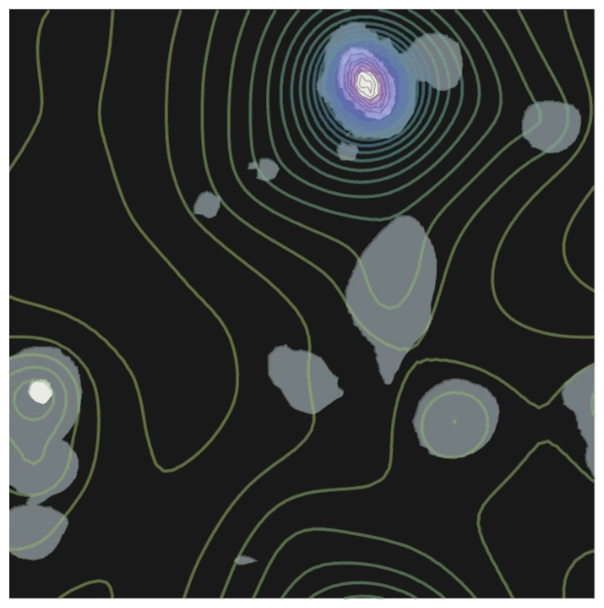


Fig. 5 – A contour plot of the energy density of the universe and the ψ field. Light areas of the background correspond to high energy densities, purple contour lines correspond to more negative values of ψ.

The areas of high energy density do correspond to larger perturbations of the metric, however perturbation theory did not break down. Additionally, the oscillons still did not decay. From these results, oscillons could not have produced primordial black holes. Figure 5 above is a 3D representation of the ψ field and the energy density of the universe.

Conclusions

Using the axion monodromy potential, oscillons were produced for coupled and uncoupled fields. Even with the addition of a canonical matter scaler field χ, oscillons did not decay within the time period where the simulations were accurately capturing the dynamics of the structures. From these simulations, however, it appears that oscillons are approximately one order of magnitude larger than predicted – this means future simulations run accurately for about 10 times longer.

By using the perturbed metric, the gravitational effects of oscillons were explored. Although they are very energy dense (up to 200 times the average energy density of the universe), ψ never grew to be large enough for perturbation theory to break down. The equations of motion were linearized, so it is possible that the non-linear portions are significant. Since oscillons present a lot of mass in a very small area, the implementation of Numerical Relativity could better model the dynamics of these structures.

References and Acknowledgements

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[2] Mustafa Amin, Richard Easther, et. al. “Oscillons After Inflation” arXiv: 1106.3335v2
[3] Mustafa Amin. “Inflaton Fragmentation: Emergence of Pseudo-Stable Inflaton Lumps (Oscillons) After Inflation” arXiv: 1006.3075v2

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