Simulating the Evolution of Oscillons

Sophia Ardell, Henry Daniels-Koch, and Thomas Baumgarte

Physics Department, Bowdoin College, Brunswick ME

Introduction

After the Big Bang, there was a period of rapid expansion in our universe. During this “inflation", the energy in the universe was dominated by a scalar field. Small and random perturbations in the scalar field later grew into larger “blobs” of matter known as oscillons. Oscillons are integral to understanding the evolution of the early universe because they may have driven the first formation of large scale structure through accretion of matter and mergers. Additionally, oscillons may have lead to the formation of primordial black holes, strong candidates for dark matter.

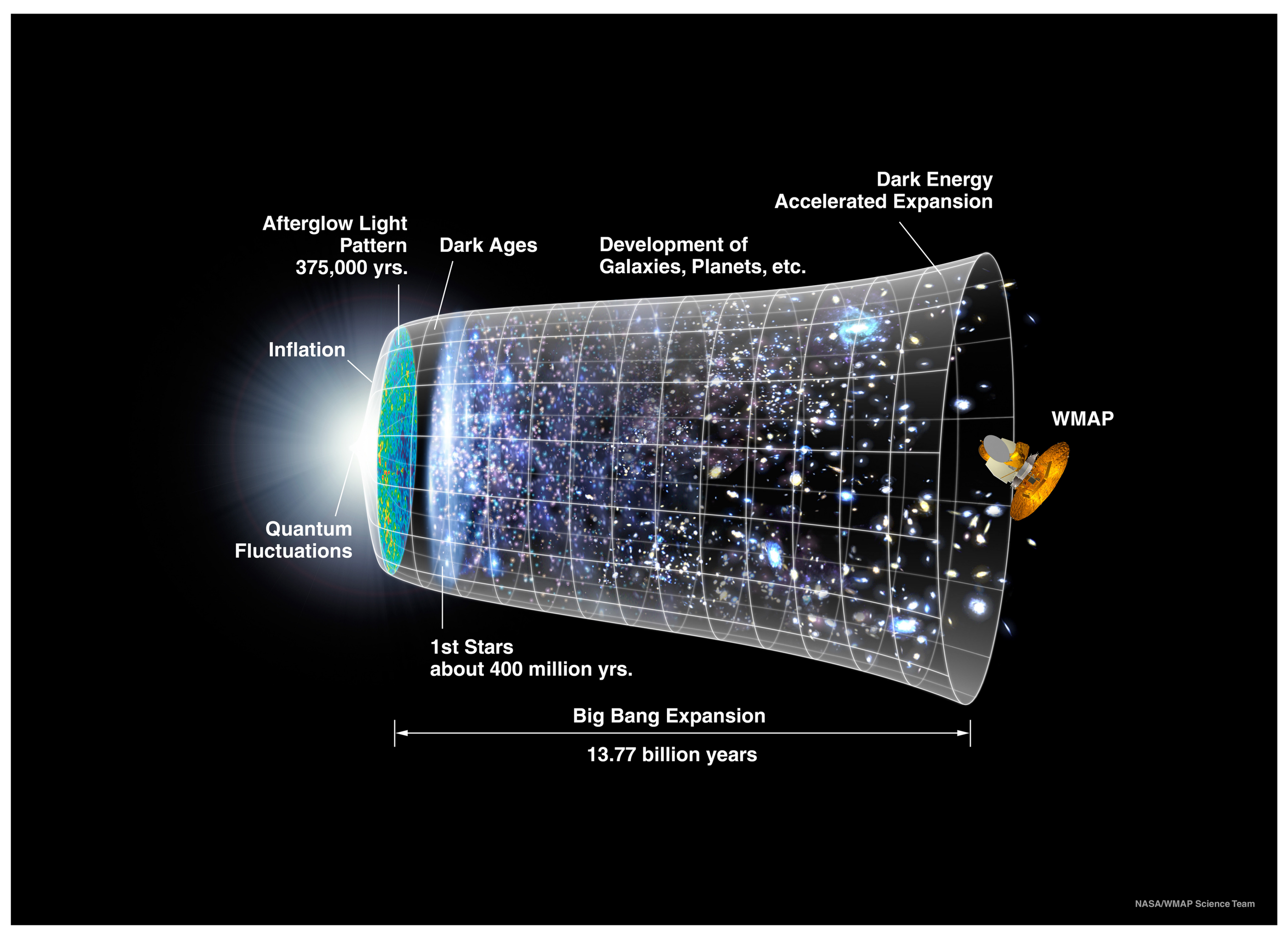

Figure 1: Timeline of the universe (Source: map.gsfc.nasa.gov).

Research Goals

While oscillons have been shown to arise as naturally, little research has been conducted on the effects of oscillons on the gravitational field that permeates the universe. Ultimately, our goal is to determine whether oscillons produce substantial gravitational waves and characterize other gravitational effects on long, post-inflationary timescales. However, we first emulate the simulation in [1] of a scalar field in $1+1$-dimensions (one spatial dimension over time) to confirm the emergence of oscillons.

Numerical Methods

To model the growth of oscillons, we solve a wave equation in the presence of a non-linear inflation potential,

$$\frac{\partial^2\varphi}{\partial t^2} - \frac{\nabla\varphi}{a^2}\varphi + H\frac{\partial\varphi}{\partial t} + V'(\varphi) = 0, \qquad (1)$$

where the potential from inflation is defined as

$$V(\varphi) = \frac{1}{2}m^2\varphi^2 - \frac{\lambda}{4}\varphi^4 + \frac{g^2}{6m^2}\varphi^6. \qquad (2)$$

We choose a predictor-corrector finite-difference scheme instead of the Lax-Friedrichs method that [1] implements to evolve our evolution equation. We initialize our model with tiny, random fluctuations of the scalar field, similar to those immediately after inflation, and evolve these fluctuations over time. Over time we expect the inflation potential to decrease with the expansion of the universe. Once the inflation potential is sufficiently small, we observe and confirm the formation of oscillons in our model.

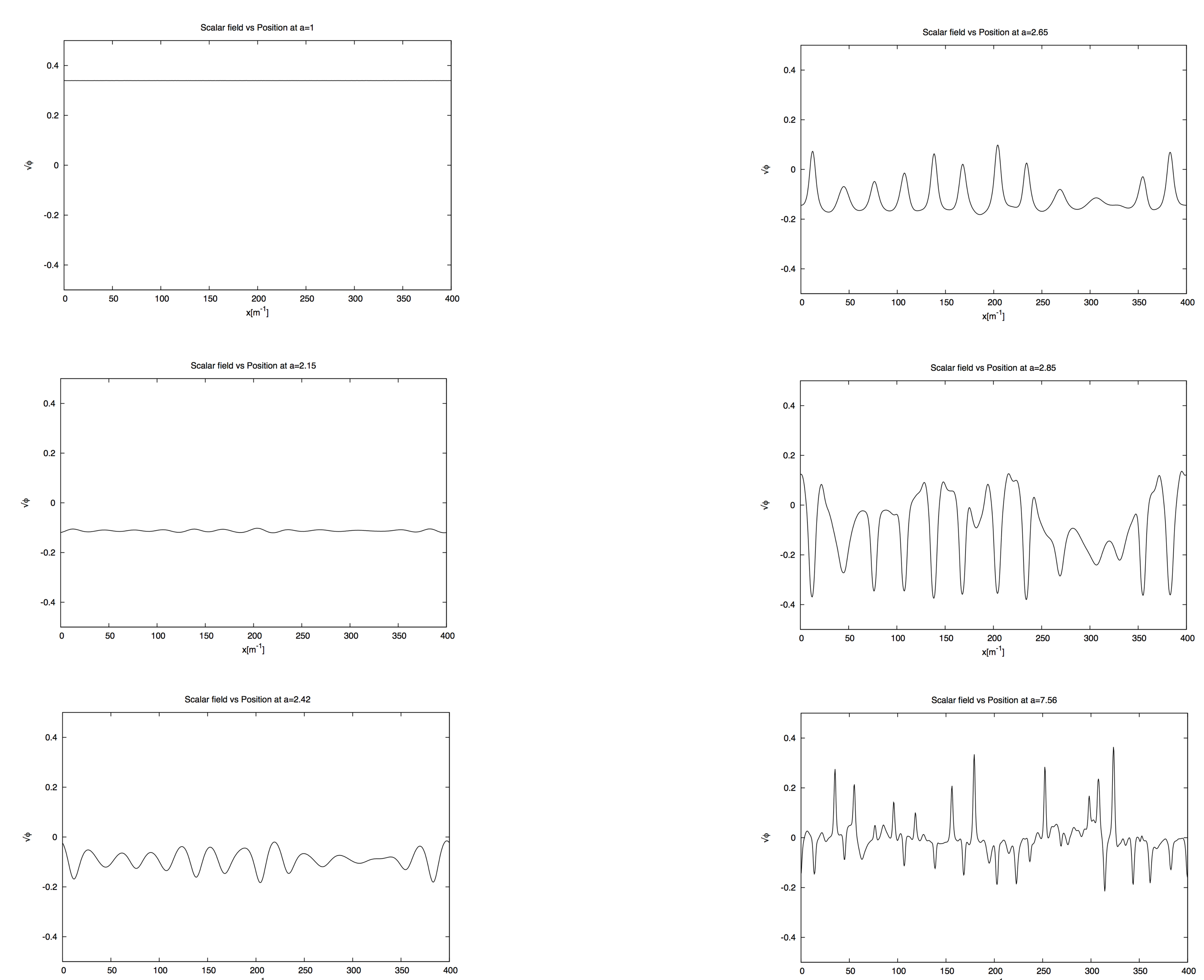

Figure 2: The scalar field, shown at six different times shows the emergence and evolution of oscillons.

OpenMP Analysis

We implement OpenMP to optimize the computational performance of the code, which we evaluate with consideration to run time and memory usage. Focusing on a $1:1$ ratio for threads to processors, we found that using 8 to 12 threads is the best compromise between memory and run time.

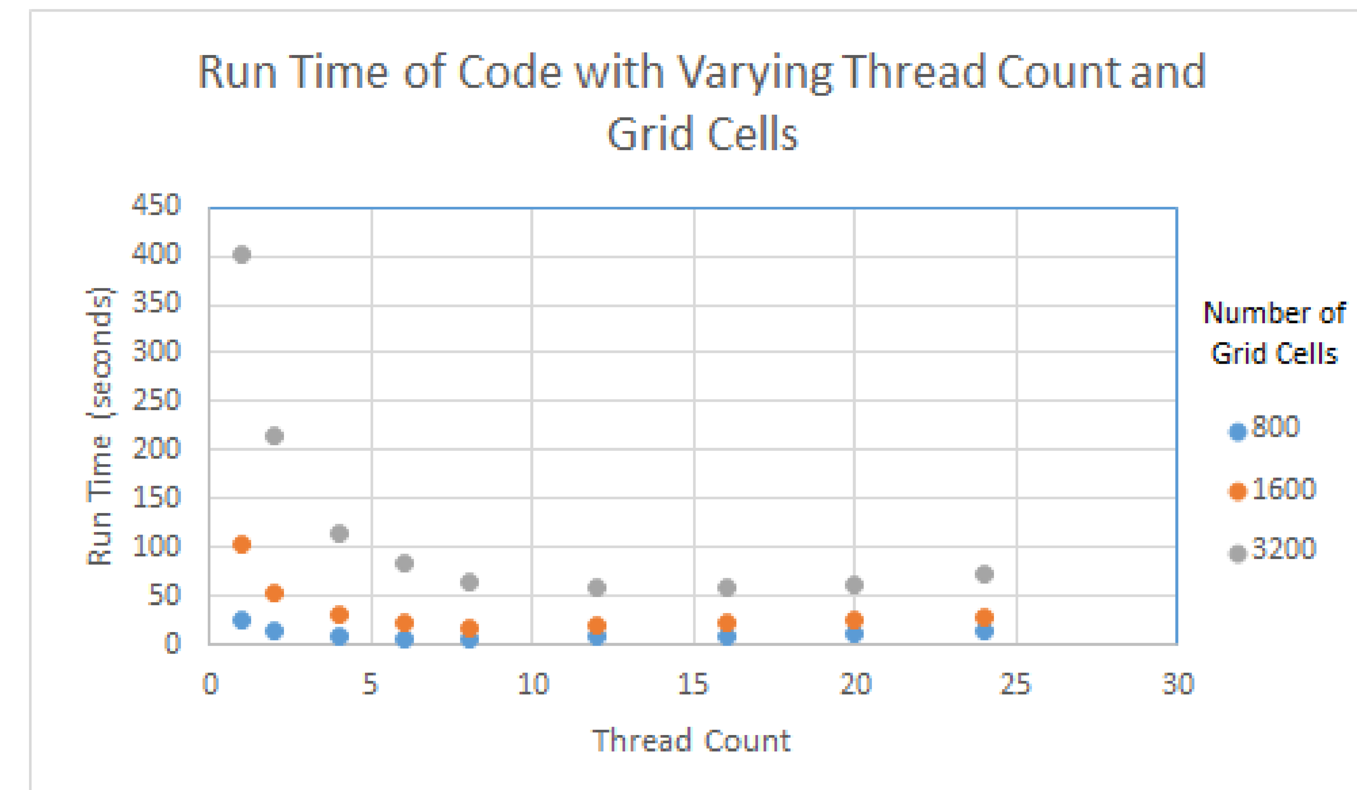

Figure 3: Visualization of performance of code with variations to thread count and grid points. We observe a decrease in run time decays in each series initially, followed by an increase beginning at 16 threads.

Conclusion

We obtained a highly similar evolution to [1] in 1+1-dimensions. We attribute our small differences in appearance to our differing implementations. In future work, we plan to evolve one oscillon in three spatial dimensions, and study its stability to non-spherical perturbations and gravitational self-interaction, as well a its emission of gravitational waves. We thank Professor Thomas Baumgarte for his guidance and support, as well as the NSF for funding part of our project.

References

[1] Mustafa A. Amin. Inflaton fragmentation: Emergence of pseudo-stable inflaton lumps (oscillons) after inflation. 2010.