Exploring Dark Matter as a Scalar Field

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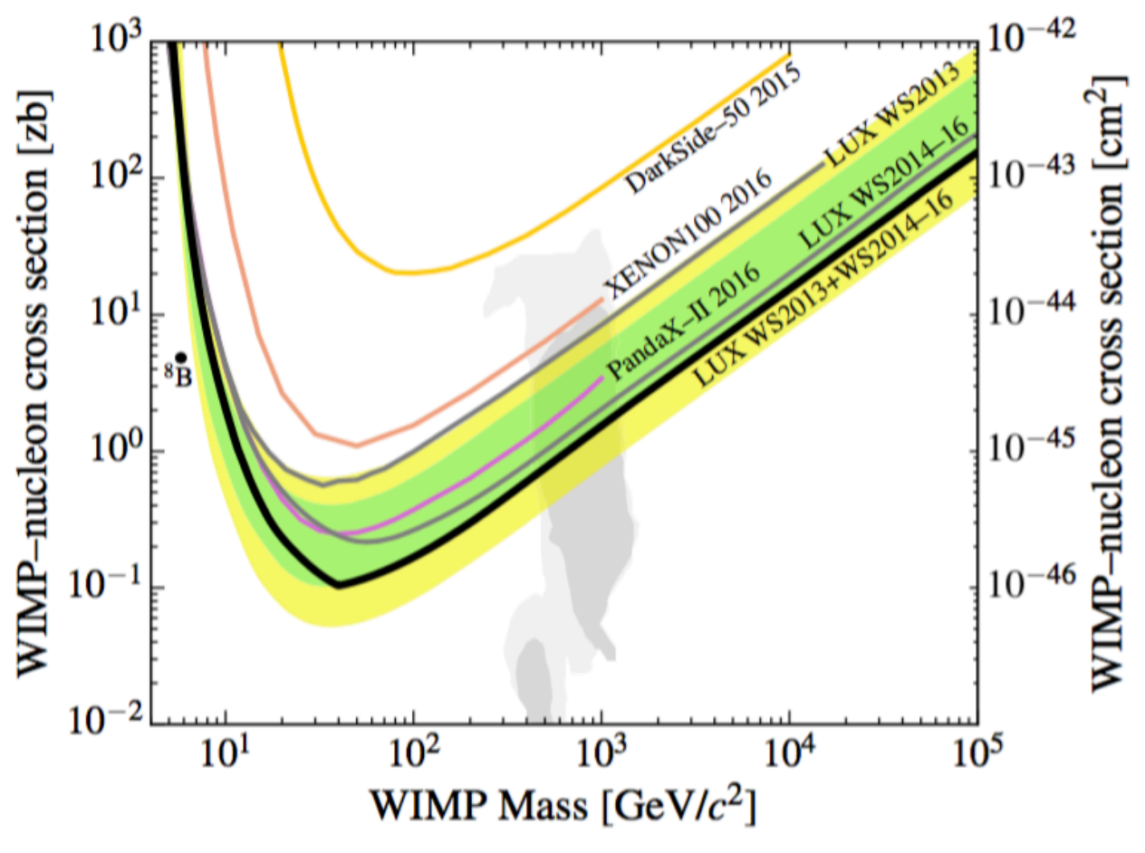
Abstract

Dark matter makes up 23% of the Universe, and we have no idea what it is. Since the late 1970s, we have developed models of dark matter centered around the idea that it can be described by a weakly interacting massive particle (WIMP). However, we have no observable evidence that WIMPs exist. Here, we explore the possibility that the Axion is Dark Matter. Axion Dark Matter is an ultralight scalar field that behaves like a classical wave. This scalar field dark matter describes large cosmic structures similarly to other Cold Dark Matter models and could better describe the formation of smaller galaxies and dark matter halos. We used numerical tools, GABE, to evolve scalar field dark matter and see if the simulated universe is similar to the universe we see today. We also assessed the dark matter behavior using power spectra of the field.

WIMP Miracle to Scalar Fields

In the late 1970s, physicists theorized that dark matter was a just another fundamental particle called a weakly interacting massive particle (WIMP). The existence of WIMPs were well received by the theoretical and observational communities because they are compatible with supersymmetry and models of the early Universe in which high temperatures lead to ``frozen out" population of them. In addition, N-body simulations, like the Millennium Simulation, used WIMPs to simulate the evolution of the Universe, and the end result looks statistically the same as the Universe we experience today. These compelling factors created the “WIMP Miracle," one of the most well liked theories for dark matter.



PhysRevLett.118.021303

However, there are problems with the WIMP Miracle. The main problem is that no particle dark matter collisions have been experimentally observed. The Xenon experiment, as well as other experiments, have never detected any dark matter interactions. So we must seriously consider alternative scenarios, such as the ultra-light scalar field.

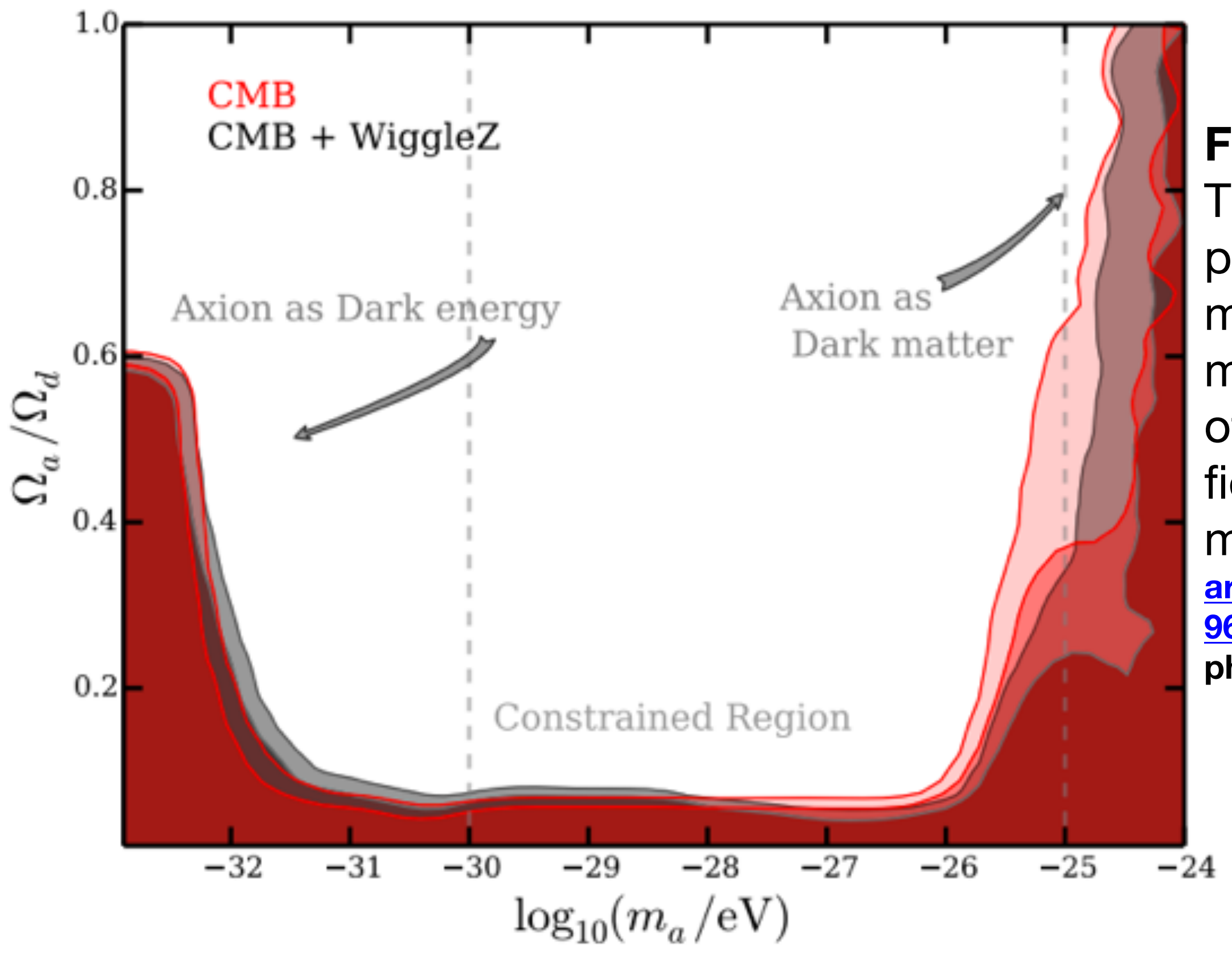


Figure 1: The physically motivated masses of scalar field dark matter. **arXiv:1410.2896 [astro-ph.CO]**

Simulating Dark Matter as a Scalar Field

We use a lattice simulation (GABE) to evolve fields in a universe along points on the lattice grid. The points are evaluated according to the field’s equations of motion. For my dark matter scalar field, I used the Klein – Gordon Equation.

$$\ddot{\phi} + 3H\dot{\phi} - \frac{\nabla^2\phi}{a^2} + \frac{\partial V}{\partial \phi} = 0$$

Where my potential V is the canonical slow roll potential

$$V(\phi) = \frac{1}{2}m^2\phi^2$$

Since dark matter interacts mainly through gravity, the Klein – Gordon is perturbed to include a linearized approximation of gravity

$$\ddot{\phi} = 4\dot{\phi}\dot{\Phi} - 3H\dot{\phi} + \frac{\nabla^2\phi}{a^2}(4\Phi + 1) - \frac{\partial V}{\partial \phi}(2\Phi + 1)$$

I used a mass of 10^{-28} eV even though its not physically motivated because it is the largest time step I could use computationally within 10 weeks (Figure 1).

Power Spectrum

The way we assess if the scalar field exhibits dark matter behavior is by looking at the modes of the field. There is a cutoff called the Jean’s Scale

$$k_J = \frac{\sqrt{4\pi G\bar{\rho}}}{c_s}$$

below which we expect modes to grow and above which we expect the modes to remain constant.

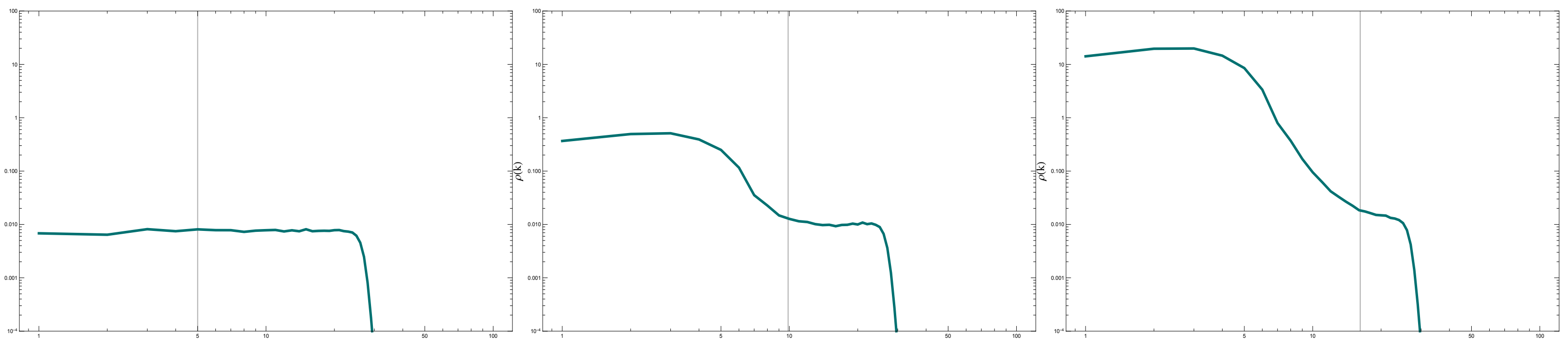


Figure 2: A sequence of spectra plots showing how the modes below the Jean’s Scale (shown in gray) grow over time.

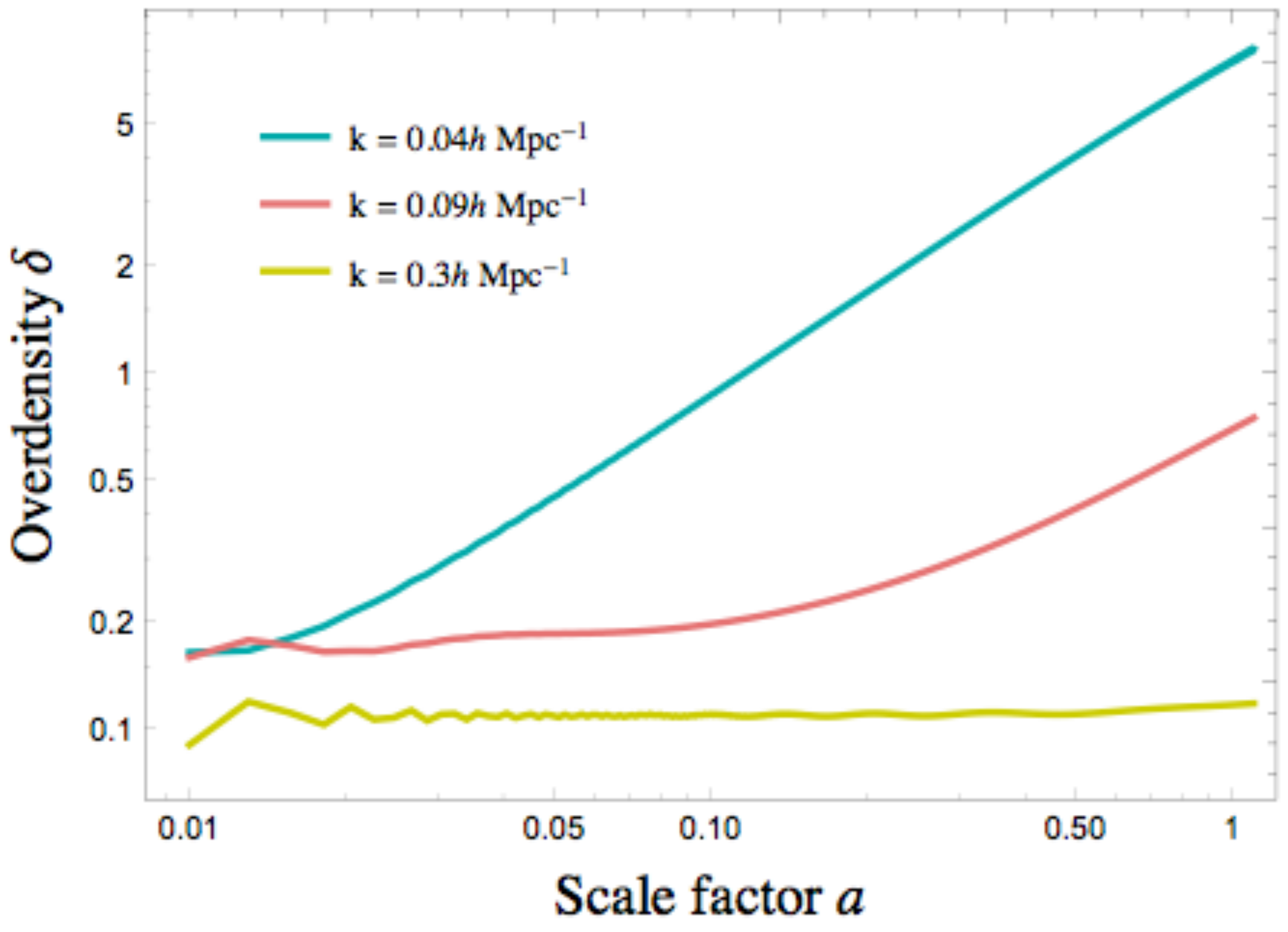


Figure 3: The individual modes plotted. In descending order, a mode below the Jean’s Scale, a mode at the Jean’s Scale, and a mode above the Jean’s Scale.

Density

Dark matter is an essential part of the formation of structures in our Universe. Since dark matter interacts primarily through the gravitational force, we expect to see clumping over time. So at the end of our simulations, we should see areas of higher energy density. Those areas are the formed structures.

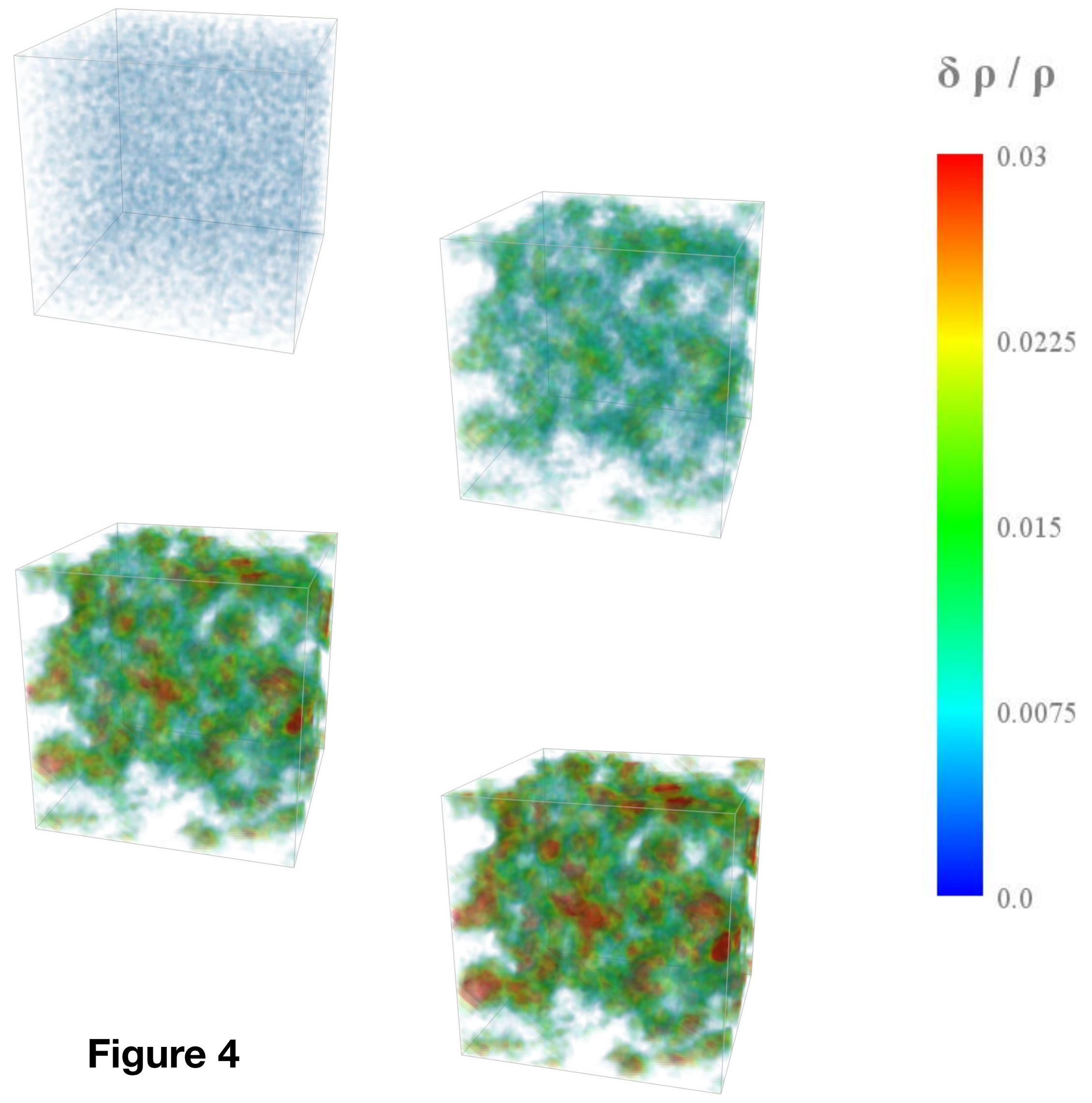


Figure 4

Conclusions

We got good results! The universe at the end of the simulation looked similar to the universe we experience today and the scalar field acted accordingly to our expectations. Not many people have modeled scalar field dark matter before with the Klein-Gordon equation because of its mass limitations. Through my summer research, we were able to verify that that scalar field dark matter could in fact be modeled using the Klein-Gordon. This is good news for the scalar field dark matter model because if something is a scalar field, it must have the ability to be represented by the Klein-Gordon. So we can proceed confidently as a cosmology community that scalar field dark matter is a possible solution to the dark matter problem.

References & Acknowledgements

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