

# **Describing Dark Matter as a Wave Function**

Maggie Murphree '19, Tom Giblin

Department of Physics, Kenyon College, Summer 2017

## Abstract

The mystery of Dark Matter has piqued the interest of many astronomers and physicists since the 1930s. Vera Rubin was the first to find conclusive evidence for the existence of Dark Matter in the late 1970s but since then we have only been able to describe how it behaves and the consequences of its existence [2,3]. In short, we do not know what the majority of matter in the Universe is.

There have been proposed theories that Dark Matter is a WIMP (Weakly Interactive Massive Particles) but due to lack of experimental support and other theoretical reasons, we have been left to search for other descriptions. Over the summer we explored Dark Matter as a wave function using the Schrödinger equation with a gravitational term as the equations of motion. With these equations of motion we were able to simulate a Universe consistent with the Klein-Gordon model.



Figure 2: Comparison plot of the Klein-Gordon (left) and Schrödinger (right) models

# Spectra

One of the tests we used to compare the results from the Schrödinger model against the Klein-Gordon model is to graph their spectra over time. The Jeans Length is the length below which we do not get collapse. Figure 6 explores the behavior of modes around the Jeans length, where modes are expected to grow if  $k < k_J$  and modes remain constant if  $k > k_J$ . Figure 7 measures the growing modes of both models against the Jeans length over time. The expression we derived for the ratio of the Jeans Length over the change in modes is:

 $k_j/dk = 5a^{1/4}$ 

## The WIMP-Miracle

We thought we knew the nature of dark matter, explained by the WIMP-miracle, which consisted of three parts:

(1) predicted by supersymmetry

(2) relic abundance, predicted by a thermal freeze out in the early Universe

(3) N-body simulations, pictured in Figure 1, that include dark matter to recreate a statistically consistent Universe.

This would have been a really good explanation for Dark Matter except that there have been no laboratory detections of particle dark matter

# The Schrödinger Equation

Other projects in our lab are working to simulate, using our lattice-evolving program GABE, the full non-linear dynamics of scalar field Dark Matter in the regime where it obeys the Klein-Gordon equation. This approach is theoretically sound (as scalar degrees of freedom do exist in the standard model of particle physics). A challenge to this prescription is the problem of timescales. In most treatments of scalar field Dark Matter, masses 10–28eV and 10–22eV, tend to have natural timescales on the order of 50 days. The time it would take for the computer to simulate billions of years (of real time) is enormous. An alternate strategy is to treat Dark Matter as a wave function in the Schrödinger interpretation:



In this picture, we don't have a fundamental scalar field, but we have a complex field that obeys a first-order differential equation (as opposed to the secondorder Klein-Gordon equation).



#### and the LHC has put sharp constraints on supersymmetry.

Figure 1: The structure of Dark Matter

# Motivations

We have started to explore the possibility that the fundamental degree of freedom that describes Dark Matter acts more like a classical wave (on galactic scales) than it does a particle. Analytic estimates suggest that galaxies predicted by particle Cold Dark Matter (CDM) should extend to much lower masses than we see in the visible Universe. Scalar field Dark Matter would predict fewer of these. At the same time, both models produce similar large scale structure [4]. Up to this point, however, very little work has been able to actually model what a universe made of scalar field Dark Matter might look like.



## **Newtonian Potential**



Figure 3: The Poisson equation relating how matter and space effect each other

0.0225

0.015

0.0075

There is an expectation that Dark Matter in this model will gravitationally interact, create potential wells in which matter accrues and then will form a sort of Bose-Einstein condensate [1]. In other words, there is a coherent wave function, that, near galaxies settles into the ground state and determines the distribution of Dark Matter. In all cases we need to couple gravitational degrees of freedom to the model, allowing the Universe both to grow and to have local inhomogeneity.

#### References and Acknowledgements

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