

Ph.D. Synopsis

Dark Matter Models and Structure Formation

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1 INTRODUCTION

In the early 1930s, Fritz Zwicky’s study of the Coma Cluster introduced the concept of dark matter, suggesting that a substantial portion of a galaxy’s mass doesn’t emit light. Subsequently, in 1969, Vera Rubin and Kent Ford’s observations of galaxy rotation curves indicated a "flat" velocity profile, implying the existence of unseen mass beyond visible stars. The 1E 0657-56 system, also known as the Bullet Cluster, located 3.7 billion light-years away, provided further evidence. This colliding galaxy cluster system exhibited a clear separation between stars/dark matter and intracluster gas, as revealed by weak lensing measurements. The findings, supported by observations of other colliding clusters, strengthened the conclusion that dark matter is a distinct and influential component in the universe.

Cosmological observations, including type Ia supernovae, cosmic microwave background radiation, large-scale structure, baryon acoustic oscillations, and strong and weak lensing data, reveal that only around 4

Dark matter exhibits several key properties. Firstly, it is optically dark or dissipationless, indicating that dark matter particles have weak electromagnetic interactions, with negligible electric charge, and do not emit light. Secondly, dark matter is collisionless, meaning it interacts weakly with other matter, and collisions do not significantly alter its distribution. Thirdly, dark matter is cold, implying it must be non-relativistic at the epoch of matter-radiation equality. This cold nature is crucial for the observed large-scale structures in the universe. Additionally, dark matter behaves as

a fluid on galaxy scales, with fine granularity that remains undetectable, and the particles forming a nearly dissipationless medium. Finally, dark matter must behave classically, adhering to classical physics principles, and this imposes constraints on the masses of both bosonic and fermionic dark matter particles.

If dark matter comprises bosons, their quantum nature becomes apparent when their mass is extremely small. For the formation of galaxies, dark matter particles must be confined within kpc scales. Considering the typical velocities in galaxies, the de Broglie wavelength (λ) of these particles is given by $\lambda \sim \left(\frac{eV}{m}\right)$ mm. Setting this wavelength to 1 kpc, it implies that particles with a mass of approximately 10^{-22} eV are only marginally confined. This mass range has been proposed as a mechanism for "fuzzy" cold dark matter, aiming to eliminate small-scale power in the galaxy power spectrum. Importantly, it also prevents the central density cusp observed in numerical simulations of galactic dark halos.

The lower mass bound for fermionic dark matter is more stringent than that for bosons. The phase space density (f) of fermions has a maximum value given by gh^{-3} , where g is the number of internal degrees of freedom. For a relativistic gas of fermions in thermal equilibrium, this value is half. In a galactic halo, the maximum phase space density, assuming a Maxwellian velocity distribution, is expressed as $f = \frac{\rho}{m^4(2\pi\sigma^2)^{3/2}}$. Pauli blocking enforces $m^4 > \frac{\rho h^3}{g(2\pi\sigma^2)^{3/2}}$. For a Milky Way-type galaxy requiring $\rho > 1 \text{ GeV cm}^{-3}$ at the center and $\sigma = 150 \text{ km s}^{-1}$, and assuming $g = 2$, the lower limit for fermionic dark matter mass is approximately 25 eV.

Mordechai Milgrom proposed a modification to Newton's second law in 1981 as an alternative to introducing new particles to explain the observed galactic rotation curves. Newton's second law, $F = ma$, works effectively on Earth and in our solar system, but Milgrom suggested altering it for smaller accelerations at galactic distances, where the same force produces less acceleration. However, Milgrom's modification cannot account for evidence of dark matter on larger scales, such as in galaxy clusters. The observation of the system 1E 0657-56, for instance, utilized x-rays emitted by hot baryonic matter to show that the baryonic matter was not in the expected location to cause gravitational lensing, indicating displacement due to a collision. No reasonable modification of Newton's laws could explain this.

The concept of particles collectively forming stable macroscopic entities has a rich history. In 1955, John Wheeler proposed the idea of geons—classical electromagnetic field configurations within the framework of General Relativity (GR). However, these geons were found to be unstable against perturbations. When the classical electromagnetic field is replaced by a complex scalar field, the

Klein-Gordon equation yields stable and localized solutions known as boson stars (BSs). The resurgence of interest in BSs follows the confirmation of the Higgs boson's existence, emphasizing the role of fundamental bosons in nature. Various theoretical extensions of the Standard Model (SM), such as the Peccei-Quinn mechanism, scalar inflaton fields in inflationary models, supersymmetric extensions, and string theory, predict the existence of fundamental complex scalar fields. Studying BSs is not only motivated by theoretical considerations but also serves as a laboratory to explore the properties of compact self-gravitating objects. Furthermore, due to their stability and mass range, there is speculation that BSs could potentially be detected through astrophysical methods and might even contribute to the elusive dark matter in the Universe.

The role of self-interaction among the bosonic dark matter particles in the kinetic regime was analyzed in^[1]. This study shows that self-interaction in the dark matter cloud can influence the mass and compactness of the Bose star. Simulation of ultralight dark matter halo formation has been carried out in^[2]. The study demonstrates a solitonic core and confirms the core-halo mass relations.

However, it should be emphasized that gravitational shearing can naturally induce rotation in star-forming clouds.. Thus, considering the ubiquity of rotation in star-forming clouds, we investigate the formation and evolution of a Bose star when the initial dark matter distribution possesses finite angular momentum. Additionally, we explore the role of self-interaction in the star formation process while the initial dark matter density is randomly distributed throughout space, satisfying the conditions associated with the kinetic regime. In this work, we consider the self-interacting scalar dark matter field described by a Gross-Pitaevskii-type equation. First, we would like to note that there are existing studies in the literature that discuss related issues. In the reference^[2], numerical solutions of the Einstein-Klein-Gordon and Einstein-Proca equations are considered to investigate the formation process of a Bose star. The initial field density profiles are examined with and without axisymmetry, where as we take a random initial distribution.

We are also investigating the possibility of detecting an axion star in the Milky Way galaxy. Previous studies have indicated that, under the influence of a strong magnetic field, axions can convert into photons. However, since the Milky Way's magnetic field is relatively weak, on the order of a few microgauss, detection becomes challenging. To address this, we are exploring alternative possibilities, such as the resonant decay of axions into photons and examining conversion scenarios due to the conductivity of interstellar plasma. Additionally, we are considering situations where an axion star is influenced by a Magnetar, an object with an exceptionally high magnetic field.

2 METHODOLOGY

2.1 GROSS-PITAEVSKI EQUATION

In the non-relativistic limit and for a high mean occupation number, the system can be represented by a classical scalar field, $\psi(\mathbf{r}, t)$, whose time evolution can be described by the Gross-Pitaevskii-Poisson equations^[1,3] :

$$i\frac{\partial\psi}{\partial t} = -\frac{1}{2m}\nabla^2\psi + m\Phi\psi + g|\psi|^2\psi, \quad (1)$$

$$\nabla^2\Phi = 4\pi Gm(|\psi|^2 - n), \quad (2)$$

Here, $\Phi \equiv \Phi(\mathbf{r}, t)$ is the gravitational potential, G is the universal gravitational constant, and n is the mean particle density of the boson gas. The parameter g represents the self-interaction coupling constant, where positive values correspond to repulsive self-interaction and negative values correspond to attractive self-interaction. The case $g = 0$ corresponds to a non-interacting scenario. For a box with a size L and a total number of particles N , the number density is given by $n = N/L^3$.

We study the gravitational collapse of a randomly distributed, non-interacting cloud of scalar bosons in the kinetic (low-density) regime. The kinetic regime is characterized by the de Broglie wavelength $(mv)^{-1}$ and time scale mv^2 of the particles, which satisfy the following conditions^[3]:

$$mvR \gg 1 \quad \text{and} \quad mv^2\tau_{\text{gr}} \gg 1 \quad (3)$$

Here, m is the mass of the dark matter particle and v is its typical velocity. R represents the halo size, and τ_{gr} is the condensation time at which the star formation process begins. The authors estimate the value of τ_{gr} using a heuristic argument.

Implemented for solving Equations 2.1 and 2.2, the sixth-order pseudo-spectral method efficiently simulates wavefunction dynamics. This algorithm employs half-steps and full steps in Fourier and position space, respectively, alternating between nonlinear potential term evolution and linear differential operators. It ensures accuracy and computational efficiency in updating the wavefunction and potential field iteratively. The process involves an initial configuration, a half-step in the nonlinear term, Fourier transform, a full step in the linear term, potential field update, inverse Fourier transform, a final half-step in the nonlinear term, and iteration for the desired time steps.

2.2 AXION-PHOTON INTERACTION IN PLASMAS

To understand the behavior of axions in the presence of galactic magnetic fields, it is essential to study the axion-photon interaction in plasmas. In a plasma, axions can mix with photons due to their coupling constant $g_{a\gamma}$, which leads to oscillations and conversions between axions and photons. This interaction can be described by the effective Lagrangian density^[4]:

$$\mathcal{L}_{\text{eff}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a\partial^\mu a + \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}, \quad (4)$$

where $F_{\mu\nu}$ is the electromagnetic field strength tensor, a is the axion field, m_a is the axion mass, and $\tilde{F}^{\mu\nu}$ is the dual electromagnetic field strength tensor.

The presence of a background magnetic field \mathbf{B} in a plasma leads to a modification of the dispersion relation for the axion field a and the photon field. In a plasma, the dispersion relation for axions and photons becomes^[4]:

$$(\omega^2 - k^2 - m_a^2) a = -ig_{a\gamma}\mathbf{B} \cdot \mathbf{E}, \quad (5)$$

$$(\omega^2 - k^2) \mathbf{E} = (\omega_p^2 - k^2) \mathbf{E} + ig_{a\gamma}\mathbf{B} a, \quad (6)$$

where ω is the frequency, k is the wave vector, \mathbf{E} is the electric field, and ω_p is the plasma frequency. These equations describe the axion-photon mixing in the presence of a plasma and a magnetic field.

3 FORMATION OF A BOSE STAR IN A ROTATING CLOUD

In this chapter, I discuss the results of our paper, where we have demonstrated how a rotating scalar field can give rise to the formation of a Bose Star in the kinetic regime. The investigation includes the incorporation of the effect of self-interaction among the particles. The discussion commences with an exploration of the impact of angular momentum of the scalar field on the formation process. Subsequently, the chapter delves into the combined effects of self-interactions and angular momentum.

It is noteworthy that the inclusion of angular momentum and self-interaction significantly influences various aspects of star formation, including the star formation time, mass-radius relation, and more. Notably, the chapter reveals that rotating boson stars are only viable in scenarios where repulsive self-interaction is present.

The comprehensive analysis presented in this chapter sheds light on the intricate interplay between rotation, self-interaction, and the resulting properties of the formed Bose Stars. These findings contribute to a deeper understanding of the factors influencing the dynamics of these astrophysical structures.^[5]

4 AXION DECAY IN GALACTIC MAGNETIC FIELDS

This chapter explores the intricate dynamics of axions and Axion-Like Particles (ALPs) within the context of magnetic fields and plasma, particularly in intergalactic environments. The discussion revolves around the axion-photon coupling and its pivotal role in governing the behavior of axions.

The chapter begins by presenting the equations that govern axion dynamics in the presence of electromagnetic fields. Emphasis is placed on understanding the effects of plasma conductivity and magnetic fields on axion stability and oscillations. The exploration delves into the nuanced interplay between axions, electromagnetic fields, and the surrounding plasma environment.

Furthermore, the chapter undertakes the calculation of the lifetime of axion stars in intergalactic space. This analysis serves to elucidate the implications of axion dynamics for astrophysical observations. The findings presented in this chapter provide valuable insights into the behavior of axions and their broader significance in the realms of dark matter and astrophysics.

The comprehensive examination of axion dynamics in the presence of magnetic fields and plasma contributes to a deeper understanding of the complex interactions governing these elusive particles. Such insights are crucial for advancing our knowledge of the role played by axions in the cosmic landscape.^[4]

5 FUTURE PROSPECTS

Currently, the method to quantify the transfer of angular momentum in the Bose Star from the surrounding field is yet to be fully developed. In our study, we have employed the vorticity magnitude as a tool to understand the signature of angular momentum transfer.

The primary challenge lies in modeling the random Brownian motion exhibited by the star within the simulation box, coupled with its intrinsic rotation. The intricate interplay between these two components poses a significant obstacle in accurately capturing and quantifying the transfer of angular momentum.

Efforts have been directed towards understanding the vorticity magnitude as an indicator of

angular momentum transfer. By examining the characteristics of vorticity within the Bose Star and its surroundings, we aim to decipher the complex dynamics associated with the transfer process.

Further developments in the quantification method are essential to provide a more comprehensive understanding of how angular momentum is exchanged between the Bose Star and its environment. Addressing the modeling challenges associated with random motion and intrinsic rotation is crucial for refining our insights into the intricate mechanisms governing angular momentum transfer in these astrophysical structures.

LIST OF PUBLICATIONS RELATED TO THIS THESIS

- K. J. Purohit, P. K. Natwariya, J. R. Bhatt, and P. K. Mehta, “Formation of a Bose star in a rotating cloud,” *Astrophys. Space Sci.*, vol. 368, no. 11, p. 97, 2023. 11
- K. J. Purohit, S. Mohanty, J. R. Bhatt, and P. K. Mehta, “Axion Decay in Galactic Magnetic Fields.” [Manuscript under preparation]

LIST OF ORAL PRESENTATIONS GIVEN DURING PH.D.

- Gave a talk on "Formation of Bose Stars" during the conference "LESS TRAVELLED PATH TO THE DARK UNIVERSE" at International Centre for Theoretical Sciences(TIFR), Bengaluru, India
- Gave a talk on "Axion Stars" during the conference "ANNUAL THEORY DISCUSSION DAYS" at Physics Research Laboratory, Ahmedabad, India

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