Bose-condensed dark matter halos with non-degenerate component

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Abstract

A galactic halo of dark matter is considered as a weakly interacting dilute Bose gas. The halo involves a core, in which some bosons form Bose-Einstein condensate, while the others remain in the non-degenerate state. The non-degenerate component is described as a gas of elementary excitations in the Hartree-Fock-Bogolyubov approximation taking into account the overall quasiparticle energy spectrum. A cloud of non-condensed bosons surrounds the core. Numerical solutions to the equations describing a dark matter density distribution show that the halo radius grows significantly when the condensate particle number fraction decreases. At the same time the radius of the condensate core remains almost the same. If the halo has comparable-sized condensate core, the non-degenerate component gives only insignificant contributions to the dark matter density profile and rotation curves when confronted with the pure condensate models. This conclusion is caused by constraints on the scattering cross section to the mass of dark matter particles ratio obtained from the Bullet Cluster measurements. It is shown that bosons with masses m ~ 100 eV do not violate these constraints if they form relatively small condensate «drops» (with a radius of about 100 astronomical units) inside a halo consisting of non-condensed particles. It is shown that in this case the DM halo has a minimum radius corresponding to the critical condensation temperature.

Purposes

- Analysis of the halo DM structure consisting of BEC in the presence of a non-degenerate component in the Hartree-Fock-Bogolyubov approximation. This approximation takes into account the entire spectrum of quasiparticles, and the anomalous mean naturally enters a self-consistent system of equations.
- Study of the DM model in which the halo consists of a nondegenerate Bose gas close to the phase transition point.
- Comparison of results of theoretical calculations with observational data.
- Estimation of boson mass in the framework of the studied models.

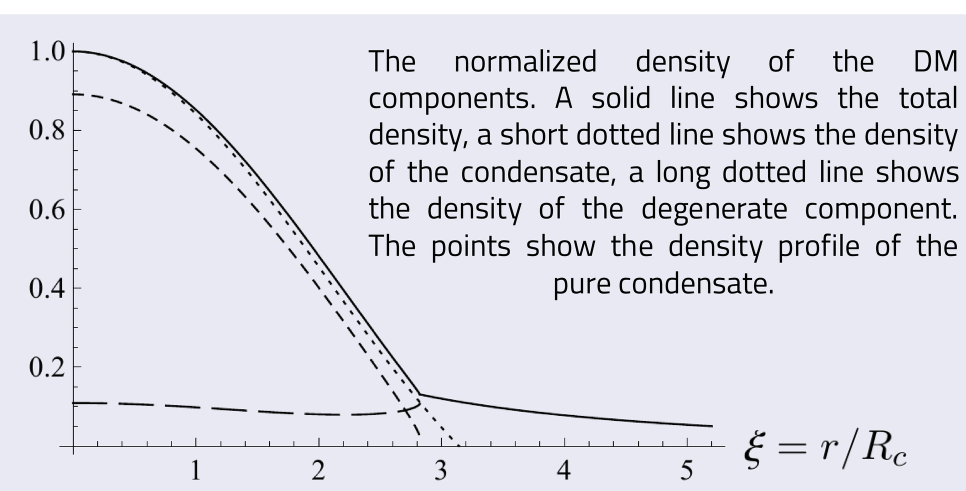
Methology

Self-consistent system of equations in the HFB approximation

$$mV(\mathbf{r}) + gn_c(\mathbf{r}) + 2gn_n(\mathbf{r}) + g\sigma_n(\mathbf{r}) = \mu_c$$
$$\nabla^2 V(\mathbf{r}) = 4\pi G m\left(n_c(\mathbf{r}) + n_n(\mathbf{r})\right)$$

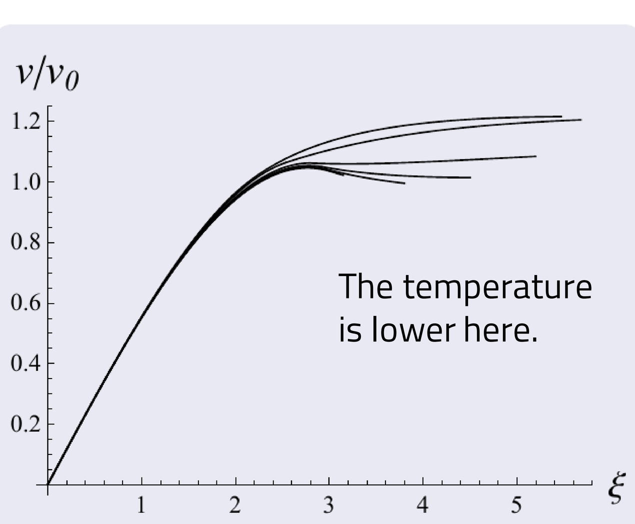
$$n_n(\mathbf{r}) = \frac{\left(mg\left(n_c(\mathbf{r})+\sigma_n(\mathbf{r})\right)\right)^{3/2}}{3\pi^2\hbar^3}\left(1+\frac{3}{\sqrt{2}}\int\limits_0^\infty \frac{\sqrt{\sqrt{t^2+1}-1}}{e^{\beta g(n_c(\mathbf{r})+\sigma_n(\mathbf{r}))t}-1}dt\right),$$

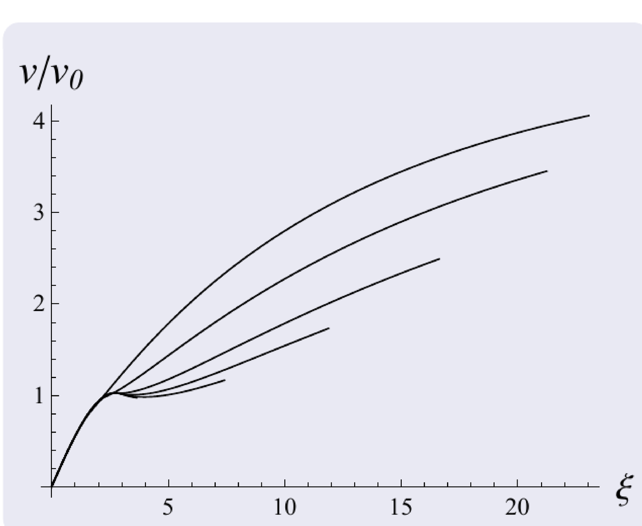
$$\sigma_n(\mathbf{r}) = \frac{\left(mg\left(n_c(\mathbf{r})+\sigma_n(\mathbf{r})\right)\right)^{3/2}}{\pi^2\hbar^3}\left(1-\int\limits_0^\infty \frac{\sqrt{\sqrt{t^2+1}-1}(t^2+1)^{-\frac{1}{2}}}{\sqrt{2}\left(e^{\beta g(n_c(\mathbf{r})+\sigma_n(\mathbf{r}))t}-1\right)}dt\right).$$



The normalized density of the DM components. A solid line shows the total density, a short dotted line shows the density of the condensate, a long dotted line shows the density of the degenerate component. The points show the density profile of the pure condensate.

Rotation curves for different ratios of the condensate and noncondensate:



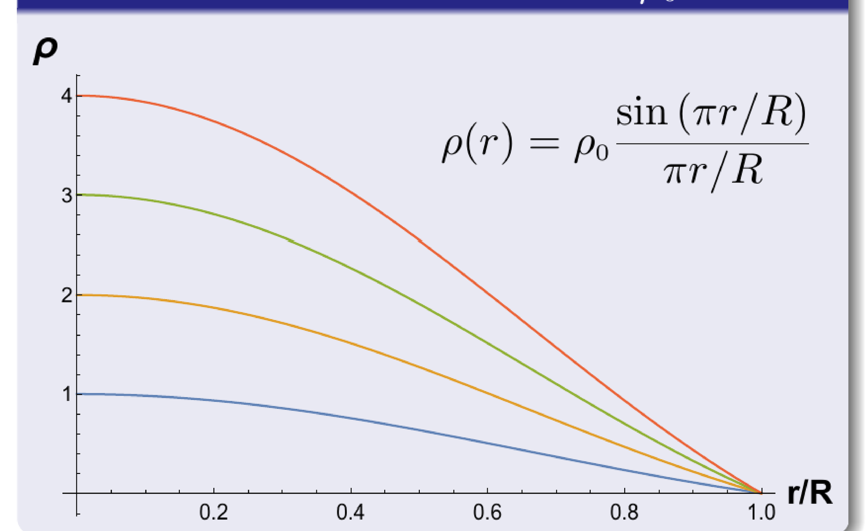


Non-degenerate Bose gas the contribution made by the in the halo of the Bose-condensate dark matter with m ~ 10 eV.

Introduction

Various extensions of the standard model of particle physics predict the existence of very light bosons, with masses ranging from about 10^{-5} eV for the QCD axion down to 10^{-33} eV for ultra-light particles. These particles could be responsible for all or part of the cold dark matter (CDM) in the Universe. For such particles to serve as CDM, their phase-space density must be high enough to form a Bose–Einstein condensate (BEC). The fluid-like nature of BEC CDM dynamics differs from that of standard collisionless CDM, however, so different signature effects on galactic haloes may allow observations to distinguish them. Standard CDM has problems with galaxy observations on small scales; cuspy central density profiles of haloes and the overabundance of subhaloes seem to conflict with observations of dwarf galaxies. It has been suggested that BEC CDM can overcome these shortcomings for a large range of particle mass m and self-interaction coupling strength g.

The density profile of the halo DM pure condensate at different ρ_0



An important advantage of BEC CDM is the natural absence of singularity in the distribution of halo density and the existence of a minimum radius of gravitationally bound BEC.

The disadvantage of the model is that the radius of the halo of pure condensate does not depend on the Central density and temperature.

Additional restriction

The restriction on particles TM from the analysis of clusters of Bullet

$$\frac{\sigma}{m} \lesssim 1\ \text{см}^2/\text{г}, \quad \sigma = 8\pi a^2$$

If the radius of the core of Bose condensate $R_c \sim 1$ кПк, то

$$m \lesssim 4\times 10^{-4}\left(\frac{R_c}{1\ \text{кПк}}\right)^{-4/5}\ \text{эВ}$$

In this case, the non-degenerate component does not give a noticeable contribution.

A non-degenerate component contributes to the $m \sim 10$ eV, then

$$R_c = \left(\frac{(\sigma/m)\,\hbar^4}{8\pi G^2 m^5}\right)^{1/4} \lesssim 11\left(\frac{\sigma/m}{1\ \text{см}^2/\text{г}}\right)^{1/4}\left(\frac{m}{10\ \text{эВ}}\right)^{-5/4}\ \text{а. е.}$$

Compact objects of a Bose condensate, called Bose-stars.

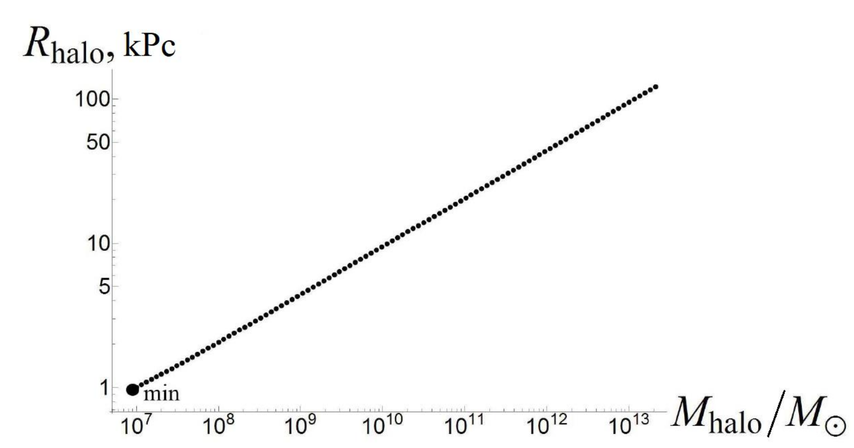
Based on the analysis, we can conclude:
If bosons with a mass of m ~ 10 - 1000 eV form a dark matter halo, then this halo can form Bose stars with a radius of up to tens of astronomical units.

In this case, the equilibrium halo of the nondegenerate Bose gas has a minimum radius corresponding to the critical condensation temperature.

In order for the minimum radius of the halo to be of the order of 1 kPc, the boson mass must be of the order of 1 Kev.

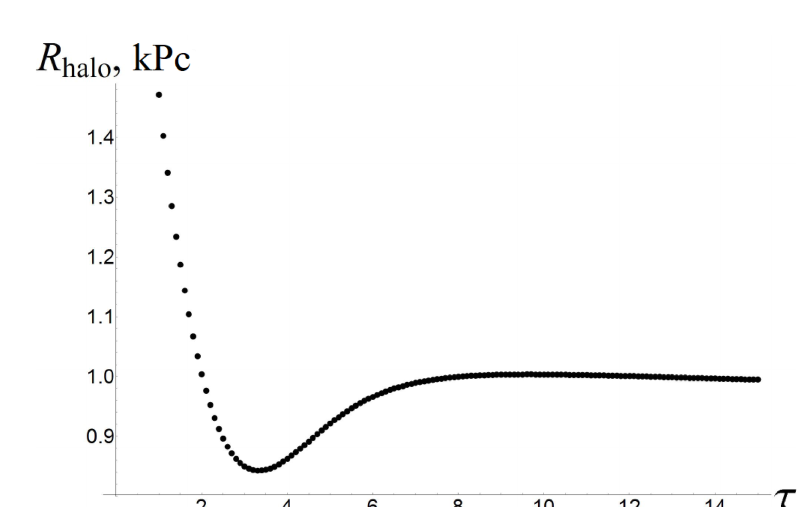
Bose stars can contribute to the halo distribution of dwarf galaxies. For large halos, Bose gas is indistinguishable from ideal.

Mass and radius of a dark matter halo from a nondegenerate Bose gas at m ~ 1 keV and different temperatures:



The minimum corresponds to the critical condensation temperature.

The radius of the halo at various speeds Bose stars



The minimum corresponds to the case when the average speed of Bose stars is comparable to the thermal speed of nondegenerate bosons.

Conclusion

1. For Bose condensate TM galactic sizes elementary excitations do not have a significant effect on the halo structure.
2. The mass of bosons in models with a nondegenerate component of 10 eV - 1 keV.
3. The radius of the condensate in a model with a nondegenerate component of the order of several astronomical units.
4. The equilibrium halo of a TM consisting of a nondegenerate Bose – gas has a minimum radius. To ensure that the minimum radius corresponds to the typical the radius of dwarf galaxies, the dark matter Bose particles should have a mass of $m \sim 1$ keV.

Publications

The first part is published in:
Abdullin I.G., Popov V.A. Bose-condensed dark matter halos with non-degenerate component // Space, time and fundamental interactions. 2019. № 1. C. 26-44.

The publication of the second part is being prepared.

Reports:
1. Temperature excitations in a Bose-Einstein condensate forming dark matter halo, 3rd International Winter School-Workshop on Gravity and cosmology "Petrov School 2017", Institute of Physics, Kazan Federal University, 11/28/2017, report.
2. Bose-Einstein condensate, as a gravitationally coupled system, 2nd International Winter School-Workshop on Gravity and Cosmology "Petrov School 2016", Institute of Physics, KFU, 12/08/2016, report.