Interacting & non-interacting fermionic dark matter and quark matter compact stars

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Introduction

In recent times, dark matter (DM) has generated considerable inquisitiveness in both astrophysics and particle physics, and it seems clear that it is the dominant matter in the universe. Recent advances in cosmological precision tests further consolidate the minimal cosmological standard model, indicating that the universe contains 4.9% ordinary matter, 26.8% DM, and 68.3% dark energy. However, the properties of DM, including its mass and interactions, are still unknown. Hence, it is of great interest to explore the properties of DM through direct or indirect methods. In the present work, the masses and radii of compact stars made of quark matter and fermionic dark matter are obtained by solving the Tolman-Oppenheimer-Volkoff (TOV) equations. Then equation of state (EoS) for DM-admixed QM is constructed by mixing energy densities in 1:1 and 5:1 ratios and adding corresponding pressures in the same ratios. The EoS for such DM admixed QM is then used in TOV for obtaining mixed star masses.

The EoS of non-self-annihilating dark matter and quark matter

We consider an interacting Fermi gas of supersymmetric fermionic DM of particle mass 1-100 GeV. The DM part may stabilize itself in a barotropic state in the same way as in the case of ordinary matter, but it is very difficult to determine what is the EoS of DM. We will take DM as Fermi gas with m_I accounting for the energy scale of the interaction, and write the energy density ε_χ and pressure P_χ of DM as those of a self-interacting Fermi gas [1] which are given by

$$\varepsilon_\chi = \frac{m_\chi^4}{(\hbar c)^3\pi^2}\int_0^{x_f} x^2\sqrt{1+x^2}dx + \left(\frac{1}{3\pi^2}\right)^2 \frac{x_f^6 m_\chi^6}{(\hbar c)^3 m_I^2}, \tag{1}$$

$$P_\chi = \frac{m_\chi^4}{3(\hbar c)^3\pi^2}\int_0^{x_f} \frac{x^4}{\sqrt{1+x^2}}dx + \left(\frac{1}{3\pi^2}\right)^2 \frac{x_f^6 m_\chi^6}{(\hbar c)^3 m_I^2} \tag{2}$$

where m_χ and m_I are masses in MeV of DM particle and boson of interaction, $x_f = \frac{\hbar k_F}{m_\chi c}$ is the dimensionless Fermi momentum of DM particle. The mass of the exchange boson determines the strength and range of the interaction implying lower the mass stronger the interaction and for non-interacting DM, m_I is infinity and second terms in above equations are absent.

The QM EoS is calculated using the MIT bag model [2] assuming massless 3-flavors. Assuming free strange matter at absolute zero, the MIT bag model EoS for massless quarks is given by

$$\varepsilon_q = g\frac{\hbar c k_f^4}{8\pi^2} + B, \tag{3}$$

$$P_q = \frac{1}{3}g\frac{\hbar c k_f^4}{8\pi^2} - B = \frac{1}{3}(\varepsilon_q - 4B) \tag{4}$$

where the degeneracy factor $g = 3flavors \times 3colors \times 2spins \times 2q\bar{q} = 36$, k_F is the Fermi momentum and B is the bag constant. If $\epsilon_q = 4B$ then $P = 0$ which shows that this system is self bound. Gluons will bose condense at absolute zero and do not contribute to the energy density and pressure of the star.

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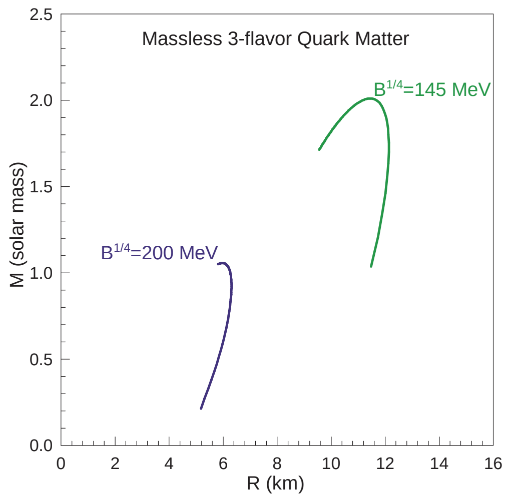

FIG. 1: Mass-radius relation of slowly rotating quark stars for the bag model EoS with thin crust.

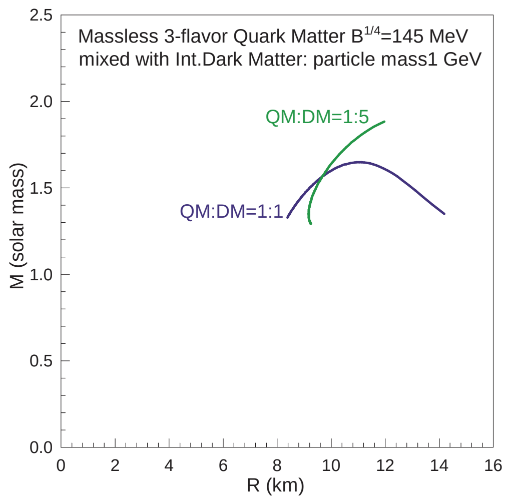

FIG. 2: Mass-radius relation of slowly rotating DM admixed quark stars with 1 GeV DM particle.

Calculations and results

The masses and radii for quark stars are calculated by solving TOV equations using QM EoS with thin crust. For calculating masses and radii of DM stars, the DM EoS is used for the entire region. The calculations are performed for non-self-interacting (m_I=∞) and strongly self-interacting (m_I=100 MeV) DM. DM-admixed QM is constructed by mixing energy densities in 1:1 and 5:1 ratios and adding corresponding pressures in same ratios. EoS for such DM admixed QM is then used in TOV for obtaining mixed star masses and radii. The maximum mass of quark stars can reach 2 $M_\odot$ for EoS of QM corresponding to bag constant $B^{1/4}$=145 MeV. Admixing of DM causes reduction in maximum mass which is more pronounced for more massive DM particle.

Summary and Conclusion

In summary, the masses and radii of compact stars made of QM, DM and DM admixed QM are calculated. It is found that maximum mass of DM stars can reach 2 $M_\odot$ for EoS of interacting DM corresponding to particle mass of 1 GeV. This result was expected since DM particle mass for this case is about the same as that of a neutron and hence masses and radii resemble to those of neutron stars. The maximum mass of quark stars can also reach 2 $M_\odot$ for EoS of QM. The DM-admixed QM causes reduction in maximum mass which is more pronounced for more massive DM particle. These results need to be compared with those obtained by solving the two-fluid TOV equations which consider QM and DM as two different fluids that interact among themselves only through gravitational interaction.

References

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