DARK MATTER
APPLIED IN STRANGE STARS

LASNPA XIV/2024

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Introduction

- Our work is focused on strongly interacting particles that are studied by Quantum Chromodynamics (QCD);
- In Quantum Chromodynamics we have quarks and gluons that are studied under different conditions of temperature and density (or through the chemical potential);
- There are two possible states of matter: the hadronic one and the quark and gluon plasma (QGP)

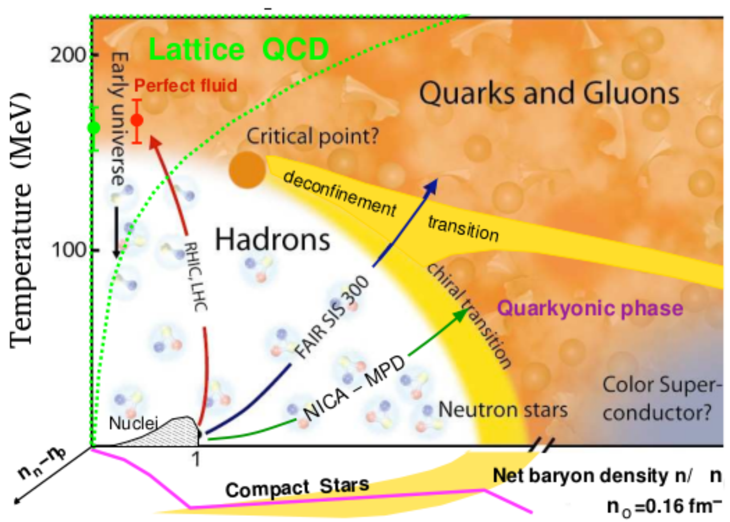

Figure: QCD phase diagram.

- The difficulty of studying QCD at the non-perturbative regime requests different approaches:
  - Lattice QCD (LQCD);
  - Dyson-Schwinger equations;
  - Effective/ phenomenological quark/gluons models:
    - Massachusetts Institute of Technology (MIT) bag model;
    - Nambu-Jona-Lasino (NJL) model;
    - The Equiparticle (EQP) model;

The equiparticle (EQP) model

- Let's begin by understanding how the Equiparticle model works;
- In the 70's, the Bodmer-Witten Hypothesis was proposed: the absolutely stable fundamental state of matter would be strange quark matter (SQM);
- The EQP model was proposed in 2014 in order to study SQM by being a density and/or temperature dependent model;
- This model corrects the lack of thermodynamic consistency present on other models of the same type.

The relevant equations describing the model are given by:

$$m_i = m_{io} + m_I = m_{io} + \frac{D}{\rho_b^{1/3}} + C\rho_b^{1/3}$$

$$p_{SQM} = -\Omega_o + \rho_b \frac{\partial m_I}{\partial \rho_b} \frac{\partial \Omega_o}{\partial m_I} \qquad \epsilon_{SQM} = \Omega_o - \sum_i \mu_i^* \frac{\partial \Omega_o}{\partial \mu_i^*}$$

$$\Omega_o = -\sum_i \frac{\gamma}{24\pi^2} \left[\mu_i^* k_{Fi} \left(k_{Fi}^2 - \frac{3}{2} m_i^2 \right) + \frac{3}{2} m_i^4 \ln \frac{\mu_i^* + k_{Fi}}{m_i} \right]$$

$$\mu_i = \mu_i^* + \frac{1}{3} \frac{\partial m_I}{\partial \rho_b} \frac{\partial \Omega_o}{\partial m_I} \qquad k_{Fi} = \sqrt{\mu_i^{*2} - m_i^2} \qquad \rho_i = \frac{\gamma k_{Fi}^3}{6\pi^2} \qquad \rho_b = \frac{1}{3} \sum_i \rho_i$$

$$\Omega_{SQM} = -p_{SQM}$$

where $i = u, d, s$ and $\gamma = 6$;

Thermodynamic consistency

The conditions that guarantee the thermodynamic consistency of the model are:

$$\Delta_i \equiv \left.\frac{dS}{d\rho_i}\right|_{T,\ \{\rho_{k\neq i}\}} - \left.\frac{d\mu_i}{dT}\right|_{T,\ \{\rho_k\}} = 0$$

$$\Delta_{ij} \equiv \left.\frac{d\mu_i}{d\rho_j}\right|_{T,\ \{\rho_{k\neq j}\}} - \left.\frac{d\mu_j}{d\rho_i}\right|_{T,\ \{\rho_{k\neq i}\}} = 0$$

$$\Delta = p - \rho^2 \frac{d}{d\rho}\left(\frac{F}{\rho}\right)_T = 0$$

Stellar matter

- In order to describe strange stars we have to consider some features of stellar matter:
  - Zero temperature and high density;
  - Beta equilibrium: $\mu_u + \mu_e = \mu_d = \mu_s$ and $\mu_u^* + \mu_e = \mu_d^* = \mu_s^*$;
  - Weak interactions: $d, s \leftrightarrow u + e + \nu_e$;
  - Charge neutrality: $\frac{2}{3}\rho_u - \frac{1}{3}\rho_d - \frac{1}{3}\rho_s - \rho_e = 0$;
  - EOS with electrons contribution:

$$\varepsilon = \epsilon_{SQM} + \frac{\mu_e^4}{4\pi^2}, \qquad \text{and} \qquad p = p_{SQM} + \frac{\mu_e^4}{12\pi^2},$$

    - with $\mu_e = (3\pi^2 \rho_e)^{1/3}$;
    - p_{SQM} and ϵ_{SQM} are the EOS of quarks contribution.

Stability window

- According to Bodmer-Witten hypothesis, in order to SQM to be absolutely stable, it needs to fullfill the following conditions:
  - $(E/A)_{\text{min}} = (\mathcal{E}/\rho_b)_{\text{min}} \leqslant 930$ MeV for SQM;
  - $(E/A)_{\text{min}} = (\mathcal{E}/\rho_b)_{\text{min}} > 930$ MeV for 2QM;
- Quarks current mass are the ones most recent data provided by the Particle Data Group (PDG):
  - For stellar matter: $m_{u0} = 2.16$ MeV, $m_{d0} = 5.15$ MeV, and $m_{s0} = 90$ MeV.
- Applying all the above we constructed the stability window for stellar matter.

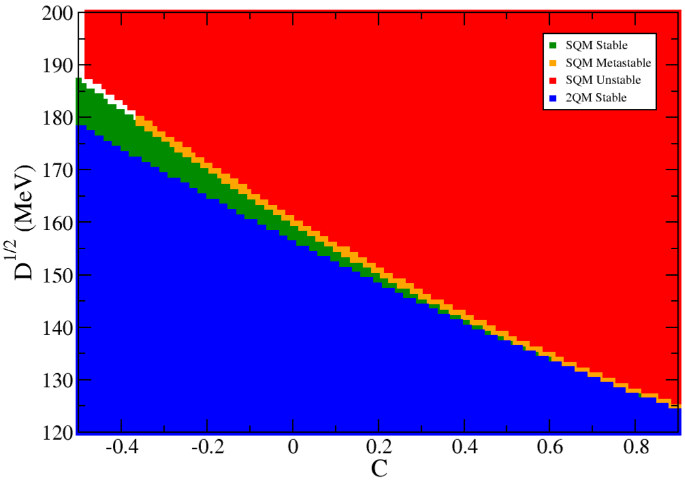

Figure: Stability window for stellar matter: EQP model.

DarK Matter

- Dark matter (DM) is thought to permeate throughout the universe, exerting gravitational effects on visible matter;
- It could be possible to have DM particles trapped within the intense gravitational fields of compact stars due to:
  - Its capture during formation;
  - Accretion;
  - Annihilation and heating;
- As a consequence, the presence of DM inside compact stars could influence its properties;
- In our current work we introduce the dark matter as a bosonic fluid in the EQP model in order to study its presence in strange stars;

Bosonic asymmetric dark matter

- Baryogenesis period: during the creation of matter-antimatter a slight asymmetry in the production of matter over antimatter occurred (allowing the formation of all the visible matter in the universe, such as: stars, galaxies, etc);
- Asymmetric dark matter could have occurred from a similar process (with DM being slight higher than anti-DM due to some fundamental differences in the interactions of dark matter particles compared to ordinary matter particles);
- This excess dark matter survived annihilation with dark antimatter and became the dark matter that we study today;
- This feature explains why DM interacts differently with ordinary matter;

- Compact stars are modeled from its equations of state introduced in the Tolman-Oppenheimer-Volkoff (TOV) equations;
- TOV equations provide us the mass-radius relation of compact stars that is calculated through the central density;
- To calculate the structure of compact stars with asymmetric dark matter, we treat the system as being composed by two separate fluids that only interact through gravity;

The equations concerning the two-fluid formalism are:

$$p(r) = p_{SQM}(r) + p_\chi(r) \qquad \epsilon(r) = \epsilon_{SQM}(r) + \epsilon_\chi(r)$$

$$\frac{d\alpha(r)}{dr} = \frac{1}{c^2}\frac{Gc^2M(r)+4\pi r^3 Gp(r)}{r[rc^2-2GM(r)]}$$

$$\frac{dp_{SQM}}{dr} = -(\epsilon_{SQM} + p_{SQM})\frac{d\alpha(r)}{dr} \qquad \frac{dp_\chi}{dr} = -(\epsilon_\chi + p_\chi)\frac{d\alpha(r)}{dr}$$

$$\frac{dM_{SQM}(r)}{dr} = 4\pi r^2 \frac{\epsilon_{SQM}(r)}{c^2} \qquad \frac{dM_\chi(r)}{dr} = 4\pi r^2 \frac{\epsilon_\chi(r)}{c^2}$$

where $M_\chi(r)$ = gravitational mass of ADM, $M_{SQM}(r)$ = gravitational mass of baryonic matter (SQM in this case) and $M(r) = M_{SQM}(r) + M_\chi(r)$;

We also need to define the ADM mass-fraction, F_χ, which is, the relative amount of gravitational mass of ADM compared to the total gravitational mass of the compact star:

$$F_\chi = \frac{M_\chi(R_\chi)}{M_\chi(R_\chi) + M_{SQM}(R_{SQM})}$$

where $M_\chi(R_\chi) =$ the total accumulated ADM gravitational mass evaluated at the ADM core radius and $M_{SQM}(R_{SQM}) =$ the baryonic matter gravitational mass evaluated at the baryonic radius.

Following, the EOS for the bosonic ADM are constructed to be:

$$\epsilon_\chi(r) = m_\chi c^2 n_\chi + \frac{g_\chi^2}{2m_\phi^2}\frac{\hbar^3}{c}n_\chi^2,$$

$$p_\chi(r) = -\epsilon_\chi + \widetilde{\mu}_\chi n_\chi = \frac{g_\chi^2}{2m_\phi^2}\frac{\hbar^3}{c}n_\chi^2,$$

$$\widetilde{\mu}_\chi(r) = \frac{\partial \epsilon_\chi}{\partial n_\chi}$$

where m_χ = ADM particle mass, n_χ = number density of ADM, $\widetilde{\mu}_\chi$ = ADM chemical potential (local Lorentz frame), and c, $\hbar$ and G are treated in natural units.

Constrains of ADM

The bosonic ADM EOS constraints are:

- To avoid the ADM particles from escaping the compact star $m_\chi \geq 10^{-2}$ MeV and $m_\chi \leq 10^8$ MeV (we chose $m_\chi = 15.10^3$ MeV);
- The effective self-interaction strength are captured in the range $10^{-2} \leq \frac{g_\chi}{m_\phi/MeV} \leq 10^3$ (we chose $\frac{g_\chi}{m_\phi/MeV} = 0.1$);
- In order to obtain the EOS of the dark matter contribution we consider $\epsilon_\chi(r) = f.\epsilon_{SQM}$, where f indicates the fraction of dark matter energy density present in the strange quark matter energy density (f varies from 0.1 to 1.0);

Results

- The observational data in the mass-radius profiles are the ones provided by LIGO and Virgo Collaboration, and the NICER mission concerning the millisecond pulsars PSR J0030+0451, and PSR J0740+6620;
- We also include the recent observational data concerning the measurement of HESS J1731-347;

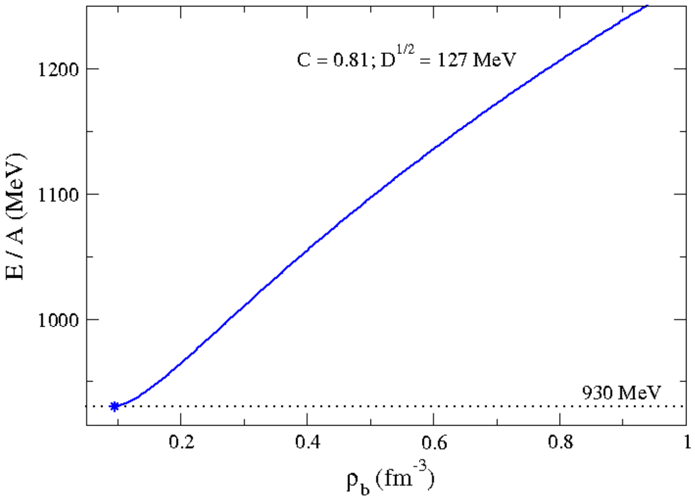

Figure: Thermodynamic consistency for stellar matter: EQP model.

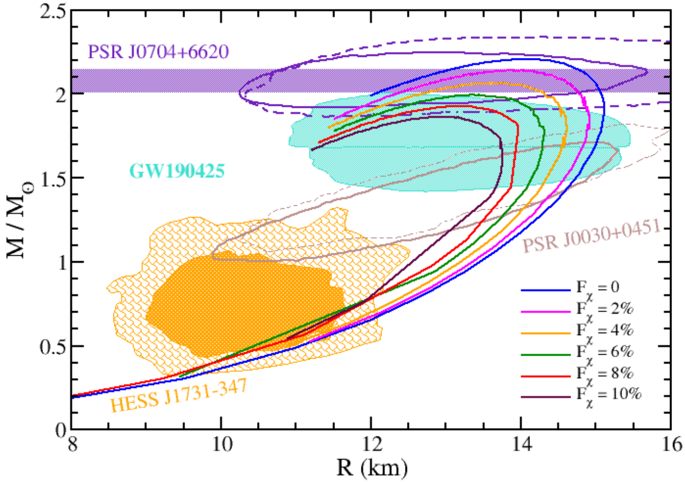

Figure: Mass-Radius profiles.

Future perspectives

- Apply the fermionic dark matter in the EQP model as proposed in the recent article "Exploring robust correlations between fermionic dark matter model parameters and neutron star properties: A two-fluid perspective";
- Discuss the results obtained from both proposals;

References

List of references

Last published article


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