Hybrid compact stars with a crossover equation of state

A. Lavagno

Department of Applied Science and Technology, Politecnico di Torino, I–10129, Torino
Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Torino, I–10126, Torino, Italy

Politecnico di Torino

Abstract

Similar to the crossover phase transition in lattice QCD, at high temperature and small baryon chemical potential, recently, the structure of neutron stars have been studied with a crossover equation of state to model a smooth transition from a pure neutron matter to massless quarks [1]. The switch function, that guides the crossover, was constrained in order to reproduce neutron stars up to about two solar masses. Afterwards, such a study has been extended by considering the relevance of color superconducting massless quarks in the cold dense matter [2]. In this contribution, we investigate the hadron to quark crossover transition by means of an equation of state which incorporates hadronic matter, composed by nucleons, hyperons and Δ-isobars, unpaired quark matter with massive strange quarks, including first-order α_s strong interaction.The beta-stability and the charge neutrality result to be globally respected during the crossover with the inclusion of the leptons degrees of freedom. In this framework, we analyze the role of the strangeness content related to the bulk properties of the compact star.

Crossover Equation of State

We are going to study the crossover transition from hadronic nuclear matter (H) to quark matter (Q) by imposing β-stability and charge neutrality conditions. Following Ref. [1], the crossover feature is mimic by

$$P_{HQ}(\mu_B,\mu_C) = [1-S(\mu_B)]\, P_H(\mu_B,\mu_C) + S(\mu_B)\, P_Q(\mu_B,\mu_C)\,, \qquad (1)$$

where the switch function is defined as [1,2]

$$S(\mu_B) = \exp[-(\mu_0/\mu_B)^r]\,, \qquad (2)$$

(in this investigation we neglect possible dependence on the electric charge chemical potential μ_C and/or on the isospin chemical potential μ_I).

P_H is the hadronic pressure obtained from the scheme of the SFHo relativistic mean-field (RMF) model [3] by including the full octect of the lightest baryons: p, n, Λ, Σ^+, Σ^0, Σ^-, Ξ^0, Ξ^- and the $\Delta(1232)$-isobar degrees of freedom. P_Q is the quark pressure in an extended Bag model including first-order $\alpha_s = \pi/2(1-a_4)$ strong nonperturabative interaction and massive strange quark (m_s =100 MeV) [4].

The thermodynamic description of the system is obtained from the relations for the baryon density

$$\rho_B(\mu_B,\mu_C) = \frac{\partial P}{\partial \mu_B}\Big|_{\mu_C} = (1-S)\,\rho_B^H + S\,\rho_B^Q + (P_Q - P_H)\,\frac{\partial S}{\partial \mu_B}\,, \qquad (3)$$

the charge density

$$\rho_C(\mu_B,\mu_C) = \frac{\partial P}{\partial \mu_C}\Big|_{\mu_B} = (1-S)\,\rho_C^H + S\,\rho_C^Q + (P_Q - P_H)\,\frac{\partial S}{\partial \mu_C}\,, \qquad (4)$$

and the energy density

$$\epsilon_{HQ} = -P_{HQ} + \mu_B\,\rho_B + \mu_C\,\rho_C\,. \qquad (5)$$

Moreover, we have to require the charge neutrality

$$\rho_C(\mu_B,\mu_C) = \rho_e(\mu_e)\,, \qquad (6)$$

and the β-stability condition: $\mu_C = -\mu_e$. Finally, we have $P = P_{HQ} + P_e$ and $\epsilon = \epsilon_{HQ} + \epsilon_e$.

The crossover and, as a consequence, the parameters of the switch function S, are fixed so that the pressure must be convex for all μ_B [5]

$$\partial^2 P/\partial \mu_B^2 = \partial \rho_B/\partial \mu_B > 0\,. \qquad (7)$$

In addition, the adiabatic sound velocity

$$c_s = \sqrt{\partial P/\partial \epsilon} = \sqrt{\partial \ln \mu_B/\partial \ln \rho_B}\,, \qquad (8)$$

cannot exceed the speed of light, c.

Results

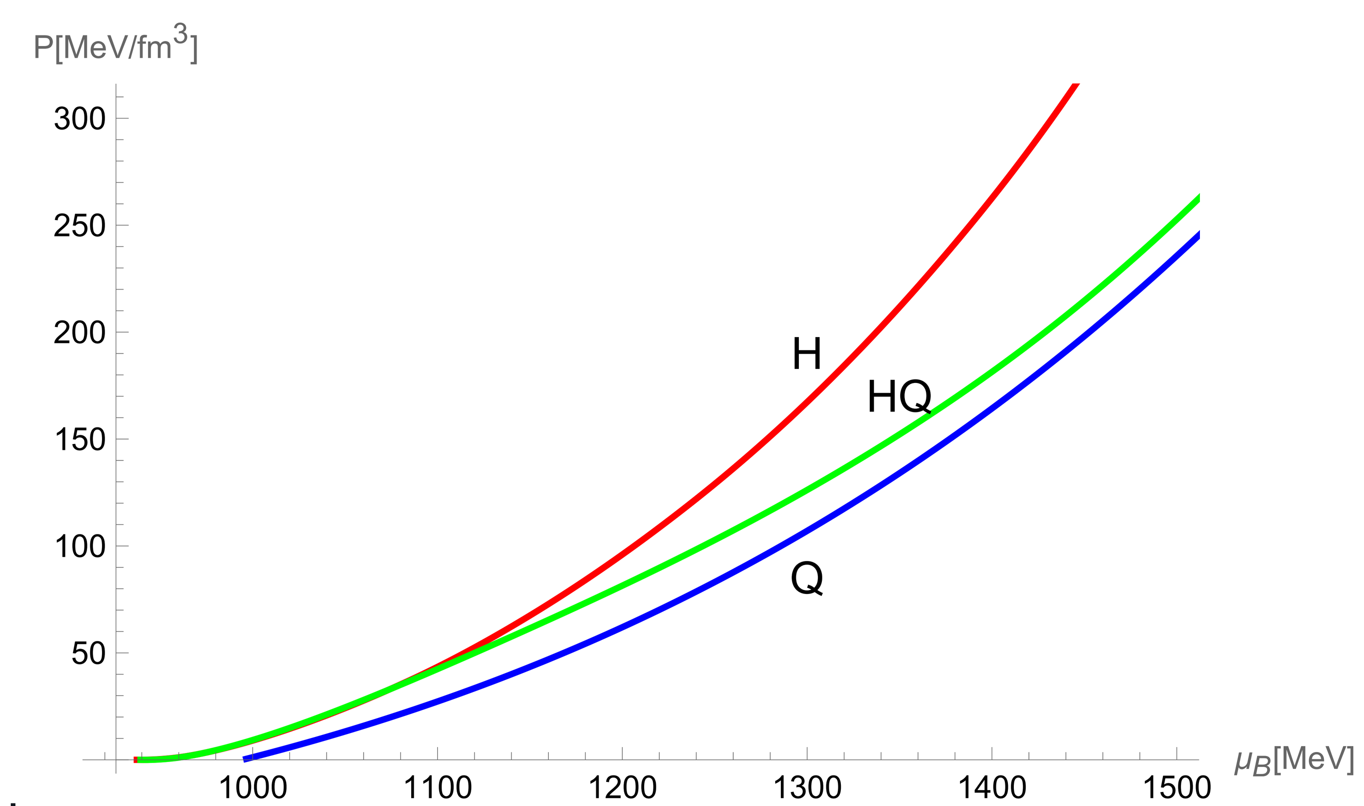

Fig. 1: Pressure as a function of the baryon chemical potential for the hadronic phase H, the pure quark phase Q and the mixed hadron-quark (HQ) crossover EOS

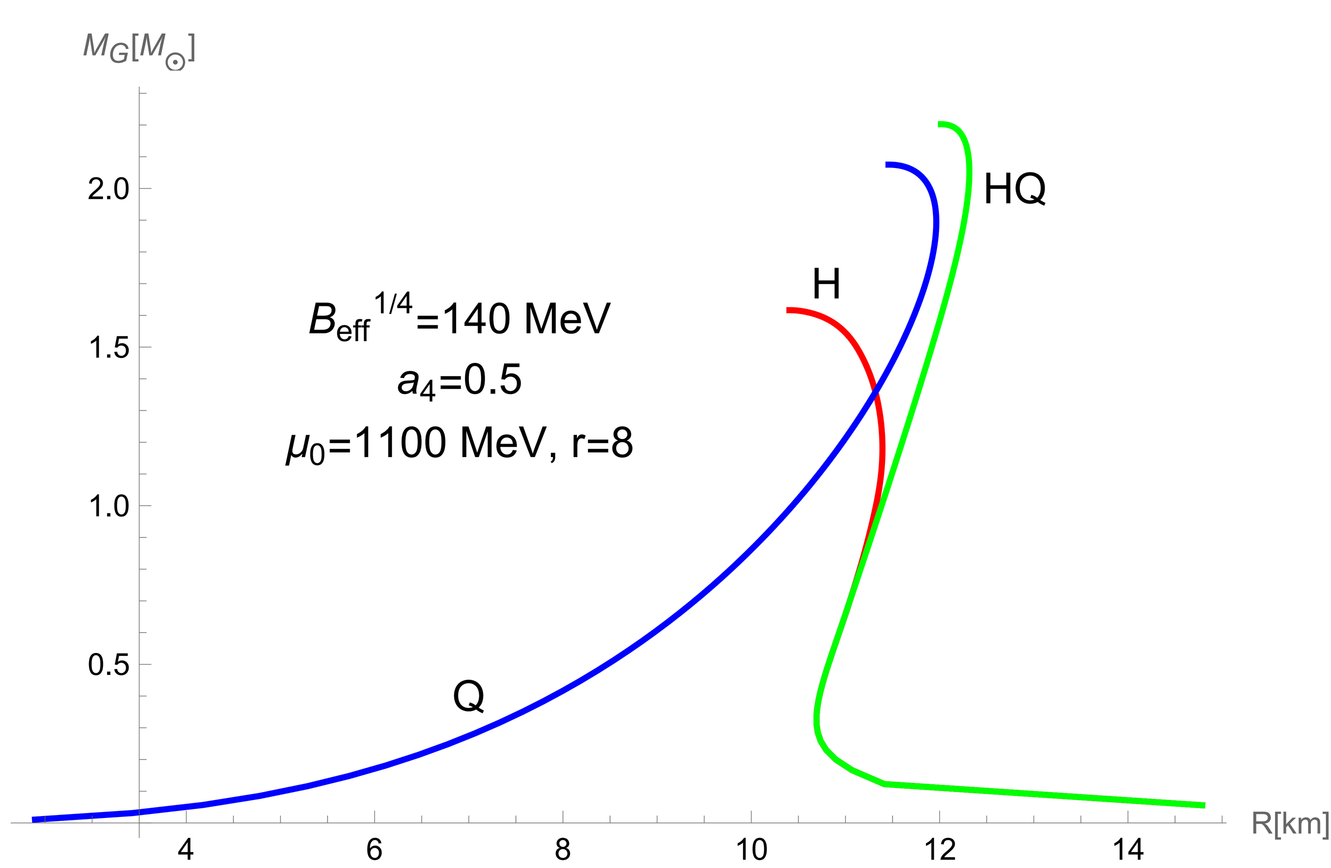

Fig. 2: Mass vr. radius for the hadronic phase H, the pure quark phase Q and the mixed hadron-quark (HQ)

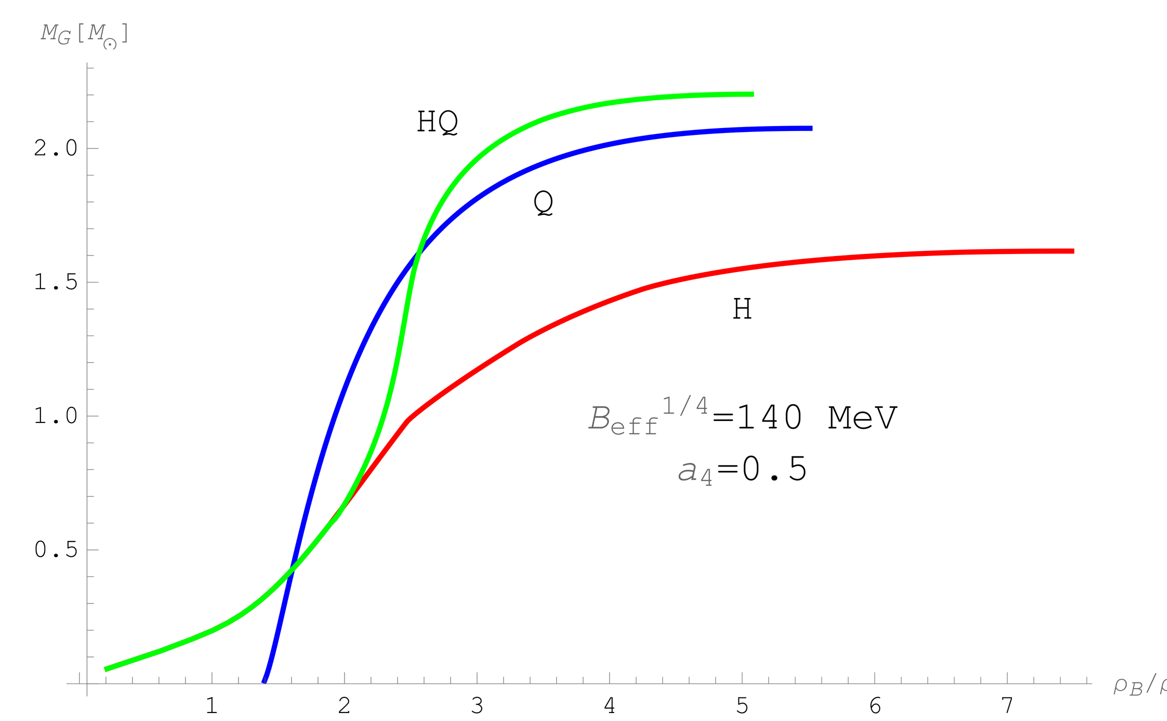

Fig. 3: Mass as a function of the central baryon density for the hadronic phase H, the pure quark phase Q and the mixed hadron-quark (HQ)

Remarks

We have studied the crossover EOS of hybrid compact stars, composed by nucleons, hyperons, Δ-isobars and quarks matter with nonperturbative effects. It is well known that adding degrees of freedom softens the equation of state, this makes it difficult to make massive neutron stars in presence of hyperons and Δ-isobars [7]. As discussed in Ref. [8], this problem could be overcome in the scenario of two coexisting families of compact stars: hadronic stars, whose EOS is soft, can be very compact with small radii and with maximum masses of about 1.5 $M_\odot$, while massive strange quark stars, whose EOS is stiff, with masses greater than 2 $M_\odot$. We have seen that massive compact stars configurations can be realized for a particular crossover EOS in presence of strong nonperturbative effects. In this context, let us remember that we are considering a system with two conserved charges, in this case the dynamics of the phase transition is more complex with respect to the one (baryon) conserved charge (related to the crossing of the hadron and quark curves in the $P-\mu_B$ plane).

We are planning to extend this preliminary investigation by taking into account color superconducting quarks effects and the role of isospin asymmetry in the crossover switch function.

References

[1] J.I. Kapusta, T. Welle, Phys. Rev. C 104, L012801 (2021)
[2] D. Blaschke, E.-O. Hanu, S. Liebing, Phys. Rev. C 105, 035804 (2022)
[3] A.W. Steiner, M. Prakash, J.M. Lattimer, P. Ellis, Phys. Rep. 411, 325 (2005)
[4] S. Weissenborn et al., ApJ 740, L14 (2011)
[5] G. Baym et al, ApJ 885, 42 (2019)
[6] C. Costantinou et al., Phys. Rev. D 104, 123032 (2021)
[7] A. Drago, A. Lavagno, G. Pagliara, Phys. Rev. C 90, 065809 (2014)
[8] A. Drago, A. Lavagno, G. Pagliara, D. Pigato, Phys. Rev. D 89, 043014 (2014)