Strange quark matter from a baryonic approach

Eduardo S. Fraga, Rodrigo da Mata, Savvas Pitsinigkos and Andreas Schmitt

Introduction

We present a baryon-meson model for cold, dense matter. The model exhibits spontaneous chiral symmetry restoration at higher densities. We will use this phase transition to describe nuclear matter (chirally broken phase) and to model quark matter (chirally restored phase). This work expands on the model of [1, 2] with the inclusion of hyperons. Hyperons, in the chirally restored phase, allow us to introduce strangeness in that phase, making the quark matter interpretation more realistic.

This single model approach paves the road for the calculation of the surface tension in a nuclear-quark matter interface and also for the exploration of possible inhomogeneous phases, such as pasta phases or the chiral density wave, in compact star conditions.

The model

The Lagrangian of the model is written $\mathcal{L} = \mathcal{L}_B + \mathcal{L}_M + \mathcal{L}_I$ where:

$$\mathcal{L}_B = \sum_i \bar{\psi}_i (i\gamma^\mu \partial_\mu + \gamma^0 \mu_i)\psi_i \tag{1}$$

The sum is over the baryon octet, $i = n, p, \Sigma^0, \Sigma^-, \Sigma^+, \Lambda, \Xi^0, \Xi^-$ and there are no explicit mass terms. Baryon mass is generated by the chiral condensate $\sigma \sim \langle u\bar{u} + d\bar{d}\rangle$. The mesonic part is:

$$\begin{aligned}\mathcal{L}_M =& \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} - \frac{1}{4}\rho^0_{\mu\nu}\rho_0^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\mu + \frac{m_\phi^2}{2}\phi_\mu\phi^\mu \\ &+ \frac{m_\rho^2}{2}\rho^0_\mu\rho_0^\mu + \frac{d}{4}(\omega_\mu\omega^\mu + \rho^0_\mu\rho_0^\mu + \phi_\mu\phi^\mu)^2\end{aligned} \tag{2}$$

where:

$$U(\sigma) = \sum_{n=1}^{4} \frac{a_n}{n!}\frac{(\sigma^2 - f_\pi^2)^n}{2^n} - \epsilon(\sigma - f_\pi) \tag{3}$$

Finally, the interactions are:

$$\mathcal{L}_I = -\sum_i \bar{\psi}_i (g_{i\sigma}\sigma + g_{i\omega}\gamma^\mu\omega_\mu + g_{i\rho}\gamma^\mu\rho^0_\mu + g_{i\phi}\gamma^\mu\phi_\mu)\psi_i \tag{4}$$

We relate the free parameters in the model with vacuum quantities and properties of symmetric nuclear matter at saturation:

- Vacuum masses of particles.
- Pion decay constant $f_\pi = 92.4$ MeV.
- Binding energy $E_B = -16.3$ MeV and density $n_0 = 0.153\ \mathrm{fm}^{-3}$ of nuclear matter at saturation.
- Incompressibility $K \simeq (200-300)$ MeV, symmetry energy $S \simeq (30.2-33.7)$ MeV and slope parameter $L \simeq (40-140)$ MeV [3] of symmetry energy at saturation.
- Effective nucleon mass at saturation $M_0 \simeq (0.7-0.8)m_N$.
- Hyperon potential depths in symmetric nuclear matter at saturation [$U_\Lambda^{(N)} = -30$ MeV, $U_{\Sigma,\Xi}^{(N)} \simeq -70$ MeV to $+30$ MeV].

We keep most of these fixed and explore the $\{L,\ M_0,\ U_{\Sigma,\Xi}^{(N)}\}$ parameter space. We study specific parameter choices, and then systematically constrain the parameter space.

Specific cases

We note some aspects specific to the single model approach:

- The critical chemical potential of the chiral phase transition can be calculated (see *left* of Fig. 1).
- The nuclear matter branch stops at some μ_n (implications for stars).

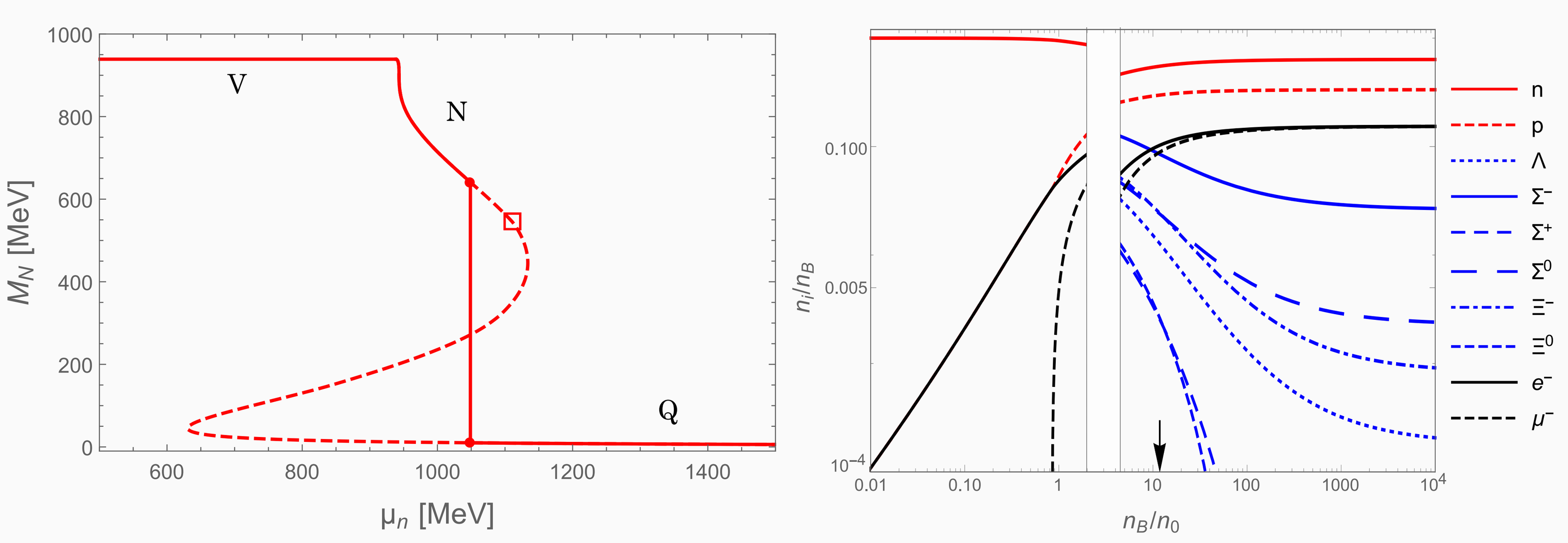

Fig. 1: *Left:* The effective nucleon mass through the chiral phase transition (vertical segment). Solid line indicates the stable phases. The open square marks the onset of strangeness. The different phases are also marked (V - vacuum, N - nuclear, Q - quark/chirally symmetric).
Right: Density fractions as a function of the baryon density: baryons (red), hyperons (blue) and leptons (black). The gap indicates the density jump associated with the chiral phase transition.

With Fig. 1 in mind, we can note the qualitatively different cases:

- Hyperon onset is dynamic and can be on either side of the chiral phase transition.
- This affects whether hyperons or strangeness in general appears in stars.
- We also encounter a chiral crossover for some parameter choices.

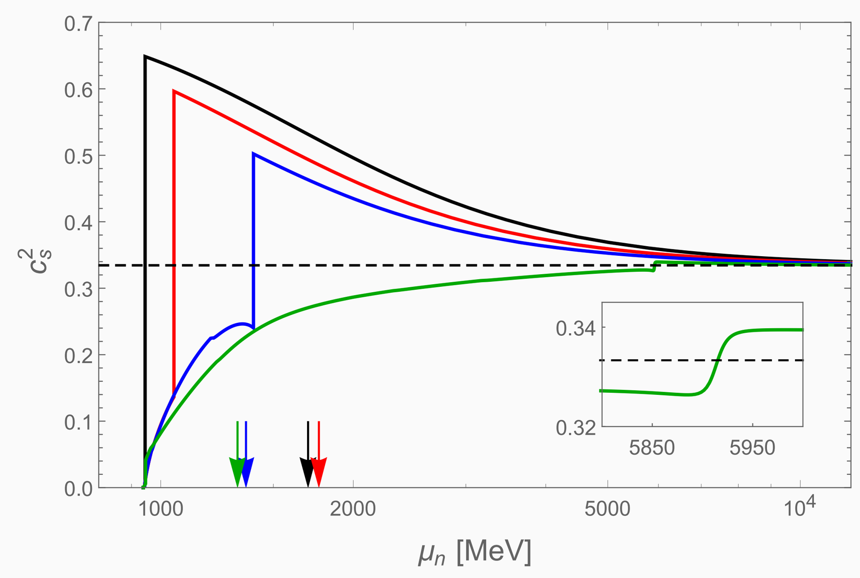

Fig. 2: Speed of sound for qualitatively different scenarios in the parameter space. Maximum chemical potential in a compact star marked with an arrow. Green is a chiral crossover case. Red corresponds to Fig. 1.

A large speed of sound is necessary to support high mass compact stars.

In our model this is achieved by the transitioning to the strongly interacting chirally symmetric phase, which has a high speed of sound $c_s^2 \sim 0.6c^2$.

This stiff phase occupies the largest volume fraction of our heavy stars.

Notice that always $c_s^2 \to \frac{1}{3}$, matching the QCD result.

Full parameter space

To constrain our parameter space, we require our model to fulfil the following:

- Stability of nuclear matter at zero pressure.
  We need the hadron-quark transition to exist.
- Strangeness in the form of chirally restored hyperons at asymptotic density.
  We expect quark matter to have strangeness asymptotically.
- Realistic neutron star masses.
  Observational constraint.

The regions that do so, are shaded with color in Fig. 3:

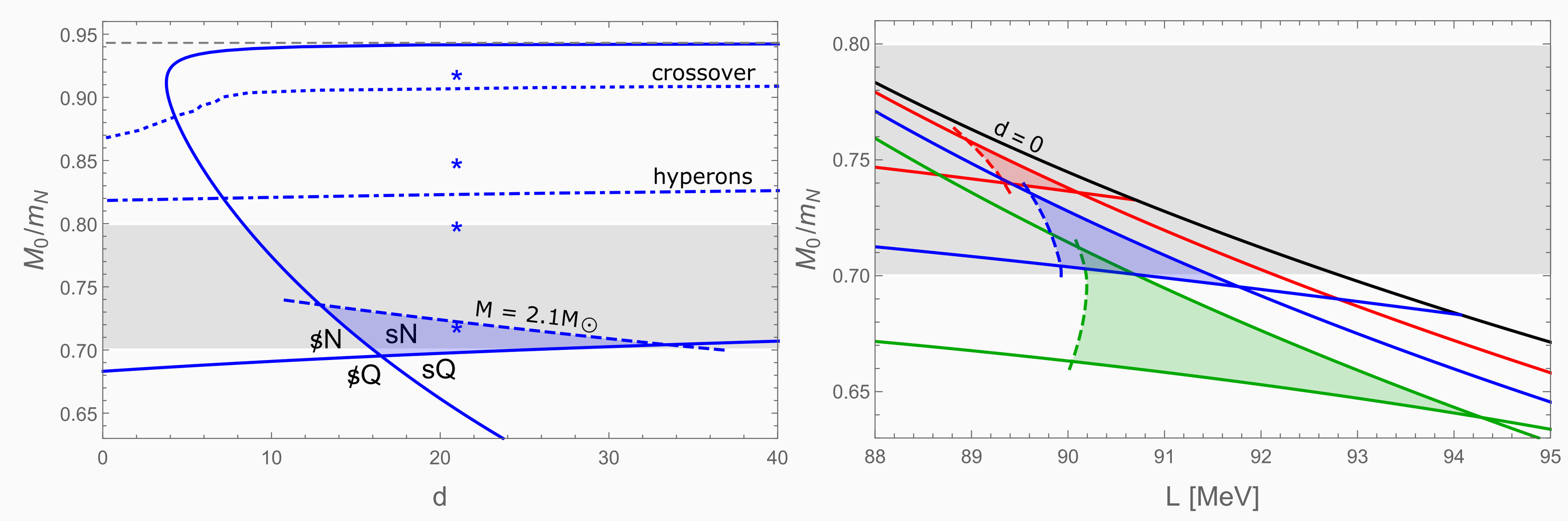

Fig. 3: Allowed regions (for the constraints discussed) shaded with color. Gray shading for the empirical M_0 range.
Left: Slope parameter L is re-parametrized by d. Chiral crossover region and hyperon appearance marked with dashed(-dotted) lines. Asterisks mark the 4 cases of Fig. 2 (green, blue, red, black from top to bottom).
Right: The same region in the $L - M_0$ parametrization now. Regions for alternative hyperon potential depths also plotted (green $U_{\Sigma,\Xi}^{(N)} = -30$ MeV, blue $U_{\Sigma,\Xi}^{(N)} = -50$ MeV, red $U_{\Sigma,\Xi}^{(N)} = -70$ MeV).

From these plots we can deduce the following conclusions:

- The slope parameter is significantly constrained within this model $L \simeq (88-92)$ MeV varying only a little with different $U_{\Sigma,\Xi}^{(N)}$ choices.
- The chiral crossover case is incompatible with the current observational limits on neutron star masses.
- Existence of hyperons (in their chirally broken, baryonic phase) is also disfavoured. An early chiral phase transition prevents their appearance and provides a resolution to the hyperon puzzle [4].

References

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