Lepton-Rich Cold Quark Matter

José C. Jiménez   Eduardo S. Fraga

Instituto de Física
Universidade Federal do Rio de Janeiro

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Content

Introduction

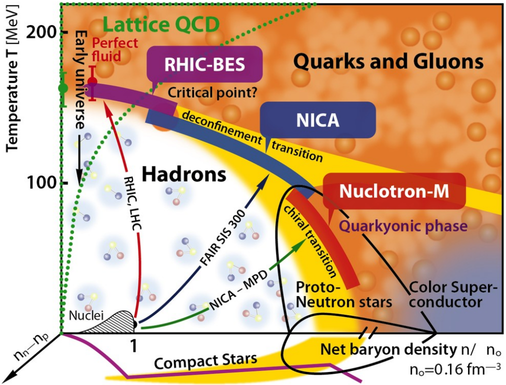

Figure : QCD phase diagram for strong interactions [NICA].

Introduction

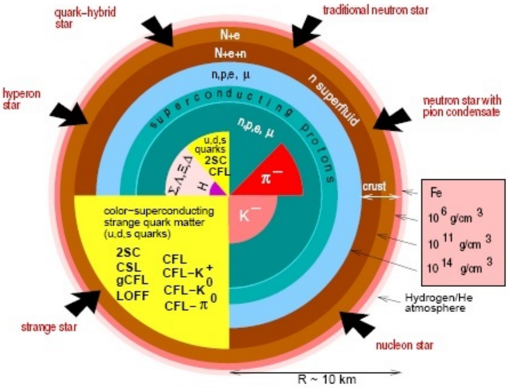

Figure : Possible neutron star interior [Weber, 1999].

Lepton-poor pQCD EoS: Cold NSs [Kurkela *et al.*, 2010]

Under the constraints of *local* charge neutrality

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = 0$$

and β-equilibrium

$$\mu_s = \mu_d \equiv \mu,$$

$$\mu_u = \mu - \mu_e,$$

one can write the total pressure as

$$P(\mu, X) = \int_{\mu_0(X)}^{\mu} d\bar{\mu} \left[n_u \left(1 - \frac{d\mu_e}{d\mu_s} \right) + n_d + n_s + n_e \frac{d\mu_e}{d\mu_s} \right] .$$

where $X = 3\bar{\Lambda}/\mu_B$.

Lepton-poor pQCD EoS: Kurkela-Romatschke-Vuorinen

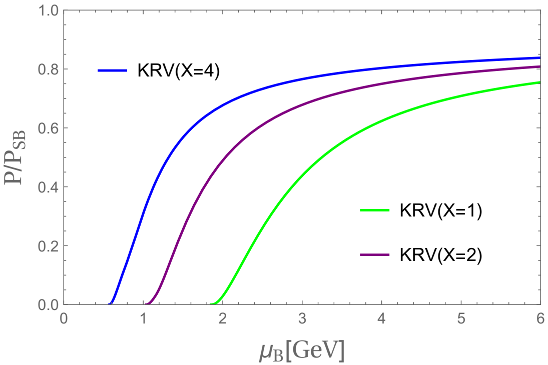

Figure : Total pressure of quarks and electrons normalized by the Stefan-Bolztmann free gas [Kurkela *et al.*, 2010].

Lepton-poor pQCD EoS: Pocket formula

One can write the total cold pressure as

$$P_{QCD}(\mu_B, X) = P_{SB}(\mu_B)\left(c_1 - \frac{a(X)}{(\mu_B/GeV) - b(X)}\right)$$

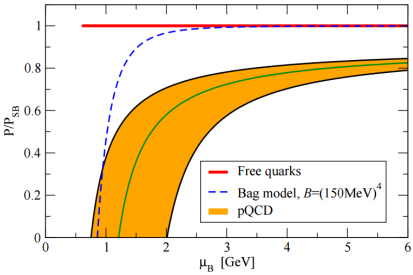

Figure : Normalized pressure of quarks and electrons [Fraga *et al.*, 2014].

Protoneutron star matter

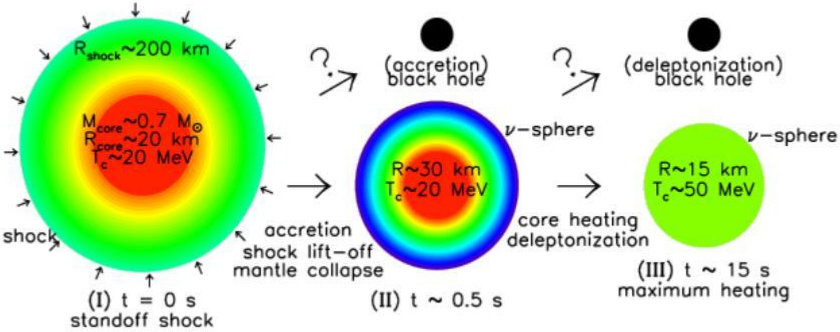

Figure : Core-collapse supernovae explosion [Pons *et al.*, 2001].

Lepton-rich pQCD EoS: Input

- *Local* Charge Neutrality:

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s = n_e^Q.$$

- Weak equilibrium :

$$\mu_d + \mu_\nu^Q = \mu_u + \mu_e^Q, \quad \mu_d = \mu_s.$$

- *Local* Lepton fraction conservation of $Y_L = 0.4$.
- Then the total pressure of quarks and leptons is

$$P(\mu, X) = \int_{\mu_0(X)}^{\mu} d\bar{\mu} \left[n_u \left(1 + \frac{d\mu_\nu}{d\mu_s} - \frac{d\mu_e}{d\mu_s} \right) + n_d + n_s + n_e \frac{d\mu_e}{d\mu_s} + n_\nu \frac{d\mu_\nu}{d\mu_s} \right].$$

Lepton-rich pQCD EoS: Output

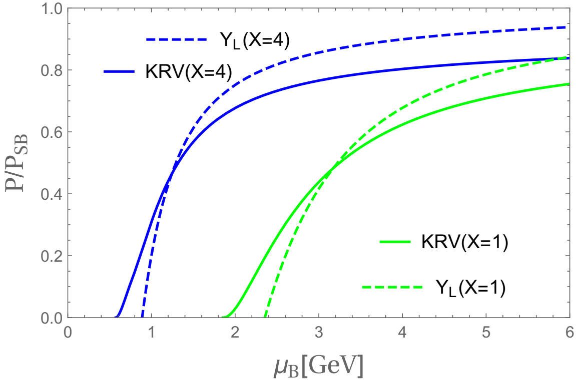

Figure : Normalized total pressure of quark and leptons, parametrized only by X [Jiménez and Fraga, 2018].

Lepton-rich Bodmer-Witten hypothesis

One can find stable configurations of stable strange quark matter if, at $P = 0$, one has

$$E/A \leq 0.93\mathrm{GeV}.$$

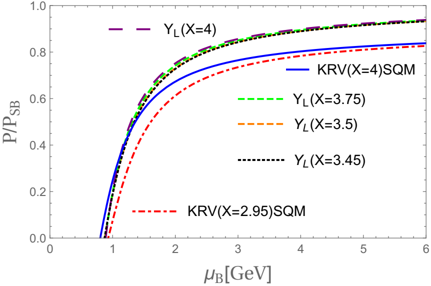

Figure : Reduced SQM configurations [Jiménez and Fraga, 2018]

Application: Lepton-rich pQCD nucleation

- **Thermal nucleation** In the *thin-wall approximation*, the rate of nucleation of critical bubbles, per unit volume, per unit time is:

$$\Gamma = T^4 \exp\left[-\frac{16\pi}{3}\frac{\sigma^3}{(\Delta P)^2 T}\right] \qquad \text{[Mintz \textit{et al}, 2010].}$$

- **Nucleation time** The time it takes for the nucleation of *one single critical bubble* inside a volume of $1km^3$ inside the core of the protoneutron star:

$$\tau \equiv \left(\frac{1}{1km^3}\right)\frac{1}{\Gamma}.$$

Lepton-poor astrophysical constraint

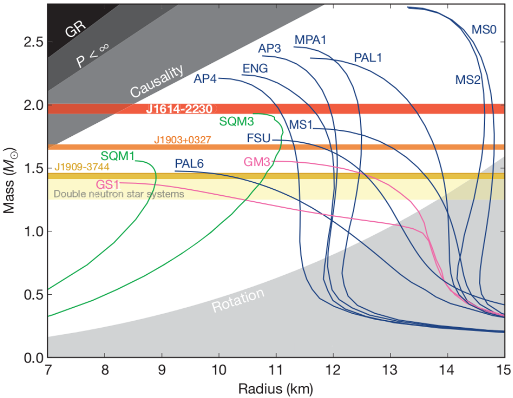

Figure : Mass-Radius relations for recent measurements of neutron stars in binary systems [Demorest, 2010].

Lepton-rich constrained band EoS

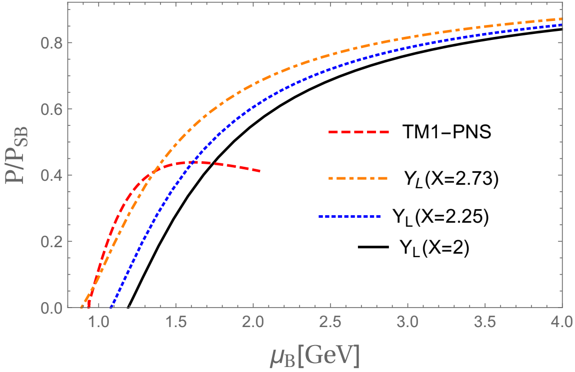

Figure : Allowed values of X to nucleate unpaired quark matter satisfying astrophysical constraints [Jiménez and Fraga, 2018].

Lepton-rich exploration of parameter space

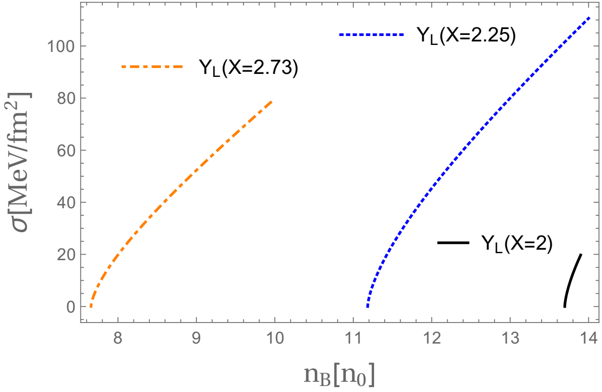

Figure : Contour lines for the surface tension varying X for a nucleation time of $\tau = 100$ms [Jiménez and Fraga, 2018].

Summary

- We have explored protoneutron star matter in the framework of perturbative QCD.
- Stable strange quark matter have a more restricted parameter space due to presence of trapped neutrinos in the system.
- Need of nonperturbative techniques for QCD at finite density and astrophysical observables like, e.g., gravitational waves.

Thanks !