Hybrid Stars: Bayesian Approach with NJL

†Milena Albino, Constança Providência, Tuhin Malik, Márcio Ferreira

CFisUC, Department of Physics, University of Coimbra, 3004-516 Coimbra, Portugal.

Abstract

Neutron stars are the most compact objects in the Universe. The core composition of these extremely compact objects remains a mystery. One possibility is that the core has such high densities that matter can deconfine into quark matter. If this is the case, then neutron stars are hybrid stars: neutron stars with a quark core surrounded by a hadron crust. In this paper, we investigate this using a Bayesian approach. The quark phase of our model is described by the Nambu-Jona-Lasinio (NJL) Lagrangian with some additional interaction terms. For the hadron phase, we use the relativistic mean-field model. Furthermore, the Bayesian approach allows us to obtain numerous equations of state satisfying some imposed constraints (such as observational data). In some sets of equations we have also imposed a constraint coming from pQCD calculations. Our results show that hybrid stars are able to satisfy the observational data. We also show that the pQCD constraint can have an effect on the results.

Equation of State

To obtain equations of state that describe a quark-hadron phase transition, we applied the Maxwell construction. For the quark phase, we used the Nambu-Jona-Lasinio (NJL) model. This is an effective theory of QCD that reproduces all the QCD symmetries. The NJL Lagrangian can be written as

$$\begin{aligned}\mathcal{L} &= \bar{\psi}\left(i\partial\!\!\!/ - m + \mu\gamma^0\right)\psi \\ &+ \frac{G}{2}\left[\left(\bar{\psi}\lambda_a\psi\right)^2 + \left(\bar{\psi}i\gamma^5\lambda_a\psi\right)^2\right] \\ &+ \mathcal{L}_{\text{'t Hooft}} + \mathcal{L}_I,\end{aligned}$$

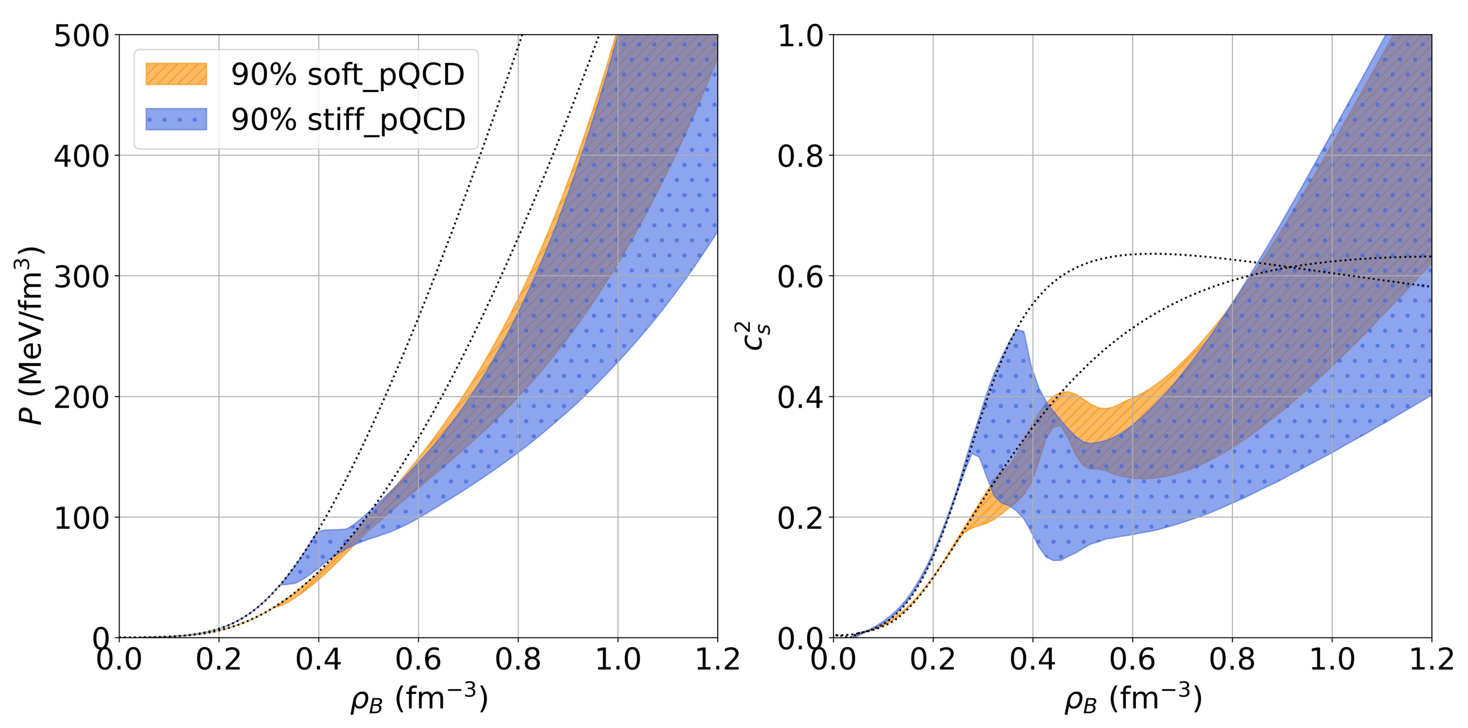
where we added the 't Hooft term to explicitly break the $U_A(1)$ symmetry,

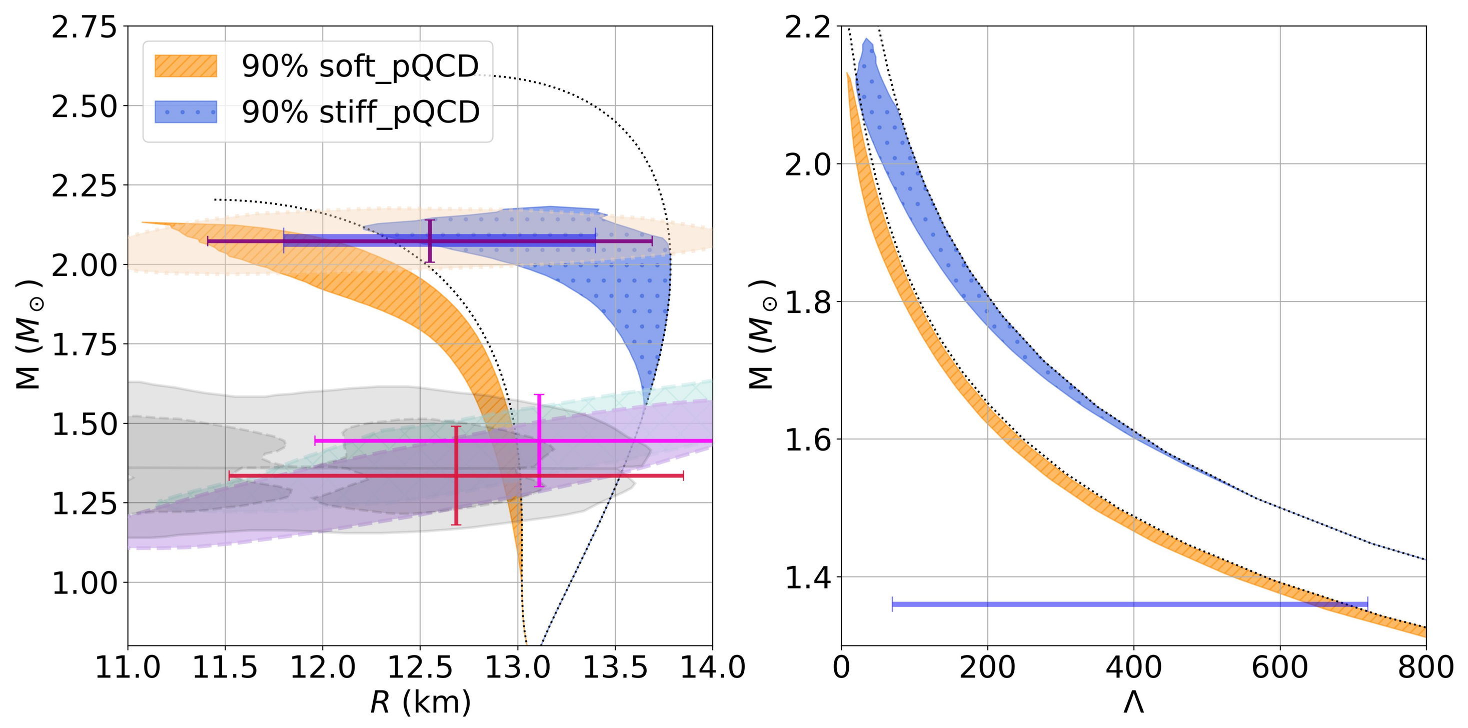
$$\mathcal{L}_{\text{'t Hooft}} = 8\kappa\left[\det\left(\bar{\psi}P_R\psi\right) + \det\left(\bar{\psi}P_L\psi\right)\right],$$

and also some interaction terms:

$$\begin{aligned}\mathcal{L}_I = &-G_\omega\left[\left(\bar{\psi}\gamma^\mu\lambda_0\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda_0\psi\right)^2\right] \\ &- G_\rho\sum_{a=1}^{8}\left[\left(\bar{\psi}\gamma^\mu\lambda^a\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda^a\psi\right)^2\right] \\ &- G_{\omega\omega}\left[\left(\bar{\psi}\gamma^\mu\lambda_0\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda_0\psi\right)^2\right]^2 \\ &- G_{\sigma\omega}\sum_{a=0}^{8}\left[\left(\bar{\psi}\lambda_a\psi\right)^2 + \left(\bar{\psi}i\gamma^5\lambda_a\psi\right)^2\right]\left[\left(\bar{\psi}\gamma^\mu\lambda_0\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda_0\psi\right)^2\right] \\ &- G_{\rho\omega}\sum_{a=1}^{8}\left[\left(\bar{\psi}\gamma^\mu\lambda_0\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda_0\psi\right)^2\right]\left[\left(\bar{\psi}\gamma^\mu\lambda_a\psi\right)^2 + \left(\bar{\psi}\gamma^\mu\gamma_5\lambda_a\psi\right)^2\right].\end{aligned}$$

We also added a constant term in the pressure in a similar way to the MIT bag model. The coupling (G's) and the bag term are our free parameters (6 parameters, in total). For the hadron phase, we obtained two equations from [1] - a soft (BMPF 220) and a stiff (BMPF 260) equation. These equations were obtained through the relativistic mean field model with non-linear meson interactions [1].





Bayesian approach

For all the sets, we imposed the following:

- phase transition should be around $1.4\rho_0$, where $\rho_0 = 0.16$ fm^{-3} is the nuclear saturation density;
- mass-radius diagram should satisfy the NICER data from PSR J0030+0451 and PSR J0740+6620;
- equations should also satisfy the Ligo-Virgo observations from GW170817.

In [2], the authors noted that pQCD calculations may have an influence in the region of neutron star density. To see how this constrains our equations, we also imposed this

- pQCD constraint*.

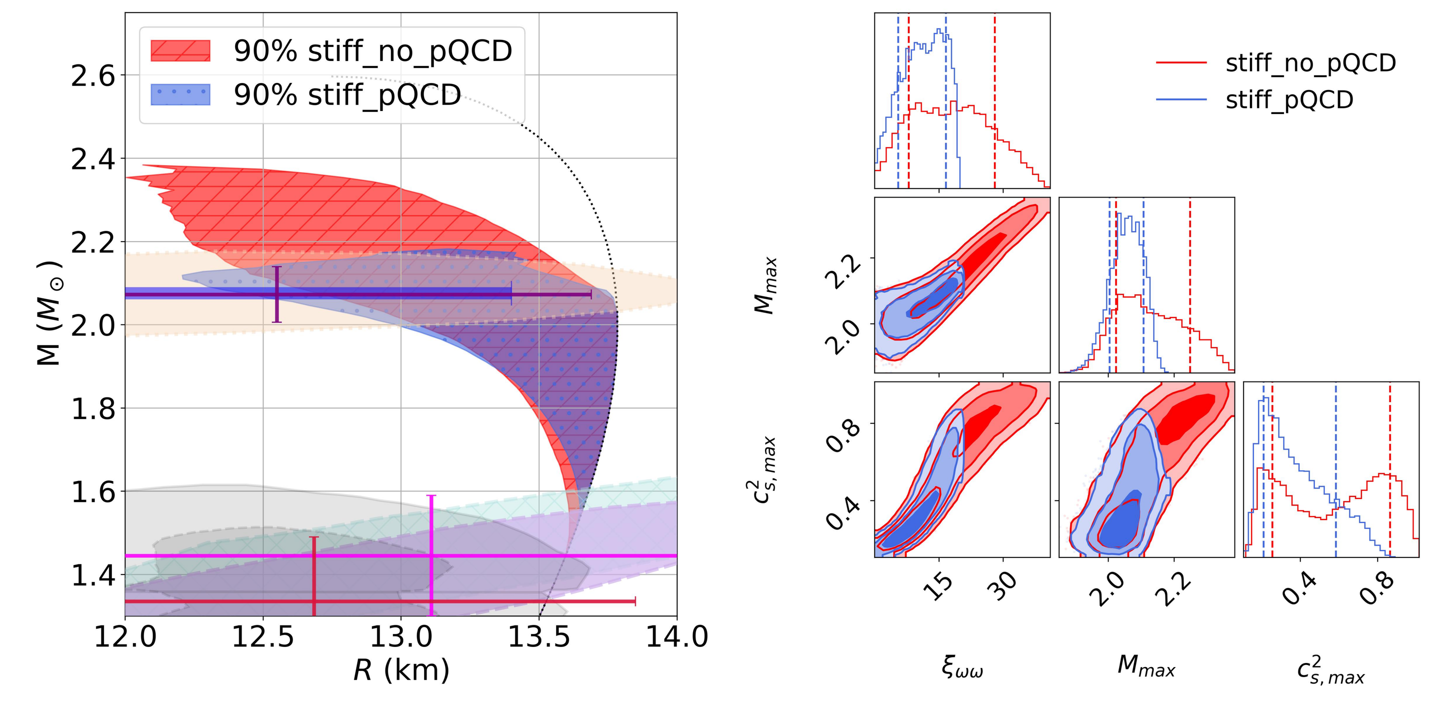
*This restriction is applied only for the "soft_pQCD" and "stiff_pQCD" sets.

Results

We obtained four sets in total:

	with pQCD	without pQCD
soft		
stiff		

The set of 'soft_no_pQCD' (without pQCD constraint) is not shown here, since these results are similar to the set of 'soft_pQCD' (with pQCD constraint). In the plots, the dotted lines show the hadronic equations. The mass-radius plots also represent the observational data: GW170817 (gray), PSR J0030+0451 (green and purple), and PSR J0740+6620 (yellow).



Conclusions

We conclude that:

- hybrid stars are able to satisfy the observational data;
- the pQCD calculation limits the $G_{\omega\omega}$ parameter, resulting in a smaller maximum mass (M_{max}) and a lower speed of sound in M_{max}.

In the future, instead of using a fixed hadronic equation, we will implement the Bayesian approach also in the hadronic phase. This will cover all possibilities of our hybrid model. We also plan to compare with the pure hadron model to determine whether neutron stars are more likely to be hybrid stars or made entirely of hadron matter.

[1] Tuhin Malik, Márcio Ferreira, Milena Bastos Albino and Constança Providência. "Spanning the full range of neutron star properties within a microscopic description". In: Physical Review D 107.10 (May 2023). DOI: 10.1103/physrevd.107.103018.

[2] Oleg Komoltsev and Aleksi Kurkela. "How Perturbative QCD Constrains the Equation of State at Neutron-Star Densities". In: Physical Review Letters 128.20 (May 2022). DOI: 10.1103/physrevlett.128.202701.

†milena.albino@student.uc.pt