Cross-Collserola PhD Meeting

Massive Compact Stars as Hybrid Stars

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Introduction

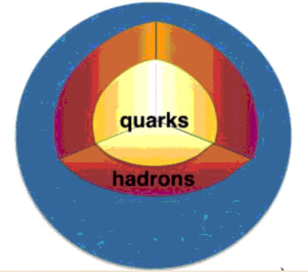
- Neutron Stars, or Compact Stars, are the end result of the stellar evolution where the initial mass was $8M_\odot \lessapprox M_{initial} \lessapprox 25M_\odot$;
- We can measure its mass and radius, but not its composition;
- So we construct EoSs that describe properly the nuclear matter and also reproduce Compact Stars with the masses and radius that have been measured;
- But are this Compact Stars Hadron Stars, Quark Stars or maybe Hybrid Stars?

Maybe Hybrid

The most massive NS we know of:

- PSR J0740+6620 → $M=2.072^{+0.067}_{-0.066}\,M_\odot$ and radius between 11.41 km and 13.70 km;
- PSR J0952-0607 → $M=2.35\pm0.17M_\odot$.

According to asymptotic freedom, the quarks may deconfine at very high energies or very high densities.



Hadronic Matter

Relativistic Mean Field QHD model

To describe the hadronic matter we use the Walecka Model with non-linear terms (NLWM):

$$
\begin{aligned}
\mathcal{L} = \sum_B \overline{\psi}_B[\gamma_\mu(i\partial^\mu - g_{B\omega}\omega^\mu - g_{B\rho}\frac{\vec{\tau}_B}{2}\vec{\rho}^\mu \\
- g_{B\phi}\phi^\mu) - m_B^*]\psi_B + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma \\
- \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3!}\kappa\sigma^3 - \frac{1}{4!}\lambda\sigma^4 \\
+ \frac{1}{2}m_\phi^2\phi_\mu\phi^\mu - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu \\
- \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu \\
+ \Lambda_v g_{N\omega}^2 g_{N\rho}^2\omega_\mu\omega^\mu\vec{\rho}_\mu\vec{\rho}^\mu,
\end{aligned}
$$

Figure: For more details see [1].

Model	NL3$^*\omega\rho$	Constraints
n_0 (fm^{-3})	0.150	0.148 - 0.170
E/A (MeV)	16.3	15.8 - 16.5
K (MeV)	258	220 - 260
M*/M	0.59	0.6 - 0.8
E_{sym} (MeV)	30.7	28.6 - 34.4
L (MeV)	42	36 - 86.8

Figure: Saturation density (n_0), energy per particle (E/A), compressibility (K), and effective nucleon mass (M^*/M) in symmetric nuclear matter, and also symmetry energy (E_{sym}) and slope of the symmetry energy (L) at n_0. The phenomenological constraints are taken from [2] and [3].

Quark Matter

Modified MIT bag model

$$\mathcal{L}_{MIT} = \sum_q \left\{ \overline{\psi}_q \left[\gamma^\mu (i\partial_\mu - g_{qqV} V_\mu) - m_q \right] \psi_q + \frac{1}{2} m_V^2 V_\mu V^\mu + \frac{1}{4} b_4 (g_{uuV}^2 V_\mu V^\mu)^2 - B \right\} \Theta(\overline{\psi}_q \psi_q) - \frac{1}{2} \overline{\psi}_q \psi_q \delta_S,$$

where the Dirac spinor ψ_q represents the quark with mass m_q, g_{qqV} the coupling constant, m_V the mass of the meson and b_4 is a dimensionless parameter. More details can be found in [4] and [5].

We make $G_V \equiv \left(\frac{g_{uuV}}{m_V}\right)^2$ and $X_V = \frac{g_{ssV}}{g_{uuV}}$.

Quark Matter

Modified MIT bag model

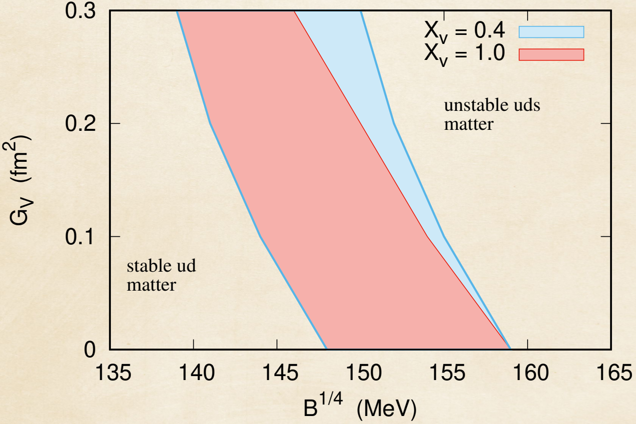
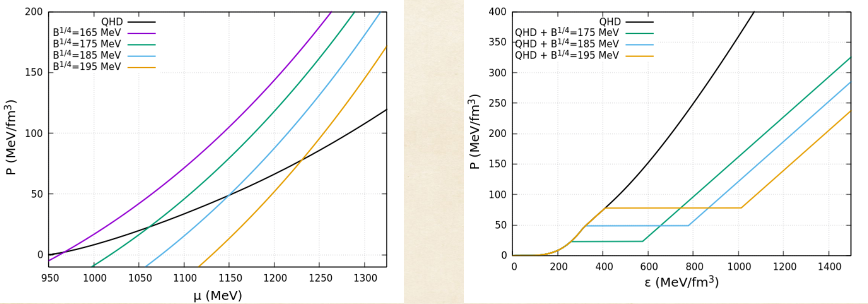


Figure: Stability window for the MIT bag model with vector interaction and different values of X_V.

Maxwell construction

Constructing the hybrid EoS



(a) Finding the crossing points

(b) Hybrid EoS

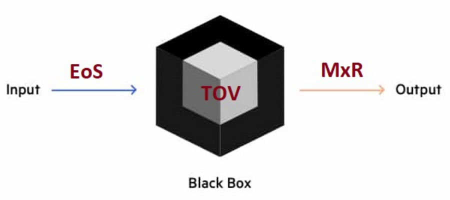
TOV equations

Connecting the microscopic to the macroscopic

This equations are obtained from the Einstein field equations, assuming that the star is spherical, static and made of a ideal and isotropic fluid.

$$\frac{dP}{dr} = -\frac{G\epsilon(r)M(r)}{r^2}\left[1+\frac{P(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2 \epsilon(r).$$



Mass-Radius Diagrams

Original MIT Bag Model

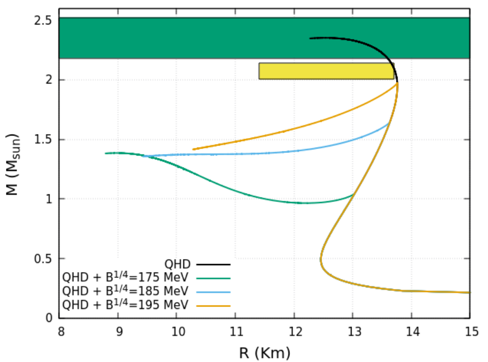
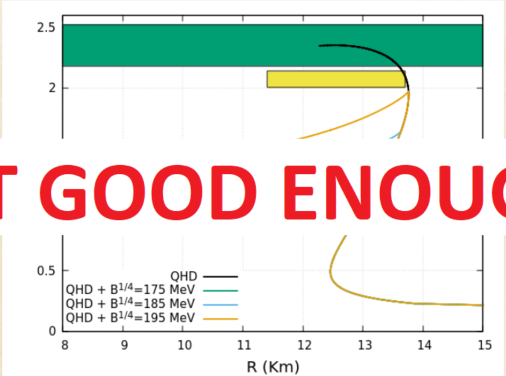


Figure: TOV solutions for different values of the Bag within the original MIT Bag model. The yellow and the green areas represent the constrains given by PSR J070+6620 and PSR J0952-0607, respectively.

Mass-Radius Diagrams

Original MIT Bag Model

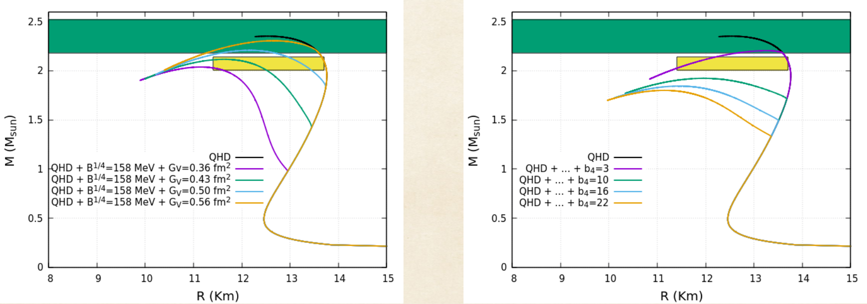


NOT GOOD ENOUGH

Figure: TOV solutions for different values of the Bag within the original MIT Bag model. The yellow and the green areas represent the constrains given by PSR J070+6620 and PSR J0952-0607, respectively.

Mass-Radius Diagrams

Modified MIT Bag Model



(a) Vector MIT bag model

(b) Self-Interacting Vector Field contribution

Figure: The yellow and the green areas represent the constrains given by PSR J070+6620 and PSR J0952-0607, respectively. For the Self-Interacting Vector Field (right) we keep G_V = 0.8 fm^2 and keep $B^{1/4}$=158 MeV. More details in [6].

Work in Progress

What happens when we add Dark Matter to this mix?

- the compact objects may get more or less compact depending on the mass of the dark matter particle, its interacting strength and the quantity of dark matter mixed with the ordinary matter;
- the quark matter may appear much earlier;
- ...

References

[1] Biesdorf, C., Menezes, D.P. and Lopes, L.L, Brazilian Journal of Physics **53**, 5, 137 (2023).

[2] Dutra, M et al., Phys. Rev. C **90**, 5, 055203 (2014).

[3] Oertel, M. et al., Reviews of Modern Physics **89**, 1, 015007 (2017).

[4] Lopes, L.L., Biesdorf, C. and Menezes, D.P., Phys. Scr. **96**, 065303 (2021).

[5] Lopes, L.L., Biesdorf, C., Marquez, K.D. and Menezes, D.P., Phys. Scr. **96**, 065302 (2021).

[6] Lopes, L.L., Biesdorf, C. and Menezes, D.P., Monthly Notices of the Royal Astronomical Society 512, 4, 5110–5121 (2022).

Thanks

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