Hybrid stars from a constrained EoS

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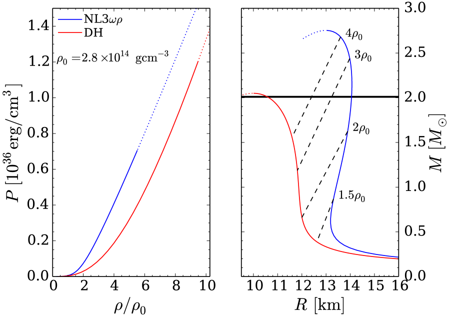
Probing the interior of Neutron Stars

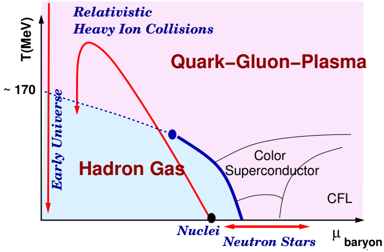
- Neutrons stars provide a laboratory for testing
  - nuclear physics: high density, highly asymmetric matter
  - QCD: deconfinement, quark matter, superconducting phases
- microscopic model → EOS $\xrightarrow{TOV}$ mass-radius



Motivation

- Do neutron stars contain deconfined quark matter?
- Are hybrid star models compatible with constraints coming from observations?
- Which are the properties of hybrid stars that satisfy observational constraints?

Márcio Ferreira , Renan Pereira, CP
(PRD101, 123030 & PRD102, 083030 & PRD103, 123020)



Constraints: Neutron star observations & nuclear/quark matter constraints

- NICER data for PSR J0030+0451: Riley et al ApJ.Lett. 887 L21, Miller et al ApJ.Lett. 887 L24

- NICER+XMM-Newton data for PSR J0740+6620: $12.39^{+1.30}_{-0.98}$ km and $2.072^{+0.067}_{-0.066} M_\odot$ (Riley et al arxiv:2105.06980v2)

- Tidal deformability GW170817: with constraint $M > 1.97 M_\odot$

- Deconfinement transition for $n_B > 0.25$ fm^{-3}

- Hadronic EoS satisfies accepted nuclear matter properties
  a) metamodel EoS for nucleonic matter;
  b) DDME2 (Lalazissis PRC71)

- Quark matter:
  chiral symmetric model (SU(3) Nambu-Jona-Lasinio with 4- and 8-quark terms), fitted to π, K, η meson vacuum properties

Hadronic EoS

- Nuclear matter meta-model: Taylor expansion (Margueron PRC97, 025805)
- Advantage of a meta-model for the hadron phase: flexibility to build hybrid EoS with 2 $M_\odot$ maximum mass providing realistic empirical nuclear parameters that satisfy known uncertainties.
- Metamodels: 354 nucleonic EoS that allow for a phase transition
- Metamodel: properties with and without phase transition

Nucleonic	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
mean	233.95	58.62	-181.97	33.32	51.56	-43.96	238.21	371.91
std	18.75	123.33	143.04	1.89	11.83	63.02	300.33	698.56
Hybrid (all)	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
mean	236.52	241.38	362.11	33.17	49.99	-37.48	191.54	503.39
std	17.73	242.03	593.75	1.84	12.55	67.23	310.48	734.69
Hybrid $(1.3 < n_t/n_0 < 2.5)$	K_{sat}	Q_{sat}	Z_{sat}	E_{sym}	L_{sym}	K_{sym}	Q_{sym}	Z_{sym}
mean	244.55	434.37	557.83	33.38	49.90	-18.07	195.39	400.46
std	16.91	174.6	743.94	2.00	11.55	57.47	300.13	672.24

- A phase transition to quark matter requires stiffer EoS:
  - higher Q_{sat} and higher (and positive) Z_{sat}, wider spread
- DDME2 EoS: K_{sat} = 250MeV, E_{sym} = 32.3MeV, L = 51.2MeV, $K_{sym} = -87$MeV.

Quark EoS

- Quark model: SU(3) NJL with 4 and 8-quark vector contributions

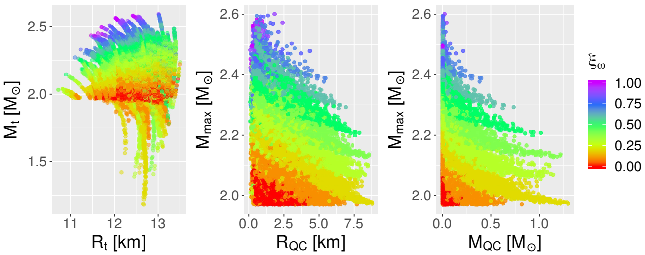
$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - \hat{m} + \hat{\mu}\gamma^0\right)\psi + G_S \sum_{a=0}^{8}\left[\left(\bar{\psi}\lambda^a\psi\right)^2 + \left(\bar{\psi}i\gamma^5\lambda^a\psi\right)^2\right]$$
$$- G_D\left[\det\left(\bar{\psi}(1+\gamma_5)\psi\right) + \det\left(\bar{\psi}(1-\gamma_5)\psi\right)\right]$$
$$- G_\omega\left[(\bar{\psi}\gamma^\mu\lambda^0\psi)^2 + (\bar{\psi}\gamma^\mu\gamma_5\lambda^0\psi)^2\right] - G_\rho \sum_{a=1}^{8}\left[(\bar{\psi}\gamma^\mu\lambda^a\psi)^2 + (\bar{\psi}\gamma^\mu\gamma_5\lambda^a\psi)^2\right]$$
$$- G_{\omega\omega}\left[(\bar{\psi}\gamma^\mu\lambda^0\psi)^2 + (\bar{\psi}\gamma^\mu\gamma_5\lambda^0\psi)^2\right]^2 + \mathcal{L}_{\omega\rho} + \mathcal{L}_{\omega\omega}.$$

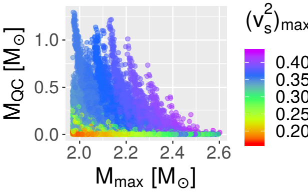
- Λ, G_S, G_D, m_i: fitted to meson vacuum properties
- Free parameters: G_ω, G_ρ, $G_{\omega\omega}$, B
- B defines the deconfinement onset: $P \to P + B$, $\epsilon \to \epsilon - B$
- Models with large quark cores: determined by effective bag B, & vector interactions $\xi_\omega = G_\omega/G_S$, $\xi_\rho = G_\rho/G_S$, $\xi_{\omega\omega} = G_{\omega\omega}/G_S^4$
- Other 8-quark vector terms ($\rho\rho$ or $\omega\rho$): minor effects, the most relevant is the $\omega\rho$ term contributing to increase strangeness fraction in 10%.

Neutron stars with large quark cores & $M > 1.97 M_\odot$

(Ferreira PRD101, 123030) , $G_{\omega\omega} = 0$, $G_\rho = 0$

- Deconfinement transtion: Maxwell const, jump in baryonic density Δn
- Large quark cores: $\Delta n/n_0 \lesssim 0.2$, $n_t < 4n_0$, $B \gtrsim 10$ MeV/fm^3
- Quarks in low mass stars: $\Delta n/n_0 \lesssim 0.65$ and $1.8 < n_t/n_0 < 2.5$
- Mass quark core $\lesssim 1 M_\odot$ and speed of sound $v_s^2 > 0.35$



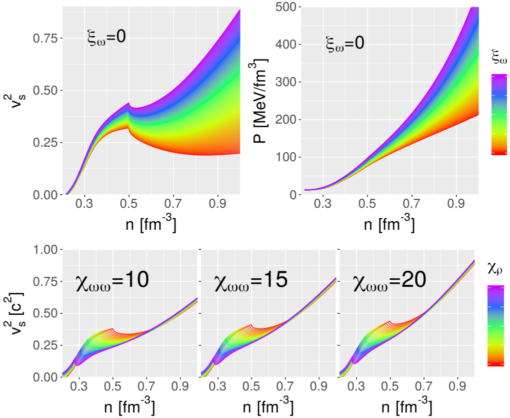


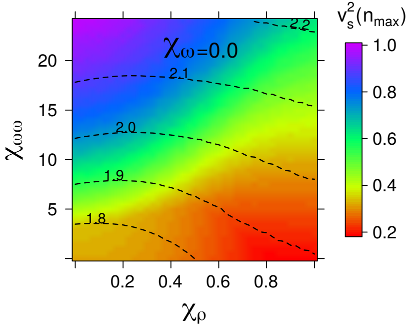
M onset quarks | *R* quark core | *M* quark core | v_s^2 M_{max} center

8-quark term $G_{\omega\omega}$

(Ferreira, PRD102(083030), PRD103(123020))

- Effect of $\xi_\omega = \chi_\omega = G_\omega / G_S$, $\chi_\rho = G_\rho / G_S$, $\chi_{\omega\omega} = G_{\omega\omega} / G_S^4$
- $G_\rho \to$ controls onset of $s-$quark: larger values imply lower onset densities of strangeness and lower overall v_s^2

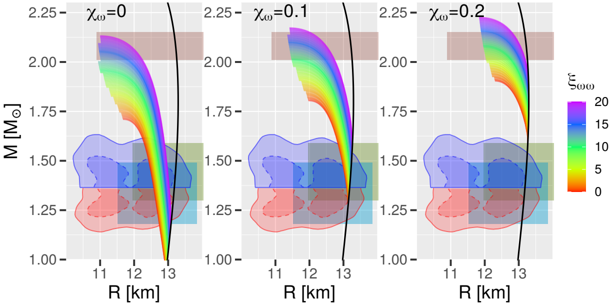




Quark matter in light neutron stars

(Ferreira PRD102, 083030)

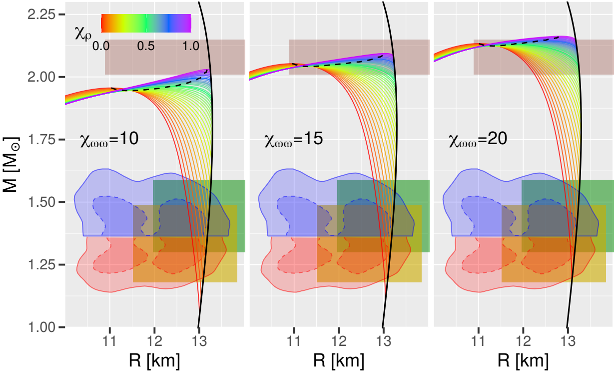
- larger values of G_ω $\rightarrow$ quark onset for larger masses, shorter quark branches, larger M_{max}
- large values of $G_{\omega\omega}$ $\rightarrow$ quark onset for low masses ($M > 1M_\odot$), massive stars are obtained $M_{max} \sim 2.2M_\odot$
- Agreement with NICER observations for PSR J0030+0451, NICER/XMM-Newton for J0740+662



Strange quark matter in light neutron stars

(Ferreira PRD102, 083030)

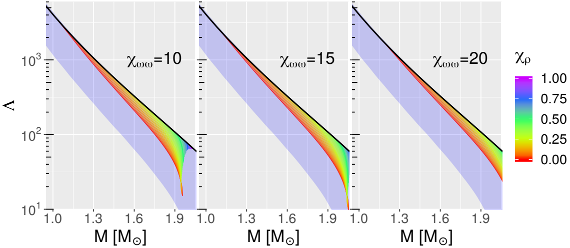
- larger values G_ρ $\rightarrow$ quark onset at larger masses, shorter quark branches, slightly larger M_{max}
- interplay between G_ρ and $G_{\omega\omega}$ $\rightarrow$ hybrid stars with considerable quark cores, large strangeness fraction and $v_s^2 \lesssim 0.65$

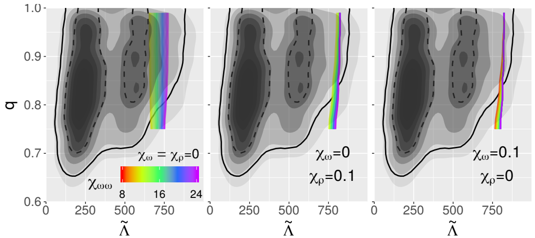


GW170817 constraints

(Ferreira PRD103, 123020), $G_\omega = 0$

- $\tilde{\Lambda} < 720$ (HPD), 800 (symetric) GW170817 ($M > .97 M_\odot$, LVC, PRX 9)
- DDME2 (at the upper limit) + hybrid stars satisfy GW170817 constraints
- $q - \tilde{\Lambda}$ $q = M_2/M_1 > 0.73$ if $G_\omega = G_\rho = 0$, $q \gtrsim 0.85$ if $G_\omega > 0$ and/or $G_\rho > 0$



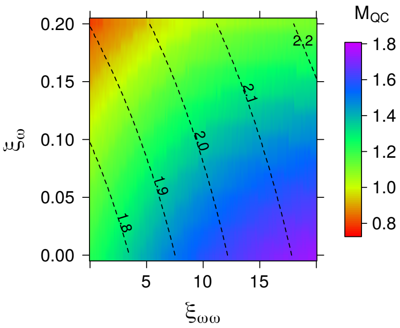


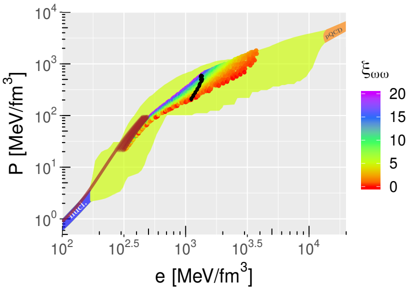
Quark matter in neutron stars

Conclusions I

- It is possible to build hybrid stars with $M \gtrsim 2M_\odot$ satisfying both observations and terrestrial constraints
- $\approx 2.1 M_\odot$ star with $\approx 1.8 M_\odot$ quark core with central $v_s^2 \approx 0.93$ were obtained
- v_s^2 and NS mass are very sensitive to $G_{\omega\omega}$
- $G_{\omega\omega}$ term gives rise to a non-linear density dependent speed of sound

  It is possible to obtain low mass stars with a quark core





Annala et al Nat. Phys. 16 (2020) 907

Quark matter in neutron stars

Conclusions II

- $\chi_\rho > 0 \rightarrow$ larger strangeness fraction, and smaller v_s^2
- $\chi_\rho > 0 \rightarrow$ smaller quark core, but still possible cores with 0.8-1 $M_\odot$
- Maximum strangeness fraction at star center : 25% in star with $1/3M$ quark core (inclusion of $\rho\omega$ term $\approx$ 28%)
- very massive stars with large quark cores have $v_s^2 > 1/3$
- Maximum masses: $\lesssim 2.2M_\odot$ $\rightarrow$ low mass companion of GW190814 is not a hybrid star (with the present quark model), unless it is rapidily rotating star (Dexheimer PRC103, 025808)