

Hybrid stars with large strange quark cores

Márcio Ferreira

Centre for Physics
University of Coimbra

Quark Confinement and the Hadron Spectrum
University of Stavanger
1–6 August 2022



FACULDADE DE
CIÊNCIAS E TECNOLOGIA
UNIVERSIDADE DE
COIMBRA



FCT Fundação
para a Ciência
e a Tecnologia

Motivation

- Do neutron stars (NS) contain deconfined quark matter?
- Are hybrid star models compatible with NS observations?
- How large is the quark core that still satisfies observations?
- Which signatures could distinguish hybrid stars?
 - Márcio Ferreira , Renan Pereira, and Constança Providência
(PRD101, 123030 & PRD102, 083030 & PRD103, 123020)

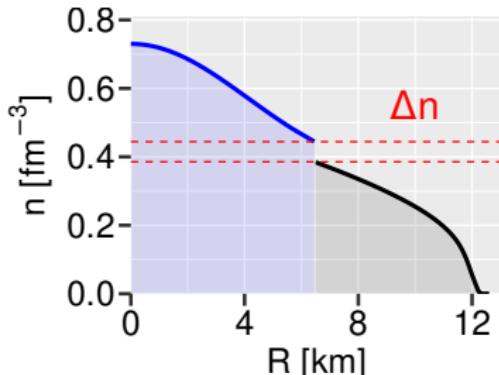
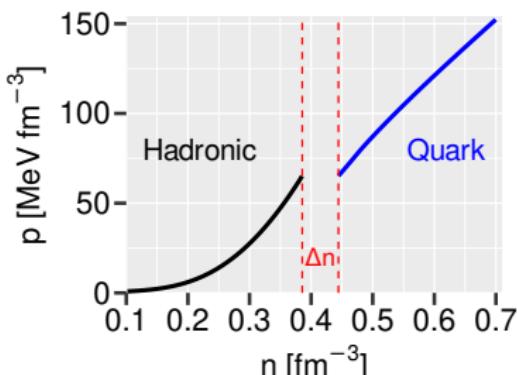
Is there quark matter in neutron stars?

- NS observations compatible with the existence of quark-matter cores in massive NSs (kink structure associated to deconfinement)
[Eemeli Annala, et al. PRX12, 011058 (2022)]
- Increase of the dominant postmerger gravitational-wave frequency when a phase transition takes place during merging
[Andreas Bauswein and Sebastian Blacher, Eur. Phys. J. Special Topics 229, 3595–3604 (2020)]
- Postmerger signal considerably different from the one expected from the inspiral if a phase transition occurs after the merger.
[Elias R. Most, et al., PRL122,061101(2019)]
- Two distinct fundamental gravitational-wave frequencies from postmerger signal as a signature of the production of quark matter
([Lukas R. Weih, et al., PRL124,171103(2020)])
- ...

Hybrid star model

- Hadronic EoS: DDME2
 - RMF model that fulfills nuclear matter and finite nuclei constraints
- Quark EoS: NJL with 4 and 8-quark vector contributions
 - Incorporates spontaneous chiral symmetry breaking
- First-order phase transition to quark matter
 - Maxwell construction:

$$\mu_B^H = \mu_B^Q, \quad P^H = P^Q, \quad \text{and} \quad T^H = T^Q$$



Quark EoS

- Nambu-Jona-Lasinio (NJL) model with 4 and 8-quark vector interactions

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

- Λ , G_S , G_D , m_i : fitted to meson vacuum properties
- $\mathcal{L}_{\omega\rho}$ and $\mathcal{L}_{\rho\rho}$ have minor effects in β -equilibrium quark matter
- Free parameters: G_ω , G_ρ , $G_{\omega\omega}$

$$\chi_\omega = G_\omega/G_S \quad \chi_\rho = G_\rho/G_S \quad \chi_{\omega\omega} = G_{\omega\omega}/G_S^4$$

Model parameters

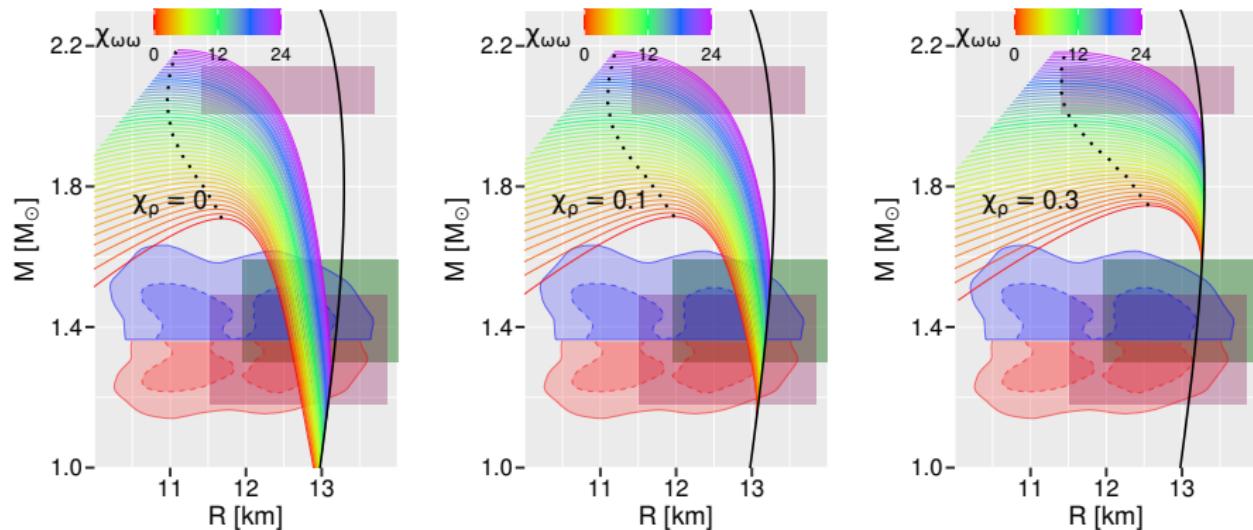
- Quark pressure is defined up to a constant B ($P \rightarrow P + B$)
- B defines the phase transition onset: we require $\mathbf{n}_t > \mathbf{0.2} \text{ fm}^{-3}$
 - We have fixed $B = 15 \text{ MeV/fm}^3$
- The main effect of χ_ω is increasing the transition density
 - reduces the the number of stable hybrid stars [small cores]
- **Our aim:** reproduce massive hybrid stars ($M_{max} > 2.0M_\odot$) with quark matter already present in light NS

$$\chi_\omega = 0 \text{ and analyze } [\chi_{\omega\omega}, \chi_\rho]$$

Effect of $\chi_{\omega\omega}$ and χ_ρ

MR constraints: T. E. Riley et al. The AJL 918:L27 (2021), T. E. Riley et al. AJL 887:L21 (2019),

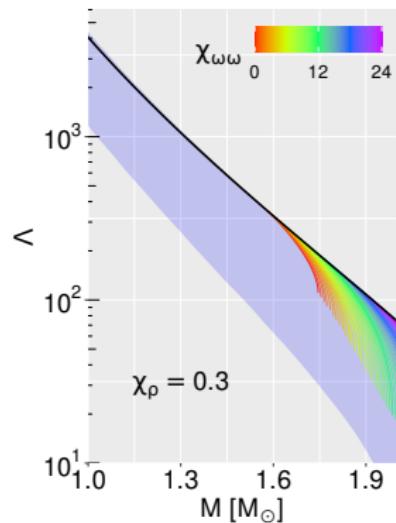
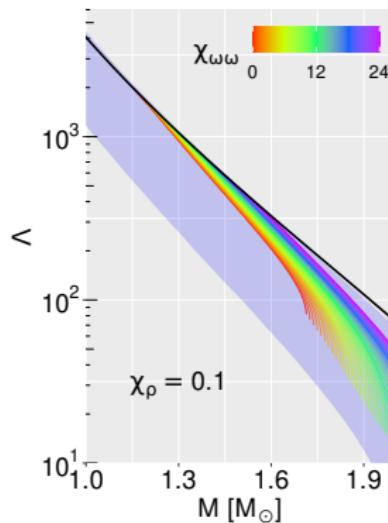
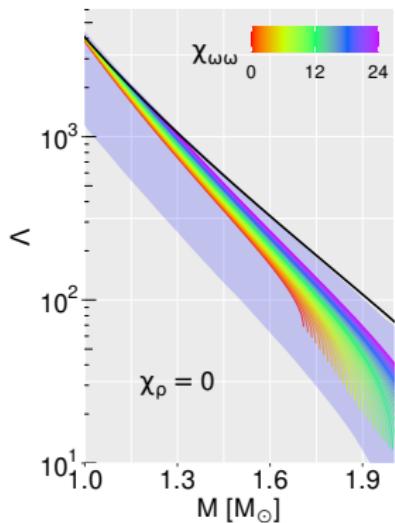
M. Miller et al., AJL 887:L24 (2019), LIGO/Virgo collaboration PRL 121, 161101 (2018).



- For $\chi_\rho < 0.1$ and $\chi_{\omega\omega} > 10$ quark matter is present in $M = 1.4M_\odot$
- These hybrid star models are consistent with $M(R)$ constraints

LIGO/Virgo - EoS constraints (GW170817)

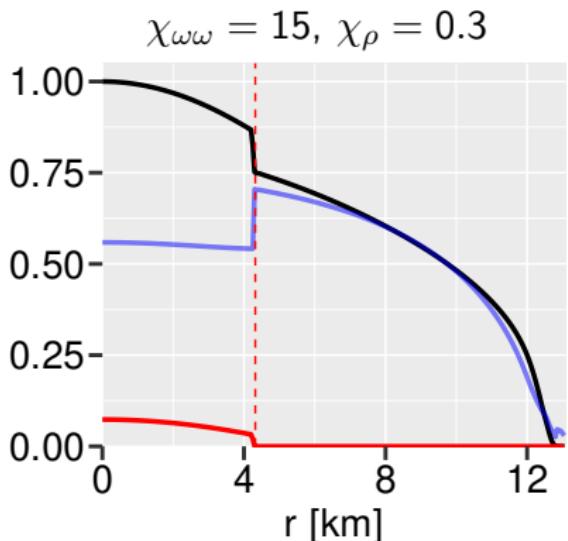
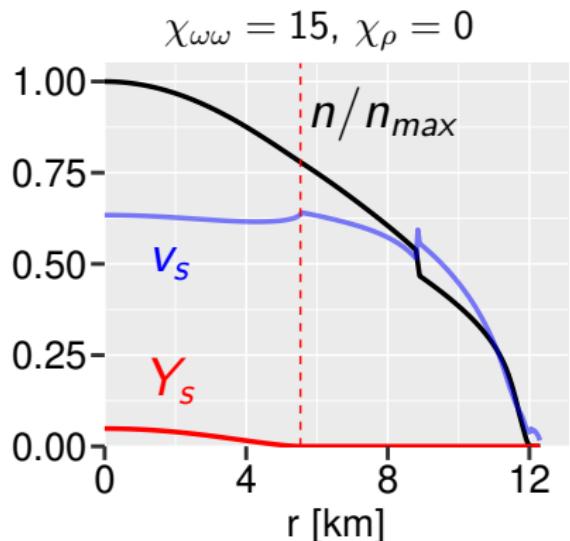
■ 90% CL when the EoS describes $1.97M_{\odot}$ (LIGO/Virgo, PRL121,161101(2018))



- $M_{max} > 1.97$ for $\chi_{\omega\omega} > 12$
- Hybrid star models are consistent with $\Lambda(M)$ constraints

Hybrid star profile - strangeness and sound velocity

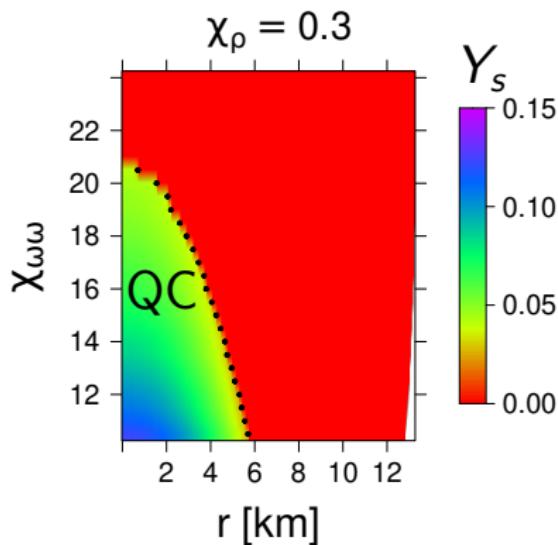
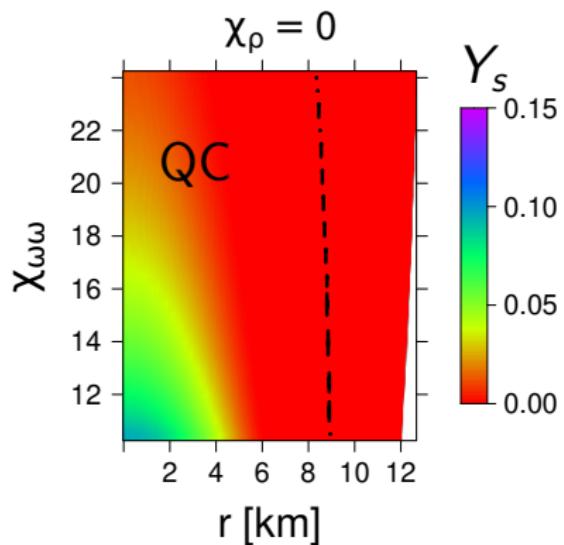
- Star's profile for $M = 1.9M_{\odot}$



- The amount of strangeness is affected by χ_{ρ}
- v_s reflects the onset of strange quark

Hybrid star profile - strangeness ($M = 1.9M_{\odot}$)

- \dots the quark matter onset

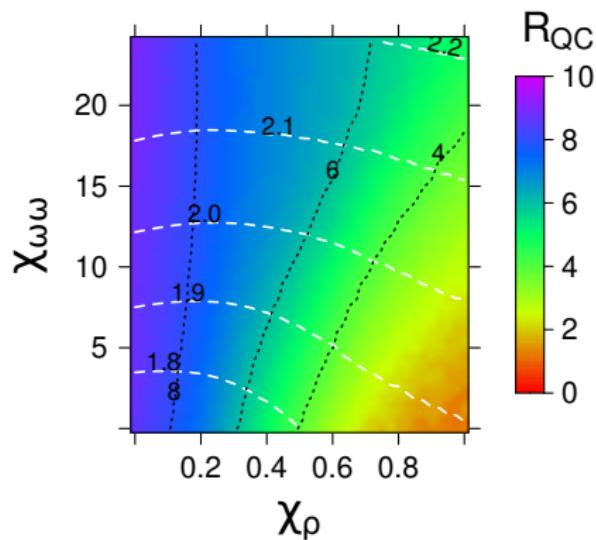
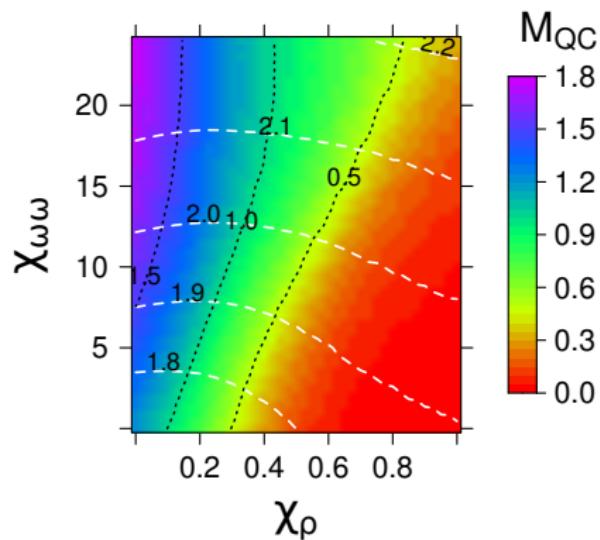


- There is a strangeness core for $\chi_{\rho} = 0$
- The whole quark core contains strangeness for $\chi_{\rho} = 0.3$

Quark core properties for M_{max}

- Mass and radius of the Quark Cores

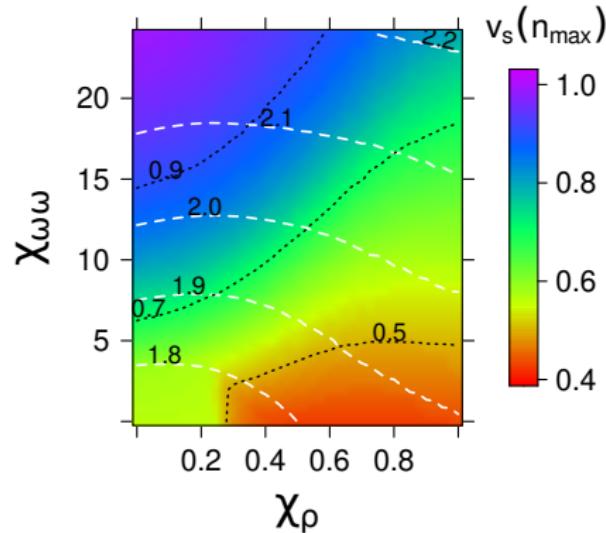
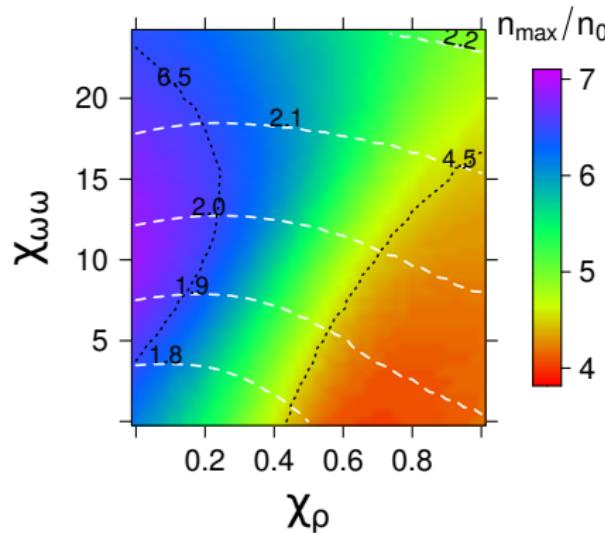
--- : M_{max}/M_\odot ; : contour lines (M_{QC}, R_{QC})



- M_{QC} and R_{QC} more sensitive to $\chi_{\omega\omega}$
- χ_ρ can produce $0.3 \lesssim M_{QC}/M_\odot \lesssim 1.8$ (larger $\chi_{\omega\omega}$)

Quark core properties for M_{max}

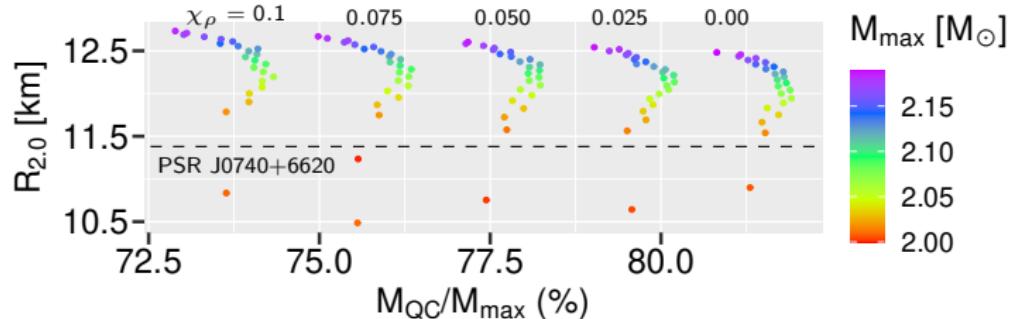
- Central density and sound velocity



- $v = 0.99c$ for $\chi_{\omega\omega} = 24$ (χ_ρ reduces v_s)
- n_{max} is non-monotonic with $\chi_{\omega\omega}$ (small χ_ρ)

Conclusions

- Can $1.4M_{\odot}$ NS have quark cores (consistent with observations)?

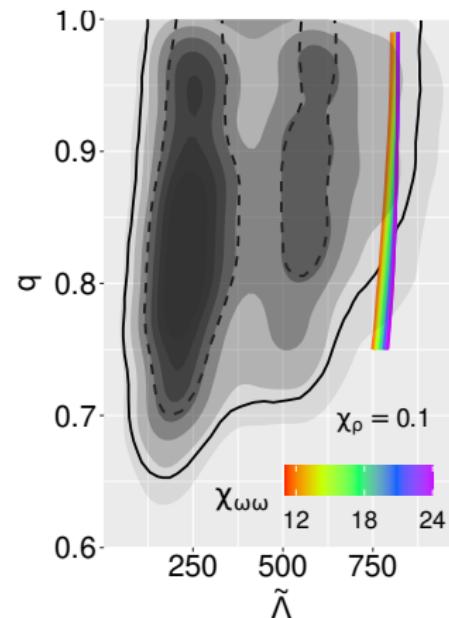
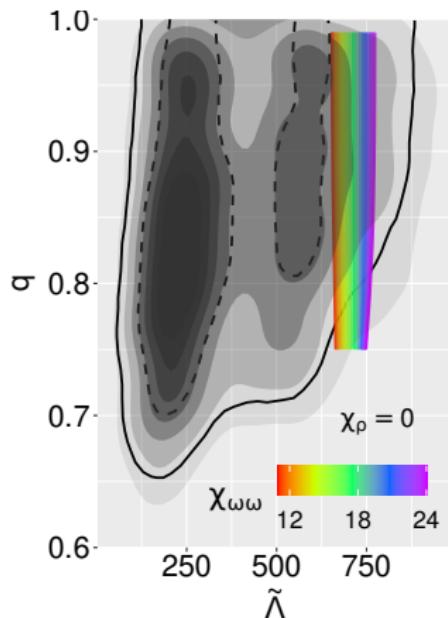


- Assuming a quark core in $M = 1.4M_{\odot}$:
 - $10.49 < R_{2.0}/\text{km} < 12.73$ for $0.72 \lesssim M_{QC}/M_{max} \lesssim 0.82$
- NICER measurement of PSR J0740+6620:
[T. E. Riley et al. AJL 918:L27 (2021)]
 - $M = 2.072^{+0.067}_{-0.066} M_{\odot}$ and $R = 12.39^{+1.30}_{-0.98}$ km (68% CI)

Conclusions

- $\tilde{\Lambda}$ constraints from GW170817 event:

■ CI for the posterior $P(\tilde{\Lambda}, q)$ ($q = M_2/M_1$) ([LIGO/Virgo PRX9,011001\(2019\)](#))



- The existence of a QC in NS (even for $1.4M_\odot$) cannot be excluded.