Hybrid stars with large strange quark cores

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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 Blacker, 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

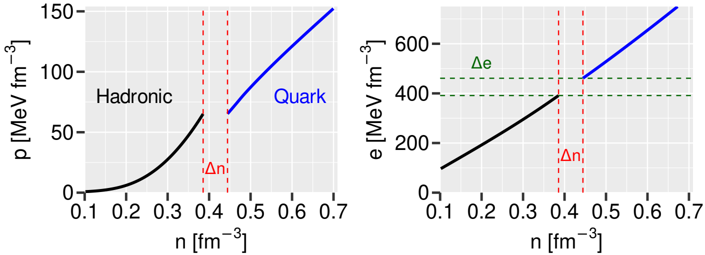
  (Lukas R. Weih, et al., PRL124,171103(2020))

- ...

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

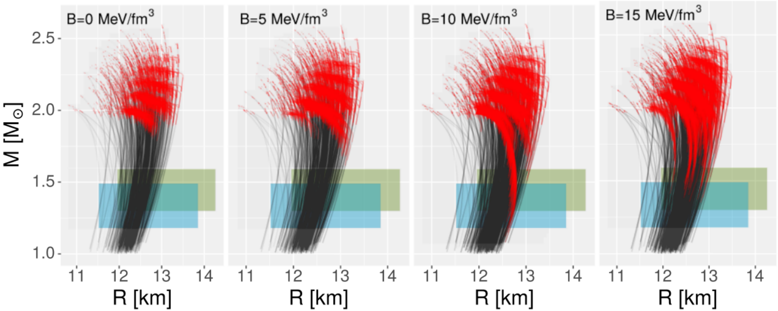
$$\mathcal{L} = \bar{\psi}(i\partial - \hat{m} + \hat{\mu}\gamma^0)\psi + G_S \sum_{a=0}^{8}[(\bar{\psi}\lambda^a\psi)^2 + (\bar{\psi}i\gamma^5\lambda^a\psi)^2]$$
$$- G_D[\det(\bar{\psi}(1+\gamma_5)\psi) + \det(\bar{\psi}(1-\gamma_5)\psi)]$$
$$-G_\omega[(\bar{\psi}\gamma^\mu\lambda^0\psi)^2 + (\bar{\psi}\gamma^\mu\gamma_5\lambda^0\psi)^2]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

- 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, $G_{\omega\omega}$

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

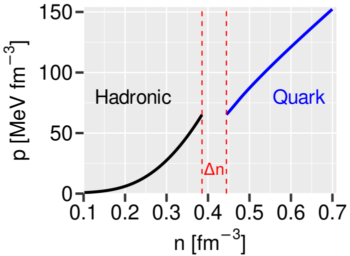
Bag constant

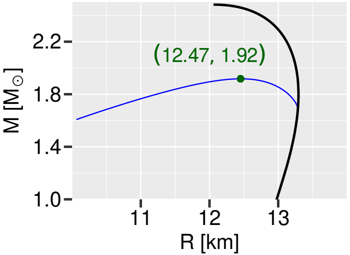
- Quark pressure is defined up to a constant B ($P \to P + B$)
- Defines the deconfinement onset: we require $\mathbf{n_t} > \mathbf{0.2}$ fm$^{\mathbf{-3}}$



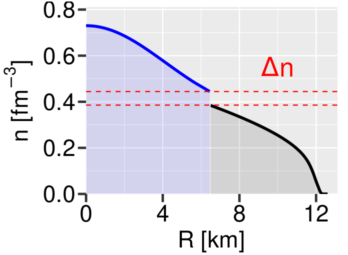
- <u>We fix $B = 15$ MeV/fm^3</u>

Example of a hybrid star





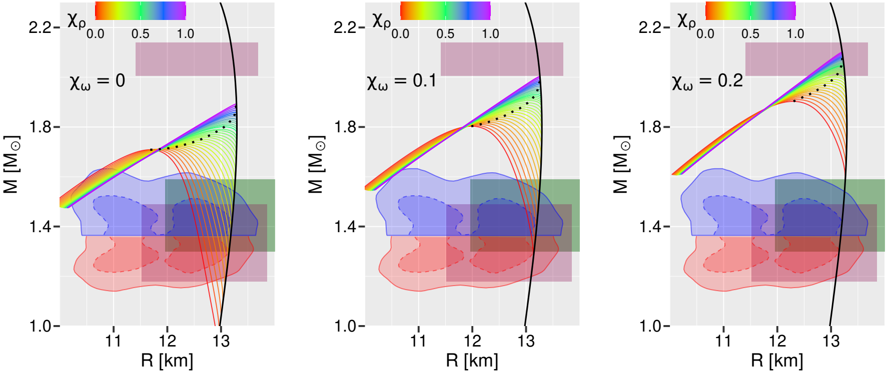
Density profile for the M_{max}



Effect of χ_ω

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

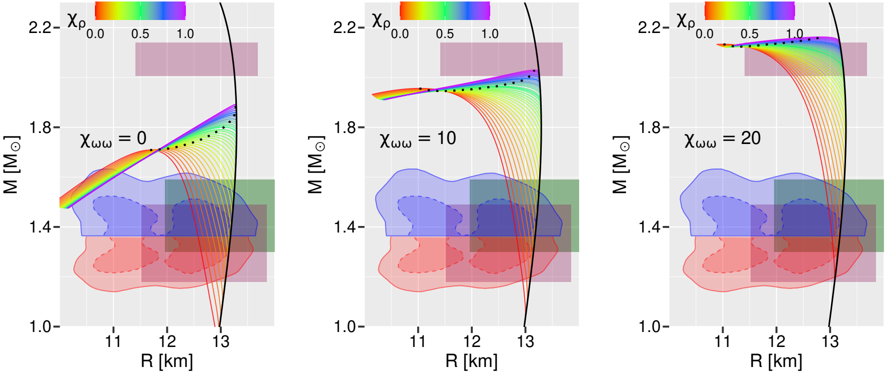
M. Miller et al., AJL 887:L24 (2019), LIGO/Virgo collaboration PRL 121, 161101 (2018).



- Small quark branches with increasing χ_ω
- **To reach $M_{max} > 2.0 M_\odot$ and still have quark matter in light NS:**

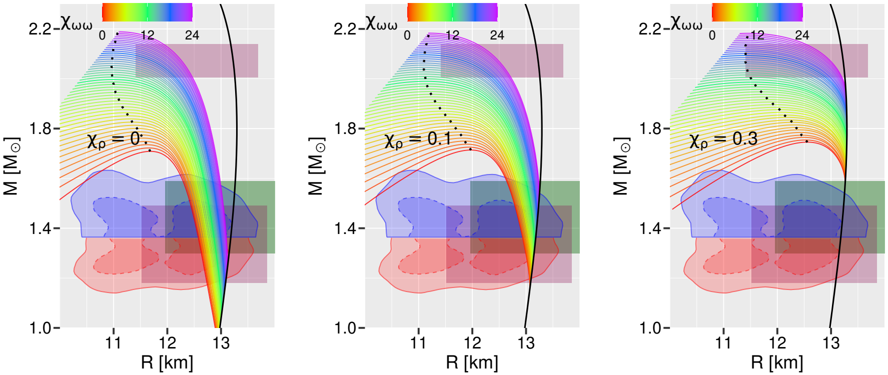
$$\chi_\omega = 0 \text{ and analyze } [\chi_{\omega\omega}, \chi_\rho]$$

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



- M_{max} increases with $\chi_{\omega\omega}$ and keeps long quark branches
- Quark matter (big cores) at smaller M ($> 1.3M_\odot$)
- Small values of χ_ρ give rise to longer quark branches

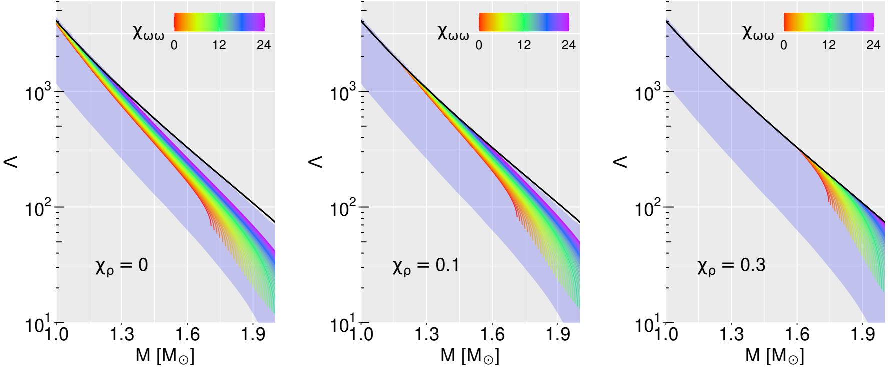
Effect of $\chi_{\omega\omega}$ for small χ_ρ values



- 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)

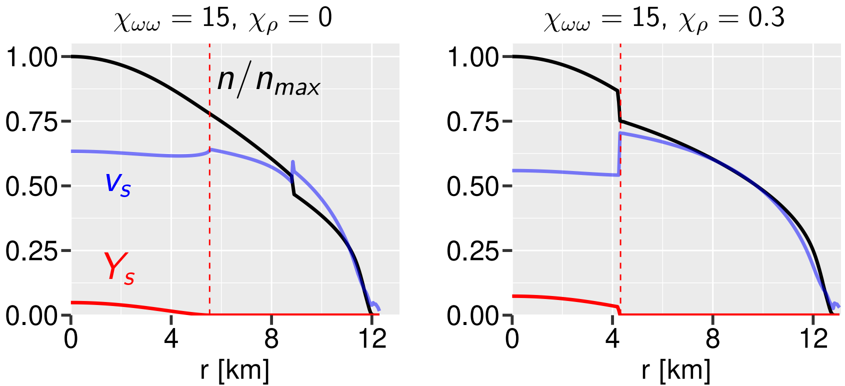
■ 90% CL when the EoS describes $1.97 M_\odot$ (LIGO/Virgo, PRL121,161101(2018))



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

Hybrid star profile - strangeness and sound velocity

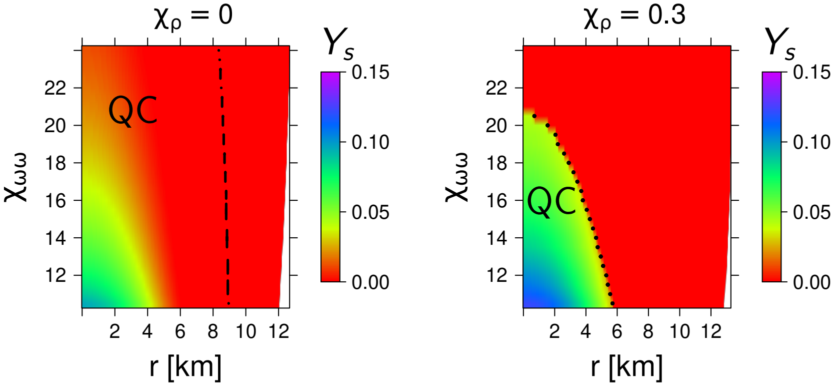
- Star's profile for $M = 1.9 M_{\odot}$



- The amount of strangeness is affected by χ_ρ
- v_s reflects the onset of strange quark

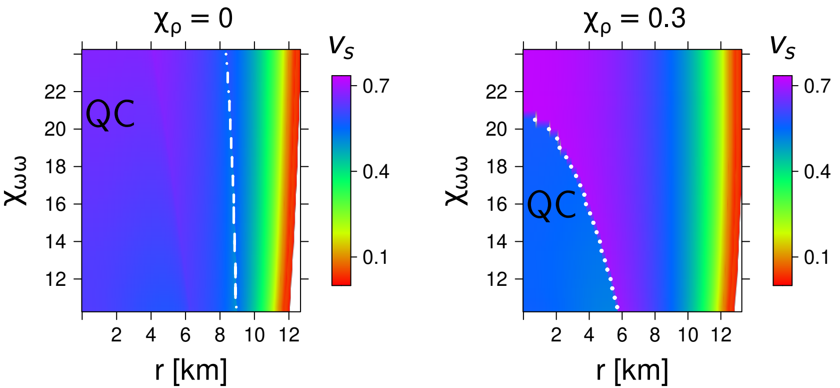
Hybrid star profile - strangeness ($M = 1.9 M_\odot$)

- $\cdots$ the quark matter onset



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

Hybrid star profile - sound velocity ($M = 1.9 M_\odot$)

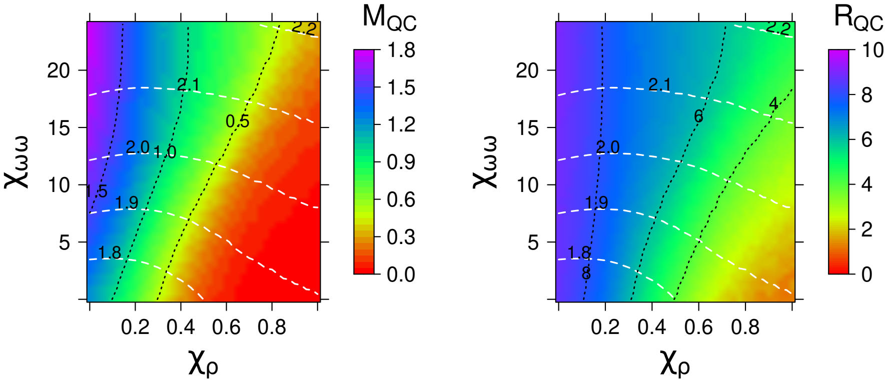


- The sound velocity drops when strangeness is present in the QC

Quark core properties for M_{max}

- Mass and radius of the Quark Cores

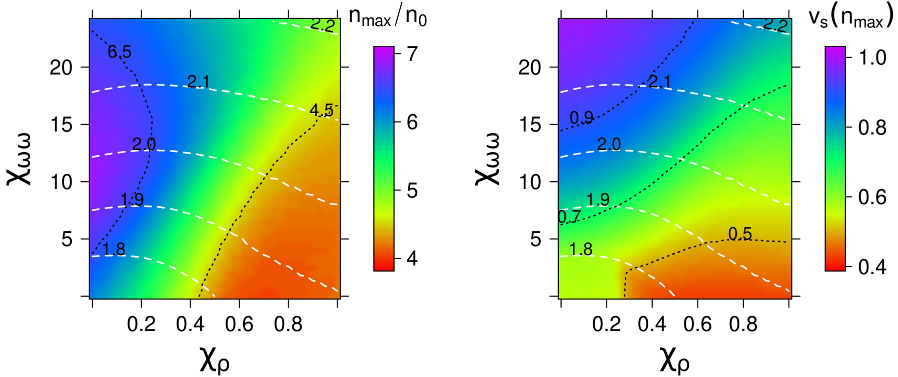
--- : $M_{max}/M_{\odot}$; ...... : contour lines (M_{QC},R_{QC})



- 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}

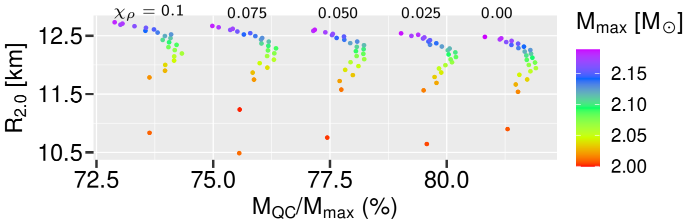
- Central density and sound velocity



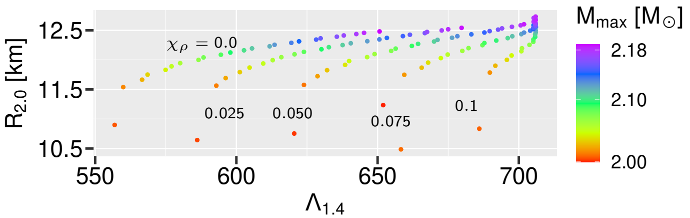
- $v = 0.99c$ for $\chi_{\omega\omega} = 24$ (χ_ρ reduces v_s)
- n_{max} is non-monotonic with $\chi_{\omega\omega}$ (small χ_ρ)

Conclusions

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



- HStars with $10.49 < R_{2.0}/\mathrm{km} < 12.73$ for $0.72 \lesssim M_{QC}/M_{max} \lesssim 0.82$

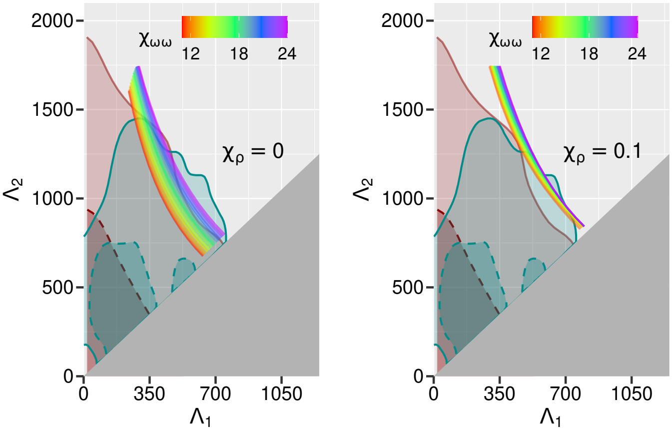


- The existence of a QC in NS (even for $1.4M_{\odot}$) cannot be excluded.

Backup slides

LIGO/Virgo - binary constraints (GW170817)

- Tidal deformabilities for the binary components ($M_{\text{chirp}} = 1.186 M_{\odot}$)
- Hybrid models with $M_{max} > 1.97 M_{\odot}$



- Very small values χ_ρ favored
- χ_ρ affects the strangeness content (next slides)

LIGO/Virgo - binary constraints (GW170817)

- CI for the posterior $P(\tilde{\Lambda}, q)$ ($q = M_2/M_1 < 1$, binary mass ratio) (LIGO/Virgo PRX9,011001(2019))