Hybrid Star Properties with NJL and MFTQCD Model:

A Bayesian Approach

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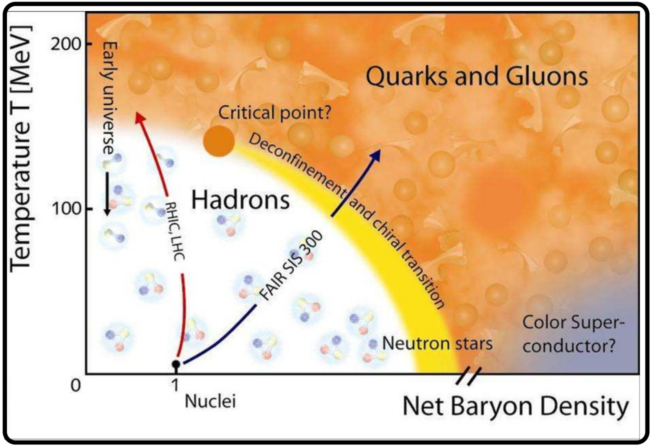
Universidade de Coimbra

QCD phase diagram

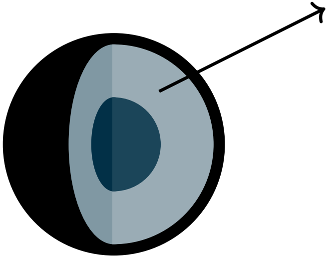


- Neutron stars (NS) are extreme objects that have high density and low temperature ($T \approx 0$);
- This density may be so high that matter may be deconfined inside neutron stars;

But this is just a possibility!

- Most of the QCD phase diagram is still unknown - including the NS region.

**Objective: answer the question
"is deconfined quark matter present in the NS core?" using microscopic models**



Hadron phase

Relativistic Mean Field (RMF)

- nucleons force is described by the exchange of a scalar (σ), a vector iso-scalar (ω) and a iso-vector-vector (ρ) mesons;
- we use two equations[1]:

Soft	Stiff
(BMPF 220)	(BMPF 260)

[1] Tuhin Malik et al. **"Spanning the full range of neutron star properties within a microscopic description".** In: *Phys. Rev. D* 107.10 (2023), p. 103018. DOI: 10.1103/PhysRevD.107.103018. arXiv: 2301.08169 [nucl-th].

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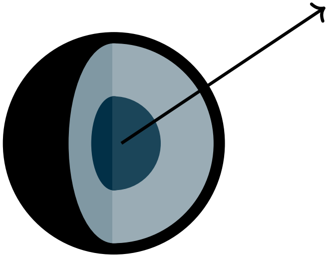

Quark phase

NJL
(Nambu-Jona-Lasinio)

- t' Hooft term;
- 5 different types of interactions.

MFTQCD
(Mean Field Theory of QCD)[2]

- from the QCD Lagrangian
- decomposition of gluon field in soft and hard momentum components.

[2] D. A. Fogaca and F. S. Navarra. **"Gluon condensates in a cold quark–gluon plasma".** In: *Phys. Lett. B* 700 (2011), pp. 236–242. DOI: 10.1016/j.physletb.2011.05.011. arXiv: 1012.5266 [hep-ph].

Nambu-Jona-Lasinio (NJL)

We use the following SU(3) NJL lagrangian:

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

standard NJL term

't Hooft term

added interation terms

We add 4- and 8-quark interaction terms:

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

EOS can be obtained through the Mean Field Approximation (MFA).

- Start with the QCD lagrangian;
- Assume we can decompose the gluon field in[3]
  - low momentum components (soft gluons);
  - high momentum components (hard gluons);

$$\tilde{G}^{a\mu}(k) = \tilde{A}^{a\mu}(k) + \tilde{\alpha}^{a\mu}(k) \qquad (2)$$

soft gluons

hard gluons

[3] Fogaca and Navarra, "Gluon condensates in a cold quark–gluon plasma".

Methods

NJL

$$\mathcal{L}_I = -G_\omega \left[(\bar\psi\gamma^\mu\lambda_0\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda_0\psi)^2 \right]$$
$$- G_\rho \sum_{a=1}^{8} \left[(\bar\psi\gamma^\mu\lambda^a\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda^a\psi)^2 \right]$$
$$- G_{\omega\omega} \left[(\bar\psi\gamma^\mu\lambda_0\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda_0\psi)^2 \right]^2$$
$$- G_{\sigma\omega} \sum_{a=0}^{8} \left[(\bar\psi\lambda_a\psi)^2 + (\bar\psi i\gamma^5\lambda_a\psi)^2 \right]$$
$$\times \left[(\bar\psi\gamma^\mu\lambda_0\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda_0\psi)^2 \right]$$
$$- G_{\rho\omega} \sum_{a=1}^{8} \left[(\bar\psi\gamma^\mu\lambda_0\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda_0\psi)^2 \right]$$
$$\times \left[(\bar\psi\gamma^\mu\lambda_a\psi)^2 + (\bar\psi\gamma^\mu\gamma_5\lambda_a\psi)^2 \right]. \quad (3)$$

$$P \to P + B. \quad (4)$$

MFTQCD[4]

$$P = \frac{27}{2}\xi^2\rho_B^2 - B + P_F, \quad (5)$$
$$\epsilon = \frac{27}{2}\xi^2\rho_B^2 + B + \epsilon_F, \quad (6)$$

where

- $\xi = g/m_G$ and $m_G = \frac{9}{32}g^2\mu_0^2$;
- $B = \frac{9}{4(34)}g^2\phi_0^4$;
- P_F and ϵ_F are the pressure and energy density of a non-interacting Fermi gas of quarks and electrons.

[4] Fogaca and Navarra, “Gluon condensates in a cold quark–gluon plasma”.

Building the hybrid equations

Bayesian inference

Bayesian inference enables us to

- Obtain a set of parameters for the EOS;
- These EOS satisfy the restrictions imposed.

Building the hybrid equations

Constraints imposed by Bayesian inference:

1. X-ray observations (NICER)

2. phase transition

3. pQCD EOS

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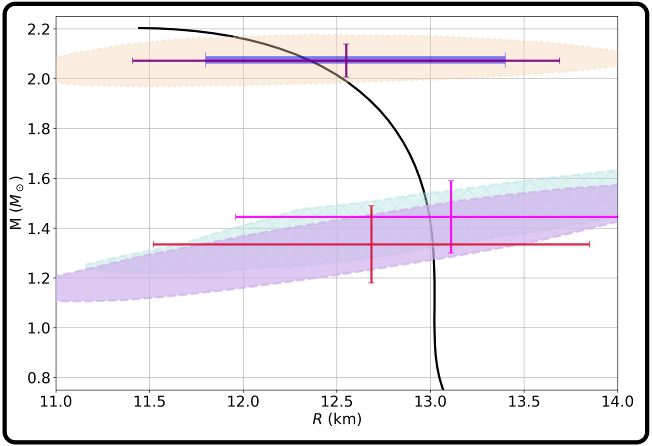

Building the hybrid equations

Constraints imposed by Bayesian inference:

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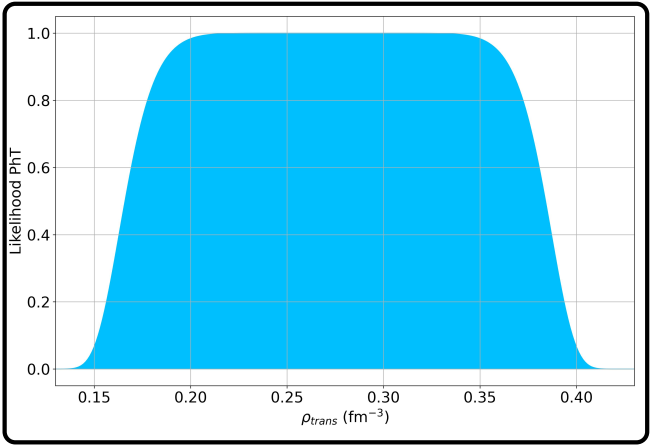
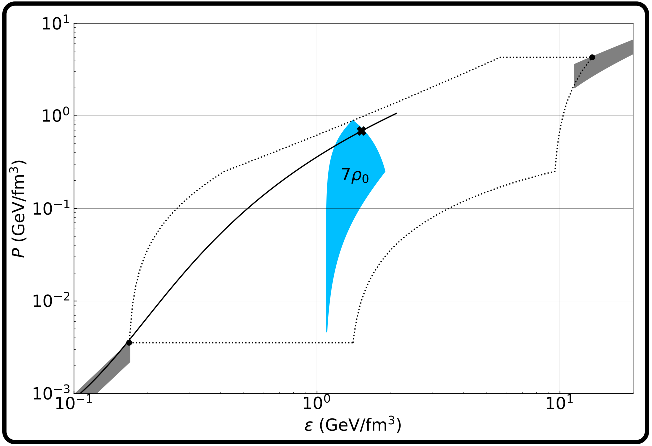


Building the hybrid equations

Constraints imposed by Bayesian inference:

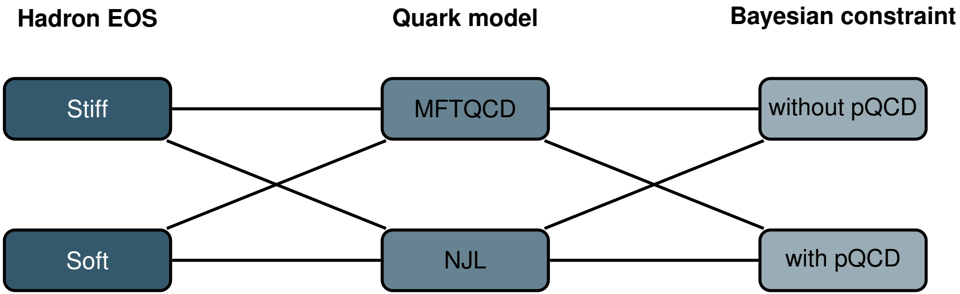
1. X-ray observations (NICER)
2. phase transition
3. pQCD EOS[5]



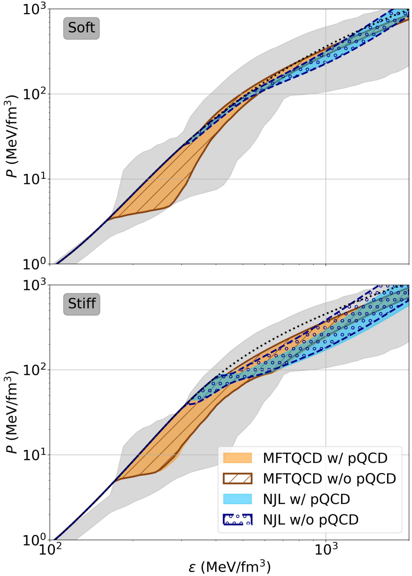
[5]Oleg Komoltsev and Aleksi Kurkela. **"How Perturbative QCD Constrains the Equation of State at Neutron-Star Densities".** In: *Phys. Rev. Lett.* 128.20 (2022), p. 202701. DOI: 10.1103/PhysRevLett.128.202701. arXiv: 2111.05350 [nucl-th].

Building the hybrid equations

- We got 8 sets combining the following options:



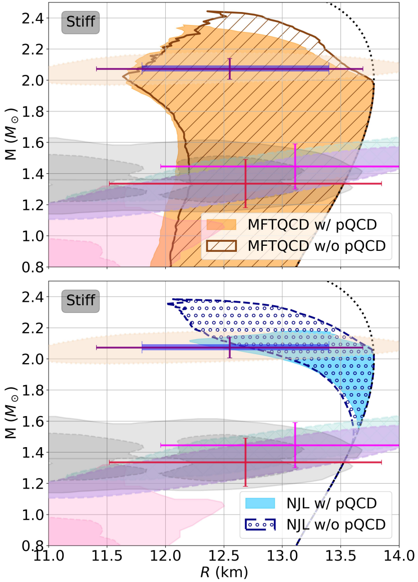
EOS Results



- compatible with results from[a] (gray);
- the MFTQCD model allows a deconfinement phase transition at much lower baryon densities compared to the NJL model.

[a] Eemeli Annala et al. **"Evidence for quark-matter cores in massive neutron stars".** In: *Nature Physics* 16.9 (June 2020), pp. 907–910. ISSN: 1745-2481. DOI: 10.1038/s41567-020-0914-9. URL:

pQCD effect

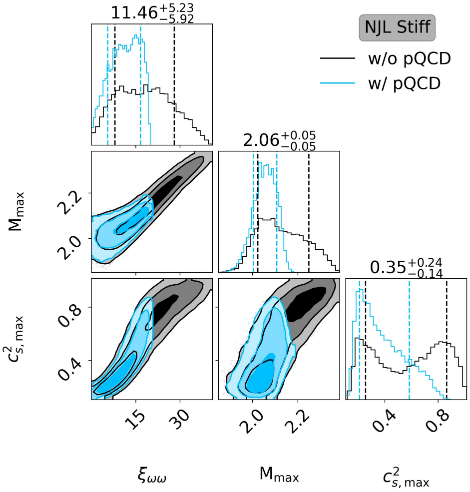


- pQCD constraint reduces the maximum mass in both NJL and MFTQCD models.

This reduction occurs with more intensity in the **NJL model**.

- There is a correlation between the $\xi_{\omega\omega}$ term, the maximum mass and the speed of sound.

pQCD effect

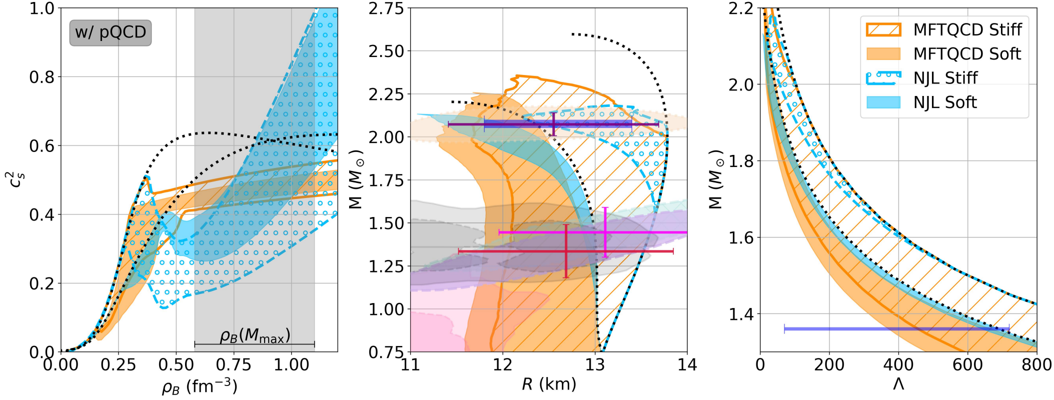


- pQCD constraint reduces the maximum mass in both NJL and MFTQCD models.

This reduction occurs with more intensity in the **NJL model**.

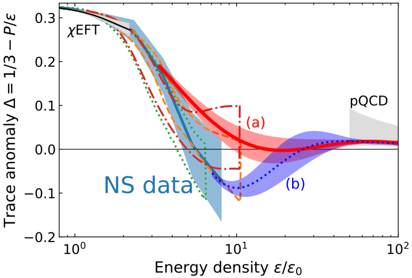
- There is a correlation between the $\xi_{\omega\omega}$ term, the maximum mass and the speed of sound.

NJL vs MFTQCD and Soft vs Stiff



- MFTQCD can reach radii below 12 km for medium mass stars;
- all sets are compatible with NICER observations;
- NJL stiff set is not able to describe the tidal deformability from GW170817 data;

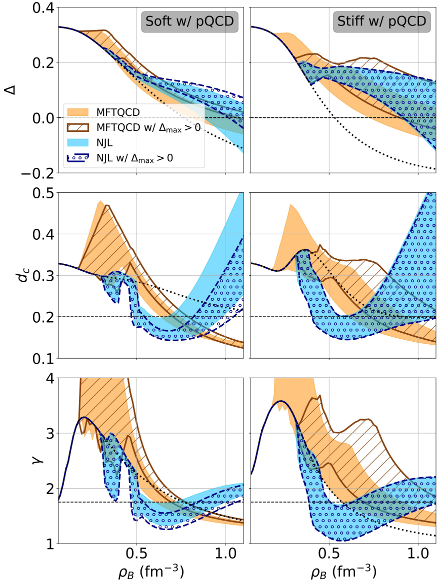
Comparison with metamodels results



Trace anomaly as a mesure of conformability[a]

$$\Delta = \frac{\epsilon - 3P}{3\epsilon}. \quad (7)$$

[a] Yuki Fujimoto et al. **"Trace Anomaly as Signature of Conformality in Neutron Stars".** In: *Physical Review Letters* 129.25 (Dec. 2022). DOI: 10.1103/physrevlett.129.252702.



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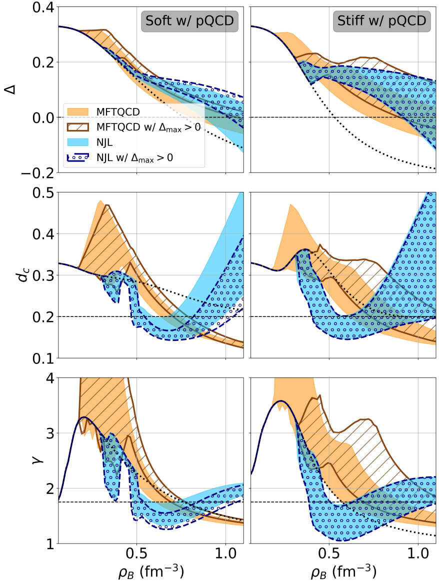

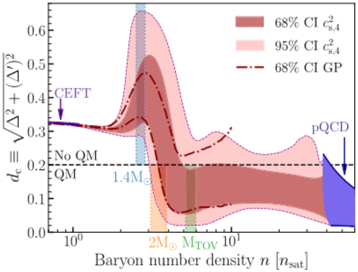

Define the quantity[a] $d_c \equiv \sqrt{\Delta^2 + (\Delta')^2}$, where $\Delta' = d\Delta/d\ln\epsilon$.

$$d_c \begin{cases} < 0.2 \Rightarrow \text{QM}; \\ > 0.2 \Rightarrow \text{HM}. \end{cases} \quad (7)$$

[a] Eemeli Annala et al. **"Strongly interacting matter exhibits deconfined behavior in massive neutron stars"**. In: *Nature Commun.* 14.1 (2023), p. 8451. DOI: 10.1038/s41467-023-44051-y.

Conclusions

- **Objective:** answer the question "is deconfined quark matter present in the NS core?" using microscopic models;
- we obtained 8 different sets, combining the following options: i) hadron EOS (soft or stiff), ii) quark model (NJL or MFTQCD), iii) with or without imposing the pQCD constraint;
- the current observational data are compatible with the existence of a quark core inside NS;
- pQCD constrains the $\xi_{\omega\omega}$ values in the NJL model;
- we obtained for the maximum star mass a value of the order of 2.1–2.3 $M_{\odot}$;
- MFTQCD results in medium and low mass NS with a smaller radius;
- NJL (MFTQCD) has a quark-hadron phase transition above $\sim$ 0.25 (0.15) fm^{-3}.

THANK YOU!

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References

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[1] Eemeli Annala et al. **"Evidence for quark-matter cores in massive neutron stars".** In: *Nature Physics* 16.9 (June 2020), pp. 907–910. ISSN: 1745-2481. DOI: 10.1038/s41567-020-0914-9. URL: http://dx.doi.org/10.1038/s41567-020-0914-9.

[2] Eemeli Annala et al. **"Strongly interacting matter exhibits deconfined behavior in massive neutron stars".** In: *Nature Commun.* 14.1 (2023), p. 8451. DOI: 10.1038/s41467-023-44051-y. arXiv: 2303.11356 [astro-ph.HE].

[3] L. S. Celenza and C. M. Shakin. **"Description of the gluon condensate".** In: *Phys. Rev. D* 34 (5 Sept. 1986), pp. 1591–1600. DOI: 10.1103/PhysRevD.34.1591.

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[8] Tuhin Malik et al. **"Spanning the full range of neutron star properties within a microscopic description".** In: *Phys. Rev. D* 107.10 (2023), p. 103018. DOI: 10.1103/PhysRevD.107.103018. arXiv: 2301.08169 [nucl-th].