Hybrid stars and the stiffness of the nuclear equation of state in light of the HESS J1731-347 remnant[1]

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[1] P. Laskos-Patkos, P.S. Koliogiannis, Ch.C. Moustakidis. Phys. Rev. D **109**, 063017, (2024)

Overview

- Neutron stars
- HESS J1731-347
- PREX-II experiment and the stiffness of the nuclear EOS
- Scope
- The hybrid EOS
- Results
- Conclusions

Bulk properties of neutron stars

Neutron Stars: Unique Extraterrestrial Laboratories

- $M \sim 1.4\ \mathrm{M}_{\odot}$
- $R \sim$ 10-15 km
- $\rho_c > 2.8 \times 10^{14}$ gr cm^{-3}
- $f \sim$ *few* Hz - 700 Hz
- $B \sim 10^{12}$ Gauss

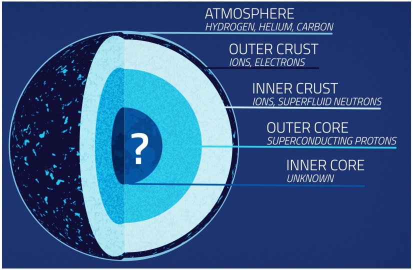

Figure: The layers of a neutron star[a]

[a] credit: NASA

Neutron star observations and nuclear physics

Different nuclear models $\rightarrow$ different equation of state $\rightarrow$ different neutron star bulk properties.

Neutron star observations and nuclear physics

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In the past years:

- The observation of massive neutron stars exceeding $2M_\odot$ posed a significant challenge in the past decades $\rightarrow$ stiff EOS behavior at high densities.
- Determination of the radii and tidal deformabilities of canonical neutron stars (LIGO/Virgo and NICER) $\rightarrow$ additional constraints at intermediate densities.

The central compact object (CCO) in the HESS J1731-347 remnant

The CCO in HESS J1731347 is particularly bright! Since 2007 it has been observed multiple times with different X-ray satellites.

- Analysis of the x-ray spectrum for the CCO in the HESS J1731-347 remnant[2] $\rightarrow$ surprising small values for its mass and radius ($M = 0.77^{+0.20}_{-0.17} M_{\odot}$ and $R = 10.4^{+0.86}_{-0.78}$km in 1σ).

[2] Nat. Astron. 6, 1444–1451 (2022)

[3] Phys. Rev. C 94, 052801(R) (2023)

[4] Prog. Theor. Exp. Phys. 041, D01 (2022)

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- The radius of low mass neutron stars is correlated with nuclear parameters at saturation[3,4] $\rightarrow$ A soft equation of state at low density is favored $\rightarrow$ low symmetry slope L and/or low incompressibility K_0.

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[3] Phys. Rev. C 94, 052801(R) (2023)

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The PREX-II experiment and neutron star structure

The Lead Radius Experiment (PREX), used the parity violating weak neutral interaction to probe the neutron distribution in ^{208}Pb (measuring its neutron skin thickness)

- The derived neutron skin thickness of Lead was found to be $\Delta R_{np} = 0.28 \pm 0.07$ (in 1σ)[5].
- ΔR_{np} of heavy nuclei is strongly correlated with the slope parameter $L \rightarrow$ Large neutron star radii for low mass configurations[6].

[5] Phys. Rev. Lett. 126, 172502 (2021)
[6] Phys. Rev. Lett. 126, 172503 (2021)

Scope

- The analysis of Doroshenko *et al.* indicated that the subsolar mass NS in the HESS J1731-347 remnant has a radius lower than 11.5 km[7].
- Different analyses suggest that the PREX-II experiment would point larger neutron star radii above 13 km[8,9].

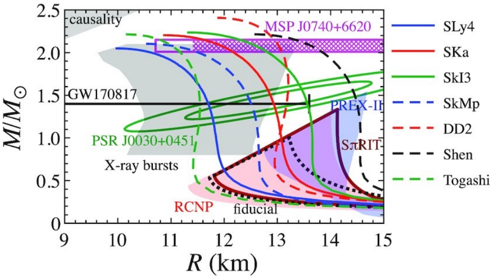

Figure: The layers of a neutron star (reproduced under CC By)[9].

[7] Nat. Astron. 6, 1444–1451 (2022)

[8] Phys. Rev. Lett. 126, 172503 (2021)

[9] Prog. Theor. Exp. Phys. 041, D01 (2022)

Scope

In the present study we aim to access the possible reconciliation of the two aforementioned events by considering the possibility of a phase transition between hadronic and deconfined quark matter.

Hybrid equation of state

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- **Hadronic EOSs:** *Ska, SkI3, SkI5* $\rightarrow \Delta R_{np}$ compatible with PREX-II and K_0 within the generally accepted range[10].
- **Quark EOS:** *vMIT Bag model*[11]

$$\mathcal{E}_Q = \sum_q \mathcal{E}_q + \frac{1}{2} G_v (n_u + n_d + n_s)^2 + B.$$

- Phase transition via **Maxwell construction**

$$P^h = P^q, \quad \mu_B^h = \mu_B^q, \quad T^h = T^q.$$

[10] Phys. Rev. C 89, 044316 (2014)

[11] MNRAS 485, 4873–4877 (2019)

Hybrid equation of state

We investigate two scenario with regards to parameter B:

- Constant (as in standard MIT bag models)
- Density dependant (the widely employed Gaussian parametrization)[12]

$$B(n) = B_{as} + (B_0 - B_{as}) \exp\left[-\beta\left(\frac{n}{n_0}\right)^2\right].$$

[12] Phys. Rev. C 66, 025802 (2002)

Case 1: Constant B

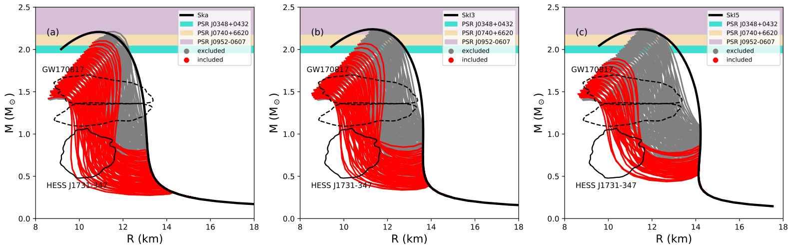

Figure: Mass-Radius diagrams for hybrid stars constructed with different hadronic models and the vMIT bag model with constant B.

Case 1: Constant B

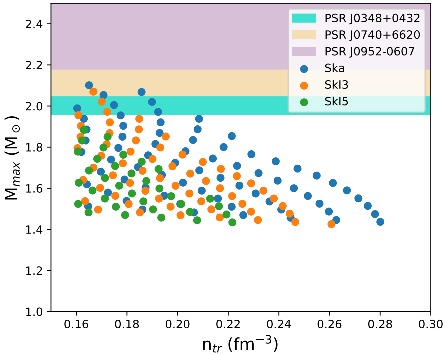

Figure: Maximum mass as a function of the phase transition density (vMIT bag model with constant B).

Case 2: Density dependant B

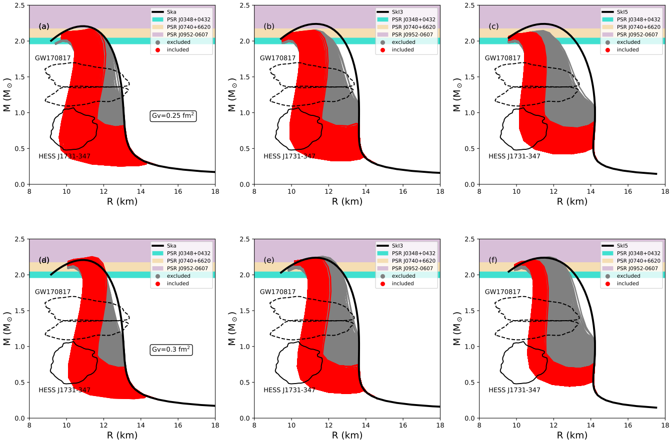

Figure: Mass-Radius diagrams for hybrid stars constructed with different hadronic models and the vMIT bag model with density dependant B.

Case 2: Density dependant B

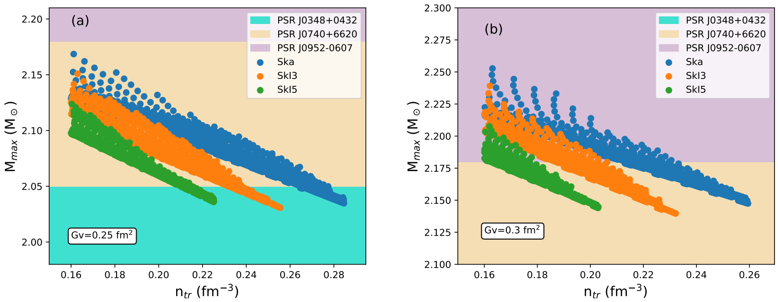

Figure: Maximum mass as a function of the phase transition density (vMIT bag model with density dependant B).

$\longrightarrow$ **The inclusion of rotational effects (709 Hz) allows for the explanation of PSR J0952-0607 for all possible transition density values (in the $G_v = 0.3$ fm^2 case).**

The puzzling GW190814 event

In 2019 Ligo/Virgo reported a merger event involving a compact object of $\sim 2.6 M_{\odot}$.

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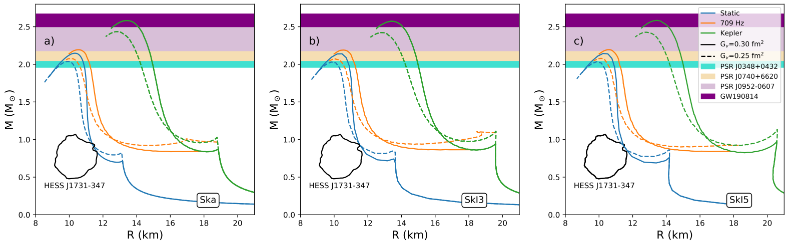

Figure: M-R diagrams for the EOSs that predict the highest possible transition density (lowest maximum mass) + rotating stellar sequences.

→ **Yes but only the under the assumption of extreme rotation.**

Conclusions and future prospects

- The reconciliation of both HESS J1731-347 and PREX-II is possible given that a strong phase transition in the neutron star interior.
- A constant density value of B allows for the explanation of the aforementioned events but fails to support massive compact stars unless the transition occurs close to nuclear saturation.
- A density dependant value of B allows for the explanation of the aforementioned events and other important astronomical data (such as maximum mass constraints).
- The puzzling GW190814 can be explained as well but only if we consider Keplerian rotation.
- We aim to revisit this study using a relativistic *ab initio* model for the description of the low density hadronic phase.