Extreme Matter meets Extreme Gravity: Observational Implications of Ultra-Heavy Neutron Stars with Cross-Overs and Phase Transitions

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Current state of QCD phase diagram

- A complete picture requires putting together astrophysics observations and laboratory measurements, in addition to lattice QCD, PQCD, ...

- Since 2015 (2017), we can also see the universe through gravitational waves
What have we learned about dense matter from GW170817

- Realistic waveform deviation from point-particle one: tidal deformability, measured in the end of inspiral
- New vector-isovector channel that can be added to any model

\[ L_{\omega\rho} = g_{\omega\rho} g_\omega^2 g_\rho^2 \omega^\mu \omega^\mu \rho^\mu \]

\( \omega\rho \) coupling

EFT “data” from Hebeler et al. for neutron matter

improves overall agreement with observation! e-Print: 1810.06109
What have we learned about dense matter from GW190814

- Merger of $23.2^{+1.1}_{-1.0}\ M_{\text{Sun}}$ black hole and a $2.59^{+0.08}_{-0.09}\ M_{\text{Sun}}$ object
- New vector interactions increase masses to $> 2\ M_{\text{Sun}}$
- Rotation close to the Kepler frequency reproduces $\sim 2.5\ M_{\text{Sun}}$ stars with hyperons and quarks

- Exotic degrees of freedom are not excluded!

\[ \begin{align*}
\text{CMF model} & \\
\omega^4 = \omega^6 = 0 & \\
\omega^4 \neq 0 & \\
\omega^6 \neq 0 & \\
\omega^4 = \omega^6 \neq 0 \text{ with quarks} & \\
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\omega^6 \neq 0 \text{ with quarks} & \\
\end{align*} \]
Using **magnetic fields** instead of rotation

- Maximum fields allowed by axi-symmetric GR codes $\sim 10^{18}$ G not enough to change significantly equation of state
- But decrease in hyperon fraction could increase stellar masses enough to explain GW190814
- Stellar radius becomes much larger
- Still, exotic degrees of freedom are not excluded when using density dependent couplings

![Graph](chart.png)

**e-Print:** [2104.05950](https://arxiv.org/abs/2104.05950)
Does it depend on a particular model?

- Model-independent parametric approaches can generate even more massive stars, such as the companion of V723 Mon with $M \geq 2.91 \pm 0.08 \, M_{\text{Sun}}$ with central densities not larger $\lesssim 4 \, n_{\text{sat}}$

- Considering GW190814 as involving a neutron star, we generate central densities $\lesssim 6 \, n_{\text{sat}}$ (otherwise the limit is $\sim 8 \, n_{\text{sat}}$)

e-prints: 2006.16296, 2106.03890
Size and position of bumps

- Reproducing $M > 2.5 \ M_{\text{Sun}}$ stars requires a steep rise in $c_s^2$ at $n_B < 3 \ n_{\text{sat}}$, consistent with a bump or a plateau that could be associated with vector interactions (see Pisarski 2021)

- Radius measurements with smaller error could help pinpointing the position of bump
More complicated structures

- Plateau heights are harder to determine observationally

- Extra bumps could be motivated by hyperons and other crossover transitions but only slightly modify max. masses
First-order phase transitions

- Still reproduce $M > 2.5 \, M_{\text{Sun}}$ stars

- More “extended” phase transitions switch from generating connecting branches, to kinks, to twin solutions

- But disconnected twins are only found with thin bumps and do not reach $2.5 \, M_{\text{Sun}}$, regardless of the slant after the transition or the height of the plateau

- Neither of these configurations violates I-Love-Q relations (variation below 1.5%)
Discussion

• Neutron-star mergers create unique ideal conditions to achieve deconfinement

• Comparisons between HI collisions and astrophysics must be performed with care ($Y_Q$, $Y_S$, leptons, chem. eqil, ...)

• Now, in addition to observe light, we can also understand the universe through gravitational waves so, maybe, there will be a clear signature for a quark deconfinement phase transition from astrophysics!

• Post-merger part of neutron-star mergers could tell us about deconfinement ... but not yet observed

• For now, we can learn from dense stellar masses, radii, and tidal deformability

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The Mass Distribution of Neutron Stars in Gravitational-Wave Binaries

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\textbf{Figure 1.} Measured masses and inferred mass distribution for NSs in GW binaries. \textit{Top:} Marginal one-dimensional mass likelihoods $P(d|m)$ for the NSs in the BNS mergers GW170817 and GW190425, the NSBH mergers GW200105 and GW200115, and the candidate NSBH merger GW190814.