GW190814 as a massive rapidly-rotating neutron star with exotic degrees of freedom

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In the context of the massive secondary object recently observed in the compact-star merger GW190814, we investigate the possibility of producing massive neutron stars from equation of state models that contain exotic degrees of freedom, such as hyperons and quarks. Our work shows that state-of-the-art relativistic mean field models can generate massive stars reaching \( \gtrsim 2.05 \, M_{\odot} \), while being in good agreement with gravitational-wave events and x-ray pulsar observations, when quark vector interactions and higher-order self-vector interactions are introduced. When rapid rotation is added, our models generate stellar masses that approach, and in some cases surpass \( 2.5 \, M_{\odot} \). We find that in such cases fast rotation does not necessarily suppress exotic degrees of freedom due to changes in stellar central density compared to non-rotating cases.

I. INTRODUCTION

In the last decade, several massive neutron stars have been observed, \( 1.97 \pm 0.04 \, M_{\odot} \) [1], \( 2.01 \pm 0.04 \, M_{\odot} \) [2], \( 2.27 \pm 0.17 \, M_{\odot} \) [3], and \( 2.14^{+0.20}_{-0.18} \, M_{\odot} \) [4], all consistent with having a mass of \( \lesssim 2.1 \, M_{\odot} \). While some of these observed neutron stars are rapidly spinning, we note that the most rapidly known pulsar PSR J1748-2446ad was found to rotate with a frequency of 716 Hz [5]. Following the multi-messenger gravitational wave event GW170817 [6], it was argued that the maximum mass of neutron stars is likely to be bounded by \( M \lesssim 2.3 \, M_{\odot} \) [7]. It has been shown [7] that such an upper bound would allow for uniformly rotating stars of up to \( M \lesssim 2.8 \, M_{\odot} \). Recently, the LIGO/VIRGO collaboration has announced the gravitational wave event GW190814 [8], which was reported to be the merger of a \( 23.2^{+1.1}_{-1.0} \, M_{\odot} \) black hole and a \( 2.59^{+0.08}_{-0.09} \, M_{\odot} \) object. The latter (secondary) object’s mass falls into the so called “mass-gap” category, in which stars are considered too light to be a black hole but too heavy to be a neutron star. The latter being due to lack of electromagnetic observations, but also due to conflicts with our current knowledge of supernova explosion mechanisms [9]. See also Ref. [10] for a recent discussion on the mass-gap in the context of GW190814 and Ref. [11] for an alternative explanation in the context of circumbinary accretion.

Recently, it was found that non-rotating nucleonic models can generate massive stars with \( M \sim 2.5 \, M_{\odot} \) [12–14], although it was shown that some of them are not necessarily compatible with constraints obtained from energetic heavy-ion collisions [15]. Including fast rotation, Ref. [15] demonstrated that using a parametrized nucleonic equation of state (EoS), \( M > 2.5 \, M_{\odot} \) stars can be stable although, again, this can create tension with other astrophysical observables [17].

Following recent advances in the literature showing that massive neutron stars should contain a quark core [18], in this Letter, we investigate the possibility of having exotic degrees of freedom in rapidly rotating neutron stars. We apply realistic relativistic models to describe the interior of massive neutron stars as containing hyperons [19] and/or quarks [20, 21], which is possible due to the introduction of different vector (repulsive) interactions. In a second step, we introduce fast rotation effects using a full general relativity numerical code that allows stars to be deformed, contain a larger baryon number, and be much more massive than static solutions.

II. RESULTS

The intermediate and high density regimes (\( \gtrsim 2 \, n_{0} \), the nuclear saturation density) that occupy a significant portion of the volume inside neutron stars are regions where neither of the reliable theories of Effective Field Theory for nucleons at low density or Perturbative Quantum Chromo Dynamics (PQCD) at extremely high density can be applied. As a result, there are very few options left. One of them is to resort to some sort of interpolation [22, 23] and another is to rely on relativistic mean-field effective models. In this work, we make use of the latter, which unlike the former, can provide a particle population and, therefore, can be tested in dynamical stellar simulations of, for example, stellar cooling. In particular, the relativistic Chiral Mean Field (CMF) model is based on a nonlinear realization of the SU(3) sigma model and is constructed in such a way that chiral invariance is restored at large temperatures and/or densities. In its present version, it contains hadronic, as
as well as quark degrees of freedom \footnote{Note that an alternative version of the CMF model includes in addition the chiral partners of the baryons and gives the baryons a finite size \cite{24,22}.}. The CMF model was fitted to reproduce low and high-energy nuclear and lattice QCD constraints \cite{26}, such as the deconfinement crossover transition expected to take place at very large temperatures, as well as tested in stellar merger \cite{27} and cooling simulations \cite{28}. For a detailed description of how this formalism can be applied to describe neutron and proto-neutron stars, while being in agreement with PQCD results for the relevant regime, see Ref. \cite{29}.

Here, we apply the CMF model with a few novel features. First, we use a new vector-isovector $\omega \rho$ kind self interaction, as recently discussed in Ref. \cite{30} for several hadronic models. It allows us to describe a more soft EoS at intermediate densities and, as a consequence, reproduces stars with small radius and small tidal deformability, in addition to being in better agreement with Effective Field Theory results for low density \cite{31}. We set our $\omega \rho$ coupling strength here to 11 in order to generate tidal deformabilities $\Lambda < 730$, in agreement with results obtained from the binary neutron-star merger GW170817 \cite{32}. Results are shown for pure hadronic matter in the solid navy-blue line of Fig. 1, made using the Baym, Pethick, and Sutherland (BPS) prescription for the crust \cite{33}. In this figure, we also vary the $\omega \rho$ coupling strength from $0 \rightarrow 62$ (as in Ref. \cite{30}) in order to illustrate how it relates to stellar radius. Note that, alternatively, varying the scalar-isoscalar coupling strength would produce a similar outcome \cite{34}, although this change is not allowed in chiral models (such as ours) in which the scalar sector is fixed in order to generate the vacuum masses of hadrons.

As the second modification to the (hadronic and quark) CMF model, we add two new higher-order vector self interactions: $\omega^4$, similar to what has been recently done in Ref. \cite{35} for the bag model, and $\omega^6$, which can produce strong repulsion at larger densities. These terms allow us to reproduce a stiffer EoS and generate more massive neutron stars. Results are shown by the dashed and dotted navy-blue lines in Fig. 1. As the third modification, we change our potential for the field $\Phi$ related to deconfinement in the CMF formalism to depend on the chemical potential to the second power (instead of fourth, as it was originally proposed). In this case, the less steep first order phase transition, with the addition of non-zero vector couplings for the quarks as the fourth modification, allows for stable stars with a pure quark core. Originally, only stable cores with a mixture of hadronic and quark phases achieved through a Gibbs construction were reproduced by the CMF model \cite{26}. Results including a phase of deconfined quarks are shown in green in Fig. 1. As shown in Tab. I, when allowing for new higher-order self-vector interactions, more massive stars are obtained, even when allowing for a phase transition to quark matter. Note that a phase transition decreases the unusually high speed of sound squared in the center of the most massive hadronic star for the $\omega^6$ parametrization, while still generating neutron stars with masses close to the ones discussed in Refs. \cite{8,36}. The results marked by an asterisk in Tab. I reproduce a late (very high density) phase transition to quark matter.

![Static mass-radius diagram for several CMF model equations of state (shown until the maximum mass only). Green curves present a first-order phase transition to deconfined quark matter. The grey lines show the results of varying the $\omega \rho$ vector-isovector self interaction coupling strength from $0 \rightarrow 62$ for hadronic matter.](image)

**TABLE I:** For each different set of high-order vector self interactions, we show the maximum allowed stellar mass $M$ of the static stellar sequence, its central density $n_c$ (in units of saturation number density), its central speed of sound squared $v_s^2$, and the radius $R$ and tidal deformability $\Lambda$ for a $M = 1.4 M_{\text{Sun}}$ star. The top rows show results for hadronic (only) matter and the bottom when allowing for a phase transition to deconfined quark matter. The results marked by an asterisk reproduce a late (very high density) phase transition to quark matter.

| Interactions | $M(M_{\text{Sun}})$ | $n_c(n_0)$ | $v_s^2$ | $R_{1.4}$ (km) | $\Lambda_{1.4}$ |
|--------------|---------------------|-------------|---------|----------------|----------------|
| hadrons only | $\omega^4 = \omega^6 = 0$ | 2.00 | 6.5 | 0.47 | 13.4 | 711 |
|              | $\omega^4 \neq 0$ | 2.08 | 6.5 | 0.57 | 13.5 | 730 |
|              | $\omega^6 \neq 0$ | 2.07 | 6.8 | 0.96 | 13.5 | 722 |
| with quarks  | $\omega^4 = \omega^6 = 0$ | 1.99 | 6.9 | 0.60 | 13.4 | 711 |
|              | $\omega^4 \neq 0$ | 2.02 | 6.0 | 0.53 | 13.5 | 730 |
|              | $\omega^6 \neq 0$ | 2.07 | 6.3 | 0.56 | 13.5 | 730 |
|              | $\omega^4 \neq 0$ | 2.03 | 6.6 | 0.61 | 13.5 | 722 |
|              | $\omega^6 \neq 0$ | 2.07 | 6.7 | 0.61 | 13.5 | 722 |
Fig. 2: Mass-central density diagram for rotating stars reproduced by the CMF model allowing for a late deconfinement to quark matter. The rotational frequency increases vertically and the (almost) horizontal lines denote constant baryon number and are spaced $0.1 M_{\odot}$ apart. The top panel shows results for $\omega^4 \neq 0$ and the bottom panel for the $\omega^6 \neq 0$ case.

The onset of hyperons and quarks is denoted by labelled vertical black lines. The color code shows angular momentum in units of $M^2$.

In reality, the amount of extra baryons to be found in a rapidly spinning neutron star close to the break-up limit is not known. In Fig. 2, one can see for each of our equations of state, the amount of baryon number above what is predicted by static solutions for the maximum mass of the sequence that is necessary to approach a $2.5 M_{\odot}$ star. For completeness, we report the characteristics of the most massive maximally spinning configuration in the first two lines of Tab. II. We note that the maximum mass of the most rapidly spinning hybrid star of the CMF models is about 1.18 times larger than the mass of the most massive non-spinning star. This is fully in line with universal relations for hadronic stars [38] but less than what has previously been reported for certain first-order phase transition models [39].

For comparison, we also show how vector interactions in the quark EoS can generate massive stars within different models. Note that all of these, including the CMF model, fulfill tidal deformability constraints from Ref. [32] and recent NICER x-ray pulsar radius constraints from Refs. [40, 41]. We start with a model combination, matching the relativistic Many-body Forces (MBF) model [42] which describes the interaction of baryons considering higher-order scalar self-couplings interpreted as many-body forces, with a vector-enhanced Bag (vBag) model. We once more add a BPS crust to the EoS [33]. The MBF model used here contains $\omega_\rho$ contributions (coupling strength of 40), following the same motivation as for the CMF model. The hybrid stars are constructed in this case via a Maxwell construction leading to a quark phase in which the higher-order vector self interaction $\omega^4$ term is also included with strength 23, while the Bag constant is $B=77 \text{ MeV fm}^{-3}$ and the quark vector coupling is $a_0=3 \text{ fm}^2$ [43, 44]. The stellar masses and radii generated by this EoS are shown in Fig. 3 and Tab. III.

In a completely different approach, we describe pure quark stars using the vector interaction enhanced bag
model (vBag) [45], which now parametrize to reproduce absolutely stable strange matter [46] with a bag constant $B=59 \text{ MeV} \text{ fm}^{-3}$ and quark vector coupling $K_v = 70 \text{ fm}^2$. It is further worth mentioning that the main difference between vBag and standard Nambu-\text{A}Ş\text{Jona-Lasinio} (NJL) models in the chirally restored phase is the value of the effective vacuum bag constant, which due to confinement is expected to be smaller in bag type models and, hence, more likely in support of the strange matter hypothesis [45]. As can be seen in Fig. 3 and Tab. III, vector repulsion is essential and sufficient to model high-mass pure quark stars.

Figure 4 shows the impact of rotation effects on the two additional models discussed above. The largest possible gravitational mass found for stars increases again with increasing rotational frequency, easily achieving and going above $2.5 \text{M}_{\odot}$. Once more, for the combined model, an increase in rotation at fixed (or small increase in) baryon number decreases the stellar central density, suppressing hyperonic and quark degrees of freedom. Only in the pure quark model, are the quarks never suppressed, irrespective of the increase or lack of increase in baryon number when compared to the static solution. The characteristics of the most massive maximally spinning configuration are shown in the last two lines of Tab. II. Note that all frequency limits in this table are within the range predicted by Ref. [10], which used universal relations to generate rapidly-rotating massive stars.

### III. CONCLUSIONS AND DISCUSSIONS

We have presented an extension of the Chiral Mean Field (CMF) hadronic and quark relativistic mean-field model that contains new vector interactions, while also comparing it with other models. We demonstrated that these interactions can increase the maximum mass of stable non-rotating hybrid stars to $\simeq 2.1 \text{M}_{\odot}$, but at the same time not creating conflict with other observations. Although it has been shown that strong vector interactions are not favored by lattice QCD [47, 48], those calculations are performed in the large temperature, low density limit and do not necessarily extrapolate to our low temperature, high density regime. For each equation of state, we have calculated using a full general-relativity
numerical code the parameter space of rapidly rotating neutron stars up to break-up frequencies of $\sim 1.5\,\text{kHz}$. While adding a larger amount of baryon number does not affect the central density of stars, a lower amount does. In this case, massive hybrid stars can be reproduced, but with some amount of hyperon and quark degrees of freedom suppressed. If such rapidly rotating neutron stars were formed as the remnants of low-mass binary neutron star mergers \[49\], it would be interesting to investigate if changes in their structure due to the deconfinement of quarks could lead to any appreciable observational signature as they spin down. An exception here is the case of pure quark stars, in which the quarks are fully present in all possible rotating configurations. The latter case also allows $\sim 2.5\,M_{\odot}$ stars to have approximately the same amount of baryons as non-spinning solutions. Several works in the literature have already investigated how the appearance of quarks in supernova events can trigger the explosion of massive stars \[50, 51\], but much more work is needed to fully understand this scenario in the context of different gravitational vs. baryon masses. Work on this topic is in progress.

We finally comment on the implications of our work for a hypothetical neutron star origin of the secondary object in GW190814. We have shown that rapid rotation can increase the maximally allowed mass of rotating hybrid stars to $\sim 2.5\,M_{\odot}$. This indicates that, with further refinement of the models, having deconfined quarks is not at odds with supporting a massive neutron star, while also not being in conflict with other recent astrophysical observations of stellar radius and tidal deformability. This type of analysis allows us to learn more about the attractive and repulsive components of strongly interacting matter in a regime otherwise not accessible. Furthermore, we find that even a slowly rotating pure quark star could explain a non-black hole massive secondary object. This is a feature that is beyond the mass range comfortably attainable with realistic hybrid-star models.

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