We investigate the possibility that the low mass companion of the black hole in the source of GW190814 was a strange quark star. This possibility is viable within the so-called two-families scenario in which neutron stars and strange quark stars coexist. Strange quark stars can reach the mass range indicated by GW190814, \( M \sim (2.5 - 2.67)M_\odot \) due to a large value of the adiabatic index, without the need for a velocity of sound close to the causal limit. Neutron stars (actually hyperonic stars in the two-families scenario) can instead fulfil the presently available astrophysical and nuclear physics constraints which require a softer equation of state. In this scheme it is possible to satisfy both the request of very large stellar masses and of small radii while using totally realistic and physically motivated equations of state. Moreover it is possible to get a radius for a 1.4 \( M_\odot \) star of the order or less than 11 km, which is impossible if only one family of compact stars exists.

PACS numbers:

**INTRODUCTION**

The gravitational wave signal GW190814 detected in 2019 by the LIGO/Virgo Collaboration \(^1\) has been generated by the merger of a binary system whose components are a 23 \( M_\odot \) black hole (BH) and a (2.5 – 2.67) \( M_\odot \) compact object. Explaining the nature of this compact object is nowadays a big challenge for astrophysics and dense matter physics. The value of its mass falls within the expected lower end of the so-called mass gap (2.5 \( M_\odot \) < \( M \) < 5 \( M_\odot \)) and, therefore, this object is not expected to be a BH. Nevertheless, there are interpretations based on the assumption that GW190814 is actually a binary BH system, and proposals for the formation of light BHs (including primordial BHs) have been put forward \(^2,3\). On the other hand, if this compact object is instead a neutron star (NS), then several issues concerning the stiffness of the equation of state (EOS) and the rotational properties of NSs need to be addressed \(^4\).

Indeed, there are currently two possible explanations for the existence of such a massive NS: the EOS of dense matter is significantly stiff in order to support such large mass \(^5,6\) or the NS was rotating very close to the keplerian limit \(^7,8\). There are, however, two major drawbacks of these kind of interpretations. In the first case one needs a rather stiff EOS, with a speed of sound \( v_s \) that should exceed \( \sqrt{0.6c} \). In turn, EOSs which allow for the existence of such massive NSs are in tension with constraints obtained from heavy ions collisions experiments \(^9\) and from the tidal deformability constraints derived from GW170817 \(^10\) which favor softer EOSs. Regarding the second explanation, one needs to explain how a BH-NS system could merge before dissipating the large natal NS angular momentum \(^1\). Other possibilities are based on extended gravity theories \(^11,12\) or on theories predicting the existence of bosonic stars or gravastars, see \(^1\) and references therein.

In this Letter, we propose a solution that does not require new physics (e.g., modified gravity or the inclusion of new particles) apart from the assumption that the true ground state of strongly interacting matter is not \(^{56}\)Fe but a deconfined mixture of up (\( u \)), down (\( d \)) and strange (\( s \)) quarks, namely strange quark matter \(^23,24\). We investigate the possibility that indeed the low mass component in GW190814 was not a BH nor an ordinary NS but a (strange) quark star (QS), i.e., a star entirely composed of deconfined \( u, d, s \) quark matter. The fact that QSs could reach large values, \( M_{\text{QS}} \sim 2.75 \ M_\odot \), of the maximum mass has been discussed (see e.g. \(^23\)) already before the discovery of compact stars with \( M \sim 2 \ M_\odot \). More importantly, those large masses can be reached without the need for sound velocities close to the causal limit because in QSs the adiabatic index diverges at the surface of the star \(^25\). It is commonly accepted however that not all compact stars can be QSs, for instance magnetar oscillations pose challenges for QSs \(^25\).

NSs and QSs could coexist, as has been proposed and discussed in detail in several papers \(^30,46\). This is a viable possibility for relieving the tension between the indications of the existence of very compact stars (\( R_{1.4} \lesssim 11.5 \) km, where \( R_{1.4} \) is the radius of a star having a gravitational mass \( M = 1.4 \ M_\odot \)) and the existence of very massive stars \(^41,46\). Interestingly, if the low mass component of GW190814 is a NS, it has been shown that, if only one family of compact stars exists, \( R_{1.4} \gtrsim (11.6 - 11.8) \) km due to the causal limit \(^4,17\). Moreover, those rather small radii are obtained only in the extreme situation in which most of the star is occupied by matter with a speed of sound close to \( c \). Two coexisting families of compact stars are thus necessary if the maximum mass \( M_{\text{max}} \sim 2.6 \ M_\odot \) and \( R_{1.4} \lesssim 11.6 \) km.
FIG. 1: Mass-radius relations of NSs (thick black and blue lines correspond to the microscopic BHF and to the RMF EOS, respectively) and of QSs (thick red line), compared with several astrophysical data. Upper left panel: thermonuclear bursts \[18\]. Upper right panel: low mass X-ray binaries in quiescence \[18\] and the RXTE results for the cooling tail spectra of 4U1702-429 \[20\]. We have modelled the mass-radius posterior distribution of 4U1702-429 by using a bivariate gaussian with $\rho = 0.9$ as in \[21\]. All constraints are at the 68% CI. Lower right panel: constraints on the two compact stars of GW170817, solid (dashed) lines correspond to the 90% (68%) CI \[22\].

**EQUATIONS OF STATE**

Let us briefly discuss the EOSs for hadronic matter (i.e., matter with quarks confined within baryons and mesons) and for quark matter that could possibly describe the two coexisting families of compact stars.

In our analysis we will consider two hadronic EOSs, based, respectively, on a microscopic non-relativistic scheme and on a relativistic mean field (RMF) approximation.

**Microscopic hadronic EOS**

The first EOS of hadronic matter (composed of nucleons and hyperons in $\beta$-equilibrium with electrons and negative muons) is obtained within the Brueckner–Hartree-Fock (BHF) many-body approach using realistic nucleon-nucleon (NN) and three-nucleon (NNN) interactions derived in chiral effective field theory ($\chi$EFT) supplemented by nucleon-hyperon (NY) and nucleon-nucleon-hyperon (NNY) interactions, see Ref. \[19\] for details. This microscopic EOS reproduces the empirical properties of nuclear matter at the saturation density $n_0 = 0.16 \text{ fm}^{-3}$, does not violate causality (i.e., $v_s < c$), and is consistent (see Fig. 2 in \[19\]) with the measured elliptic flow of matter in collision experiments between heavy atomic nuclei \[15\]. When computing the mass-radius (M-R) relation for the corresponding ordinary NSs (also referred to as hadronic stars (HSs), i.e., compact stars with no fraction of deconfined quark matter) we obtain: i) a maximum mass $M_H^{\text{max}} \sim 2 M_\odot$ (the transition to a QS is discussed later); ii) a tidal deformability of the $1.4 M_\odot$ configuration $\Lambda_{1.4} = 388$, compatible with the constraints derived from GW170817 \[54\]; and iii) a threshold mass, for the prompt collapse to a BH of the postmerger compact object in GW170817, $M_{\text{threshold}} = 2.79 M_\odot$ (estimated by using the empirical formula given in Ref. \[51\]) indicating that GW170817 is compatible with being a NS-NS system if NSs are described by this EOS.

**Relativistic mean field hadronic EOS**

The second EOS we consider in this Letter is based on a RMF scheme in which nucleons, hyperons and $\Delta$-resonances are present \[52\]. The effect of the production
of $\Delta s$ is a further softening of the EOS: from one side this allows values of $R_{1.4}$ as small as 11 km [41, 53] to be reached, but on the other side the maximum mass is limited to be $M_{\text{max}}^H \approx 1.6 M_\odot$. The tidal deformability is $\Lambda_{1.4} \approx 150$ and $M_{\text{threshold}} \approx 2.5 M_\odot$ [54]. Therefore, when using this EOS, GW170817 cannot be described as a NS-NS merger, but it can be a NS-QS merger. In that case the average tidal deformability associated with the mixed binary system is $\Lambda \sim 450 - 550$, depending on the adopted quark EOS [53], and $M_{\text{threshold}} \approx (3 - 3.5) M_\odot$, again depending on the quark EOS.

**Quark matter EOS**

For the second family of compact stars, QSs, we use the simple quark matter model suggested in Ref. [55] where the grand canonical potential reads:

$$\Omega = -\frac{3}{4\pi^2}a_4 \mu^4 + \frac{3}{2\pi^2} \mu^2 (m_s^2 - 4\Delta^2) + B$$

where $\mu$ is the quark chemical potential, the bag constant is $B^{1/4} = 135$ MeV, the parameter $a_4$ (encoding perturbative QCD corrections) is set to $a_4 = 0.7$, the color–flavor locking (CFL) superconducting gap is $\Delta = 80$ MeV, and the strange quark mass is taken $m_s = 100$ MeV. This parameter set allows us to obtain a maximum mass $M_{\text{max}}^Q \approx 2.6 M_\odot$ due to an effective reduction of the bag constant caused by the presence of a (large) superconducting gap.

**No early quark production in symmetric matter**

It is well known that in the limit of massless, non-interacting quarks the maximum mass of QSs scales as $B^{-1/2}$ [24] and, therefore, to obtain very massive QSs in that simple scheme one has to adopt small values of the bag constant. In turn, such small values of $B$ easily lead to an unreasonably small critical density for the phase transition to quark matter, which is excluded by heavy ions experiments [55]. By using Eq. 1 we avoid that problem, because the CFL gap can exist only if strange quarks are present and abundant [57]. We have explicitly checked that in the case of symmetric, two-flavor quark matter at $T = 0$ nuclear matter is energetically favored with respect to quark matter up to very large densities.

**MASS-RADIUS RELATIONS**

We display in Fig. 1 the M-R relations for HSs and for QSs, compared with several astrophysical constraints. The two hadronic EOSs discussed in this Letter are soft enough to satisfy most of the constraints suggesting small radii for stars having a mass of about $(1.4 - 1.5) M_\odot$. The RMF EOS can reach particularly small radii, displaying a $R_{1.4} < 11$ km, but it is not clear from the present observational data if this is really needed because the constraints on masses and radii depend strongly on the composition of the stellar atmosphere, and larger radii are obtained when assuming a He rather than a H atmosphere, see e.g. [58]. It is clear that M-R relations giving values of $R_{1.4}$ in the range (11-12) km can be obtained with EOSs sitting in between the BHF and the RMF. Notice that in the case of the RMF EOS the corresponding $M_{\text{max}}^H$ is smaller than $2 M_\odot$. This is not a problem within the two-families scenario since $2 M_\odot$ compact stars belong to the QSs family. It is interesting to note that the constraints coming from NICER and from GW170817 can be satisfied by using both BHF and RMF EOSs, but as already mentioned, in the case of BHF GW170817 was a NS-NS merger (although a NS-QS merger could also be possible) whilst when using the RMF EOS GW170817 can only be explained as an NS-QS merger [58, 59, 53]. The constraint from NICER suggests either an HS or a QS when using the BHF EOS whilst in the case of the RMF EOS the QS interpretation seems more likely. Finally, 4U 1702-429 limits are satisfied by the BHF EOS, whereas the interpretation as a QS seems more problematic, at least with the present quark EOS.

**CONVERSION OF A HADRONIC STAR INTO A QUARK STAR**

It has been shown [31, 33] that HSs above a threshold value of their gravitational mass (corresponding to a critical central density) become metastable in respect to the conversion to QSs. This conversion process is triggered by the nucleation of a drop of quark matter in the center of a metastable HS [31, 53, 44, 61] and it releases a huge amount of energy of the order of $10^{53}$ erg [30]. A way to produce QSs is therefore through mass accretion onto an HS (as can happen in binary systems [31, 61]) or during the slow-down of a rapidly rotating HS [45]. Within the two-families scenario QSs can also be produced through the merger of two HSs [54, 56] and, potentially, through the conversion of a proto-neutron star into a QS immediately after the pre-supernova collapse [62, 38, 40, 60].

In Fig. 2 we show how the process of conversion of an HS into a QS can proceed. The critical density is the one for which it is energetically convenient to nucleate via quantum tunneling the first droplet of quark matter with the same flavor content as that of the hadronic matter at the center of the star (lower left panel: the droplet of quark matter at the same pressure of the center of the star has to have a lower Gibbs potential in order to be formed). The precise value of the critical density needs
FIG. 2: Upper left panel: gravitational mass vs radius for HSs (black and blue lines) and QSs (red line). Also shown an example of jump (orange arrow) from the first family to the second family of stars. Upper right panel: relations between gravitational mass and baryonic mass $M_b$ for HSs and QSs. QSs are more bound than HSs with the same baryonic mass. Lower left panel: relation between central pressure and central Gibbs potential for the two possible HS branches and the QS branch. Since, at fixed pressure, the Gibbs potential of the quark phase is smaller than the one of the hadronic phase, quark matter nucleation is allowed. Lower right panel: Relations between gravitational mass and central pressure for HSs and QSs. The dots in all panels indicate the critical hadronic configuration, for each EOS model, and the final QS configuration having the same baryonic mass of the initial one. Notice that the final QS configurations are very close in mass (see text) and therefore both are indicated by the same red dot.

Once the process of deconfinement starts it proceeds at first as a rapid deflagration (notice that the central pressure of the QS is smaller than the pressure of the original HS, lower right panel) and then as a diffusion [63]: during this process the baryon number is conserved (upper right panel), but the gravitational mass decreases because the process is strongly exothermic. The critical baryonic masses are of $1.67 M_\odot$ and $1.68 M_\odot$ for the BHF and the RMF EoSs, respectively. Thus, the final QS configurations are very close in mass and therefore both indicated by the same dot.

The possibility for an HS to convert into a QS with larger radius has been analysed in detail in Ref. [46].

The total binding energy of compact stars is the sum of the gravitational and of the nuclear binding energies, the last being related to the microphysics of the interactions [30]. An HS can convert into a QS with a larger radius because the consequent reduction of gravitational binding is overcompensated by the large increase in the nuclear binding. Thus, the total binding energy increases due to the conversion and the process is exothermic.

DISCUSSION AND CONCLUSIONS

We have shown that within the two-families scenario it is possible to have compact stars reaching a mass similar to the one indicated by GW190814 and that those massive objects are QSs. We have also shown that we can obtain that result while using physically motivated EOSs for the hadrons and for the quarks and without the need to assume velocities of sound close to the causal limit. Finally, we have shown that the stars populating the hadronic branch can have very small radii, breaking the limits derived by assuming only one family of com-
pact stars exists.

Which are the possible evolutionary paths leading to the formation of a $(2.5 - 2.6)M_\odot$ QS in GW190814? One possibility is that GW190814 originates from a triple system and the QS formed from the merger of two lighter NSs. Another possibility is that it was produced directly as a heavy QS from an anomalous supernova explosion powered by quark deconfinement, as mentioned above.

What are the implications of $M_{\text{max}} \sim (2.5 - 2.6)M_\odot$? Firstly, since in the case of GW170817 $M_{\text{tot}} \sim 2.73M_\odot$, the outcome of that merger was most likely a stable QS and not a BH. Only a small amount of rigid rotation, if any, would be needed to avoid collapse to a BH since the mass of the final object is smaller than $M_{\text{tot}}$ due to the ejection of matter and of energy in the form of GWs and neutrinos. This possibility would fit with the suggestion that a long-lived NS was the outcome of GW170817 and not a BH. Only a small amount of rigid rotation, if any, would be needed to avoid collapse to a BH since baryons stop being ablated and ejected once the surface of the star is made of nucleons. In Ref. [64, 65] and the QS formed from the merger of two compact stars in binary systems is peaked around $1M_\odot$ [66]. Secondly, since the distribution of masses of compact stars is rather general and do not refer specifically to a QS, a more direct implication can be drawn when considering possible mechanisms for the generation of short gamma-ray bursts. Clearly, if the outcome of the merger is a stable or a supramassive QS, mechanisms based on the protomagnetar model [68–71]. In that model though a problem exists concerning the duration of the burst, which is related to the time during which a jet with the appropriate baryon load is produced: typically that time is of the order of seconds or tens of seconds if the surface of the star is made of nucleons. In Ref. [72] it has been shown that, if during the merger a QS is produced, then that time reduces to tenths of a second since baryons stop being ablated and ejected once the surface of the star converted into quarks. Therefore our suggestion that the binary system generating GW190814 contained a QS is consistent with a global scenario of gamma-ray burst production.

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