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MERGER OF TWO NEUTRON STARS: PREDICTIONS FROM THE TWO-FAMILIES SCENARIO

Alessandro Drago[(a)] and Giuseppe Pagliara[(a)]
[(a)]Dip. di Fisica e Scienze della Terra dell'Università di Ferrara and INFN Sez. di Ferrara, Via Saragat 1, I-44100 Ferrara, Italy
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ABSTRACT

If only one family of "neutron stars" exists, their maximum mass must be equal or larger than $2M_\odot$ and then only in less than about 18% of cases the outcome of the merger of two neutron stars is a prompt collapse to a black hole, since the newly formed system can avoid the collapse at least until differential rotation is present. In the so-called two-families scenario, stars made of hadrons are stable only up to about $(1.5-1.6)M_\odot$, while the most massive compact stars are entirely made of strange quark matter. We show that in this scenario the outcome of the merger of two compact stars, entirely composed by hadrons, is a prompt collapse in at least 34% of the cases. It will therefore be easy to discriminate between the two scenarios once the gravitational waves emitted at the moment of the merger are detected. Finally, we shortly discuss the implications of GW170817-GRB170817A.

The detection of Gravitational Waves (GWs) has made available a new tool to investigate the properties of matter at extreme density. In particular, the future detection of GWs from neutron star - neutron star mergers will provide information about the Equation of State (EoS) of matter from the analysis of both the inspiral and of the postmerger phase (Baiotti & Rezzolla 2017). One of the main open questions concerns the composition of matter at the center of a compact star: hyperons, delta resonances or even deconfined quark matter could appear. Quark matter could be present only at the center of the star (hybrid stars) or occupy the whole star (Strange Quark Stars, SQSs) (Bodmer 1971; Witten 1984; Alcock et al. 1986; Haensel et al. 1986).

What characterizes the two-families scenario is the idea that by increasing the central density of a compact star, more and more resonances are produced (deltas, hyperons etc.) and this (in the absence of quark deconfinement) leads to a dramatic softening of the EoS entailing a small value of the maximum mass of Hadronic Stars, HSs, (smaller than about $2M_\odot$) and the possibility of very small radii. If quark deconfinement can take place, the EoS becomes much stiffer and stable configurations with masses up to $2M_\odot$ (or more) can be obtained as SQSs. Thus in the two-families scenario, HSs and SQSs coexist (Drago et al. 2016b; Drago & Pagliara 2016). HSs can be very compact (with radii smaller than about 11 km) and have a maximum mass $M^H_{\rm max} \sim (1.5-1.6)M_\odot$. The small radius of these stellar objects is mainly due to the appearance of delta resonances. On the other hand, SQSs are larger and can reach a maximum mass $M^Q_{\rm max}$ which in principle can be even significantly larger than $2M_\odot$ (Kurkela et al. 2010; Fraga et al. 2014).

The co-existence of these two families implies three possible types of mergers: HS-HS, HS-SQS and SQS-SQS. In the present letter we concentrate on the first possibility.

The two families scenario is based on the so called Bodmer-Witten hypothesis (Bodmer 1971; Witten 1984) for which the true ground state of strongly interacting matter is not nuclear matter but strange quark matter. In this scenario, strange quark matter would appear not only in stellar size objects but also in "small" nuggets, named strangelets, which could be formed for instance during the merger of two SQSs (Bauswein et al. 2009). Strangelets propagating within the galaxy could in principle trigger the conversion of all neutron stars into SQSs (Madsen 1988) but it has been shown in Wiktorowicz et al. (2017) that the galactic density of strangelets due to SQS mergers can be as small as 10^{-35} gr/cm^3. For the present discussion, we assume that the process of conversion of a HS into a SQS is never triggered by external seeding from a strangelet. Instead an HS can convert "spontaneously" into SQS once a sizable fraction of strangeness appears in its core via hyperons' formation. The formation of hyperons can be due to the increase of the central density of the star, originated e.g. by the magnetic driven spin down in the case of an isolated neutron star (Pili et al. 2016), or by mass accretion in binary systems (Wiktorowicz et al. 2017). The process of deconfinement starts when a critical density is reached, which corresponds (for cold and non rotating stars) to a critical mass slightly smaller than $M^H_{\rm max}$. Rotation and temperature can modify the value of the critical mass.

The process of conversion can be divided into two different stages (Drago & Pagliara 2015):
a) a turbulent combustion which, in a time scale $t_{\rm turb}$ of the order of a few ms, converts most of the star;
b) a diffusive combustion which converts the unburnt hadronic layer in a time scale $t_{\rm diff}$ of the order of ten seconds. It has been shown that the hybrid star configuration, HybS, obtained after phase a), is roughly as stiff as the final SQS configuration and therefore has a maximum mass $M^{Hyb}_{\rm max} \sim M^Q_{\rm max}$.

The merger of two neutron stars could possibly lead to the formation of a SQS (Cheng & Dai 1996; Drago et al. 2016a). A necessary condition is that the newly formed system lives at least for a time scale of the order of $\sim t_{\rm turb}$. A prompt collapse occurs if even a strong differential rotation is not able to delay the collapse to a Black Hole (BH). When this happens, the collapse takes place within $t_{\rm coll} \sim$ 1ms. Therefore in the case of a prompt collapse, $t_{\rm coll} \sim$ 1ms $< t_{\rm turb}$ and quark deconfinement does not even start. The only relevant EoS in this case

is the hadronic one.

The condition for obtaining a prompt collapse is that the mass of the newly formed compact object exceeds the maximum mass of hypermassive stars $M_{\rm max,dr}$. A first simple estimate of $M_{\rm max,dr}$ can be done by using the very recent analysis of Weih et al. (2017): by using several zero temperature EoSs and by adopting the commonly used constant angular momentum law, it has been found, within a full GR code, that $M_{\rm max,dr} = (1.54\pm0.05)M_{\rm TOV}$ with $M_{\rm TOV}$ being the maximum mass of cold and non-rotating stellar configurations. By setting $M^H_{\rm max} = 1.6M_\odot$, one obtains $M_{\rm max,dr} \sim 2.5M_\odot$ within the two families scenario and $M_{\rm max,dr} \sim 3M_\odot$ within the one family scenario (assuming a maximum mass of $2M_\odot$). Notice however that the real angular velocity profile after the merger can only be obtained through explicit simulations of the merger as done in Bauswein et al. (2013, 2016); Bauswein & Stergioulas (2017) within the conformal flatness approximation of Einsteins field equations. In these studies also thermal effects have been included by using tabulated finite temperature EoSs. Notice that the thermal pressure helps in stabilizing the remnant. It turns out that $M_{\rm threshold}$ (the maximum mass not leading to a prompt collapse) depends on the compactness of the merging stars and it can be as high as $1.7M_{\rm TOV}$. Finally, general relativistic hydrodynamics simulations of the merger in a full GR framework have been performed in Hotokezaka et al. (2013); Feo et al. (2017); Maione et al. (2017) for a few representative EoSs and by parametrizing the thermal effects with an effective adiabatic index.

Independently from the actual value of $M_{\rm max,dr}$, the key point is that in the case of a prompt collapse, within the two-families scenario, $M_{\rm TOV}$ corresponds to $M^H_{\rm max}$ and not to $M^Q_{\rm max}$ because there is not enough time for the SQS to start forming at the center of the newly born stellar object. As we will explain in the following, this difference between the one-family and the two-families scenario will allow to unambiguously rule out one of them already after a few detections of Gravitational Waves (GWs) by the LIGO and VIRGO experiments.

We can make predictions on the fate of a merger by using the present knowledge on the mass distribution of compact stars in binary systems. In Kiziltan et al. (2013), it is shown that the mass distribution of pulsars in double neutron star systems peaks at $1.33M_\odot$ with a $\sigma \sim 0.11M_\odot$. Thus, by assuming that this distribution coincides with the mass distribution of all neutron stars in binary systems, one can estimate the distribution of the total mass of merging binaries $M_{\rm tot}$ as peaked at $2.66M_\odot$ with $\sigma \sim \sqrt{2}\times 0.11M_\odot$. Notice however that the mass distribution of systems merging within a Hubble time could be shifted to larger values with respect to the distribution of Kiziltan et al. (2013).

We can now estimate the fraction of events which lead to a prompt collapse as follows. We adopt the empirical relations for $M_{\rm threshold}$ which have been obtained by fitting the results of explicit numerical simulations of mergers (Bauswein et al. 2013, 2016; Bauswein & Stergioulas 2017). In particular, we use the relation between $M_{\rm threshold}$ and the compactness of the maximum mass configuration, $C_{\rm max} = M_{\rm TOV}/R_{\rm TOV}$ which reads: $M_{\rm threshold} = (2.43 - 3.38\times C_{\rm max})\times M_{\rm TOV}$. By using this parametrization, within the one-family scenario, one can notice from Table 1 of Bauswein & Stergioulas (2017) that the minimum value of $M_{\rm threshold}$ is of the order of $2.8M_\odot$. This result has been obtained by many independent simulations. In Hotokezaka et al. (2013), among the six different EoSs used for the numerical simulations, the SLy EoS (Douchin & Haensel 2001) provides the smallest value of $M_{\rm threshold}$ which turns out to be of the order of $2.8M_\odot$. Similar results for the Sly EoS have been obtained within the numerical simulations of Feo et al. (2017); Maione et al. (2017). By using the mass distribution of Kiziltan et al. (2013), the probability of a prompt collapse $\rm P_{prompt}$ turns out to be $\rm P_{prompt} < 18\%$ (see lower panel of Fig.1). We regards this number as an upper limit for the rate of prompt collapses within the one family scenario.

For the two-families scenario, by varying $M^H_{\rm max}$ in the range $(1.5-1.6)M_\odot$ and the corresponding radii within the range $(10-11)$km we can compute $C_{\rm max}$ and thus $M_{\rm threshold}$ which turns out to vary in the range $(2.52-2.72)M_\odot$. Correspondingly, $34\% < \rm P_{prompt} < 82\%$ (see upper panel of Fig.1). It is clear therefore that within the two-families scenario one expects a significant number of prompt collapses whereas within the one-family scenario this possibility is suppressed.

From all these analyses one can conclude that the two-families scenario predicts a number of prompt collapses significantly larger than in the case of the one-family scenario. Therefore in the near future it will be possible to rule out one of the two scenarios. Indeed, the signal emitted in the case of a prompt collapse is clearly distinguishable from the signal of a differentially rotating remnant, see Baiotti & Rezzolla (2017) for a recent review.

The cases (in both scenarios) in which the post-merger remnant is stable, for at least a few ms, deserve a separate discussion. Remarkably, the GW signal emitted from the remnant can also bring important information on the EoS. There are several studies indicating that a Fourier analysis of the post-merger GW signal allows to identify the predominant oscillation mode, whose frequency (indicated with f_{peak} in Bauswein & Janka (2012) and f_2 in Stergioulas et al. (2011); Takami et al. (2014); Maione et al. (2017)) depends strongly on the stiffness of the EoS: stiffer EoSs predict smaller values of f_2. Moreover, sub-dominant modes at frequencies lower than the one of f_2 have been identified in Stergioulas et al. (2011); Takami et al. (2014); Bauswein & Stergioulas (2015); Maione et al. (2017) which, if detected together with the f_2 mode, could strongly constrain the EoS.

Let us now discuss which are the expected signatures in the GWs signal of the two-families scenario during the postmerger phase. In this scenario, the postmerger remnant is at the beginning very compact (because the star is made of hadronic matter). We can estimate the initial value of f_2 by using the empirical relation found in Bauswein et al. (2016): f_2 ranges from 3.3 to 3.7 kHz for $M_{\rm tot}$ ranging from 2.4 to $2.7M_\odot$. Here we have assumed the radius of the $1.6M_\odot$ star to be $R_{1.6} \sim 11$km. Notice that also some purely nucleonic EoSs, such as APR4 and Sly, predict very large values of f_2 (Bauswein & Janka 2012; Takami et al. 2014; Maione et al. 2017). However the expected number of events of prompt collapse in those cases would be significantly smaller respect to the one predicted in the two-families scenario. Moreover, two

major drawbacks of these type of EoSs must be remarked: first, the center of the compact star reaches densities so high (see Hanauske et al. (2017)) that it seems unrealistic to neglect non-nucleonic degrees of freedom. Secondly, they predict a radius for the $1.4M_\odot$ configuration smaller than 12km. On the other hand, the recent metamodeling analysis of Margueron et al. (2017), which is based only on nuclear physics constraints, has suggested that compact stars composed exclusively of nucleons and leptons have a radius of 12.5 ± 0.4 km for masses ranging from 1 up to $1.6M_\odot$.

A second feature of the two-families scenario is linked to the moment in which quarks start being formed in the center of the compact star. Once the burning process is triggered, the stiffening of the EoS, resulting from the formation of quark matter, leads to a significant structural change of the central part of the star within a time scale of the order of a few ms (Pagliara et al. 2013; Drago & Pagliara 2015). Consequently, also the spectrum of the emitted GWs should be significantly different with respect to the one displayed during the first milliseconds. It is very difficult though to make even qualitative predictions on such a modification of the spectrum because there are at least two different mechanisms potentially shifting f_2 to opposite directions. The stiffening of the EoS entails a larger radius (at least for a non-rotating star) but at the same time it increases the moment of inertia thus reducing the rotational frequency of the star. Since the equatorial radius increases with the rotational frequency, those two effects could potentially compensate when studying deconfinement in a rapidly rotating star. In conclusion, while the process of deconfinement will surely leave an imprint on the spectrum, it is not clear if f_2 will significantly change and in which direction.

The fate of compact star mergers is related also to the phenomenology of Short-Gamma-Ray-Bursts SGRBs (Gao et al. 2016; Piro et al. 2017). In particular, the two mostly discussed models for their inner engine are based either on the formation of a rapidly spinning BH surrounded by a hot and highly magnetized torus (Rezzolla et al. 2011) or on the formation of a protomagnetar (Duncan & Thompson 1992; Rowlinson et al. 2013). One can roughly divide SGRBs in two sub-classes: those displaying only a prompt emission and typically lasting a fraction of a second and those in which some form of prolonged emission is present. The existence of an extended X-ray emission can be modelled by assuming the formation of a supramassive and highly magnetized star (Rezzolla & Kumar 2015; Ciolfi & Siegel 2015; Lu et al. 2015; Drago et al. 2016a) while hypermassive stars are associated with SGRBs displaying only a prompt emission. Within the one-family scenario, in Piro et al. (2017) it has been shown that to populate both sub-classes $M_{\rm TOV}$ should be close to $2M_\odot$ (for larger values of $M_{\rm TOV}$ one needs to assume that a significant fraction of SGRBs are due to BH-NS mergers). Similar considerations apply also to the two-families scenario. For instance, let us set $M^H_{\rm max} = 1.6M_\odot$, $M^Q_{\rm max} \sim M^{Hyb}_{\rm max} = 2M_\odot$ and let us assume $M_{\rm threshold} = 1.6 \times M^H_{\rm max} = 2.56M_\odot$

By adopting for the maximum mass of supramassive HybS $M^{Hyb}_{\rm supra} = 1.2 \times M^{Hyb}_{\rm max} = 2.4M_\odot$ (Breu & Rezzolla 2016), we obtain the following possible outcomes for the merger depending on its gravitational mass M_g:
a) if $M_g > M_{\rm threshold} = 2.56M_\odot$ we have a direct collapse to a BH without any significant prompt emission;
b) if $M^{Hyb}_{\rm supra} = 2.4M_\odot < M_g < M_{\rm threshold} = 2.56M_\odot$ we have the formation of a hypermassive HyBS (SGRBs without extended emission);
c)if $M_g < M^{Hyb}_{\rm supra} = 2.4M_\odot$ we have the formation of supramassive HyBS which can be associated with SGRBs with an extended emission.

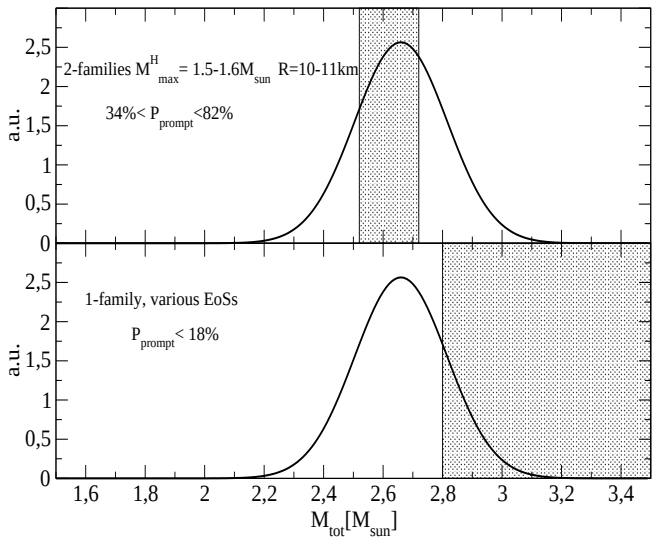

FIG. 1.— Distribution of $M_{\rm tot} = m_1 + m_2$ (solid line) estimated by using the analysis of Kiziltan et al. (2013). In the upper panel the range of values of $M_{\rm threshold}$ for $M^H_{\rm max} = (1.5-1.6)M_\odot$ are indicated by the grey area (two-families scenario). In the lower panel the range of values of $M_{\rm threshold}$ in the one-family case is indicated. In this figure the results of the analyses of Bauswein et al. (2013, 2016); Bauswein & Stergioulas (2017); Hotokezaka et al. (2013); Feo et al. (2017); Maione et al. (2017) have been used.

To estimate the fractions of mergers populating these three cases one needs to compute the relation between gravitational mass and baryonic mass for rapidly rotating stars, as done in Piro et al. (2017). From a qualitative viewpoint, we can conclude that also in the two-families scenario if $M^Q_{\rm max} \sim 2M_\odot$ it is possible at least in principle to assume that all SGRB are due to NS-NS merger.[1]

Two models have been proposed to explain the extended emission, both based on the formation of a supramassive star: in Rezzolla & Kumar (2015); Ciolfi & Siegel (2015) the prompt emission is produced by the collapse of the supramassive star to a BH, due to the magnetic spin-down having a time scale which can easily exceed 10^3 s. In this model one needs to assume a "time-reversal" scenario in which the extended emission is generated before the prompt emission but it appears later. In Drago et al. (2016a), the prompt emission is due to the formation of a SQS and the extended emission is powered by the supramassive SQS: no time reversal is needed in this case. The delay between the merger and

[1] It is interesting to notice that, while values of $M^Q_{\rm max}$ significantly larger than $\sim 2M_\odot$ have been discussed in the literature (Kurkela et al. 2010; Fraga et al. 2014), when chiral models are used to describe the quark dynamics the value of $M^Q_{\rm max}$ is $\sim 2M_\odot$ (Chen et al. 2016; Dondi et al. 2017).

the prompt is due to the time needed to convert completely the HyBS into a SQS and it is of the order of 10 s. The detection of both the GW signal at merger and the electromagnetic emission of the prompt will allow to easily distinguish between the two models.

The analyses presented in this paper are based on simulations which do not take into account the effect of the viscous dissipation. Very recently the effect of shear and bulk viscosity has been investigated in Alford et al. (2017) and Shibata & Kiuchi (2017). As shown in Shibata & Kiuchi (2017), the lifetime of the hypermassive configuration can be significantly reduced if a rather large value of the shear viscosity is assumed. On the other hand, since we have discussed prompt collapses occurring on a time scale of $\lesssim 1$ ms, one can notice from Shibata & Kiuchi (2017) that viscous dissipation plays a marginal role in this case.

Finally, let us summarize what one can learn from GWs detections concerning the two-families scenario assuming that both stars are HSs. Observations can lead to falsification and confirmation tests.

Tests falsifying the model:

– No evidence of rapid collapse to a BH (within a few ms from the merger) for a system having total mass larger than $M_{\rm threshold}$, whose maximum value is of about $2.7M_\odot$. E.g., the merger of two $1.4M_\odot$ HSs would rule out the two-families scenario if it does not collapse immediately into a BH.

– Indications, during the inspiral and/or during the first milliseconds of the postmerger phase, of a very stiff EoS (low values of f_2, smaller than about 3 kHz, (Maione et al. 2017)).

Tests against the model although not conclusive:

No significant change of the spectrum during the first few tens milliseconds (the conversion to quark matter could occur at later times when the GWs signal is too weak to be detectable).

Validating (but not conclusive) tests:

Very low stiffness of the EoS during the inspiral or immediately after the merger (f_2 larger than about 3.3 kHz).

Strong confirmation tests:

Rapid collapse to a BH of a merger having a total gravitational mass smaller than about $2.7M_\odot$.

During the process of review of this paper, the first detection of gravitational waves from a neutron star merger has been announced: GW170817 (Abbott et al. 2017a). Together with the GW signal, also a SGRB, GRB170817A, and a delayed kilonova, AT2017gfo, have been detected (Abbott et al. 2017c,b). From the GW signal, it has been possible to measure the total mass of the system which turns out to be $M_{\rm tot} = 2.74^{+0.04}_{-0.01}M_\odot$. Although not completely excluded, the possibility that the merger led to a prompt collapse is very unlikely since in that case it would be very difficult to explain the SGRB and the kilonova (Margalit & Metzger 2017; Bauswein et al. 2017). Therefore one can conclude that $M_{\rm threshold} > 2.74M_\odot$. As we have shown in this work, within the two families scenario $M_{\rm threshold}$ can barely reach $2.72M_\odot$ in the case of a HS-HS merger. On the other hand, in a HS-SQS merger, a HybS configuration forms without any delay and a prompt collapse is avoided. This hybrid configuration lasts $\sim$ 10 s (Drago & Pagliara 2015), long enough to allow the emission of the nuclear material which then produces the kilonova. Further analyses and discussions will be presented in a forthcoming paper.

We thus conclude that in our scenario GW170817 is likely not a HS-HS merger but could be a HS-SQS merger.

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