Neutron skins and neutron stars in the multi-messenger era

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The historical first detection of a binary neutron star merger by the LIGO-Virgo collaboration [B. P. Abbott et al. Phys. Rev. Lett. 119, 161101 (2017)] is providing fundamental new insights into the astrophysical site for the γ-process and on the nature of dense matter. A set of realistic models of the equation of state (EOS) that yield an accurate description of the properties of finite nuclei, support neutron stars of two solar masses, and provide a Lorentz covariant extrapolation to dense matter are used to confront its predictions against tidal polarizabilities extracted from the gravitational-wave data. Given the sensitivity of the gravitational-wave signal to the underlying EOS, limits on the tidal polarizability inferred from the observation translate into constraints on the neutron-star radius. Based on these constraints, models that predict a stiff symmetry energy, and thus large stellar radii, can be ruled out. Indeed, we deduce an upper limit on the radius of a 1.4 \(M_\odot\) neutron star of \(R_s^{\text{neutron}} < 13.76\) km. Given the sensitivity of the neutron-skin thickness of \(^{208}\text{Pb}\) to the symmetry energy, albeit at a lower density, we infer a corresponding upper limit of about \(R_s^{\text{neutron}} < 0.25\) fm. However, if the upcoming PREX-II experiment measures a significantly thicker skin, this may be evidence of a softening of the symmetry energy at high densities—likely indicative of a phase transition in the interior of neutron stars.

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What are the new states of matter at exceedingly high density and temperature? and how were the elements from iron to uranium made? are two of the “eleven science questions for the next century” identified by the National Academies Committee on the Physics of the Universe [1]. In framing these questions, the committee recognized the deep connections between the very small and the very large. In one clean sweep, the historical first detection of a binary neutron star (BNS) merger by the LIGO-Virgo collaboration [2] has started to answer these fundamental questions by providing critical insights into the nature of dense matter and on the synthesis of the heavy elements.

Gravitational waves (GW) from the BNS merger GW170817 emitted from a distance of about 40 Mpc were detected by the LIGO gravitational-wave observatory [2]. About two seconds later, the Fermi Gamma-ray Space Telescope (Fermi) [3] and the International Gamma-Ray Astrophysics Laboratory (INTEGRAL) [4] identified a short duration γ-ray burst associated with the BNS merger. Within eleven hours of the GW detection, ground- and spaced-based telescopes operating at a variety of wavelengths identified the associated kilonova—the electromagnetic transient powered by the radioactive decay of the heavy elements synthesized in the rapid neutron-capture process (\(\gamma\)-process). Characteristic features of the optical spectrum are consistent with the large opacity typical of the lanthanides (atomic number 57–71) and have revealed that about 0.05 solar masses (or about \(10^4\) earth masses) of \(\gamma\)-process elements were synthesized in this single event [5–7]. The gravitational wave detection from the BNS merger, together with its associated electromagnetic counterparts, open the new era of multi-messenger astronomy and provide compelling evidence in favor of the long-held belief that neutron-star mergers play a critical role in the production of heavy elements in the cosmos.

Besides the identification of the BNS merger as a dominant site for the \(\gamma\)-process, such an unprecedented event imposes significant constraints on the EOS of dense matter. In particular, the tidal polarizability (or deformability) is an intrinsic neutron-star property highly sensitive to the stellar compactness [8–13] that describes the tendency of a neutron star to develop a mass quadrupole as a response to the tidal field induced by its companion [13–15]. The dimensionless tidal polarizability \(\Lambda\) is defined as follows:

\[
\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{GM} \right)^5 = \frac{64}{3} k_2 \left( \frac{R}{R_s} \right)^5, \tag{1}
\]

where \(k_2\) is the second Love number [16,17], \(M\) and \(R\) are the neutron star mass and radius, respectively, and \(R_s \equiv 2GM/c^2\) is the Schwarzschild radius. A great virtue of the tidal polarizability is its high sensitivity to the stellar radius (\(\Lambda \sim R^5\)) a quantity that has been notoriously difficult to constrain [18–25]. Pictorially, a “fluffy” neutron star having a large radius is much easier to polarize than the corresponding compact star with the same mass but a smaller radius. Finally, a derived quantity from the individual tidal polarizabilities \(\Lambda_1\) and \(\Lambda_2\) related to the phase of the gravitational wave [15,17,29,30] is given

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by
\[
\tilde{\Lambda} = \frac{16}{13} \left[ \frac{(M_1 + 12M_2)M_1^4}{(M_1 + M_2)^5} \Lambda_1 + \frac{(M_2 + 12M_1)M_2^4}{(M_1 + M_2)^5} \Lambda_2 \right].
\] (2)

Note that for the equal-mass case, \( \tilde{\Lambda} = \Lambda_1 = \Lambda_2 \). Remarkably, the tidal polarizability determined from the first BNS merger is already stringent enough to rule out a significant number of previously viable EOSs [2].

In this letter we explore in greater detail the impact of the BNS merger on the EOS and on those laboratory observables that are particularly sensitive to the nuclear symmetry energy—a quantity that represents the increase in the energy of the system as it departs from the symmetric limit of equal number of neutrons and protons; see Refs. [31–33] and references contained therein. Particularly uncertain is the density dependence of the symmetry energy, often encoded in a quantity denoted by \( L \) that is closely related to the pressure of pure neutron matter at saturation density.

A laboratory observable that has been identified as strongly correlated to both \( L \) and to the radius of low-mass neutron stars is the neutron-skin thickness of atomic nuclei—defined as the difference between the neutron \( (R_n) \) and proton \( (R_p) \) root-mean-square radii: \( R_{\text{skin}} = R_n - R_p \). Despite a difference in length scales of 19 orders of magnitude, the size of a neutron star and the thickness of the neutron skin share a common origin: the pressure of neutron-rich matter. That is, whether pushing against surface tension in an atomic nucleus or against gravity in a neutron star, both the neutron skin and the stellar radius are sensitive to the same EOS.

The pioneering Lead Radius Experiment (PREX) at the Jefferson Laboratory has provided the first model-independent evidence in favor of a neutron-rich skin in \( ^{208}\text{Pb} \) \cite{34, 35}: \( R_{\text{skin}}^{208} = 0.33^{+0.16}_{-0.18} \) fm. Although the central value is significantly larger than suggested by most theoretical predictions, the large statistically-dominated uncertainty prevents any real tension between theory and experiment. In an effort to impose meaningful theoretical constraints, an approved follow-up experiment (PREX-II) is envisioned to reach a 0.06 fm sensitivity.

To connect the tidal polarizability to nuclear observables sensitive to the density dependence of the symmetry energy \cite{12}, we model the EOS using a relativistic mean-field (RMF) approach pioneered by Serot and Walecka \cite{36, 37}; which has been continuously improved throughout the years \cite{38, 39}. The effective Lagrangian density is written exclusively in terms of conventional degrees of freedom (neutrons, protons, electrons, and muons) and includes a handful of parameters that are calibrated to provide an accurate description of finite nuclei and—critically to the description of neutron stars—a Lorentz covariant extrapolation to dense nuclear matter. Although increasingly sophisticated fitting protocols are now able to incorporate more stringent constraints from finite nuclei and neutron stars \cite{12}, the isovector sector of the effective Lagrangian—responsible for generating the density dependence of the symmetry energy—remains largely unconstrained. To mitigate this problem we follow a simple procedure first proposed in Ref. [40] that enables one to fine tune the value of the slope of the symmetry energy \( L \) without compromising the success of the model in reproducing well measured observables. We label the set of models generated in this manner the “FSUGold2 family”.

In Fig. 1 we use the FSUGold2 family to predict the tidal polarizability \( \Lambda_1^{4\star} \) of a 1.4 \( M_\odot \) neutron star as a function of the neutron-skin thickness of \( ^{208}\text{Pb} \) (lower abscissa) and the radius of a 1.4 \( M_\odot \) neutron star (upper abscissa) as predicted by the FSUGold2 family of relativistic interactions. Constraints on \( R_{\text{skin}}^{208} \) and \( R_1^{4\star} \) are inferred from adopting the \( \Lambda_1^{4\star} \leq 800 \) limit deduced from GW170817 [2].

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soft. The evolution from stiff to soft may be indicative of a phase transition in the interior of neutron stars.

While the FSUGold2 family provides the flexibility to generate a continuum of realistic models with varying neutron skins, the models span a fairly narrow range of neutron-star radii (see Fig.1). To alleviate this problem—and in the spirit of Ref. [2]—we provide predictions using a representative set of RMF models. As in the case of the FSUGold2 family, these models are successful in reproducing laboratory observables and are also consistent with the $M_\star = 2.01 \pm 0.04 M_\odot$ limit [13, 14]. Yet, being less restrictive than the FSUGold2 family, they can generate a wider range of stellar radii. For reference, the ten models adopted in this letter are: NL3 [15, 16], IU-FSU [17], TAMU-FSU [18], FSUGold2 [19], and FSUGarnet together with three parametrizations denoted by RMF022, RMF028, and RMF032 [19].

In Fig.2 we display predictions from all ten models for the individual tidal polarizabilities $\Lambda_1$ and $\Lambda_2$ associated with the high-mass $M_1$ and low-mass $M_2$ components of the binary predicted by a set of ten distinct RMF models.

In analogy to Fig.1, we display in Fig.3 the tidal polarizability of a $1.4 M_\odot$ neutron star as a function of the corresponding stellar radius and the neutron-skin thickness of $^{208}\text{Pb}$, but now for the ten RMF models discussed in the text.

As shown in Eq. (1), the tidal polarizability is highly sensitive to the compactness of the neutron star. For a given mass, models with a stiff symmetry energy (large $L$) are highly effective in pushing against gravity, thereby generating large stellar radii and correspondingly large tidal polarizabilities. The 90% contour recommended by the LIGO-Virgo collaboration is stringent enough to disfavor overly stiff EOSs. Indeed, the four RMF models with the stiffest symmetry energy are ruled out. The next two stiffest models considered here—FSUGold2 and RMF028—follow closely the 90% contour.
the $R_{1.4}^\Lambda < 13.9 \text{ km}$ limit inferred previously from Fig. [1]. However, the $\Lambda_{1.4}^\star \lesssim 800$ limit is now stringent enough to rule out all but the four models with the softest symmetry energy. Given that both $L$ and $R_{\text{skin}}^{208\text{Pb}}$ are correlated to the radius of “low-mass” neutron stars [30], deducing limits on these two quantities from the radius of a $1.4M_\odot$ neutron star may be model dependent. Nevertheless, using the stiffest of the models that survives the $\Lambda_{1.4}^\star \lesssim 800$ constraint as a guideline (i.e., TAMUC-FSU) one obtains: $R_{1.4}^\star = 13.6 \text{ km}$, $R_{\text{skin}}^{208\text{Pb}} = 0.25 \text{ fm}$, and $L = 82.5 \text{ MeV}$.

As already mentioned, all RMF models generate an EOS that is sufficiently stiff to support a $M_\star \approx 2M_\odot$ neutron star [23, 24]. In addition, Fig. [3] incorporates our newly-inferred $13.76 \text{ km}$ upper limit on $R_{1.4}^\star$. Interestingly enough, a lower limit on the stellar radius of a $1.6M_\odot$ neutron star of $R_{1.6}^\star = 10.68^{+0.15}_{-0.04}$ was obtained by Bauswein et al., under the assumption that the BNS merger did not result in a prompt collapse [55]. Finally, we use the results obtained in Fig. [3] to deduce a lower limit on the tidal polarizability of a $1.4M_\odot$ neutron star. To do so, we note that PREX imposes a lower bound on the neutron-skin thickness of $208\text{Pb}$ of $R_{\text{skin}}^{208\text{Pb}} \approx 0.15 \text{ fm}$, which corresponds to a stellar radius of $R_{1.4}^\star \approx 12.55 \text{ km}$. Using the fit displayed in Fig. [3], the limit on $R_{1.4}^\star$ translates into a corresponding lower limit on the tidal polarizability of $\Lambda_{1.4}^\star \approx 490$: see Ref. [56] for an alternative extraction of a lower bound on the tidal deformability parameter. Thus, combining observational constraints from the LIGO-Virgo collaboration with laboratory constraints from the PREX collaboration, the tidal polarizability of a $1.4M_\odot$ neutron star falls within the following range of values: $490 \lesssim \Lambda_{1.4}^\star \lesssim 800$.

In summary, we have examined how the historical first detection of gravitational waves from the merger of two neutron stars improves our knowledge of the EOS of dense matter. While the BNS merger provides fundamental insights on the site of the r-process and confirms its association to short $\gamma$-ray burst, our aim in this letter was to illuminate its connection to laboratory observables. Such a connection is possible because of the sensitivity of the tidal polarizability to the stellar radius, which probes the symmetry energy at about twice nuclear-matter saturation density. Assuming that one can extrapolate down to saturation density, constraints from GW170817 provide limits on the neutron-skin thickness of $208\text{Pb}$—a fundamental laboratory observable that is strongly correlated to the slope of the symmetry energy at saturation density. Indeed, by exploring the consequences of the $\Lambda_{1.4}^\star \lesssim 800$ limit provided by the LIGO-Virgo collaboration, we deduced a limit on the stellar radius of a $1.4M_\odot$ neutron star of $R_{1.4}^\star < 13.76 \text{ km}$. In turn, this translates into a neutron-skin thickness of $208\text{Pb}$ of $R_{\text{skin}}^{208\text{Pb}} \lesssim 0.25 \text{ fm}$, which is well below the upper limit obtained by the PREX collaboration. Conversely, by relying on PREX lower limit on $R_{\text{skin}}^{208\text{Pb}}$, we were able to provide a lower limit on the tidal polarizability of $\Lambda_{1.4}^\star \gtrsim 490$. Finally, given that the PREX experiment reported a central value of $R_{\text{skin}}^{208\text{Pb}} \lesssim 0.33 \text{ fm}$—albeit with large error bars—an intriguing possibility emerges. If the follow-up experiment PREX-II confirms that $R_{\text{skin}}^{208\text{Pb}}$ is large, this will suggest that the EOS at the typical densities found in atomic nuclei is stiff. In contrast, the relatively small neutron-star radii suggested by GW170817 implies that the symmetry energy at higher densities is soft. The evolution from stiff to soft may be indicative of a phase transition in the neutron-star interior. Undoubtedly, the multi-messenger era is in its infancy and much work remains to be done. Yet, it is remarkable that the very first

\[ \text{FIG. 4: (Color online). Mass-vs-Radius relation predicted by the ten RMF models discussed in the text. Radius and mass constraints obtained from observation have been also incorporated into the plot.} \]
observation of a BNS merger already provides a treasure trove of insights into the nature of dense matter.

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