

GW190814: Impact of a 2.6 solar mass neutron star on the nucleonic equations of stateF. J. Fattoyev ^{1,*}, C. J. Horowitz ^{2,†}, J. Piekarewicz ^{3,‡} and Brendan Reed ^{4,§}¹*Department of Physics, Manhattan College, Riverdale, New York 10471, USA*²*Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*³*Department of Physics, Florida State University, Tallahassee, Florida 32306, USA*⁴*Department of Astronomy, Indiana University, Bloomington, Indiana 47405, USA*

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Is the secondary component of GW190814 the lightest black hole or the heaviest neutron star ever discovered in a double compact-object system [Abbott *et al.* *Astrophys. J.* **896**, L44 (2020)]? This is the central question animating this paper. Covariant density functional theory provides a unique framework to investigate both the properties of finite nuclei and neutron stars, while enforcing causality at all densities. By tuning existing energy density functionals we were able to: (i) account for a $2.6 M_{\odot}$ neutron star, (ii) satisfy the original constraint on the tidal deformability of a $1.4 M_{\odot}$ neutron star, and (iii) reproduce ground-state properties of finite nuclei. Yet, for the class of models explored in this work, we find that the stiffening of the equation of state required to support supermassive neutron stars is inconsistent with either constraints obtained from energetic heavy-ion collisions or from the low deformability of medium-mass stars. Thus, we speculate that the maximum neutron star mass can not be significantly higher than the existing observational limit and that the $2.6 M_{\odot}$ compact object is likely to be the lightest black hole ever discovered.

DOI: [10.1103/PhysRevC.102.065805](https://doi.org/10.1103/PhysRevC.102.065805)**I. INTRODUCTION**

The first direct detection of gravitational waves from the binary merger of two black holes launched the new era of gravitational-wave astronomy [1]. Two years later, the detection of gravitational waves from GW170817—a binary neutron star merger [2]—in association with its electromagnetic counterpart [3–6], greatly advanced multimessenger astronomy. And two years after GW170817, the LIGO-Virgo Collaboration continues to challenge the physics community after reporting the detection of gravitational waves from the coalescence of a binary system with the most extreme mass ratio ever observed: a 23 solar mass black hole and a 2.6 solar mass compact object [7]. Although data from all three instruments (LIGO-Livingston, LIGO-Hanford, and Virgo) allowed good sky localization of the source, no electromagnetic counterpart has been reported. Moreover, unlike GW170817, no measurable tidal signature was imprinted on the gravitational waveform, which seems consistent with the relatively large mass of the $2.6 M_{\odot}$ compact object. Hence, one is left speculating whether the compact object is either the most massive neutron star or the lightest black hole ever discovered [8,9].

The discovery paper suggests that, based on several current estimates of the maximum neutron star mass, “GW190814 is unlikely to originate in a neutron star-black hole (NSBH)

coalescence” [7]. Yet the paper leaves open the possibility that improved knowledge of the equation of state or further observations could alter this assessment. The absence of very massive neutron stars is consistent with the analysis by Margalit and Metzger who argue against their formation based on the lack of evidence of a large amount of rotational energy in the ejecta during the spin-down phase of GW170817 [10]. Interestingly, the suggested upper limit of $M_{\max} \lesssim 2.17 M_{\odot}$ [10] is in full agreement with the recent observation by Cromartie and collaborators of the heaviest $2.14^{+0.10}_{-0.09} M_{\odot}$ neutron star to date [11]. However, given that one can not definitively exclude the existence of very massive neutron stars, we explore here the implications of a $2.6 M_{\odot}$ neutron star on nucleonic equations of state, particularly in the framework of covariant density functional theory.

It has been known for more than two decades that the class of covariant energy density functionals (EDFs) used in this work can reproduce nuclear observables at normal nuclear densities and also generate neutron stars with maximum masses that differ by more than one solar mass [12]. Hence, stable neutron stars with $2.6 M_{\odot}$ —and even higher—can be readily generated. The challenge, however, is not to reconcile supermassive neutron stars with the properties of finite nuclei, but rather, with neutron-star properties that are sensitive to the equation of state (EOS) at 2–3 times nuclear densities, such as stellar radii and tidal deformabilities that favor a rather soft EOS [2,13].

In particular, GW170817 has provided stringent constraints on the EOS of neutron-rich matter at a few times nuclear densities from the measurement of three observables pertaining to the binary system: the chirp mass, the combined tidal

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TABLE I. Parameters, as in Ref. [36], for the three models discussed in the text. The scalar mass m_s and κ are in MeV. The vector-meson masses are fixed at $m_v = 782.5$ MeV and $m_\rho = 763.0$ MeV, respectively, and the nucleon mass at $M = 939$ MeV.

Model	m_s	g_s^2	g_v^2	g_ρ^2	κ	λ	ζ	Λ_v
IUFSU	491.500	99.4266	169.8349	184.6877	3.38081	+0.000296	0.03000	0.046000
FSUGarnet	496.939	110.3492	187.6947	192.9274	3.26018	-0.003551	0.02350	0.043377
BigApple	492.730	93.5074	151.6839	200.5562	5.20326	-0.021739	0.00070	0.047471

deformability, and the mass ratio [2]. From these observables, the tidal deformability of a $M = 1.4 M_\odot$ neutron star was extracted and confronted against theoretical predictions [13–27]. Constraints from GW170817 seem to favor compact stars with relatively small stellar radii, suggesting a relatively soft EOS. These constraints are consistent with the recent determination of both the mass and radius of PSR J0030+0451 by the Neutron star Interior Composition Explorer (NICER) [28,29]. Pulse-profile modeling of the thermal emission from the pulsar’s hot spots suggest a mass of about $1.4 M_\odot$ and a radius of nearly 13 km, with a $\pm 10\%$ uncertainty on both quantities [28,29]. Note that although consistent with GW170817, NICER results can accommodate slightly stiffer equations of state. However, a real tension develops as one aims to reconcile a relatively soft EOS as demanded by GW170817, with the much stiffer EOS required to account for heavy neutron stars with masses in the vicinity of $2 M_\odot$ [11,30,31]. Based on this combined evidence, suggestions have been made for the existence quark matter cores in massive neutron stars [32]. Although the claim may be premature, after all there are purely nucleonic EOS that satisfy all experimental and observational constraints to date [15], the prospect of identifying an assumed phase transition in the stellar cores is exciting. As shown below, the tension is exacerbated if the EOS must be stiffened even further to account for the possible existence of supermassive neutron stars.

II. FORMALISM

To test the possible existence of a $2.6 M_\odot$ neutron star we rely on density functional theory [33]. The energy density functional employed here is defined in terms of an underlying Lagrangian density that has been extensively discussed in earlier publications [34–36], so we limit ourselves to highlight those terms of relevance to the high-density component of the equation of state. That is,

$$\mathcal{L} = \dots + \frac{\xi}{4!} g_v^4 (V_\mu V^\mu)^2 + \Lambda_v (g_\rho^2 \mathbf{b}_\mu \cdot \mathbf{b}^\mu) (g_v^2 V_\nu V^\nu). \quad (1)$$

The basic degrees of freedom of the model are neutrons and protons interacting via the exchange of photons and mesons. Besides the conventional Yukawa couplings (not shown) the model includes nonlinear meson interactions that serve to simulate the complicated many-body dynamics and that are required to improve the predictive power of the model. The two terms shown in Eq. (1) fall into this category and are of critical importance to the behavior of dense, neutron-rich matter. The first term in the expression (proportional to ζ) describes a quartic self-interaction of the isoscalar-vector field V^μ , which affects the EOS of symmetric nuclear matter

at high densities [12]. In turn, the last term (proportional to Λ_v) includes a mixed quartic coupling between V^μ and the isovector-vector field \mathbf{b}^μ . Here g_v and g_ρ represent the strength of the Yukawa coupling of the nucleon to the corresponding vector mesons [12]. The Λ_v term was introduced to modify the density dependence of the symmetry energy, which plays a critical role in the structure of both neutron-rich nuclei and neutron stars [34]. Note that the symmetry energy is to a very good approximation equal to the difference in the energy per nucleon between pure neutron matter and symmetric nuclear matter. Covariant density functional theory provides a relativistic consistent framework as one extrapolates to dense matter as it ensures—unlike nonrelativistic formulations—that the EOS remains causal at all densities. Finally, the structure of neutron stars will be explored by enforcing both charge neutrality and chemical equilibrium. As such, the basic constituents of the model are nucleons and leptons (both electrons and muons). No exotic degrees of freedom—such as hyperons, meson condensates, or quarks—will be considered.

III. RESULTS

As already alluded to, tuning the ζ parameter in Eq. (1) allows one to stiffen the symmetric-matter EOS to produce supermassive neutron stars. For example, two of the EDFs used in Ref. [15]—IUFSU [37] and FSUGarnet [38]—that are consistent with both the $2 M_\odot$ constraint [11,30,31] and the tidal deformability of a $1.4 M_\odot$ neutron star [2], can be adjusted to produce maximum stellar masses of at least $2.8 M_\odot$. However, we find no need to strain the model to such an extreme, so we tune ζ to produce a maximum neutron star mass of $2.6 M_\odot$. Reducing the ζ parameters requires tuning the other model parameters. To do so, we start with the bulk properties predicted by IUFSU—together with the analytical transformation described in Ref. [36]—to connect the bulk properties to the model parameters. Next, we slightly decrease the value of the slope of the symmetry energy to obtain a neutron skin of 0.15 fm for ^{208}Pb . Since the centroid energy of the giant monopole resonance is sensitive to the value of the incompressibility coefficient of neutron-rich matter $K(\alpha)$ [39], we reduce the incompressibility coefficient to $K = 227$ MeV to maintain a similar value for $K(\alpha)$. Finally, we readjust the values of m_s , the saturation density ρ_0 , and the binding energy at saturation ϵ_0 to ensure that the binding energies and charge radii of both ^{40}Ca and ^{208}Pb remain intact. We refer to this nuclear EDF as “BigApple” and display its parameters, as defined in Ref. [36], in Table I alongside the other two covariant EDFs used in this work.

TABLE II. Theoretical predictions alongside experimental data (in parentheses) for the binding energy per nucleon [40] and charge radii [41] for a representative set of doubly magic and semimagic nuclei; the experimental charge radius of ^{68}Ni is from Ref. [42]. The last column displays predictions for the neutron skin thickness. With the exception of ^{208}Pb [43] no electroweak measurements of neutron skins are presently available.

Nucleus	$B/A(\text{MeV})$	$R_{\text{ch}}(\text{fm})$	$R_{\text{skin}}(\text{fm})$
^{40}Ca	8.552 (8.551)	3.452 (3.478)	-0.050
^{48}Ca	8.536 (8.666)	3.476 (3.477)	0.168
^{68}Ni	8.643 (8.682)	3.875 (3.887)	0.170
^{90}Zr	8.666 (8.710)	4.255 (4.269)	0.061
^{132}Sn	8.294 (8.355)	4.708 (4.709)	0.212
^{208}Pb	7.868 (7.867)	5.503 (5.501)	0.151 ($0.33^{+0.16}_{-0.18}$)

One of the central tenets of nuclear density functional theory is to provide a universal EDF that can reproduce nuclear observables over an enormous range of densities and isospin asymmetries. The goal is to build a nuclear EDF that can be used to explore both the properties of finite nuclei as well as the structure of neutron stars—dynamical objects that differ in length scales by more than 18 orders of magnitude. In this context, we display in Table II binding energies and charge radii as predicted by the BigApple.

Before moving on to discuss neutron star properties, we display in Table III some bulk properties of infinite neutron-rich matter that encode its behavior in the vicinity of the saturation density; the definitions are as in Ref. [44]. The saturation point of symmetric nuclear matter is defined in terms of the saturation density ρ_0 and the value of the energy per particle ϵ_0 . Because the pressure at saturation density vanishes, the rate at which the energy per particle increases is controlled by the incompressibility coefficient K , a quantity that is strongly correlated to the centroid energy of the giant monopole resonance [45]. In turn, J and L are fundamental parameters of the symmetry energy that encode the increase in the energy per particle and its density dependence as the system becomes neutron rich. In particular, given that the pressure of symmetric nuclear matter vanishes at saturation, L is closely related to the pressure of pure neutron matter at saturation density. As such, it is strongly correlated to both

TABLE III. Bulk properties of nuclear matter as predicted by three covariant EDFs: IUFSU [37], FSUGarnet [38], and Big Apple. The listed properties are the saturation density of symmetric nuclear matter together with the energy per particle and incompressibility coefficient at saturation. Also shown is the value of the symmetry energy J and its slope L at saturation density. All quantities are given in MeV except for ρ_0 , which is given in fm^{-3} .

Model	ρ_0	ϵ_0	K	J	L
IUFSU	0.155	-16.397	231.333	31.296	47.205
FSUGarnet	0.153	-16.231	229.628	30.917	50.961
BigApple	0.155	-16.344	227.001	31.315	39.800

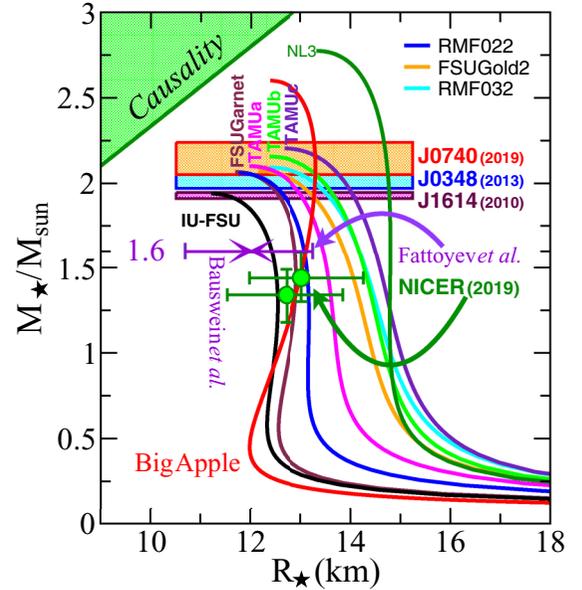


FIG. 1. Mass-vs-radius relation predicted by a variety of covariant EDFs. The figure has been adapted from Ref. [15] and is supplemented by maximum-mass constraints from J0740 [11], by NICER's constraints [28,29], and by our predictions from BigApple. Also shown are earlier maximum-mass constraints from J1614 [30] and J0348 [31].

the neutron skin thickness of heavy nuclei and the radius of neutron stars [46].

We observe from Table III that, with the exception of L , all three models are in very close agreement. It is important to note that the calibration of FSUGarnet relied exclusively on physical observables that can be either measured in the laboratory or extracted from observation, so the bulk properties listed in Table III are genuine model predictions. However, the current set of observables can not constrain the slope of the symmetry energy and hence the observed spread in the values of L .

Displayed in Fig. 1 is the mass-radius relation as predicted by a variety of covariant EDFs, including BigApple. The figure has been adapted from Ref. [15] and includes, besides earlier constraints on the maximum neutron star mass [30,31], the newest constraint from Cromartie *et al.* [11] as well as the recent NICER results [28,29]. All models support a $\sim 2 M_\odot$ neutron star and, with couple of exceptions, agree with the (1σ) NICER results. Yet, several of these models generate stellar radii for medium mass neutron stars that are inconsistent with the tidal deformability extracted from GW170817 [2]. Note, however, that BigApple, with a maximum neutron-star mass of $2.6 M_\odot$, satisfies all observational constraints; see also Table IV.

We now proceed to examine the microphysics responsible for the macroscopic properties displayed in Fig. 1. The underlying neutron-star matter EOS alongside the square of the speed of sound, defined as the derivative of the pressure with respect to the energy density, is displayed in Fig. 2. Predictions from the BigApple energy density functional suggest a softer EOS at intermediate densities (as suggested by

TABLE IV. Stellar properties as predicted by the three covariant EDFs used in this work. The maximum mass is given in solar masses, both radii in km, and the tidal deformability is dimensionless. The subscript “1.4” refers to the properties of a “1.4” M_{\odot} neutron star whereas the subscript “max” is associated with the maximum mass configuration.

Model	$R_{1.4}$	$\Lambda_{1.4}$	M_{\max}	R_{\max}	Λ_{\max}
IUFSU	12.528	499.2	1.939	11.265	20.9
FSUGarnet	12.869	624.8	2.066	11.706	18.2
BigApple	12.960	717.3	2.600	12.417	5.0

GW170817) and a significant stiffness at high densities, in an effort to account for the possible existence of very massive neutron stars. For the uniform stellar core, we use an EOS predicted by the various covariant EDFs introduced in Table I. Besides the EOS for the high-density core, one must also specify the EOS for the nonuniform crust.

The outer stellar crust is composed of a Coulomb lattice of neutron-rich nuclei embedded in a degenerate electron gas [47,48]. The nuclear physics input consists solely of nuclear masses in the $26 \leq Z \lesssim 40$ region, with the pressure support provided primarily by the degenerate electrons. Hence, the EOS for this region is relatively well known [47,49,50], except for the masses of exotic nuclei near the neutron drip line. For the very low-density region of the outer crust ($4.7 \times 10^{-15} \text{ fm}^{-3} < \rho < 6.93 \times 10^{-13} \text{ fm}^{-3}$) we adopt the equation of state of Feynman, Metropolis, and Teller (FMT) [49]. Still within the outer crust but at slightly higher densities (up to $1.966 \times 10^{-4} \text{ fm}^{-3}$) we use the equation of state of Haensel, Zdunik, and Dobaczewski [50]. At a density of about $2.6 \times 10^{-4} \text{ fm}^{-3}$, the nuclei in the outer crust become so neutron rich that they can no longer bind additional neutrons, so neutrons start dripping out. This region defines the boundary between the outer and the inner crust.

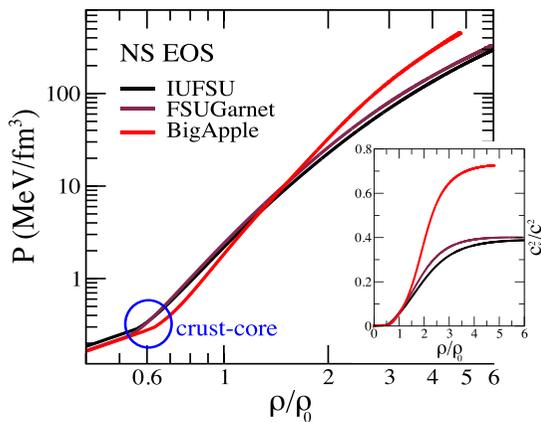


FIG. 2. Equation of state—pressure as a function of baryon density—for neutron-star matter in chemical equilibrium. Here $\rho_0 \simeq 0.154 \text{ fm}^{-3}$ is the density of nuclear matter at saturation (see Table III), and the inset displays the associated speed of sound squared in units of the speed of light squared.

The inner crust extends from the neutron-drip density up to about $\rho \approx 2/3\rho_0$, where the uniformity in the system is restored. On the top layers of the inner crust, nucleons continue to cluster into a Coulomb crystal of neutron-rich nuclei embedded in a uniform electron gas; however, now the system is also in chemical equilibrium with a dilute superfluid neutron gas [51]. As the density continues to increase further, the spherical nuclei start to deform in an effort to reduce the Coulomb repulsion. As a result, the inner crust exhibits complex and exotic structures that are collectively known as nuclear pasta [52–54], which emerge from a dynamical competition between the short-range nuclear attraction and the long-range Coulomb repulsion. Although significant progress has been made in simulating this exotic region [55–58], the equation of state for this region remains highly uncertain and must be inferred from theoretical calculations. While detailed knowledge of the EOS in this region is important for the interpretations of cooling observations [59], its impact on the bulk properties of neutron stars is minimal. Therefore, for this region we resort to the equation of state of Negele and Vautherin [60].

Returning to Fig. 2, we note that the kink in the pressure at around $2/3$ saturation density signals the transition from the solid crust to the liquid core. At saturation density the pressure is generated exclusively by the symmetry energy. This pressure determines the thickness of the neutron skin in neutron-rich nuclei [61–64]. In turn, the pressure at 2–3 times saturation density appears to control the radius of medium-mass neutron stars [23–25,65]. Indeed, all three models share the same pressure just below $2\rho_0$ and, as consequence, predict similar radii for a canonical $1.4 M_{\odot}$ neutron star. However, the maximum mass of stable neutron stars is highly sensitive to the pressure at the highest densities [27]. Indeed, a dramatic rate of increase in the pressure—best reflected in the speed of sound—is required to support a supermassive $2.6 M_{\odot}$ neutron star.

Based on the evidence presented so far, there seems to be no compelling argument against the possible existence of a supermassive $2.6 M_{\odot}$ neutron star. Note, however, that whereas the relatively large tidal deformability predicted by BigApple is consistent with the limits presented in the discovery paper [2], the revised limit of $\Lambda_{1.4} = 190^{+390}_{-120}$ [13] presents a more serious challenge. However, the most serious evidence against such a stiff EOS comes from laboratory experiments involving the energetic collision between two gold nuclei, a violent encounter that compressed matter to pressures in excess of 10^{34} Pa [66]; note that $1 \text{ Pa} = 10 \text{ dyn/cm}^2 = 6.242 \times 10^{-33} \text{ MeV/fm}^3$.

We display in Fig. 3 constraints on the EOS of symmetric nuclear matter as extracted from the analysis of particle flow in heavy-ion collisions [66]. We observe that IUFSU and FSUGarnet (the two lower lines in the figure) with predictions of $1.94 M_{\odot}$ and $2.07 M_{\odot}$ for the maximum neutron star mass, already sit near the upper edge of the allowed region. In contrast, the very stiff EOS predicted by the NL3 parametrization [67] that is displayed by the green upper line, was explicitly ruled out by the heavy-ion data [66]. Following a similar trend as NL3, it is clear that the stiff EOS predicted by BigApple and required to account for supermassive neutron stars is also

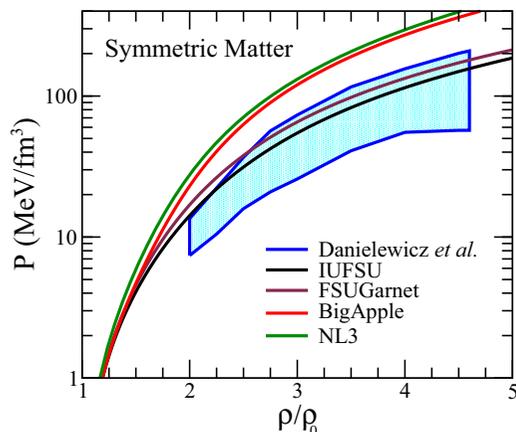


FIG. 3. Equation of state—pressure as a function of baryon density—of symmetric nuclear matter. The blue shaded area represents the EOS extracted from the analysis of flow data using a value of $\rho_0 \simeq 0.16 \text{ fm}^{-3}$ for the saturation density [66].

ruled out. Given that FSUGarnet is approaching the upper boundary allowed by the heavy-ion data, it is unlikely that the maximum neutron star mass can go much beyond the present observational limit of $2.14 M_\odot$ [11].

IV. SUMMARY

In summary, motivated by the recent identification of a compact object in the $2.5\text{--}5.0 M_\odot$ mass gap [7], we have explored the possibility that such an object could be a supermassive neutron star. Given the lack of an electromagnetic counterpart to GW190814 and the absence of tidal distortions to the gravitational waveform, it is unlikely that the nature of the $2.6 M_\odot$ compact object will ever be resolved by a further analysis of the data. In this paper we have adapted a class of modern covariant EDFs to account for a stable $2.6 M_\odot$ neutron star, while ensuring that earlier constraints on the structure of neutron stars as well as ground-state properties of finite nuclei are accurately reproduced. Indeed, we demonstrated that such an EDF, dubbed BigApple, successfully accounts for the binding energy and charge radii of a representative set of spherical nuclei, is consistent with the bulk properties of infinite nuclear matter, reproduces the recent NICER data, and is compatible with the limits on the tidal deformability of

a $1.4 M_\odot$ neutron star, as reported in the GW170817 discovery paper. In particular, our predictions are well aligned (see Table IV) with the constraints extracted from GW190814 under the NSBH scenario: $R_{1.4} = 12.9^{+0.8}_{-0.7} \text{ km}$ and $\Lambda_{1.4} = 616^{+273}_{-158}$ [7].

However, despite the considerable success of the model, two sets of data strongly disfavor such a stiff EOS. First, the revised upper limit from GW170817 of $\Lambda_{1.4} = 190^{+390}_{-120}$ (at the 90% level) [13] is significantly lower than the $\Lambda_{1.4} \simeq 720$ value predicted by BigApple. This would require a softening of the EOS, particularly of the symmetry energy. Second, constraints on the EOS of symmetric nuclear matter extracted from particle flow in high-energy nuclear collisions rule out an overly stiff nuclear matter EOS. For example, BigApple predicts a pressure at four times saturation density that is nearly twice as large as the upper limit extracted from the flow data. In principle, by adding additional interactions at high densities one could soften the EOS of symmetric nuclear matter to bring it into agreement with the heavy-ion data at the expense of needing to stiffen the symmetry energy. Whereas such a procedure may still result in an overall EOS that can account for a $2.6 M_\odot$ neutron star, it may require considerable fine tuning to keep the pressure of nuclear matter and the tidal deformability low enough. Hence, we conclude that the low deformability demanded by GW170817 combined with the heavy-ion data for symmetric nuclear matter make it highly unlikely that the maximum mass could be as large as $2.6 M_\odot$, at least for the class of models used in this work. So as one is left speculating whether the $2.6 M_\odot$ compact object in GW190814 is either the most massive neutron star or the lightest black hole ever detected, our analysis points strongly in favor of the latter. However, a primordial black hole explanation for the secondary component of GW190814 also appears to be improbable [68], suggesting that the mystery is unlikely to be resolved any time soon.

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