Physics Letters B 668 (2008) 1–5

Contents lists available at ScienceDirect

Physics Letters B

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# Nuclear limits on gravitational waves from elliptically deformed pulsars

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ARTICLE INFO

*Article history:*
Received 14 May 2008
Received in revised form 23 July 2008
Accepted 31 July 2008
Available online 9 August 2008
Editor: W. Haxton

ABSTRACT

Gravitational radiation is a fundamental prediction of General Relativity. Elliptically deformed pulsars are among the possible sources emitting gravitational waves (GWs) with a strain-amplitude dependent upon the star's quadrupole moment, rotational frequency, and distance from the detector. We show that the gravitational wave strain amplitude $h_0$ depends strongly on the equation of state of neutron-rich stellar matter. Applying an equation of state with symmetry energy constrained by recent nuclear laboratory data, we set an upper limit on the strain-amplitude of GWs produced by elliptically deformed pulsars. Depending on details of the EOS, for several millisecond pulsars at distances 0.18 kpc to 0.35 kpc from Earth, the *maximal* $h_0$ is found to be in the range of $\sim [0.4\text{–}1.5] \times 10^{-24}$. This prediction serves as the first *direct* nuclear constraint on the gravitational radiation. Its implications are discussed.



## 1. Introduction

Gravitational waves are tiny disturbances in space–time and are a fundamental, although not yet directly confirmed, prediction of General Relativity. They can be triggered in cataclysmic events involving (compact) stars and/or black holes. They could even have been produced during the very early Universe, well before any stars had been formed, merely as a consequence of the dynamics and expansion of the Universe. Because gravity interact extremely weakly with matter, gravitational waves would carry a genuine picture of their sources and thus provide undisturbed information that no other messenger can deliver [1]. Gravitational wave astrophysics would open an entirely new non-electromagnetic window making it possible to probe physics that is hidden or dark to current electromagnetic observations [2].

(Rapidly) rotating neutron stars could be one of the major candidates for sources of continuous gravitational waves in the frequency bandwidth of the LIGO [3] and VIRGO (e.g., Ref. [4]) laser interferometric detectors. It is well known that a rotating object self-bound by gravity and which is perfectly symmetric about the axis of rotation does not emit gravitational waves. In order to generate gravitational radiation over extended period of time, a rotating neutron star must have some kind of long-living axial asymmetry [5]. Several mechanisms leading to such an asymmetry have been studied in literature: (1) Since the neutron star crust is solid, its shape might not be necessarily symmetric, as it would be for a fluid, with asymmetries supported by anisotropic stress built up during the crystallization period of the crust [6]. (2) Additionally, due to its violent formation (supernova) or due to its environment (accretion disc), the rotational axis may not coincide with a principal axis of the moment of inertia of the neutron star which make the star precess [7]. Even if the star remains perfectly symmetric about the rotational axis, since it precesses, it emits gravitational waves [7,8]. (3) Also, the extreme magnetic fields presented in a neutron star cause magnetic pressure (Lorenz forces exerted on conducting matter) which can distort the star if the magnetic axis is not aligned with the axis of rotation [9], which is widely supposed to occur in order to explain the pulsar phenomenon. Several other mechanisms exist that can produce gravitational waves from neutron stars. For instance, accretion of matter on a neutron star can drive it into a non-axisymmetric configuration and power steady radiation with a considerable amplitude [10]. This mechanism applies to a certain class of neutron stars, including accreting stars in binary systems that have been spun up to the first instability point of the so-called Chadrasekhar–Friedman–Schutz (CFS) instability [11]. Also, Andersson [12] suggested a similar instability in $r$-modes of (rapidly) rotating relativistic stars. It has been shown that the effectiveness of these instabilities depends on the viscosity of stellar matter which in turn is determined by the star's temperature.

Gravitational wave strain amplitude depends on the degree to which the neutron star is deformed from axial symmetry which, in turn, is dependent upon the equation of state (EOS) of neutron-rich stellar matter. At present time the EOS of matter under extreme conditions (densities, pressures and isospin asymmetries) is still rather uncertain and theoretically controversial. One of the main source of uncertainties in the EOS of neutron-rich matter is the poorly known density dependence of the nuclear symmetry en-

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0370-2693/$ – see front matter 
doi:10.1016/j.physletb.2008.07.105

ergy, $E_{\rm sym}(\rho)$, e.g., [13]. On the other hand, heavy-ion reactions with radioactive beams could provide unique means to constrain the uncertain density behavior of the nuclear symmetry energy and thus the EOS of neutron-rich nuclear matter, e.g., [14–17,26]. Applying several nucleonic EOSs, in this Letter we calculate the gravitational wave strain amplitude for selected neutron star configurations. Particular attention is paid to predictions with an EOS with symmetry energy constrained by very recent nuclear laboratory data. These results set an upper limit on the strain amplitude of gravitational radiation expected from rotating neutron stars.

The pulsar population is such that most have spin frequencies that fall below the sensitivity band of current detectors. In the future, the low-frequency sensitivity of VIRGO [45] and Advanced LIGO [46] should allow studies of a significantly larger sample of pulsars. Moreover, LISA (the Laser Interferometric Space Antenna) is currently being jointly designed by NASA in the United States and ESA (the European Space Agency), and will be launched into orbit by 2013 providing an unprecedented instrument for gravitational waves search and detection [2].

## 2. Formalism

In what follows we review briefly the formalism used to calculate the gravitational wave strain amplitude. A spinning neutron star is expected to emit GWs if it is not perfectly symmetric about its rotational axis. As already mentioned, non-axial asymmetries can be achieved through several mechanisms such as elastic deformations of the solid crust or core or distortion of the whole star by extremely strong misaligned magnetic fields. Such processes generally result in a triaxial neutron star configuration [3] which, in the quadrupole approximation and with rotation and angular momentum axes aligned, would cause gravitational waves at *twice* the star's rotational frequency [3]. These waves have characteristic strain amplitude at the Earth's vicinity (assuming an optimal orientation of the rotation axis with respect to the observer) of [18]

$$h_0=\frac{16\pi^2 G}{c^4}\frac{\epsilon I_{zz}\nu^2}{r}, \tag{1}$$

where $\nu$ is the neutron star rotational frequency, $I_{zz}$ its principal moment of inertia, $\epsilon=(I_{xx}-I_{yy})/I_{zz}$ its equatorial ellipticity, and $r$ its distance to Earth. The ellipticity is related to the neutron star maximum quadrupole moment (with $m=2$) via [19]

$$\epsilon=\sqrt{\frac{8\pi}{15}}\frac{\Phi_{22}}{I_{zz}}, \tag{2}$$

where for *slowly* rotating (and static) neutron stars $\Phi_{22}$ can be written as [19]

$$\Phi_{22,\max}=2.4\times10^{38}\ \mathrm{g\,cm^2}\left(\frac{\sigma}{10^{-2}}\right)\left(\frac{R}{10\ \mathrm{km}}\right)^{6.26}\left(\frac{1.4M_\odot}{M}\right)^{1.2}. \tag{3}$$

In the above expression $\sigma$ is the breaking strain of the neutron star crust which is rather uncertain at present time and lies in the range $\sigma=[10^{-5}\text{–}10^{-2}]$ [18]. To maximize $h_0$ in this work we take $\sigma=10^{-2}$ which might be too optimistic. From Eqs. (1) and (2) it is clear that $h_0$ does not depend on the moment of inertia $I_{zz}$, and that the total dependence upon the EOS is carried by the quadrupole moment $\Phi_{22}$. Thus Eq. (1) can be rewritten as

$$h_0=\chi\frac{\Phi_{22}\nu^2}{r}, \tag{4}$$

with $\chi=\sqrt{2045\pi^5/15}G/c^4$. In a recent work we have calculated the neutron star moment of inertia of both static and (rapidly) rotating neutron stars. For slowly rotating neutron stars Lattimer and Schutz [20] derived the following empirical relation

$$I\approx(0.237\pm0.008)MR^2\left[1+4.2\frac{M\ \mathrm{km}}{M_\odot R}+90\left(\frac{M\ \mathrm{km}}{M_\odot R}\right)^4\right]. \tag{5}$$

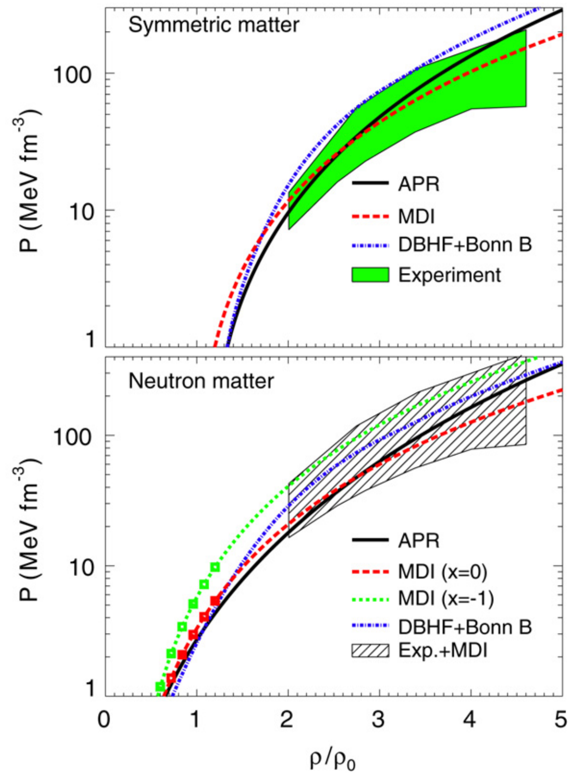


**Fig. 1.** (Color online.) Pressure as a function of density for symmetric (upper panel) and pure neutron (lower panel) matter. The green area in the upper panel is the experimental constraint on symmetric matter extracted by Danielewicz, Lacey and Lynch [22] from analyzing the collective flow in relativistic heavy-ion collisions. The corresponding constraint on the pressure of pure neutron matter, obtained by combining the flow data and an extrapolation of the symmetry energy functionals constrained below $1.2\rho_0$ ($\rho_0=0.16\ \mathrm{fm}^{-3}$) by the isospin diffusion data, is the shaded black area in the lower panel. Results are taken partially from Ref. [22].

This expression is shown to hold for a wide class of equations of state which do not exhibit considerable softening and for neutron star models with masses above $1M_\odot$ [20]. Using Eq. (5) to calculate the neutron star moment of inertia and Eq. (3) the corresponding quadrupole moment, the ellipticity $\epsilon$ can be readily computed (via Eq. (2)). Since the global properties of spinning neutron stars (in particular the moment of inertia) remain approximately constant for rotating configurations at frequencies up to $\sim300$ Hz [21], the above formalism can be readily employed to estimate the gravitational wave strain amplitude, provided one knows the exact rotational frequency and distance to Earth, and that the frequency is relatively low (below $\sim300$ Hz). These estimates are then to be compared with the current upper limits for the sensitivity of the laser interferometric observatories (e.g., LIGO).

## 3. Results and discussion

We calculate the gravitational wave strain amplitude $h_0$ for several selected pulsars employing several nucleonic equations of state. We assume a simple model of stellar matter of nucleons and light leptons (electrons and muons) in beta-equilibrium. For many astrophysical studies (as those in this Letter), it is more convenient to express the EOS in terms of the pressure as a function of density and isospin asymmetry. In Fig. 1 we show pressure as a function of density for two extreme cases: symmetric (upper panel) and pure neutron matter (lower panel). We pay particular attention to the EOS calculated with the MDI [23] (momentum dependent) interaction because its symmetry energy has been constrained in the subsaturation density region by the available nuclear laboratory data. The EOS of symmetric nuclear matter with the MDI interaction is constrained by the available data on collective flow in relativistic heavy-ion collisions. The parameter $x$ is introduced in the single-particle potential of the MDI EOS to account for the largely uncertain density dependence of the nuclear symmetry energy $E_{\rm sym}(\rho)$ as predicted by various many-body frameworks and models of the nuclear force. Since it was demonstrated by Li and Chen [24] and Li and Steiner [25] that only equations of state with $x$ in the range between $-1$ and 0 have symmetry energy consistent with the isospin-diffusion laboratory data and measurements of the skin thickness of $^{208}$Pb, we therefore consider only these two limiting cases in calculating boundaries of the possible (rotating) neutron star configurations. It is interesting to note that the symmetry energy extracted very recently from isoscaling analysis of heavy-ion reactions is consistent with the MDI calculation of the EOS with $x = 0$ [27]. The MDI EOS has been applied to constrain the neutron star radius [25] with a suggested range compatible with the best estimates from observations. It has been also used to constrain a possible time variation of the gravitational constant $G$ [28] via the *gravitochemical heating* approach developed by Jofre et al. [30]. More recently we applied the MDI EOS to constrain the global properties of (rapidly) rotating neutron stars [21,29]. In Fig. 1 the green area in the density range of $\rho = [2.0\text{–}4.6]\rho_0$ is the experimental constraint on the pressure $P_0$ of symmetric nuclear matter extracted by Danielewicz, Lacey and Lynch from analyzing the collective flow data from relativistic heavy-ion collisions [22]. The pressure of pure neutron matter $P_{PNM} = P_0 + \rho^2 dE_{\rm sym}(\rho)/d\rho$ depends on the density behavior of the nuclear symmetry energy $E_{\rm sym}(\rho)$. Since the constraints on the symmetry energy from terrestrial laboratory experiments are only available for densities less than about $1.2\rho_0$ as indicated by the green and red squares in the lower panel, which is in contrast to the constraint on the symmetric EOS that is only available at much higher densities, the most reliable estimate of the EOS of neutron-rich matter can thus be obtained by extrapolating the underlying model EOS for symmetric matter and the symmetry energy in their respective density ranges to all densities. Shown by the shaded black area in the lower panel is the resulting best estimate of the pressure of high density pure neutron matter based on the predictions from the MDI interaction with $x = 0$ and $x = -1$ as the lower and upper bounds on the symmetry energy and the flow-constrained symmetric EOS. As one expects and consistent with the estimate in Ref. [22], the estimated error bars of the high density pure neutron matter EOS are much wider than the uncertainty range of the symmetric EOS. For the four interactions indicated in the figure, their predicted EOSs cannot be distinguished by the estimated constraint on the high density pure neutron matter. In addition to the MDI EOS, in Fig. 1 we show results by Akmal et al. [31] with the $A18 + \delta\upsilon + UIX*$ interaction (APR) and recent Dirac–Brueckner–Hartree–Fock (DBHF) calculations [32,33] with Bonn B One-Boson-Exchange (OBE) potential (DBHF + Bonn B) [34]. Below the baryon density of approximately 0.07 fm$^{-3}$ the equations of state applied here are supplemented by a crustal EOS, which is more suitable for the low density regime. Namely, we apply the EOS by Pethick et al. [35] for the inner crust and the one by Haensel and Pichon [36] for the outer crust. At very high densities we assume a continuous functional for the EOSs employed in this work. (See [33] for a detailed description of the extrapolation procedure for the DBHF + Bonn B EOS.) The saturation properties of the nuclear equations of state applied in this work are summarized in Table 1.

Fig. 2 displays the neutron star moment of inertia (left frame) and quadrupole moment (right frame). The moment of inertia is calculated through Eq. (5) and the quadrupole moment through Eq. (3). Note that these relations are valid only for *slowly* rotating neutron star models. We notice that $\Phi_{22}$ decreases with increasing stellar mass for all EOSs considered in this study. The rate of this decrease depends upon the EOS and is largest for the $x = -1$ EOS. This behavior is easily understood in terms of the increased central density with stellar mass—more massive stars are more compact and, since the quadrupole moment is a measure of the star's deformation (see Eq. (2)), they are also less deformed with respect to less centrally condensed models. Moreover, it is well known that the mass is mainly determined by the symmetric part of the EOS while the radius of a neutron star is strongly affected by the density slope of the symmetry energy. More quantitatively, an EOS with a stiffer symmetry energy, such as the $x = -1$ EOS, results in less compact stellar models, and hence more deformed pulsars. Here we recall specifically that the $x = -1$ EOS yields neutron star configurations with larger radii than those of models form the rest of the EOSs considered in this study (e.g., see Fig. 3 in Ref. [29]). These results are consistent with previous findings which suggest that more compact neutron star models are less altered by rotation, e.g., see Ref. [37]. Consequently, it is reasonable also to expect such configurations to be more "resistant" to any kind of

**Table 1**
Saturation properties of the nuclear EOSs (for symmetric nuclear matter) shown in Fig. 1. The first column identifies the equation of state. The remaining columns exhibit the following quantities at the nuclear saturation density: saturation (baryon) density; energy-per-particle; compression modulus; nucleon effective mass; symmetry energy

| EOS | $\rho_0$ (fm$^{-3}$) | $E_s$ (MeV) | $\kappa$ (MeV) | $m^*(\rho_0)$ (MeV/$c^2$) | $E_{\rm sym}(\rho_0)$ (MeV) |
|---|---|---|---|---|---|
| MDI | 0.160 | −16.08 | 211.00 | 629.08 | 31.62 |
| APR | 0.160 | −16.00 | 266.00 | 657.25 | 32.60 |
| DBHF + Bonn B | 0.185 | −16.14 | 259.04 | 610.30 | 33.71 |

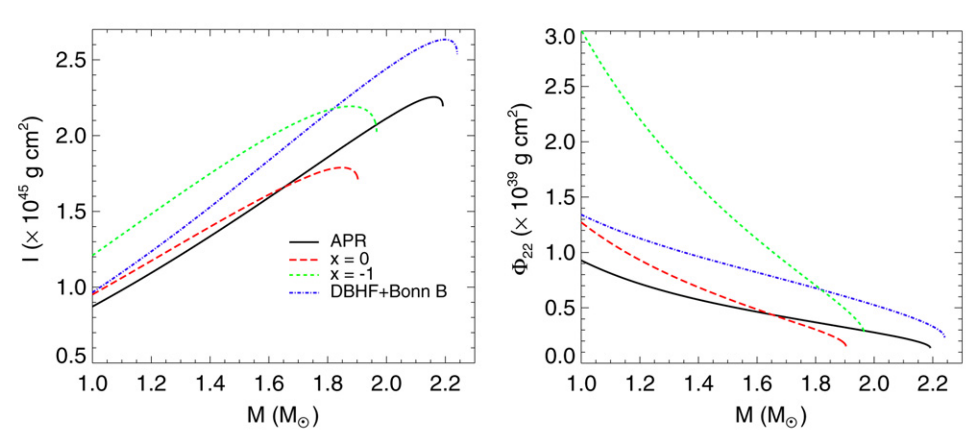


**Fig. 2.** (Color online.) Neutron star moment of inertia (left panel; taken from Ref. [21]) and quadrupole moment (right panel). $I$ is calculated via Eq. (5) while $\Phi_{22}$ via Eq. (3).

deformation. In Fig. 3 we show the ellipticity as a function of the neutron star mass. Since $\epsilon$ is proportional to the quadrupole moment $\Phi_{22}$ (scaled by the moment of inertia $I_{zz}$), it decreases with increasing stellar mass. The results shown in Fig. 3 are consistent with the maximum ellipticity $\epsilon_{max} \approx 2.4 \times 10^{-6}$ corresponding to the largest crust "mountain" one could expect on a neutron star [18,38]. (The estimate of $\epsilon_{max}$ in Refs. [18,38] has been obtained assuming breaking strain of the crust $\sigma = 10^{-2}$, as we have assumed in the present Letter in calculating the neutron star quadrupole moment.)

In Fig. 4 we display the GW strain amplitude, $h_0$, as a function of stellar mass. Predictions are shown for three selected millisecond pulsars, which are relatively close to Earth ($r < 0.4$ kpc), and have rotational frequencies below 300 Hz so that the corresponding momenta of inertia and quadrupole moments can be computed approximately via Eqs. (5) and (3), respectively. The properties of these pulsars (of interest to this study) are summarized in Table 2. The error bars in Fig. 4 between the $x = 0$ and $x = -1$ EOSs provide a constraint on the *maximal* strain amplitude of the gravitational waves emitted by the millisecond pulsars considered here. The specific case shown in the figure is for neutron star models of $1.4M_\odot$. Depending on the exact rotational frequency, distance to detector, and details of the EOS, the *maximal* $h_0$ is in the range $\sim [0.4\text{–}1.5] \times 10^{-24}$. These estimates do not take into account the uncertainties in the distance measurements. They also should be regarded as upper limits since the quadrupole moment (Eq. (3)) has been calculated with $\sigma = 10^{-2}$ (where $\sigma$ can go as low as $10^{-5}$). Here we recall that the mass of PSR J0437-4715 (Fig. 4 right panel) is $1.3 \pm 0.2M_\odot$ [40]. (Another mass constraint, $1.58 \pm 0.18M_\odot$, was given previously by van Straten et al. [41].) The results shown in Fig. 4 suggest that the GW strain amplitude depends on the EOS of stellar matter, where this dependence is stronger for lighter neutron star models. In addition, it is also greater for stellar configurations computed with stiffer EOS. As explained, such models are less compact and thus less gravitationally bound. As a result, they could be more easily deformed by rotation or/and other deformation driving mechanisms and phenomena, and therefore are expected to emit stronger gravitational radiation (Eq. (1)).

In Fig. 5 we take another view of the results shown in Fig. 4. We display the maximal GW strain amplitude as a function of the GW frequency and compare our predictions with the best current

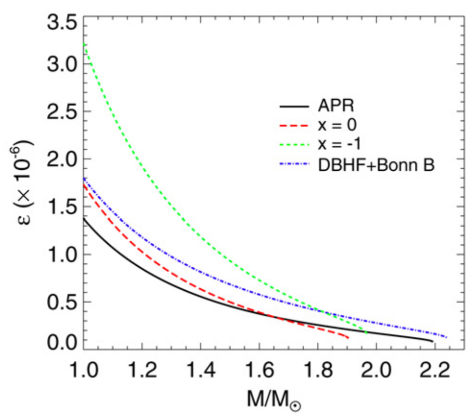


**Fig. 3.** (Color online.) Ellipticity as a function of the neutron star mass.

**Table 2**
Properties of the pulsars considered in this study. The first column identifies the pulsar. The remaining columns exhibit the following quantities: rotational frequency; mass (if known); distance to Earth; corresponding references. Notice that only the mass of PSR J0437-4715 is known from orbital dynamics [40,41] (as the pulsar has a low-mass white dwarf companion). The masses of PSRs J2124-3358 and J1024-0719 are presently unknown as they are both isolated neuron stars [39]

| Pulsar | $\nu$ (Hz) | $M$ ($M_\odot$) | $r$ (kpc) | Reference |
|---|---|---|---|---|
| PSR J2124-3358 | 202.79 | – | 0.25 | [39] |
| PSR J1024-0719 | 193.72 | – | 0.35 | [39] |
| PSR J0437-4715 | 173.91 | $1.3 \pm 0.2$ | 0.18 | [40,41] |

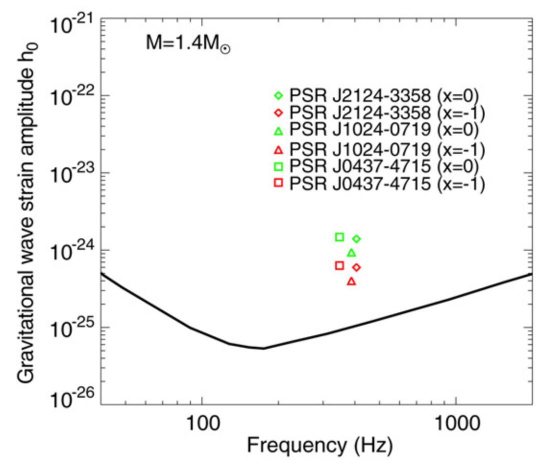


**Fig. 5.** (Color online.) Gravitational wave strain amplitude as a function of the gravitational wave frequency. The characters denote the strain amplitude of the GWs expected to be emitted from spinning neutron stars ($\nu < 300$ Hz) with mass $1.4M_\odot$. Solid line denotes the current upper limit of the LIGO sensitivity. Adapted from Ref. [3].

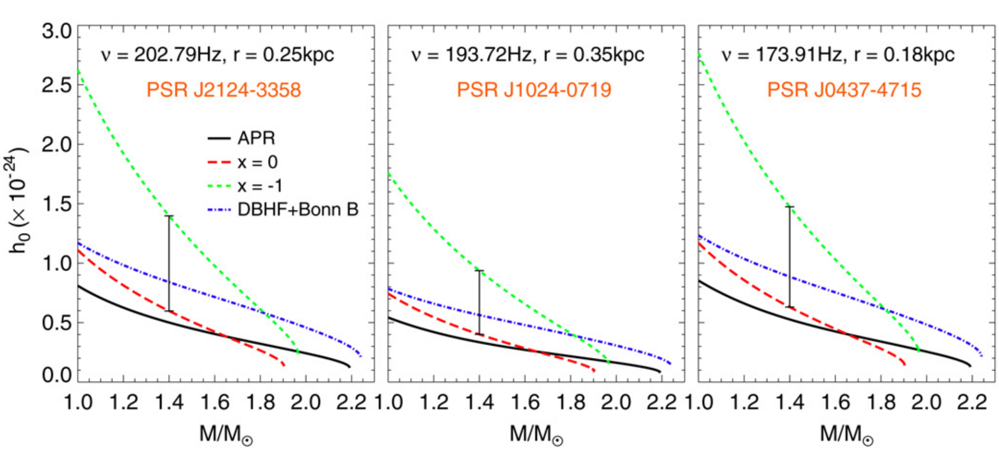


**Fig. 4.** (Color online.) Gravitational-wave strain amplitude as a function of the neutron star mass. The error bars between the $x = 0$ and $x = -1$ EOSs provide a limit on the strain amplitude of the gravitational waves to be expected from these neutron stars, and show a specific case for stellar models of $1.4M_\odot$.

detection limit of LIGO. The specific case shown is for neutron star models with mass $1.4M_\odot$ computed with the $x = 0$ and $x = -1$ EOSs. Since these EOSs are constrained by the available nuclear laboratory data they provide a limit on the possible neutron star configurations and thus gravitational emission from them. The results shown in Fig. 5 would suggest that presently the gravitational radiation from the three selected pulsars should be within the detection capabilities of LIGO. The fact that such a detection has not been made yet deserves a few comments at this point. First, as we mentioned, in the present calculation we assume breaking strain of the neutron star crust $\sigma = 10^{-2}$ which might be too optimistic. As pointed out by Haskell et al. [18], we are still away from testing more conservative models and if the true value of $\sigma$ lies in the low end of its range, we would be still far away from a direct detection of a gravitational wave signal. Second, while we have assumed a specific neutron star mass of $1.4M_\odot$, Fig. 4 tells us that $h_0$ decreases with increasing stellar mass, i.e., heavier neutron stars will emit weaker GWs. Here we recall that from the selected pulsars only the mass of PSR J0437-4715 is known (within some accuracy [40,41]). The masses of PSR J2124-3358 and PSR J1024-0719 are unknown. Third, in the present study we assume a very simple model of stellar matter consisting only beta equilibrated nucleons and light leptons (electrons and muons). On the other hand, in the core of neutron stars conditions are such that other more exotic species of particles could readily abound. Such novel phases of matter would soften considerably the EOS of stellar medium [43] leading to ultimately more compact and gravitationally tightly bound objects which could withstand larger deformation forces (and torques). Lastly, the existence of quark stars, truly exotic self-bound compact objects, is not excluded from further considerations and studies. Such stars would be able to resist huge forces (such as those resulting from extremely rapid rotation beyond the Kepler, or mass-shedding, frequency) and as a result retain their axial symmetric shapes effectively dumping the gravitational radiation (e.g. [44]). At the end, we recall that Eq. (1) implies that the best possible candidates for gravitational radiation (from spinning relativistic stars) are *rapidly* rotating pulsars relatively close to Earth ($h_0 \sim \Phi_{22}\nu^2/r$). Increasing rotational frequency (and/or decreasing distance to detector, $r$) would alter the results shown in Figs. 4 and 5 in favor of a detectable signal by the current observational facilities (e.g., LIGO). On the other hand, for more realistic and quantitative calculations, the neutron star quadrupole moment must be calculated numerically exactly by solving the Einstein field equations for rapidly rotating neutron stars. (Such calculations have been reported, for instance, by Laarakkers and Piosson [42].) Studies of gravitational waves emitted from rapidly rotating neutron stars are under way and are left for a future report.

## 4. Summary

We have reported predictions on the upper limit of the strain amplitude of the gravitational waves to be expected from elliptically deformed pulsars at frequencies $< 300$ Hz. By applying an EOS with symmetry energy constrained by recent nuclear laboratory data, we obtained an upper limit on the gravitational-wave signal to be expected from several pulsars. Depending on details of the EOS, for several millisecond pulsars 0.18 kpc to 0.35 Kpc from Earth, the *maximal* $h_0$ is found to be in the range of $\sim [0.4\text{–}1.5] \times 10^{-24}$. This prediction sets the first direct nuclear constraint on the gravitational waves from elliptically deformed pulsars.

## Acknowledgements

The authors gratefully acknowledge support from the National Science Foundation under Grant No. PHY0652548, the Research Corporation under Award No. 7123 and the Texas Coordinating Board of Higher Education grant No. 003565-0004-2007.

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