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Probing the physics of neutron stars with gravitational waves

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Abstract. In this paper we give a brief overview of how the detection of gravitational waves emitted by neutron stars may impact on our understanding of the physics of neutron stars.

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1. Introduction

Neutron stars radiate gravitational waves in a number of astrophysical processes. For instance, if they are rotating deformed stars, if they oscillate as a consequence of some perturbation, or when they interact with a compact companion in inspiralling binaries. Modelling these different phenomena is not easy, since we need to combine different fields of physics including general relativity, magnetohydrodynamics, nuclear physics, superfluids and superconductors physics, etc. The extreme conditions which prevail in the inner core of a neutron star (NS) are such that, in that regime, the theory of nuclear interactions is only partially constrained by the results of high energy experiments in laboratories; consequently the equation of state which we use to model neutron star matter relies on models of this interaction which we hope to validate using gravitational wave (GW) observations. Similarly, the estimate of the degree of asymmetry that a neutron star can have, and consequently the GW flux it emits when rotating, is affected by many uncertainties: which is the maximum strain that the crust can support without breaking? What is the effect of the magnetic field, and of the presence of a superconductive core, on the stellar shape? In the following sections I will discuss how the gravitational signal emitted by rotating or oscillating neutron stars, or by a NS disrupted by the tidal interaction with a black hole, is related to the NS internal structure and to the structure of the stellar magnetic field.

2. Rotating neutron stars

Rotating NSs emit GWs if they have a certain degree of asymmetry, which can be generated by different mechanisms. For instance, while a rotating fluid is axisymmetric

with respect to the rotation axis, this may not be the case for a mature NS, since deviation from axisymmetry may be supported by anisotropic stresses in the solid crust. Let us assume that the NS is located at a distance r from Earth, that it has a triaxial shape and rotates around a principal axis with angular velocity Ω; in this case the gravitational signal it emits is a sinusoid at twice the rotation frequency:

$$h_+ = h_0 \frac{1+\cos^2 i}{2} \cos 2\Omega(t - r/c) \ , \qquad h_\times = h_0 \cos i \sin 2\Omega(t - r/c) \ , \quad (1)$$

where i is the angle between the rotation axis and the line of sight (joining the star and the Earth centres), and the wave amplitude h_0 is given by

$$h_0 = \frac{4G\Omega^2}{c^4} \frac{I|\epsilon_Q|}{r} \ . \quad (2)$$

Thus, the wave amplitude depends on the moment of inertia, I, with respect to the rotation axis and on the *quadrupole ellipticity* ϵ_Q, which is a measure of the entire stellar bulk deformation. It is defined as $\epsilon_Q = Q/I$, where Q is the star mass-energy quadrupole moment, whereas the moment of inertia is given by $I = J/\Omega$, J being the stellar angular momentum. For a stationary, axisymmetric compact object, Q can be extracted by the far field limit of the metric, being the coefficient of the $P_2(\cos\theta)/r^3$ term in the expansion of g_{00} in powers of $1/r$ and in Legendre polynomials $P_l(\theta)$ [1]: $g_{00} \to \ldots - 2QP_2(\cos\theta)/r^3$. The above expressions are valid even for highly relativistic stars, provided the star distortion is small. In the weak field limit ϵ_Q can be written in terms of the inertia tensor $e_Q = (I_{11} - I_{22})/I_{33}$. For a homogeneous ellipsoid with semiaxes a, b, c, in the limit of small asymmetry $a \simeq b$, the quadrupole ellipticity can be written as $e_Q = (b-a)/a + O(\epsilon^2)$

Even if the star has an axisymmetric shape, it would radiate GWs if the rotation and the symmetry axes are misaligned; this may happen as a consequence of some violent phenomena occurring in the early life of the star, or later, due to accretion if the NS is in a binary system. Let us assume that α is the wobble angle between the symmetry and the rotation axis, which we assume to be directed along x_3; the motion of the star is the superposition of two rotations: one about x_3 (i.e. about the angular momentum $\mathbf{J}$), with frequency Ω, said *inertial precession frequency*, one about the symmetry axis, with angular velocity $\omega_{prec} = (I_{33} - I_{22})/I_{33}\Omega\cos\alpha$, called the *free precession frequency*. Since for NS deviations from spherical simmetry are small, i.e. $(I_{33} - I_{22})/I_{33} \ll 1$, then $\omega_{prec} \ll \Omega$. In this case the gravitational wave signal is [2]

$$h_+ = h_0 \sin\alpha \left[\frac{1}{2} \cos\alpha \sin i \cos i \cos\Omega(t - r/c) - \sin\alpha \frac{1+\cos^2 i}{2} \cos 2\Omega(t - r/c) \right]$$
$$h_\times = h_0 \sin\alpha \left[\frac{1}{2} \cos\alpha \sin i \cos i \sin\Omega(t - r/c) - \sin\alpha \cos i \sin 2\Omega(t - r/c) \right] \ ; \quad (3)$$

the wave amplitude h_0 is still given by Eq. (2), where now in the weak field limit the quadrupole ellipticity is $e_Q = (I_{33} - I_{22})/I_{33}$. Thus, for an axysimmetric freely precessing body GW emission has two harmonic components: one at the rotation

frequency Ω ‡ and one at twice the rotation frequency.

Equation (2) shows that, in general, the gravitational wave amplitude depends on the moment of inertia and on the quadrupole ellipticity. Theoretical studies on the moment of inertia of neutron stars have been performed in several papers [4, 5]; these studies use a large set of equations of state (EOS) proposed to describe NS matter at supranuclear densities, and show that $I \sim [1-3] \times 10^{38}$ kg m^2, depending on the EOS and on the rotation rate. It is now interesting to summarize what we presently know about the quadrupole ellipticity.

2.1. The quadrupole ellipticity

A first upper limit on ϵ_Q can be put by looking for the maximal strain that the crust can sustain without breaking. The most detailed modelling of crustal strains indicates that [6]

$$\epsilon_Q < 2 \times 10^{-5} \left(\frac{u_{\rm break}}{0.1} \right), \tag{4}$$

where $u_{\rm break}$ is the crustal breaking strain. Recent molecular dynamics simulations [7] suggest that $u_{\rm break}$ may be as large as 0.1, i.e. the NS crust could be much stronger than previously thought. If this is the case, the NS crust would break if the deformation were to exceed about 20 cm.

In "ordinary" NS the core is supposed to be fluid and the crust solid. However, it has been proposed that solid phases may also be present in the core, in which case stars with larger deformations may be possible. For instance, for a solid strange quark star one may have [8] $\epsilon_Q < 6 \times 10^{-4} (u_{\rm break}/10^{-2})$, whereas if the star has a crystalline colour superconducting quark core $\epsilon_Q < 10^{-3} (u_{\rm break}/10^{-2})$ [9]. Thus, the maximum quadrupole deformation sustainable by a neutron star (or a quark star) depends upon the physics of the crust and upon the equation of state (EOS) of matter at supranuclear density.

2.1.1. The effect of a magnetic field. A magnetic field may distort the star to an extent which depends on its strength in the stellar interior, on the field structure, and on the core EOS. For a star with a fluid core we can summarize the magnetic field effects with the following "order of magnitude"-formula [10, 11]

$$\epsilon_Q \approx 10^{-12} \left(\frac{B}{10^{12}\,{\rm G}} \right)^2 . \tag{5}$$

Typical values of pulsars field strength range within $\sim 10^9 - 10^{12}$ G and these fields are too weak to induce sizeable deformations. The presence of a superconducting core could produce larger asymmetries. For instance, for a type II superconducting core it could be as large as [12, 13]

$$\epsilon_Q \approx 10^{-9} \left(\frac{B}{10^{12}\,{\rm G}} \right) \left(\frac{H_{\rm crit}}{10^{15}\,{\rm G}} \right) , \tag{6}$$

‡ An expansion of the quadrupole formula up to second order in the wobble angle shows that this component is, more precisely, emitted at a frequency $\Omega + \omega_{prec}$[3]

where $H_{\rm crit}$ is a critical field strength.

The geometry of the magnetic field inside the NS is also important. In general, the magnetic field is expected to have both poloidal and toroidal components. Indeed, toroidal fields should form during the first seconds after core collapse, when the star is likely to be rapidly and differentially rotating, since the fluid motion would drag the poloidal field lines [14]; in addition, convective motions could also create toroidal components by dynamo processes[15]. These toroidal fields are expected to survive when the proto-neutron star cools down and the crust forms. Moreover, it has been shown that purely poloidal or purely toroidal fields are unstable on timescales much shorter than the star's life [16, 17], thus, both fields have to be included to construct accurate, and stable, models of magnetic stars. It is known that a toroidal field tends to make the star prolate ($e_Q < 0$), while the poloidal field tends to make it oblate (see for instance [18]). If the star has a prolate shape it would be secularly unstable: the wobble angle between the angular momentum and the star magnetic axis would grow on a dissipation timescale, until they become orthogonal ("spin flip"). This instability should be associated to an intense flux of gravitational waves, potentially detectable by advanced LIGO and VIRGO [12, 19]. However, whether the toroidal component of the magnetic field actually prevails in the NS interior over the poloidal one is actually unclear. Recent studies on the subject try to establish which are the possible field configurations [11, 18, 20, 21]. As an example, in a recent paper [21] models of non rotating NSs endowed with a strong, stationary magnetic field have been constructed in the framework of General Relativity. In these models the poloidal component extends throughout the star and in the exterior, whereas the toroidal component is confined into a torus-shaped region inside the star. These *twisted torus* configurations have been found to be a quite generic outcome of dynamical simulations in the framework of Newtonian gravity which, due to magnetic helicity conservation, appear to be stable on dynamical time-scales [17, 22]. In these configurations the toroidal field never contributes to more than $\sim 13\%$ of the total magnetic energy stored inside the star [21]. Consequently, the quadrupole ellipticity ϵ_Q is always positive, and its maximum value is obtained in the purely poloidal limit. Therefore, twisted torus configurations are not compatible with the spin-flip mechanism. For these stars ϵ_Q can be written as

$$\epsilon_Q \lesssim k \left(\frac{B_{pole}[G]}{10^{16}} \right)^2 \times 10^{-4} \ , \tag{7}$$

where B_{pole} is the strenght of the $l = 1$ magnetic field component at the pole, which is the quantity estimated from spin-down measurements, and k is a parameter which, for a neutron star with mass $M = 1.4\ M_\odot$, is in the range $k \sim (4-9)$ depending on the stellar compactness, i.e. on the EOS of matter in the NS interior. Less compact stars have larger deformations. Equation (7) shows that very high values of ϵ_Q ($\sim 10^{-3} - 10^{-4}$) could be obtained only for extremely strong magnetic fields, of the order of those observed in magnetars. Since these large deformations cannot be supported by a NS crust, they can occur only during the first few hours of the stellar life, when the star is still liquid and no crust has formed yet; if this happens, the deformation may persist

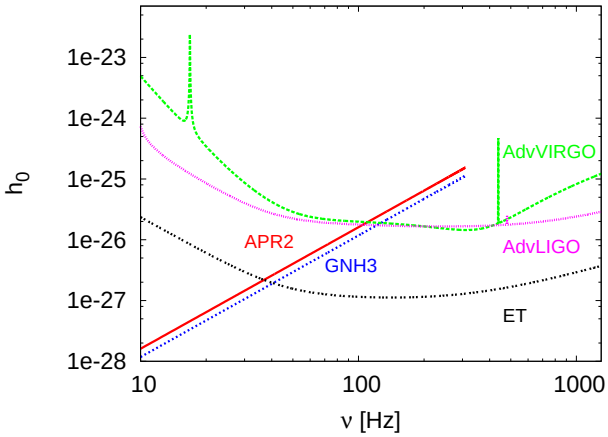

Figure 1. Gravitational signal emitted by a rotating NS with the ellipticity given in Eq. (7), assuming $B = 10^{15}$ G, wobbling angle $\alpha = 3°$, distance d =1 kPc and an integration time of three months. The two lines refer to two NS with the same mass $M = 1.4M_{\odot}$ and different EOS, named APR2 [23] and GNH3 [24]. The APR2 star has a larger compactness ($R = 11.58$ km) than the GNH3 star ($R = 14.19$ km).

since as the star cools down the crust would freeze in a non-spherical shape. However, if the star is endowed with a magnetic field so large as to produce such large deformation, it would dissipate its rotational energy predominantly in the electromagnetic channel, spinning down the star in a quite short time, which depends on the magnetic field strenght. Thus the NS would be a strong emitter of gravitational waves, but only for a quite short period of time. For instance, if we assume that the initial magnetic field is $B = 10^{15}$ G and that the wobble angle is $\alpha = 3°$, a NS at a distance of 1 kPc initially rotating at, say, 300 Hz, would stay in the bandwidth of ground based interferometers less than three months, producing the signal shown in Fig. 1§.

2.1.2. Are neutron stars freely precessing? This is an interesting question, because it is related to the inner structure of a neutron star. On one side we have compelling observational evidence: free precession has been seen in the radio signature of PSR B1828-11 [26] and supported by a subsequent analysis [27]. The wobble angle estimated for this source is $\simeq 3°$. On the other hand, models of neutron stars assuming superfluid vortex pinning of the star crust to the core are incompatible with a free precession, since vortex pinning would exert a large torque on the crust and the wobble angle would be damped in a short time, much shorter than that associated to the energy loss due to gravitational wave emission [28]. Mechanisms that would sustain precession, such as those associated to accretion torques or to electromagnetic effects, do not appear to have a significant effect [28]. Further studies on the problem of vortex pinning indicate that hydrodynamic forces present in a precessing star would be sufficient to unpin all

§ Indicating with B_{dipole} the mean surface dipole field, the electromagnetic spindown can be evaluated using the formula $B_{dipole} = 3.2 \times 10^{19}\sqrt{P\dot{P}}$ G, where P is the rotation period [25].

of the vortices of the inner crust, so that long period free precession would be possible; conversely, pinning would be effective in absence of precession and this would explain the giant glitches observed in many radio pulsars [29].

Moreover, it should be remembered that if the star has a prolate deformation, the internal dissipation would increase the wobble angle through the spin-flip mechanism. However studies on the effect of magnetic fields and limits imposed by crustal strain indicate that it is unlikely that neutron stars have a prolate shape [11, 21, 28].

From this short review it emerges that, in order to explain the observed free precession in PSR B1828-11 (and in some other sorces), further studies on the role of a superfluid inside the star and its interaction with the crust, and on magnetic field effects are needed. The hope is that gravitational wave observations will contribute to solve this puzzle.

3. Stellar pulsations

The detection of gravitational waves emitted by a star oscillating in its quasi-normal modes appears a promising strategy for constraining the physics of neutron stars. Indeed different families of modes can be associated with different core physics. For example, the frequency of the fundamental f-mode (which should be the most efficient GW emitter) scales with the average density of the star, the pressure p-modes are associated to the sound speed inside the star, the gravity g-modes are sensitive to thermal/composition gradients and the w-modes are spacetime oscillations. Pulsation modes are also associated to the dynamical behaviour of the crust and of the internal magnetic field. As an example, in Fig. 2 we plot the f-mode frequency for neutron/hybrid stars modeled

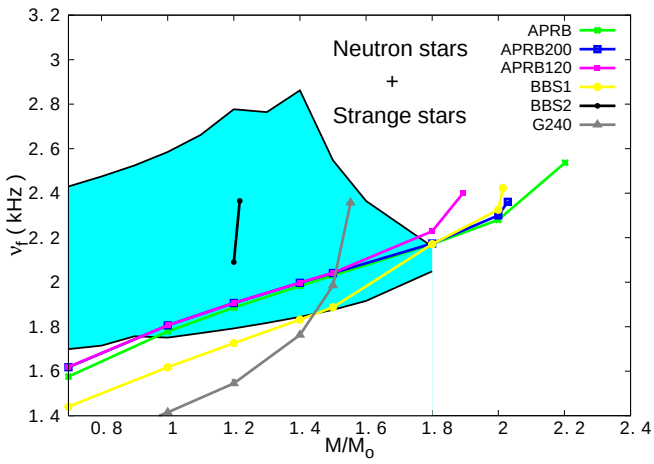

Figure 2. The frequency of the fundamental mode is plotted as a function of the mass of the star, for neutron/hybrid stars (continuous lines) and for strange stars modeled using the MIT bag model, spanning the allowed range of the parameters of the model (shadowed region).

with a number of EOSs representative of the current literature on the subject (continuous

lines), and for strange stars, i.e. stars entirely made of strange, up and down quarks, modeled using the MIT bag model and spanning the allowed range of parameters (the Bag constant, the coupling constant α_S and the quark masses. See [30] for details). From figure 2 we see that strange stars cannot emit gravitational waves with $\nu_f \lesssim 1.7$ kHz, for any values of the mass in the range we consider. Note that 1.8 $M_\odot$ is the maximum mass above which no stable strange star can exist. There is a small range of frequency where neutron/hybrid stars are indistinguishable from strange stars; however, there is a large frequency region where only strange stars can emit. For instance if $M = 1.4\ M_\odot$, a signal with $\nu_f \gtrsim 2$ kHz would belong to a strange star. Even if we do not know the mass of the star (as it is always the case for isolated pulsars) the knowledge of ν_f allows to gain information about the source nature; indeed, if $\nu_f \gtrsim 2.2$ kHz, apart from a very narrow region of masses where stars with hyperons would emit (EOS BBS2 and G240), we can reasonably exclude that the signal is emitted by a neutron star. In addition, it is possible to show that if a signal emitted by an oscillating strange star is detected, since ν_f is an increasing function of the bag constant B it would be possible to set constraints on B much more stringent than those provided by the available experimental data [30].

In principle oscillation modes may be excited as a consequence of any internal/external perturbation, such as a glitch or accretion processes. However, we do not know how much energy is actually channeled in the various modes. Let us take as a bench-mark the energy involved in a typical pulsar glitch, which is of the order of $\sim 10^{-13} M_\odot c^2$. Assuming that the star is at a distance $d = 1$ kpc, and is oscillating, say, in the f-mode with frequency and damping time $\nu_f \sim 1500$ Hz and $\tau_f \sim 0.1$ s, then the wave amplitude corresponding to this oscillation would be $\mathcal{A} \approx 5 \times 10^{-24}$; this is too low to be detected with present or advanced Virgo/LIGO, but it would be detectble by 3rd generation detectors like ET [31, 32].

Oscillations from newly-born neutron stars are more promising, because in this case more energy can be channeled in the modes. During the early phases of the stellar evolution, in particular during the first minute after core collapse, the mode frequencies of the hot remnant would change, as shown in Fig. 3a); these changes would trace the star evolution, while it cools down and thermal and entropy gradients in its interior are smoothed out [33]. As an example, in Fig. 3b) we show the signal which would be emitted by the newly born star oscillating in the fundamental mode or in the first g-mode. Assuming the energy stored in the f-mode to be $\Delta E_f = 1.6 \times 10^{-9}\ M_\odot c^2$, and the star to be located in the Galaxy, the signal to noise ratio would be $SNR = 2.7$ for Virgo+, and $SNR = 8$ for Advanced Virgo. Even more interesting is what the g-modes would tell us about the evolution of the star if the wave signal is detected. Indeed, the g-mode frequency is directly related to entropy and temperature gradients, therefore, the slope of the corresponding strain amplitude would tell us how fastly these gradients are smoothed out inside the star by dissipative processes, essentially driven by neutrino diffusion and emission. In this case assuming a mode energy $\Delta E_g = 6.7 \times 10^{-9}\ M_\odot c^2$, the signal to noise ratio would be $SNR = 1.7$ for Virgo+, and $SNR = 8$ for Advanced Virgo.

p-mode

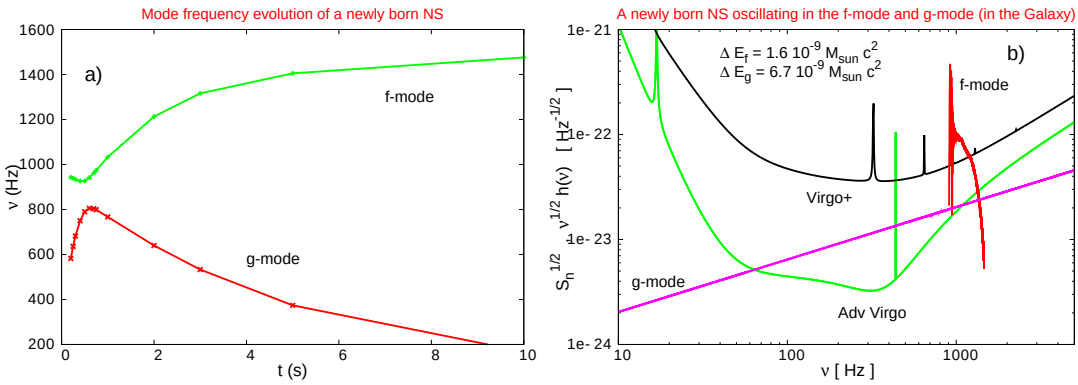

Figure 3. In panel a), the frequencies of the fundamental mode, and of the first g-mode of an evolving proto–neutron star are plotted as functions of the time elapsed from the gravitational collapse, during the first 5 seconds of evolution. In panel b) we plot the signal emitted by the star oscillating in the f- and g-mode, assuming a distance $d = 10$ kPc and energies $\Delta E_f = 1.6 \times 10^{-9}\ M_\odot c^2$ and $\Delta E_g = 6.7 \times 10^{-9}\ M_\odot c^2$, respectively.

Needless to say that ET would be a fantastic instrument to explore the evolution of young NSs.

4. Tidal disruption in BH-NS coalescing binaries

Black hole - neutron star coalescing binaries are among the most promising candidates for detection by ground-based laser interferometers. When the NS is disrupted before reaching the innermost stable circular orbit, the wave amplitude of the emitted signal is expected to decrease abruptly, and to exhibit a cutoff frequency ν_{GWtide}, corresponding to the orbit at which the disruption occurs [34]. The frequency cutoff is thus a distinctive feature of the GW signal emitted by BH-NS coalescing binaries and denotes the tidal disruption of the star. A further reason of interest in these sources is that they have been invoked as possible progenitors of short gamma-ray bursts [35]. In a recent paper [36], using a quasi-stationary approach and an improved version of the affine model we studied the disruption of a neutron star due to the tidal interaction with a black hole, calculating ν_{GWtide} for several equations of state describing matter inside the neutron star, and for a large set of the binary parameters, i.e. the neutron star mass, M_{NS}, the black hole angular momentum a/M_{BH}, the mass ratio $q = M_{BH}/M_{NS}$. The results are summarized in Fig. 4, where we plot the NS radius versus ν_{GWtide}, for a system composed by a NS with mass $M_{NS} = 1.4\, M_\odot$ and a black hole with angular momentum $a/M_{BH} = 0.9$ and mass $M_{BH} = 7\ M_\odot$ ($q = 5$). Each point refers to a different EOS, and the horizontal and vertical error bars are due to the errors which affect the estimate of the binary parameters, assuming that they have been extracted from a detected chirp using the matched filtering technique. For instance, for a system composed by a NS with mass in the range $(1.2-1.6)\ M_\odot$ and a total mass within $\sim (5-26)\ M_\odot$, (i.e. mass ratios $q \sim (3-15)$), the fractional error on the chirp mass $\mathcal{M} = \eta^{3/5}(M_{BH} + M_{NS})$ is

smaller than $\sim 10^{-3}$, while for the symmetric mass ratio $\eta = M_{BH}M_{NS}/(M_{BH}+M_{NS})^2$ is of the order of $\sim 1-3\cdot 10^{-2}$. These data refer to advanced LIGO, assuming the source at a fixed distance of 300 Mpc. In Fig. 4 we assume, as an example, that the measured

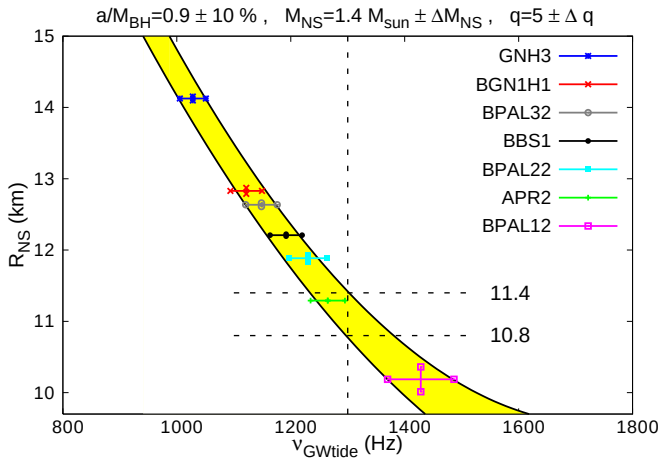

Figure 4. R_{NS} versus ν_{GWtide} is plotted for $M_{NS} = 1.4M_\odot \pm \Delta M_{NS}$, $q = 5 \pm \Delta q$ and $a/M_{BH} = 0.9 \pm 10\%$. The black continuous lines are the parabolic fits of the extreme points of the horizontal error bar for each EOS. The vertical dashed line corresponds to a supposed detected value of ν_{GWtide} equal to 1300 Hz; the two horizontal dashed lines identify the uncertainty on the evaluation of R_{NS}.

cutoff frequency is 1300 Hz (vertical dashed line), and we find that it is compatible with $10.8\,\mathrm{km} \leq R_{NS} \leq 11.4\,\mathrm{km}$, i.e. R_{NS} is found with an error of 2.7%. The error would be smaller(larger) if the detected value of ν_{GWtide} is smaller(larger); for instance, for 1400 Hz and 1200 Hz it would be 3.3% and 2.5% respectively. Knowing ν_{GWtide} could thus help placing a constraint on the radius of a NS disrupted by the BH tidal field, and would rule out some of the proposed equations of state.

Thus, as in the case of rotating and pulsating stars, the detection of a gravitational wave emitted by a neutron star disrupted by the tidal interaction with a black hole would provide valuable information on the source structure and on the behaviour of matter in the stellar core.

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