Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Constraining three-nucleon forces with multimessenger data

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Abstract. A detailed description of the properties of dense matter in extreme conditions, as those within Neutron Star cores, is still an open problem, whose solution is hampered by both the lack of empirical data, and by the difficulties in developing a suitable theoretical framework for the microscopic nuclear dynamics in such regimes.

We report here the results of a study aimed at inferring the properties of the repulsive three-nucleon interaction, driving the stiffness of the equation of state at high densities, by performing bayesian inference on current and future astrophysical observations.

Keywords. stars: neutron, gravitational waves, dense matter, equation of state

1. Introduction

The description of nuclear matter at low temperature and high density, exceding by several times the nuclear saturation density $\varrho_0 = 0.16\, fm^{-3}$, is still an open and challenging problem. If on one hand the quantum chromodynamics (QCD) is well established as the fundamental theory of strong interactions, on the other hand it is non-perturbative unless at very high energy scales ($>> \Lambda_{QCD} \sim 300\, MeV$). Since the only way to deal with non-perturbative QCD is through lattice calculation, which are limited at low densities because of the sign problem, see Stephanov (2006), whereas effective field theory approaches are reliable only up to 1-2 ϱ_0, see Essick *et al.* (2020), we are in lack of an *ab initio* theoretical framework describing a broad region of the QCD-phase diagram. In order to describe matter in this region we have to rely upon phenomenological models as much as possible constrained by empirical data. On this respect astrophysical observations involving neutron stars (NSs) are of prominent importance in order to shed new light on the nature of nuclear interactions.

The first detection of gravitational waves (GWs) emitted by a binary neutron star (BNS) system —Abbott *et al.* (2017), Abbott *et al.* (2019)—opened the possibility of a new source of information that together with the progress in electromagnetic observations — e.g. the X-ray timing and spettroscopic observations performed by the NICER satellite, see Riley *et al.* (2019)—could largely improve our knowledge of NS internal composition.

In our work, comprehensive discussed in Maselli, Sabatucci & Benhar (2021), we have made a first attempt to exploit multimessenger astronomy in order to constrain the strength of the three-nucleon repulsive interaction. This analysis is motivated by the fact that a better understanding of the three-nucleon potential at high-densities, other than improving our knowledge of strong interactions could also impact on the calculation of a lot of astrophysical observables requiring something more than the EOS, such as transport coefficients and neutrino interactions.

2. Framework

The EOS considered in our study is carried out in the framework of non-relativistic nuclear many-body theory (NMBT). In this framework nuclear matter is thought as an infinite system of pointlike nucleons interacting through two- and three-body potentials. We can define the hamiltonian

$$\mathcal{H} = \sum_i \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}. \tag{2.1}$$

The introduction of a three-body interaction is necessary in order to account for processes involving the internal structure of nucleons, which aren't actually point-like. Unlike the NN interaction which is accurately fitted on the large body of scattering data up to densities $\sim 4\,\rho_0$, the NNN interaction is only constrained around saturation density.

The hamiltonian we have considered —used to derive the APR EOS by Akmal, Pandharipande & Revenhall (1998)—comprises the Argonne v_{18} nucleon-nucleon (NN) potential (AV18) and the Urbana IX three-nucleon (NNN) potential (UIX). The UIX model for the NNN interaction comprises two terms

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R}. \tag{2.2}$$

The first is the attractive Fujita-Myazawa two-pion exchange potential, and the latter is a repulsive isoscalar contribution. The coupling constants of these two terms, are fixed in order to independently reproduce the binding energy of ^{3}H and the correct value of nuclear saturation density respectively. The repulsive NNN potential being purely phenomenological and entirely determined by the physics at saturation density, has no guarantee to be suited to describe the high density behavior of nuclear matter. For this reason in our analysis we have treated the coupling constant of the repulsive NNN potential as a free parameter to be inferred from NS measurements.

By performing the replacement

$$\langle V_{ijk}^{R} \rangle \to \alpha \langle V_{ijk}^{R} \rangle \tag{2.3}$$

we have generated a set of APR-like EOSs depending only on the value of α. For more details see also Tonetto, Sabatucci & Benhar (2021).

Stellar configurations generated with such EOSs are specified only by the values of α and the central pressure p_c, and provide two macroscopic observables: the mass $M(\alpha, p_c)$ and either the radius, $R(\alpha, p_c)$, or the tidal deformability, $\Lambda(\alpha, p_c)$, to be compared with observations.

To constrain the parameters associated with the EOS, we sampled their probability distribution through a bayesian approach based on Markov Chain Monte Carlo (MCMC) simulations. For a given astrophysical dataset O comprising n observed stars, the probability distribution of $\theta = \{\alpha, p_c^{(i=1,\ldots n)}\}$, is given by

$$\mathcal{P}(\theta|O) \propto \mathcal{P}_0(\theta)\mathcal{L}(O|D(\theta)) \tag{2.4}$$

where $\mathcal{P}_0$ is the prior information on θ, and $\mathcal{L}$ is the likelihood function, with $D(\theta)$ being the set of NS observables needed to interpret the data, i.e. the mass, the radius and/or the tidal deformability.

3. Results

We have considered two classes of datasets: (i) the GW observation of the BNS event GW170817, and (ii) the spectroscopic observation of the millisecond pulsars PSR

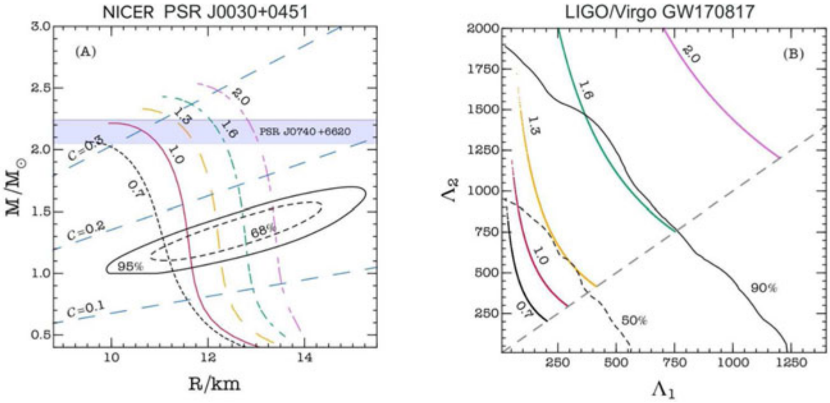

Figure 1. Mass-radius relations (left panel) and the $\Lambda_1 - \Lambda_2$ plane (right panel) of NS obtained using EOSs corresponding to the values of α specified on top of each curve.

J0030+0451 performed by the NICER satellite. Figure 1 shows the confidence intervals for the two datasets considered, together with the results corresponding to stellar configurations having different values of α.

For the GW event we fixed the chirp mass to its median value $\mathcal{M} = 1.186\ M_\odot$. Finally, we also required that the maximum mass supported by each EOS, has to be compatible with the one provided by radio pulsar timing of the binary PSR J0740+6620 i.e. $M_{\rm max} = 2.14^{+0.10}_{-0.09} M_\odot$. We sampled the posterior distribution using the *emcee* alghorithm with stretch move discussed by Foreman-Mackey *et al.* (2013).

The results of the posterior distribution are reported in Fig. 2. We can see that GWs alone are unable to set relevant constraints on the strength of NNN repulsion and the shape of the distribution appears to be dominated by the maximum mass requirement. However this analysis, yielding $\alpha = 1.32^{+0.48}_{-0.51}$ at 90% confidence level, has shown that there is sensitivity of NS observables with respect to the considered microscopic parameter, suggesting that an increasing number of observations and/or an increasing precision of the detectors have the potential to strongly improve the picture.

On this respect, we also report a preliminary analysis carried out with a set of mocked data simulating thirty BNS observations performed by the designed Einstein Telescope (ET). For this analysis we have generated each binary with two different values of α, respectively $\alpha = 1.0$ and $\alpha = 1.3$, in order to explore the capability of the ET to resolve between them. The inferred values of α at 90% confidence level for all binaries are reported in Fig. 3.

These results appears to be quite encouraging since for binaries with smaller chirp mass the ET is able to resolve between the two different injected values of α with just one observation.

4. Summary

We have performed bayesian inference on the current available astrophysical datasets involving neutron stars, in order to constrain the strength of the NNN repulsive interaction. Our results involving the LIGO/Virgo and NICER datasets, together with the maximum mass requirement provided by the pulsar PSR J0740+6620, suggest that current facilities are still not accurate enough to extract significant information. Conversely the analysis on the Einstein Telescope mocked data has shown that future facilities have

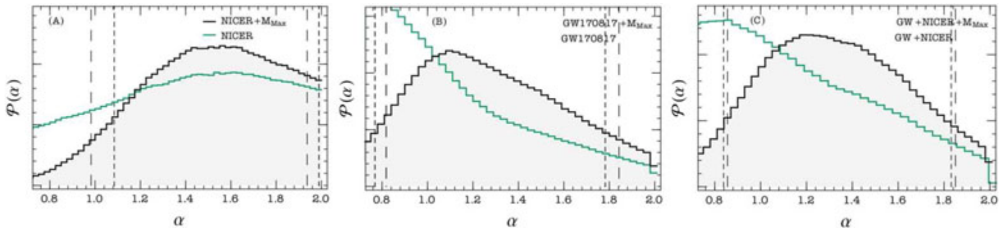

Figure 2. Posterior probability distribution of α inferred using NICER (a), LIGO/Virgo (b), and the combination of both these datasets (c). Filled and empty histograms correspond to results obtained including and neglecting the bound on the maximum mass imposed by PSR J0740+6620. Long- and short-dashed vertical lines identify 90% symmetric and highest posterior density intervals, respectively.

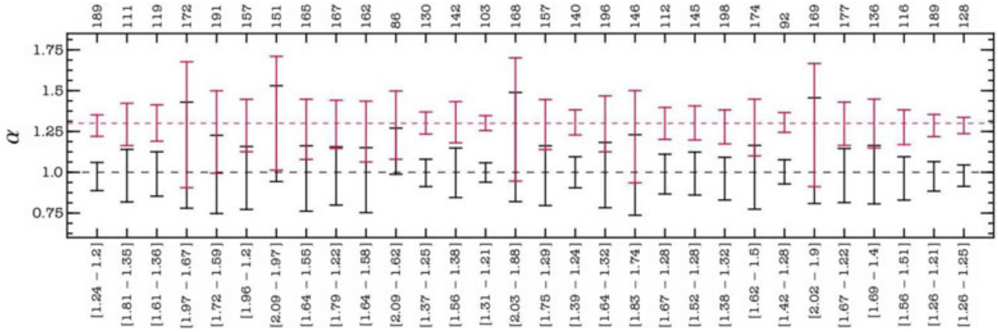

Figure 3. 90% confidence level of α extracted from the Einstein Telescope simulated likelihood. Black and red bars are referred to the different injected values of $\alpha = 1.0$ and 1.3 respectively. On the top line we have reported the distance of the source (Mpc), whereas the bottom line shows the injected masses of the stars ($M_\odot$).

the potential to significantly constrain the NNN repulsion with just a single observation. This is a strong evidence that with the upcoming third generation detectors, our understanding of neutron star matter will make a great step forward.

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References

Maselli, A., Sabatucci, A., Benhar, O. 2021, *Phys. Rev. C*, 103, 065804
Abbott, B. *et al.* (LIGO Scientific, Virgo) 2017, *Phys. Rev. Lett.*, 119, 161101
Abbott, B. *et al.* (LIGO Scientific, Virgo) 2019, *Phys. Rev. X*, 9, 011001
Riley, T. E., *et al.* 2019, *ApJ Lett.*, 887, L21
Akmal, A., Pandharipande, V. R., Revenhall, D. G. 1998, *Phys. Rev. C*, 58, 1804
Essick, R., Tews, I., Landry, P., Reddy, S., Holz, D. E. 2020, *Phys. Rev. C*, 102, 055803
Foreman-Mackey, D., Hogg, D. W., Lang, D., Goodman, J. 2013, *PASP*, 125, 306-312
Stephanov, M. A. 2006, *PoS LAT2006*, 024
Tonetto, L., Sabatucci, A., Benhar, O. 2021, *Phys. Rev. D*, 104, 083034