Prospectives Nationales 2020-2030 : contribution Astro-particles Physics (GT04)

Title: Probing extreme matter physics with gravitational waves

Principal Author:
Name: Jérôme Margueron
Institution: Institut de Physique des 2 infinis (IP2I)
Email: j.margueron@ipnl.in2p3.fr
Phone: +33 4 7243 1309

Co-authors:
AIM: Thierry Foglizzo, Jérôme Guilet
APC: Sarah Antier, Ed. Porter
GANIL: Anthea Fantina
IAP, Sorbonne Université: Frédéric Daigne, Irina Dvorkin
IP2I Lyon: Alexandre Arbey, Jérôme Degallaix, Hubert Hansen
L2IO: Elias Khan
LPC Caen: Francesca Gulminelli
LUTh Meudon: Jérôme Novak, Micaela Oertel
ARTEMIS/Lagrange Nice: Marie-Anne Bizouard, Nelson Christensen, Astrid Lamberts

Abstract:
This contribution to the 2020 national prospective illustrates how gravitational waves (GW) contribute to the understanding of the most extreme forms of matter composed of stable baryons, quarks and leptons. One of the best examples for such a contribution is the merging of two neutron-stars (NS) forming a supra-massive object whose central density is expected to lie well above the nuclear matter density, typical of atomic nuclei. A better characterization, through observations, of the properties of the merging stars and their supra-massive remnant, e.g. their masses, their tidal deformability, the post-merger oscillations, the electromagnetic emission, and so on, can be translated into an improved knowledge of the equation of state (EoS) of dense matter, with expected hints on the phase transition to quark matter. To that end, nuclear and astro-physicists have a common project in the modeling of extreme matter and in the global modeling of transient events and the resulting GW waveforms, which will be directly used by GW observers. This project requires however a strong support and coordination from our institutions, and a global strategy is proposed in this contribution.

In the close future, existing or new facilities such as Advanced LIGO, Advanced Virgo, KAGRA and Advanced LIGO India, as well as the 3rd generation ground based interferometer (ET) proposed by Europeans will contribute to the increase of the number of observed events, as well as to the source variety: binary neutron-star (BNS) and black-hole neutron-star (BHNS) mergers, core-collapse supernovae (CCSN) and bursting neutron-stars (NS). These new instruments will therefore foster the general understanding of extreme matter physics, as well as their interplay with the observational properties of transient events.

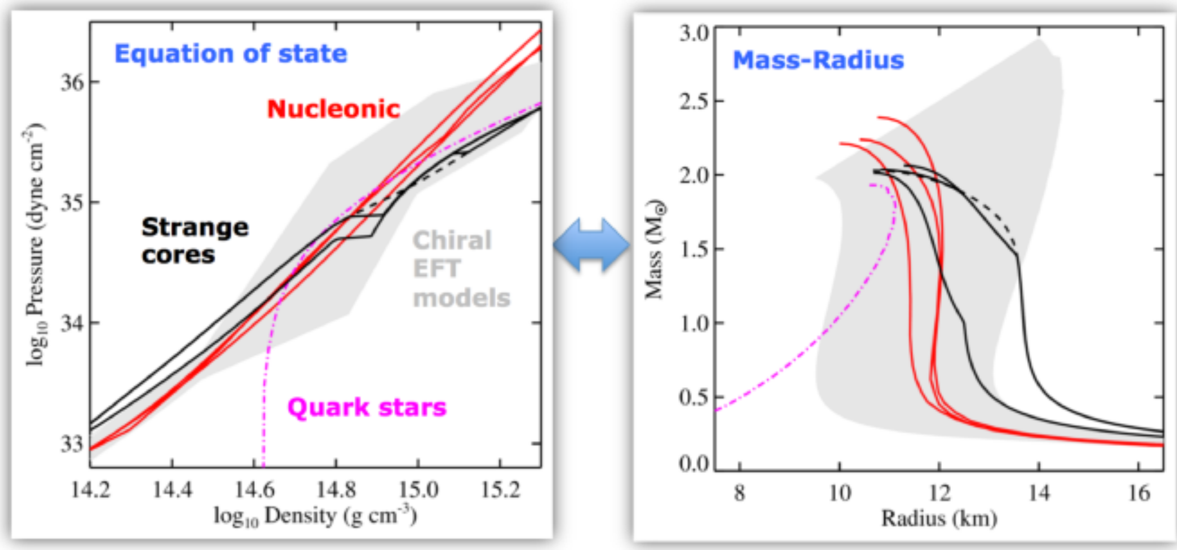
This contribution aims at showing how the existing French teams from different fields can interact together for the better understanding of extreme matter physics, within the support requested in this contribution.

White paper (max of five pages including figures):

The first detection of gravitational waves (GWs) from a binary black hole (BBH) merger by the LIGO-Virgo collaboration (LVC) in September 2015 has founded a new GW-based astronomy [Abbott 2016]. In August 2017 the first detection of GWs from a binary neutron star merger (BNS), the event GW170817, in coincidence with the observation of a gamma ray burst (GRB) and an electro-magnetic (EM) counterpart established the beginning of multi-messenger astronomy [Abbott 2017]. The O3 campaign which started in April 2019 has already provided a flow of additional detections confirming the expected rate: about 10 BBH, 1 BNS and 0.1 black hole neutron star (BHNS) mergers per month. With the Japanese KAGRA detector as well as the planned Einstein telescope (ET), the sensitivity will be further increased. This rapidly evolving new astronomy is revolutionizing the exploration of the universe by addressing fundamental questions such as the nature of gravity, of dark matter, the origin of elements heavier than Iron, the properties of dense matter in neutron stars (NS) and the structure of these compact stars themselves.

The global properties observed from NS, e.g. masses, radii, moments of inertia, tidal deformabilities, red-shift, etc... can be converted into a better knowledge of the dense matter EOS. In their seminal study, Tolman, Oppenheimer and Volkov have predicted maximum mass for NS without nuclear interaction (so little was known at that time) to be around 0.7 Msun [TOV 1939]. The fact that it is observed to be larger than 2 Msun illustrates the crucial role of the nuclear interaction to stabilize NS against the huge gravity field. To better illustrate the link between global NS properties and the EOS, we show in Fig. 1 a confrontation of various EOS based on different dense matter modeling, left panel, against their predictions for families of masses and radii, right panel where the running parameter is the NS central density. A better measurement of both masses and radii for a set of NS can be converted into a better understanding of dense matter EOS. Similar plots can be done with couples of other global properties, e.g. masses against tidal deformabilities for instance.

Fig. 1: EOS versus mass-radius for a set of different modeling of dense matter: nucleonic, hybrid with strange cores and quark stars [Watts 2014].



The 2017 GW event GW170817 have shown the huge contribution of GW to constrain dense matter EOS. Indeed, during most of the inspiral of BNS and BHNS mergers, the parameters of the trajectories, the masses, spins and tidal deformability of the compact objects are captured by post-Newtonian (PN) calculations, whereas the modeling of the merger and post-merger phase requires state-of-the-art numerical simulations associating 3D (magneto-)hydrodynamics in general relativity, neutrino transport and microphysical inputs (EoS, transport properties, neutrino interactions). The properties of the BNS merger remnant, e.g. its stability, temperature, neutrino emissivity, are crucial for the understanding of the GW and EM signals [Shibata 2017]. Moreover, it is expected that post-merger GWs, not yet observed [LVC 2018], will be emitted at fixed frequencies correlated to the NS compactness [Bauswein 2016]. The detection of the post-merger signal, among the possibilities of detectors in the (near) future, will thus allow to obtain additional important information on the EoS of dense matter in its most extreme conditions. Additionally, it contains the imprint of a potential phase transition in dense matter at NS densities [Bauswein 2019].

This contribution addresses a very timely physics case, the understanding of the first GW observed from a BNS merger and the many additional data expected soon (BHNS, CCSN, bursting NS, etc...). In the future, advances in the understanding of these exciting present and future observations rely on their successful confrontation to theoretical modelling , for which still many questions remain open. These are either related to microscopic properties such as transport properties (viscosity, turbulence, magnetic instabilities), the dense matter EoS and neutrino interaction rates, or related to global simulations, combining together GR hydrodynamics, the influence of the magnetic field, rotation and neutrino propagation, challenging as well as massive computational facilities. The French teams are very well positioned to address the following questions: what is the impact of most recent microphysics calculations on the dynamics of BNS and BHNS mergers? How it is translated in terms of GWs? More precisely, what will BNS mergers tell us about the properties and composition of dense matter and, incidentally, what kind of phase transition(s) can be expected by compressing matter to several times the density of an atomic nucleus?

The French community will focus its efforts in the coming years into the following topics:

- Global simulations of transient phenomena producing GW: NS merger, core-collapse SN.
- Dense matter properties: equation of state (EoS), reaction rates, neutrino emissivity are the microphysical inputs for global simulations which should be consistently calculated.
- Confront the outputs of the latter with present and future observations.
- Confront GW with other multi-messenger observations, refine merger rate and understand the origin of r-process elements.
- Theoretical waveforms needed for the LIGO-Virgo data analysis.

The success in our efforts, based on an interdisciplinary strategy, strongly relies into the support from our institutions as well as into their coordination. More is developed at the end of this contribution.

In the coming years and with the help of our institutions, we expect that the French community will be running a global BNS merger simulation including newly developed input tools for realistic microphysics to test the impact of the latter on GW emission, and the ejecta properties. The major advance from the French community will thus be the creation of realistic microphysics libraries, an extension of the data base CompOSE1, including more EoS data and a newly developed neutrino toolkit. These new tools will be freely released to the scientific community, as it has been done in the past by some of the participants of this contribution (LORENE, CompOSE, Kadath, BlackHawk, etc…) and validated within global simulations.

Dense matter Equation of state (EoS). The French community plans to improve the dense matter equation of state [Oertel 2017] used in merger simulations. It is indeed very important to control the microphysics inputs in these simulations at its best. This will be achieved by the employment of a very flexible meta-modeling [Margueron 2018a], which has been developed for cold purely nucleonic neutron star matter [Margueron 2018b] and applied with success among others to the analysis of X-ray data to obtain neutron star radii [Baillot 2019]. This meta-model can also be applied to inhomogeneous matter present in the crust of a neutron star [Chatterjee 2017]. It will be extended to span the various scenarios from purely nucleonic matter [Margueron 2018a] to quark matter, passing via hadronic matter [Massot 2012, Oertel 2016] (with the possible appearance of Delta resonances, hyperons, pions or kaons) and to include thermal effects as well as matter out of weak equilibrium.

Neutrino reaction rates. It is known since many years that the dynamics of CCSN strongly depend on the heating of the shocked matter by neutrinos and that therefore neutrino interactions are very important in this context. In contrast to core-collapse supernovae, the dynamics of BNS mergers only marginally depend on neutrino interactions. However, ejecta composition and nucleosynthesis

1 https://CompOSE.obspm.fr

conditions are very sensitive to the neutrino treatment and neutrino interactions. Since simulations are very expensive, analytic expressions have been derived for relevant reaction rates [Bruenn 1985, Rosswog 2003] which are, however based on very crude approximations. Since then, several corrections have been added, such as weak magnetism and recoil [Burrows 1998, Horowitz 2002], nuclear structure corrections [Horowitz 1997, Bruenn 1997], effective masses and chemical potentials for nucleons in dense matter [Roberts 2012, Martinez-Pinedo 2012] and additional reactions [Hannestad 1998, Fischer 2018]. Nuclear physicists have pointed out since decades that in dense matter different effects can modify the neutrino matter interaction rates and neutrino emissivity by orders of magnitude, in particular collective effects [Reddy 1999, Margueron 2001]. (Special) relativistic effects can play an important role, too [Leinson 2001].

Global simulation of BNS, BHNS, CCSN. This is a central piece in our future plans since it combines together our expertise in microphysics and in general relativistic hydrodynamics as well as neutrino transport to develop a code for simulations. The different libraries, data and tools developed among the French community (CompOSE and neutrino toolkit) will be interfaced with a numerical code, and its success necessitates a close collaboration between the experts in dense matter physics and in numerical relativity and hydrodynamics. A particular effort in high performance computing is needed to ensure that the parallelised code is able to run fast enough to resolve the 3D hydrodynamical instabilities that shape the neutrino and gravitational wave signals, which carry direct information about the explosion engine.

Population studies and observational constraints. To understand the respective contributions of mergers and CCSN to the production of the heaviest elements, the direct multi-messenger observations and the global simulations of these events can be complemented by other studies, at the interface of the IN2P3 and INSU expertise: (i) population models predicting event rates in a cosmological perspective and the associated chemical evolution [Vangioni 2016]; (ii) measurements of r process element abundances in various astrophysical sites to constrain such models [Francois 2007, Skuladottir 2019]; (iii) in the case of mergers, search of *orphan* kilonovae, i.e. kilonovae observations not triggered by GW, in large surveys such as LSST.

The present proposal is complementary to the two others submitted to GT04, *Understanding the core collapse supernova explosion mechanism* and *Neutrino Astrophysics*, sharing common goals and means.

Strategy for the future years. IN2P3 is one of the first research organisations investing massively in the detection of GW, within the Virgo interferometer. The first observation of GW from BNS has immediately revealed the huge impact that GW has for the understanding of dense matter at its limits of stability, establishing a strong connection between the GW community, astrophysicists and nuclear physicists, as shown in this document. A strong and structured research program has now emerged, in lines with the PHAROS COST Action assembling European efforts to bring these communities together as well as with the GWIC supervising the future investments in GW facilities.

To reach the goals presented in this document, there are however important requirements that we wish to express to our institutions.

The first one is related to the GW facilities: Concerning Virgo, it is obvious that we support the upgrading program helping in improving the sensitivity of the interferometer and continuing to accumulate new events. At the same time, it is also important to position IN2P3 with respect to the third generation of GW earth-detector. The european project developped with the GWIC is Einstein Telescope (ET). It is designed to the observation of stellar mass compact objects (BH, NS) with a sensitivity peaked in the domain going from Hertz to kHertz. The kHertz frequency region is of particular interest to probe the dynamics of post merger BNS and the measure of quasi-normal mode of BH [Miao 2018]. It should also be noted that this frequency region is well outside the one of LISA, which is design to target sources below the Hertz. It will increase by a factor 10 the observational horizon of present interferometers, increasing largely the number of observed events and lowering the noise for the closer ones. GW from CCSN or bursting NS, which are not visible with the present facilities, will certainly become observable and contribute to improve our knowledge on the dense matter properties of these objects. GW170817 has also shown the importance of multi-messenger observations by associating Fermi, XMM-Newton, most of earth telescopes, etc..., to the follow-up observation of AT2017gfo. The EM emission is very important to estimate the mass and velocity of the ejected matter, which can be confronted to the predictions of the global modeling. In this regard, the LSST project is also very timely since it will be able to continuously scrutinize a large fraction of the sky and possibly detect the EM emission in a very short time after the GW detection (or possibly together). The impact of these new facilities on the understanding of supra-dense matter is going well beyond all other existing means. We thus seek strong involvement of the French research agencies in the advance Virgo upgrades, in the future ET project as well as in the LSST telescope.

Note that nuclear physics facilities also contribute to the understanding of dense matter and this is further developped in a contribution addressed to the GT02 of the national prospectives.

The second request is related to the theoretical modeling, which represents an interdisciplinary and coherent effort going from the understanding of the microscopic properties of matter (nuclear and particle physics) up to the global properties captured in (magneto-)hydrodynamical framework. While all the teams associated to this aim expect strong support for the next years, the French community deeply needs a strong support for the development of hydro-dynamical codes for BNS and BHNS mergers, as well as for CCSN. These kinds of global codes assemble together the state-of-the-art understanding of microscopic matter properties (EoS, cross-sections, transport properties) with the expertise in gravity in strong field, the present knowledge in astrophysics, the astronomical observations and the GW detection. There is a great advantage in being master of our own global modeling for the detailled understanding of the various asumptions and simplifications introduced in the code, for the identification of microscopic key properties, and for the push for further developments on either nuclear side or hydro-dynamical side, etc... The French community needs a very close, structured and inter-disciplinary collaboration to become one the leading actor in the de-coding of GW. It is thus urgent to create and invest into the development of a (magneto-)hydro-dynamical general relativity code in France as well as to continue strong support for the existing teams.

Finally our last request is about recruitment of young physicists (CR level). Our field relies strongly on the existence of inter-disciplinary researchers being very well aware of the latest developments in microscopic theories and their confrontation, for instance, to the latest nuclear physics data as well as to the issues related to global simulations and astrophysical data. We however suffer from the existence of structured institutes at CNRS, where it can be difficult to recruit people being in-between. In order to foster interdisciplinary activities, such as ours, we propose to either continue the existing exchanges between CNRS institutes on CR positions, at the cost of better cross-coordination between institutes, or to have interdisciplinary commissions, as it used to exist about a decade ago with the 47 commission for instance. The advantage to the interdisciplinary commission is the better sharing of the expertise among its member, making the final and common decision very well grounded.

References :

[Abbott 2016] B.P. Abbott et al., LVC, Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016).

[Abbott 2017] B.P. Abbott et al., LVC., GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral, Phys. Rev. Lett. 119, 161101 (2017).

[Arbey 2010, 2018] A. Arbey and F. Mahmoudi, SuperIso Relic: A program for calculating relic density and flavor physics observables in Supersymmetry, Comput. Phys. Commun. 181, 1277 (2010); A. Arbey, F. Mahmoudi, G. Robbins, SuperIso Relic v4: A program for calculating dark matter and flavour physics observables in Supersymmetry, CERN-TH-2018-149, arXiv:1806.11489 (hep-ph,astro-ph.CO).

[Arbey 2012, 2018] A. Arbey, AlterBBN: A program for calculating the BBN abundances of the elements in alternative cosmologies, Comput. Phys. Commun. 183, 1822 (2012); A. Arbey, J. Auffinger, K.P. Hickerson, E.S. Jenssen, AlterBBN v2: A public code for calculating Big-Bang nucleosynthesis constraints in alternative cosmologies, CERN-TH-2018-146, arXiv:1806.11095 (astro-ph.CO).

[Baillot 2019] N. Baillot d'Etivaux, S. Guillot, J. Margueron, N. Webb, M. Catelan, A. Reisenegger, New Constraints on the nuclear equation of state from neutron stars thermal emission (2019), submitted to ApJ..

[Bauswein 2012] A. Bauswein, H.-T. Janka, K. Hebeler, A. Schwenk, Phys. Rev. D 86, 063001 (2012).

[Bauswein 2016] A. Bauswein, N. Stergioulas, H.-Th. Janka, Exploring properties of high-density matter through remnants of neutron-star mergers, Eur. Phys. J. A 52, 56 (2016).

[Bauswein 2019] A. Bauswein, N.-U. Bastian, D.B. Blaschke, K. Chatziioannou, J.A. Clark, T. Fischer, M. Oertel, Identifying a first-order phase transition in neutron star mergers through gravitational waves, Phys. Rev. Lett. 122, 061102 (2019).

[Bejger2005] M. Bejger, D. Gondek-Rosińska, E. Gourgoulhon, P. Haensel, K. Taniguchi & J. L. Zdunik : Impact of the nuclear equation of state on the last orbits of binary neutron stars, Astron. and Astrophys. 431, 297 (2005).

[Biguet 2015] A. Biguet, H. Hansen, T. Brugière, P. Costa, P. Borgnat, Sensitivity of predictions in an effective model – application to the chiral critical end point position in the Nambu--Jona-Lasinio model, Eur. Phys. J. A51, 121 (2015).

[Bruenn 1985] S. Bruenn, Stellar core collapse: Numerical model and infall epoch, Astrophys. J Suppl. 58, 771 (1985).

[Bruenn 1997] S. Bruenn, A. Mezzacappa, Ion screening effects and stellar collapse, Phys. Rev. D 56, 7529 (1997).

[Burrows 1998] A. Burrows, R.F. Sawyer, The Effects of correlations on neutrino opacities in nuclear matter, Phys. Rev. C 58, 554 (1998).

[Ciolfi 2017] R. Ciolfi, Kastaun et al., General relativistic magnetohydrodynamic simulations of binary neutron star mergers forming a long-lived neutron star, PRD, 95, 063016 (2017).

[Chatterjee 2017] D. Chatterjee, F. Gulminelli, Ad. R. Raduta, J. Margueron, Constraints on the nuclear equation of state from nuclear masses and radii in a Thomas-Fermi meta-modeling approach, Phys. Rev. C 96, 065805 (2017).

[Fischer 2018] T. Fischer et al, Neutrino signal from proto-neutron star evolution: effects of opacities from charged current neutrino interactions and inverse neutron decay, arxiv 1804.10890.

[Fortin 2010] M. Fortin, F. Grill, J. Margueron, D. Page, and N. Sandulescu, Thermalization time and specific heat of the neutron stars crust, Phys. Rev. C 82, 065804 (2010).

[Francois 2007] Francois et al., First stars. VIII. Enrichment of the neutron-capture elements in the early Galaxy, A&A 476, 935 (2007).

[Gourgoulhon 2001] E. Gourgoulhon, P. Grandclément, K. Taniguchi, J.-A. Marck, S. Bonazzola, Quasiequilibrium sequences of synchronized and irrotational binary neutron stars in general relativity: Method and tests, Phys. Rev. D 63, 064029 (2001).

[Gourgoulhon 2016] E. Gourgoulhon, P. Grandclément, J-A Marck, J. Novak, K. Taniguchi, LORENE: Spectral methods differential equations solver,Astrophysics Source Code Library, record ascl:1608.018.

[Grandclément 2010a] P. Grandclément, « Kadath : spectral solver for theoretical physics », J. of Comp. Phys., 229, 3334 (2010).

[Grandclément 2009] P. Grandclément, J. Novak, « Spectral methods for numerical relativity », Living Reviews in Relativity 12, 1 (2009).

[Gourgoulhon2012] E. Gourgoulhon : 3+1 Formalism in General Relativity; Bases of Numerical Relativity, Springer (Berlin) (294 pages) (2012).

[Hansen 2007] H. Hansen, W.M. Alberico, et al., mesonic correlation functions at finite temperature and density in the Nambu-Jona-Lasinio model with Polyakov loop, Phys. Rev. D 75, 065004 (2007).

[Hannestadt 1998] S. Hannestad, G. Raffelt, Supernova neutrino opacity from nucleon-nucleon Bremsstrahlung and related processes, Astrophys. J 507, 339 (1998).

[Horowitz 1997] C. Horowitz, Neutrino trapping in a supernova and ion screening,Phys. Rev. D 55, 4577 (1997).

[Horowitz 2002] C. Horowitz, Weak magnetism for anti-neutrinos in supernovae, Phys. Rev. D 65, 043001 (2002).

[Leinson 2001] L.B. Leinson, A. Perez, Relativistic direct Urca processes in cooling neutron stars, Phys. Lett.B 518, 15 (2001); erratum ibid 522, 358 (2001).

[Leinson 2002] L.B. Leinson, Direct Urca processes on nucleons in cooling neutron stars, Nucl. Phys. A 707, 543 (2002).

[LVC 2018] Search for gravitational waves from a long-lived remnant of the binary neutron star merger GW170817, arXiv:1810.02581, (2018).

[Margueron 2001] J. Margueron, neutrino propagation in dense matter, PhD thesis, Université Paris Sud 2001.

[Margueron 2018a] J. Margueron, R. Hoffmann Casali, and F. Gulminelli, Equation of state for dense nucleonic matter from metamodeling. I. Foundational aspects, Phys. Rev. C 97, 025805 (2018).

[Margueron 2018b] J. Margueron, R. Hoffmann Casali, and F. Gulminelli, Equation of state for dense nucleonic matter from metamodeling. II. Predictions for neutron star properties, Phys. Rev. C 97, 025806 (2018).

[Martinez-Pinedo 2012] G. Martinez-Pinedo, T. Fischer, A. Lohs, L. Hüther, Charged-current weak interaction processes in hot and dense matter and its impact on the spectra of neutrinos emitted from proto-neutron star cooling, Phys. Rev. Lett. 109, 251104 (2012).

[Massot 2012] E. Massot, J. Margueron, G. Chanfray, Europhys. Lett. 97, 39002 (2012).

[Meliani 2016] Z. Meliani, P. Grandclement, F. Casse, F. H. Vincent, O. Straub, and F. Dauvergne, GR-AMRVAC code applications: accretion onto compact objects, boson stars versus black holes, CQG 33, 155010 (2016).

[Meliani 2017] Z. Meliani, Y. Mizuno, H. Olivares, O. Porth, L. Rezzolla, and Z. Younsi., Simulations of recoiling black holes: adaptive mesh refinement and radiative transfer, Astron. and Astrophys. 38, 598, (2017).

[Metzger 2017] Brian D. Metzger, Kilonovae, Living Reviews in Relativity 20:3 (2017).

[Miao 2018] H. Miao, H. Yang, and D. Martynov, Towards the design of gravitational wave detectors for probing neutron-star physics, Phys. Rev. D 98, 044044 (2018).

[Oertel 2016] M. Oertel, F. Gulminelli, C. Providencia, A.R. Raduta, Hyperons in neutron stars and supernova cores, Eur. Phys. J. A52, 50 (2016).

[Oertel 2017] M. Oertel, M. Hempel, T. Klähn, S. Typel, Equations of state for supernovae and compact stars, Rev. Mod. Phys. 89, 015007 (2017).

[Reddy 1999] S. Reddy, M. Prakash, J.M. Lattimer, J. Pons, Effects of strong and electromagnetic correlations on neutrino interactions in dense matter, Phys. Rev. C 59, 2888 (1999).

[Roberts 2012] L. F. Roberts, S. Reddy, G. Shen, Medium modification of the charged current neutrino opacity and its implications, Phys. Rev. C 86, 065803

[Skuladottir 2019] Skuladottir, Hansen, Salvadori, Choplin, Neutron-capture elements in dwarf galaxies I: chemical clocks and the short timescale of the r-process, to appear in A&A (2019).

[Shibata 2006] M. Shibata, K. Taniguchi, Numerical relativity, Gravitational waves: theory, Relativistic stars: structure stability and oscillations, 73, 4027 (2006).

[Shibata 2011] M. Shibata, K. Kiuchi, Y. Sekiguchi, Y. Suwa, Prog. Theor. Phys. 125, 1255 (2011).

[Shibata 2017] M. Shibata, et al., Modeling GW170817 based on numerical relativity and its implications, Phys. Rev. D 96, 123012 (2017).

[TOV 1939] Tolman, Phys. Rev. 55, 364 (1939); Oppenheimer and Volkoff, Phys. Rev. 55, 374 (1939).

[Tews 2018] I. Tews, J. Margueron, S. Reddy, How well does GW170817 constrain the equation of state of dense matter?, Phys. Rev. C 98, 045804 (2018) Editor’s suggestion.

[Tews 2019] I. Tews, J. Margueron, S. Reddy, Confronting gravitational-wave observations with modern nuclear physics constraints, Eur. Phys. J. A special issue on GW (2019).

[Vangioni 2016] Vangioni, Goriely, Daigne, Francois and Belcsynski, Cosmic NS merger rate and GW constrained by the r-process nucleosynthesis, MNRAS 455, 17 (2016).

[Watts 2014] A. Watts et al., "Advancing Astrophysics with the Square Kilometre Array", Proceedings of Science, PoS (AASKA14) 043