Nuclear Physics in Neutron Star Mergers - Going Beyond the Equation of State

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I. SCIENTIFIC MOTIVATION

Neutron stars and binary neutron star mergers present a unique laboratory for the investigation of fundamental matter described by the standard model of particle physics, nuclear physics, and even beyond the standard model physics. Due to the recent discovery of gravitational waves from binary neutron star mergers by the LIGO and VIRGO observatories, a new way to examine the underlying physics of these stellar objects has emerged [1]. Planned next-generation detectors like Cosmic Explorer in the US [2], the Einstein Telescope in Europe [3], and NEMO in Australia [4] will push the reach of gravitational wave detectors to the edge of the observable universe. Events of similar signal strength as the first binary neutron star merger event (GW170817) observed with third-generation detectors will allow us to not only see the inspiral of two neutron stars but also their actual merger and post-merger evolution. This phase of a merger is predominantly driven by the microscopic properties of dense nuclear (or more exotic) matter.

Unveiling the structure of the phase diagram of quantum chromodynamics (QCD) and finding the true degrees of freedom of dense matter at densities achieved in compact stars is one of the great scientific challenges of our time[2, 3, 5–7]. While heavy-ion collision experiments are capable of exploring the QCD phase diagram at high temperatures and low to intermediate densities, neutron star mergers offer a unique opportunity to explore the high-density, low to intermediate temperature regime. One measurable property of dense matter is the equation of state (EOS), on which much effort has been expended in the last decades, yielding hints at the existence of a first-order phase transition from nuclear matter to quark matter inside heavy neutron stars [8, 9], although this remains an open question.

However, in terrestrial condensed matter physics it is well known that the EOS is not the optimal observable for mapping the phase diagram of a material. An example of this is the "masquerade problem": For a class of EOS for matter with a weak first-order phase transition from nuclear matter to quark matter, one can find identical mass-radius curves and stellar structures, including tidal deformabilities, that are indistinguishable from a purely nucleonic EOS without quark matter [10, 11]. Fig. 1 shows such an example, where EOSes with and without a transition to quark matter give similar mass-radius relations. In contrast, in terrestrial condensed matter physics, different phases are mainly distinguished via their spectrum of low-energy excitations, which are most easily detected via differences in transport or equilibration properties. In searching for the critical temperature for superconductivity, for example, one measures a transport property, electrical conductivity. We advocate applying this principle to the QCD phase diagram.

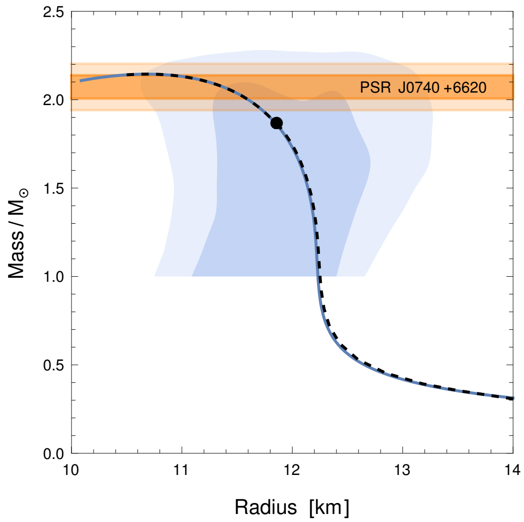

FIG. 1. Mass-Radius curves of a purely nucleonic EOS and a hybrid EOS with a nuclear mantle and a quark matter core modeled with the constant speed of sound model. The hybrid EOS and the nuclear EOS are indistinguishable within achievable measurement errors for the radius and the mass of heavy stars. This is known as the "masquerade problem" and highlights the need to go beyond the EOS in order to determine the underlying degrees of freedom. The nuclear EOS shown here is called QMC-RMF3 [12, 13]. The hybrid EOS is obtained by a thermodynamically consistent matching of QMC-RMF3 and a quark matter EOS modeled with the constant speed of sound model [14, 15] at four times saturation density.

Current research shows that a strong first-order phase transition with a large latent heat is unlikely to occur in nature [16], which makes it more likely that the true EOS falls in this parameter space. This implies that

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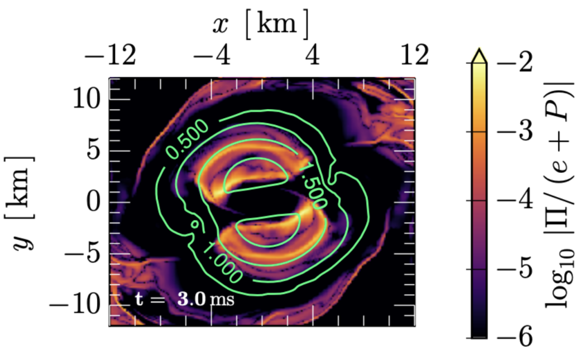

FIG. 2. Upper bound on viscous pressure, Π, expected for Urca processes in a neutron star merger. Expressed relative to the fluid enthalpy density $h = e + P$. Plots taken from Ref. [17].

constraints on the tidal deformability from the inspiral might be insufficient to truly determine the nuclear degrees of freedom of dense matter. However, additional insights can be provided by the following approaches that we would like to cover during our workshop:

- **Chemical equilibration and neutrino interactions**: Nuclear matter in neutron stars relaxes towards isospin ("beta") equilibrium; its steady state has an equilibrium proton fraction which is a function of baryon density and temperature. Equilibrium is established by weak interactions which operate on a timescale that can range from microseconds to minutes. Astrophysical phenomena such as density oscillations in neutron stars, which can be on a similar timescale, can therefore drive the system out of equilibrium, and the dynamics of the relaxation process may be relevant to our understanding of the astrophysics and lead to transport phenomena like bulk viscosity. There has been considerable recent interest in understanding this phenomenon by means of numerical simulations [17–23]. However, the uncertainties in the physical conditions and their modelling remain large [24, 25]. The few simulations that include these weak interaction processes use very crude approximations for the so-called modified and direct Urca rates, which will require drastic theoretical improvements on the nuclear physics side in the future. Recently, it has been shown that chemical equilibration indeed acts on timescales comparable to the dynamical time of the post-merger phase [26, 27]. There is thus a pressing need to understand how to best model these effects in numerical relativity simulations of neutron star mergers. This will require bringing together expertise from both the numerical simulation and nuclear physics communities.

  All the phenomena described above crucially depend on the mean-free path of neutrinos and their interactions with nuclei. Direct and modified Urca rates are drastically faster if neutrinos are completely trapped [28] and strongly influence bulk viscous damping. Existing calculations either assume that neutrinos are completely free streaming or completely trapped. However, in the real physical environment the neutrino mean free path depends on the energy of the individual neutrino, which means that in the temperature range of a few MeV, some neutrinos will be trapped while other, less energetic neutrinos can still escape the merger. This requires a completely new formulation and calculation of the neutrino emission and absorption rates in dense nuclear matter. The influence of thermal conductivity and shear viscosity also strongly depends on neutrino-trapping [26]. An improved treatment of neutrinos in merger simulations, neutrino emission, and absorption rates, and the resulting transport phenomena is therefore essential for accurate modeling and understanding of the post-merger phase.

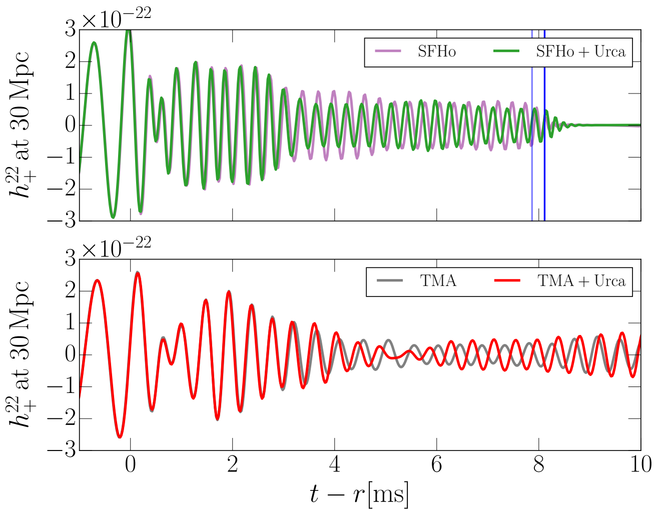

FIG. 3. Normalized gravitational wave strain, h_+^{22} for the $l = m = 2$ component for two different EOSs. Upper bounds on differences due to transport as a result of weak interactions in the post-merger are clearly visible. All times, t, are stated relative to the merger time and extraction radius r. The vertical lines indicate times of black hole formation. Graphic is taken from Ref. [21].

- **Transport phenomena and electromagnetic counterparts**: Neutron star mergers show strong spatial and temporal variations of their density, temperature, and fluid flow velocity. This makes it plausible that in addition to bulk viscosity from chemical equilibration, also shear viscosity, as well as thermal conductivity [29] may play a role in the dynamics of the merger [26]. Transport may not solely originate from nuclear processes. Driven by strong amplification throughout the earlier merger stages, stellar merger remnants will feature strong magnetic fields. These magnetic fields have been shown to cause different forms of novel angular momentum transport that may critically affect

the lifetime of the system, and our ability to infer equation of state constraints from gravitational wave events [30, 31]. Some of them may also critically depend on the thermodynamic conditions probed in the merger [32].
As a particular example, we highlight the recent discovery of kilohertz quasi-periodic oscillations in archival gamma-ray burst data [33]. While their precise origin remains unclear, one of the tantalizing possibilities put forward is that they stem from quasi-periodic oscillations of the merger remnant, offering the possibility to relate them to the equation of state [34]. Fully understanding such a connection will require significant cross-talk between the numerical relativity and nuclear physics communities. One of the major challenges of incorporating such effects generically (i.e., without first principle approaches such as neutrino transport in the case of equilibration [22]), is the lack of numerical relativity codes incorporating causal formulations of dissipative hydrodynamics [35–37], which only recently have been started to be investigated. At the same time, nuclear physicists have long pushed the frontier of the modeling of such effects in the context of heavy-ion collisions [38]. Bringing together experts from different communities, thus, promises to drive major advances in this nascent field.

- **Exotic matter**: **Quark matter** in compact stars, if it exists, is most likely in a color superconducting state, since the critical temperatures for the most commonly postulated color superconducting phases are estimated to be tens of MeV. One possible manifestation of the presence of superconducting quark matter would be its chemical (flavor) equilibration properties such as bulk viscosity and phase conversion dissipation. If the phase diagram includes a first-order phase transition at a critical pressure that separates nuclear matter from quark matter then in a neutron star there may be regions of quark matter separated from nuclear matter by sharp phase boundaries. Density oscillations will cause these boundaries to move as fluid elements cross the critical pressure. However, the speed at which the phase boundary can move is limited by the rate of flavor-changing (weak interaction) processes. These are needed because the quark matter phase will have a different flavor content (e.g. more strangeness) from nuclear matter. One of the effects of a phase boundary moving at a finite speed in an oscillatory system, which is out of phase with the external oscillation, is dissipation. This is similar to bulk viscosity, but an effect of the first-order transition and the resulting interface and is called "phase conversion dissipation" [39]. Especially for masquerading EOS models, this is a potential smoking gun signal for the existence of quark matter in mergers, since other signatures [40–43] may be absent in this case. Furthermore, (color-)superfluid and superconducting gaps drastically change the low-energy excitations and can, depending on the exact gap structure, exponentially dampen transport properties and cooling of the remnant. It is currently unclear how these effects can actually be incorporated in merger simulations and how strongly they can influence the signal, motivating further inter-disciplinary study on the topic.

- **Cooling and supernovae**: One important property of nuclear matter is the so-called direct Urca (density-) threshold. Above this threshold, the much faster (compared to their "modified" counterparts) direct Urca processes can operate. It is currently unclear whether nuclear matter possesses a direct Urca threshold and if it does, at which density it can be found. While the location of a direct Urca threshold has little to no effect on the static properties of a neutron star, like mass-radius curves, the tidal deformability or in short the equation of state, it strongly influences dissipative transport properties and the thermal conductivity of nuclear matter. This ambiguity makes calculations as we describe in the prior points very challenging. Observations of cooling of supernovae and isolated (proto-)neutron stars have the potential to reveal the location of the threshold since the direct Urca processes lead to a much faster cooling [44]. Work is needed to understand how to best combine input from these observations with that obtained from neutron star mergers, to advance these theoretical models.

- **Beyond the standard model particles** can influence the signal in similar ways, by changing transport properties, influencing cooling rates [45, 46] or the outcome,i.e. the fate or longevity of the neutron star after the merger, yet they are only beginning to be included in self-consistent neutron star merger simulations – for example, with first simulations of axion cooling in merger simulations [47], neutron star mergers containing a mirror dark matter component [48, 49], or electromagnetic interactions around compact objects [50]. Work is needed to identify the most promising models to investigate numerically and to develop the infrastructure for performing such beyond-the-standard -model simulations.

II. IMPACT ON NUCLEAR PHYSICS AND OTHER FIELDS

Neutron star mergers probe temperatures and densities in extreme regimes, potentially allowing us to confront the phase diagram of the strong interaction with this exotic astrophysical system. Indeed, the first detection of gravitational waves from a neutron star merger event, GW170817, has allowed for novel constraints on the equation of state, through the tidal deformability [see e.g., 51, 52, for reviews] as well as indirectly through electromagnetic counterparts [e.g., 30, 31]. Especially the latter come with large uncertainties governed by the dynamics of the post-merger system that involve not only the equation of state but also transport processes associated with neutrino physics or magnetic fields. Detecting gravitational waves from the post-merger phase of a binary neutron star merger has the potential to deliver completely new insights into the nuclear and particle physics aspects of this process. However, secondary processes associated with neutrinos and magnetic fields may systematically bias our ability to correctly interpret the post-merger gravitational wave signal, as well as associated electromagnetic counterparts. Such a scenario is not unlike the one encountered in heavy-ion physics, where out-of-equilibrium processes can provide substantial dynamical corrections to the pressure tensor [e.g., 38]. Making progress on deciphering this puzzle will be crucial to enable future breakthroughs of next-generation gravitational wave detectors, and their ability to shed new light on nuclear physics.

These goals are complementary to the efforts of studying the equation of state. With the proposed workshop, we will extend the motivations for detectors such Cosmic Explorer to include additional nuclear physics phenomena beyond the EOS, and will provide a unique opportunity to identify the theoretical advances necessary to study these phenomena in the coming decade.

Our workshop aims to create an environment that can drive crucial progress and advancements in this highly interdisciplinary field. More specifically, this workshop will facilitate interdisciplinary collaborations between astrophysicists, particle physicists, members of the numerical general relativity community, and nuclear physicists. This collaborative effort will provide a stepping stone for crucial progress needed to decipher signals of extreme nuclear physics from gravitational waves events in the next decade.

Moreover, the workshop aims to have an educational impact, providing a platform for young researchers and early-career scientists to learn from and interact with leading experts in the field. The opportunity to interact with established researchers, participate in discussions, and present their own work can be invaluable for young scientists, fostering their growth and inspiring their future contributions to nuclear physics. By promoting inclusivity and diversity, the workshop will also encourage the participation of individuals from underrepresented groups, ensuring a broader and more comprehensive range of perspectives in nuclear physics research.

[1] LIGO Scientific, Virgo collaboration, B. P. Abbott et al., *GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral*, *Phys. Rev. Lett.* **119** (2017) 161101, [`1710.05832`].

[2] M. Evans et al., *A Horizon Study for Cosmic Explorer: Science, Observatories, and Community*, `2109.09882`.

[3] M. Maggiore et al., *Science Case for the Einstein Telescope*, *JCAP* **03** (2020) 050, [`1912.02622`].

[4] K. Ackley et al., *Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network*, *Publ. Astron. Soc. Austral.* **37** (2020) e047, [`2007.03128`].

[5] S. Bogdanov et al., *Determining the Equation of State of Cold, Dense Matter with X-ray Observations of Neutron Stars*, `1903.04648`.

[6] A. Lovato et al., *Long Range Plan: Dense matter theory for heavy-ion collisions and neutron stars*, `2211.02224`.

[7] S. Bogdanov et al., *Snowmass 2021 Cosmic Frontier White Paper: The Dense Matter Equation of State and QCD Phase Transitions*, in *2022 Snowmass Summer Study*, 9, 2022. `2209.07412`.

[8] E. Annala, T. Gorda, A. Kurkela, J. Nättilä and A. Vuorinen, *Evidence for quark-matter cores in massive neutron stars*, *Nature Phys.* **16** (2020) 907–910, [`1903.09121`].

[9] E. Annala, T. Gorda, J. Hirvonen, O. Komoltsev, A. Kurkela, J. Nättilä et al., *Strongly interacting matter exhibits deconfined behavior in massive neutron stars*, `2303.11356`.

[10] M. Alford, M. Braby, M. W. Paris and S. Reddy, *Hybrid stars that masquerade as neutron stars*, *Astrophys. J.* **629** (2005) 969–978, [`nucl-th/0411016`].

[11] W. Wei, B. Irving, T. Klähn and P. Jaikumar, *Camouflage of the Phase Transition to Quark Matter in Neutron Stars*, `1811.09441`.

[12] M. G. Alford, L. Brodie, A. Haber and I. Tews, *Tabulated Equations of State From Models Informed by Chiral Effective Field Theory*, `2304.07836`.

[13] M. G. Alford, L. Brodie, A. Haber and I. Tews, *Relativistic mean-field theories for neutron-star physics based on chiral effective field theory*, *Phys. Rev. C* **106** (2022) 055804, [`2205.10283`].

[14] M. G. Alford, S. Han and M. Prakash, *Generic conditions for stable hybrid stars*, *Phys. Rev. D* **88** (2013) 083013, [`1302.4732`].

[15] L. Brodie and A. Haber, *Nuclear and Hybrid Equations of State in Light of the Low-Mass Compact Star in HESS J1731-347*, `2302.02989`.

[16] T. Gorda, K. Hebeler, A. Kurkela, A. Schwenk and A. Vuorinen, *Constraints on strong phase transitions in neutron stars*, `2212.10576`.

[17] E. R. Most, S. P. Harris, C. Plumberg, M. G. Alford, J. Noronha, J. Noronha-Hostler et al., *Projecting the likely importance of weak-interaction-driven bulk viscosity in neutron star mergers*, *Mon. Not. Roy. Astron. Soc.* **509** (2021) 1096–1108, [`2107.05094`].

[18] P. Hammond, I. Hawke and N. Andersson, *Thermal aspects of neutron star mergers*, *Phys. Rev. D* **104** (2021) 103006, [`2108.08649`].

[19] P. Hammond, I. Hawke and N. Andersson, *Impact of nuclear reactions on gravitational waves from neutron star mergers*, *Phys. Rev. D* **107** (2023) 043023, [`2205.11377`].

[20] D. Radice, S. Bernuzzi, A. Perego and R. Haas, *A new moment-based general-relativistic neutrino-radiation transport code: Methods and first applications to neutron star mergers*, *Mon. Not. Roy. Astron. Soc.* **512** (2022) 1499–1521, [`2111.14858`].

[21] E. R. Most, A. Haber, S. P. Harris, Z. Zhang, M. G. Alford and J. Noronha, *Emergence of microphysical viscosity in binary neutron star post-merger dynamics*, `2207.00442`.

[22] F. Zappa, S. Bernuzzi, D. Radice and A. Perego, *Binary neutron star merger simulations with neutrino transport and turbulent viscosity: impact of different schemes and grid resolution*, `2210.11491`.

[23] G. Camelio, L. Gavassino, M. Antonelli, S. Bernuzzi and B. Haskell, *Simulating bulk viscosity in neutron stars. II. Evolution in spherical symmetry*, *Phys. Rev. D* **107** (2023) 103032, [`2204.11810`].

[24] A. Perego, S. Bernuzzi and D. Radice, *Thermodynamics conditions of matter in neutron star mergers*, *Eur. Phys. J. A* **55** (2019) 124, [`1903.07898`].

[25] A. Endrizzi, A. Perego, F. M. Fabbri, L. Branca, D. Radice, S. Bernuzzi et al., *Thermodynamics conditions of matter in the neutrino decoupling region during neutron star mergers*, *Eur. Phys. J. A* **56** (2020) 15, [`1908.04952`].

[26] M. G. Alford, L. Bovard, M. Hanauske, L. Rezzolla and K. Schwenzer, *Viscous Dissipation and Heat Conduction in Binary Neutron-Star Mergers*, *Phys. Rev. Lett.* **120** (2018) 041101, [`1707.09475`].

[27] M. G. Alford, A. Haber and Z. Zhang, *Isospin Equilibration in Neutron Star Mergers*, `2306.06180`.

[28] M. Alford, A. Harutyunyan and A. Sedrakian, *Bulk Viscosity of Relativistic $npe\mu$ Matter in Neutron-Star Mergers*, *Particles* **5** (2022) 361–376, [`2209.04717`].

[29] R. De Pietri, A. Feo, J. A. Font, F. Löffler, F. Maione, M. Pasquali et al., *Convective Excitation of Inertial Modes in Binary Neutron Star Mergers*, *Phys. Rev. Lett.* **120** (2018) 221101, [`1802.03288`].

[30] B. Margalit and B. D. Metzger, *Constraining the Maximum Mass of Neutron Stars From Multi-Messenger Observations of GW170817*, *Astrophys. J. Lett.* **850** (2017) L19, [`1710.05938`].

[31] L. Rezzolla, E. R. Most and L. R. Weih, *Using gravitational-wave observations and quasi-universal relations to constrain the maximum mass of neutron stars*, *Astrophys. J. Lett.* **852** (2018) L25, [`1711.00314`].

[32] B. Margalit, A. S. Jermyn, B. D. Metzger, L. F. Roberts and E. Quataert, *Angular-momentum Transport in Proto-neutron Stars and the Fate of Neutron Star Merger Remnants*, *Astrophys. J.* **939** (2022) 51, [`2206.10645`].

[33] C. Chirenti, S. Dichiara, A. Lien, M. C. Miller and R. Preece, *Kilohertz quasiperiodic oscillations in short gamma-ray bursts*, *Nature* **613** (2023) 253–256, [`2301.02864`].

[34] C. Chirenti, M. C. Miller, T. Strohmayer and J. Camp, *Searching for hypermassive neutron stars with short gamma-ray bursts*, *Astrophys. J. Lett.* **884** (2019) L16, [`1906.09647`].

[35] M. Shibata, K. Kiuchi and Y.-i. Sekiguchi, *General relativistic viscous hydrodynamics of differentially rotating neutron stars*, *Phys. Rev. D* **95** (2017) 083005, [`1703.10303`].

[36] E. R. Most and J. Noronha, *Dissipative magnetohydrodynamics for nonresistive relativistic plasmas: An implicit second-order flux-conservative formulation with stiff relaxation*, *Phys. Rev. D* **104** (2021) 103028, [`2109.02796`].

[37] A. Pandya, E. R. Most and F. Pretorius, *Conservative finite volume scheme for first-order viscous relativistic hydrodynamics*, *Phys. Rev. D* **105** (2022) 123001, [`2201.12317`].

[38] P. Romatschke, *New Developments in Relativistic Viscous Hydrodynamics*, *Int. J. Mod. Phys. E* **19** (2010) 1–53, [`0902.3663`].

[39] M. G. Alford, S. Han and K. Schwenzer, *Phase conversion dissipation in multicomponent compact stars*, *Phys. Rev. C* **91** (2015) 055804, [`1404.5279`].

[40] E. R. Most, L. J. Papenfort, V. Dexheimer, M. Hanauske, S. Schramm, H. Stöcker et al., *Signatures of quark-hadron phase transitions in general-relativistic neutron-star mergers*, *Phys. Rev. Lett.* **122** (2019) 061101, [`1807.03684`].

[41] A. Bauswein, N.-U. F. Bastian, D. B. Blaschke, K. Chatziioannou, J. A. Clark, T. Fischer et al., *Identifying a first-order phase transition in neutron star mergers through gravitational waves*, *Phys. Rev. Lett.* **122** (2019) 061102, [`1809.01116`].

[42] L. R. Weih, M. Hanauske and L. Rezzolla, *Postmerger Gravitational-Wave Signatures of Phase Transitions in Binary Mergers*, *Phys. Rev. Lett.* **124** (2020) 171103, [`1912.09340`].

[43] A. Prakash, D. Radice, D. Logoteta, A. Perego, V. Nedora, I. Bombaci et al., *Signatures of deconfined quark phases in binary neutron star mergers*, *Phys. Rev. D* **104** (2021) 083029, [`2106.07885`].

[44] S. Beloin, S. Han, A. W. Steiner and K. Odbadrakh, *Simultaneous Fitting of Neutron Star Structure and Cooling Data*, *Phys. Rev. C* **100** (2019) 055801, [`1812.00494`].

[45] A. Sedrakian, *Axion cooling of neutron stars*, *Phys. Rev. D* **93** (2016) 065044, [`1512.07828`].

[46] S. P. Harris, J.-F. Fortin, K. Sinha and M. G. Alford, *Axions in neutron star mergers*, *JCAP* **07** (2020) 023, [`2003.09768`].

[47] T. Dietrich and K. Clough, *Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung*, *Phys. Rev. D* **100** (2019) 083005, [`1909.01278`].

[48] M. Emma, F. Schianchi, F. Pannarale, V. Sagun and T. Dietrich, *Numerical Simulations of Dark Matter Admixed Neutron Star Binaries*, *Particles* **5** (2022) 273–286, [`2206.10887`].

[49] M. Hippert, E. Dillingham, H. Tan, D. Curtin, J. Noronha-Hostler and N. Yunes, *Dark matter or regular matter in neutron stars? How to tell the difference from the coalescence of compact objects*, *Phys. Rev. D* **107** (2023) 115028, [`2211.08590`].

[50] N. Siemonsen, C. Mondino, D. Egana-Ugrinovic, J. Huang, M. Baryakhtar and W. E. East, *Dark photon superradiance: Electrodynamics and multimessenger signals*, *Phys. Rev. D* **107** (2023) 075025, [`2212.09772`].

[51] C. A. Raithel, *Constraints on the Neutron Star Equation of State from GW170817*, *Eur. Phys. J. A* **55** (2019) 80, [`1904.10002`].

[52] K. Chatziioannou, *Neutron star tidal deformability and equation of state constraints*, *Gen. Rel. Grav.* **52** (2020) 109, [`2006.03168`].