Snowmass2021 - Letter of Interest

Compact binaries as probes of dense matter and QCD phase transitions

Thematic Areas: (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
☐ (Other) *[Please specify frontier/topical group]*

Contact Information:

M. Coughlin (University of Minnesota) [cough052@umn.edu],
T. Dietrich (University of Potsdam) [tim.dietrich@uni-potsdam.de],
R. Essick (University of Chicago) [],
P. Landry (California State University) [plandry@fullerton.edu],
J. Read (California State University) [jread@fullerton.edu],
N. Stergioulas (Aristotle University of Thessaloniki) [niksterg@auth.gr],
I. Tews (Los Alamos National Laboratory) [itews@lanl.gov]
Authors: see end of document

Abstract: (maximum 200 words) Compact binary mergers that include at least one NS have opened the opportunity to study the dense-matter equation of state through gravitational-wave and electromagnetic observations. Combined with theoretical nuclear-physics calculations, we can use such observations to extract crucial astrophysical information about the phase diagram of quantum chromodynamics and matter at the most extreme conditions in our Universe. Here, we elucidate a number of science frontiers enabled by these observations, which are changing how we understand dense matter, astronomical systems, and cosmology.

Motivation. Neutron stars (NSs) probe matter at the highest densities in our cosmos, yielding insights into the strong interactions described by quantum chromodynamics (QCD). Observations of compact binary mergers consisting of two neutron stars (BNS) or a NS and a black hole (BH) encode information about both fundamental physics and the behaviour of dense matter. The advanced LIGO [1] and Virgo [2] gravitational-wave (GW) detectors' discovery of a BNS merger in 2017, GW170817 [3], ushered in a new era of multimessenger astronomy. Electromagnetic (EM) facilities observed a coincident short gamma-ray burst [4] and subsequent kilonova [5,6], demonstrated that BNSs are the formation site for many of the heavy elements found in nature [7,8]. Analyses of the GW data provided limits on the size of NSs [9–19], and joint GW/EM analyses enabled the independent measurement of cosmological parameters [19–22]. The most recent LIGO-Virgo observing run produced another BNS merger [23] as well as NS-BH candidates [24,25].

The current network of LIGO, Virgo, and KAGRA [26] will reach its initial design sensitivity c. 2022. Upgrades c. 2025, including the addition of a fifth detector (LIGO-India), will improve the detection rate by another factor of 8 [27]. Third generation (3G) detectors [28–30], currently in the design stage, will reach the outermost regions of our Universe. At the same time, EM surveys such as the Vera C. Rubin Observatory's (VRO) Legacy Survey of Space and Time (LSST) [31] and the Dark Energy Spectroscopic Instrument (DESI) [32], as well as the advent of 30 m class telescopes, will push the boundaries of depth and cadence. The combined operation of GW and EM observatories in the next decade will provide a unique opportunity to resolve long-standing questions such as the nature of the NS *equation of state* (EOS) including a possible *phase transitions* to exotic matter, an independent measurement of the *expansion rate of the Universe*, and a possibility to reveal the nature of *dark matter* (DM).

Dense matter in the NS interior. GW and EM observations constraining NS masses and radii are sensitive to the dense matter EOS, due to the one-to-one correspondence between macroscopic observables and microphysical interactions. Analyses of GW170817 already provide stringent constraints of the radius of typical $1.4 M_\odot$ NSs [9–19,33]. Several of these estimates included multi-messenger input, combining GW and EM observations of BNS mergers, radio observations of massive pulsars [34–36], X-ray observations by NASA's Neutron Star Interior Composition Explorer (NICER) mission [37,38], and nuclear-physics constraints [16], e.g., [39–47].

In the next decade, by combining information from multiple events, e.g., [18,48,49], stronger EOS constraints will enable percent-level measurements of the NS radius and the fundamental interactions of dense nuclear matter [44,47,50–62]. At the same time, it will be increasingly important control systematic errors in our prior assumptions about the EOS and to determine the mass distribution of NSs in binaries [63], emphasizing the need to understand the population of GW and EM sources as a whole. Precise knowledge of both the EOS and the mass distribution, particularly any sharp features therein, may enable GW observations alone to constrain the local expansion rate of the universe [64–66]. What's more, the nuclear EOS and interactions may directly imprint on the mass distribution itself [67]. Going beyond static EOS properties, future BNS signals may reveal dynamical processes, e.g. stellar oscillations, that probe transport properties of normal matter or exotica such as boson condensates, hyperons, and quarks [40,68–70].

Exotic phases in the neutron-star interior and black hole formation. While the inspiral of two merging NSs probes cold, dense matter up to a few times nuclear saturation density, the density and temperature increase dramatically in the post-merger phase, up to the highest observable densities, close to the ones necessary to form black holes. Therefore, NSs enable us to probe not only the low-temperature QCD phase diagram, but provide a window on the most extreme conditions in the universe, which will shed additional light on the existence of phase transitions or exotic forms of matter. While these transitions or the breakdown of purely hadronic models could be detected during the inspiral phase under certain conditions [47,71–73], their existence may be more apparent during the post-merger phase when densities are higher [74–80]. The required sensitivity to detect the post-merger GW signal from a GW170817-like event is likely to be achieved with future GW detector upgrades [58,59] and high detection rates are expected with the planned 3G facilities or with the proposed dedicated high-frequency GW detectors [81, 82]. Once the number of detections increases and we are able to observe post-merger GW signatures, the threshold mass for prompt collapse of the merger remnant to a BH will be determined with increasing accuracy [83]. This will allow stringent constraints on the EOS and identify possible strong phase transitions in the NS EOS [84–86]. In addition, knowledge of the exact threshold mass can inform future EM counterpart searches as systems undergoing prompt collapse are most often not connected to bright, detectable EM signals, e.g., [87,88], and can be used to distinguish between different types of compact binary progenitors [89], possibly resolving long-standing issues associated with the lower "mass gap" between observed NSs and BHs, as well as uncertainties in the core-collapse supernova (CCSN) explosion mechanism (e.g., [90, 91]) and the nucleosythesis therein.

Matter outflows and r-process nucleosynthesis. Postmerger GW and EM observations trace the dynamic aftermath in the extreme environments created by compact mergers. The successful search and detection of the *kilonova* associated with GW170817 revealed NS mergers as a critical site of rapid neutron-capture process (r-process) nucleosynthesis. Combined with the inferred BNS merger rate [3] and detailed nucleosynthesis simulations, future multimessenger observations of NS mergers will elucidate the processes that make the heavy elements [5, 92]. An interdisciplinary effort implicating GW and EM observations, numerical relativity (NR) simulations, and nuclear theory calculations will enable detailed predictions of the abundances of individual elements. Postmerger GWs captured by 3G detectors will directly probe the remnant matter, combining with information from inspiral GWs and NR simulations to predict potential matter outflows and light curves, thereby improving time-critical EM counterpart search capabilities. With the possibility of detecting multiple BNSs per day in a 3G network, these advances will help overcome the the large sky localizations [93–95].

Dark matter in neutron stars and exotic compact objects. Because of their strong gravity and extreme core densities, NSs may accumulate DM from their environment by capturing DM particles after they scatter off of nucleons [96, 97]. Depending on the DM-nucleon interaction cross-section and the DM particle mass, the DM could form a core [98–100] or become admixed with the baryonic matter [101, 102]. DM could even be produced during the merger of two NSs [103]. For certain DM models, a configuration of baryonic and non-baryonic matter is gravitationally stable [104–106]. The DM concentration is then sensitive to the NS's age, mass and environment, producing diversity in the EOS-dependent observables, like tidal deformabilities, measured in the population. Alternatively, DM that is formed out of ultra-light scalar field could agglomerate on its own, forming compact objects that mimic true NSs and BHs [107, 108]. GW observations over the next decade, especially in the 3G detector era, combined with EM searches will give access to the full population of compact binary mergers, allowing us to search for "smoking-gun" EOS variability due to DM.

Requirements for the coming decade. We call upon the community to build the multidisciplinary ingredients necessary for multi-messenger astronomy of compact binary systems. This includes the installation of highly-sensitive observatories, such as 3G GW detectors and the next generation of EM telescopes, and the development of an efficient, reliable, and interdisciplinary hierarchical Bayesian framework for the interpretation of the growing number of upcoming multi-messenger sources. Such a framework must account for selection effects within both GW and EM observations while considering all aspects of the source population simultaneously, including the fundamental aspects of the QCD phase diagram that govern their formation, composition, and interactions. By reliably extracting source properties (masses, radii, dynamical states, magnetic field structures, ejecta properties, etc.), this framework will enable reliable measurements of the dense matter EOS, the QCD phase diagram, and r-process nucleosynthesis. Ultimately, future observations of these astronomical systems at the extremes of gravity and density have the potential to reveal physics beyond the Standard Model.

References

[1] LIGO Scientific Collaboration, J. Aasi, B. P. Abbott, R. Abbott, T. Abbott, M. R. Abernathy, K. Ackley, C. Adams, T. Adams, P. Addesso, and et al. Advanced LIGO. *Classical and Quantum Gravity*, 32(7):074001, April 2015.

[2] F. Acernese, M. Agathos, K. Agatsuma, D. Aisa, N. Allemandou, A. Allocca, J. Amarni, P. Astone, G. Balestri, G. Ballardin, and et al. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Classical and Quantum Gravity*, 32(2):024001, January 2015.

[3] Abbott, B. P. et al. GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Phys. Rev. Lett.*, 119:161101, Oct 2017.

[4] V. Savchenko, C. Ferrigno, E. Kuulkers, A. Bazzano, E. Bozzo, S. Brandt, J. Chenevez, T. J.-L. Courvoisier, R. Diehl, A. Domingo, L. Hanlon, E. Jourdain, A. von Kienlin, P. Laurent, F. Lebrun, A. Lutovinov, A. Martin-Carrillo, S. Mereghetti, L. Natalucci, J. Rodi, J.-P. Roques, R. Sunyaev, and P. Ubertini. Integral detection of the first prompt gamma-ray signal coincident with the gravitational-wave event GW170817. *The Astrophysical Journal Letters*, 848(2):L15, 2017.

[5] The LIGO Scientific Collaboration and Virgo Collaboration. Estimating the Contribution of Dynamical Ejecta in the Kilonova Associated with GW170817. *The Astrophysical Journal Letters*, 850(2):L39, 2017.

[6] B. P. Abbott et al. Multi-messenger observations of a binary neutron star merger. *The Astrophysical Journal Letters*, 848(2):L12, 2017.

[7] Mansi M Kasliwal, Daniel Kasen, Ryan M Lau, Daniel A Perley, Stephan Rosswog, Eran O Ofek, Kenta Hotokezaka, Ranga-Ram Chary, Jesper Sollerman, Ariel Goobar, and David L Kaplan. Spitzer Mid-Infrared Detections of Neutron Star Merger GW170817 Suggests Synthesis of the Heaviest Elements. *MNRS: Letters*, 01 2019.

[8] Darach Watson et al. Identification of strontium in the merger of two neutron stars. *Nature*, 574(7779):497–500, 2019.

[9] B. P. Abbott, R. Abbott, T. D. Abbott, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, V. B. Adya, et al. GW170817: Measurements of neutron star radii and equation of state. *Phys. Rev. Let.*, 121(16):161101, October 2018.

[10] A. Bauswein, O. Just, H.-T. Janka, and N. Stergioulas. Neutron-star Radius Constraints from GW170817 and Future Detections. *Astrophys. J. Let.*, 850:L34, December 2017.

[11] S. De, D. Finstad, J. M. Lattimer, D. A. Brown, E. Berger, and C. M. Biwer. Tidal deformabilities and radii of neutron stars from the observation of GW170817. *Phys. Rev. Let.*, 121(9):091102, August 2018.

[12] E. R. Most, L. R. Weih, L. Rezzolla, and J. Schaffner-Bielich. New constraints on radii and tidal deformabilities of neutron stars from GW170817. *Phys. Rev. Let.*, 120(26):261103, June 2018.

[13] Gloria Montana, Laura Tolos, Matthias Hanauske, and Luciano Rezzolla. Constraining twin stars with GW170817. *arXiv e-prints*, page arXiv:1811.10929, November 2018.

[14] F. J. Fattoyev, J. Piekarewicz, and C. J. Horowitz. Neutron skins and neutron stars in the multimessenger era. *Phys. Rev. Let.*, 120(17):172702, April 2018.

[15] D. Radice and L. Dai. Multimessenger parameter estimation of GW170817. *Eur. Phys. J. A*, 55:50, October 2018.

[16] I. Tews, J. Margueron, and S. Reddy. Confronting gravitational-wave observations with modern nuclear physics constraints. *European Physical Journal A*, 55(6):97, June 2019.

[17] Collin D. Capano, Ingo Tews, Stephanie M. Brown, Ben Margalit, Soumi De, Sumit Kumar, Duncan A. Brown, Badri Krishnan, and Sanjay Reddy. Stringent constraints on neutron-star radii from multimessenger observations and nuclear theory. *Nature Astronomy*, March 2020.

[18] Philippe Landry, Reed Essick, and Katerina Chatziioannou. Nonparametric constraints on neutron star matter with existing and upcoming gravitational wave and pulsar observations. *Phys. Rev. D*, 101(12):123007, June 2020.

[19] Tim Dietrich, Michael W. Coughlin, Peter T. H. Pang, Mattia Bulla, Jack Heinzel, Lina Issa, Ingo Tews, and Sarah Antier. New Constraints on the Supranuclear Equation of State and the Hubble Constant from Nuclear Physics – Multi-Messenger Astronomy. *arXiv e-prints*, page arxiv:2002.11355, 2020.

[20] B.P. Abbott et al. A gravitational-wave standard siren measurement of the Hubble constant. *Nature*, 551(7678):85–88, 2017.

[21] Michael W. Coughlin, Tim Dietrich, Jack Heinzel, Nandita Khetan, Sarah Antier, Mattia Bulla, Nelson Christensen, David A. Coulter, and Ryan J. Foley. Standardizing kilonovae and their use as standard candles to measure the Hubble constant. *Phys. Rev. Res.*, 2(2):022006, 2020.

[22] Michael W. Coughlin, Sarah Antier, Tim Dietrich, Ryan J. Foley, Jack Heinzel, Mattia Bulla, Nelson Christensen, David A. Coulter, Lina Issa, and Nandita Khetan. Measuring the Hubble Constant with a sample of kilonovae. *Nature Commun.*, 11(1):4129, 2020.

[23] The LIGO Scientific Collaboration, the Virgo Collaboration, B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, and et al. GW190425: Observation of a Compact Binary Coalescence with Total Mass ~ 3.4 $M_\odot$. *Astrophys. J. Let.*, 892(1):L3, March 2020.

[24] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo S200105ae: A subthreshold GW compact binary merger candidate. *GRB Coordinates Network*, 26640, January 2020.

[25] LIGO Scientific Collaboration and Virgo Collaboration. LIGO/Virgo S200115j: Identification of a GW compact binary merger candidate. *GRB Coordinates Network, Circular Service, No. 26759, #1 (2020/Jan-0)*, 26759, 2020.

[26] Yoichi Aso, Yuta Michimura, Kentaro Somiya, Masaki Ando, Osamu Miyakawa, Takanori Sekiguchi, Daisuke Tatsumi, and Hiroaki Yamamoto. Interferometer design of the KAGRA gravitational wave detector. , 88(4):043007, August 2013.

[27] B.P. Abbott et al. Prospects for Observing and Localizing Gravitational-Wave Transients with Advanced LIGO, Advanced Virgo and KAGRA. *Living Rev. Rel.*, 21(1):3, 2018.

[28] M. Punturo et al. The Einstein Telescope: A third-generation gravitational wave observatory. *Class. Quant. Grav.*, 27:194002, 2010.

[29] S. Hild et al. Sensitivity Studies for Third-Generation Gravitational Wave Observatories. *Class. Quant. Grav.*, 28:094013, 2011.

[30] Denis Martynov, Haixing Miao, Huan Yang, Francisco Hernandez Vivanco, Eric Thrane, Rory Smith, Paul Lasky, William E. East, Rana Adhikari, Andreas Bauswein, Aidan Brooks, Yanbei Chen, Thomas Corbitt, Andreas Freise, Hartmut Grote, Yuri Levin, Chunnong Zhao, and Alberto Vecchio. Exploring the sensitivity of gravitational wave detectors to neutron star physics. *Phys. Rev. D*, 99(10):102004, May 2019.

[31] Željko Ivezić et al. LSST: from Science Drivers to Reference Design and Anticipated Data Products. *Astrophys. J.*, 873(2):111, 2019.

[32] Amir Aghamousa et al. The DESI Experiment Part I: Science,Targeting, and Survey Design. *arXiv e-prints*, page 1611.00036, October 2016.

[33] G. Raaijmakers et al. Constraining the dense matter equation of state with joint analysis of NICER and LIGO/Virgo measurements. *Astrophys. J. Lett.*, 893(1):L21, 2020.

[34] John Antoniadis et al. A Massive Pulsar in a Compact Relativistic Binary. *Science*, 340:6131, 2013.

[35] Zaven Arzoumanian et al. The NANOGrav 11-year Data Set: High-precision timing of 45 Millisecond Pulsars. *Astrophys. J. Suppl.*, 235(2):37, 2018.

[36] H. Thankful Cromartie et al. Relativistic Shapiro delay measurements of an extremely massive millisecond pulsar. *Nature Astron.*, 4(1):72–76, 2019.

[37] M.C. Miller et al. PSR J0030+0451 Mass and Radius from *NICER* Data and Implications for the Properties of Neutron Star Matter. *Astrophys. J. Lett.*, 887(1):L24, 2019.

[38] Thomas E. Riley et al. A *NICER* View of PSR J0030+0451: Millisecond Pulsar Parameter Estimation. *Astrophys. J. Lett.*, 887(1):L21, 2019.

[39] Luca Baiotti. Gravitational waves from neutron star mergers and their relation to the nuclear equation of state. *Progress in Particle and Nuclear Physics*, 109:103714, November 2019.

[40] Andreas Guerra Chaves and Tanja Hinderer. Probing the equation of state of neutron star matter with gravitational waves from binary inspirals in light of GW170817: a brief review. *Journal of Physics G Nuclear Physics*, 46(12):123002, December 2019.

[41] Carolyn A. Raithel. Constraints on the neutron star equation of state from GW170817. *European Physical Journal A*, 55(5):80, May 2019.

[42] Reed Essick, Philippe Landry, and Daniel E. Holz. Nonparametric Inference of Neutron Star Composition, Equation of State, and Maximum Mass with GW170817. *Phys. Rev. D*, 101(6):063007, 2020.

[43] David Radice, Sebastiano Bernuzzi, and Albino Perego. The Dynamics of Binary Neutron Star Mergers and of GW170817. *arXiv e-prints*, page arXiv:2002.03863, February 2020.

[44] Tim Dietrich, Tanja Hinderer, and Anuradha Samajdar. Interpreting Binary Neutron Star Mergers: Describing the Binary Neutron Star Dynamics, Modelling Gravitational Waveforms, and Analyzing Detections. *arXiv e-prints*, page arXiv:2004.02527, April 2020.

[45] Sebastiano Bernuzzi. Neutron Stars Merger Remnants. *arXiv e-prints*, page arXiv:2004.06419, April 2020.

[46] Katerina Chatziioannou. Neutron star tidal deformability and equation of state constraints. *arXiv e-prints*, page arXiv:2006.03168, June 2020.

[47] Reed Essick, Ingo Tews, Philippe Landry, Sanjay Reddy, and Daniel E. Holz. Direct Astrophysical Tests of Chiral Effective Field Theory at Supranuclear Densities. *arXiv e-prints*, page arXiv:2004.07744, April 2020.

[48] S. Bose, K. Chakravarti, L. Rezzolla, B. S. Sathyaprakash, and K. Takami. Neutron-star radius from a population of binary neutron star mergers. *Phys. Rev. Let.*, 120(3):031102, January 2018.

[49] H. Yang, V. Paschalidis, K. Yagi, L. Lehner, F. Pretorius, and N. Yunes. Gravitational wave spectroscopy of binary neutron star merger remnants with mode stacking. *Phys. Rev. D*, 97(2):024049, January 2018.

[50] Walter Del Pozzo, Tjonnie G. F. Li, Michalis Agathos, Chris Van Den Broeck, and Salvatore Vitale. Demonstrating the Feasibility of Probing the Neutron-Star Equation of State with Second-Generation Gravitational-Wave Detectors. *Phys. Rev. Let.*, 111(7):071101, August 2013.

[51] Katerina Chatziioannou, Kent Yagi, Antoine Klein, Neil Cornish, and Nicolás Yunes. Probing the internal composition of neutron stars with gravitational waves. *Phys. Rev. D*, 92(10):104008, November 2015.

[52] Benjamin D. Lackey and Leslie Wade. Reconstructing the neutron-star equation of state with gravitational-wave detectors from a realistic population of inspiralling binary neutron stars. *Phys. Rev. D*, 91(4):043002, February 2015.

[53] Francisco Hernandez Vivanco, Rory Smith, Eric Thrane, Paul D. Lasky, Colm Talbot, and Vivien Raymond. Measuring the neutron star equation of state with gravitational waves: The first forty binary neutron star merger observations. *Phys. Rev. D*, 100(10):103009, November 2019.

[54] A. Bauswein and H.-T. Janka. Measuring Neutron-Star Properties via Gravitational Waves from Neutron-Star Mergers. *Phys. Rev. Let.*, 108(1):011101, January 2012.

[55] A. Bauswein, H.-T. Janka, K. Hebeler, and A. Schwenk. Equation-of-state dependence of the gravitational-wave signal from the ring-down phase of neutron-star mergers. *Phys. Rev. D*, 86(6):063001, September 2012.

[56] A. Bauswein, N. Stergioulas, and H.-T. Janka. Revealing the high-density equation of state through binary neutron star mergers. *Phys. Rev. D*, 90(2):023002, July 2014.

[57] J. Clark, A. Bauswein, L. Cadonati, H.-T. Janka, C. Pankow, and N. Stergioulas. Prospects for high frequency burst searches following binary neutron star coalescence with advanced gravitational wave detectors. *Phys. Rev. D*, 90(6):062004, September 2014.

[58] J. A. Clark, A. Bauswein, N. Stergioulas, and D. Shoemaker. Observing gravitational waves from the post-merger phase of binary neutron star coalescence. *Classical and Quantum Gravity*, 33(8):085003, April 2016.

[59] A. Torres-Rivas, K. Chatziioannou, A. Bauswein, and J. A. Clark. Observing the post-merger signal of GW170817-like events with improved gravitational-wave detectors. *Phys. Rev. D*, 99(4):044014, February 2019.

[60] Matteo Breschi, Sebastiano Bernuzzi, Francesco Zappa, Michalis Agathos, Albino Perego, David Radice, and Alessandro Nagar. Kilohertz gravitational waves from binary neutron star remnants: Time-domain model and constraints on extreme matter. *Phys. Rev. D*, 100(10):104029, November 2019.

[61] Stamatis Vretinaris, Nikolaos Stergioulas, and Andreas Bauswein. Empirical relations for gravitational-wave asteroseismology of binary neutron star mergers. *Phys. Rev. D*, 101(8):084039, April 2020.

[62] Paul J. Easter, Sudarshan Ghonge, Paul D. Lasky, Andrew R. Casey, James A. Clark, Francisco Hernand ez Vivanco, and Katerina Chatziioannou. Detection and parameter estimation of binary neutron star merger remnants. *arXiv e-prints*, page arXiv:2006.04396, June 2020.

[63] Daniel Wysocki, Richard O'Shaughnessy, Leslie Wade, and Jacob Lange. Inferring the neutron star equation of state simultaneously with the population of merging neutron stars. 1 2020.

[64] Stephen R. Taylor and Jonathan R. Gair. Cosmology with the lights off: Standard sirens in the einstein telescope era. *Phys. Rev. D*, 86:023502, Jul 2012.

[65] Will M. Farr, Maya Fishbach, Jiani Ye, and Daniel E. Holz. A future percent-level measurement of the hubble expansion at redshift 0.8 with advanced LIGO. *The Astrophysical Journal*, 883(2):L42, oct 2019.

[66] Walter Del Pozzo, Tjonnie G. F. Li, and Chris Messenger. Cosmological inference using only gravitational wave observations of binary neutron stars. *Phys. Rev. D*, 95:043502, Feb 2017.

[67] Robert Farmer, Mathieu Renzo, Selma de Mink, Maya Fishbach, and Stephen Justham. Constraints from gravitational wave detections of binary black hole mergers on the $^{12}\mathrm{C}\,(\alpha,\gamma)^{16}\mathrm{O}$ rate. 6 2020.

[68] Tanja Hinderer, Luciano Rezzolla, and Luca Baiotti. *Gravitational Waves from Merging Binary Neutron-Star Systems*, volume 457 of *Astrophysics and Space Science Library*, page 575. 2018.

[69] Kostas Glampedakis and Leonardo Gualtieri. *Gravitational Waves from Single Neutron Stars: An Advanced Detector Era Survey*, volume 457 of *Astrophysics and Space Science Library*, page 673. 2018.

[70] Wynn C. G. Ho. Gravitational waves from neutron stars and asteroseismology. *Philosophical Transactions of the Royal Society of London Series A*, 376(2120):20170285, May 2018.

[71] Katerina Chatziioannou and Sophia Han. Studying strong phase transitions in neutron stars with gravitational waves. *Phys. Rev. D*, 101(4):044019, February 2020.

[72] Sebastian Blacker, Niels-Uwe F. Bastian, Andreas Bauswein, David B. Blaschke, Tobias Fischer, Micaela Oertel, Theodoros Soultanis, and Stefan Typel. Constraining the onset density of the hadron-quark phase transition with gravitational-wave observations. *arXiv e-prints*, page arXiv:2006.03789, June 2020.

[73] Peter T.H. Pang, Tim Dietrich, Ingo Tews, and Chris Van Den Broeck. Parameter estimation for strong phase transitions in supranuclear matter using gravitational-wave astronomy. *arXiv e-prints*, page arXiv:2006.14936, 6 2020.

[74] David Radice, Sebastiano Bernuzzi, Walter Del Pozzo, Luke F. Roberts, and Christian D. Ott. Probing Extreme-density Matter with Gravitational-wave Observations of Binary Neutron Star Merger Remnants. *Astrophys. J. Let.*, 842(2):L10, June 2017.

[75] Andreas Bauswein, Niels-Uwe F. Bastian, David B. Blaschke, Katerina Chatziioannou, James A. Clark, Tobias Fischer, and Micaela Oertel. Identifying a First-Order Phase Transition in Neutron-Star Mergers through Gravitational Waves. *Phys. Rev. Let.*, 122(6):061102, February 2019.

[76] Roberto De Pietri, Alessandro Drago, Alessandra Feo, Giuseppe Pagliara, Michele Pasquali, Silvia Traversi, and Grzegorz Wiktorowicz. Merger of Compact Stars in the Two-families Scenario. *Astrophys. J.*, 881(2):122, August 2019.

[77] Matthias Hanauske, Luke Bovard, Elias Most, Jens Papenfort, Jan Steinheimer, Anton Motornenko, Volodymyr Vovchenko, Veronica Dexheimer, Stefan Schramm, and Horst Stöcker. Detecting the Hadron-Quark Phase Transition with Gravitational Waves. *Universe*, 5(6):156, June 2019.

[78] Elias R. Most, L. Jens Papenfort, Veronica Dexheimer, Matthias Hanauske, Stefan Schramm, Horst Stöcker, and Luciano Rezzolla. Signatures of Quark-Hadron Phase Transitions in General-Relativistic Neutron-Star Mergers. *Phys. Rev. Let.*, 122(6):061101, February 2019.

[79] Lukas R. Weih, Matthias Hanauske, and Luciano Rezzolla. Post-merger gravitational-wave signatures of phase transitions in binary mergers. *arXiv e-prints*, page arXiv:1912.09340, December 2019.

[80] Elias R. Most, L. Jens Papenfort, Veronica Dexheimer, Matthias Hanauske, Horst Stoecker, and Luciano Rezzolla. On the deconfinement phase transition in neutron-star mergers. *European Physical Journal A*, 56(2):59, February 2020.

[81] D. Martynov, H. Miao, H. Yang, F. Hernandez Vivanco, E. Thrane, R. Smith, P. Lasky, W. E. East, R. Adhikari, A. Bauswein, A. Brooks, Y. Chen, T. Corbitt, T. Corbitt, H. Grote, Y. Levin, C. Zhao, and A. Vecchio. Exploring the sensitivity of gravitational wave detectors to neutron star physics. *Phys. Rev. D*, 99:102004, January 2019.

[82] K. Ackley, V. B. Adya, P. Agrawal, P. Altin, G. Ashton, M. Bailes, E. Baltinas, A. Barbuio, D. Beniwal, C. Blair, D. Blair, G. N. Bolingbroke, V. Bossilkov, S. Shachar Boublil, D. D. Brown, B. J. Burridge, J. Calderon Bustillo, J. Cameron, H. Tuong Cao, J. B. Carlin, A. Casey, S. Chang, P. Charlton, C. Chatterjee, D. Chattopadhyay, X. Chen, J. Chi, J. Chow, Q. Chu, A. Ciobanu, T. Clarke, P. Clearwater, J. Cooke, D. Coward, H. Crisp, R. J. Dattatri, A. T. Deller, D. A. Dobie, L. Dunn, P. J. Easter, J. Eichholz, R. Evans, C. Flynn, G. Foran, P. Forsyth, Y. Gai, S. Galaudage, D. K. Galloway, B. Gendre, B. Goncharov, S. Goode, D. Gozzard, B. Grace, A. W. Graham, A. Heger, F. Hernandez Vivanco, R. Hirai, N. A. Holland, Z. J. Holmes, E. Howard, E. Howell, G. Howitt, M. T. Hübner, J. Hurley, C. Ingram, V. Jaberian Hamedan, K. Jenner, L. Ju, D. P. Kapasi, T. Kaur, N. Kijbunchoo, M. Kovalam, R. Kumar Choudhary, P. D. Lasky, M. Y. M. Lau, J. Leung, J. Liu, K. Loh, A. Mailvagan, I. Mand el, J. J. McCann, D. E. McClelland, K. McKenzie, D. McManus, T. McRae, A. Melatos, P. Meyers, H. Middleton, M. T. Miles, M. Millhouse, Y. Lun Mong, B. Mueller, J. Munch, J. Musiov, S. Muusse, R. S. Nathan, Y. Naveh, C. Neijssel, B. Neil, S. W. S. Ng, V. Oloworaran, D. J. Ottaway, M. Page, J. Pan, M. Pathak, E. Payne, J. Powell, J. Pritchard, E. Puckridge, A. Raidani, V. Rallabhandi, D. Reardon, J. A. Riley, L. Roberts, I. M. Romero-Shaw, T. J. Roocke, G. Rowell, N. Sahu, N. Sarin, L. Sarre, H. Sattari, M. Schiworski, S. M. Scott, R. Sengar, D. Shaddock, R. Shannon, J. SHI, P. Sibley, B. J. J. Slagmolen, T. Slaven-Blair, R. J. E. Smith, J. Spollard, L. Steed, L. Strang, H. Sun, A. Sunderland, S. Suvorova, C. Talbot, E. Thrane, D. Töyrä, P. Trahanas, A. Vajpeyi, J. V. van Heijningen, A. F. Vargas, P. J. Veitch, A. Vigna-Gomez, A. Wade, K. Walker, Z. Wang, R. L. Ward, K. Ward, S. Webb, L. Wen, K. Wette, R. Willcox, J. Winterflood, C. Wolf, B. Wu, M. Jet Yap, Z. You, H. Yu, J. Zhang, J. Zhang, C. Zhao, and X. Zhu. Neutron Star Extreme Matter Observatory: A kilohertz-band gravitational-wave detector in the global network. *arXiv e-prints*, page arXiv:2007.03128, July 2020.

[83] Michalis Agathos, Francesco Zappa, Sebastiano Bernuzzi, Albino Perego, Matteo Breschi, and David Radice. Inferring prompt black-hole formation in neutron star mergers from gravitational-wave data. *Phys. Rev. D*, 101(4):044006, February 2020.

[84] A. Bauswein, T. W. Baumgarte, and H.-T. Janka. Prompt Merger Collapse and the Maximum Mass of Neutron Stars. *Physical Review Letters*, 111(13):131101, September 2013.

[85] A. Bauswein and N. Stergioulas. Semi-analytic derivation of the threshold mass for prompt collapse in binary neutron-star mergers. *Mon. Not. R. Astron. Soc.*, 471:4956–4965, November 2017.

[86] Andreas Bauswein, Sebastian Blacker, Vimal Vijayan, Nikolaos Stergioulas, Katerina Chatziioannou, James A. Clark, Niels-Uwe F. Bastian, David B. Blaschke, Mateusz Cierniak, and Tobias Fischer. Equation of state constraints from the threshold binary mass for prompt collapse of neutron star mergers. *arXiv e-prints*, page arXiv:2004.00846, April 2020.

[87] Michael W. Coughlin et al. Implications of the search for optical counterparts during the second part of the Advanced LIGO's and Advanced Virgo's third observing run: lessons learned for future follow-up observations. *Mon. Not. Roy. Astron. Soc.*, 497(1):1181–1196, 2020.

[88] Michael W. Coughlin, Tim Dietrich, Sarah Antier, Mattia Bulla, Francois Foucart, Kenta Hotokezaka, Geert Raaijmakers, Tanja Hinderer, and Samaya Nissanke. Implications of the search for optical counterparts during the first six months of the Advanced LIGO's and Advanced Virgo's third observing run: possible limits on the ejecta mass and binary properties. *Mon. Not. Roy. Astron. Soc.*, 492(1):863–876, 2020.

[89] Reed Essick and Philipe Landry. Discriminating between Neutron Stars and Black Holes with Imperfect Knowledge of the Maximum Neutron Star Mass. *arXiv e-prints*, page arXiv:2007.01372, July 2020.

[90] Chris L. Fryer and Vassiliki Kalogera. Theoretical black hole mass distributions. *The Astrophysical Journal*, 554(1):548–560, jun 2001.

[91] Krzysztof Belczynski, Grzegorz Wiktorowicz, Chris L. Fryer, Daniel E. Holz, and Vassiliki Kalogera. MISSING BLACK HOLES UNVEIL THE SUPERNOVA EXPLOSION MECHANISM. *The Astrophysical Journal*, 757(1):91, sep 2012.

[92] J. M. Lattimer and D. N. Schramm. Black-hole-neutron-star collisions. *Astrophys. J.*, 192:L145, 1974.

[93] Stephen Fairhurst. Triangulation of gravitational wave sources with a network of detectors. *New J. Phys.*, 11:123006, 2009. [Erratum: New J.Phys. 13, 069602 (2011)].

[94] Leo P. Singer et al. The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo. *Astrophys. J.*, 795(2):105, 2014.

[95] Reed Essick, Salvatore Vitale, Erik Katsavounidis, Gabriele Vedovato, and Sergey Klimenko. Localization of short duration gravitational-wave transients with the early advanced LIGO and Virgo detectors. *Astrophys. J.*, 800(2):81, 2015.

[96] Arnaud de Lavallaz and Malcolm Fairbairn. Neutron stars as dark matter probes. *Phys. Rev. D*, 81(12):123521, June 2010.

[97] Chris Kouvaris and Peter Tinyakov. Can neutron stars constrain dark matter? *Phys. Rev. D*, 82(6):063531, September 2010.

[98] Gianfranco Bertone and Malcolm Fairbairn. Compact stars as dark matter probes. *Phys. Rev. D*, 77(4):043515, February 2008.

[99] Paolo Ciarcelluti and Fredrik Sandin. Have neutron stars a dark matter core? *Physics Letters B*, 695(1-4):19–21, January 2011.

[100] Moira I. Gresham and Kathryn M. Zurek. Asymmetric dark stars and neutron star stability. *Phys. Rev. D*, 99(8):083008, April 2019.

[101] S. C. Leung, M. C. Chu, and L. M. Lin. Dark-matter admixed neutron stars. *Phys. Rev. D*, 84(10):107301, November 2011.

[102] Ann E. Nelson, Sanjay Reddy, and Dake Zhou. Dark halos around neutron stars and gravitational waves. *J. Cosmol. Astropart. Phys.*, 2019(7):012, July 2019.

[103] Tim Dietrich and Katy Clough. Cooling binary neutron star remnants via nucleon-nucleon-axion bremsstrahlung. *Phys. Rev. D*, 100(8):083005, 2019.

[104] Grigorios Panotopoulos and Ilídio Lopes. Dark matter effect on realistic equation of state in neutron stars. *Phys. Rev. D*, 96(8):083004, October 2017.

[105] Maksym Deliyergiyev, Antonino Del Popolo, Laura Tolos, Morgan Le Delliou, Xiguo Lee, and Fiorella Burgio. Dark compact objects: An extensive overview. *Phys. Rev. D*, 99(6):063015, March 2019.

[106] Abdul Quddus, Grigorios Panotopoulos, Bharat Kumar, Shakeb Ahmad, and S. K. Patra. GW170817 constraints on the properties of a neutron star in the presence of WIMP dark matter. *Journal of Physics G Nuclear Physics*, 47(9):095202, September 2020.

[107] Katy Clough, Tim Dietrich, and Jens C. Niemeyer. Axion star collisions with black holes and neutron stars in full 3D numerical relativity. *Phys. Rev. D*, 98(8):083020, 2018.

[108] Tim Dietrich, Francesca Day, Katy Clough, Michael Coughlin, and Jens Niemeyer. Neutron star–axion star collisions in the light of multimessenger astronomy. *Mon. Not. Roy. Astron. Soc.*, 483(1):908–914, 2019.

Additional Authors:

K. Clough (University of Oxford) [katy.clough@physics.ox.ac.uk],
M. Coughlin (University of Minnesota) [cough052@umn.edu],
T. Dietrich (University of Potsdam) [tim.dietrich@uni-potsdam.de],
R. Essick (University of Chicago) [],
P. Landry (California State University) [plandry@fullerton.edu],
P. T. H. Pang (Nikhef) [thopang@nikhef.nl],
J. Read (California State University) [jread@fullerton.edu],
A. Samajdar (Nikhef & Utrecht University) [a.samajdar@nikhef.nl],
N. Stergioulas (Aristotle University of Thessaloniki) [niksterg@auth.gr],
I. Tews (Los Alamos National Laboratory) [itews@lanl.gov]