Feature article, Nuclear Physics News, September 2021

Fundamental physics in the gravitational-wave era

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"Recording a GW [...] has never been a big motivation for LIGO,
the motivation has always been to open
a new window to the Universe"
– Kip Thorne (BBC interview, 2016)

The landmark detection of gravitational waves (GWs) emitted by black-hole (BH) and neutron-star (NS) binaries has opened a new era in physics, giving access to hitherto unexplored systems and regimes. In parallel to their countless astrophysical applications, these discoveries open new avenues to explore fundamental physics.

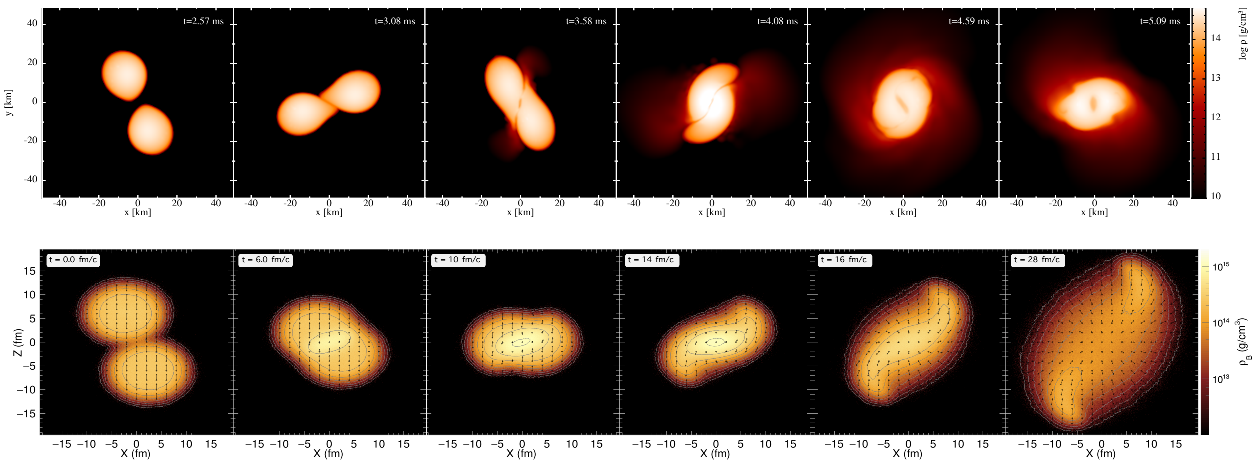

Figure 1. General relativity "meets" QCD matter equation of state. (Top panel) During a NS merger, the GW signal carries vital information about the matter content of the stellar interior. Shown is the merger of two 1.4 solar mass NSs, simulated with the Lagrangian Numerical Relativity code SPHINCS_BSSN [1]. (Bottom panel) Simulation of a heavy-ion collision at SIS18 energies using transport code UrQMD [2], taken from [3].

With approximately 50 BH and a few NS merger events detected by the LIGO and Virgo interferometers to date [4] -- and many more expected in the next few years -- *GW science* is now in full blossom. This truly interdisciplinary and cross-cutting field is fostering synergies between different and previously disjoint branches of physics, paving the way for novel developments, which will be instrumental to exploit the huge scientific potential of future GW detectors. GW, electromagnetic (EM), neutrino, and cosmic-ray observations of the same source provide a novel global way to explore the cosmos and will shed light on the nature of merging BHs, the composition of NSs, the engine of relativistic jets and other high-energy phenomena, and on the environments where these sources live. However, the unique opportunities offered by *multi-messenger astronomy* come with outstanding scientific challenges related to a rapid accurate detection and characterization of GW signals for EM follow-up, the identification of the EM counterpart amongst a fog of other astrophysical transients and variables, the complexity of astrophysical simulations given the multi-physics and multi-scale nature of violent EM sources and transients, as well as an *integrated* analysis and interpretation of the data in the context of astrophysics, nuclear and atomic physics, fundamental physics, and cosmology.

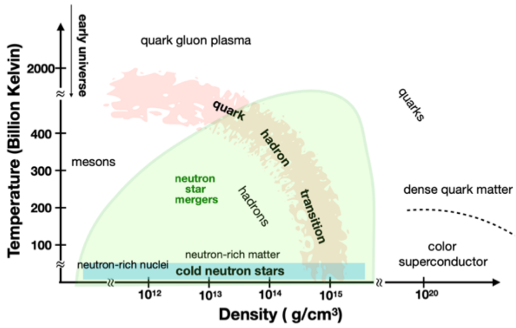

Figure 2. Sketch of the phase diagram of strongly interacting matter in the temperature-baryon density plane. The conjectured region of the quark-hadron phase transition is indicated and shows great overlap with the region probed by NS mergers. Toward lower densities the transition can be probed in relativistic heavy-ion collisions. Taken from [5].

Matter under extreme conditions. GWs from binary NS mergers provide a way to investigate strongly interacting matter at ultra-high density, temperature, and isospin. Outstanding open issues that can be tackled include the equation of state of NS matter and its phase structure, e.g. the determination of possible existence of hyperons and quark matter in the NS core. Temperatures and densities (see Figure 1) in different phases of the coalescence may reach those attained in relativistic heavy-ion collision experiments, providing complementarity and strong synergy between these fields [3]. A single detection with a third-generation detector such as the Einstein Telescope [6] will constrain the properties of nuclear matter to unprecedented levels. An established first-order phase transition at high densities between quarks and hadrons would have dramatic consequences for the phase diagram at lower densities, as it would prove the existence of a (high-energy) critical point, possibly within the reach of the study of relativistic heavy-ion collisions (see Figure 2). This high-energy critical point of QCD is searched for with increased experimental and theoretical efforts via the study of dynamical fluctuation observables [7].

Nuclear and atomic physics and their role in multi-messenger astronomy. The rapid neutron capture or "*r*-process" proceeds via extremely neutron-rich, unstable nuclei for which no experimental data is available and one therefore has to rely on theoretical nuclear models. Nuclear theory is not yet able to provide input with the required precision. Figure 3 shows the observed solar-system abundance for heavy elements. When performing large-scale nuclear network calculations to reproduce the solar-system *r*-process abundances, more than 5,000 nuclei and 50,000 reaction rates must be included. Most of the reaction rates are very hard or not possible to measure directly as they involve extremely neutron-rich, unstable nuclei that cannot be studied in laboratories on Earth. Huge efforts on the nuclear-physics side are now emerging to address these theoretical and experimental challenges, with the aim to greatly improve our understanding of the *r*-process.

The discovery of EM radiation in the optical and near-infrared band following the NS merger event GW170817 is the strongest evidence to date of heavy-element nucleosynthesis through the *r*-process. Also in modelling this "kilonova" emission theoretical nuclear models are crucial. While different models perform well close to the “valley of stability”, they differ substantially in their predictions for the nuclear heating rates resulting from the decay of extremely neutron-rich nuclei. The kilonovae predicted by different nuclear models can therefore differ in their brightness by as much as a factor of ~5 [8]. Therefore, the observation of the EM post-merger signal will provide astronomical constraints on the physics of neutron-rich nuclei.

The appearance and detectability of kilonovae is to a high degree determined by atomic physics. The major source of opacity in the radioactive ejecta are bound-bound transitions in the freshly synthesized heavy elements. Due to their enormous number of line transitions (in some cases >10^8 [9]) lanthanides are a particularly efficient source of opacity and their presence or absence is crucial for the colour of the resulting EM transient.

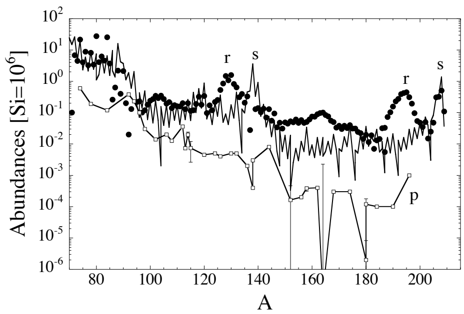

Figure 3. Solar-system abundances broken down to r-process (black dots), s-process (jagged line) and p-process contributions (open squares). Figure: courtesy of M. Arnould [10].

Like for nuclear data, not all necessary atomic data is currently available with the needed accuracy. Next-generation instruments onboard future x-ray satellite missions (e.g. XRISM, Athena) will deliver high-resolution spectra [11]. The accuracy of derived parameters, like elemental composition, density, temperature, and velocity, will be limited by the uncertainties of atomic data, like line positions, line strengths, and cross-sections of different atomic-scale processes. However, these parameters are, among other things, key for our understanding of accretion of mass onto BHs in active galactic nuclei (AGN), and the feedback mechanisms during the co- evolution of AGNs with their host galaxies [11]. Understanding spectra and the mechanisms behind them requires efforts from atomic structure theory, in combination with existing and upcoming x-ray satellite missions (e.g. NICER, GRAVITY, Athena), eXTP, and future GW data. In particular, the recent NICER observations of heavy NSs probe regimes complementary to GW detections so far, and are improving multi-messenger constraints on dense matter to unprecedented levels.

Figure 4. Mind map of gravitational wave probes of dark matter, see [12] for details.

Fundamental problems in high-energy and gravitational physics. GWs are a unique probe of foundational and outstanding questions in physics. Given the universal coupling of gravity to any form of matter-energy, GWs present a unique channel for discovering new fundamental particles and fields over an enormous range of masses, in particular the lightest regimes that lie well outside the reach of lab methods. From the particle physics viewpoint, GWs can provide novel information on the *nature and phenomenology of dark matter* (e.g., whether it is made of heavy particles, light fields, compact objects, or a mixture thereof, see Figure 4), and on the *existence of new fundamental fields* (e.g. GW searches for axion-like particles and dark-photons which extend beyond the range of ongoing lab searches [13,14,15], see Figures 5-6). From the gravitational viewpoint, violent GW events like mergers of compact objects provide novel probes of possible (classical and quantum) extensions of *General Relativity* [16], *as well as* elucidate whether the properties of the *BH horizon* and the formation of *spacetime singularities* conform or not to Einstein's theory. Any departure from the standard expectation would be a major breakthrough in fundamental physics [14]. At the same time, the discovery potential in GW science has reinvigorated efforts to efficiently solve the infamous two-body problem in General Relativity. Next-generation detectors urgently call for the development of *high-accuracy waveforms* in order to reduce the modelling systematics. This motivates the extension of sophisticated computational methods from particle physics that have been instrumental to search for *"new physics"* at colliders through precision data [17].

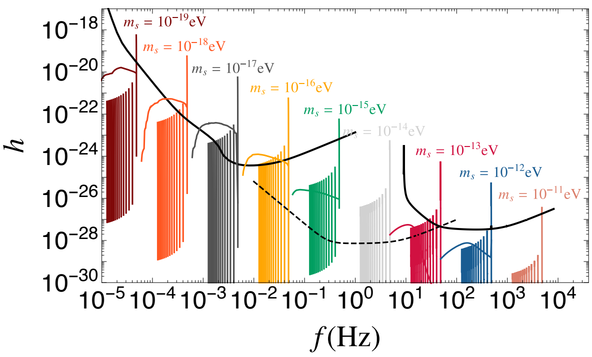

Figure 5. Continuous GW signal expected from isolated spinning BHs in models of ultralight dark matter fields (such as axions and dark photons). An array of detectors can potentially probe the masses of these beyond Standard Model particles across several orders of magnitude which are inaccessible to lab experiments. Taken from [18].

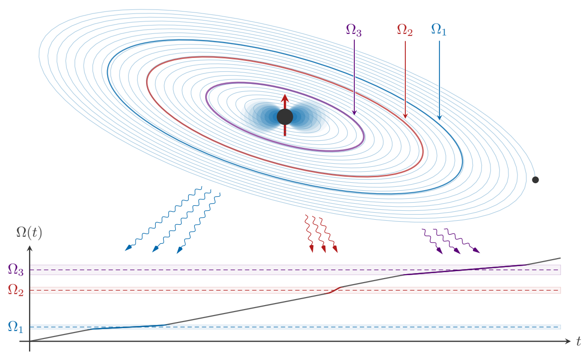

Figure 6. Illustration of a gravitational atom in a binary system due to presence of ultralight bosons, which induce level mixing and resonances, leaving distinct imprints in the GW emission. Taken from [15].

GWs & Cosmology. GWs will also help in accessing *standard sirens* at large redshifts leading to novel and exquisite measurements of the expansion rate of the universe, thus shedding light on fundamental cosmological questions, such as what is the *nature of the dark energy* or *whether gravity is modified* at cosmological distances. At the same time, a confirmed detection of a stochastic background of GWs [19,20] would open a window into the *primordial universe* and give us the opportunity to study fundamental phenomena like *primordial inflation* and *phase transitions*. Finally, third-generation interferometers will unambiguously confirm/disprove the tantalizing possibility that some of the detected GW events (in particular BH binaries in the mass gaps forbidden by astrophysical formation scenarios) may be due to BHs formed after the inflation [21].

The experimental, theoretical, and community challenges associated with these grand problems are enormous. From an experimental viewpoint there is a strong interest of funding agencies worldwide into ground-breaking experiments and space missions. From a theoretical point of view current gravitational waveforms should be improved for reliable physical interpretation, given the high-precision data expected from future experiments. Last but not least, GW science requires organizing the effort of large and diverse communities and to exploit their synergies. This will also require training the next generation of leaders in GW physics, who will be able to communicate across a spectrum of sub-fields. Such an effort is instrumental to maximize the benefit from theoretical developments and from the current and future wealth of data from GW interferometers, radio, and x-ray observatories, and from particle accelerators facilities. These are the goals of the *"Gravitational Wave Probes of Fundamental Physics"* [22], an initiative endorsed by 600+ scientists from 25+ countries across the world and from different areas (astroparticle-, atomic-, nuclear-, high-energy, and gravitational physics, cosmology, and GW and multi-messenger astronomy) and supported by the JENAA (Joint ECFA-NuPECC-APPEC Activities) [23].

References.

1. *S. Rosswog and P. Diener, „SPHINCS_BSSN: A general relativistic Smooth Particle Hydrodynamics code for dynamical spacetimes", Class.Quant.Grav. 38 (2021) 11, 115002. https://doi.org/10.1088/1361-6382/abee65*
2. *M. Bleicher et al., „Relativistic hadron hadron collisions in the ultrarelativistic quantum molecular dynamics model", J.Phys.G 25 (1999) 1859-1896. https://doi.org/10.1088/0954-3899/25/9/308*
3. *HADES Collaboration, "Probing dense baryon-rich matter with virtual photons", Nature Phys. 15 (2019) 10, 1040-1045. https://doi.org/10.1038/s41567-019-0583-8*
4. *LIGO-Virgo Collaborations, "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run", Phys. Rev. X 11 (2021) 021053. https://doi.org/10.1103/PhysRevX.11.021053*
5. *Science Book "The next generation global gravitational wave observatory", GW International Committee (2021). https://gwic.ligo.org/3Gsubcomm/docs/GWIC_3G_Science_Book.pdf*
6. *M. Maggiore et al., "Science Case for the Einstein Telescope", JCAP 03 (2020) 050. https://doi.org/10.1088/1475-7516/2020/03/050*
7. *M. Bluhm et al., "Dynamics of critical fluctuations: Theory – phenomenology – heavy-ion collisions", Nucl. Phys. A 1003 (2020), 122016. https://doi.org/10.1016/j.nuclphysa.2020.122016*
8. *S. Rosswog et al. "Detectability of compact binary merger macronovae", Class.Quant.Grav. 34 (2017) 10, 104001. https://doi.org/10.1088/1361-6382/aa68a9*
9. *D. Kasen et al., „Opacities and Spectra of the r-process Ejecta from Neutron Star Mergers", Astrophys.J. 774 (2013) 25. https://doi.org/10.1088/0004-637X/774/1/25*
10. *M. Arnould et al., "The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries", Phys.Rept. 450 (2007) 97-213. https://doi.org/10.1016/j.physrep.2007.06.002*
11. *G. Betancourt-Martinez et al., "Unlocking the Capabilities of Future High-Resolution X-ray Spectroscopy Missions Through Laboratory Astrophysics", Science White paper submitted to the Astro2020 Decadal Survey. https://arxiv.org/abs/1903.08213v1*
12. *G. Bertone et al., "Gravitational wave probes of dark matter: challenges and opportunities", SciPost Phys.Core 3 (2020) 007. https://doi.org/10.21468/SciPostPhysCore.3.2.007*
13. *A. Arvanitaki et al., „String Axiverse", Phys.Rev.D 81 (2010) 123530. https://doi.org/10.1103/PhysRevD.81.123530*
14. *V. Cardoso and P. Pani, „ Testing the nature of dark compact objects: a status report", Living Rev.Rel. 22 (2019) 1, 4. https://doi.org/10.1007/s41114-019-0020-4*
15. *D. Baumann et al., „Gravitational Collider Physics", Phys.Rev.D 101 (2020) 8, 083019. https://doi.org/10.1103/PhysRevD.101.083019*
16. *E. Berti et al., "Testing General Relativity with Present and Future Astrophysical Observations", Class.Quant.Grav. 32 (2015) 243001. https://doi.org/10.1088/0264-9381/32/24/243001*
17. *R. A. Porto, "The effective field theorist's approach to gravitational dynamics", Phys.Rept. 633 (2016) 1-104. https://doi.org/10.1016/j.physrep.2016.04.003*
18. *Raaijmakers et al., 2021 (ApJL in press)*
19. *NanoGRAV Collaboration, „The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background", Astrophys.J.Lett. 905 (2020) 2, L34. https://doi.org/10.3847/2041-8213/abd401*
20. *R. Brito et al., „Stochastic and resolvable gravitational waves from ultralight bosons", Phys.Rev.Lett. 119 (2017) 13, 131101. https://doi.org/10.1103/PhysRevLett.119.131101*
21. *V. De Luca et al., „Bayesian Evidence for Both Astrophysical and Primordial Black Holes: Mapping the GWTC-2 Catalog to Third-Generation Detectors", JCAP 05 (2021) 003. https://doi.org/10.1088/1475-7516/2021/05/003*
22. *https://agenda.infn.it/e/GWFundPhys*
23. *http://www.nupecc.org/jenaa/?display=eois*