Chapter 19
Multi-messenger Astronomy

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Abstract On 2015 September 14, the first observation of gravitational-waves by the Advanced Laser Interferometer Gravitational-wave Observatory detectors concluded a long scientific quest, which began 100 years before with Einstein's prediction of their existence. This detection opened a new exploration of the Universe making it possible to access the properties of space-time at extreme regime, to probe the properties of compact objects (binary systems of neutron stars and stellar-mass black holes), and investigate their formation and evolution. On August 17, 2017, the first observation of gravitational waves from the inspiral and merger of a binary neutron-star system by the Advanced LIGO and Virgo network, followed 1.7 s later by a weak short gamma-ray burst detected by the Fermi and INTEGRAL satellites initiated the most extensive world-wide observing campaign which led to the detection of multi-wavelength electromagnetic counterparts. Multi-messenger discoveries are unveiling the rich physics of most energetic transient phenomena in the sky, probing relativistic astrophysics, nuclear physics, nucleosynthesis, and cosmology. Here, we give an overview of the recent gravitational-wave and multi-messenger discoveries, and the perspectives for the future.

19.1 Introduction

The multimessenger astronomy is based on observations of astrophysical objects through different cosmic messengers (electromagnetic radiation, gravitational waves, neutrinos and cosmic rays) which can provide a complementary and complete view of astrophysical sources and their environment. Its onset resides in the discovery of neutrinos from a supernova exploded in the Large Magellanic Cloud in 1987, SN1987A [29, 44]; the neutrinos arrived a few hours before the optical emission and

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were detected by Kamiokande II, the Irvine-Michigan-Brookhaven detector, and the Baksan Neutrino Observatory.

Another recent discovery marked the history of multi-messenger observations, giving a huge boost to the field and showing the tremendous potential of combining multi-messenger observations to probe the physics of the most energetic events of the Universe: GW170817. On 2017 August 17, the merger of a binary neutron-star system has been observed through gravitational waves (GW170817) [13], and multi-wavelength photons from gamma rays (GRB 170817A), X-ray, ultraviolet-optical-near infrared (AT2017gfo), to radio [7]. The multi-messenger signals associated with this spectacular event represent the first strong observational evidence that binary neutron-star mergers power short gamma-ray bursts [6, 40, 62] and kilonovae [33], unveiling properties of relativistic jets [38, 54] and showing that binary neutron-star mergers are one of the major channels of the formation of heavy (r-process) elements in the Universe [56]. Neutron stars are unique laboratories to probe matter in extreme conditions, and the multi-messenger observations can constrain the neutron-star equation of state [51, see e.g.]. The distance estimated from the gravitational-wave signal combined with the recessional velocity of the host galaxies enable to evaluate the Universe expansion rate, showing a new way to make cosmology [5].

This paper covers the major discoveries related to the gravitational-wave astronomy since 2015 (Sect. 19.2), the multi-messenger observations of GW170817 and their scientific return (Sect. 19.3), the perspectives of the future multi-messenger astronomy (Sect. 19.4).

19.2 Gravitational-Wave Astronomy

The LIGO-Hanford, LIGO-Livingstone [1] and Virgo [25] interferometers observing the sky as a network made it possible to observe gravitational-waves. They have performed three run of observations; the first observational run lasted from September 2015 to January 2016, the second run from November 2016 to the end of August 2017, the third run from April 2019 to the end of March 2020. During the intervals between runs, technological upgrades increased the sensitivity of the detectors, making larger and larger volumes of the Universe accessible through gravitational wave observations. Rare events such as the coalescences of binary systems of neutron stars, neutron stars and black holes, and black holes have begun to be observed, and the frequency of their observations has increased significantly from the first run to the following ones. The first run led to the detection by the LIGO interferometers of three gravitational-wave signals from the coalescence of a binary system of stellar-mass black holes [11, 12]. These events showed us that black-holes exist in binary systems, that they can merge within the Hubble time, and that stellar-mass black-hole can be more massive ($> 30M_{sun}$) than expected before [10]. The second run increased the detected events to eleven, including binary black-hole coalescences and a binary neutron star coalescence, GW170817 [16]. During the third gravitational waves have been detected with a rate of about 1.5 detections per week. Seventy-nine candidate gravitational-wave events have been added to the 11 confident detections of the first and second observation runs. The majority of the signals are classified as binary black hole coalescences, but they also include another binary-neutron-star and two confident binary neutron-star black-hole coalescences [4, 18]. In a few years from a few merging binary black-holes, a significant number of detections was accumulated making possible population studies [2, 15, 19]. We have now direct measurements of binary black-hole properties, such us mass and spin distributions, and their frequency of merging. This had a huge impact on our knowledge of formation and evolution of these astrophysical systems, and indirectly also on their progenitors, the death of massive stars [10]. These events also provide unique access to the properties of space-time at extreme conditions under the strong-field and high-velocity regime. They enable us to define stringent constraints on testing general relativity [3, 17, 20]. Among the detections, some events were particularly interesting. GW190412 is a signal from a highly asymmetric mass binary black-hole system, component masses of $30M_{sun}$ and $8M_{sun}$. This signal made it possible to find for the first time strong evidence for gravitational radiation beyond the leading quadrupolar order, in complete consistency with the Einstein's general theory of relativity [21]. GW190814 is a signal from the coalescence of a black hole of $23M_{sun}$ with a compact object of mass $2.6M_{sun}$. Its unequal mass ratio and its secondary component consistent either with the lightest black hole or the heaviest neutron star ever discovered in a binary compact-object system are unprecedented, and challenges all current models of the formation of compact-object binaries [23]. GW190425 is the second detected signal from a binary neutron-star merger after GW170817. The total mass of the system, $3.4M_{sun}$, is significantly larger than those of any other known binary neutron-star system [8]. GW190521 is a signal from the coalescence of a highest mass binary black-hole system ($66 - 85M_{sun}$) forming a final black hole of $142M_{sun}$. This is the firm evidence of the existence of intermediate-mass black holes ($100 - 1000M_{sun}$) [22, 24].

19.3 Multi-messenger Astronomy Including Gravitational-Waves

The first detection of gravitational waves from a binary system of neutron stars by the Virgo and LIGO network, GW170817 is an epochal discovery which represents a landmark for multi-messenger astrophysics including gravitational waves [13]. The relatively small sky-localization of the signal enabled the most extensive electromagnetic observational campaign in human history, which led to the observation of the gravitational-wave source in all electromagnetic wavelengths (X-rays, ultraviolet, optical, infrared, and radio) [7]. In the following we summarize the different observations (see Fig. 19.1) and the implications of the revealed signals in the astrophysical knowledge of the source.

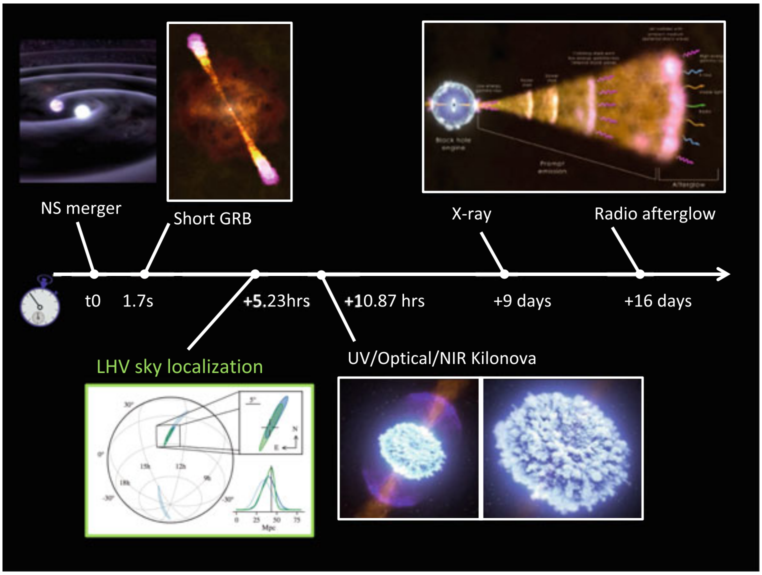

Fig. 19.1 Timeline of the discovery of the gravitational-wave signal (GW170817), the gamma-ray burst (GRB 170817A), the release of the gravitational-wave sky localization, the discovery of the optical emission from the kilonova (AT 2017gfo), and the discoveries of the X-ray and radio emission from the GRB relativistic jet

The gravitational wave signal enabled to infer the component masses of the binary system in the range $0.86 - 2.26M_{sun}$ which is consistent with the masses of known neutron stars in our Galaxy [13]. It also enabled to constrain the neutron star tidal deformability (each neutron star in the binary system is tidally deformed when under the influence of tidal field of the other). This macroscopic observable can be used to study neutron star interiors, in particular to infer the neutron star equation of state (EoS). The measurement obtained for GW170817 favors larger tidal deformability values, and thus softer EoSs are preferred with respect to stiffer ones [14]. The amount of tidally ejected mass which gives origin to the baryon mass powering the electromagnetic emission depends on the EoSs with stiffer EoSs producing larger amount of tidally ejected mass than the softer ones (see also below for EoS constraints from the electromagnetic observations).

The Fermi and INTEGRAL satellites independently detected a short gamma-ray burst (GRB) with a time delay of 1.7 s from the merger time. The time delay and the source distance made it possible to measure the propagation speed of gravitational waves; gravitational waves propagate at the speed of light to within $1{:}10^{15}$ [6]. This ruled out several classes of modified gravity models. Nine and sixteen days after the merger an X-ray signal [64] and a radio signal [42] were discovered. The following observations showed a slow non-thermal emission flux-rise in the radio, optical, and X-rays for about 150 days [49, 52] and then a slow decay [27, 34, 36, 41]. These multi-wavelength observations are consistent with both a slightly relativistic isotropic outflow (choked jet) and a successful structured jet (with energy and velocity decreasing with angular distance from the jet axis) observed off-axis. The magnificent resolution of Very Long Baseline Interferometry observations enabled to measure a superluminal proper motion of the radio counterpart [54] and to constrain the apparent size of the source [38], demonstrating that the later scenario, i.e. a relativistic jet successfully emerged from the neutron star merger, has occurred. GW170817 and observations from the gamma to the radio, have provided the first firm observational evidence that binary neutron-star mergers power short GRBs.

Neutron star mergers represent the perfect event for producing heavy elements, the temperature ($T > 10^9$K) and high neutron start density (10^{22} cm^{-3}) of the merger dynamical ejecta make neutron capture much faster than the β-decay. The formed heavy nuclei radioactively decay heating the material around and powering an ultraviolet (UV), optical and infrared (IR) transient, known as kilonova. While in the tidal tail ejecta the nucleosynthesis produce heavy elements up to lanthanides and actinides, whose opacity makes the spectral peak of the emission in the near-infrared and the peak of the light curve on one week timescale, in other components of the ejecta, such as the shock-heated ejecta and the accretion disc wind outflow, weak interactions (neutrino absorption, electron/positron capture) prevent the production of the heavier elements. This gives rise to smaller opacity and a bluer kilonova component peaking on day timescale (for a complete review see [53]). Eleven hours after the merger, optical transient emission was discovered from a galaxy, NGC 4993, at the same distance as the one evaluated from the gravitational-wave signal, pinpointing the location of the merger [33]. The observations from the near infrared to the ultraviolet taken for about ten days showed a transient thermal emission with a blue component fading within two days and a red component evolving in one week [65, e.g.]. The spectra revealed signatures of the radioactive decay of r-process nucleosynthesis [56, 63, 66], showing that binary neutron star mergers are one of the major channels of formation of heavy elements in the Universe. The brightness and evolution of the UV/optical/infrared data enabled to constrain the ejected masses providing a lower bound on the tidal deformability, and ruling out extremely soft equations of state. Joint kilonova and gravitational-wave observations are thus complementary, and rule out EoS in different directions [58]. The identification of the host galaxy through the kilonova detection enabled to use the recessional velocity of the host galaxies together with distance estimated from the gravitational-wave signal to evaluate the Hubble constant [5]. Figure 19.2 shows a summary of the major implications in astrophysics of the multi-messenger discovery of GW170817.

In the next run of observations of the current gravitational-wave detectors, currently planned to start at the end of 2022/early 2023, a few to ten binary neutron star mergers are expected to be detected [9]. The search of the electromagnetic counterparts will be more difficult due to the larger distances accessible by the upgrades of the LIGO, Virgo and KAGRA detectors. However, improved sensitivity observatories are expected to operate in synergy with the gravitational-wave detectors, for example the James Webb Space Telescope [46, JWST], the Vera C. Rubin Observa-

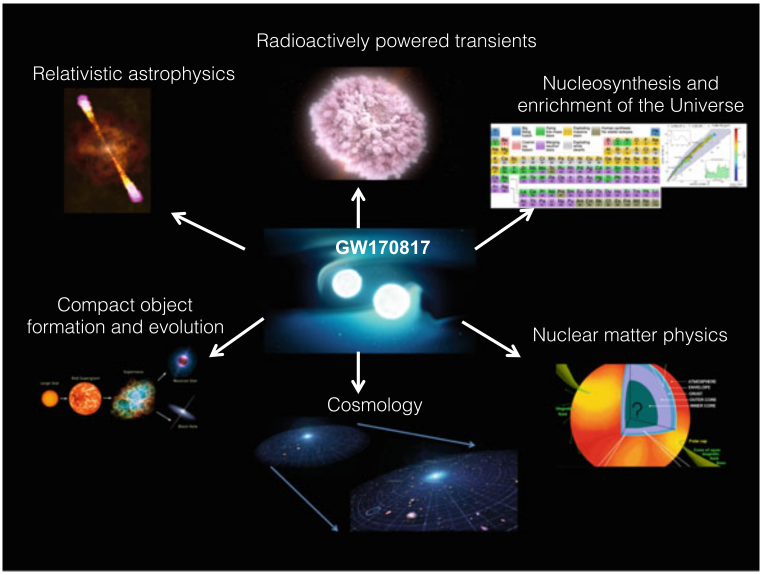

Fig. 19.2 Summary of the major astrophysical fields impacted by the multi-messenger discovery of GW170817

tory [45], GECAM [47], the Space-based multi-band astronomical Variable Objects Monitor ECLAIRs [67, SVOM-ECLAIRs], and Einstein Probe [68] to mention a few.

19.4 The Future of Gravitational-Wave and Multi-messenger Astronomy

Despite the enormous impact of LIGO-Virgo discoveries on many research fields, from fundamental physics and astrophysics to nuclear physics and cosmology, we are only at the dawn of this new exploration of the Universe. A new generation of more sensitive detectors is needed to address fundamental questions of gravitational-wave astro(physics) and cosmology which require to make precise measurements of the source parameters, to observe the evolution of the sources along the cosmic history, and to reach and explore the early Universe. The Einstein Telescope is the European ground-based gravitational-wave detector, evolution of second-generation detectors, which was recently included in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap.

It will feature a system of triangular shape nested detectors, where the arm length is increased to 10 km (compared to 3 km for Virgo and 4 km for LIGO). The larger size and the implementation of new technologies will enable to achieve an improved sensitivity by at least a factor of ten compared to the second generation instruments. ET will be built a few hundred meters underground, reducing terrestrial gravity noise and seismic noise and thus extending the sensitivity toward low frequencies. The ET extraordinary sensitivity and wide frequency band will make it possible to access the entire population of stellar mass black-holes up to the early Universe, to detect primordial black holes, and to unveil intermediate mass black-holes (up to $1000M_{sun}$) enabling us to understand their origin, evolution, and demography. It will probe the physics near the black-hole horizon enabling unprecedented general-relativity test. It will help understanding the nature of dark energy and possible modifications of general relativity at cosmological scales. ET will make gravitational waves powerful tools for comprehending fundamental forces in extreme regimes such as in the interiors of neutron stars, revealing the nature of compact objects and the properties of nuclear matter [50]. New gravitational-wave sources are expected to be detected including core-collapse supernovae, isolated neutron stars, stochastic backgrounds of astrophysical and cosmological origin, and cosmic strings. ET will operate in synergy with a new generation of innovative electromagnetic observatories, such as the Cherenkov Telescope Array [26, CTA], Athena [55, 57], the Vera Rubin Observatory, JWST, the European Southern Observatory Extremely Large Telescope [39, ELT], the Square Kilometre Array [35, SKA] and the mission concepts THESEUS [28, 32] and TAP [31]. Multi-messenger observations will probe the population of binary systems of compact objects in connection with kilonovae and short GRBs along with the star formation history and chemical evolution of the Universe.

ET is expected to detect $10^4 - 10^5$ binary neutron star coalescences per year. Thanks to the access at low frequencies, ET will detect binary neutron star mergers before the merger (minutes but also several hours before in the case of close events), and the Earth rotation imprint on the signal will be used to determine the sky localisation. Thus ET, also operating as a single detector will be able to localize a few hundreds detections per year with sky-localization ($90\% c.r.$) $<$100 square degrees. For these events, it will be possible to send early warning alerts. The detection and localization capabilities significantly improve, observing in a network of next generation gravitational-wave observatories (see Fig. 19.3). Thousands of detections per year will have a sky-localization ($90\% c.r.$) $<$10 square degrees, and thousands of detections sky-localization ($90\% c.r.$) $<$1 square degrees for ET observing with Cosmic Explorer [37, 59], and two Cosmic Explorer (one in USA and one in Australia). For recent works on ET and CE detection and localization capabilities see [30, 43, 48, 60]. Since the kilonovae optical emission is intrinsically faint and difficult to detect at redshift larger 0.3, the counterparts at larger redshift will be mainly detected in the high-energy band. A recent comprehensive study [60], starting from simulated binary neutron star population and GRB modelling calibrated and normalized to reproduce properties of observed short GRB samples, has analyzed the joint gravitational wave and gamma and X-ray detections modelling the prompt and afterglow emissions and considering different observational strategies. Almost all detected short GRB will have a gravitational-wave counterparts. Depending on the specific gamma-ray

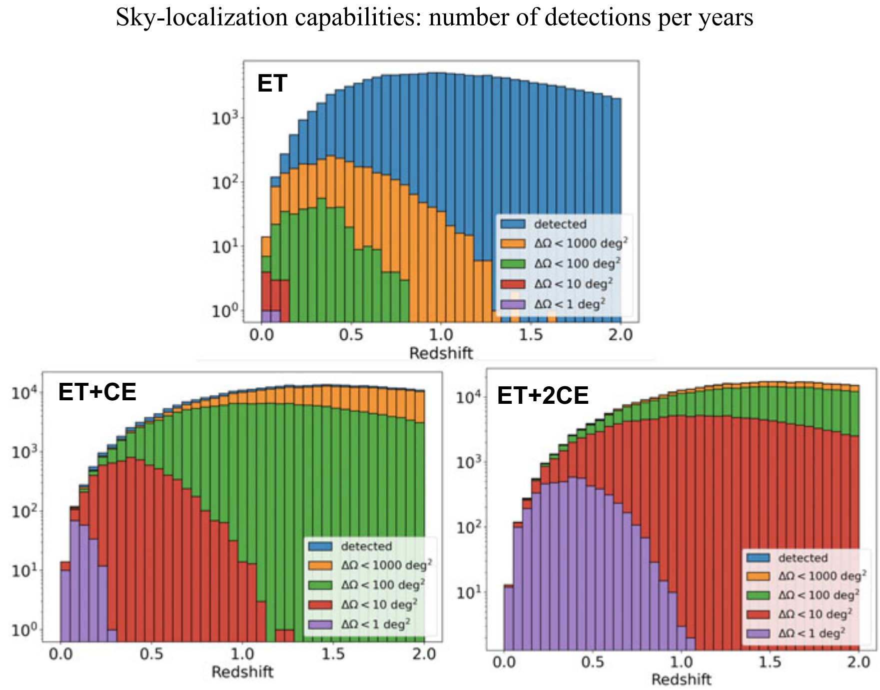

Fig. 19.3 Sky-localization capabilities. The figures (from [61]) show the population of injected binary neutron stars in blue, the number of detections per year localized better than 1000, 100, 10, 1 square degrees in orange, green, red and purple, respectively. Top plot Einstein telescope operating as a single observatory, bottom plots ET in the network of ET and Cosmic Explorer in USA, and ET and two Cosmic Explorer (left plot), one in USA and one in Australia (right plot)

satellites (operating in survey mode), we will have tens to hundreds of gravitational-wave and prompt gamma-ray detections per year. Instead, wide field of view X-ray satellites, such as Einstein Probe, THESEUS, and TAP, are expected to give tens of X-ray afterglow counterparts per year when operating in survey mode. Pointing relatively well localized events (<100 square degrees) by the network given by ET and CE, could increase the detections to hundreds. However, it will be challenging the prioritization of the triggers (based on distance, sky-localization, and viewing angles) to select the ones with a higher chance to be detectable. In summary, ET will make a revolution in our knowledge of the Early Universe, fundamental physics, and transient astrophysics.

References

1. J. Aasi et al., LIGO Scientific Collaboration. Advanced LIGO. Class. Quantum Gravity **32**(7), 074001 (2015)
2. B.P. Abbott, R. Abbott et al., The population of merging compact binaries inferred using gravitational waves through GWTC-3. arXiv:2111.03634
3. B.P. Abbott, R. Abbott et al., Tests of General Relativity with GWTC-3. arXiv:2112.06861
4. B.P. Abbott et al. GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run. arXiv:2111.03606
5. B.P. Abbott et al., A gravitational-wave standard siren measurement of the Hubble constant. Nature **551**(7678), 85–88 (2017)
6. B.P. Abbott et al., Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A. Astrophys. J. Lett. **848**(2), L13 (2017)
7. B.P. Abbott et al., Multi-messenger observations of a Binary Neutron Star Merger. Astrophys. J. Lett. **848**(2), L12 (2017)
8. B.P. Abbott et al., GW190425: observation of a compact binary coalescence with total mass $\sim$3.4 $M_{\odot}$. Astrophys. J. Lett. **892**(1), L3 (2020)
9. B.P. Abbott et al., Kagra Collaboration, LIGO Scientific Collaboration, and VIRGO Collaboration. Prospects for observing and localizing gravitational-wave transients with Advanced LIGO, Advanced Virgo and KAGRA. Liv. Rev. Relativ. **23**(1), 3 (2020)
10. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Astrophysical implications of the binary black-hole Merger GW150914. Astrophys. J. Lett. **818**(2), L22 (2016)
11. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Binary black hole mergers in the first advanced LIGO observing run. Phys. Rev. X **6**(4), 041015 (2016)
12. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Observation of Gravitational waves from a binary black hole merger. Phys. Rev. Lett. **116**(6), 061102 (2016)
13. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GW170817: observation of gravitational waves from a binary neutron star inspiral. Phys. Rev. Lett. **119**(16), 161101 (2017)
14. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GW170817: measurements of neutron star radii and equation of state. Phys. Rev. Lett. **121**(16), 161101 (2018)
15. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Binary black hole population properties inferred from the first and second observing runs of advanced LIGO and advanced Virgo. Astrophys. J. Lett. **882**(2), L24 (2019)
16. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GWTC-1: a gravitational-wave transient catalog of compact binary mergers observed by LIGO and Virgo during the first and second observing runs. Phys. Rev. X **9**(3), 031040 (2019)D
17. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Tests of general relativity with the binary black hole signals from the LIGO-Virgo catalog GWTC-1. Phys. Rev. D **100**(10), 104036 (2019)
18. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GWTC-2: compact binary coalescences observed by LIGO and Virgo during the first half of the third observing run. Phys. Rev. X **11**(2), 021053 (2021)
19. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Population properties of compact objects from the second LIGO-Virgo gravitational-wave transient catalog. Astrophys. J. Lett. **913**(1), L7 (2021)
20. B.P. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Tests of general relativity with binary black holes from the second LIGO-Virgo gravitational-wave transient catalog. Phys. Rev. D **103**(12), 122002 (2021)
21. R. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GW190412: observation of a binary-black-hole coalescence with asymmetric masses. Phys. Rev. D **102**(4), 043015 (2020)

22. R. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GW190521: a binary black hole merger with a total mass of 150 $M_{\odot}$. Phys. Rev. Lett. **125**(10), 101102 (2020)
23. R. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. GW190814: gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object. Astrophys. J. Lett. **896**(2), L44 (2020)
24. R. Abbott et al., LIGO Scientific Collaboration, and Virgo Collaboration. Properties and astrophysical implications of the 150 $M_{\odot}$ binary black hole merger GW190521. Astrophys. J. Lett. **900**(1), L13 (2020)
25. F. Acernese, et al., Virgo Collaboration. Advanced Virgo: a second-generation interferometric gravitational wave detector. Class. Quantum Grav. **32**(2), 024001 (2015)
26. B.S. Acharya et al., CTA Consortium. Introducing the CTA concept. Astropart. Phys. **43**, 3–18 (2013)
27. K.D. Alexander et al., A decline in the X-Ray through Radio Emission from GW170817 continues to support an Off-axis structured jet. Astrophys. J. Lett. **863**(2), L18 (2018)
28. L. Amati et al., Theseus Consortium. The THESEUS space mission: science goals, requirements and mission concept. Exp. Astron. **52**(3), 183–218 (2021)
29. R.M. Bionta et al., Observation of a neutrino burst in coincidence with supernova 1987A in the Large Magellanic Cloud. Phys. Rev. Lett. **58**(14), 1494–1496 (1987)
30. S. Borhanian, B.S. Sathyaprakash, Listening to the Universe with Next Generation Ground-Based Gravitational-Wave Detectors, Feb. 2022. arXiv:2202.11048
31. J. Camp et al., Transient astrophysics probe, in *Bulletin of the American Astronomical Society*, vol. 51, p. 85, Sept. 2019
32. R. Ciolfi et al., Multi-messenger astrophysics with THESEUS in the 2030s. Exp. Astron. **52**(3), 245–275 (2021)
33. D.A. Coulter et al., Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. Science **358**(6370), 1556–1558 (2017)
34. P. D'Avanzo et al., The evolution of the X-ray afterglow emission of GW 170817/ GRB 170817A in XMM-Newton observations. Astron. Astrophys. **613**, L1 (2018)
35. P.E. Dewdney, P.J. Hall, R.T. Schilizzi, T.J.L.W. Lazio, The Square Kilometre Array. IEEE Proc. **97**(8), 1482–1496 (2009)
36. D. Dobie et al., A turnover in the radio light curve of GW170817. Astrophys. J. Lett. **858**(2), L15 (2018)
37. M. Evans et al., A horizon study for cosmic explorer science, observatories, and community. dcc.cosmicexplorer.org/CE-P2100003/public
38. G. Ghirlanda et al., Compact radio emission indicates a structured jet was produced by a binary neutron star merger. Science **363**(6430), 968–971 (2019)
39. R. Gilmozzi, J. Spyromilio, The European extremely large telescope (E-ELT). The Messenger **127**, 11 (2007)
40. A. Goldstein et al., An ordinary short Gamma-Ray burst with extraordinary implications: Fermi-GBM Detection of GRB 170817A. Astrophys. J. Lett. **848**(2), L14 (2017)
41. A. Hajela et al., Two years of nonthermal emission from the binary neutron star merger GW170817: rapid fading of the jet afterglow and first constraints on the Kilonova Fastest Ejecta. Astrophys. J. Lett. **886**(1), L17 (2019)
42. G. Hallinan et al., A radio counterpart to a neutron star merger. Science **358**(6370), 1579–1583 (2017)
43. J. Harms et al., GWFish: a simulation software to evaluate parameter-estimation capabilities of gravitational-wave detector networks, May 2022. arXiv:2205.02499
44. K. Hirata et al., Observation of a neutrino burst from the supernova SN1987A. Phys. Rev. Lett. **58**(14), 1490–1493 (1987)
45. Z. Ivezic et al., LSST Collaboration. Large synoptic survey telescope: from science drivers to reference design. Serbian Astronom. J. **176**, 1–13 (2008)
46. J. Kalirai, Scientific discovery with the James Webb Space Telescope. Contemp. Phys. **59**(3), 251–290 (2018)

47. Y. Li et al., The GECAM and its payload. Scientia Sinica Physica, Mechanica & Astronomica **50**(12), 129508 (2020)
48. Y. Li et al., Exploring the sky localization and early warning capabilities of third generation gravitational wave detectors in three-detector network configurations, Sept. 2021. arXiv:2109.07389
49. J.D. Lyman et al., The optical afterglow of the short gamma-ray burst associated with GW170817. Nat. Astron. **2**, 751–754 (2018)
50. M. Maggiore et al., Science case for the Einstein telescope. J. Cosmol. Astropart. Phys. **2020**(3), 050 (2020)
51. B. Margalit, B.D. Metzger, Constraining the maximum mass of Neutron Stars from Multi-messenger observations of GW170817. Astrophys. J. Lett. **850**(2), L19 (2017)
52. R. Margutti et al., The binary neutron star event LIGO/Virgo GW170817 160 days after merger: synchrotron emission across the electromagnetic spectrum. Astrophys. J. Lett. **856**(1), L18 (2018)
53. B.D. Metzger, Kilonovae. Liv. Rev. Relativ. **23**(1), 1 (2019)
54. K.P. Mooley et al., Superluminal motion of a relativistic jet in the neutron-star merger GW170817. Nature **561**(7723), 355–359 (2018)
55. K. Nandra et al., The Hot and Energetic Universe: A White Paper presenting the science theme motivating the Athena+ mission, June 2013. arXiv:1306.2307
56. E. Pian et al., Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. Nature **551**(7678), 67–70 (2017)
57. L. Piro et al., Multi-messenger-Athena Synergy White Paper, Oct. 2021. arXiv:2110.15677
58. D. Radice, A. Perego, F. Zappa, S. Bernuzzi, GW170817: joint constraint on the neutron star equation of State from multimessenger observations. Astrophys. J. Lett. **852**(2), L29 (2018)
59. D. Reitze et al., Cosmic explorer: The US contribution to gravitational-wave astronomy beyond LIGO. Bull. Am. Astron. Soc. **51**, 035, 7 (2019)
60. S. Ronchini et al., Perspectives for multi-messenger astronomy with the next generation of gravitational-wave detectors and high-energy satellites, Apr. 2022. arXiv:2204.01746
61. F. Santoliquido et al., The cosmic merger rate density of compact objects: impact of star formation, metallicity, initial mass function, and binary evolution. Mon. Not. R. Astronom. Soc. **502**(4), 4877–4889 (2021)
62. V. Savchenko et al., INTEGRAL detection of the first prompt Gamma-Ray signal coincident with the Gravitational-wave event GW170817. Astrophys. J. Lett. **848**(2), L15 (2017)
63. S.J. Smartt et al., A Kilonova as the electromagnetic counterpart to a gravitational-wave source. Nature **551**(7678), 75–79 (2017)
64. E. Troja et al., The X-ray counterpart to the gravitational-wave event GW170817. Nature **551**(7678), 71–74 (2017)
65. V.A. Villar et al., The combined ultraviolet, optical, and near-infrared light curves of the Kilonova associated with the binary neutron star merger GW170817: unified data set, analytic models, and physical implications. Astrophys. J. Lett. **851**(1), L21 (2017)
66. D. Watson et al., Identification of strontium in the Merger of two Neutron Stars. Nature **574**(7779), 497–500 (2019)
67. J. Wei et al., The Deep and Transient Universe in the SVOM Era: New Challenges and Opportunities—Scientific prospects of the SVOM mission, Oct. 2016. arXiv:1610.06892
68. W. Yuan et al., Einstein Probe—a small mission to monitor and explore the dynamic X-ray Universe, in *Proceedings of Swift: 10 Years of Discovery (SWIFT 10)*, p. 6, Dec. 2014