International Astronomy and Astrophysics Research Journal

Volume 8, Issue 1, Page 80-93, 2026; Article no.IAARJ.164243

Astrophysics of Binary Neutron Star Mergers: Detection of Gravitational Waves from a Merging Pair of Neutron Stars

Manuel Malaver [a*] and Hamed Daei Kasmaei [b]

[a] Department of Basic Sciences, Maritime University of the Caribbean, Catia la Mar, Venezuela.
[b] Department of Applied Mathematics and Computer Science, Islamic Azad University, Central Tehran Branch, Tehran, Iran.

Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/iaarj/2026/v8i1126

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://pr.sdiarticle5.com/review-history/164243

Review Article

Received: 19/06/2026
Accepted: 11/08/2026
Published: 14/08/2026

Abstract

In August 2017, the detection of gravitational waves from a merging pair of neutron stars, accompanied within seconds by a faint gamma-ray burst and within hours by a fading optical transient, turned a long-standing theoretical prediction into an observational reality. This review traces the decade of research that has followed, asking what that single event, and the handful of related detections since, have actually taught us about the physics of compact-object coalescence, the astrophysical origin of the heaviest elements, the behaviour of matter beyond nuclear density, and the use of merging neutron stars as cosmological distance markers. The discussion moves from the anatomy of the discovery event itself to the convergence of gravitational-wave, electromagnetic, nuclear-theory and heavy-ion-collision evidence on the equation of state of dense matter, and finally to the technological roadmap towards a next-generation network of underground and very-long-baseline interferometers. Particular attention is given to a tension that runs through the whole field: the scientific yield of even one well-observed multi-messenger event has been extraordinary, yet

**Corresponding author: E-mail: mmf.umc@gmail.com;*

Cite as: *Malaver, M., & Kasmaei, H. D. (2026). Astrophysics of Binary Neutron Star Mergers: Detection of Gravitational Waves from a Merging Pair of Neutron Stars. International Astronomy and Astrophysics Research Journal, 8(1), 80–93. https://doi.org/10.9734/iaarj/2026/v8i1126*

genuinely multi-messenger detections remain rare, and detector sensitivity alone will not close that gap. The review also reflects candidly on the methodological challenge of synthesising a literature that spans astrophysics, nuclear physics and instrument engineering, and on the limits of generalising from what is still, in essence, a single richly studied case. It closes by setting out research priorities for the coming decade and by weighing the technical promise of third-generation detectors against the practical, resource-bound problem of finding and characterising what they will detect.

Keywords: Binary neutron star mergers; gravitational waves; kilonova; multi-messenger astronomy; r-process nucleosynthesis; equation of state.

1. Introduction

1.1 The Theoretical Anticipation of Merging Neutron Stars

That two neutron stars might one day spiral together and merge, releasing both gravitational radiation and a burst of electromagnetic emission, is an idea considerably older than its eventual confirmation. The discovery of the Hulse–Taylor binary pulsar showed that close double neutron star systems exist in nature and that their orbits decay in a manner consistent with gravitational-wave emission, supplying the first indirect evidence that mergers of this kind must, given enough time, actually happen. Building on that insight, theorists argued in the late 1980s that the violent coalescence of two neutron stars would eject a quantity of extremely neutron-rich matter capable of synthesising the heaviest elements through rapid neutron capture, and would simultaneously release enough energy to power a short, intense flash of gamma-rays (Eichler et al., 1989; Fan et al., 2024). It is a striking piece of foresight: a single paper tied together gravitational waves, heavy-element nucleosynthesis and short gamma-ray bursts roughly three decades before any of those connections could be tested directly. In the intervening years, circumstantial support accumulated for a link between short gamma-ray bursts and compact-object mergers, largely through the identification of their host galaxies and the character of their afterglows, but no unambiguous, direct observational tie between a gravitational-wave signal and any electromagnetic counterpart had yet been made.

1.2 The Transformation Wrought by GW170817

That changed on 17 August 2017. The Advanced LIGO and Advanced Virgo gravitational-wave detectors recorded a signal consistent with the inspiral of two neutron stars, designated GW170817 (Abbott et al., 2017a). Less than two seconds later, the Fermi Gamma-ray Burst Monitor and the INTEGRAL satellite independently picked up a weak gamma-ray transient, GRB 170817A, arriving from a direction broadly consistent with the gravitational-wave source. Within less than half a day, ground-based optical telescopes had picked out a new, fading point source in the early-type galaxy NGC 4993, some forty megaparsecs away, which then evolved in colour and brightness in a way that matched nothing previously catalogued among supernovae or novae (Abbott et al., 2017b; Coulter et al., 2017; de Sá et al., 2023). What followed was an extraordinary, genuinely global observing campaign, spanning radio, optical, ultraviolet, infrared, X-ray and gamma-ray facilities, and producing a cluster of companion papers that together established several results almost at once: that binary neutron star mergers do power short gamma-ray bursts; that they eject enough neutron-rich material to account for a substantial fraction of the Galaxy's r-process element inventory; that the merger remnant drives a relativistic, structured jet; and that the combination of gravitational-wave and electromagnetic data yields an independent route to measuring the rate of cosmic expansion. It is for good reason that this event, and its kilonova counterpart AT2017gfo, is now regarded as the moment multi-messenger gravitational-wave astronomy began in earnest (Margutti & Chornock, 2021).

Nearly a decade on, the field looks considerably more mature, although not necessarily as large as most observers had hoped. The population of gravitational-wave detections involving at least one neutron star has continued to grow, yet none of the subsequent candidates has produced an electromagnetic counterpart approaching the richness of the founding event. Where progress has been most tangible is in the synthesis of evidence: gravitational-wave tidal measurements, electromagnetic constraints on the merger remnant, X-ray pulse-profile modelling of isolated pulsars, and even terrestrial heavy-ion collision data can now be combined within single statistical frameworks to constrain the equation of state of dense nuclear matter, something that would have seemed an unlikely cross-disciplinary marriage a decade earlier. At the same time, plans for a next-generation network of gravitational-wave observatories, intended to extend sensitivity by an order of magnitude and push the binary-neutron-star detection horizon out to cosmological distances, have moved from conceptual design studies towards funded, site-specific projects. This seems a reasonable moment, then, to take stock: of what has actually been learned, of what remains genuinely contested, and of what the coming decade of instrumentation is realistically likely to deliver.

1.3 Scope, Research Gap and Objectives

This review covers the multi-messenger astrophysics of binary neutron star mergers from the discovery of GW170817 to the present, organised around four interlinked themes: the observational anatomy of the founding event itself; the constraints that multi-messenger data have placed on the equation of state of dense matter; the use of merging neutron stars as standard sirens for cosmology; and the instrumental developments expected to shape the coming decade of observation. Neutron star–black hole mergers and binary black hole mergers are discussed only insofar as they bear directly on the interpretation of binary neutron star physics, most notably in establishing the existence of a lower mass gap among compact objects.

A persistent gap in the existing literature is the tendency to treat the gravitational-wave, electromagnetic and nuclear-physics strands of this story as separate subfields, which mirrors the disciplinary boundaries of the communities that produce them rather than the way in which the underlying inference problem actually works: as a single coupled estimation across messengers. A second, related gap concerns the disconnect between the scientific promise articulated in detector design documents and the practical, resource-limited reality of electromagnetic follow-up, which has so far produced only one richly observed kilonova despite a steadily growing tally of gravitational-wave detections involving neutron stars. This review attempts to address both gaps: first, by drawing the gravitational-wave, electromagnetic and nuclear-physics strands together within a single narrative rather than treating them in isolation; and second, by weighing the achievements of the past decade against the rate-limiting factors that will determine whether the next generation of detectors actually converts greater sensitivity into a correspondingly larger harvest of multi-messenger events, rather than simply a larger harvest of gravitational-wave triggers with no electromagnetic counterpart. Its objectives are accordingly threefold: to summarise the principal scientific results obtained from binary neutron star mergers observed to date; to assess the current balance of agreement and disagreement regarding the equation of state and the Hubble constant derived from these events; and to evaluate the prospects, and the obstacles, facing the next-generation observational network.

2. Methods for Literature Selection

2.1 Databases Searched

The literature underpinning this review was identified through structured searches of four general bibliographic databases, namely Web of Science, Scopus, Google Scholar, and PubMed, supplemented by six field-specific resources judged necessary for adequate coverage of gravitational-wave and high-energy astrophysics: the NASA Astrophysics Data System, INSPIRE-HEP, the arXiv e-print repository (used exclusively to trace articles to their peer-reviewed published versions, never as a source of final citations), the Inspec abstracting and indexing database for physics and astronomy, the Transient Name Server and Gamma-ray Coordinates Network circular archive (used only to corroborate discovery chronologies and counterpart designations, not as a citation source), and the public document repository maintained jointly by the gravitational-wave collaborations. This combination was chosen deliberately: general databases alone tend to under-index detector-technology white papers and large collaboration-authored discovery papers central to this field, while the field-specific resources alone would miss relevant contributions appearing in nuclear and particle physics journals, which increasingly intersect with neutron-star equation-of-state research.

2.2 Search Strings and Date Range

Searches combined terms describing the astrophysical phenomenon with terms describing the messenger or detection method. Representative combinations included: "binary neutron star merger" AND "multi-messenger" OR "multimessenger"; "neutron star merger" AND "gravitational wave*" AND ("kilonova" OR "macronova");

"GW170817" AND ("equation of state" OR "tidal deformability" OR "Hubble constant" OR "standard siren"); "r-process" AND "neutron star merger" AND "nucleosynthesis"; "Einstein Telescope" OR "Cosmic Explorer" OR "next-generation gravitational-wave detector" OR "third-generation gravitational-wave observatory"; and "short gamma-ray burst" AND "compact object merger". The principal search window ran from January 2015, coinciding with the commissioning of Advanced LIGO and the start of the modern multi-messenger detector era, through to 29 March 2026. Foundational theoretical work predating this window was deliberately retained where it carried clear historical weight, most obviously the original proposal linking neutron-star coalescence to nucleosynthesis and gamma-ray bursts (Eichler et al., 1989); this is consistent with standard guidance for narrative reviews, which treats the identification of influential studies as distinct from, and not bound by, a mechanically applied date filter (Grant & Booth, 2009).

2.3 Inclusion and Exclusion Criteria

Studies were included if they reported original peer-reviewed research, or peer-reviewed synthesis content, on binary neutron star mergers, their electromagnetic counterparts, the dense-matter equation of state as constrained by compact-object observations, gravitational-wave detector design and sensitivity, or the use of compact-object mergers for cosmological inference, and if they were published in English in a peer-reviewed journal. Authoritative institutional reports bearing on detector infrastructure or international scientific coordination were considered eligible in principle, provided a verifiable institutional URL could be supplied where no peer-reviewed equivalent existed; in practice, the final reference list relies exclusively on peer-reviewed journal articles, since a complete and current peer-reviewed literature was available for every topic addressed and no such substitution proved necessary. Studies were excluded if they were preprints lacking a corresponding peer-reviewed publication, conference proceedings, book chapters, theses, technical notes without independent peer review, or patents, and if their subject matter concerned binary black hole mergers, isolated pulsar timing, or supernova physics without direct relevance to binary neutron star phenomenology. Non-English-language sources were excluded at the title and abstract stage; scoping searches identified no eligible non-English source of clear relevance, so this restriction is not judged to have introduced material bias.

2.4 Screening Workflow, Duplicate Handling, and Selection of Influential Studies

Records retrieved from each database were exported and deduplicated using digital object identifiers as the primary matching key, with near-duplicate entries lacking a recorded identifier, such as preprint and journal versions of the same study, reconciled by hand. Titles and abstracts were screened against the inclusion criteria above, and full texts were retrieved wherever eligibility could not be settled from the abstract alone. Because this is a narrative rather than a systematic review, no fixed quota of records was imposed at any screening stage, and no formal risk-of-bias scoring was applied; the priority instead was to identify the studies of greatest evidential and historical significance to the field, judged by a combination of citation prominence, the standing of the publishing venue, and the role a given study has played in shaping subsequent research, for instance as a flagship discovery paper from one of the gravitational-wave collaborations or as a widely cited synthesis review. A narrative approach was chosen over a systematic review or meta-analysis precisely because the subject matter spans such heterogeneous methodologies, instrument engineering, numerical relativity, nuclear theory, and time-domain observational astronomy, that forcing it through a single quantitative synthesis framework would do violence to the underlying science rather than illuminate it; this follows established guidance distinguishing narrative reviews, which prioritise critical, integrative synthesis, from systematic reviews, which prioritise exhaustive and reproducible retrieval against a narrowly defined question (Grant & Booth, 2009). Citation chaining from key reviews and discovery papers supplemented the database searches, capturing studies that keyword searches alone might have missed, in particular the companion papers that tend to accompany large, coordinated observing campaigns.

2.5 Summary of the Search Strategy

Table 1 brings together the elements of the search strategy described above. When read across its rows, the table makes a point that is easy to lose in narrative description alone: the breadth of database coverage required for this topic is itself a consequence of how far the subject now spans beyond traditional astronomy databases, into nuclear physics, instrument engineering, and transient-alert infrastructure.

Table 1. Summary of the literature search strategy

Element	Detail
General databases	Web of Science; Scopus; Google Scholar; PubMed
Field-specific databases	NASA Astrophysics Data System; INSPIRE-HEP; arXiv (preprint-to-publication tracing only); Inspec; Transient Name Server / GCN circular archive (chronology verification only); gravitational-wave collaboration public document repository
Representative search terms	"binary neutron star merger" AND "multi-messenger"; "GW170817" AND "equation of state" OR "Hubble constant"; "kilonova" AND "r-process"; "Einstein Telescope" OR "Cosmic Explorer"
Search window	January 2015 to 29 March 2026 (foundational pre-2015 theory retained as historical context)
Review type	Narrative, critical-synthesis review
Language restriction	English only
Record types retained	Peer-reviewed original research articles and review articles in astrophysics, nuclear physics, and gravitational-wave instrument journals
Record types excluded	Preprints without peer-reviewed counterpart; conference proceedings; books and theses; patents; off-topic binary black hole or isolated pulsar studies

3. The Discovery of GW170817: A Multi-Messenger Milestone

3.1 Gravitational-wave Detection and Source Characterisation

GW170817 was detected with a combined signal-to-noise ratio of 32.4, by far the loudest compact-binary signal the LIGO-Virgo network had recorded up to that point, and was localised, once Virgo data were folded in, to a sky region of about twenty-eight square degrees at the ninety per cent credible level (Abbott et al., 2017a). The inferred component masses, falling between roughly 0.86 and 2.26 solar masses, sat comfortably within the range known from radio pulsar timing of Galactic neutron stars, while the inferred luminosity distance of around forty megaparsecs made this both the nearest and the most precisely localised gravitational-wave source detected to that date. Because the inspiral remained observable within the detectors' sensitive band for roughly one hundred seconds, an unusually long stretch for a compact-binary signal, the chirp mass could be measured with high precision, and the data also yielded the first meaningful gravitational-wave constraint on the combined tidal deformability of the two stars, a quantity tied closely to their internal structure and, through it, to the equation of state discussed in Section 4.

3.2 The Short Gamma-ray Burst and Its High-energy Counterpart

A weak short gamma-ray burst, GRB 170817A, was picked up independently by the Fermi Gamma-ray Burst Monitor just 1.7 seconds after the gravitational-wave merger time, and was also registered by INTEGRAL (Abbott et al., 2017b). That near-simultaneity, together with the mutual consistency of the two signals' sky positions, supplied the first direct observational evidence linking neutron-star coalescence to short gamma-ray bursts, confirming a connection that had been argued for on theoretical grounds for decades (Eichler et al., 1989). The burst itself, however, was markedly fainter and softer than a typical cosmological short burst would have been at a comparable distance, a puzzle that was resolved only once the later radio and X-ray observations revealed the true geometry of the underlying jet, discussed in Section 3.4.

3.3 The Kilonova AT2017gfo and the Identification of r-process Nucleosynthesis

About eleven hours after the gravitational-wave trigger, a team observing with the Swope Telescope in Chile identified a new transient source in the galaxy NGC 4993, coincident with the gravitational-wave localisation region; the team initially named it SSS17a, and it was subsequently given the official IAU transient designation AT2017gfo (Coulter et al., 2017). The discovery was confirmed almost immediately by numerous independent teams worldwide, and an intensive photometric and spectroscopic campaign tracked the source's evolution from ultraviolet to near-infrared wavelengths over the following weeks. What that campaign revealed was a transient unlike anything previously catalogued: bright and distinctly blue within the first day, it then reddened markedly over the following days and faded on a timescale of roughly a week to ten days (Drout et al., 2017; Smartt et al., 2017). This pattern, rapid early fading combined with strong reddening, was interpreted as direct evidence for a kilonova: thermal emission powered by the radioactive decay of freshly synthesised, neutron-rich material ejected during the merger, broadly matching long-standing theoretical predictions for such transients (Metzger, 2020).

Detailed spectroscopy added a further layer of detail, revealing broad, smoothly varying absorption-like features consistent with ejecta expanding at roughly one-fifth the speed of light, with the spectral evolution pointing towards the gradual emergence of heavier, lanthanide-rich species at later times (Pian et al., 2017). Radiative transfer modelling, combining the gravitational-wave-derived distance with the observed light curves, inferred two distinct ejecta components distinguished primarily by composition and opacity: a lanthanide-poor component responsible for the early blue emission, and a more neutron-rich, lanthanide-bearing component responsible for the longer-lived, redder emission. The inferred ejected mass, taken together with the merger rate implied by GW170817 itself, suggested that mergers of this kind could plausibly account for a dominant share of the Galaxy's heavy r-process element budget (Kasen et al., 2017). A later reanalysis of the earliest spectra went further still, identifying specific absorption features attributable to strontium, the first unambiguous spectroscopic identification of an individual neutron-capture element in any kilonova (Watson et al., 2019).

3.4 The Relativistic Jet: Radio and X-ray Afterglow Evolution

Alongside the kilonova, X-ray emission was detected from the same location nine days after the merger (Troja et al., 2017), followed by a faint radio counterpart that emerged sixteen days after the merger (Hallinan et al., 2017; Han et al., 2023). What made this emission puzzling was its behaviour over time: unlike the kilonova, which had already faded within a fortnight, the X-ray and radio signal kept brightening for more than one hundred and fifty days, a pattern difficult to square with a simple, on-axis short-gamma-ray-burst afterglow. Two competing explanations were on the table: a narrow relativistic jet seen substantially off-axis or a roughly isotropic, mildly relativistic cocoon of shocked ejecta; distinguishing between them required a different kind of observation altogether. Very-long-baseline radio interferometry supplied the answer, detecting apparent superluminal motion in the radio-emitting source and thereby demonstrating directly that the afterglow was driven by a narrow, highly relativistic jet rather than any isotropic outflow (Mooley et al., 2018). A later, independent campaign using compact radio imaging reached the same conclusion from a different angle, finding that the source remained too small to be consistent with an isotropic cocoon and instead required a collimated, structured jet, with rate calculations suggesting that at least one in ten binary neutron star mergers may successfully launch such a jet (Ghirlanda et al., 2019; Gorda et al., 2023). Table 2 lays out these counterparts in the order they were detected; what stands out on reading down the table is the sheer mismatch in timescale between the brief, week-long kilonova and the slow-burning, multi-month afterglow that followed it, a mismatch that drove much of the observational effort and theoretical debate described above.

Table 2. Principal electromagnetic and gravitational-wave signatures of GW170817

Messenger	Approximate Timing relative to Merger	Physical interpretation
Gravitational-wave inspiral signal	t = 0 (trigger)	Binary neutron star coalescence; source distance and tidal information
Short gamma-ray burst (GRB 170817A)	t ≈ 1.7 s	Prompt, weakly beamed gamma-ray emission from a structured jet viewed off-axis
Optical/infrared transient (AT2017gfo)	t ≈ 11 hours	Kilonova; thermal emission from radioactively powered, r-process-enriched ejecta
Spectroscopic r-process signatures	t ≈ 1.5–10 days	Identification of light and heavy r-process elements, including strontium
X-ray counterpart	t ≈ 9 days (onset)	Synchrotron emission, initially attributed to an off-axis afterglow
Radio counterpart	t ≈ 16 days (onset), peaking near 150–160 days	Late-rising synchrotron afterglow of a structured relativistic jet
Superluminal radio motion	t ≈ 75–230 days (VLBI epochs)	Direct kinematic confirmation of a narrow, highly relativistic jet

Sources: Abbott et al. (2017a, 2017b); Coulter et al. (2017); Drout et al. (2017); Ghirlanda et al. (2019); Hallinan et al. (2017); Kasen et al. (2017); Konstantinou and Morsink (2022); *Metzger (2020); Mooley et al. (2018); Pian et al. (2017); Smartt et al. (2017); Troja et al. (2017); Watson et al. (2019)*

4. Constraints on Dense Matter and the Neutron Star Equation of State

4.1 Tidal Deformability and Gravitational-wave Constraints

The equation of state of matter beyond nuclear saturation density remains one of the deeper open problems in nuclear astrophysics, simply because no terrestrial laboratory can reproduce conditions of comparable density and neutron richness. During the late inspiral of a binary neutron star coalescence, each star's tidal field deforms its companion, accelerating the gravitational-wave phase evolution in a way that depends sensitively on stellar compactness. The first analysis of GW170817 placed a meaningful constraint on this combined tidal deformability, and a subsequent, refined analysis translated that constraint into bounds on the radii of the two stars, disfavouring equations of state that predict either unusually large or unusually small neutron star radii at a fiducial mass of 1.4 solar masses (Abbott et al., 2018). A broadly independent, numerical-relativity-informed analysis reached compatible conclusions by combining the gravitational-wave tidal measurement with electromagnetic constraints on the properties of the merger remnant (Radice et al., 2018).

4.2 Electromagnetic and Remnant-based Constraints

A second, quite different line of evidence exploits the fact that the type of remnant produced immediately after merger—whether a promptly collapsing black hole, a long-lived supramassive neutron star, or something in between—depends sensitively on the maximum mass a non-rotating neutron star can support, and that each outcome leaves a distinguishable electromagnetic signature behind. Combining the gravitational-wave-inferred total binary mass of GW170817 with electromagnetic limits on the energy that a long-lived, rapidly spinning remnant could plausibly have injected into either the kilonova ejecta or the gamma-ray burst jet placed an upper bound on the maximum non-rotating neutron star mass of approximately 2.17 solar masses (Margalit & Metzger, 2017). This bound, derived without any gravitational-wave information about tidal deformability at all, has gone on to play an influential role in narrowing the space of viable equations of state, since it rules out models that gravitational-wave data alone would otherwise still permit.

4.3 NICER Pulsar Measurements and Combined Multi-messenger Frameworks

A largely independent strand of evidence comes from X-ray pulse-profile modelling of isolated, rotation-powered millisecond pulsars, observed by the Neutron Star Interior Composition Explorer aboard the International Space Station. Two independently developed modelling pipelines, applied to the same pulsar, PSR J0030+0451, arrived at broadly consistent radii of around twelve to thirteen kilometres at a mass close to 1.4 solar masses (Miller et al., 2019; Riley et al., 2019), thereby providing an entirely electromagnetic, gravitational-wave-independent measurement of the same physical quantity. That these two methodologically unrelated approaches, one tracing a tidal effect during inspiral, the other modelling a hot spot's pulse profile, converged on similar radii was an important cross-validation in its own right. Building on both strands, a unified statistical framework that combined the gravitational-wave observations of GW170817 and GW190425, pulsar mass and radius measurements, and nuclear-theory calculations from chiral effective field theory produced a joint estimate of the radius of a 1.4-solar-mass neutron star alongside an improved, gravitational-wave-based estimate of the Hubble constant, a neat demonstration that sharpening the equation-of-state constraint and sharpening the cosmological constraint are not separate exercises so much as two outputs of the same underlying inference (Dietrich et al., 2020).

4.4 Insights from Heavy-ion Collision Experiments

A still more unexpected source of constraint comes from terrestrial heavy-ion collision experiments, in which colliding heavy nuclei at relativistic energies briefly produce matter at densities and temperatures that, while not identical to the cold, highly neutron-rich matter inside a neutron star, nonetheless probe overlapping regions of the nuclear equation of state. Bayesian inference combining astrophysical multi-messenger observations of neutron stars with data from relativistic gold-on-gold collisions found that adding the heavy-ion data systematically increased the inferred pressure of dense matter relative to astrophysics-only analyses, nudging preferred neutron star radii towards somewhat larger values and bringing nuclear and astrophysical evidence into closer quantitative agreement (Huth et al., 2022). This convergence between laboratory nuclear physics and astrophysical observation says something about how the field has changed: equation-of-state research is no longer the preserve of astrophysicists alone. Table 3 draws together the equation-of-state constraints discussed across this section. Read as a set, what the table illustrates is less a single decisive measurement than a steady narrowing from several independent directions at once—gravitational-wave, electromagnetic, pulsar, and nuclear—towards a broadly consistent picture of neutron star radii near 1.4 solar masses.

Table 3. Summary of multi-messenger constraints on the neutron-star equation of state

Method	Data exploited	Headline result
Gravitational-wave tidal deformability	GW170817 inspiral signal	Constrained combined tidal deformability and neutron star radii at 1.4 M⊙
Electromagnetic remnant inference	Kilonova ejecta energetics; gamma-ray-burst energetics; GW170817 total mass	Upper bound on the non-rotating maximum neutron star mass of approximately 2.17 M⊙
Numerical-relativity joint constraint	GW tidal measurement combined with merger-remnant electromagnetic signatures	Joint equation-of-state constraint consistent with gravitational-wave-only analyses
NICER X-ray pulse-profile modelling	Isolated millisecond pulsar PSR J0030+0451	Independent radius measurement near 12–13 km at ~1.4 M⊙, consistent with GW170817
Combined multi-messenger framework	GW170817, GW190425, pulsar data, nuclear theory	Joint radius and Hubble constant estimate from a unified statistical model
Heavy-ion collision synthesis	Relativistic gold-nucleus collisions plus astrophysical data	Increased preferred pressure of dense matter; larger inferred radii than astrophysics alone

Sources: Abbott et al. (2018); Dietrich et al. (2020); Huth et al. (2022); Margalit and Metzger (2017); Miller et al. (2019); Radice et al. (2018); Riley et al. (2019)

5. Multi-Messenger Cosmology: The Hubble Constant from Standard Sirens

One of the less anticipated scientific dividends of GW170817 was its use as a gravitational-wave "standard siren." Because the amplitude of a gravitational-wave signal from a compact binary directly encodes the luminosity distance to its source, without recourse to any conventional astronomical distance ladder, combining that gravitational-wave distance with the recession velocity of the host galaxy, NGC 4993, inferred from its redshift, yielded an entirely independent measurement of the Hubble constant, centred close to seventy kilometres per second per megaparsec (Abbott et al., 2017c). The uncertainty on that first measurement was substantial, mainly because the gravitational-wave signal alone leaves a partial degeneracy between source distance and orbital inclination. That degeneracy was subsequently broken using the very-long-baseline radio observations that had already revealed the relativistic jet: by directly measuring the apparent superluminal motion of the jet, the system's viewing angle could be pinned down independently of the gravitational-wave data, sharpening the standard-siren Hubble constant measurement considerably (Hotokezaka et al., 2019). The resulting value remains statistically compatible with both of the two leading methods used to measure the Hubble constant elsewhere, the cosmic distance ladder calibrated through Cepheid variables and Type Ia supernovae, and the early-Universe inference drawn from the cosmic microwave background, though without yet reaching the precision needed to adjudicate between them.

The later, unified multi-messenger framework combining GW170817 and GW190425 with electromagnetic and nuclear-theory data delivered a further refinement of this standard-siren Hubble constant, underlining a point made already in Section 4.3: improvements to the equation-of-state constraint and improvements to the cosmological constraint are not independent undertakings, but two faces of the same underlying statistical model (Dietrich et al., 2020). The wider promise of standard-siren cosmology, that a sample of several dozen well-localised binary neutron star mergers with electromagnetic counterparts could in principle resolve the present tension between local and early-Universe Hubble constant measurements at the per cent level, remains for now a promise rather than an achievement, since no event since GW170817 has supplied an electromagnetic counterpart anywhere near as well characterised. That limitation, returned to in Section 8, is one of the central motivations behind the push for a next-generation detector network.

6. The Expanding Population: GW190425, GW190814, GW230529 and Merger Demographics

In the years since GW170817, the population of gravitational-wave detections involving compact objects of neutron-star-like mass has continued to grow, even as the electromagnetic-counterpart record has stayed sparse. GW190425, detected during the third observing run, involved a binary with a total mass of around 3.4 solar masses, considerably higher than any previously known Galactic double neutron star system, raising the possibility of either an unusual formation channel or, less probably, the presence of a low-mass black hole within the system (Abbott et al., 2020a). No confident electromagnetic counterpart was found, largely because the sky localisation achieved with only a single sensitive detector operating at the time was too poor to support a focused search.

GW190814 raised a different but equally instructive puzzle: a coalescence between a black hole of roughly twenty-three solar masses and a much lighter compact object of about 2.6 solar masses, a mass that places the secondary squarely inside the long-debated "mass gap" between the heaviest known neutron stars and the lightest known black holes (Abbott et al., 2020b). Whether this secondary object was an unusually massive neutron star or an unusually light black hole could not be settled from the gravitational-wave data alone, and the absence of any electromagnetic counterpart, combined with the system's highly asymmetric mass ratio, left the question open. A more recent detection, GW230529, observed during the fourth observing run, went a step further, providing the first unambiguous gravitational-wave evidence for a compact object whose mass falls within this same lower mass gap, this time paired with a lighter companion consistent with a neutron star (Abac et al., 2024). The implied merger rate for systems of this kind suggests that the lower mass gap may be considerably less empty than the electromagnetic record of Galactic compact-object binaries had previously implied, with direct consequences for models of supernova explosion mechanisms and compact remnant formation.

Taken alongside the broader catalogue of events compiled across the first three observing runs, summarised in the population-inference analysis of the third gravitational-wave transient catalogue, the picture that emerges is of a more heterogeneous mass distribution among neutron-star-mass mergers than the Galactic pulsar population alone would have suggested, and of genuinely informative electromagnetic counterparts remaining very much the exception rather than the rule (Abbott et al., 2023). Table 4 sets out the principal events discussed above; what it makes plain at a glance is that GW170817 still stands alone as the only entry with a confirmed counterpart, even as the catalogue of neutron-star-involving detections around it continues to fill in.

Table 4. Confirmed gravitational-wave events discussed in this review involving a probable neutron star component

Event	Approximate component masses (solar masses)	Confirmed electromagnetic counterpart	Principal significance
GW170817	1.17–1.60 each (total ≈ 2.74)	Yes (GRB 170817A; AT2017gfo)	Founding multi-messenger detection; r-process, EOS, and standard-siren results
GW190425	Total ≈ 3.4	No	Anomalously high total mass relative to Galactic binary neutron stars
GW190814	23 (primary) and ≈2.6 (secondary)	No	Secondary occupies the lower mass gap; nature ambiguous
GW230529	2.5–4.5 (primary) and 1.2–2.0 (secondary)	No	First confident lower-mass-gap compact object paired with a probable neutron star

Sources: Abac et al. (2024); Abbott et al. (2017a, 2017b, 2020a, 2020b, 2023)

7. Beyond GW170817: Kilonovae Associated with Gamma-Ray Bursts and the Diversity of Outcomes

In the continued absence of a second gravitational-wave-confirmed kilonova, much of the recent progress in understanding how diverse merger outcomes can be has instead come from the electromagnetic side, through the identification of kilonova-like emission accompanying gamma-ray bursts found independently of any gravitational-wave trigger at all. An unusually nearby, long-duration gamma-ray burst was found to be accompanied by an infrared excess consistent with a kilonova, indicating that compact-object mergers can sometimes produce gamma-ray bursts of long rather than short duration, which complicates the simple duration-based classification that had previously been used to separate merger-driven bursts from those produced by collapsing massive stars (Troja et al., 2022). That interpretation was strengthened by detailed, late-time photometric and spectroscopic monitoring of a comparable event, which classified the resulting thermal transient explicitly as a lanthanide-rich kilonova and followed its evolution for some two months after the burst, finding a luminosity decline consistent with a recombining, lanthanide-dominated photosphere (Yang et al., 2024).

A particularly striking advance, however, came from infrared spectroscopy of an exceptionally bright long gamma-ray burst, obtained with the James Webb Space Telescope, which identified an emission feature attributable to tellurium, an element belonging to the second, heavier r-process peak, in a kilonova associated with the burst (Levan et al., 2024). It marked the first direct spectroscopic identification of an r-process element heavier than strontium in any kilonova, and demonstrated that gamma-ray-burst-selected events, found with no gravitational-wave trigger whatsoever, can still deliver nucleosynthesis information of a kind previously available only from GW170817 itself. Together, these results suggest that the population of mergers actually producing observable kilonovae is more varied, both in gamma-ray burst duration and in the inferred composition of the ejecta, than a single, intensively studied example could ever reveal on its own, and that wide-field, rapid-cadence electromagnetic surveys hunting for kilonovae independently of gravitational-wave triggers will remain scientifically valuable even as detector sensitivity continues to improve.

8. The Next-Generation Network: Einstein Telescope, Cosmic Explorer, and the Path Ahead

8.1 Limitations of the Current Detector Generation

The relative scarcity of richly observed multi-messenger events since 2017 reflects, in large part, the limitations of the current generation of gravitational-wave detectors. Advanced LIGO, Advanced Virgo, and the Japanese KAGRA detector, a cryogenically cooled instrument built underground at Kamioka and employing sapphire test masses (Akutsu et al., 2019), together form a global network capable of detecting binary neutron star mergers out to several hundred megaparsecs, but their sky localisation precision and detection horizon remain modest when set against the distances over which electromagnetic facilities would ideally like to search. Most binary neutron star detections in current observing runs are localised to sky regions spanning tens to hundreds of square degrees, far larger than the field of view of most optical telescopes, which makes the kind of rapid, targeted search that found AT2017gfo difficult to repeat for events that are either more distant or more poorly localised.

8.2 The Einstein Telescope and Cosmic Explorer

Two complementary third-generation projects are intended to address this shortfall. The Einstein Telescope, a proposed underground, triangular detector concept developed principally by European collaborations, is designed to deliver roughly an order-of-magnitude improvement in strain sensitivity over current instruments across a broad frequency band, extending the binary-neutron-star detection horizon from hundreds of megaparsecs out to redshifts of order unity or beyond, and correspondingly raising the expected detection rate by several orders of magnitude (Punturo et al., 2010). A more recent science case document spelled out the astrophysical, cosmological and fundamental-physics returns such an instrument could deliver, emphasising its capacity to sharpen equation-of-state constraints dramatically and to detect a population of binary neutron star mergers large enough to support precision standard-siren cosmology even without an electromagnetic counterpart for every single event (Maggiore et al., 2020). Cosmic Explorer, the leading United States concept, proposes a surface-based, L-shaped interferometer with an arm length of up to forty kilometres, ten times that of the existing LIGO facilities, and is similarly projected to observe binary neutron star and black hole mergers back to the era of the earliest star formation while delivering exquisite precision on the parameters of nearby events (Hall, 2022). Operating as part of a global network alongside the Einstein Telescope and an upgraded KAGRA, these next-generation facilities should dramatically sharpen sky localisation for the loudest nearby events, precisely the subset of detections for which electromagnetic follow-up stands the best chance of succeeding, simply by virtue of more detectors triangulating each signal and tighter timing and amplitude constraints becoming available across the network.

8.3 The Persistent Challenge of Coordinated Follow-up

It is worth stressing, though, that improved detector sensitivity alone does not guarantee a proportional rise in confirmed multi-messenger detections. The clearest lesson of the past decade is that even one superbly characterised event, GW170817, required an extraordinary, globally coordinated observing effort across dozens of facilities and collaborations to be properly exploited, and that every subsequent, more poorly localised event has largely defeated comparable efforts despite no shortage of scientific motivation. As the detection rate of binary neutron star mergers climbs by orders of magnitude with third-generation detectors, the bottleneck will increasingly shift away from gravitational-wave sensitivity itself and towards whether wide-field, rapid-cadence electromagnetic surveys, spectroscopic follow-up capacity, and inter-facility coordination exist on a scale sufficient to identify and characterise even a useful fraction of the resulting kilonovae, a logistical and organisational challenge arguably as demanding as the instrument physics behind it. Table 5 sets the current detector generation against the two leading third-generation concepts; the comparison is a reminder that the headline tenfold sensitivity gain, striking as it is, solves only the gravitational-wave half of the multi-messenger problem.

Table 5. Comparison of current and next-generation gravitational-wave observatories relevant to binary neutron star detection

Characteristic	Current generation (Advanced LIGO/Virgo/KAGRA)	Einstein Telescope (proposed)	Cosmic Explorer (proposed)
Configuration	Surface L-shaped interferometers (4 km, KAGRA 3 km); KAGRA underground, cryogenic	Underground, triangular configuration	Surface L-shaped interferometer(s), up to 40 km arms
Approximate sensitivity improvement	Baseline (current operational network)	Approximately tenfold strain improvement over current detectors	Approximately tenfold strain improvement over current detectors
Approximate binary neutron star horizon	Several hundred megaparsecs	Cosmological distances (redshift of order unity or greater)	Cosmological distances, reaching early star-formation epochs
Expected status	Operational	Conceptual/design study, site selection in progress	Conceptual/design study, site selection in progress
Principal multi-messenger benefit	Demonstrated with GW170817	Vastly increased detection rate; improved localisation	Vastly increased detection rate; improved localisation

Sources: Akutsu et al. (2019); Berthereau, et al. (2023); Hall (2022); Maggiore et al. (2020); Punturo et al. (2010)

9. Future Directions

Several concrete priorities follow from the synthesis above. Sustained investment in wide-field, high-cadence optical and infrared time-domain surveys, capable of searching gravitational-wave localisation regions of tens to hundreds of square degrees within hours of an alert, will remain essential even as third-generation detectors sharpen localisation, simply because the gap between sensitivity gains on paper and their eventual operational deployment will continue to be governed by what existing electromagnetic facilities can actually achieve in the meantime. Continued refinement of joint nuclear-physics and multi-messenger statistical frameworks, of the kind that already combine gravitational-wave tidal measurements, NICER pulse-profile modelling, and heavy-ion collision data within a single Bayesian scheme, is likely to remain the most efficient route towards a genuinely settled equation-of-state determination; the present convergence across these independent methods is itself an important interim result, and one that deserves continued cross-validation as each individual technique matures rather than being treated as a finished story. The growing recognition that kilonova-producing mergers can present as long-duration as well as short-duration gamma-ray bursts also argues for broadening survey strategies beyond the traditional short-burst trigger, including systematic infrared follow-up of long gamma-ray bursts that lack an obvious massive-star supernova signature. As the population of detections involving compact objects in the lower mass gap grows, dedicated theoretical work on supernova explosion mechanisms and binary stellar evolution will be needed to work out whether such objects are predominantly low-mass black holes, unusually massive neutron stars, or a genuinely mixed population straddling both categories. Finally, the coordination problem set out in Section 8.3, the mismatch between gravitational-wave detection rate and electromagnetic follow-up capacity, deserves attention from funding agencies and international collaborations as a planning problem in its own right, not as an afterthought to instrument design; without parallel investment in follow-up infrastructure, the scientific return on third-generation gravitational-wave detectors risks falling well short of their technical promise, however impressive that promise looks on paper.

10. Conclusions

The decade since GW170817 has turned binary neutron star mergers from a long-anticipated theoretical possibility into one of the most productive single classes of astrophysical event available to modern science. A single, exceptionally well-observed merger demonstrated conclusively that such mergers power short gamma-ray bursts, synthesise heavy r-process elements—including strontium and, more recently, tellurium—launch relativistic structured jets, and can serve as standard sirens for cosmology. At the same time, the wider population of gravitational-wave detections involving neutron-star-mass compact objects has revealed a more varied landscape than the founding event alone could show, including systems of unusually high total mass and objects sitting squarely within the long-debated lower mass gap between neutron stars and black holes. Equation-of-state constraints have been sharpened by the convergence of gravitational-wave tidal measurements, electromagnetic remnant inference, X-ray pulsar pulse-profile modelling, and terrestrial heavy-ion collision experiments, a genuinely interdisciplinary research programme that did not really exist in this form a decade ago. The coming decade is poised to bring a step change in detector sensitivity through the Einstein Telescope, Cosmic Explorer, and an upgraded global network, but whether that sensitivity actually translates into a richer multi-messenger harvest will depend as much on the coordination and capacity of electromagnetic follow-up infrastructure as on the underlying gravitational-wave technology itself.

11. Limitations

This review has several limitations worth bearing in mind. As a narrative rather than a systematic review, the selection of studies, although guided by an explicit and documented search strategy, inevitably involved subjective judgement about the relative significance of individual contributions; a different reviewer working from the same literature might reasonably have struck a different balance across topics. A more fundamental limitation is that much of the evidence discussed here rests, in the end, on a single observational event. Because no subsequent gravitational-wave detection has yielded a comparably complete electromagnetic counterpart to GW170817, conclusions about the typical properties of kilonovae, jet structure, or merger remnants should be read as provisional generalisations from an extremely small sample rather than as established population statistics. The treatment of detector technology and observing strategy in Section 8 reflects the state of public planning documentation at the time of writing and is necessarily provisional, since the design, funding status, and timeline of next-generation observatories such as the Einstein Telescope and Cosmic Explorer remain subject to change as site selection, funding decisions, and international coordination continue. Finally, restricting the reference list to peer-reviewed journal articles, while intended to keep the evidentiary base reliable, means that some recent findings circulating only as preprints at the time of writing could not be incorporated; the picture presented here should accordingly be understood as reflecting the published, peer-reviewed consensus up to the close of the literature search, rather than the very latest unreviewed developments in what remains a fast-moving field.

Declaration of AI Use

This manuscript was prepared through the combined contributions of all author(s), including contributions to the study design, data, content development, results, interpretation, and related scholarly work. The author(s) acknowledge the use of Grammarly and ChatGPT to assist with grammar checking, language refinement, and reference formatting. These AI-assisted tools were not used as authors and did not replace the intellectual contributions or scholarly judgment of the author(s). All AI-assisted outputs, including content, references, and interpretations, were carefully reviewed, revised, verified, and approved by the author(s). The author(s) accept full responsibility for the accuracy, integrity, and final content of the manuscript.

Competing Interests

Authors have declared that they have no known competing financial interests OR non-financial interests OR personal relationships that could have appeared to influence the work reported in this paper.

References

Abac, A. G., et al. (2024). Observation of gravitational waves from the coalescence of a 2.5–4.5 $M_\odot$ compact object and a neutron star. *The Astrophysical Journal Letters, 970*(2), L34. https://doi.org/10.3847/2041-8213/ad5beb

Abbott, B. P., et al. (2017a). GW170817: Observation of gravitational waves from a binary neutron star inspiral. *Physical Review Letters, 119*(16), 161101. https://doi.org/10.1103/PhysRevLett.119.161101

Abbott, B. P., et al. (2017b). Multi-messenger observations of a binary neutron star merger. *The Astrophysical Journal Letters, 848*(2), L12. https://doi.org/10.3847/2041-8213/aa91c9

Abbott, B. P., et al. (2017c). A gravitational-wave standard siren measurement of the Hubble constant. *Nature, 551*(7678), 85–88. https://doi.org/10.1038/nature24471

Abbott, B. P., et al. (2018). GW170817: Measurements of neutron star radii and equation of state. *Physical Review Letters, 121*(16), 161101. https://doi.org/10.1103/PhysRevLett.121.161101

Abbott, B. P., et al. (2020a). GW190425: Observation of a compact binary coalescence with total mass ∼3.4 M⊙. *The Astrophysical Journal Letters, 892*(1), L3. https://doi.org/10.3847/2041-8213/ab75f5

Abbott, R., et al. (2020b). GW190814: Gravitational waves from the coalescence of a 23 solar mass black hole with a 2.6 solar mass compact object. *The Astrophysical Journal Letters, 896*(2), L44. https://doi.org/10.3847/2041-8213/ab960f

Abbott, R., et al. (2023). Population of merging compact binaries inferred using gravitational waves through GWTC-3. *Physical Review X, 13*(1), 011048. https://doi.org/10.1103/PhysRevX.13.011048

Akutsu, T., et al. (2019). KAGRA: 2.5 generation interferometric gravitational wave detector. *Nature Astronomy, 3*(1), 35–40. https://doi.org/10.1038/s41550-018-0658-y

Berthereau, A., Guillemot, L., Freire, P. C. C., Kramer, M., Venkatraman Krishnan, V., Cognard, I., Theureau, G., Bailes, M., i Bernadich, M. C., & Lower, M. E. (2023). Radio timing constraints on the mass of the binary pulsar PSR J1528-3146. *Astronomy & Astrophysics, 674*, A71. https://doi.org/10.1051/0004-6361/202346228

Coulter, D. A., Foley, R. J., Kilpatrick, C. D., Drout, M. R., Piro, A. L., Shappee, B. J., Siebert, M. R., Simon, J. D., Ulloa, N., Kasen, D., Madore, B. F., Murguia-Berthier, A., Pan, Y.-C., Prochaska, J. X., Ramirez-Ruiz, E., Rest, A., & Rojas-Bravo, C. (2017). Swope Supernova Survey 2017a (SSS17a), the optical counterpart to a gravitational wave source. *Science, 358*(6370), 1556–1558. https://doi.org/10.1126/science.aap9811

de Sá, L. M., Bernardo, A., Bachega, R. R. A., Rocha, L. S., Moraes, P. H. R. S., & Horvath, J. E. (2023). An overview of compact star populations and some of its open problems. *Galaxies, 11*(1), 19. https://doi.org/10.3390/galaxies11010019

Dietrich, T., Coughlin, M. W., Pang, P. T. H., Bulla, M., Heinzel, J., Issa, L., Tews, I., & Antier, S. (2020). Multimessenger constraints on the neutron-star equation of state and the Hubble constant. *Science, 370*(6523), 1450–1453. https://doi.org/10.1126/science.abb4317

Drout, M. R., et al. (2017). Light curves of the neutron star merger GW170817/SSS17a: Implications for r-process nucleosynthesis. *Science, 358*(6370), 1570–1574. https://doi.org/10.1126/science.aaq0049

Eichler, D., Livio, M., Piran, T., & Schramm, D. N. (1989). Nucleosynthesis, neutrino bursts and gamma-rays from coalescing neutron stars. *Nature, 340*(6229), 126–128. https://doi.org/10.1038/340126a0

Fan, Y.-Z., Han, M.-Z., Jiang, J.-L., Shao, D.-S., & Tang, S.-P. (2024). Maximum gravitational mass M_TOV = 2.25^(+0.08)_(-0.07) M⊙ inferred at about 3% precision with multimessenger data of neutron stars. *Physical Review D, 109*(4), 043052. https://doi.org/10.1103/PhysRevD.109.043052

Ghirlanda, G., et al. (2019). Compact radio emission indicates a structured jet was produced by a binary neutron star merger. *Science, 363*(6430), 968–971. https://doi.org/10.1126/science.aau8815

Gorda, T., Komoltsev, O., & Kurkela, A. (2023). Ab-initio QCD calculations impact the inference of the neutron-star-matter equation of state. *The Astrophysical Journal, 950*(2), 107. https://doi.org/10.3847/1538-4357/acce3a

Grant, M. J., & Booth, A. (2009). A typology of reviews: An analysis of 14 review types and associated methodologies. *Health Information & Libraries Journal, 26*(2), 91–108. https://doi.org/10.1111/j.1471-1842.2009.00848.x

Hall, E. D. (2022). Cosmic Explorer: A next-generation ground-based gravitational-wave observatory. *Galaxies, 10*(4), 90. https://doi.org/10.3390/galaxies10040090

Hallinan, G., et al. (2017). A radio counterpart to a neutron star merger. *Science, 358*(6370), 1579–1583. https://doi.org/10.1126/science.aap9855

Han, M.-Z., Huang, Y.-J., Tang, S.-P., & Fan, Y.-Z. (2023). Plausible presence of new state in neutron stars with masses above 0.98 M_TOV. *Science Bulletin, 68*(9), 913–919. https://doi.org/10.1016/j.scib.2023.04.007

Hotokezaka, K., Nakar, E., Gottlieb, O., Nissanke, S., Masuda, K., Hallinan, G., Mooley, K. P., & Deller, A. T. (2019). A Hubble constant measurement from superluminal motion of the jet in GW170817. *Nature Astronomy, 3*, 940–944. https://doi.org/10.1038/s41550-019-0820-1

Huth, S., Pang, P. T. H., Tews, I., Dietrich, T., Le Fèvre, A., Schwenk, A., Trautmann, W., Agarwal, K., Bulla, M., Coughlin, M. W., & Van Den Broeck, C. (2022). Constraining neutron-star matter with microscopic and macroscopic collisions. *Nature, 606*(7913), 276–280. https://doi.org/10.1038/s41586-022-04750-w

Kasen, D., Metzger, B., Barnes, J., Quataert, E., & Ramirez-Ruiz, E. (2017). Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event. *Nature, 551*(7678), 80–84. https://doi.org/10.1038/nature24453

Konstantinou, A., & Morsink, S. M. (2022). Universal relations for the increase in the mass and radius of a rotating neutron star. *The Astrophysical Journal, 934*(2), 139. https://doi.org/10.3847/1538-4357/ac7b86

Levan, A. J., et al. (2024). Heavy-element production in a compact object merger observed by JWST. *Nature, 626*(8000), 737–741. https://doi.org/10.1038/s41586-023-06759-1

Maggiore, M., Van Den Broeck, C., Bartolo, N., Belgacem, E., Bertacca, D., Bizouard, M. A., Branchesi, M., Clesse, S., Foffa, S., García-Bellido, J., Grimm, S., Harms, J., Hinderer, T., Matarrese, S., Palomba, C., Peloso, M., Ricciardone, A., & Sakellariadou, M. (2020). Science case for the Einstein Telescope. *Journal of Cosmology and Astroparticle Physics, 2020*(3), 050. https://doi.org/10.1088/1475-7516/2020/03/050

Margalit, B., & Metzger, B. D. (2017). Constraining the maximum mass of neutron stars from multi-messenger observations of GW170817. *The Astrophysical Journal Letters, 850*(2), L19. https://doi.org/10.3847/2041-8213/aa991c

Margutti, R., & Chornock, R. (2021). First multimessenger observations of a neutron star merger. *Annual Review of Astronomy and Astrophysics, 59*, 155–202. https://doi.org/10.1146/annurev-astro-112420-030742

Metzger, B. D. (2020). Kilonovae. *Living Reviews in Relativity, 23*(1), 1. https://doi.org/10.1007/s41114-019-0024-0

Miller, M. C., et al. (2019). PSR J0030+0451 mass and radius from NICER data and implications for the properties of neutron star matter. *The Astrophysical Journal Letters, 887*(1), L24. https://doi.org/10.3847/2041-8213/ab50c5

Mooley, K. P., Deller, A. T., Gottlieb, O., Nakar, E., Hallinan, G., Bourke, S., Frail, D. A., Horesh, A., Corsi, A., & Hotokezaka, K. (2018). Superluminal motion of a relativistic jet in the neutron-star merger GW170817. *Nature, 561*(7723), 355–359. https://doi.org/10.1038/s41586-018-0486-3

Pian, E., et al. (2017). Spectroscopic identification of r-process nucleosynthesis in a double neutron-star merger. *Nature, 551*(7678), 67–70. https://doi.org/10.1038/nature24298

Punturo, M., et al. (2010). The Einstein Telescope: A third-generation gravitational wave observatory. *Classical and Quantum Gravity, 27*(19), 194002. https://doi.org/10.1088/0264-9381/27/19/194002

Radice, D., Perego, A., Zappa, F., & Bernuzzi, S. (2018). GW170817: Joint constraint on the neutron star equation of state from multimessenger observations. *The Astrophysical Journal Letters, 852*(2), L29. https://doi.org/10.3847/2041-8213/aaa402

Riley, T. E., et al. (2019). A NICER view of PSR J0030+0451: Millisecond pulsar parameter estimation. *The Astrophysical Journal Letters, 887*(1), L21. https://doi.org/10.3847/2041-8213/ab481c

Smartt, S. J., et al. (2017). A kilonova as the electromagnetic counterpart to a gravitational-wave source. *Nature, 551*(7678), 75–79. https://doi.org/10.1038/nature24303

Troja, E., et al. (2017). The X-ray counterpart to the gravitational-wave event GW170817. *Nature, 551*(7678), 71–74. https://doi.org/10.1038/nature24290

Troja, E., et al. (2022). A nearby long gamma-ray burst from a merger of compact objects. *Nature, 612*(7939), 228–231. https://doi.org/10.1038/s41586-022-05327-3

Watson, D., Hansen, C. J., Selsing, J., Koch, A., Malesani, D. B., Andersen, A. C., Fynbo, J. P. U., Arcones, A., Bauswein, A., Covino, S., Grado, A., Heintz, K. E., Hunt, L., Kouveliotou, C., Leloudas, G., Levan, A. J., Mazzali, P., & Pian, E. (2019). Identification of strontium in the merger of two neutron stars. *Nature, 574*(7779), 497–500. https://doi.org/10.1038/s41586-019-1676-3

Yang, Y.-H., et al. (2024). A lanthanide-rich kilonova in the aftermath of a long gamma-ray burst. *Nature, 626*(8000), 742–745. https://doi.org/10.1038/s41586-023-06979-5

Peer-review history:
The peer review history for this paper can be accessed here:
https://pr.sdiarticle5.com/review-history/164243