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REVIEW ARTICLE

Rates of compact object coalescences

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Abstract
Gravitational-wave detections are enabling measurements of the rate of coalescences of binaries composed of two compact objects—neutron stars and/or black holes. The coalescence rate of binaries containing neutron stars is further constrained by electromagnetic observations, including Galactic radio binary pulsars and short gamma-ray bursts. Meanwhile, increasingly sophisticated models of compact objects merging through a variety of evolutionary channels produce a range of theoretically predicted rates. Rapid improvements in instrument sensitivity, along with plans for new and improved surveys, make this an opportune time to summarise the existing observational and theoretical knowledge of compact-binary coalescence rates.

Keywords Black holes · Neutron stars · Stellar binaries · Gravitational waves

Contents

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1 Introduction

It has been more than a decade since Abadie (2010) reviewed the literature on compact-object merger rate predictions. At that time, a handful of ultimately merging double neutron star (NS) systems in the Milky Way Galaxy were known from radio pulsar observations, starting with the discovery of Hulse and Taylor (1975). It was believed that short gamma-ray bursts (SGRBs) were associated with mergers of two NSs. But no actual compact object mergers were definitively observed. Therefore, most of the rate predictions, particularly for mergers involving black holes (BHs), were based purely on theoretical models (see, e.g., Mandel and O'Shaughnessy 2010 for a review of the status of models at that time).

The intervening decade has completely changed this landscape. On 14 September, 2015, the advanced Laser Interferometer Gravitational-wave Observatory (LIGO, Aasi et al. 2015) detected the first chirp of gravitational waves from a binary BH merger, GW150914 (Abbott et al. 2016b). Since then, nine more binary BH coalescences were observed during the first and second observing runs of advanced LIGO and Virgo detectors (Abbott et al. 2019b). The data release from the third observing run brought the total number of confidently detected binary BH coalescences to approximately 70 (Abbott et al. 2021d). The first detection of a binary neutron star merger, GW170817 (Abbott et al. 2017b), was accompanied by a short GRB (Abbott et al. 2017a) and a kilonova (Abbott et al. 2017c), firmly establishing the connection between these phenomena. A second confident binary neutron star detection, GW190425 (Abbott et al. 2020a), followed, along with detections of two NS–BH mergers, GW200105 and GW200115 (Abbott et al. 2021a).

At the same time, significant progress has been made in the theoretical modelling of the sources of compact binary coalescences. This has included more detailed exploration of the classical channel of isolated binary evolution, typically through the common-envelope phase (van den Heuvel 1976; Smarr and Blandford 1976; Tutukov and Yungelson 1993) (or possibly through stable mass transfer alone, van den Heuvel et al. 2017; Inayoshi et al. 2017), along with significant new developments in the investigation of alternative channels, including dynamical interaction in dense stellar environments (Sigurdsson and Hernquist 1993; Kulkarni et al. 1993; Portegies Zwart and McMillan 2000); mergers in binaries of rapidly rotating stars undergoing chemically homogeneous evolution (Mandel and de Mink 2016; Marchant et al. 2016); mergers facilitated by the Lidov–Kozai resonance (Lidov 1962; Kozai 1962) in hierarchical triple systems; and even mergers of primordial black holes of cosmological rather than astrophysical origin (Bird et al. 2016; Ali-Haïmoud et al. 2017).

The coupled advances in observations and theory are making it possible to quantitatively compare rate predictions against observations for the first time (e.g., Abbott et al. 2019a, 2021e; Belczynski et al. 2018a; Wysocki et al. 2018; Neijssel et al. 2019; Belczynski et al. 2020; Farmer et al. 2020; Bavera et al. 2021). Beyond this, they provide critical input into understanding the chemical enrichment of the Universe, particularly with elements created through r-process nucleosynthesis likely associated with mergers involving NSs with their neutron-rich material (Kasen et al. 2017; Côté et al. 2018; Metzger 2019; Kobayashi et al. 2020). The merger rates determine prospects for future Earth-based and space-borne gravitational-wave detectors, and will impact detector design (Amaro-Seoane et al. 2017; Adhikari et al. 2019; Reitze et al. 2019). Merger rates feed into constraints or predictions on other observables, ranging from kilonovae associated with binary NS mergers (e.g., Kasliwal et al. 2020; Mochkovitch et al. 2021) to gravitational-wave stochastic backgrounds (Abbott et al. 2016a) to, possibly, fast radio bursts (e.g., Zhang 2020). This, then, is an opportune time for a review of the current state of the observations and predictions of compact object merger rates—and, given the expectation of continuing rapid development in this field, it particularly calls for a Living Review.

This review is organised as follows. We provide an executive summary of the observed and theoretically predicted compact-binary merger rates in Sect. 2. We then provide more detailed information and discussion of the observations in Sect. 3 and of the models in Sect. 4 before concluding in Sect. 5. The collated data and code to reproduce all tables and figures in this review are publicly available through Broekgaarden and Mandel (2021),[1] where we also provide supplementary information on how we obtained the data in the tables and figures.

2 Executive summary

We summarise the coalescence rates in tables and figures below: NS–NS binaries in Table 1 and Fig. 1, NS–BH binaries (where we do not distinguish whether the BH or NS formed first) in Table 2 and Fig. 2, and BH–BH binaries in Tables 3 and 4 and Fig. 3.

Coalescence rates are, in general, functions of redshift; we quote current local rates at redshift $z = 0$ per unit source time per unit comoving volume in units of $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, but caution that these could be an order of magnitude larger at higher redshifts. Where initially stated in different units, we convert these, using, as appropriate, factors of 1.7×10^{10} solar blue-light luminosities per Milky Way equivalent galaxy (MWEG), 1.17×10^{-2} MWEG per Mpc^3 (Kopparapu et al. 2008), a globular cluster space density of 2.9 per Mpc^3 at $z = 0$ (Portegies Zwart

[1] The current paper is based on version 5 of the Zenodo data; supplementary material is available on Github.

Table 1 Summary of local NS–NS coalescence rates (GitHub and Zenodo)

Source	Rate [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]	References
Observations:		
Gravitational-wave observations, PDB (ind)	250^{+640}_{-200}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, MS	470^{+1400}_{-410}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, BGP	99^{+260}_{-86}	GWTC-3; Abbott et al. (2021e)
Short GRBs	[5, 1800]	Coward et al. (2012)
Short GRBs	[500, 1500]	Petrillo et al. (2013)
Short GRBs	270^{+1580}_{-180}	Fong et al. (2015)
Short GRBs, based on GW170817	352^{+810}_{-281}	Della Valle et al. (2018)
Short GRBs	1109^{+1432}_{-657}	Jin et al. (2018)
Short GRBs, based on GW170817	190^{+440}_{-160}	Zhang et al. (2018)
Short GRB, based on GW170817, SWIFT	160^{+200}_{-100}	Dichiara et al. (2020)
Kilonovae lower limit	> 8.1	Jin et al. (2016)
Kilonovae, DES, upper limit	< 24000	Doctor et al. (2017)
Kilonovae, PTF, upper limit	< 800	Kasliwal et al. (2017)
Kilonovae, ATLAS, upper limit	< 30000	Smartt et al. (2017)
Kilonovae, DLT40, upper limit	< 99000	Yang et al. (2017)
Kilonovae, ZTF, upper limit	< 900	Andreoni et al. (2021)
Galactic pulsar binaries	$\approx 830^{+2110}_{-680}$	O'Shaughnessy and Kim (2010)
Galactic pulsar binaries	250^{+330}_{-160}	Kim et al. (2015)
Galactic pulsar binaries	450^{+290}_{-140}	Pol et al. (2020)
Galactic pulsar binaries	370^{+230}_{-100}	Grunthal et al. (2021)
Models:		
Isolated binary population synthesis, StarTrack	[30, 1700]	O'Shaughnessy et al. (2010)
Isolated binary population synthesis, Scenario Machine	[1050, 3860]	Lipunov and Pruzhinskaya (2014)
Isolated binary population synthesis, Brussels code	$[\leq 1.3, 1800]$	Mennekens and Vanbeveren (2014)
Isolated binary population synthesis, StarTrack	[30, 540]	de Mink and Belczynski (2015)
Isolated binary population synthesis, StarTrack	[52, 162]	Dominik et al. (2015)
Isolated binary population synthesis, BSE	[240, 1800]	Ablimit and Maeda (2018)
Isolated binary population synthesis, StarTrack	[8, 50]	Belczynski et al. (2018a)
Isolated binary population synthesis, StarTrack	[1.5, 631]	Chruslinska et al. (2018)
Isolated binary population synthesis, MOBSE	[10, 510]	Giacobbo and Mapelli (2018)
Isolated binary population synthesis, StarTrack	[24, 68]	Klencki et al. (2018)
Isolated binary population synthesis, COMBINE	[2.7, 159]	Kruckow et al. (2018)
Isolated binary population synthesis, MOBSE	[19, 591]	Mapelli and Giacobbo (2018)
Isolated binary population synthesis, COMPAS	[61.5, 362]	Vigna-Gómez et al. (2018)
Isolated binary population synthesis, MOBSE	238	Artale et al. (2019)
Isolated binary population synthesis, MOBSE	[12, 400]	Baibhav et al. (2019)
Isolated binary population synthesis, SEVN	70	Boco et al. (2019)
Isolated binary population synthesis, StarTrack	[48, 885]	Chruslinska et al. (2019)
Isolated binary population synthesis, BPASS	[339, 2178]	Eldridge et al. (2019)
Isolated binary population synthesis, COMPAS	[20, 245]	Neijssel et al. (2019)

Table 1 continued

Source	Rate [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]	References
Isolated binary population synthesis, StarTrack	[49.3, 524]	Belczynski et al. (2020)
Isolated binary population synthesis, MOBSE	[20, 640]	Giacobbo and Mapelli (2020)
Isolated binary population synthesis, MOBSE	283^{+97}_{-75}	Santoliquido et al. (2020)
Isolated binary population synthesis, BPASS	[394, 3190]	Tang et al. (2020)
Isolated binary population synthesis, COSMIC	[600, 8900]	Zevin et al. (2020)
Isolated binary population synthesis, COMPAS	[0.32, 330]	Broekgaarden et al. (2021a, b)
Isolated binary population synthesis, BSE,	[0.4, 1404]	Chu et al. (2021)
Isolated binary population synthesis, BPASS	[43, 745]	Ghodla et al. (2021)
Isolated binary population synthesis, StarTrack	[148, 322]	Olejak et al. (2021)
Isolated binary population synthesis, MOBSE	[4.3, 1036.8]	Santoliquido et al. (2021)
Hierarchical triples, SecularMultiple	[164, 3793]	Hamers and Thompson (2019)
Hierarchical quadruples, MSE	[0.8, 30.2]	Vynatheya and Hamers (2021)
Globular cluster dynamics	30	Lee et al. (2010)
Globular cluster dynamics	[0.32, 3.2]	Bae et al. (2014)
Globular cluster dynamics	121	Samsing et al. (2014)
Globular cluster dynamics, MOCCA	[0.02, 0.5]	Belczynski et al. (2018a)
Globular cluster dynamics, CMC	$[0.009, \lesssim 25.5]$	Ye et al. (2020)
Nuclear star cluster dynamics with SMBH	[0.004, 1.4]	Antonini and Perets (2012)
Nuclear star cluster dynamics, with SMBH	$\lesssim 0.02$	Petrovich and Antonini (2017)
Nuclear star cluster dynamics	[0.007, 0.1]	Belczynski et al. (2018a)
Nuclear star cluster dynamics, with SMBH	$\lesssim 400$	McKernan et al. (2020)
Nuclear star cluster dynamics, with SMBH	$\gtrsim [0.15, 0.3]$	Wang et al. (2021)
Young star clusters	[0.03, 0.15]	Ziosi et al. (2014)
Young/Open star clusters, Nbody7	$[0.01-0.1]$	Fragione and Banerjee (2020)
Young star clusters, MOBSE	151^{+59}_{-38}	Santoliquido et al. (2020)

and McMillan 2000) and a local supernova rate of $1.06 \times 10^5\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ (Taylor et al. 2014). Of course, such simple re-scalings do not account for the dependence of merger rates on the star formation history and metallicity (de Freitas Pacheco et al. 2006; Belczynski et al. 2010; Dvorkin et al. 2016; Neijssel et al. 2019; Chruslinska and Nelemans 2019; Mapelli 2021).

In general, we follow original papers in stating the rates; a discussion follows in the next two sections. Where uncertainties are stated, we try to indicate them with $\pm$ subscripts and superscripts; however, these are not always available, and may not be attributable to a specific confidence interval when available. Sometimes, we state a range in square brackets without a central value.

The vast literature on compact-object merger rate predictions dating back to at least 1979 (Clark et al. 1979) makes a complete historical review implausible. Therefore, we focus on the latest contributions from each group, except where contributions use significantly different methodology or examine the impact of

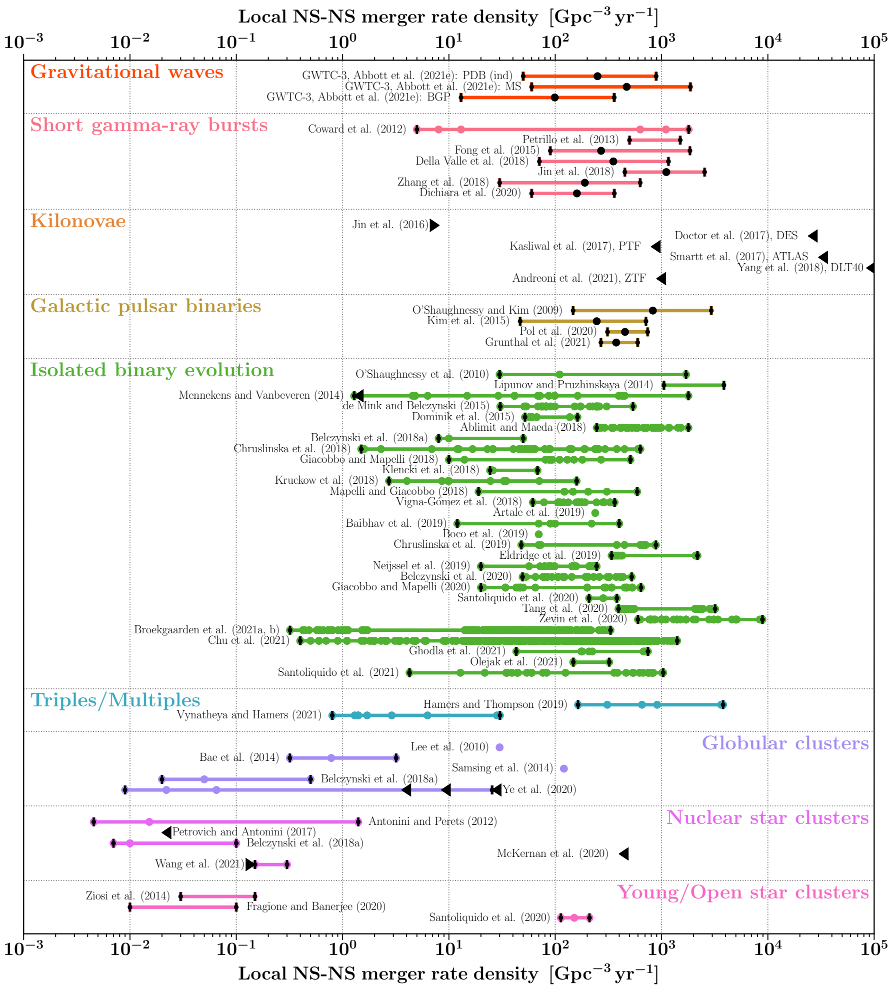

Fig. 1 NS–NS merger rates from Table 1. Black lines denote the interval boundaries. Triangles mark upper and lower limits. Colored circles mark inferred or simulated values, where multiple values are given in a study. Black circles mark the median or mean of a confidence interval, where one is provided. (Standalone PDF image in this article's Supplementary Material. Source code: GitHub)

different assumptions. We generally eschew papers published before 2010 as these have typically been superseded by observational and theoretical advances.

We combine rates into several broad categories for ease of viewing, but multiple different channels with a broad range of physics may be at play within any one category. For example, the category of "nuclear star clusters" may include dynamical captures in nuclear clusters without a massive black hole, mergers in hierarchical triples involving a massive black hole, or mergers aided by an accretion disk in an active galactic nucleus. We do not include some very rare channels with predicted rates below the range shown in the figures.

Table 2 Summary of local NS–BH coalescence rates (GitHub and Zenodo)

Source	Rate [$Gpc^{-3}\,yr^{-1}$]	References
Observations:		
Gravitational-wave observations, PDB (ind)	170^{+150}_{-89}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, MS	57^{+120}_{-42}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, BGP	32^{+62}_{-25}	GWTC-3; Abbott et al. (2021e)
Galactic pulsar binaries	$\lesssim 1800$	Pol et al. (2021)
Models:		
Isolated binary population synthesis, StarTrack	[10, 280]	O'Shaughnessy et al. (2010)
Isolated binary population synthesis, Brussels code	[0.06, 800]	Mennekens and Vanbeveren (2014)
Isolated binary population synthesis, StarTrack	[9, 115]	de Mink and Belczynski (2015)
Isolated binary population synthesis, StarTrack	[0.04, 20]	Dominik et al. (2015)
Isolated binary population synthesis, BSE	[1, 160]	Ablimit and Maeda (2018)
Isolated binary population synthesis, MOBSE	[5, 780]	Giacobbo and Mapelli (2018)
Isolated binary population synthesis, StarTrack	[13.3, 26.7]	Klencki et al. (2018)
Isolated binary population synthesis, COMBINE	[2, 53]	Kruckow et al. (2018)
Isolated binary population synthesis, MOBSE	[9, 115]	Mapelli and Giacobbo (2018)
Isolated binary population synthesis, MOBSE	78	Artale et al. (2019)
Isolated binary population synthesis, MOBSE	[4, 37]	Baibhav et al. (2019)
Isolated binary population synthesis, SEVN	20	Boco et al. (2019)
Isolated binary population synthesis, StarTrack	[5, 230]	Chruslinska et al. (2019)
Isolated binary population synthesis, BPASS	[209, 269]	Eldridge et al. (2019)
Isolated binary population synthesis, COMPAS	[19, 204]	Neijssel et al. (2019)
Isolated binary population synthesis, StarTrack	[0.48, 297]	Belczynski et al. (2020)
Isolated binary population synthesis, MOBSE	[6, 80]	Giacobbo and Mapelli (2020)
Isolated binary population synthesis, MOBSE	49^{+48}_{-34}	Santoliquido et al. (2020)
Isolated binary population synthesis, BPASS	[58, 6225]	Tang et al. (2020)
Isolated binary population synthesis, COSMIC	[3.7, 1100]	Zevin et al. (2020)
Isolated binary population synthesis, COMPAS	[2.2, 830]	Broekgaarden et al. (2021a, b)
Isolated binary population synthesis, BPASS	[8.7, 498]	Ghodla et al. (2021)
Isolated binary population synthesis, StarTrack	[4, 16]	Olejak et al. (2021)
Isolated binary population synthesis, POSYDON	[5.7, 77]	Román-Garza et al. (2021)
Isolated binary population synthesis, MOBSE	[1.8, 128]	Santoliquido et al. (2021)
Isolated binary population synthesis, BSE	[10, 72]	Shao and Li (2021)
Chemically homogeneous evolution, MESA	[0.02, 0.2]	Marchant et al. (2017)
Population III stars	[0.0002, 0.016]	Belczynski et al. (2017)
Hierarchical triples	$[1.9 \times 10^{-4}, 22]$	Fragione and Loeb (2019a, 2019b)
Hierarchical triples, SecularMultiple	[345, 680]	Hamers and Thompson (2019)
Hierarchical triples in young star clusters, OKINAMI,	[0.04, 0.34]	Trani et al. (2021)
Hierarchical quadruples, MSE	[5.7, 57.1]	Vynatheya and Hamers (2021)
Globular cluster dynamics	[0.01, 0.12]	Clausen et al. (2013)
Globular cluster dynamics, ARCHAIN	$\lesssim 0.1$	Arca Sedda (2020b)
Globular cluster dynamics, CMC	$[0.009, \lesssim 5.5]$	Ye et al. (2020)

Table 2 continued

Source	Rate [$\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$]	References
Nuclear star cluster dynamics, with SMBH	[0.02, 0.4]	Petrovich and Antonini (2017)
Nuclear star cluster dynamics, with SMBH	$\gtrsim[2, 5]$	Stephan et al. (2019)
Nuclear star cluster dynamics,	$\lesssim 0.01$	Arca Sedda (2020b)
Nuclear star cluster dynamics, with SMBH	$\lesssim 300$	McKernan et al. (2020)
Nuclear star cluster dynamics, with SMBH	$\gtrsim[0.15, 0.3]$	Wang et al. (2021)
Young star clusters, starlab	$\lesssim 0.1$	Ziosi et al. (2014)
Young/Open star clusters, Nbody7	$\lesssim 3\times 10^{-3}$	Fragione and Banerjee (2020)
Young star clusters, MOBSE	$\lesssim 28$	Rastello et al. (2020)
Young star clusters, MOBSE	41^{+33}_{-23}	Santoliquido et al. (2020)
Young star clusters,	[0.04, 36.6]	Arca Sedda (2021)

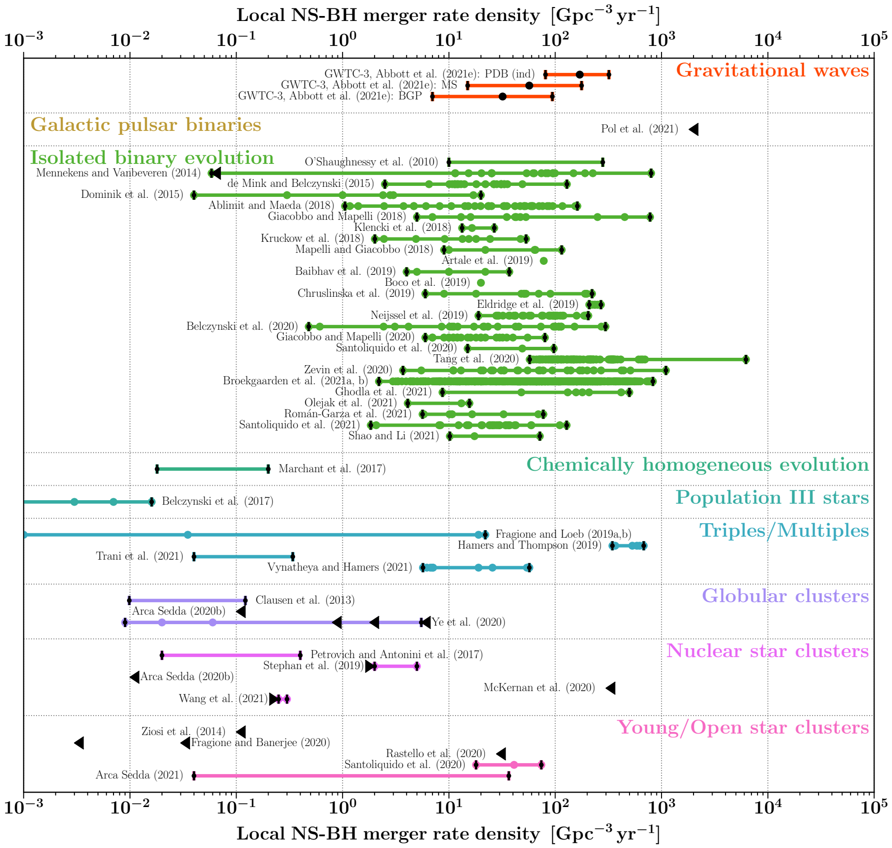

Fig. 2 NS–BH merger rates from Table 2. Notation as in Fig. 1. (Standalone PDF image in this article's Supplementary Material. Source code: GitHub)

Table 3 Summary of predictions of local BH–BH coalescence rates, part 1: observations and isolated binary evolution models (GitHub and Zenodo)

Source	Rate [Gpc^{-3} yr^{-1}]	References
Observations:		
Gravitational-wave observations, PDB (ind)	22^{+9}_{-6}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, MS	42^{+88}_{-20}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, BGP	33^{+16}_{-10}	GWTC-3; Abbott et al. (2021e)
Gravitational-wave observations, z-dependent	18^{+12}_{-8}	GWTC-3; Abbott et al. (2021e)
Models:	Rate	
Isolated binary population synthesis, StarTrack	[2, 40]	O'Shaughnessy et al. (2010)
Isolated binary population synthesis, Brussels code	[≤ 96, 1140]	Mennekens and Vanbeveren (2014)
Isolated binary population synthesis, StarTrack	[14, 2500]	de Mink and Belczynski (2015)
Isolated binary population synthesis, StarTrack	[0.5, 221]	Dominik et al. (2015)
Isolated binary population synthesis, BSE	850	Lamberts et al. (2016)
Isolated binary population synthesis, Scenario Machine	100	Lipunov et al. (2017)
Isolated binary population synthesis, MOBSE	[20, 572]	Mapelli et al. (2017)
Isolated binary population synthesis, BSE	[20, 320]	Ablimit and Maeda (2018)
Isolated binary population synthesis, StarTrack	[32, 1072]	Chruslinska et al. (2018)
Isolated binary population synthesis, MOBSE	[43, 1500]	Giacobbo and Mapelli (2018)
Isolated binary population synthesis, StarTrack	[89, 203]	Klencki et al. (2018)
Isolated binary population synthesis, COMBINE	[0.6, 109]	Kruckow et al. (2018)
Isolated binary population synthesis, MOBSE	[146, 240]	Mapelli and Giacobbo (2018)
Isolated binary population synthesis, MOBSE	142	Artale et al. (2019)
Isolated binary population synthesis, MOBSE	[30, 60]	Baibhav et al. (2019)
Isolated binary population synthesis, StarTrack	[12, 1072]	Chruslinska et al. (2019)
Isolated binary population synthesis, BPASS	[56, 174].	Eldridge et al. (2019)
Isolated binary population synthesis, COMPAS	[59, 1157]	Neijssel et al. (2019)
Isolated binary population synthesis, SEVN	90	Spera et al. (2019)
Isolated binary population synthesis, StarTrack	[1.24, 1368]	Belczynski et al. (2020)
Isolated binary population synthesis, MOBSE	[43, 160]	Giacobbo and Mapelli (2020)
Isolated binary population synthesis, MOBSE	50^{+71}_{-37}	Santoliquido et al. (2020)
Isolated binary population synthesis, BPASS	[10, 219]	Tang et al. (2020)
Isolated binary population synthesis, COSMIC	[84, 6900]	Zevin et al. (2020)
Isolated binary population synthesis, POSYDON	[39, 170]	Bavera et al. (2021)
Isolated binary population synthesis, COMPAS,	[3.8, 810]	Broekgaarden et al. (2021a, b)
Isolated binary population synthesis, BPASS	[31, 873]	Ghodla et al. (2021)
Isolated binary population synthesis, MOBSE	[6, 37]	Mapelli et al. (2021)
Isolated binary population synthesis, StarTrack	[18, 89]	Olejak et al. (2021)
Isolated binary population synthesis, COMPAS	[51, 87]	Riley et al. (2021)
Isolated binary population synthesis, POSYDON	[70, 203]	Román-Garza et al. (2021)
Isolated binary population synthesis, MOBSE	[10, 105.4]	Santoliquido et al. (2021)
Isolated binary population synthesis, BSE	[43, 76]	Shao and Li (2021)
Chemically homogeneous evolution	[2, 80]	Mandel and de Mink (2016)
Chemically homogeneous evolution, MESA	[0.7, 16]	Marchant et al. (2016)

Table 3 continued

Source	Rate [Gpc^{-3} yr^{-1}]	References
Chemically homogeneous evolution, MESA	[5.8, 7]	du Buisson et al. (2020)
Chemically homogeneous evolution, COMPAS	[4, 32]	Riley et al. (2021)
Population III stars	[12, 25]	Kinugawa et al. (2014)
Population III stars, StarTrack	[0.016, 1.9]	Belczynski et al. (2017)
Population III stars, BSE	[0.38, 2.9]	Hijikawa et al. (2021)
Population III stars, BSE	[0.13, 0.66]	Kinugawa et al. (2021)
Population III stars in Nuclear Star Clusters	[0.02, 0.6]	Liu and Bromm (2021)
Population III stars, BSE	0.1	Tanikawa et al. (2021)

Table 4 Summary of predictions of local BH–BH coalescence rates, part 2: dynamical formation models and primordial black holes (GitHub and Zenodo)

Source	Rate [Gpc^{-3} yr^{-1}]	References
Hierarchical triples, Rebound package	[0.14, 6.3]	Silsbee and Tremaine (2017)
Hierarchical triples, TRES	[0.3, 2.5]	Antonini et al. (2017)
Hierarchical triples	[2, 25]	Rodriguez and Antonini (2018)
Hierarchical triples in globular clusters, CMC	[$\gtrsim$0.35, 1]	Martinez et al. (2020)
Hierarchical triples in young star clusters, OKINAMI,	[0.2, 1.44]	Trani et al. (2021)
Hierarchical quadruples, MSE	[8.5, 39.8]	Vynatheya and Hamers (2021)
Globular cluster dynamics	[7.25, 29]	Bae et al. (2014)
Globular cluster dynamics, CMC	[3.8, 13]	Rodriguez et al. (2015)
Globular cluster dynamics	5	Antonini and Rasio (2016)
Globular cluster dynamics, CMC	[2, 20]	Rodriguez et al. (2016a)
Globular cluster dynamics, MOCCA	[5.4, 30]	Askar et al. (2017)
Globular cluster dynamics	[13, 57]	Fujii et al. (2017)
Globular cluster dynamics, Nbody6	[6.5, 26]	Park et al. (2017)
Globular cluster dynamics	[4, 60]	Fragione and Kocsis (2018)
Globular cluster dynamics	[0.8, 20]	Hong et al. (2018)
Globular cluster dynamics, CMC	[4, 18]	Rodriguez and Loeb (2018)
Globular cluster dynamics	≈ 6	Choksi et al. (2019)
Globular cluster dynamics, cBHBd	[0.2, 50]	Antonini and Gieles (2020)
Globular cluster dynamics, CMC	[9, 30]	Kremer et al. (2020)
Globular cluster dynamics, MOBSE	[0.8, 7]	Mapelli et al. (2021)
Nuclear star cluster dynamics, without SMBH	[1, 10]	Miller and Lauburg (2009)
Nuclear star cluster dynamics, with SMBH	[0.002, 0.6]	Antonini and Perets (2012)
Nuclear star cluster dynamics, without SMBH	1.5	Antonini and Rasio (2016)
Nuclear star cluster dynamics:, with SMBH	~ 1.2	Bartos et al. (2017)
Nuclear star cluster dynamics, with SMBH	[0.6, 15]	Petrovich and Antonini (2017)
Nuclear star cluster dynamics, with SMBH	~ 3	Stone et al. (2017)
Nuclear star cluster dynamics, with SMBH	[0.01, 0.4]	Hamers et al. (2018)
Nuclear star cluster dynamics, with SMBH	[1, 3]	Hoang et al. (2018)

Table 4 continued

Source	Rate [Gpc^{-3} yr^{-1}]	References
Nuclear star cluster dynamics, with SMBH	[0.002, 0.04]	Rasskazov and Kocsis (2019)
Nuclear star cluster dynamics, with SMBH	$\gtrsim[7, 15]$	Stephan et al. (2019)
Nuclear star cluster dynamics with SMBH	[3.3, 8.6]	Arca Sedda (2020a)
Nuclear star cluster dynamics with SMBH	[0.002, 18]	Gröbner et al. (2020)
Nuclear star cluster dynamics	[0.09, 10]	Mapelli et al. (2021)
Nuclear star cluster dynamics, with SMBH	[0.02, 60]	Tagawa et al. (2020)
Nuclear star cluster dynamics, with SMBH	[0.1, 1.6].	Yang et al. (2020)
Nuclear star cluster dynamics, with SMBH	[6, 20]	Ford and McKernan (2021)
Nuclear star cluster dynamics, with SMBH	$\gtrsim[0.3, 5]$	Wang et al. (2021)
Young star clusters, starlab	$\lesssim 1.5$	Ziosi et al. (2014)
Young star clusters, starlab	$\gtrsim 1$	Mapelli (2016)
Open star clusters, NBODY7	$\lesssim 2$	Rastello et al. (2019)
Young star clusters, NBODY6	$\lesssim[55, 110]$	Di Carlo et al. (2020)
Open star clusters, NBODY6	[35, 70]	Kumamoto et al. (2020)
Young star clusters, MOBSE	64^{+34}_{-20}	Santoliquido et al. (2020)
Young and open star clusters, NBODY7	[0.5, 37.9]	Banerjee (2021)
Young star clusters, MOBSE	[0.1, 18]	Mapelli et al. (2021)
Young star clusters, NBODY6 MOBSE	88^{+34}_{-26}	Rastello et al. (2021)
Primordial binaries	$[0.02, \lesssim 3]$	Bird et al. (2016)
Primordial binaries	$\lesssim[0.2, 10^5]$	Ali-Haïmoud et al. (2017)
Primordial binaries	$\lesssim[6, 10^4]$	Raidal et al. (2019)

We do not quote predictions for the number of detections per year for a given instrument because such predictions must take into account the variation in both the merger rate and the mass distribution of merging binaries with redshift for detectors sensitive to cosmological distances, and this information is frequently not readily available in the literature. Derivations of how to do such calculations are provided by, e.g., Belczynski et al. (2014) and de Mink and Mandel (2016); both analytical fits (e.g., Fishbach and Holz 2017) and numerical codes (e.g., Gerosa 2017; Team COMPAS: Riley et al. 2021) are available.

3 Observed rates

In this section, we discuss the latest observational constraints on compact-object coalescence rates. There are direct observations of compact binary mergers, either through gravitational waves or through electromagnetic transients accompanying such mergers, particularly short gamma-ray bursts. Alternatively, there are observations of binaries that are not yet merging, but are expected to do so as compact objects in the future, such as Galactic double neutron stars and perhaps some high-mass X-ray binaries.

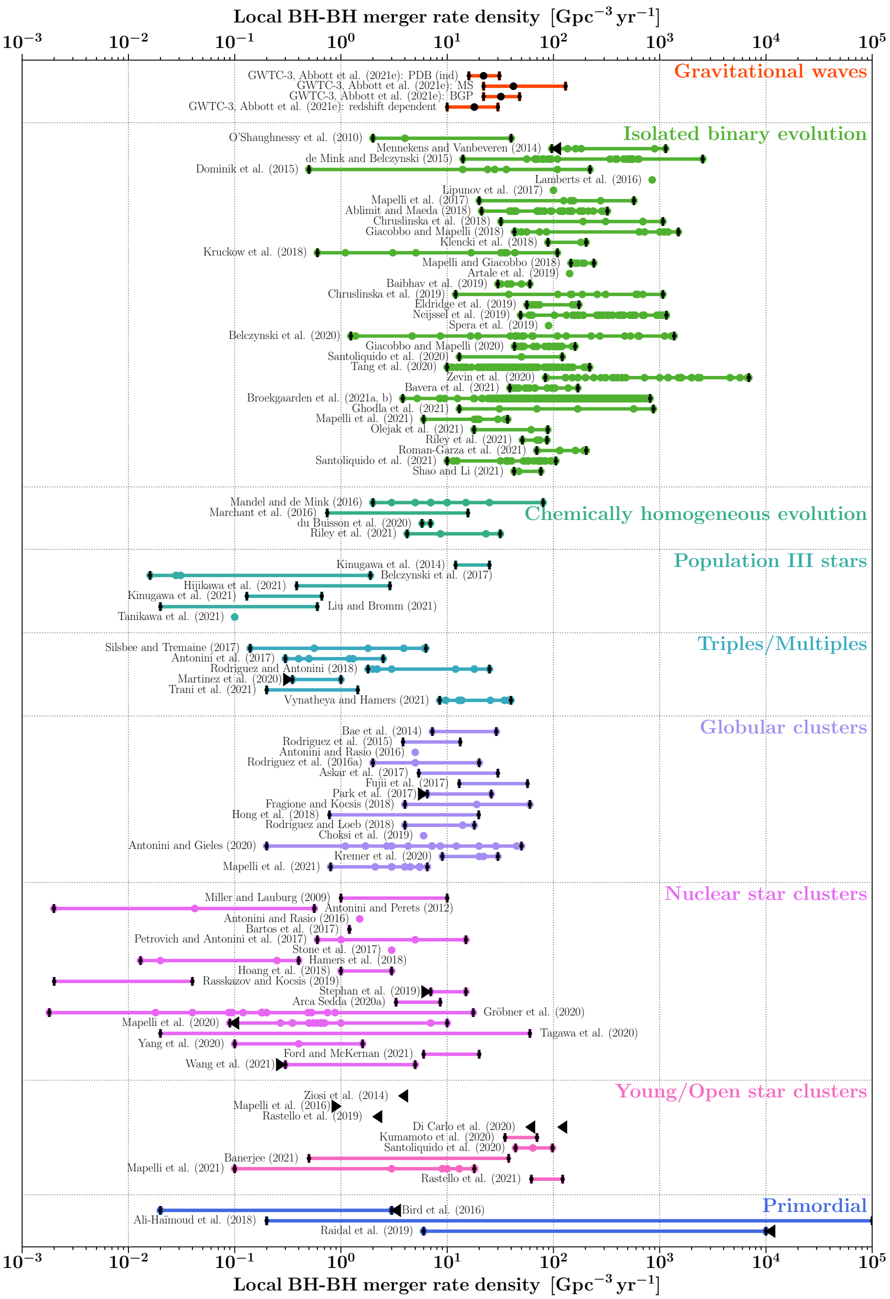

Fig. 3 BH–BH merger rates from Table 3. Notation as in Fig. 1. (Standalone PDF image in this article's Supplementary Material. Source code: GitHub)

In all cases the key challenge in accurately inferring rates from limited observations comes from significant selection effects, which may be particularly difficult to quantify when the data set is inhomogeneous, and/or when the distribution of the intrinsic loudness of the signals is not known. Moreover, in some cases there can be uncertainty in the interpretation of the signals. Meanwhile, for systems that are not yet merging, there may be uncertainties in their future evolution. We discuss these challenges below.

3.1 Gravitational waves

Gravitational-wave data should, at first glance, enable straightforward rate estimates. These are direct observations of compact-object coalescences. The data are homogeneous, with well-understood selection effects which can be modelled by injecting mock signals into the data stream and measuring how many of them will be successfully extracted by the search pipelines. Once the surveyed time$\times$volume of the instruments is thus estimated, the volumetric merger rate is given by the number of detections in this time$\times$volume. We might therefore expect that analysing some 70 confident BH–BH mergers from the first, second, and third advanced detector observing run in Abbott et al. (2021e) would enable the BH–BH merger rate to be inferred to a fractional accuracy of $1/\sqrt{70} \approx 12\%$ based on Poisson statistics.

However, there are several complicating factors to this story, as a result of which the total binary black hole merger rate is still uncertain at the factor of two level. Firstly, the detection rate is a sensitive function of mass, with more massive binaries typically providing higher-amplitude gravitational-wave signals that can be detected through a greater volume. Therefore, inferring the total merger rate relies on simultaneously measuring the mass distribution of merging black holes, which requires many more observations (Abbott et al. 2021e). One way to partially overcome this uncertainty is to focus on observations in a more narrow mass band (Roulet et al. 2020; Abbott et al. 2021c); for example, Roulet et al. (2020) find that the merger rate of 20–30 $M_\odot$ BHs[2] is 1.5–5.3 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, while Abbott et al. (2021c) find a BH–BH merger rate in the same mass range of $3.7^{+1.6}_{-1.1}$ or $2.6^{+1.9}_{-1.3}$ $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$depending on the assumed mass distributions. The inferred merger rates reported in the summary tables and figures as "PDB (ind)", "MS", and "BGP" refer to the corresponding mass distribution models described in Abbott et al. (2021e): Power law + dip + break (with independent mass pairings for the two components), Power law + peak multi-source (separate BH mass models in BH–BH and NS–BH binaries) and Binned Gaussian process (unmodelled with regularisation).

Secondly, another uncertainty arises from the possibility that the merger rate varies with redshift, for which there is already significant support in the data (Fishbach et al. 2021; Abbott et al. 2021e). Allowing for the variation of the merger rate with redshift (but not yet of the mass distribution with redshift, although some

[2] We generally use solar masses ($M_\odot$) and solar radii ($R_\odot$) as mass and distance units.

theoretical models predict this) further shifts the binary black hole merger rate at redshift $z = 0$. The "z-dependent" rate reported for BH–BH mergers comes from the redshift-dependent merger rate model evaluated at $z = 0$ (Abbott et al. 2021e).

Thirdly, details of search methodology and tuning can impact the set of detections (e.g., Abbott et al. 2021b, d), and independent searches over the publicly released LIGO-Virgo data have yielded slightly different source populations (e.g., Zackay et al. 2019; Venumadhav et al. 2020; Nitz et al. 2021a, b). While searches with slightly different sensitivities and different numbers of detections should still yield consistent rate estimates, some fluctuation is to be expected, especially through the impact of different inferred mass distributions as described above.

Fourthly, while the chirp mass $m_1^{3/5} m_2^{3/5} (m_1 + m_2)^{-1/5}$ is measured accurately for low-mass binaries through gravitational-wave signals, the mass ratio measurement is much less accurate, making it difficult to distinguish neutron stars from low-mass black holes (see, e.g., Hannam et al. 2013). A measurement of tidal deformation could point unambiguously to a neutron star rather than a black hole, but such measurements require sensitivity at higher frequencies, and only upper limits have been placed so far (Abbott et al. 2017b). Therefore, in the absence of an electromagnetic counterpart, it is not clear how to classify a system such as GW190814 (Abbott et al. 2020d), which consisted of a $\approx 23\,M_\odot$ BH coalescing with a $\approx 2.6\,M_\odot$ compact object that is probably a low-mass black hole but could be a very high-mass neutron star.

Estimates of the NS–NS and NS–BH merger rates are based on a very small number of confident detections, including GW170817 and GW190425 in the former category and GW200105 and GW200115 in the latter category (Abbott et al. 2017b, 2020a, 2021a). Furthermore, these estimates are particularly sensitive to assumptions about the poorly constrained mass distributions in NS–NS and NS–BH binaries.

3.2 Short gamma-ray bursts and kilonovae

Mergers of two neutron stars have long been expected to be accompanied by a short burst of spectrally hard gamma radiation accompanying an ultra-relativistic jet, with subsequent synchrotron radiation afterglow from the interaction of the jet with the circumstellar medium (Paczyński and Rhoads 1993; Rosswog and Ramirez-Ruiz 2002; Nakar 2007). Meanwhile, the formation and subsequent radioactive decay of neutron-rich elements through r-process nucleosynthesis was conjectured to power an optical kilonova (Li and Paczyński 1998; Rosswog et al. 1999; Metzger et al. 2010; Kasen et al. 2013). Both expectations were spectacularly confirmed with the detection of a short gamma-ray burst (Abbott et al. 2017a), followed by the observation of a kilonova (Abbott et al. 2017c; Kasen et al. 2017; Metzger 2019), and finally a broad-spectrum (radio through optical to X-ray) afterglow (Mooley et al. 2018; Lyman et al. 2018; Troja et al. 2017) following the NS–NS merger GW17017.

One concern with using short gamma-ray bursts (SGRBs) to infer binary neutron star coalescence rates is the uncertainty in a one-to-one association between these events. On the one hand, some SGRBs and perhaps even kilonovae could be associated with NS–BH mergers (Troja et al. 2008; Berger 2014; Li et al. 2017; Gompertz et al. 2020). However, this is likely only possible for those events when the neutron star is tidally disrupted at a sufficient distance from the black hole, requiring the black hole to be low in mass and/or rapidly rotating (Foucart et al. 2018). Therefore, the contribution of NS–BH mergers to SGRBs is likely low (e.g., Drozda et al. 2020). On the other hand, given the challenges in reproducing ultra-relativistic jet formation in numerical merger simulations (Mösta et al. 2020), it cannot be determined with confidence whether all neutron star mergers should be accompanied by SGRBs.

Nevertheless, SGRBs have been used for more than a decade as proxies for the NS–NS merger rate, with Nakar et al. (2006) estimating the merger rate as at least 10 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, but possibly several orders of magnitude higher. The key challenge is the uncertainty in the angular size of the jet: the smaller the jet, the smaller fraction of SGRBs beamed toward Earth, and hence the larger the intrinsic rate based on the observed rate of SGRBs. Fong et al. (2012) used evidence for jet breaks to constrain the angular size of the jet, allowing them to infer an NS–NS merger rate. However, the evidence from GW170817 firmly indicated that the jet has spatial structure, rather than a simple top-hat profile (Troja et al. 2018; Resmi et al. 2018; Lamb et al. 2019). This requires a re-evaluation of earlier models, an ongoing effort (Paul 2018); for example, Margutti and Chornock (2021, see their Fig. 3) estimate the rate of GW170817A-like SGRBs as $\gtrsim 300\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$given the observed off-axis angle under the assumption that other SGRBs would have similar jet profiles.

The first kilonova observation was made in 2013 (Tanvir et al. 2013). While more candidates have been observed in the last few years, they are still difficult to unambiguously distinguish from other transients. At present, their luminosity function is not yet sufficiently well known to infer an accurate rate. However, the absence of transients with a kilonova signal similar to that accompanying GW170187 in data from the Palomar Transient Factor allowed Kasliwal et al. (2017) to place a conservative 3-σ upper limit of $800\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$. Andreoni et al. (2021, see their Fig. 9) compile a list of optical kilonova surveys with upper limits between 900 and 99000 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

3.3 Pulsars in Galactic compact object binaries

Observations of double compact object binaries prior to merger are the next best thing to direct merger observations for measuring merger rates. Provided that the masses, period or separation, and eccentricity of the binary are known, the time to merger through the emission of gravitational waves can be computed (Peters 1964). Assuming a steady-state configuration, which is a reasonable assumption for our Galaxy with its slowly evolving metallicity and star formation rate, an observed population of pre-merger compact object binaries yields an estimate of the coalescence rate.

So far, NS–NS binaries are the only double compact objects for which direct observations are available. Nearly 20 such binaries have been observed in the Galaxy through radio pulsar pulsar observations (see, e.g., Tauris et al. 2017; Farrow et al. 2019, for recent compilations). Of course, these are expected to represent a relatively small fraction of all Galactic double neutron stars, with most remaining unobserved because neither neutron star is a pulsar or any pulsars are too dim or beamed away from the Earth. Moreover, pulsars in the tightest binaries are rare because of their rapid inspiral and may be challenging to detect because the pulsations are Doppler shifted by orbital modulation. Therefore, the key challenge in inferring the merger rate of close double neutron stars in the Galaxy from these observations lies in accounting for selection effects, particularly the uncertain luminosity function and beaming fraction of pulsars.

Fortunately, the rapidly growing amount of pulsar data since the pioneering efforts of Phinney (1991) and Narayan et al. (1991) to infer NS–NS merger rates from binary pulsar observations enables increasingly accurate treatments of these selection effects. Much of the recent literature follows the statistical framework of Kim et al. (2003), with the addition of varying models of the luminosity distribution (Kalogera et al. 2004), more sophisticated models of the pulsar beaming fraction which could vary with pulsar age (O'Shaughnessy and Kim 2010), an attempt to account for the observation of both pulsars in the double pulsar J0737-3039 (Kim et al. 2015) and the addition of new systems (with the relatively small number of known Galactic binaries, a single new short-lived double neutron star could impact the rate estimate at the factor of two level, as shown by Kim et al. 2006). We report the rates from a few recent papers to indicate the evolving estimates of the double neutron star merger rate (see Abadie 2010, for a compilation including older results).

There are several complicating factors in extracting coalescence rates from the observed Galactic double neutron stars. B2127+11C and possibly J1807-2500 are known double neutron stars in Galactic globular clusters; these are generally excluded from rate estimates because they are believed to be rare dynamically formed systems (Ye et al. 2020, but see Andrews and Mandel 2019). Another concern is that the detectability of a Galactic double neutron star may correlate with the evolutionary channel and with the system properties, e.g., through the amount of recycling the pulsar experiences. This could lead some sub-populations of pulsars—perhaps the more massive ones like GW190425 (Abbott et al. 2020a; Romero-Shaw et al. 2020; Vigna-Gómez et al. 2021a)—to be missed in Galactic surveys. Moreover, extrapolation from the Milky Way merging double neutron star rate to a volumetric rate depends on the accuracy of estimating the local star formation rate (de Freitas Pacheco et al. 2006) and on the sensitivity of the yield of merging double neutron stars to metallicity.

No Galactic radio pulsars in NS–BH binaries have been detected so far. However, the lack of such observations only weakly constrains the NS–BH merger rate from above. If the heavier BH forms first, which appears intuitive given the shorter lifetimes of more massive stars, the NS will not be recycled by accretion, which limits the time during which it can be observed as a radio pulsar (Chattopadhyay et al. 2021). Mass transfer can invert the mass ratio, allowing the

NS to form first from the originally more massive star; however, the formation rate of such systems is likely quite low (Pfahl et al. 2005).

3.4 High-mass X-ray binaries

As we will discuss in the next section, most compact object binaries formed through isolated binary evolution are expected to go through a high-mass X-ray binary stage, in which the first companion to form a black hole or neutron star accretes from the wind of the stellar companion. This phase may directly precede the formation of two compact objects, and can therefore be used to constrain compact binary coalescence rates. For example, Bulik et al. (2011) used the extragalactic high-mass BH X-ray binaries IC10 X-1 and NGC300 X-1 to estimate the merger rate of BH–BH binaries at 360^{+500}_{-260} $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$.

However, such estimates suffer from significant uncertainties. Firstly, there are often large systematic errors in the masses and separations of the observed systems; in particular, the masses of IC10 X-1 and NGC300 X-1 may be much lower than in the analysis of Bulik et al. (2011) because orbital velocities are very challenging to measure in the presence of optically thick Wolf-Rayet winds (Laycock et al. 2015). Even well-studied high-mass X-ray binaries such as Cygnus X-1 (Orosz et al. 2011) may require significant corrections to their masses (Miller-Jones et al. 2021), while the uncertain present properties of Cygnus X-3 translate into uncertainty about its future fate (Belczynski et al. 2013). Secondly, the observed systems typically come from a heterogeneous set of observations, complicating the determination of selection effects. Thirdly, the future evolution of such systems is sensitive to assumptions about the dynamical stability of any future mass transfer episodes (van den Heuvel et al. 2017), the amount of mass loss in winds (cf. Belczynski et al. 2011 and Neijssel et al. 2021 for the case of Cygnus X-1), and the remnant mass and natal kick of the remaining supernova.

Inoue et al. (2016) and Finke and Razzaque (2017) use observations of ultra-luminous X-ray sources (ULXs) with X-ray luminosities exceeding $10^{39}\,\mathrm{erg\,s}^{-1}$ to estimate BH–BH merger rates of $\lesssim 100$ $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$and 15–400 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$, respectively. These estimates, however, are highly uncertain. They rely on the assumption that all ULXs are powered by accretion onto a BH, which is contradicted by observations that at least some ULXs (perhaps all with confidently identified compact objects?) are powered by accretion onto an NS (Bachetti et al. 2014). They also make simplifying assumptions about the future evolutionary history of ULXs.

3.5 Other observational constraints

Abadie (2010) suggested that a strict upper limit of $< 5 \times 10^4$ mergers $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ could be placed on the NS–NS merger rate by assuming that at least one companion must have been formed through a type Ib/Ic supernova (taking an optimistic rate estimate from Cappellaro et al. 1999). However, this upper limit is likely a very significant over-estimate, as most type Ib/Ic supernovae happen in other systems than merging binary neutron stars (perhaps even in systems that had already been disrupted, Hirai et al. 2020). At the same time, the type Ib/Ic supernova rate cannot even be considered a strict upper limit, because many merging neutron star binaries could form through a combination of electron-capture supernovae and ultra-stripped supernovae rather than classical core-collapse supernovae (Podsiadlowski et al. 2004; Dall'Osso et al. 2014; Tauris et al. 2015, 2017; Vigna-Gómez et al. 2018), and some compact remnants may form in the absence of any explosions.

Signatures of chemical enrichment associated with binary neutron star mergers, particularly the evolution of r-process nucleosynthesis elements, could serve as a useful constraint on the binary neutron star merger rate (Mennekens and Vanbeveren 2014; Hotokezaka et al. 2015; Beniamini et al. 2016). However, Siegel et al. (2019), Kobayashi et al. (2020) propose that magneto-rotational supernovae could instead be responsible for r-process enrichment.

Compact-object mergers or the subsequent evolution of compact-object merger products have been proposed as a source for some fast radio bursts (Totani 2013; Ravi and Lasky 2014); however, there are likely multiple progenitor channels for fast radio bursts (Pleunis et al. 2021), so these cannot presently be confidently used for merger rate estimates.

4 Modelled rates

In this section, we summarise some of the ongoing efforts to model the rates of compact object mergers formed through a variety of evolutionary channels. These channels offer alternative pathways to overcoming a key challenge in gravitational-wave astronomy. Gravitational-wave emission is only efficient in close binaries: in order for a circular binary with equal-mass components of mass M to merge within a time T exclusively through radiation reaction from gravitational-wave emission, the separation a must be smaller than

$$a \lesssim 3.7\, R_\odot \left(\frac{M}{M_\odot}\right)^{3/4} \left(\frac{T}{14\,\mathrm{Gyr}}\right)^{1/4}. \tag{1}$$

Thus, to merge within the current age of the Universe, 14 Gyr, two $1.4\, M_\odot$ neutron stars must be fewer than 5 solar radii apart, while even two $35\, M_\odot$ black holes must be within a quarter of an astronomical unit.

On the other hand, massive stars typically expand to several au (hundreds to thousands of solar radii; 1 au $\approx$ 215 $R_\odot$) in size during their evolution. Therefore, the key challenge to forming a merging compact-object binary lies in fitting a peg into a hole that is one or two orders of magnitude smaller than the size of the peg. The proposed solutions generally take the form of either relying on stellar evolution and mass transfer to overcome the problem in an isolated binary, or circumventing the problem altogether by relying on dynamics to form binaries with a sufficiently small separation that gravitational-wave emission can drive them to merge. Here we sketch out the key steps in the proposed formation channels, undertake back-of-the-envelope estimates of the rates, following Mandel and Farmer (2018), and describe some of the key uncertainties leading to the typically broad range of model predictions.

One particular source of uncertainty that is common to all models described below is the uncertain rate and metallicity of star formation across cosmic history. Even binaries merging in the relatively local Universe (detections through the third LIGO/Virgo observing run had moderate redshifts $z \lesssim 1$, Abbott et al. 2021d) could have formed at high redshift (Belczynski et al. 2016). Therefore, the rate of star formation at higher redshift influences local merger rates. Moreover, the yield of coalescing compact objects per unit star forming mass depends strongly on metallicity (Dominik et al. 2013; Neijssel et al. 2019). This is particularly true for black holes, whose massive progenitors can lose large fractions of their mass in winds in high-metallicity environments, widening the binaries and reducing merger rates. Therefore, the local merger rate is sensitive to the poorly known metallicity-specific star formation rate at high redshifts (Belczynski et al. 2010; Mapelli et al. 2017; Klencki et al. 2018; Chruslinska et al. 2019; Neijssel et al. 2019; Chruslinska and Nelemans 2019; Tang et al. 2020; Briel et al., 2021; Broekgaarden et al. 2021a, b; Santoliquido et al. 2021; van Son et al. 2021).

4.1 Isolated binary evolution modelling (population synthesis)

Almost all stars massive enough to form neutron stars and black holes are born in binaries or higher-multiplicity systems (Sana et al. 2012; Moe and Di Stefano 2017). We begin by considering compact-object coalescences in isolated binaries, namely those which do not appreciably interact with their environment. This channel has been studied since the 1970s. Some of the ground-breaking works particularly relevant to the formation of coalescing compact-object binaries include (Tutukov and Yungelson 1973; van den Heuvel and De Loore 1973; De Loore et al. 1975; Flannery and van den Heuvel 1975; Tutukov and Yungelson 1993; Lipunov et al. 1997; Bethe and Brown 1998; Dewi et al. 2006; Nelemans et al. 2001; Voss and Tauris 2003; Kalogera et al. 2007; O'Shaughnessy et al. 2008) (see Mandel and Farmer 2018 for a brief summary of the early history).

4.1.1 Isolated binary evolution with mass transfer

In this channel, two massive stars are born in a wide binary, giving them sufficient space to evolve. The binary shrinks as a consequence of mass transfer just when the stars themselves shrink in radius, allowing gravitational waves to take over.

We begin by sketching out a very simplified version of binary evolution in this model. The primary—the initially more massive star—completes core hydrogen fusion first. At the end of the main sequence, its helium-rich core contracts and the hydrogen-rich envelope expands. As the star fills the so-called Roche lobe, tidal gravity from the companion overcomes the self-gravity of the primary, and mass transfer onto the secondary commences. Eventually, the primary leaves behind a naked helium star, which continues nuclear fusion, losing mass through winds, until it collapses into a compact object. The mass loss and/or the natal kick from asymmetric mass ejection accompanying the supernova may unbind the binary. If it does not, the binary continues its evolution until the secondary expands and commences mass transfer onto the now compact-object primary. Because of the mass gain of the secondary during the first episode of mass transfer and the mass loss of the primary due to mass transfer, winds, and the supernova, the secondary may be significantly more massive than the primary at this stage. Consequently, mass transfer could harden the binary (van den Heuvel et al. 2017), and could even become dynamically unstable, leading to the formation of a common envelope (Paczyński 1976). Once the common envelope is not co-rotating with the binary, drag forces dissipate orbital energy, which may allow for common-envelope ejection after the binary hardens by two or three orders of magnitude (Ivanova et al. 2013). At this stage, the secondary has lost its envelope to become a naked helium star, so it can fit into the tight binary. (It is also possible that both stars are evolved giants during the first mass transfer interaction, leading to the simultaneous ejection of both envelopes during a single common-envelope event, as described by Dewi et al. 2006.) After more mass loss through winds the secondary may also collapse into a compact object. Assuming the second supernova leaves behind a bound, compact binary, this binary will eventually merge by emitting gravitational waves.

We can crudely estimate the expected merger rate through this channel with a Drake-like equation describing the fraction of all binaries that go on to make merging double compact objects of a particular type (Mandel and Farmer 2018), with chosen values corresponding to binary black hole formation:

$$
\begin{aligned}
f_{\mathrm{DCO}} &= f_{\mathrm{primary}} \times f_{\mathrm{secondary}} \times f_{\mathrm{init\,sep}} \times f_{\mathrm{survive\,SN1}} \times f_{\mathrm{CE}} \times f_{\mathrm{survive\,SN2}} \\
&\quad \times f_{\mathrm{merge}} \sim 0.001 \times 0.5 \times 0.5 \times 1 \times 0.1 \times 1 \times 0.2 = 5 \times 10^{-6}.
\end{aligned} \tag{2}
$$

Assuming a local star formation rate of $\sim 10^7\, M_\odot$ Gpc^{-3} yr^{-1} (Madau and Dickinson 2014) with an average mass of $\sim M_\odot$, a yield of $f_{\mathrm{DCO}} = 5 \times 10^{-6}$ would lead to a compact-object merger rate of ~ 50 Gpc^{-3} yr^{-1}.

Here we describe the terms in this equation, which allows us to highlight the broad range of physics involved and to comment on the key uncertainties. In practice, most modern models rely on some form of population synthesis, where large numbers of stellar binaries are evolved in order to compute the yield, frequently by using simplified recipes to reduce computational cost (Postnov and Yungelson 2014; Han et al. 2020).

Stars with initial mass at zero age on the main sequence of roughly $\gtrsim 20\, M_\odot$ can form a BH, so the fraction of all stars drawn from the initial mass function that will have mass in this range is $f_{\mathrm{primary}} \approx 0.001$. Meanwhile, for forming an NS, the zero-age main sequence mass should be roughly between 8 and $20\, M_\odot$, so $f_{\mathrm{primary}} \approx 0.002$. The mass ratio between secondary and primary is roughly uniformly distributed (Sana et al. 2012), so if the primary falls in the mass range of interest, roughly half the secondaries will do so, i.e., $f_{\mathrm{secondary}} \approx 0.5$. The fraction of binaries with initial separations in the range to allow for the first episode of mass transfer from evolved donors is quite large, $f_{\mathrm{init\,sep}} \approx 0.5$, given the significant amount of expansion during this phase and the uniform in the logarithm distribution of initial separations (Öpik 1924).

The probabilities of the binary surviving the first and second supernovae without being disrupted, $f_{\mathrm{survive\,SN1}}$ and $f_{\mathrm{survive\,SN2}}$, are both close to 1 for the heavier black holes that may form through complete collapse with negligible natal kicks (Mirabel 2017, but see Repetto et al. 2012; Mandel 2016; Atri et al. 2019). However, the high typical natal kicks of neutron stars, of order $300\,\mathrm{km\,s^{-1}}$ (Hobbs et al. 2005; Verbunt et al. 2017), can disrupt $\gtrsim 95\%$ of wide binaries in the first supernova (Vigna-Gómez et al. 2018; Renzo et al. 2019). Reduced kicks in electron-capture supernova (Podsiadlowski et al. 2004; Gessner and Janka 2018) may protect some of the wide binaries from unbinding, increasing $f_{\mathrm{survive\,SN1}}$. By the time of the second supernova, the binary will have gone through a common envelope in this channel, hardening it and making disruption less likely; moreover, low-mass helium star progenitors of neutron stars may re-expand after the helium main sequence, engage in another mass transfer episode (case BB mass transfer) and ultimately explode in very weak ultra-stripped supernovae with greatly reduced kicks (Tauris et al. 2015, but see Mandel and Müller 2020). Therefore, it is plausible that $f_{\mathrm{survive\,SN2}} \approx 1$, even for double neutron stars, although observed eccentricities of ~ 0.6 for a subset of Galactic double neutron stars, including the Hulse–Taylor binary, could point to a subpopulation of systems that avoid ultra-stripping and may be disrupted by the second supernova.

The common-envelope phase is perhaps the least certain one in massive binary evolution (Dominik et al. 2012). There are questions about both the onset of the common-envelope phase (do the mass ratio and the evolutionary state of the donor and accretor make mass transfer dynamically unstable?) and about the ultimate outcome of the evolution (is sufficient energy deposited in the envelope to eject it, or does this episode end in merger?). Typical population synthesis models based on current, very simplified recipes for both the stability mass transfer and the survivability of the common-envelope phase yield $f_{\mathrm{CE}} \approx 0.1$.

The fraction of compact-object binaries that ultimately coalesce in the age of the Universe f_{merge} is set by the distribution of masses and separations. If the post-common-envelope binary separation is distributed uniformly in the logarithm, the delay time τ between formation and merger, which scales with the fourth power of the separation, will also follow a log-uniform distribution, i.e., $p(\tau) \propto 1/\tau$. In that case, the logarithmic distribution allows for typical $f_{\mathrm{merge}} \approx 0.2$; however, as mentioned above, this can be significantly reduced, e.g., if winds increase the BH binary separation at high metallicity.

We now describe the key uncertainties in these estimates. Different treatments of some of the physics summarised below are responsible for the broad range of predictions reported in the executive summary.

The first significant uncertainty lies in the distribution of initial conditions: the masses of the two companions, their separations, and the binary eccentricity (Sana et al. 2012; Moe and Di Stefano 2017). These alone can impact the merger rate at the level of a factor of ~ 6 due to uncertainty in the initial mass function (Kroupa 2002) and by up to a factor of 2–3 due to uncertainty in the other parameters (de Mink and Belczynski 2015; Klencki et al. 2018).

The treatment of mass transfer represents a key source of uncertainty in isolated binary evolution (Belczynski et al. 2022). Is the mass transfer dynamically stable? Stability thresholds can be formulated in terms of the mass ratio (Claeys et al. 2014) or the relative radial response of the star and its Roche lobe to mass transfer (Soberman et al. 1997; Ge et al. 2015). The depth of the convective envelope of the donor may play a critical role (Klencki et al. 2021). If the mass transfer is dynamically stable, how conservative is it, i.e., what fraction of mass lost by the donor does the companion accrete (e.g., Kippenhahn and Meyer-Hofmeister 1977), including the case of accretion onto compact objects (e.g., van Son et al. 2020)? And how much angular momentum is carried away by any mass that leaves the system, changing the orbital separation of the binary (e.g., Vinciguerra et al. 2020)? How does mass transfer in eccentric binaries affect their orbit (e.g.,. Sepinsky et al. 2010; Dosopoulou and Kalogera 2016)? If the mass transfer is dynamically unstable, leading to the formation of a common envelope, can the envelope be ejected, and what sets the orbital separation after the envelope ejection? Simple energy scalings are typically used to treat the common-envelope phase of binary evolution (Webbink 1984; de Kool 1990), partly because, despite decades of modelling common envelopes (Ivanova et al. 2013), the first incomplete models of this phase for massive stars are only just appearing (Ricker et al. 2019; Law-Smith et al. 2020; Lau et al. 2021). Last but not least, how does the history of mass transfer impact the final outcomes of stellar evolution, including supernova explosions (e.g., Brown et al. 2001; Schneider et al. 2021)?

A range of uncertainties in single stellar evolution play a key role. How much massive stars expand at various stages in their lives determines the onset and outcomes of mass transfer (e.g., Laplace et al. 2020). Stellar winds affect the final masses and separations (Vink 2017). The efficiency of tidal coupling determines orbital circularisation (Zahn 1977; Hut 1981; Vick and Lai 2018). The amount of mass lost in supernovae and the natal kicks that supernova remnants receive impact binary survival during the stellar explosions (Sipior and Sigurdsson 2002; Fryer et al. 2012; Müller 2020). Even relatively rare supernova variants such as electron-capture supernovae and (pulsational) pair-instability supernovae are important for coalescing compact object formation (e.g., Belczynski et al. 2018b; Stevenson et al. 2019; Farmer et al. 2020).

4.1.2 Isolated binaries: chemically homogeneous evolution and population III stars

One way to avoid the problem of fitting very extended stars into a binary tight enough to merge through gravitational waves is to prevent the stars from expanding in the first place. Here we consider two magic wands that might prevent expansion: efficient mixing or initially metal-free composition.

Suppose the stars are sufficiently massive, their metallicity is low enough to suppress strong winds, and they are close enough to be tidally locked in an orbit that enforces rotation at a significant fraction of the break-up velocity. Then the formation of temperature gradients between the poles and equator of the star may lead to large-scale circulation and efficient mixing (Eddington 1925; Sweet 1950; Endal and Sofia 1978). The mixing of helium out of the core into the envelope and fresh hydrogen from the envelope into the core allows the star to evolve chemically homogeneously, fusing almost all of the hydrogen into helium on the main sequence (Heger et al. 2000; Maeder and Meynet 2000; Yoon et al. 2006). After the end of hydrogen fusion, the entire star contracts into a naked helium star. Such systems avoid mass transfer after the main sequence, and may form heavy, ultimately coalescing black hole binaries in situ (Mandel and de Mink 2016; Marchant et al. 2016; de Mink and Mandel 2016). The high mass required for chemically homogeneous evolution makes this channel relevant only for the formation of merging black holes and, perhaps, rare NS–BH binaries (Marchant et al. 2017).

We can write a similar Drake's equation to Eq. (2) for the chemically homogeneous evolution channel. Following Mandel and de Mink (2016), the fraction of binaries that form coalescing binary black holes through this channel is

$$\begin{aligned} f_{\mathrm{BH-BH}} &= f_{\mathrm{primary}} \times f_{\mathrm{secondary}} \times f_{\mathrm{init\,sep}} \times f_Z \times f_{\mathrm{merge}} \\ &\sim 0.0002 \times 0.5 \times 0.1 \times 0.1 \times 1 = 10^{-6}. \end{aligned} \tag{3}$$

Only the most massive stars with initial masses above $\sim 50\,M_\odot$ are likely to experience sufficient mixing to evolve chemically homogeneously, lowering f_{primary} to $\approx 2 \times 10^{-4}$. A flat mass ratio distribution would again yield $f_{\mathrm{secondary}} \approx 0.5$. The range of initial separations allowing for chemically homogeneous evolution is at most a factor of two: stars that are initially too far apart either avoid tidal locking or do not rotate sufficiently rapidly, while stars that are too close overflow the L2 Lagrange point and promptly merge. If initial separations cover some 5 orders of magnitude and a uniform in the logarithm distribution of separations is assumed, up to $f_{\mathrm{init\,sep}} \approx 0.1$ of binaries with the right mass range could still experience chemically homogeneous evolution. However, this also requires a sufficiently low metallicity, in part to avoid binary widening through excessive mass loss in winds, necessitating a factor describing the fraction of star formation at metallicities of interest, estimated here as $f_Z \approx 0.1$. On the other hand, if a binary evolves chemically homogeneously and forms black holes in situ, it is likely to be sufficiently compact to merge within the age of the Universe through gravitational-wave emission, so $f_{\mathrm{merge}} \approx 1$. The overall yield estimate of $f_{\mathrm{BH-BH}} \approx 10^{-6}$ would suggest a binary black hole coalescence rate of $\sim 10\ \mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ for this channel.

The chemically homogeneous evolution channel as described above does not involve mass transfer after the main sequence and hence avoids some of uncertainties discussed in the previous subsection. On the other hand, the very possibility of efficient chemical mixing is uncertain. The observational evidence ranges from tentative to contradictory (Almeida et al. 2015; Mandel and de Mink 2016; Abdul-Masih et al. 2021) and theoretical models of mixing differ in the predicted thresholds on its efficiency. Moreover, much of the parameter space in this channel likely requires over-contact binaries (Marchant et al. 2016; du Buisson et al. 2020; Riley et al. 2021), which bring extra modelling challenges and uncertainties. On the other hand, a star could be spun up to rapid rotation and chemically homogeneous evolution by mass accretion from the companion (Cantiello et al. 2007). This mode of quasi chemically homogeneous evolution could also make a significant contribution to high-mass BH–BH mergers originating in low-metallicity environments (Eldridge and Stanway 2016).

First-generation metal-free stars in the early Universe, known as population III stars, may represent an alternative way to avoid radial expansion after the main sequence. The absence of primordial carbon, nitrogen and oxygen in these stars prevents the CNO cycle from operating, so that hydrogen fusion can proceed only through the pp-chain reaction. While the core becomes hot enough for helium produced in the core to form carbon through the triple-alpha reaction, eventually allowing CNO cycle hydrogen fusion to take over, this may not happen to the same extent in the hydrogen shell around the helium core after core hydrogen exhaustion. Therefore, population III stars may experience reduced radial expansion relative to more metal-rich stars (Marigo et al. 2001) and can avoid mass transfer and many of the complications of the classical isolated binary evolution channel. Moreover, this means that the hydrogen envelope of such stars remains tightly bound, and is unlikely to be ejected during the stellar collapse as would be the case for population I and II supergiants (Nadezhin 1980; Lovegrove and Woosley 2013; Fernández et al. 2018) allowing the star to retain most of its mass (Kinugawa et al. 2021), akin to chemically homogeneously evolving stars. This mass retention is further aided by the drastically reduced wind-driven mass loss at zero metallicity. Finally, the lack of metals has been conjectured to suppress the fragmentation of a giant molecular cloud during star formation, increasing the typical mass of population III stars and making these prime progenitor candidates for binary black hole coalescences (Belczynski et al. 2004; Kinugawa et al. 2014; Inayoshi et al. 2016, 2017).

The lack of observational evidence and challenges in theoretical models put many of these assumptions in doubt. There are conflicting models for the initial properties of population III binaries (Hirano et al. 2014; Stacy et al. 2016) which could drastically reduce the predicted merger rate (Hartwig et al. 2016; Belczynski et al. 2017), while the possibility of significant stellar expansion could remove this altogether as an independent channel.

4.2 Dynamical formation

Dynamical formation broadly encompasses compact object mergers in which gravitational interactions with other stars played a significant role in bringing the two merging objects closer. Dynamical formation can be broadly divided into several categories based on environment. Historically, the focus has been primarily on young star clusters and globular clusters, where dynamical formation has been explored by Sigurdsson and Hernquist (1993), Kulkarni et al. (1993), Portegies Zwart and McMillan (2000), O'Leary et al. (2006), Banerjee et al. (2010), Downing et al. (2011), Morscher et al. (2015) through a mix of numerical gravitational experiments and semi-analytical estimates. We illustrate the expectations for globular cluster dynamical formation with another Drake's equation before discussing other dynamical formation environments: galactic nuclei and hierarchical triple systems.

4.2.1 Young star clusters and globular clusters

The compact objects in the cluster may or may not have started out in the same binary. In the classical version of dynamical formation in a dense stellar environment the black holes, being heavier than other cluster objects, sink toward the centre of the cluster through mass segregation (Spitzer 1969; Binney and Tremaine 2008). Once there, they readily form binaries or substitute into existing binaries through three-body interactions: in a binary-single interaction, the lightest object is most likely to be ejected, while the two heavier objects remain behind in a binary (Sigurdsson and Phinney 1993; Ginat and Perets 2021). If the binary is hard—i.e., if its orbital velocity is larger than the velocity dispersion for the case of comparable component and interloper masses—subsequent interactions will further harden the binary as the energy of the binary is shared with the interlopers. Eventually, the binary may harden enough for gravitational waves to take over, provided the interaction rate is sufficiently high and the binary is not prematurely ejected from the cluster. This suggests that the number of BH–BH mergers per globular cluster is:

$$\begin{aligned} N_{\mathrm{BH-BH,\,cluster}} &= N_{\mathrm{stars}} \times f_{\mathrm{BH}} \times f_{\mathrm{retain}} \times f_{\mathrm{merge}} \\ &\sim 10^6 \times 0.001 \times 0.2 \times 1 = 200. \end{aligned} \tag{4}$$

Here, we focus on BH–BHs, because neutron stars, being lighter, are preferentially ejected during interactions, reducing their formation rate (Ye et al. 2020). We consider the heaviest globular clusters with $N_{\mathrm{stars}} \approx 10^6$ stars. We optimistically assume that all $\gtrsim 20\,M_\odot$ stars will form a BH, ignoring the likelihood that natal kicks will eject some of the BHs from the cluster, whose escape velocity is only $\sim 50\,\mathrm{km\,s^{-1}}$. This sets $f_{\mathrm{BH}} \approx 0.001$. In order for a binary to merge through the emission of gravitational-waves within 10 Gyr, its orbital velocity must be $\sim 500\,\mathrm{km\,s^{-1}}$ (Peters 1964). This is almost two orders of magnitude larger than the typical velocity dispersion of $10\,\mathrm{km\,s^{-1}}$. Tens of strong binary-single scattering interactions, mostly with other black holes, will be necessary to harden one binary by two orders of magnitude (Quinlan 1996). Once the binary becomes sufficiently hard, the lightest of the three interacting objects will typically be ejected from the cluster, depleting the fraction of retained black holes by a factor of a few (Heggie and Hut 2003). We therefore set the fraction of black holes retained for possible mergers to $f_{\mathrm{retain}} \approx 0.2$. Finally, we consider a cluster sufficiently dense (central BH density above $\sim 10^5\,\mathrm{pc^{-3}}$) that most of the BHs that avoid being ejected do succeed in merging within 10 Gyr, so that $f_{\mathrm{merge}} = 1$. Even with these optimistic assumptions, and allowing for a constant merger rate over the 10 Gyr lifetime of globular clusters, whose space density is $\sim 1\,\mathrm{Mpc^{-3}}$, we estimate a maximum merger rate of $200 \times 10^9\,\mathrm{Gpc^{-3}} \times 10^{-10}\,\mathrm{yr^{-1}} = 20\ \mathrm{Gpc^{-3}\,yr^{-1}}$.

This very crude estimate helps highlight some of the issues that may impact the event rates. What is the fraction of compact objects retained in clusters despite natal kicks? What were the initial properties (mass distribution, binary fraction, density, velocity dispersions) of globular clusters, before the $\gtrsim 10\,\mathrm{Gyr}$ of evolution typical for the locally observed clusters (Fragione and Kocsis 2018)? What fraction of merger products avoid being ejected by gravitational-wave recoil kicks and can be reused for subsequent hierarchical mergers (Rodriguez et al. 2018; Gerosa and Fishbach 2021)? What role does ongoing stellar evolution, including BH growth through tidal disruption of stars and gas accretion (Vesperini et al. 2010), play in dynamical formation? While multiple approaches to modelling cluster gravitational dynamics (e.g., N-body and Monte Carlo models) are expected to yield consistent results, the range of predictions highlighted in the executive summary tables and figures illustrates the impact of different approaches to answering the questions posed in this paragraph.

4.2.2 Nuclear star clusters

Dynamical formation has also been explored in the context of nuclear clusters in the centres of galaxies. Miller and Lauburg (2009) and Antonini and Rasio (2016) pointed out that nuclear clusters in the absence of a massive black hole, which are characterised by deeper potentials and hence higher escape velocities than globular clusters, could be promising environments for BH–BH dynamical formation. O'Leary et al. (2009), Tsang (2013), Hoang et al. (2020), Rasskazov and Kocsis (2019) explored direct gravitational-wave bremsstrahlung captures from 2-body scattering. Other potential contributions include the deposition of stellar-mass black holes near a massive black hole by the infall of a globular cluster (Arca-Sedda and Gualandris 2018). We quote a selection of the latest predictions for all of these channels in the executive summary.

Meanwhile, Bellovary et al. (2016), Bartos et al. (2017), Stone et al. (2017), McKernan et al. (2018) emphasised the important role that an accretion disk in an active galactic nucleus could play in enhancing the rate of binary black hole mergers. The rich physics of the deep potential well combined with gas interactions can yield new merger channels (Tagawa et al. 2020). Compact objects may be captured by the disk or directly form in the disk; in fact, gas may not even be strictly necessary for this, as vector resonant relaxation against the stellar background could naturally lead massive objects to settle into a dis (Szölgyén and Kocsis 2018). Migration traps have been suggested as breeding grounds for dynamical interactions that will enhance the BH+BH merger rate (Bellovary et al. 2016; Yang et al. 2019; Secunda et al. 2019; Peng and Chen 2021), although there is robust debate in the literature about their efficacy (e.g., Pan and Yang 2021). Gas accretion may aid gravitational waves in driving binaries toward merger as well as grow the black hole mass. Meanwhile, the very high escape velocity in the vicinity of a supermassive black hole ensures that recoil kicks are unlikely to eject merger products, so hierarchical mergers should be more common than in other dynamical environments (Yang et al. 2019; Secunda et al. 2020; Tagawa et al. 2021). The rich physics of active galactic nuclei make this channel both promising and complex, with many details such as the feedback from BH-gas interaction and accretion remaining a topic of ongoing work, leading to a broad range of merger rate predictions (Tagawa et al. 2020).

4.2.3 Hierarchical 3-body systems

Another notable dynamical formation channel involves hierarchical triple systems (see Naoz 2016 for a review). In these systems, the transfer of angular momentum back and forth between the inner binary and the wider outer orbit of the third companion can cyclically increase the eccentricity of the inner binary (Lidov 1962; Kozai 1962). Once the eccentricity of the inner binary becomes sufficiently high, energy can be dissipated by gravitational waves or tides. This could drive the inner binary to merger (e.g., Wen 2003; Liu and Lai 2018). This channel may operate in a number of regimes, from isolated stellar triples (Silsbee and Tremaine 2017) to dynamically formed triples in clusters (Antonini et al. 2016) to triples in which the outer companion is a massive black hole in a galactic center (Antonini and Perets 2012; Hoang et al. 2018).

Unlike other dynamical formation scenarios, which are most promising for BH–BH mergers, hierarchical triples could be important for NS–NS formation, although predictions are sensitive to assumed NS natal kicks (Hamers and Thompson 2019). Extensions to the triple channel include higher multiplicity systems, such as quadruples (Fragione et al. 2020; Hamers et al. 2021; Vynatheya and Hamers 2021). Some authors have associated specific gravitational-wave sources, such as GW190814, with formation in hierarchical triples (e.g., Lu et al. 2021).

The triple channel can also operate in conjunction with other channels. For example, stellar evolution and associated mass loss could force a previously stable stellar triple into instability or drive the inner binary toward merger (Perets and Kratter 2012; Shappee and Thompson 2013; Stephan et al. 2016), while chemically homogenous evolution and triple dynamics could produce sequential BH–BH mergers (Vigna-Gómez et al. 2021b). In fact, it is the combination of triple dynamics with stellar evolution, mass transfer, tides and gravitational waves (as well as the possibility of other dynamical interactions with external perturbers) which makes it particularly challenging to analyse. The uncertain initial conditions, such as a possible correlation between the mutual inclination, separations and eccentricities of the inner and outer binaries (Moe and Di Stefano 2017), query the efficacy of this channel (Toonen et al. 2020) (but see Rose et al. 2019, who find that the observed orbits of massive stars may be consistent with being driven by triple dynamics).

4.3 Exotica

So far, we focussed exclusively on black holes of astrophysical origin, rather than primordial black holes forming from the collapse of early-Universe perturbations. The latter are potentially very interesting sources of gravitational waves. Bird et al. (2016), Ali-Haïmoud et al. (2017), Chen and Huang (2018) have argued that a significant fraction of dark matter could be contained in black holes with masses of tens of solar masses, and their mergers could be responsible for some of the gravitational-wave signals observed to date. However, even allowing for a significant amount of mass in primordial black holes, merger rate predictions are sensitive assumptions about the initial distribution of such sources in binaries or small clusters (e.g., Ali-Haïmoud et al. 2017; Korol et al. 2020; De Luca et al. 2020a) as well as possible accretion onto primordial black holes (De Luca et al. 2020b). Meanwhile, some of the scenarios proposed for the formation of BH–BH binaries involve physics beyond the standard model (Sakstein et al. 2020) and cosmological coupling (Croker et al. 2021).

The discovery of the BH–BH merger GW190521, which left behind a $\sim 150\,M_\odot$ remnant (Abbott et al. 2020c), naturally renews interest in the possibility of intermediate mass black hole (IMBH) mergers. IMBH mergers may be a natural consequence of binary or dynamical evolution (e.g., Amaro-Seoane and Santamaría 2010; McKernan et al. 2012; Belczynski et al. 2014), and the gravitational waves from mergers of few hundred solar-mass IMBHs could be detected by current instruments (Veitch et al. 2015; Graff et al. 2015; Abbott et al. 2017d). Alternatively, stellar-mass compact objects could spiral into IMBHs in clusters. These intermediate-mass-ratio inspirals are also potentially detectable as gravitational-wave signals (Mandel et al. 2008; Haster et al. 2016b, a). However, the prevalence of IMBHs remains highly uncertain despite a variety of approaches to their detection (e.g., Pasham et al. 2014; Paynter et al. 2021). The challenges associated with observing IMBHs are discussed by Miller and Colbert (2004) and Greene et al. (2020). Given the many orders of magnitude uncertainties, we resist the temptation to review the merger rates of binaries involving IMBHs. Similarly, we do not specifically discuss hierarchical mergers of stellar-mass black holes or IMBHs as a channel for forming supermassive back holes at high redshifts (e.g., Volonteri 2010; Kroupa et al. 2020). The heaviest merging binaries observed through gravitational waves could represent the tail end of this process of hierarchical massive black-hole formation associated with mergers of ultra-dwarf galaxies (Palmese and Conselice 2021), and many more such mergers may be observable with third-generation gravitational-wave detectors (Gair et al. 2009).

5 Outlook

We reviewed the current estimates of compact-binary merger rates, including both direct observational constraints and theoretical models motivated by observations. We highlighted some of the key sources of uncertainty in both observations and models. Of course, these uncertainties can be alternatively viewed as opportunities.

The number of observations is growing rapidly. The number of direct gravitational-wave detections has grown from 0 to 50 between 2015 and 2020. The range, the number of observed sources, and the measurement accuracy will all increase as the detector sensitivity improves (Abbott et al. 2020b). Eventually, third-generation gravitational-wave instruments will be able to precisely probe the evolving compact binary merger rate and mass distribution across cosmic time (e.g., Kalogera et al. 2019; Ng et al. 2021). The number and quality of electromagnetic observations are also rapidly growing, again with a very positive outlook, e.g., for kilonovae as new instruments like the Vera C. Rubin Observatory come online (e.g., Chase et al. 2021).

These improvements in observations are being matched by a growing sophistication in the models. On the one hand, increasingly complex models of binary evolution and dynamics are sensitive to a broad range of uncertain assumptions about initial conditions, stellar evolution, mass loss, mass transfer, supernova kicks, and the cosmic star formation history of the Universe. On the other hand, there is growing evidence that observations of the rates and properties of compact-object mergers, coupled with other observational constraints, will make it possible to resolve these uncertainties and come away with a deep understanding of the physics of compact binary formation (e.g., Mandel and O'Shaughnessy 2010; Stevenson et al. 2015; Barrett et al. 2018; Wong et al. 2021).

While we focussed on overall rate estimates in this review, specific formation channels are likely to carry distinguishable observational signatures. We mention two predictions for merging binary black holes by way of example. Dynamically formed binary black holes should have isotropically oriented spin directions, while BH–BH mergers from isolated binary evolution are expected to have spins preferentially aligned with the orbital angular momentum (e.g., Farr et al. 2017; Rodriguez et al. 2016b). Is there already evidence for a separate population of dynamically formed systems based on spin-orbit misalignment angles (Abbott et al. 2021c; Roulet et al. 2021; Galaudage et al. 2021)? Meanwhile, the orbits of most binary black holes are expected to circularise through gravitational-wave emission by the time they approach merger and become detectable with current instruments (Peters 1964). But a $\sim 5\%$ fraction of binaries that evolve through binary-single dynamical scatterings may buck the trend, becoming captured at very high eccentricities and small separations through gravitational-wave bremsstrahlung during chaotic interactions (Samsing et al. 2014; Rodriguez et al. 2018). Could the tentative evidence for eccentric binary black holes in gravitational-wave data (Romero-Shaw et al. 2021) lead to an inferred measurement of the rate of dynamically formed binaries (Zevin et al. 2021)?

Reviewing such a rapidly developing field presents obvious challenges, and we are aware that we have only shown a selection of highlights. We hope that this is still a useful snapshot of the status of the field against which future rapid progress can be compared. In fact, we find ourselves in the awkward position of wishing for this review to become obsolete soon after it is written, to be updated as the field moves forward!

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