Merging stellar-mass binary black holes

Based on the review by Ilya Mandela,b,c, Alison Farmerd
[Merging stellar-mass binary black holes (arxiv.org)]

Abstract

GW detections of compact binary mergers raise the hope that these could be used as a probe of stellar and binary evolution, and perhaps tellar dynamics.

This article summarizes:
The existing observations;
Theoretical predictions for formation channels (for stellar mass BBHs) with their rates and their observable properties;
Some prospects for GW astronomy

Introduction

Within up-to-date detections, we are only beginning to xplore the population of mergering compact binaries. The understanding of the formation channels of GW sources s evolving with each new data release.

What questions may GW observation answer is itself a thrilling question.
Examples:
What can GW observation of merging binaries tell about **the stellar and binary evolution that preceded the mergers**?
Can observation constrain **the amount of mass loss and expansion experienced by massive stars**?
Or the stability and consequences of mass transfer, including the infamous common envelope phase of evolution?
Or the amount of mass fallback during supernova explosions, or the kicks that supernovae impart to compact objects?
Does the redshift distribution of merging compact objects contain an imprint of the star formation history of the Universe?
Can we use these mergers to probe dynamics in dense stellar environments such as globular clusters?
...

In the following sections, we:
Summarize the **existing observations of merging binary black holes and closely related**

systems.
Describe the **plausible formation scenarios for BBHs**.
Discuss the predicted **merger rates and merging objects properties**.
Speculate about the **prospects for GW astronomy**.

2. OBSERVATIONS

2.1 GW Observations

2.1.1 Confirmed detections to-date

2.1.2 Information encoded in GW signals

GW signature encodes the properties of the GW source - n today's context - merging BBHs (or BNS, BHNS): component masses and spins. (Refer to waveform modeling articles like [288]). Coupled with multiple detectors, we ca infer the sky location and orientation, and the distance of the GW source.

Some of the source parameters are strongly correlated.
For heaviest BBHs, **total mass** is measured more accurately, cuz the latest stage of waveform - ringdown - whose frequency is a function of total mass - falls in the sensitive frequency band of current GW detectors.
For lower mass BBHs, **chirp mass** is the better measured parameter, since it determines to lowest order the rate of frequency evolution during the early inspiral stage of waveform.
The **mass ratio** is often **poorly constrained**, cuz it enters the GW phase evolution uring inspiral at a higher order in the ratio of orbital velocity to the speed of light, and is particularly degenerate with the BH spins.

2.1.3 Information extracted from observed GW signals

Masses

Range from about 2.6 to 80 solar masses. There is a significant **selection bias toward detecting more massive systems** (cuz detectors sensitivity has a dependency on system mass). (Reasons...)
Once selection effects are accounted for, mass distribution for **more massive BHs** appear to be consistent with a **power law of index** 3.4, reminiscent of the **stellar initial mass function** [280].
A **peak** at about 34 solar masses.
The vast majority BBH merges have both components masess bellow 45 solar masses.
Most detections are consistent with **having equal-mass components**, with exceptions.

Spins

Individual spins of BBH components are **difficult to measure precisely** via GWs.
Most detections are consistent with having **negligible spins**; but some events show evidence of **zon-zero effective spin** $\chi_{\rm eff}$ (defined as mass-weighted dimensionless spin along the orbital angular momentum of merger).
Spin distribution is still a topic of active ongoing discussion. **Galaudage**: 80% of merging BBHs have negligible spins on both components, the remaining have **positive and preferentially aligned spins**, no observed event displaying a definite negative $\chi_{\rm eff}$.
The **degree of precession** due to **spin-orbit misalignment** is also **unclear**.

Distance and Sky Location

All observed BBH signals ame from **medium redshifts** between $z = 0.05$ to $z = 0.9$, consistent with the sensitivity of detectors in the first three observing runs.

With just two operating detectors of LIGO, events prior to GW170814 could only be localized to 90% credible interval spans hundreds to more than one thousand square degrees n the sky; the participation of Virgo reduce the predicted sky region of the source of GW170824 to only 60 square degrees. Nonetheless, **association with specific host galaxies re impossible for all observed events**.

Eccentricity

Some detections show signs of **non-negligible eccentricity**.
However, there is a possible **degeneracy** between eccentricity and precession. And analysis generally do not include both effects.

Confidence of GR

Merger Rate

The uncertainty in BBH mass distribution is relayed into the uncertainty on the inferred merger rate.

There is strong evident that **merger rate increases with redshift.**

2.2 Electromagnetic Observation

EM observations of systems at various stages along the possible paths to BBH formations. (progenitors?)

In this section we describe some of the key electromagnetic observations that shed light on compact object binary formation and evolution preceding the merger.

A wide variety of EM observations inform our understanding of **stellar evolution of massive stellar binaries**, including:
The **initial mass and period** distributions of binary stars **at formation**.
Luminous red novae, which may be associated with common envelope events.
Galatic binary radio pulsars.
Short gamma ray bursts.
Supernovae and long gamma-ray bursts.
X-ray binaries.
Black holes in detached binaries, and microlensing observations.

2.2.1 X-ray binaries

Black-hole X-ray binaries consist of **a star transferring mass onto a black hole companion**, leading to the **emission of X-ray radiation from the accretion disk surrounding the black hole**.

X-ray binaries containing accreting black holes can be divided into **two categories**, low-mass and high-mass, in reference to the mass of the black hole's companion star.
The accretion process differs between the two types:
In **low-mass X-ray binaries**, the tidal gravitational pull of the black hole causes mass to stream from the companion onto the black hole in the process known as **Roche-lobe overflow**;
While in **high-mass X-ray binaries**, the black hole accretes only a fraction of the material (stellar wind) driven off the companion's surface.

Now lets move to the information we can extract from EM observations of X-ray binaries.

Black-Hole Masses

Until recently, black-hole X-ray binaries with dynamical mass measurement provided the **only secure measurement of BH masses**, other than GW observations. (This situation has changed thanks to **observations of detached binaries** and **micro-lensing data**.)

Range from 5 to over 20 solar masses.

Spin Magnitudes

Continuum fitting of the X-ray flux from the accretion disk and iron K-α line fits to the disk reflection profile can both be used to infer the location of the inner edge of the disk, which is assumed to correspond to the radius of the innermost stable circular orbit, a sensitive function of black-hole spin.
Quasi-periodic oscillations also have the potential to provide spin measurements.
Unfortunately, the underlying physical mechanisms are not fully understood at present, and the inferred spins may suffer from significant systematics

Spin Directions

We know even less about spin directions than magnitudes.

Misalignment? Realighment?
(Between orbital angular momentum and caomponent spin?)

Inconsistency with Spin Measurement from GW Observations? (INTERESTING)

All three high-mass X-ray binaries with available spin measurements – Cygnus X-1, LMC X-1 and M33 X-7 – **show evidence of rapid dimensionless spins in excess of & 0.85, where 1 is the spin magnitude of a maximally spinning black hole** [266]. This is significant, because unlike long-lived low-mass X-ray bina ries, whose spin magnitudes could be altered by accretion from the companion, especially if they started out with intermediate-mass companions [257, 125], high-mass X-ray binaries are too short-lived to enable significant spin changes due to accretion [159].
Isolated binaries that form binary black holes are expected to go through the high-mass X-ray binary phase during their evolution (though Hirai & Mandel [144] argue that only binaries with optical companions that are close to Roche-lobe overflow may be X-ray bright). **Thus, if the high spin magnitude measurements in black-hole X-ray binaries are to be believed, then the observed high-mass X-ray binaries and merging binary black holes should predominantly sample different evolutionary histories** (see section 4.2.3).

2.2.2 Other EM measurements on BH masses

Detached Binaries

Until recently, only stellar-mass black holes in X-ray binaries allowed accurate dynamical mass measurements. However, this has recently changed with observations of wide binaries with a luminous companion detached from a non-accreting black hole.

Micro-lensing

Microlensing observations provide a tool for measuring the masses of single black holes. When such black holes pass between a luminous star and the observer, they temporarily lens the star, increasing its luminosity while the alignment is roughly within the lens's Einstein ring. Mircolensing measurements, together with gravitational-wave and detached black-hole binary observations, **suggest that there is no evidence for a mass gap between neutron stars and black holes** [344, 229]

Selection Effects

Finally, it is worth remembering that all observations are likely to suffer from a range of selection effects. These could be:

Malmquist biases which favour observations of the brightest or loudest sources, such as the enhanced detectability of more massive binaries in gravitational-wave data or of more rapidly accreting X-ray binaries (though more complex detectability thresholds related to wind morphology may be relevant for high-mass X-ray binaries [144]).

Alternatively, they could be **evolutionary selection effects** which can skew the observed populations; for example, X-ray binaries may contain few low-mass black holes, creating an impression of a mass gap between neutron star and black hole masses, if low-mass black holes get larger natal kicks that tend to disrupt binaries [201].

3. FORMATION SCENARIOS

When the detection of GW150914 was first announced, many were surprised that:

It's a BBH instead of a BNS, since there was **no direct evidence for merging binary black holes until GW150914**.

It's **high BH masses, exceeding all that observed by EM observation on BH X-ray binaries**.

Below, we explain why – on the face of it – **it is rather startling that compact massive binaries exist at all**.

We then describe the leading **candidate formation channels**.

(And in the next section we discuss **the ways in which gravitational-wave observations might be used to distinguish them**.)

3.1 Why It's Startling Compact Massive Binaries Exist - The Orbital Separation Question

Only Very Tight Binaries can Merge via GW (Emission?)

GW emission is a very strong function of separation.

During a compact binary merger, the luminosity in gravitational waves is a few thousandths of the Planck luminosity, c 5/G [e.g., 81]; at nearly 1057 ergs per second, such mergers “outshine” all the stars in the visible Universe combined.

But because **GW luminosity is inversely proportional to the fifth power of binary separation**: widely separated binaries loose energy very slowly; only very close binaries can be brought to merger by GW emission within the age of universe.

(For the two ~ 30M black holes responsible for GW150914, the initial separation at periapsis must have been **less than ~ 50R** – just a quarter of the distance from the Earth to the Sun – if the merger was driven by gravitational-wave emission alone.)

But Progenitor Stars Can NOT Get So Close

Stars expand as they evolve.
The stars that evolve into BHs (these stars have initial mass above 20 solar masses) may reach thousands of solar radii at their maximum size.
There appears to be a problem: **If the parent stars begin life in a close binary with a separation from which gravitational waves could bring their remnants together**, the stars will expand to sizes much larger than their separation as they evolve, and we might therefore expect that they would merge long before they collapse into black holes. **If they start sufficiently far apart to avoid merger before collapse into black holes**, their remnant binaries will take many millions of times longer than the age of the Universe to merge. In either case, no gravitational-wave sources would exist today.

The Problem is Already There at Birth

实际上，根据合理的质量损失模型（包括由恒星风驱动的质量损失和超新星爆发时的质量损失），即使是主序星阶段初始恒星半径也太大，无法形成一个仅通过引力波辐射就能在宇宙年龄内合并的双星系统。**图3中黑色“洛希瓣”曲线** 显示了恒星能够适应于一个圆形轨道、等质量双星系统并最终合并的最大可能尺寸（参见图2）。这个最大尺寸比图中所示所有恒星质量对应的零龄主序星半径都要小：**因此，即使不考虑恒星膨胀或由于质量损失导致的双星轨道扩张，这一“分离问题”仍然存在**
In fact, for reasonable models of wind-driven mass loss and mass loss during supernovae, even the initial stellar radii at the start of the main sequence are too large to fit into a binary that could merge within the age of the Universe just through gravitational-wave emission. The black ‘Roche Lobe’ curve in Figure 3 shows the maximum size that a star could have in order to fit into a circular, merging equal-mass binary (see Figure 2). This size is smaller than the zero-age main sequence radius for all stellar masses shown in the figure: the separation problem thus exists even without accounting for the exacerbating factors of stellar expansion or binary widening through mass loss.

So Why fo the GW Sources Exist At All - Problem to the Solve

In fact, Dyson [105] conjectured about the existence of merging neutron star binaries even before the first neutron star was observed; Tutukov & Yungelson [324] predicted that binary compact objects must naturally (albeit rarely, and at wide separations in their model) form as a result of massive binary evolution; van den Heuvel & De Loore [327] argued that tight high-mass X-ray binaries – progenitors of compact object binaries – must also form; and the Hulse–Taylor binary pulsar [150] demonstrated the existence of binary compact objects that would merge within the age of the Universe [for early explanations of its formation in the context of binary evolution, see 122, 91].

The proposed formation scenarios for merging compact binaries **generally fall into two categories**:

1. The **evolution of isolated binaries composed of two massive stars**;
2. Binaries form or merge with the assistance of **gravitational dynamical interactions**.

Bellow we discuss four examples of these scenarios:

1. Finely tuned **binary evolution** that **brings the stars closer as they expand and interact**;
2. Finely tuned **stellar evolution** that **prevents the parent stars from expanding at all**;
3. **Assembly** of a close binary from black holes that formed from stars not born in the same binary;
4. **Stellar and binary evolution and dynamic**s operating jointly in triple systems.

(We will not discuss some of the **more exotic proposed mechanisms**, such as the fragmentation of a single stellar core into two black holes [188] (Woosley [342] and Dai et al. [90] discuss the problems with this picture); cosmological coupling [89]; or physics beyond the standard model [279].

We **limit our discussion to black holes of astrophysical origin**. Mergers of primordial black holes formed through the collapse of early-Universe density perturbations have been proposed as sources of gravitational waves [73].
The **contribution of primordial black hole mergers to the observed population of gravitational-wave signals** is sensitive to the masses of primordial black holes, the total fraction of dark matter they comprise, their initial distribution in binaries or small clusters, and the possibility of gas accretion onto primordial black holes)

And as we will see in section 4, only a small fraction of stars, of order one in a million, need to end up in merging black-hole binaries in order to explain the observed merger rates: even quite unusual or (apparently) finely tuned evolutionary pathways could therefore be viable candidates.

3.2 The Candidate Formation Scenarios (IMPORTANT)

I need to read this part again when possible.

3.2.1 Coming closer later in life: classical isolated binary evolution via the common-envelope phase

This channel is the most studied one.

The two stars are **born in a relatively wide separation**, allowing them space to expand. However, at a critical moment in its evolution, the binary is **tightened by a factor of two or**

more orders of magnitude through **dynamically unstable mass transfer**, known as a **common envelope phase** [187, 154]
The resulting tight binary may then be **close enough to merge through gravitational-wave emission**.

Rather than summarizing all of the steps and challenges in our understanding of massive binary evolution (see the papers above and the review by Postnov & Yungelson [260] for details), we provide **a schematic outline of an evolutionary scenario that leads to the formation of a GW150914-like merging system**.

A Schematic Outline of this Channel

Check the diagram fig.

1. Two massive stars of **perhaps 100 and 75 solar masses** are born in a binary at a **separation of ~ 10 AU in a low-metallicity environment** (~ 5% of solar metallicity, or metal fraction — the fraction Z of the star's mass contained in elements heavier than hydrogen and helium).
2. The more massive **primary reaches the end of its main sequence evolution first**. At this stage, it has completed fusing hydrogen into helium in its core, and with the loss of energy input, **the core begins to contract**. The associated release of gravitational binding energy and the eventual onset of hydrogen shell burning cause the **hydrogen-rich envelope to expand**. **For a sufficiently close binary, the primary expands past the equipotential surface known as the Roche Lobe and begins to transfer mass onto the secondary.** (This mass transfer proceeds on the thermal timescale of the primary donor and could be significantly non-conservative, as the less evolved secondary, with its correspondingly longer thermal timescale, is unable to accept mass at the rate at which it is being donated. **The loss of mass from the binary, in addition to wind-driven mass loss, can widen the system to perhaps ∼ 20 AU.**)
3. The **primary loses its entire envelope**, leaving behind a n**aked helium burning star – a Wolf-Rayet star**.
4. Following **wind-driven mass loss**, which **further widens the system**, the **primary collapses into a black hole**; this collapse may be complete, or there may be some ejected mass and an associated natal kick.
5. When, a **few hundred thousand years later**, **the secondary reaches the end of its main sequence**, the process repeats in reverse: **the secondary expands until it commences mass transfer onto the primary**. By this time, the primary has lost around two thirds of its initial mass through a combination of envelope stripping, winds, and possible mass loss during a supernova (if the fallback is not complete). **The mass transfer onto the black hole would need to be almost wholly non-conservative if the accretion obeys the Eddington limit**, which corresponds to an equilibrium between

gravity and the pressure of the radiation released during accretion on infalling material. **Mass transfer from a massive donor to a lower-mass accretor adds specific angular momentum to the transferred mass, so conservation of angular momentum requires that binary's orbit to shrink**. Consequently, mass transfer would lead to a rapid hardening of the binary at a rate that is faster than the reduction in the size of the secondary donor as it loses mass. As a result, **the more mass it donates, the more the donor overflows its Roche lobe**.

6. This runaway process of dynamically unstable mass transfer leads to **the formation of a common envelope of gas** (from the donor's envelope) around the binary. The drag force on the black hole from the envelope leads to **rapid spiral-in**. **The dissipated orbital energy is deposited in the envelope, and may ultimately lead to the expulsion of the envelope**.
7. **After the expulsion of the common envelope**, the resulting black hole – **Wolf-Rayet binary** has a separation of only **~ 35R** in this example.
8. Following further **wind-driven mass loss from the secondary** and **its collapse into a black hole**, **the black-hole binary is formed**. While this entire process takes only a few million years from the formation of a stellar binary to the formation of a binary black hole, **the subsequent inspiral through gravitational-wave emission will last for around 10 billion years before merge**r.

3.2.2 Abracadabra, thou shalt not expand: chemically homogeneous evolution

Without an expansion phase, the parent stars would be in no danger of merger;
if almost all of the star's mass was converted into a black hole rather than the ~30–50% of the mass which typically becomes the helium core, the merger timescale would shrink for a given separation, lifting the Roche lobe radius curve in Figure 3 and removing the "separation problem at birth".

No fine-tuning of binary evolution would then be required to construct a plausible formation scenario for tight black-hole binaries. **Efficient mixing in high-mass, low-metallicity stars in close binaries, known as chemically homogeneous evolution, could enable this scenario.**

A Schematic Outline of this Channel

1. Binary companions raise **tides** on each other, much like the Moon's tides on Earth. If a binary is tight enough that each star fills a significant fraction of its Roche lobe, tidal energy dissipation is rapid and proceeds until the stars are **tidally locked**, i.e. the rotation periods of the stars are synchronised to the orbital period of the binary. **This also means that the stars are rotating at a few tens of percent of their break-up velocities.**

2. Such rapidly rotating stars will develop **significant temperature gradients between the poles and the equator**, which may **lead to efficient large-scale meridional circulation within each star** [106, 306]. Endal & Sofia [112] and subsequent studies [e.g., 141, 191, 346, 308] explored the internal shears and their impact on the mixing of chemical species within the star. Although quantitative predictions differ, it appears that rapidly rotating massive stars may efficiently transport hydrogen into the core and helium out into the envelope until nearly all of the hydrogen in the star is fused into helium.
3. Then, **at the end of the main sequence**, the star behaves essentially as a **Wolf-Rayet naked helium star**, contracting rather than expanding. As long as the metallicity is sufficiently low that the wind-driven mass loss does not significantly widen the binary – which would lead to the loss of co-rotation and chemically homogeneous evolution [95] – the binary can avoid mass transfer.

(Comments)

3.2.3 The BH matchmaking club: dynamical formation in dense stellar environments

The merging BHs may not have formed in the same binary at all.
Instead, in this channel, they are remnants of independent massive stars, who are then introduced to each other by a 'matchmaker', or rather a whole array of 'matchmakers'.

A Schematic Outline of this Channel

1. Suppose the two BHs formed in a **dense stellar environment** such as a globular cluster.
2. As the most massive objects in the cluster, **the BHs segregate toward the cluster centre** as kinetic energy is equipartitioned by dynamical scattering interactions [298, 72], but see [322]. Once there, they may f**orm binaries through three-body interactions**, in which one of three initially unbound objects is endowed with sufficient kinetic energy to leave a bound binary, or by substituting into existing binaries: in a 2 + 1 interaction, the lightest object is usually ejected in favour of the two heavier objects forming a binary [143]
3. **If the orbital speed of the binary's components is greater than the typical speed of stars in the cluster (the binary is 'hard')**, then subsequent interac tions with other objects in the cluster – the matchmakers – will **gradually tighten the black-hole binary** [142]. The interlopers are likely to leave with slightly higher speeds than they arrived with, each time removing energy from the binary. (Meanwhile, 'soft' binaries, with orbital speeds smaller than the velocity dispersion in the cluster, will be disrupted.)
4. If the density of objects is high enough to ensure a suitable rate of inter actions, the binary will be hardened until it is compact enough to merge through gravitational-wave emission, provided it does not get kicked out of the cluster through a recoil kick from the last interaction – and even then, it may still go on to merge outside of the cluster.

3.2.4 A Team effort: combining multiple interactions

Of course, the channels outlined above need not be distinct, and the same binary may have benefited from multiple types of interaction while en route to coalescence.

New studies are now attempting to consistently combine **stellar and binary evolution and dynamics** at comparable levels of fidelity [e.g., 284].

...

4. EXPECTED PROPERTIES OF MERGING SYSTEMS

In this section we describe the expected hallmarks (imprints) of each formation channel, in the properties of observed BBH mergers.
Hallmarks on: merger rates, BH masses, mass ratio, spins, orbit eccentricities, formation environments.

Other than the LIGO and Virgo sources, there are no known direct observa tions of binary black holes (except for a very speculative potential observation through microlensing [101]).
As the population of gravitational-wave detections grows, so does our ability to infer merger rates and typical system properties from observed data (see the following section for a discussion of the current state of these efforts.).

In the meantime, our understanding of the expected merger rates and properties of binary black holes rests largely on theoretical modeling.

For the **isolated binary evolution channel** (section 3.2.1), this modeling typically uses a **population synthesis approach**, i.e., forward modelling of large populations of stellar binaries distributed according to observed initial mass and separation distributions, some (small) fraction of which end up merging as binary black holes. Population synthesis techniques can be applied either to initial binaries at formation, or to specific observed systems at intermediate evolutionary stages, such as Cygnus X-1 [76, 233] and Cygnus X-3 [60].
Models of the **dynamical formation channel** are typically based on either (i) computationally expensive **N-body cluster models with direct integration of the equations of motion for each object**, or (ii) a less computationally costly **Monte Carlo approach** in which the evolution of the distribution of the cluster components in phase space is coupled with stochastically sampled strong 3- body and 4-body interactions modeled with few-body dynamics, or (iii) semi analytical prescriptions that attempt to emulate these methods at a fraction of the computational cost.

Now lets move to the imprints of various formation scenarios on observables.

4.1 Merger Rate

Here we outline high-level estimates of merger rates for three candidate formation channels. The value of this back-of-the-envelope merger rate analysis is not so much in matching the rate inferred from gravitational-wave observations a posteriori as in setting the stage for some of the predictions of the properties of merging binaries (see below) and the discussion of evolutionary uncertainties (see section 5).

The merger rate predictions and observed rates are summarised by [195] (see [1] for a historical summary from a decade earlier).
Broadly, predictions **for isolated binary evolution**, including contributions from chemically homogeneous evolution and population III stars, **are consistent with or exceed the observed rate of binary black hole mergers of [16, 130] Gpc−3 yr−1 [31]**;
While predicted **dynamical formation** rates (including contributions from globular, nuclear, and young stellar clusters, as well as hierarchical triples) **tend toward the lower end of the observed merger rate**.

Now lets move to the predictions on merger rates from the three formation channels:

4.1.1 Binary evolution via the common-envelope phase

In order to survive an evolutionary pathway such as the one depicted in **Figure 4 (merging black-hole binary formation through isolated binary evolution via the common envelope phase)**, a binary must
(i) have the **right component masses** to form two black holes;
(ii) have the **right separation** to avoid a premature merger, yet be close enough to interact;
(iii) **avoid disruption by supernova kicks**;
(iv) engage in and survive a **common envelope phase**; and
(v) **end up sufficiently compact** at binary black hole formation to merge within the age of the Universe.
We describe below the development of a **"Drake equation" for the probability that an isolated stellar binary will end its life as a merging binary black hole**, addressing each of these five factors in turn. In reality, of course, the probabilities for each key stage are coupled in a rather complex manner.

(Derivations)

Merging probability predicted by **Drake equation** is about 5×10^{-6}.
Merging binary black holes are rare outcomes indeed! Merging binary neutron stars are similarly rare: while stars with initial masses sufficient to form a neutron star, between roughly 8 and 20 solar masses, are more common than the heavier stars necessary to form black holes,

neutron star natal kicks and mass loss during supernovae are more likely to disrupt binaries; the expected yields for binary neutron star mergers are within an order of magnitude of those for binary black holes.

Local **merger rate... of ∼ 50 Gpc−3 yr−1**
population synthesis...

4.1.2 Chemically homogeneous evolution

We can write a similar **Drake-like equation** for the chemically homogeneous evolution channel. Following Mandel & de Mink [197], the yield fraction is about 10^{-6}.

If this channel is viable, t**he rate of binary black hole mergers produced through the chemically homogeneous evolution channel could reach perhaps ∼ 10 Gpc−3 yr−1** , which is one fifths of the common-envelope channel, but with a preference for much higher masses than classical isolated binary evolution.

4.1.3 Dynamical formation

...

The **upper limit** on the merger rate from this channel is ∼ 1000 × 10−10yr−1 × 1 Mpc−3 ≈ **100 Gpc−3 yr−1 .** Which is twice the prediction of common-envelope channel.
...

(comments)

4.2 System Properties

4.2.1 Masses

The masses of black holes in the binaries of interest **will not change appreciably after the black hole has formed** by stellar collapse or supernova explosions.
The **first** black hole to form is unlikely to accrete a significant amount of mass from its companion: doubling its mass would take more than 100 million years, as the mass-gain rate is M /M˙ . 10−8 yr−1 at the Eddington limit, and the massive companion will only survive as a non-degenerate potential donor star for a small fraction of that time (though some models allow super-Eddington accretion [111, 57, 329]);
No further accretion is expected in the system after the second compact object is formed, except in very gas rich environments like active galactic nuclei.
The mass of each black hole is thus almost equal to its mass at formation.

Isolated Binary Evolution Channel

Broad **mass range**, matching most observations.
In fact, contrary to mistaken lore, the high masses of the first observed black holes were not entirely surprising: such systems were predicted to form in low-metallicity environments [206, 59] and to make a signifi cant contribution to the detected population because more massive binaries emit more energy in gravitational waves [100]; the effect of metallicity is discussed further in section 4.2.5 below.

Dynamical Formation in Globular Clusters

Also lead to a range of masses, but **many favor more massive binaries**, lighter black holes would be ejected by heavier ones in three-body interactions [273].
The **mass distribution is sensitive to natal kicks**, which may eject BH at formation.
Chatterjee et al. [82] argued that dynamical formation could explain most black hole binary merger observations, with old, metal-poor clusters preferentially contributing more massive black-hole binaries and younger, metal-rich clusters contributing lighter binaries

Chemically Homogeneous Evolution

This channel can **only produce massive binaries**, with system's total mass above about 50 solar masses.

Challenges for All Channels Above: Component Mass Over 50 Solar Masses

The **first is how to explain merging components above about 50 solar masses**.
Models suggest that black holes in this mass range should not exist, as their progenitors would lose mass through **pulsations** or **explode completely in pair-instability supernovae**, driven by a sudden drop in the radiation pressure support as high-energy photons spontaneously produce electron positron pairs [e.g., 343, 114].

While early gravitational-wave observations appeared consistent with a **maximum component mass** and a**n excess of ≈ 30–40M black holes due to pulsational pair-instability supernovae** [e.g., 303];
This is no longer the case with systems like GW190521, whose components fall into the **anticipated pair-instability mass gap**.

Possible explanations include:
Multiple generations of BH mergers in clusters;
Additional growth due to accretion, particularly in an **active galactic nucleus gas disk**;
A **reassessment of the location of the pair-instability mass gap**.

Another Challenge: Very Asymmetric Binaries

Very asymmetric binaries, particularly **GW190814**, present another challenge for most evolutionary channels [349, 201];
one recently proposed scenario relies on the possibility that some massive progenitors may leave light remnants be hind, particularly if their explosibility is enhanced by a change in compactness due to previous episodes of mass transfer [42].

4.2.2 Mass ratio

Isolated Binary Evolution Channel

Mass ratio likely to be **one the equal side of 2:1**.
Because of the mass ratio constraint for: **stable mass transfer from the primary to the secondary** and the following **unstable reverse mass transfer**.

Dynamical Formation Channel

May also favor **comparable masses**.
Because the **heaviest black holes** in a cluster are **most likely to merge with each other following dynamical exchanges**.

However, **more extreme mass ratios are also possible** if the globular cluster contains a particularly heavy stellar-mass black hole or a about 100M intermediate-mass black hole that merges with lower-mass black holes [196, 62

Chemically Homogeneous Evolution Channel

Has a **much stringer preference for euqal masses**.
Marchant et al. [211] and Riley et al. [267] concluded that nearly equal-mass black holes would be produced from the evolution of systems that were in contact (shared mass) on the main sequence, before disengaging during subsequent phases of chemically homogeneous evolution and proceeding along the pathway sketched out in section 3.2.2.

4.2.3 Spin magnitudes and directions

The spins of merging black holes may carry imprints of their evolutionary history [e.g., 128].

Spin Directions

Isolated binary formation channel and **chemically homogeneous evolution channel** both expects:
to have **preferentially aligned spins**, since they have undergo episodes of mass transfer and/or tidal coupling;
although natal kicks and possible spin tilts during supernovae **could lead to misalignment**.

Dynamical formation channel on the other hand, expects **spin directions** to be distributed **isotropically**.

On the other hand, black holes merging through the **Lidov-Kozai resonance in hierarchical triples** could preferentially have spins in the orbital plane [185, 270].

Spin Magnitudes

A **massive star** may contain a **large amount of angular momentum**, far in excess of the maximum allowed for a spinning black hole.
Of which the vast majority of that angular momentum will be **contained in the outer layers of the star** and can therefore readily be lost through winds or via envelope stripping by a companion.
Therefore, black holes formed from stars that were rapidly spinning at some point in their evolution may still spin slowly **unless** the stars are spun up through mass transfer or tides shortly before collapse [173, 148, 347], or, less likely, during the supernova itself [54, 289].
Consequently, if angular momentum transport within a star is at least moderately efficient, we may expect that the first-formed black hole **in an isolated binary** will always be slowly spinning, while the second born black hole will be rapidly spinning only in the tightest binaries, when its helium star progenitor can be spun up through tides

Meanwhile, there is active debate in the literature about the **black-hole spin distribution of gravitational-wave events (see section 2.1.3)**.
Among spin variables that remain approximately constant during the inspiral, gravitational-wave spin measurements most accurately constrain **the effective spin** χ_{eff} [263, 35], which enters the phasing of gravitational waves at the 1.5 post-Newtonian order [258].

Low spin magnitudes
Low values of χ_{eff} could point to **either low spin magnitudes or isotropically directed spins or a combination of both** [117], with **isotropic spin directions being the hallmark of dynamical formation**.

High (significant) spin magnitudes
The diverging conclusions regarding the fraction of binaries with **significant and preferentially aligned component spins** [28, 31, 278, 79, 127] appear to be a consequence of the chosen parametrized model, which may be mis-specified in some cases. At face value, the absence of confidently negative measurements of χeff and the roughly one fifth fraction of observed binaries with positive χeff inconsistent with zero suggest that **80% of observed binaries contain non-spinning black holes while 20% have moderate net spin in the direction of the orbital angular momentum**. This appears consistent with isolated binary evolution with occasional tidal spin-up as the dominant channel. The distribution of spin between binary

components, the degree of spin precession, and possible correlations between spins and masses remain open issues.

4.2.4 Orbital eccentricities

Because **gravitational waves are very efficient at damping out orbital eccentricity**, **isolated binaries are expected to merge on circular orbits**.

Dynamically formed systems may, however, **retain detectable eccentricities at merger if** their orbits are very tight at formation.

4.2.5 Formation environment (DNF)

5. PROSPECTS FOR GW ASTRONOMY

GW events to date have provided insights into:
astrophysics of **BBHs** and their **progenitors**,
but many questions remain open.

Fortunately, these observations indicate a **BBH merger rate of around 20 Gpc^{-3} yr^{-1} at redshift zero** with a **likely higher merger rate at higher redshifts** [31].
Which points to the **prospect of hundreds of detections within the next few years, once the LIGO and Virgo instruments reach design sensitivity [13]**

In this section, we describe some of the prospects for **extracting information from the growing data set of observations over the next few years**, including:
Single informative observations,
Population statistical inference,
And theoretical modeling.

5.1 Individual Exciting Events

i.e. those unpredicted by existing models

For example, for those we have observed in the past few years:
observation include **component mass in the predicted mass gap** due to pair-instability supernovae;
observation include **component mass in the possible mass gap** between NS and BH.
With GW190521 and GW190814, both have now been observed.

Other exciting events include:

Intermediate mass BH (about a few hundreds solar masses).
This indicates the formation history:

either as a merger of two such black holes [e.g., 40, 331, 132] or as an intermediate mass-ratio inspiral of a stellar-mass compact object into such a BH.

A source with detectable eccentricity (detectable when frequency exceeds 10 Hz, for current round-based detectors).
This would clearly signal a **dynamical capture**.

A measurement of **effective spin magnitude close to either -1 or +1**.
A substantial positive effective spin coupled with high masses would point to the likelihood of **chemically homogeneous formation** [211];
While a substantially negative effective spin measurement would indicate **an unexpected anti-alignment between rapid spins and the binary's orbital angular momentum**, perhaps through either a supernova spin tilt or dynamical formation.

Gravitationally Lensed GW Signal
Gravitational waves can be gravitationally lensed; lensing would amplify the signal and provide additional information on the gravitational-wave source [e.g., 74, 137, 209].

EM Transients Counterpart
Although electromagnetic transients are not broadly expected to be associated with binary black hole mergers [e.g., 189], any such observations would point to the persistence of material around the merging binary [e.g., 96].

5.2 Population Statistics

Population statistics will generally **yield more information than individual events**.
We can use the statistical analysis of sufficiently large observational data sets to infer **bulk properties of the source population**, such as the mass and spin distributions, and to search for distinct subpopulations.

Approaches to inference on the observed population can be separated into two types:
One is **unmodeled or weakly modeled inference**;
The other is **inference that relies on specific accurate models**.

At the most basic end of weakly modeld inference is the (possibly non parametric) reconstruction of an underlying distribution, such as the mass function of merging black holes [4, 28, 31], while accounting for measurement uncertainties and selection effects.
For example, Fishbach & Holz [118] and Edelman et al. [107] explored weakly parametrized mass models to search for the presence of a mass gap due to pair-instability supernovae or an excess peak due to pul sational pair-instability supernovae, while Rinaldi & Del Pozzo [268] considered a completely non-parametric Dirichlet process Gaussian mixture model for the mass distribution. Meanwhile, as discussed above, several groups investigated inference on the mass and spin distributions with parametrized phenomenological models [e.g., 312, 28, 79, 12].

We can look for distinct subpopulations or "clusters" of events in the observable parameter space, in the hope of finding distinct categories corresponding to different evolutionary channels. These approaches have been proposed for both mass [200, 198] and spin [115, 261] distributions. It is worth noting that such clustering or classification schemes cannot hope to correctly assign individual events to a specific cluster, which is generally impossible given the significant measurement uncertainties [184]; instead, the goal is to identify the various clusters and measure the relative frequencies of events in these categories.

The next level of population-based inference relies on assuming that precise, possibly parametrized, subpopulation distributions are known.
In this case, hierarchical modeling (extreme deconvolution in the language of [147]) can be used to simultaneously determine:
the **ratios of different subpopulations** (e.g., arising from different formation channels),
and **any free parameters in the subpopulation models**.
Again, such approaches have been applied to both mass [e.g., 348] and spin [e.g., 339, 301] distributions and are generally expected to have greater resolving power than clustering in the absence of accurate population models.
On the other hand, reliance on precise models in the face of significant modeling uncertainties [e.g., 67] increases the the risk of misleading 43 results through model misspecification.

5.3 The Future of Population Synthesis Techniques

There is, of course, a multitude of uncertain physics within any given model, both limiting the usefulness of approaches that rely on a precise knowledge of subpopulation distributions and, more importantly, providing a set of key science questions that we would like to answer with the aid of gravitational wave observations.

How much mass do stars lose in winds, and what exactly is the impact of metallicity and rotation on stellar evolution [181]?
What happens to the star's angular momentum during collapse, how much mass is ejected, and how much of an asymmetric kick does the remnant receive?
How conservative is mass transfer in binaries and how much orbital angular momentum is carried away by the mass lost from the binary during non-conservative mass transfer?
What are the conditions for the onset of a common-envelope phase and common envelope ejection, and how does the binary change in the process?
How do dynamical interactions affect binary evolution?
And, in turn, how do massive stellar binaries and their compact remnants feed back into astrophysics and cosmology on all scales?

One approach to addressing these big questions is to use the framework of population synthesis, **which makes it possible to parametrize the uncertain physics and predict the expected source rates and distributions under different models**.

Historically, most efforts relied on a discrete set of a few models in the parameter space of population synthesis assumptions [e.g., 99, 302]. Even with the low computational cost of population synthesis, it is not feasible to explore more than tens or hundreds of models, and this is not sufficient to cover the full parameter space or to investigate the correlations between model parameters.
However, **recent** successes in building accurate and computationally efficient emulators over the model parameter space [51, 317, 341, 182] suggest that a full exploration of this space will soon be possible. For example, Barrett et al. [50] applied Fisher information matrix techniques to the space of model parameters and found that parameters such as those describing mass loss rates 44 during the Wolf-Rayet and luminous blue variable phases of evolution, and common-envelope energetics, could be measured to the level of a few percent with a thousand detections. 5.4. Other datasets and future missions Additional observational d

5.4 Other Datasets and Future Missions

In the future, the sensitive band will be broadened by decihertz-hertz-kilohertz detectors. Prospect of observing the **evolution of the populations of merging binaries** (or individual systems) across a broad band of frequencies.

Meaning that we will have the ability to track **individual sources** and **source populations** across the (rather wide) **frequency spectrum**:
This will make it possible to combine information which can best be measured at **low frequencies** (like eccentricity and sky location) and **high frequency** (like spin).

Meanwhile, a **stochastic background of gravitational waves from individually unresolvable binary black holes** could be measured in the next few years [5], possibly providing additional insight on high-redshift populations; however,
the only constraining parameter in a detection of such a background will likely be its amplitude, which carries only limited information [78].

5.5 Outlook

Today we have around 80 observations of merging binary black holes. That is 80 more than 6 years ago, and we have already learned a great deal.
Binary black holes **exist**.
They **merge**.
They do so relatively **frequently**.
They have a **broad range of masses**.
None of the sources seen so far **seem to have rapid net spins in the direction opposite to the orbital angular momentum**.
We also have several **plausible evolutionary channels**, some of which appear to explain many of the observed properties: merger rates, masses, and possibly spins.

At the same time, we have the **tools** in place to create detailed models of stellar and binary evolution and of dynamical interactions under a variety of parametrizable assumptions. **Statistical techniques** are in place for analyzing the data and inferring properties directly from the observations or by comparison with the detailed models.

Most importantly, we have wonderful **detectors** which are continuing to improve, and we expect to obtain enough data in the next few years to carry out these analyses.
Perhaps in a few years we will know that all of the channels described here contribute non-negligibly to binary black hole formation; that black holes receive small kicks at birth; and that they spin slowly in merging binaries except when stripped helium stars are spun up through tides. We may also have made the first detections of new objects such as 200M intermediate-mass black holes

The future of gravitational-wave astronomy holds the thrilling prospect of addressing the inverse problem of massive binary stellar evolution: **inferring the formation channels and their physics from observations of the merging compact object binary population**.
We can now use merging black holes — remnants of massive stars — to probe the **behavior of those stars**, and particularly **their evolution in binaries**.

Reference Table