A new route towards merging massive black holes[1]
(*Or:* Understanding the origin of the first direct detection of gravitational waves with Advanced LIGO)

Abstract

The Advanced LIGO (aLIGO) gravitational-wave detector has just reported the discovery of the first *direct* detection of gravitational waves[2], confirming Einstein's Theory of Relativity in its extreme limit. The sources of these gravitational waves were *merging relatively massive stellar-mass black holes (BHs)* that were much more massive than had been predicted before. In a study, led by Pablo Marchant at the University of Bonn, we have shown that such systems are expected to form from massive binary stars that are so close that their rapid rotation keeps both massive stars well mixed, transforming them into relatively massive black holes. Our theory predicts that the black holes in these system should have very similar masses and should only be seen in galaxies with a metallicity[3] less than 10 % of the metallicity of the Sun. We also predict that the most massive black-hole mergers can be detected with aLIGO throughout a large fraction of the observable Universe, allowing us to test the theory of massive stars throughout most of the history of the Universe with implications for other enigmatic events such as gamma-ray bursts and superluminous supernovae.

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1 The discovery of gravitational waves with Advanced LIGO

Advanced LIGO (aLIGO), a US-based interferometer designed to detect gravitational waves that started its operations in September 2015, has just reported the first direct discovery of such waves, caused by the merger of two stellar-mass black holes. This is one of the most important breakthroughs in astrophysics in the last 50 years and undoubtedly the most important discovery in physics since the discovery of the Higgs boson in 2012: it confirms one of the main predictions of Einstein's Theory of General Relativity and indeed the very existence of black holes[5]. According to Einstein's theory, measurements of space and time are distorted in the presence of a massive object ("space is curved"; see Figure 1). If two massive objects are bound to each other and orbit each other periodically (as in the case of the two pulsars illustrated in the right panel of Figure 1), these distortions of spacetime move with the massive objects, causing a periodic distortion of spacetime that propagates through space with the speed of light; such a "ripple" in spacetime is called a *gravitational wave.* When such a gravitational wave passes through a detector on Earth, it causes a small distortion of the local spacetime that can be measured with an interferometer such as aLIGO.

The principal expected sources of gravitational waves that are detectable with aLIGO are the final inspiral and ultimate merger of binaries consisting of two extremely dense, compact objects, such as neutron stars

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[1] Background material to an article accepted for publication in Astronomy & Astrophysics by Pablo Marchant, Norbert Langer, Philipp Podsiadlowski, Thomas, M. Tauris, and Takashi J. Moriya [1] [http://dx.doi.org/10.1051/0004-6361/201628133].

[2] The effects of gravitational radiation had previously been inferred from the decay of the orbital period in binaries containing two neutron stars, in particular the Hulse-Taylor pulsar, PSR 1913+16, for which Hulse and Taylor were awarded the Nobel prize in 1993, but this discovery was indirect and did not detect gravitational waves directly.

[3] Metallicity defines the fraction of mass in elements heavier than hydrogen and helium.

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[5] The existence of black holes in stellar systems and at the centres of galaxies has so far only been inferred indirectly, generally based on measurements of their masses and/or mass concentrations. The existence of an event horizon from below which photons cannot escape, which is the defining property of a black hole, had not been demonstrated convincingly before.

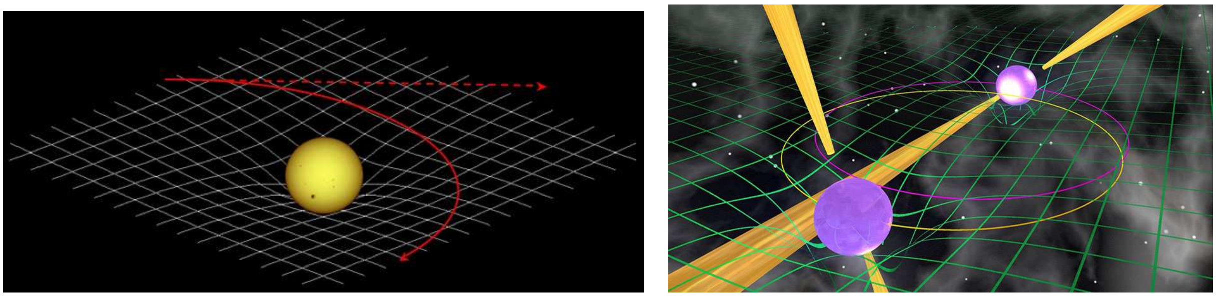

Figure 1: *Left panel:* illustration of the distortion of spacetime caused by the presence of a gravitational mass; this causes a distortion of how space and time are measured near a mass and is responsible for the phenomenon of 'bending of light' as indicated (source: Time Travel Research Center). *Right panel:* illustration of the periodic distortion of spacetime caused by two orbiting pulsars (neutron stars), such as the binary pulsar PSR J0737-3039, causing a *gravitational wave* that propagates throughout space with the speed of light (©MPIfR, M. Kramer).

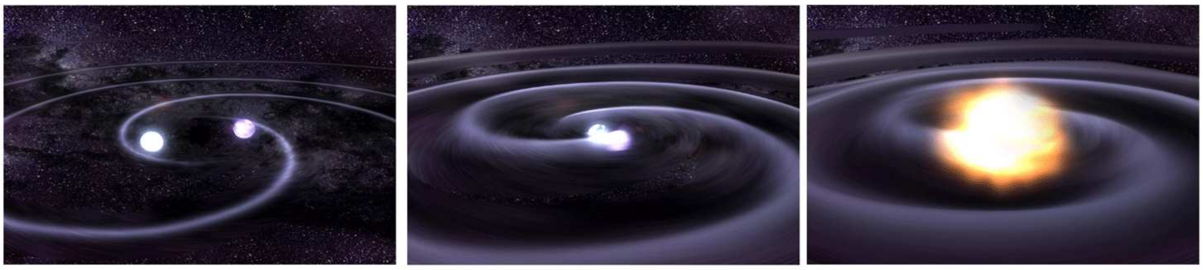

Figure 2: The inspiral and eventual merger of two compact objects causing the type of gravitational-wave signal observed by aLIGO (source: NASA/CXC/GSFC/T.Strohmayer).

and black holes[6] (see Figure 2). Before the start of aLIGO, theoretical models predicted that the most likely sources for gravitational waves would be systems consisting of two neutron stars (pulsars) and/or black holes (with a typical expected mass of around 10 solar masses). It is therefore somewhat of a surprise that the first detection announced was caused by the mergers of two black holes and that the black-hole masses were much larger than the typical masses of stellar black-hole candidates in our own Milky Way galaxy (roughly 30 solar masses instead of 10 solar masses). Moreover, no mergers of two neutron stars, which were predicted to be detectable with aLIGO with a similar frequency as black-hole mergers, have yet been reported.

2 Merging 'massive' stellar-mass black holes

In order for a binary consisting of two black holes to merge in less than the age of the Universe (about 14 billion years), the separation of the two black holes after their formation has to be small enough that gravitational radiation can drive them together. For a system composed of two black holes, each with a mass of 30 solar masses, this implies a maximum separation of 34 solar radii (corresponding to an orbital period of 3 days). However, the massive-star progenitors of these black holes would not have fitted into such a tight orbit[7]. Therefore, in the standard model, the formation of such close compact systems requires a phase where one or both stars spiral inside the other's envelope (a so-called 'common-envelope phase') transforming an initially very wide system into a very compact binary. The physics of this phase is very poorly understood leading to uncertainties of several orders of magnitude in the expected aLIGO

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[6] Neutron stars (often observed as pulsars) and black holes are the remnants of massive stars (more massive than ten solar masses). A neutron star is mainly composed of neutrons and has a typical mass of 1.4 solar masses and a radius of 10 km. A black hole is so compact that even light cannot escape from it; for a black hole of ten solar masses, this mass has to be confined to within a radius of 30 km.

[7] Massive stars can reach radii as large as 1000 solar radii.

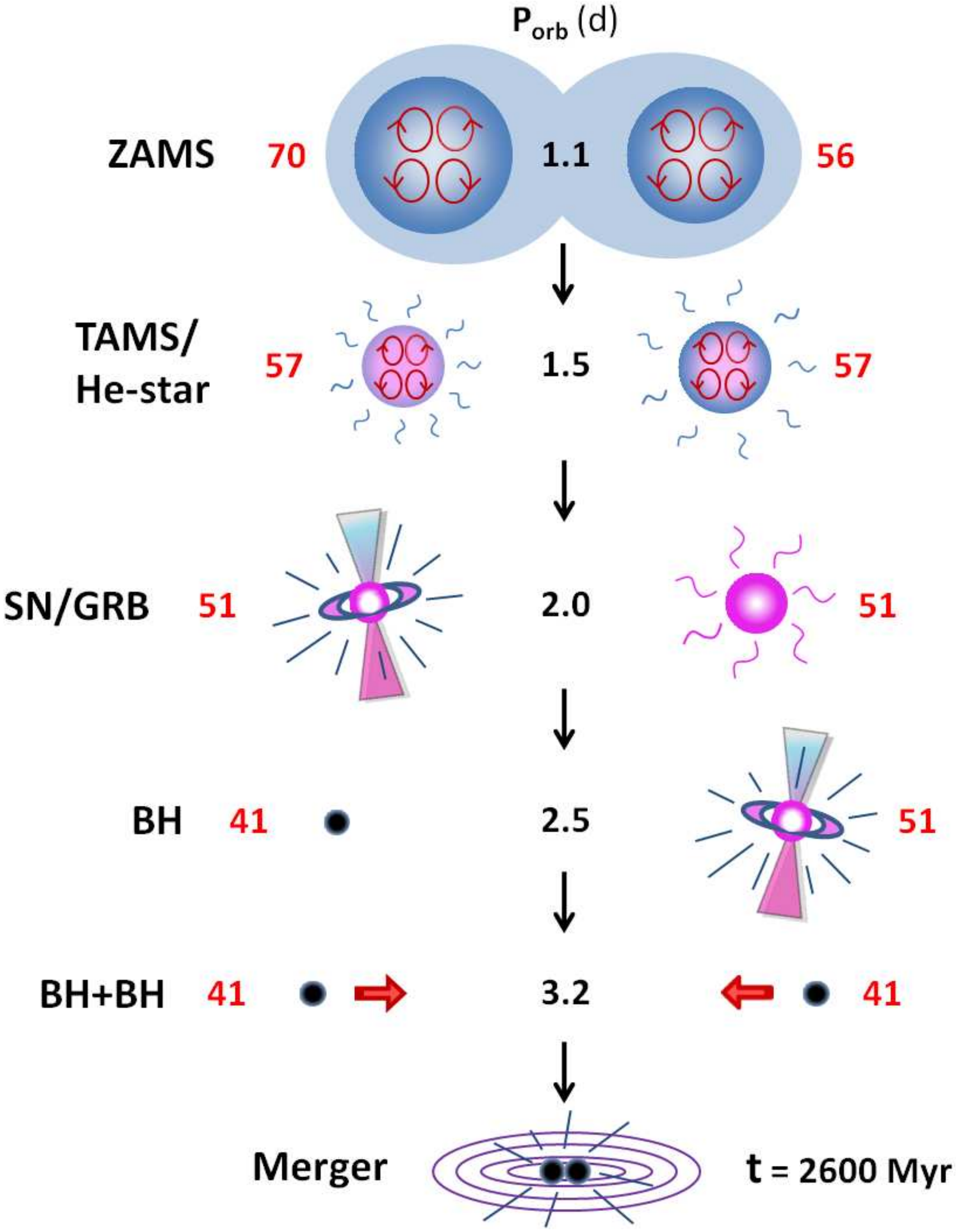

Figure 3: Cartoon illustrating the evolution of a massive binary system consisting of two stars with initial masses of 70 and 56 solar masses from its birth to the formation of a double-black-hole binary (with black-hole masses of 41 solar masses each) that will merge after 2,6 billion years. The red figures give the masses of the two objects (in solar masses) at each stage, while the central figure gives the corresponding orbital periods. ZAMS stands for zero-age main sequence (i.e., the initial evolutionary phase); TAMS for the terminal main sequence (when all the hydrogen in the centre of the stars has been exhausted); He-star for helium star; SN for supernova; GRB for gamma-ray burst; BH for black hole. (From [1].)

detection rates [2].

The model which we just published avoids this difficulty as it does not involve a common-envelope phase, and it produces, in a very natural way, rather massive black-hole binaries of comparable mass. Figure 3 shows the typical evolution that can lead to the merger of two massive black holes. The initial system consists of two massive stars (here with masses of 70 and 56 times the mass of the Sun) but the system is so close (it has an initial orbital period of 1.1 days) that tidal forces are strong enough to lock the rotation of both stars to the orbit (i.e., makes both stars rotate with the same spin period as the orbital period, similarly to how the moon's rotation about its own axis is tidally locked to its orbit around the Earth). This makes the stars rotate very rapidly and induces circulation currents within the stars that very efficiently mix the whole star continually. The nuclear fusion of hydrogen to helium provides the main power source of a star in the initial evolutionary phase. Because it only occurs near the very centre of a star, slowly rotating stars only convert their hydrogen to helium in the core region. This is, for example, the case for our own Sun, where the composition changes in the centre due to the nuclear fusion reactions whilst the outer layers keep their initial hydrogen-rich composition. In contrast, in the rapidly rotating stars in our tidally locked systems, the whole star evolves 'homogeneously', and the initial hydrogen-rich star is converted gradually into a helium star without the distinct core–envelope structure that characterizes slowly rotating stars. This has dramatic consequences for the further evolution once hydrogen burning in the core has been extinguished. While slowly rotating stars will expand dramatically after having completed their hydrogen burning and become large red supergiants (with radii up to about 1000 solar radii), the initially rapidly rotating stars will remain compact, in fact become even more compact. As a consequence, the orbital periods of these systems do not increase much during the whole evolution and can be short enough that, even after two supernova explosions (in which the black holes form), the resulting double-black-hole systems can be compact enough that they merge within the age of the Universe (in the example in the figure after 2.6 billion years).

One important effect that tends to widen such binary systems is stellar-wind mass loss in the first two evolutionary phases (similar to the solar wind) and mass loss associated with the supernovae (if the massive stars do not collapse completely to black holes). The amount of mass lost in a stellar wind is a strong function of the metallicity of the stars[8]. Indeed, we find that, in order for black-hole binaries to merge within the age of the Universe, their metallicity has to be less than about 1/10 of the metallicity of the Sun. Such stars are relatively rare in a galaxy like our Milky Way. Therefore, we predict that these mergers should preferentially originate from very small galaxies that typically have much lower metallicities or from systems that formed at a much higher redshift (i.e., formed in the distant Universe).

Figure 4 shows the distribution of the chirp masses[9] for different metallicities as predicted by our simulations. Because of the metallicity dependence of the mass loss, the black-hole masses are larger for lower metallicities. The black-hole mass distribution is bimodal with two mass ranges: 25 to 60 solar masses and more than 130 solar masses. The reason for the gap is that helium stars in the intermediate-mass range explode as pair-instability supernovae where the whole star is disrupted because the fusion of oxygen nuclei becomes explosive. In stars more massive than 130 solar masses, there is not enough energy to explode the stars, leading to the formation of rather massive stellar black holes. Even though these mergers are predicted to be relatively rare, as in our models they only occur at very low metallicity (less than 1/50 solar metallicity), these can be seen throughout most of the observable Universe and therefore could make a significant contribution to aLIGO detections.

A further prediction of our calculations is that, in most systems below the pair-instability gap, the two black holes are of very similar mass. The reason for this that, in the first stage shown in Figure 3, the stars are so close that mass is transferred back and forth between the two stars (in a phase where both stars overflow their so-called Roche lobes, which we refer to as a "massive overcontact binary" [MOB] phase). This process tends to equalize the masses of the two stars. So even if there is a significant difference in the component masses initially, the final black-hole masses are expected to be very close to each other.

As our calculations predict the final properties of massive binaries in this scenario in detail, we can estimate the rates of such mergers, relating them to the explosions of massive stars (so-called core-collapse supernovae). At a metallicity less than about 1/10 the solar metallicity, we expect roughly 1

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[8] For the stellar-wind mass loss, heavy elements such as iron are particularly important.

[9] The chirp mass is a characteristic mass that can be directly inferred from the final inspiral (see Figure 6). For a system consisting of two equal-mass black holes, the mass of each black hole is just 1.15 times the chirp mass.

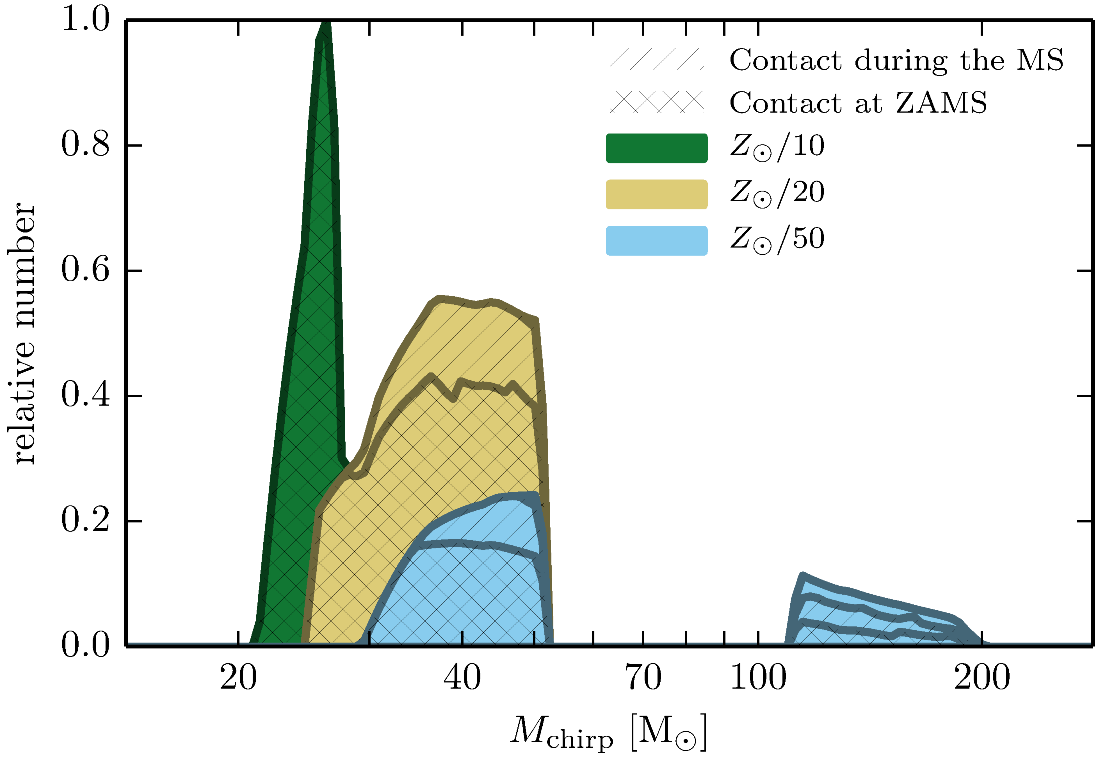

Figure 4: The distribution of the "chirp" masses[9] (in solar masses [$M_\odot$]) predicted by our simulations for different metallicities (assuming that there is no mass loss when the star collapses to a black hole at the end of its evolution). Note that, at the lowest metallicity ($\sim Z_\odot/50$, where $Z_\odot$ refers to the metallicity of the Sun), very massive black-hole binaries can be formed; mergers of such systems are detectable throughout most of the Universe. (Based on [1].)

merger of two black holes for every 1000 core-collapse supernovae. To relate this to an actual aLIGO detection rate is more difficult, as this is strongly dependent on the evolution of the metallicity with cosmic time (redshift) and the distribution of metallicities of star-forming regions at a given redshift. Making some simple approximations, we have estimated aLIGO detection rates (at the aLIGO design limit) of 20 to 600 per year for black-hole mergers below the pair-instability gap and 2 to 400 per year above the pair-instability gap. This implies that, even for conservative assumptions, aLIGO should detect these predicted mergers and that they could actually be the dominant source for aLIGO detections; indeed, it would not be surprising if the black-hole merger announced by the aLIGO team from the 1st science run orginated from this channel.

3 Other implications

Our calculations predict the mergers of rather massive black-hole binaries, the most massive of which can be seen throughout most of the observable Universe. Therefore aLIGO detections of such systems and, in particular, the observed chirp mass distribution (as shown in Figure 4) can be used to directly constrain the evolution of massive stars throughout the Universe[10].

As rapid rotation plays an important role in our scenario, some of the stars will be rotating too rapidly at the end of their evolution to collapse directly to a black hole. Those system are candidates for long-

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[10] Of course, other channels for forming double-black-hole binaries may also contribute and need to be taken into account in any detailed analysis.

Figure 5: Photos of the two aLIGO detectors in Livingston (Lousiana, left) and Hanford (Washington, right). These are Michelson interferometers, where each arm has a length of 4 km. The two detectors are located 3,000 km apart to allow the distinction of an astronomical event from local noise sources (source: LIGO website).

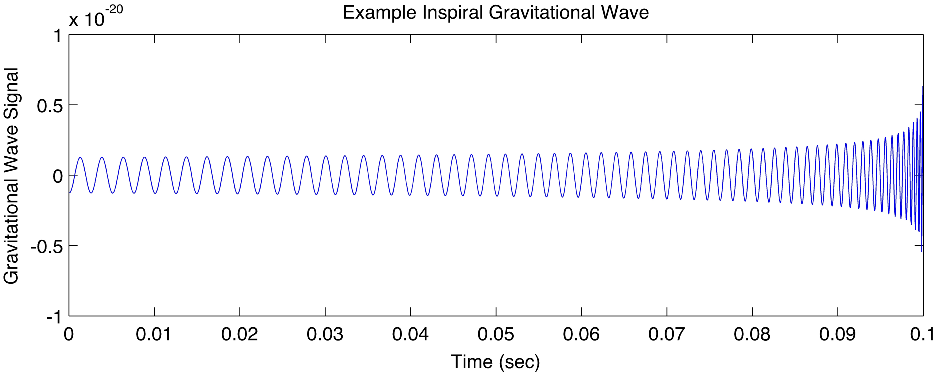

Figure 6: Example of an aLIGO inspiral signal caused by the merger of two compact objects (source: A. Stuver/LIGO).

duration gamma-ray bursts and perhaps superluminous supernovae[11]. Both of these classes of objects appear to be observationally linked to stellar populations with low metallicities.

4 Further information

When a gravitational wave passes through a gravitational-wave detector such as aLIGO, it causes a contraction or expansion of local space. The aLIGO detectors can measure changes in the length of one of the arms of the interferometers that are smaller than 10^{-18} m, which is less than 1/1000 of the size of a proton[12]! As there are many local noise sources that can produce signals that are many orders of magnitude larger (e.g. a truck passing by near one of the detectors at a distance of several kms), aLIGO uses two detectors 3,000 km apart (see Figure 5) to filter out a real astronomical signal from local noise. The observed delay of arrival times also allows for a very rough constraint on the direction from which the gravitational wave has arrived.

Figure 6 shows the expected signal for the inspiral and final merger of two compact objects. Its charac-

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[11] Long-duration gamma-ray bursts are short bursts of gamma rays, lasting 10s to 1000s of seconds, that are believed to be caused by the collapse of rapidly rotating massive stellar cores. Superluminous supernove are supernovae that appear to be up to 100 times more luminous than typical core-collapse supernovae and may also be linked to rapidly rotating stars.

[12] This is equivalent to measuring the Earth-Sun distance to a precision of the size of a hydrogen atom.

teristic time dependence helps to distinguish between a real astronomical signal and local noise.

5 Historical notes

de Mink et al. [3] were the first to propose that tidal locking in very close massive binaries can make both stars evolve homogeneously because of forced rapid rotation and suggested that these could produce long-duration gamma-ray bursts. As the resulting black-hole binaries could be very close systems, this provided the main motivation for our study to explore whether these systems could be potential progenitors of double-black-hole mergers detectable with aLIGO. In our study, we provide the first detailed, first-principle stellar-evolution calculations of such systems. This has only become possible with the recent progress in modelling binary stars. Specifically, we use the public-domain, stellar-evolution code MESA [4], which can now calculate the evolution of such binaries self-consistently. Indeed, the first author of the paper, Pablo Marchant, has been a key developer of the MESA binary module and has implemented the necessary modifications to the MESA code as part of his PhD thesis [5].

In a related paper, Mandel & de Mink [6] also explore the same scenario as originally proposed by [3]. That paper is very much complementary to ours; it concentrates on the cosmic evolution of rates of such mergers using a particular metallicity, while our paper concentrates on understanding the detailed stellar evolution physics of these systems and therefore makes more specific predictions on the metallicity dependence, etc. While there are differences in the detailed predictions in the two papers, they broadly agree in their main conclusions.

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