On the likelihood of detecting gravitational waves from Population III compact object binaries

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ABSTRACT
We study the contribution of binary black hole (BH-BH) mergers from the first, metal-free stars in the Universe (Pop III) to gravitational wave detection rates. Our study combines initial conditions for the formation of Pop III stars based on N-body simulations of binary formation (including rates, binary fraction, initial mass function, orbital separation and eccentricity distributions) with an updated model of stellar evolution specific for Pop III stars. We find that the merger rate of these Pop III BH-BH systems is relatively small ($\lesssim 0.1$ Gpc$^{-3}$ yr$^{-1}$) at low redshifts ($z < 2$), where it can be compared with the LIGO empirical estimate of $9-240$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al. 2016). The predicted rates are even smaller for Pop III double neutron star and black hole neutron star mergers. Our rates are compatible with those of Hartwig et al. (2016), but significantly smaller than those found in previous work (Bond & Carr 1984; Belczynski, Bulik & Rudak 2004; Kinugawa et al. 2014; Kinugawa, Nakamura & Nakano 2016). We explain the reasons for this discrepancy by means of detailed model comparisons and point out that (i) identification of Pop III BH-BH mergers may not be possible by advanced LIGO, and (ii) the level of stochastic gravitational wave background from Pop III mergers may be lower than recently estimated (Kowalska, Bulik & Belczynski 2012; Inayoshi et al. 2016; Dvorkin et al. 2016). We further estimate gravitational wave detection rates for third-generation interferometric detectors. Our calculations are relevant for low to moderately rotating Pop III stars. We can now exclude significant (> 1 per cent) contribution of these stars to low-redshift BH-BH mergers. However, it remains to be tested whether (and at what level) rapidly spinning Pop III stars (homogeneous evolution) can contribute to BH-BH mergers in the local Universe.

Key words: Stars: massive – Black-hole physics – Gravitational waves

1 INTRODUCTION

The discovery of gravitational waves by the LIGO collaboration (Abbott et al. 2016b), in addition to probing gravity in an extreme regime, has also opened a new window on the end state of massive stars, and the compact objects that they leave behind. The first detected event, GW150914, resulted from the merger of two massive black holes (BH-BH) with chirp mass $M_{\text{chirp}} \equiv (M_1 M_2)^{3/5}/(M_1 + M_2)^{1/5} = 28_{-2}^{+5} M_\odot$, where $M_1$ and $M_2$ are the individual source-frame BH masses. The fact that this signal was observed so early during the first LIGO observing run (O1) suggests that similar systems could be rather common. The chirp mass $M_{\text{chirp}} = 8.9^{+0.3}_{-0.3} M_\odot$ of the second detected event, GW151226, was smaller (Abbott et al. 2016c); a third lower-significance trigger, LVT151012, if astrophysical in origin, was produced by a BH-BH binary with chirp mass in an intermediate range, $M_{\text{chirp}} = 10^{+1}_{-1} M_\odot$ (Abbott et al. 2016).

While these few detections already show that there is a spread of masses in the BH-BH mass distribution, it is the higher end of the mass distribution which is particularly intriguing. In general, high-mass BH-BH systems should form from very massive, metal-poor binary stars (Belczynski et al.

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These stars are expected to be more numerous at higher redshifts, and the requirement that they should be detectable within the LIGO horizon sets some constraints on their merger time scales.

Belczynski et al. (2016b) reported a suite of numerical simulations of BH-BH binary formation via the evolution of isolated binary stars. They found that the progenitor stars of GW150914 had masses in the range of $40 - 100 M_{\odot}$, and formed in an environment where the metallicity is less than 10 per cent of the solar metallicity. Their progenitors were likely formed when the Universe was about 2 Gyr old. This, so called classical evolution channel, was also recently studied by other authors (e.g., Eldridge & Stanway 2016 Lipunov et al. 2017).

Alternative scenarios for the formation of massive BH-BH binaries involve dynamical interactions at the center of star clusters (e.g., Ziosi et al. 2014 Rodriguez, Chatterjee & Rasio 2016 Askar et al. 2017). For example, single BHs can pair with a BH companion via three-body binary formation and binary-mediated exchange interactions, which tend to result in the ejection of the lightest BH, while the two most massive BHs form a binary (e.g., Heggie & Hut 2003 Chatterjee & Tan 2012 Morscher et al. 2015 Ryu, Tanaka & Perna 2016). Massive BH-BH formation was also proposed by binary evolution of rapidly rotating stars, so called homogeneous evolution channel (e.g., Marchant et al. 2016 Mandel & de Mink 2016 Woosley 2016).

The formation of massive BH-BH binaries would also be a natural outcome if the BHs were the end products of Population III (Pop III) stars. These are believed to be the first stars formed in the Universe, and hence would naturally occur in metal-free environments (e.g. Omukai & Nishi 1998 Abel, Bryan & Norman 2000 Bromm, Coppi & Larson 2002). The possibility that binaries of Pop III star remnants could be contributing sources of gravitational waves has been considered by a number of authors (see e.g. Bond & Carr 1984 Belczynski, Bulik & Rudak 2004 Kulczycki et al. 2006 Kinugawa et al. 2014 Hartwig et al. 2016), who investigated a range of initial mass functions and initial binary parameters. In particular, Kinugawa et al. (2014) concluded that Pop III BH binary remnants can account for a significant fraction of current and future gravitational wave detections.

In this paper we revisit this important question, motivated by the fact that the computation of the local merger rate of Pop III BH-BH binaries is very sensitive to the choice of the initial binary parameters, such as masses and initial orbital separations. We couple Pop III initial conditions determined via N-body simulations of binary formation (Ryu, Tanaka & Perna 2016) of stars born in primordial halos (Stacy, Greif & Bromm 2010 Greif et al. 2012) with a state-of-the-art numerical computation of binary evolution (Belczynski et al. 2016b) with updates specific to Pop III evolution. We estimate the contribution to the merger rates detectable by current and future detectors using phenomenological models calibrated to numerical relativity simulations of the binary BH merger signal, as in Dominik et al. (2015). We predict significantly lower merger rates with respect to Kinugawa et al. (2014), and we discuss the underlying reasons for this discrepancy.

The paper is organized as follows. Sec. 2 describes the (dynamically-determined) initial conditions for the Pop III binary stars. Sec. 3 details how they are evolved, as well as their redshift distribution. The specific evolutionary scenarios ensuing from our initial conditions are described in Sec. 4. In Sec. 5 we describe our findings for the properties of the BH-BH population and we compute gravitational wave detection rates for Advanced LIGO and several planned future instruments. We devote Sec. 6 to a detailed model comparison with Kinugawa et al. (2014). In Sec. 7 we summarize our findings and indicate possible directions for future work.

2 INITIAL PROPERTIES OF POP III STARS

In this study, we track the evolutions of Pop III stars in binaries using StarTrack. We use the models of Ryu, Tanaka & Perna (2016) to determine the initial properties of the Pop III binary stars—that is, the mass of the primary star, the mass ratio between secondary and primary star, the semi-major axis and the eccentricity. We briefly review their models below, but refer the reader to Ryu, Tanaka & Perna (2016) for details.

Using N-body simulations, Ryu, Tanaka & Perna (2016) investigated the formation of Pop III X-ray binaries in star-forming gas clouds. They considered multiple systems of Pop III stars embedded in a uniform gas medium, and included the physical effects from the gas medium (i.e. dynamical friction and background potential). Their simulations followed the dynamics of the stars initially in quasi-Keplerian orbit on a disk until isolated and stable binaries had formed.

For this study, we consider two specific scenarios with very different physical size of a gas cloud (mini-halo). This choice is motivated by the two available state-of-the-art Pop III star formation numerical models in mini-halos at high-redshift: large mini-halos; $\sim 2000$AU (Stacy & Bromm 2013) and small mini-halos; 10-20AU (Greif et al. 2012). These two models, while being very different, encompass the Pop III star formation uncertainties. In each scenario, a mini-halo is populated with $N = 5$ single stars. They are placed at random positions within a given mini-halo and are subjected to dynamical friction and are allowed to dynamically interact with each other. As a result some of these stars form binaries and occasionally higher-multiplicity systems. Such simulation is repeated (10-250) times to obtain initial distributions of Pop III binary star parameters.

(i) Model FS1: moderate orbital separations

This model assumes that Pop III stars form in a gas cloud of spatial range of $\sim 2000$ AU (Stacy & Bromm 2013). The number density of the pristine gas medium is $10^{3}$ cm$^{-3}$ and the masses of stars follow a top-heavy initial mass function (IMF) $\frac{dN}{dM_{\odot}} = M_{\odot}^{-0.17}$ with $M_{\odot} = 140$ $M_{\odot}$ and $M_{\odot} = 0.1$ $M_{\odot}$ (Stacy & Bromm 2013). The binary parameters are collected when the binary begins to shrink predominantly via dynamical friction with mini-halo gas after single stars and binaries (or triples) are formed and isolated from one another; in other words, when no further dynamical interactions between stars are expected (or $t \sim 1$ Myr).

(ii) Model FS2: small orbital separations

In the second model we consider a rather small gas cloud...
of spatial range of $\sim 10 - 20$ AU, motivated by the findings of [Greif et al. (2012)]. Their simulations showed that as a result of fragmentation of gas clouds, multiple, less massive protostars form around the most massive one, several AU apart from each other. We adopt the same number density of the gas medium in a mini-halo as above ($10^6$ cm$^{-3}$). In order to mimic their findings, we use the same IMF as in the FS1 model, but alter $M_{\text{max}}$ in each of 5 drawings. In the first drawing we adopt $M_{\text{max}} = 200 M_\odot$. Subsequently, we generate stars with $M_{\text{max}} = 200 M_\odot - [\text{the sum of the masses of the previously generated stars}]$. In this model, the dynamical stellar interactions typically end in a few to tens of thousands years due to smaller initial separations between stars. The initial conditions for binary evolution with StarTrack population synthesis are extracted at $t \sim 1$ Myr.

A summary of the main features of our models of Pop III binary dynamical formation is given in Table 1. Note that in the simulations of both models triples also are formed, but only the inner binaries in the triples were the ones taken into account. The distributions of parameters for binaries formed in the above simulations are taken as initial input for population synthesis evolutionary calculations and are given in Table 2. This dynamical approach to determine the initial binary properties of Pop III stars is an important difference with respect to previous studies.

### Table 1. Summary of the two models of Pop III binary formation

| Model  | Number of stars N per run | Gas number density $n$ | Initial spatial range | IMF$^a$ | $M_{\text{min}}$ | $M_{\text{max}}$ |
|--------|---------------------------|------------------------|-----------------------|--------|-----------------|-----------------|
| FS1    | 5                         | $10^6$ cm$^{-3}$       | 2000 AU               | $\alpha = 0.17$ | $0.1 M_\odot$ | $140 M_\odot$ |
| FS2    |                           |                        | 10 - 20 AU            | $0.1 M_\odot$ | $0.1 M_\odot$ | $200 M_\odot$ |

$^a$ The masses of the stars are drawn from a top-heavy IMF with $\alpha = 0.17$ ($dN/dM = M^{-\alpha}$), [Stacy & Bromm (2013)]. The distributions of the initial binary parameters used for the population synthesis calculations in Table 2 are based on those binaries which dynamically formed and were not subsequently disrupted by dynamical interactions.

### 3 EVOLUTION OF POP III STARS

Population synthesis calculations were performed with the StarTrack code [Belczynski, Kalogera & Bulik (2002) Belczynski et al. (2008)]. Recently we updated this code with improved physics. The improvements relevant for massive star evolution include updates to the treatment of CE evolution ([Dominik et al. (2012)], the compact object masses produced by core collapse/supernovae [Fryer et al. (2012) Belczynski et al. (2012)], and observationally constrained star formation and metallicity evolution over cosmic time [Belczynski et al. (2016)]. Here we discuss the existing updates and also introduce another set of updates that are especially relevant for Pop III stars.

#### 3.1 Radius evolution

In our model we employ modified [Hurley, Pols & Tout (2000)] rapid evolutionary formulae. These formulae do not include the effects of stellar rotation, and they are limited in both metallicity ($Z = 0.03 - 0.0001$) and initial star mass range ($M_{\text{zams}} = 0.08 - 80 M_\odot$). We have extended and calibrated the use of these formulae to higher mass ($M_{\text{zams}} = 0.08 - 150 M_\odot$; Belczynski et al. 2008). The effects of stellar rotation on stellar evolution become significant for high rotation speeds: e.g., homogeneous evolution at rotation speeds close to breakup velocity is very different [Marchant et al. (2016) Mandel & de Mink (2016) Woosley (2016)] and it is not taken into account within our model.

We use our lowest metallicity model ($Z = 0.0001$) to approximate the evolution of metal-free stars. Since stellar wind mass loss is expected to be negligible for massive Pop III stars [e.g. Baraffe, Heger & Woosley (2001)], we assume that no mass is lost in stellar winds. We also limit the radial expansion of Pop III stars. We use the evolutionary models of [Marigo et al. (2001)] and impose upper limits on the radial expansion of our $Z = 0.0001$ models to approximately match those for $Z = 0$ stars. The evolutionary tracks on the Hertzsprung-Russell (H-R) diagram for our models are presented in Figure 1. Our tracks may be directly compared with those presented in Figure 1 of Kinugawa et al. (2014), who were the first to implement the results by Marigo et al. (2001) into their population synthesis. Our tracks are slightly more luminous and extend to slightly lower temperatures (and thus to slightly larger radii) as compared to [Kinugawa et al. (2014)].

We use the original [Hurley, Pols & Tout (2000)] limit between Hertzsprung gap and core He burning (CHeB); marked in Figure 1. For massive stars this distinction is somewhat ambiguous, as HG stars are already burning He in their cores. This is true for both Pop III stars and Pop I/II stars. However, the initial (HG) expansion of massive stars after the main sequence (MS) does not lead to the formation of a convective envelope. Only later evolutionary phases when stars become cool (during CHeB) may potentially allow the formation of a convective envelope. This was recently demonstrated for high- and moderate-metallicity stars ($Z = Z_\odot$ and $Z = 0.1 Z_\odot$) by Pavlovskii et al. (2016). For example, their $80 M_\odot$ model for $Z = 0.1 Z_\odot$ develops a convective envelope only after exceeding a radius $R \approx 2000 R_\odot$. For smaller metallicity, like in the case of our models, this radius should be smaller. For comparison, our $100 M_\odot$ model reaches the CHeB phase at a radius $R \approx 400 R_\odot$. In contrast, Kinugawa et al. (2014) includes HG phase in CHeB phase, and their $100 M_\odot$ model enters the CHeB phase at $R \approx 20 R_\odot$ (see their Figure 1). This leads to much larger parameter space for entering CE phase and for the formation of BH-BH mergers than indicated by recent detailed CE calculations [Pavlovskii et al. 2016].

#### 3.2 Black hole mass spectrum

We employ the rapid supernova model from [Fryer et al. (2012)]. This model is able to reproduce the mass gap be-
the Pop III star formation rate. We assume that the first stars form in the redshift range \( z = 2 - 50 \). The Pop III star formation rate is highly uncertain. We have adopted a rather optimistic model (high rate) from de Souza, Yoshida & Ioka (2011), as Kinugawa et al. (2014) did. The Pop III star formation rate consistent with the recent Planck cosmic microwave background data on optical depth to electron scattering in Universe is factor of \(~ 2\) lower (Inayoshi et al. 2016) than what we have adopted in this study. It means that all our merger rate and detection rate predictions could be factor of two lower than reported in following sections.

For comparison, we also show the star formation rate

\[ \frac{\dot{M}}{\text{sun}} \]
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Figure 2. Black hole mass spectrum for our model of Pop III stars as a function of stellar initial mass at Zero Age Main Sequence. We mark regions of fallback and direct BH formation. We also mark the region where stars forming BHs are subject to pair-instability pulsation supernovae (PPSN), and stars that are totally disrupted by pair-instability supernovae (PSN). The additional line shows the helium core mass at the time of core-collapse; above $M_{\text{He}} > 45 M_\odot$ stars are subject to pair-instabilities.

Figure 3. The explanation of the concept of finding the total mass of stars that can lead to the formation of BH-BH mergers detectable by AdLIGO. C is the present, B is the currently observable volume element, and A is the distant past of this volume element (see Sec. 3.3 for details).

Figure 4. Our adopted model for the star formation rate of Pop III stars. For comparison we also show two different estimates of star formation rate of Pop I/II stars. Note that Pop III stars form only (at most) ~ 0.3% of all stars in Universe that can contribute to AdLIGO detectable BH-BH mergers (see Sec. 3.3 for details).

The total stellar mass available in entire Universe for the formation of BH-BH, BH-NS and NS-NS mergers that are detectable by AdLIGO is given by the integral

$$M = \int_0^\infty dz \frac{dV}{dz} \int_{t(z)}^{t} SFR(t) \, dt,$$

where $SFR(t)$ is the star formation rate at a given time. We first integrate the star formation rate to obtain the density of stars formed up to a given time since the Big Bang, and then integrate the stellar mass density with the cosmic volume to obtain the total mass. The concept is explained in Figure 3. The point C corresponds to the present moment where the observer is located. The observer sees the Universe only along the light cone extending to the past denoted by dashed lines. Thus the past of the observer contains the entire region below the dashed line. However only the hyper-surface denoted by the dotted line is visible to the observer. Nevertheless any volume $dV$ that is seen by the observer contains stars or their remnants that were formed in $dV$ during its past. This is denoted by the dotted line. Thus in order to find the star density we first integrate the star formation rate over time along the dotted line to obtain the density of stellar mass formed in the past of the volume element $dV$, going from A to B. Then we integrate the density with the volume seen by the observer along the dashed line going from B to C.

The SFR formulae can be found in Belczynski et al. (2016, for Pop I/II) and de Souza, Yoshida & Ioka (2011, for Pop III). Integrating eq. 1 we find that the total mass of Pop III stars formed in the observable Universe (in the redshift range $0 < z < 50$) is on the order of $2.1 \times 10^{18} M_\odot$, whereas the total mass in Population I/II stars (within $z < 15$) is $8.0 \times 10^{20} M_\odot$, so about 2.5 orders of magnitude higher.
3.4 Initial conditions

In Table 2 we provide the details of our adopted initial binary distributions that are used for the evolution of Pop III binaries. The origin of these distributions is presented in Section 2. In Figures 5, 6, 7 and 8 we show these initial distributions.

4 EVOLUTIONARY CHANNELS

4.1 Model FS1: moderate orbital separations

In this model majority of BH-BH mergers are formed along one specific evolutionary channel (see Table 3). Since most of the initial binaries have similar mass components (see mass ratio distribution in Fig. 6) and since all stars follow similar evolution (specific to zero metallicity) we find that BH-BH mergers form predominantly along just one evolutionary sequence. A typical example of the evolution is given in the following.

Evolution begins with two massive, very similar, stars
\( M_1 = 69.6 \ M_\odot \) and \( M_2 = 65.6 \ M_\odot \) on a moderately wide \((a = 9955 \ R_\odot)\) and rather eccentric orbit \((e = 0.73)\). Not only initial mass ratio peaks at high values \(q \sim 0.8 - 1\) (Fig. 4), but also systems with very low mass ratios tend to evolve through two CE phases and they are very likely to merge during one of the CE event, barring the formation of BH-BH merger.

The first Roche-lobe overflow (RLOF) phase starts while both stars are already evolved core helium burning stars (CHeBs). The onset of RLOF begins when the stars meet at periastron \((d_{\text{per}} = a(1-e) = 2690 \ R_\odot)\). The orbit is not circularized by tidal forces due to relatively weak tidal efficiency noted in massive stars (Claret 2007), and due to the very short time of 0.2 Myr since the primary star left MS \((R_1 = 20 \ R_\odot)\) until it has reached RLOF during CHeB \((R_1 = 1073 \ R_\odot)\). At the onset of RLOF we instantaneously circularize the orbit at periastron \((a = 2690 \ R_\odot, e = 0)\) assuming that effective dissipation will take place at periastro passages. The RLOF develops into stable but non-conservative mass transfer (half of the mass lost by the donor is ejected from the system). Very quickly, the mass ratio is reversed, and now the donor primary is the least massive star. The mass lost from the system carries off specific angular momentum \((J_{\text{loss}} = 1.0 \ \text{defined in Podsiałowski et al. 1992})\) and the orbit expands. At the time when the primary is depleted to \(M_1 = 43.7 \ M_\odot\) the orbit has expanded to \(a = 3436 \ R_\odot\). At the same time the secondary star, which is also on CHeB, has gained mass to \(M_2 = 78.6 \ M_\odot\) and its radius has reached its Roche lobe \((R_2 = 1534 \ R_\odot)\). At this point the system enters a double common envelope (CE) phase with two helium cores inspiraling within the two H-rich envelopes of both stars.

We perform CE with \(\alpha = 100\%\) efficient energy transfer from the orbit into ejection of the primary and secondary envelopes. We use a physical estimate of the envelope binding energy with \(\lambda = 0.07\) and 0.05 for the primary and the secondary, respectively (Xu & Li 2010, Dominik et al. 2012), i.e. the envelopes are 14 – 20 times more bound to their cores (and harder to eject) than typically assumed in Pop III population synthesis studies (e.g., Kimugawa et al. 2014 uses \(\lambda = 1.0\)). After the ejection of the massive double envelope \((64.0 \ M_\odot)\) the orbital separation decreases to \(a = 6.7 \ R_\odot\), and it hosts two massive naked helium cores \((M_1 = 30.2 \ M_\odot, M_2 = 28.0 \ M_\odot)\).

After CE, both helium cores evolve toward core-collapse. At \(t = 4.3\) Myr after binary formation, the primary undergoes core-collapse. Its CO core mass is \(M_{1,\text{co}} = 24.0 \ M_\odot\) and the BH forms through direct collapse of a star to a BH with no mass ejection and no natal kick (Fryer et al. 2012). We only assume 10\% mass loss in neutrino emission, which induces a small orbital widening and small eccentricity of the system \((a = 7.1 \ R_\odot, e = 0.05)\). At \(t = 4.4\) Myr since binary formation, the secondary undergoes core-collapse. Its CO core mass is \(M_{2,\text{co}} = 22.1 \ M_\odot\) and the BH forms with no mass ejection and no natal kick (Fryer et al. 2012). We again assume 10\% mass loss in neutrino emission, which induces further orbital widening and increases the eccentricity of the system \((a = 7.5 \ R_\odot, e = 0.08)\). The two massive black holes \(M_{1,\text{bh}} = 27.1 \ M_\odot\) and \(M_{2,\text{bh}} = 25.2 \ M_\odot\) have formed on a very close orbit with a total delay time of 17 Myr (evolutionary time of 4.3 Myr and merger time of 12.7 Myr).

### 4.2 Model FS2: small orbital separations

In this model the formation of BH-BH mergers is almost totally suppressed. The only evolutionary channel that allows the formation of BH-BH mergers (described below) is most likely an artifact that emerged due to limitations of our evolutionary model. At best, even if this unlikely scenario works, due to very low BH-BH merger formation rate and short merger times, the BH-BH merger rate within Advanced LIGO horizon is zero.

We describe only one particular system that has formed BH-BH merger in this model framework. The other systems have very similar initial properties and the same evolutionary sequence. Evolution begins with two massive stars \(M_1 = 67.7 \ M_\odot\) and \(M_2 = 52.1 \ M_\odot\) on a relatively close \((a = 36.3 \ R_\odot)\) and almost circular orbit \((e = 0.12)\). The first RLOF starts while both stars are still on MS and develops into stable but non-conservative mass transfer. The donor, the more massive primary, keeps losing mass as it evolves off MS, through Hertzsprung gap (HG) and becomes a CHeB. At the end of the mass transfer phase, the primary has lost most of its mass \((M_1 = 12.5 \ M_\odot)\), half of which was accreted
onto and rejuvenated the secondary star ($M_2 = 79.7 \ M_\odot$) and half is lost from the binary. The mass transfer leads to the orbital expansion and circularization ($a = 208 \ R_\odot$, $e = 0$).

The primary, which lost most of its H-rich envelope during CHeB, becomes a naked helium (He) star and quickly evolves toward core-collapse. At $t = 4.8 \ Myr$, the primary explodes in Type Ib/c supernova. Its CO core mass is $M_{1,co} = 9.3 \ M_\odot$ and the BH that forms is subject to mass ejection and natal kick (Fryer et al. [2012]). The combined effects of mass ejection and natal kick place a newly formed black hole ($M_{1,bh} = 8.7 \ M_\odot$) on an extremely wide and eccentric orbit ($a = 1.6 \times 10^8 \ R_\odot$, $e = 0.999$). At closest approach (periastron) the orbital separation is $a_{per} = 1600 \ R_\odot$, with primary and secondary Roche lobe radii of $R_{1,rl} = 345 \ R_\odot$ and $R_{2,rl} = 927 \ R_\odot$, respectively.

The secondary evolves off MS, goes through HG and evolves along CHeB until its size becomes larger than its natal kick. We assume that 10% of the mass of the secondary this massive star does not explode, so it is not subject to a core-collapse. At $t = 6 \ Myr$, the primary overfills its Roche lobe and half is lost from the binary. The mass transfer leads to a wide and eccentric orbit ($a = 208 \ R_\odot$, $e = 0$). The periastron passages where the dissipation of tidal energy is not able to reduce the separation below about $50 \ R_\odot$.

Table 3. Major formation channels of BH-BH mergers

| Model | Evolutionary sequence* |
|-------|------------------------|
| FS1   | MT1(4-4) CE1(4-7-7) BH1 BH2 |
| FS2   | MT1(1/2/4-1) BH1 CE2(14-4-7) BH2 |
| M10   | MT1(2/4-1) BH1 CE2(14-4-7) BH2 |
| KK1   | MT1(4-4) CE12(4-7-7) BH1 BH2 |
| M10   | MT1(2/4-1) BH1 CE2(14-4-7) BH2 |
| KK2   | MT1(4-4) BH1 CE2(14-2/4-7) BH2 |
|       | CE1(4-1-7) BH1 CE2(14-4-7) BH2 |
|       | CE1(4-1-7) BH1 CE2(7-2-7) BH2 |

*MT – stable mass transfer, CE – common envelope, BH – black hole, CHeB – core-helium burning, HG – helium burning, MS – main sequence, He – helium, POP III – Population III, CE – common envelope, BH – black hole, PNe – planetary nebulae, SN – supernova, MT – mass transfer.

The typical evolution of binaries that form BH-BH mergers starts with two massive stars and wide orbits, and proceeds in the order of stable mass transfer, BH formation, CE evolution and second BH formation (e.g., see Fig. 1 of Belczynski et al. [2016a]). A summary of this sequence, along with the Pop III formation channels, is given in Table 3.
BH-BH mergers from Pop III stars

5 RESULTS

5.1 BH-BH merger formation efficiency

In Table 4 we list the number of BH-BH, BH-NS, NS-NS binaries formed in each simulated stellar population model. The mass ($M_{\text{sim}}$) includes mass in single stars and binary stars (and in triples for models FS1 and FS2) in the entire IMF ranges listed in Table 2. We also translate these numbers into formation efficiency (per unit mass) for BH-BH mergers.

For Pop I/II stars (model M10), the formation efficiency of BH-BH mergers increases with decreasing metallicity due to the higher BH masses and easier CE development/survival at low metallicity (Bełczynski et al. 2010b). For very low metallicity ($Z = 0.0002$) this efficiency is high: at the level of $3.0 \times 10^{-5}$ M$_{\odot}^{-1}$.

For Pop III stars in model FS1, the efficiency of BH-BH mergers is even higher: $9.5 \times 10^{-5}$ M$_{\odot}^{-1}$. This comes from the fact that the IMF in model FS1 favors BH formation: the number of massive stars increases with initial star mass. This is very specific for Pop III star formation and provides a major boost to BH-BH merger formation. For comparison, for Pop I/II stars (M10) the number of massive stars decreases with initial star mass (see Fig. 5).

For Pop III stars in model FS2 the efficiency of BH-BH mergers is very low: $3.8 \times 10^{-9}$ M$_{\odot}^{-1}$. In this model, initial orbital separations do not reach the typical large separations that are required to form BH-BH mergers ($a \gtrsim 1000$ R$_{\odot}$; see de Mink & Bełczynski 2019). The large separations are required for slow to moderately rotating stars that do not undergo homogeneous evolution. As explained in Section 4.2, the formation of BH-BH mergers follows only from a supernova injection of the first BH on a very wide (and eccentric) orbit, that after the circularization and CE evolution, produces a BH-BH merger. This is a very unusual process with extremely low formation efficiency.

| model | $X_{\text{BHBH}}$ | $M_{\text{sim}}^{b}$ | $M_{\text{BHBH}}^{a}$ | $N_{\text{BHBH}}^{c}$ | $N_{\text{BHNS}}^{c}$ | $N_{\text{NSNS}}^{c}$ |
|-------|------------------|------------------|------------------|------------------|------------------|------------------|
| FS1   | $9.5 \times 10^{-5}$ | $3.5$ | $332,003$ | $56$ | $0$ |
| FS2   | $3.8 \times 10^{-9}$ | $1.6$ | $6$ | $0$ | $0$ |
| M10$^d$ | $3.0 \times 10^{-5}$ | $1.0$ | $14,157$ | $750$ | $2,580$ |
| 0.0002 | $1.1 \times 10^{-5}$ | $1.7$ | $16,082$ | $2,325$ | $2,275$ |
| 0.02  | $1.9 \times 10^{-7}$ | $1.4$ | $270$ | $65$ | $7,630$ |
| KK1   | $3.5 \times 10^{-5}$ | $2.0$ | $70,353$ | $87$ | $0$ |
| KK2   | $5.8 \times 10^{-4}$ | $2.0$ | $1,162,155$ | $1,224$ | $0$ |

$^a$ BH-BH merger formation efficiency per unit of star forming mass: $X_{\text{BHBH}} = \frac{N_{\text{BHBH}}}{M_{\text{sim}}}$.

$^b$ Total mass of stars across entire IMF (single, binaries, triples) corresponding to a given simulation.

$^c$ Number of BH-BH, BH-NS and NS-NS binaries formed with delay time below Hubble time.

$^d$ Model M10 for Pop I/II stars is obtained with non-trivial combination of 32 different metallicity models (in range $Z = 0.03 - 0.0001$). Here we show three representative metallicity models from M10: $Z = 0.0002, 0.002, 0.02$.

Figure 9. Total intrinsic (solid lines) and redshifted (dashed lines) BH-BH merger mass for BH-BH mergers that take place within redshift of 2 ($z < 2$). Note significantly higher average mass for Pop III BH-BH mergers: $M_{\text{tot}} = 63.4$ M$_{\odot}$ ($M_{\text{tot},z} = 162$ M$_{\odot}$) for model FS1, as compared with the Pop I/II mergers: $M_{\text{tot}} = 29.7$ M$_{\odot}$ ($M_{\text{tot},z} = 73.7$ M$_{\odot}$) for model M10. For model FS2 the corresponding values are: $M_{\text{tot}} = 34.1$ M$_{\odot}$ ($M_{\text{tot},z} = 101$ M$_{\odot}$).

5.2 BH-BH merger mass

In Figure 9 we show the distribution of total BH-BH merger mass. We include only systems that merge within reach of advanced LIGO at full design sensitivity: $z < 2$. We show total intrinsic mass ($M_{\text{tot}} = M_{\text{BH1}} + M_{\text{BH2}}$) and total redshifted mass ($M_{\text{tot},z} = (1+z)M_{\text{tot}}$) that is observed in gravitational wave detectors like LIGO or VIRGO.

The intrinsic mass of Pop III BH-BH mergers in model FS1 is found in the range $M_{\text{tot}} \approx 30 - 80$ M$_{\odot}$. The average total intrinsic mass is $63.4$ M$_{\odot}$. Stars that form BH-BH mergers evolve through stable mass transfer and CE (see Tab. 2). These events remove H-rich envelopes from massive stars. Therefore, even in case of direct BH formation, the BH mass is limited by the mass of the He core. This, along with pair-instability pulsation supernova mass loss, sets a maximum BH mass in BH-BH merger of $M_{\text{BH,max}} \approx 45$ M$_{\odot}$, while single Pop III stars that retain an H-rich envelope may form much more massive BHs $M_{\text{BH,max}} \approx 90$ M$_{\odot}$ (see Fig. 2).

The total redshifted BH-BH merger mass in model FS1 is found in a broad range $M_{\text{tot},z} \approx 30 - 250$ M$_{\odot}$. This is the result of significant redshifting for BH-BH mergers as the BH-BH merger rate density increases with redshift in the entire considered redshift range ($z = 0 - 2$; see Sec. 5.4).

In comparison, Pop I/II BH-BH mergers (M10) are found in a broader mass range $M_{\text{tot}} \approx 10 - 80$ M$_{\odot}$ and with significantly lower average total intrinsic mass of $29.7$ M$_{\odot}$. This follows from the combination of two things. First, Pop I/II stars are subject to significant wind mass loss, which reduces the average BH mass in comparison with Pop III evolution. Second, the significant radial expansion experienced by Pop I/II stars leads to early interactions (envelope removal) and thus smaller masses for the He and CO cores compared with Pop III stars, which are more compact.
5.3 BH-BH delay time

In Figure 10, we show the delay time distributions for our models of Pop III stars (FS1 and FS2). The delay time includes evolutionary time from star formation, to the formation of BH-BH binary, and the coalescence time to the final merger. The delay time distribution for model FS1 is a steep power-law: for very short delay times ($t_{\text{delay}} < 0.5$ Gyr) the number of BH-BH mergers falls off as $\propto t^{-3}$, and for longer delay times it falls off a bit faster than $\propto t^{-1}$.

The delay time is the result of a convolution of the initial separation distribution that gets modified by stable mass transfer and CE during evolution (see Tab. 3) and the timescale for orbital decay due to emission of gravitational waves once the BH-BH binary is formed. Stable mass transfer does not modify the orbital size significantly, while CE leads to significant contraction. For massive BH progenitors, the CE contraction reduces the orbital size typically by a factor of about 100, and does not significantly change the shape of the distribution of orbital separations.

For initial separations that are flat or approximately flat in logarithm ($\propto a^{-1}$) in the range of BH-BH formation ($a \gtrsim 1000 \, R_\odot$), the convolution with gravitational radiation emission orbital decay timescale ($\propto a^{-4}$; Peters 1964) results in power-law delay time distribution $\propto t^{-1}$, because the delay time scales like $a^{-1}(da/dt)_{GR} \propto t^{-1/4}(d(t^{1/4})/dt) \propto t^{-1}$). In fact, for Pop I/II binaries BH-BH delay times follow such a power-law $\propto t^{-1}$ (e.g. Belczynski et al. 2016d). However, since Pop III BH-BH mergers host BHs with larger masses (see Fig. 9) than Pop I/II mergers, the delay time becomes steeper for Pop III mergers. The coalescence time is proportional to $[M_1 M_2 (M_1 + M_2)]^{-1}$ (Peters 1964).

5.4 BH-BH Merger Rate Density

In Figure 11 we show the rate density of BH-BH mergers from our Pop III models, FS1 and FS2. For comparison we also show the results for our population synthesis model for Pop I/II stars, M10.

The merger rate density is a combination of star formation rate density (see Fig. 4), BH-BH merger formation efficiency (see Tab. 4) and time delay from formation of stars to BH-BH merger (Fig. 10).
BH-BH mergers from Pop III stars

Since the delay times are in a form of steep (negative) power-laws for all our models (most systems have relatively short delay times) the evolution of the BH-BH merger rate density with redshift has a shape similar to the star formation rate density appropriate for each stellar population. For Pop III model FS1, the rate density starts at high redshift (\(z \approx 45\)), and then increases to its peak at \(z \approx 10 - 13\), and then decreases for smaller redshifts. In the redshift range of interest for advanced LIGO (\(z < 2\)), the rate density is at the level of \(R_{\text{BHBB}} \approx 0.1 \text{ Gpc}^{-3} \text{ yr}^{-1}\).

In Figure 12 we show the noise power spectral densities (PSDs) for present and future Earth-based detector designs. From top to bottom, the figure shows the sensitivity of the first Advanced LIGO observing run (O1); the expected sensitivity for the second observing run (O2); the Advanced LIGO design sensitivity (AdLIGO) (The LIGO Scientific Collaboration et al. 2013); pessimistic and optimistic ranges of Advanced LIGO designs with squeezing (\(A^+, A^{++}\)) (Miller et al. 2015); the most sensitive interferometers that can be built in current facilities, Vrt and Voyager (Adhikari 2014; Abbott et al. 2016c); Cosmic Explorer (CE1), basically \(A^+\) in a 40-km facility (Dwyer et al. 2015); CE2 wide and CE2 narrow, i.e. 40-km detectors with Voyager-type technology but different signal extraction tuning (Abbott et al. 2016c); and two possible Einstein Telescope designs, namely ET-B and ET-D in the “xylophone” configuration (Hild et al. 2010).

In order to compare the detectability of Pop I/II and Pop III sources, a particularly interesting quantity is the horizon redshift \(z_{\text{hor}}\). We define \(z_{\text{hor}}\) as the redshift out to which any given detector can observe the full inspiral-merger-ringdown signal from an optimally oriented, non-spinning BH binary. Dominik et al. (2015) showed that spin effects may increase BH-BH detection rates by as much as a factor of 3, but for simplicity we will ignore spins in our model comparisons. The maximum horizon redshift is achieved for equal-mass binaries, and it is shown in Figure 13 as a function of the total intrinsic mass \(M_{\text{tot}}\) of a non-spinning BH binary (as measured in the source frame). For this calculation we estimate the gravitational wave signal using the phenomenological PhenomC waveforms of Santamaria et al. (2010). The sensitivity of a gravitational wave detector network depends on the details of the search pipeline and the detector data quality, but following Abadie et al. (2010) we set a single-detector SNR threshold \(\rho \geq 8\) as a proxy for detectability by the network. The left panel shows that binaries of source mass \(\approx 10^2 M_\odot\) can be detected out to \(\approx 1\) in the second observing run O2, \(\approx 2\) by AdLIGO at design sensitivity, and \(\approx 4\) by an Advanced LIGO detector with squeezing in the “optimistic” (\(A^{++}\)) configuration. The right panel shows that detectors such as Voyager or ET could reach redshifts of order 10, and that detectors of the “Cosmic Explorer” class would see gravitational waves from binaries throughout the whole Universe.

From Figure 11 we see that BH-BH mergers first occur around \(z \approx 15\) for the Pop I/II model M10; the merger rate density peaks at \(z \approx 2\), and decreases for smaller redshifts. In the LIGO range (\(z < 2\)) the rate density is at the level of \(R_{\text{BHBB}} \approx 1000 \text{ Gpc}^{-3} \text{ yr}^{-1}\). Note that the Pop I/II merger rate density is about four orders of magnitude larger than for Pop III. This is a direct result of the fact that (i) Pop I/II star formation produces many more stars (99.7%) than Pop III (0.3%), (ii) Pop I/II star formation peaks within the Advanced LIGO horizon (\(z \approx 2\)), while Pop III stars form mostly well outside the Advanced LIGO horizon (\(z \approx 10 - 13\)), (iii) the delay times from star formation to BH-BH mergers are short for both Pop I/II and Pop III mergers (\(t^{-1}\)), and (iv) the formation efficiency of BH-BH mergers per unit of star forming mass is similar (\(10^{-5} M_\odot^{-1}\) and \(10^{-4} M_\odot^{-1}\) for Population I/II and Pop III, respectively).

Even before computing rates, we can already attempt a rough comparison with existing LIGO data. In the lo-

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1 See [http://www.et-gu.eu/etdsdocument](http://www.et-gu.eu/etdsdocument)
Table 5. Merger rate densities and detection rates for AdLIGO

| model        | merger type | rate density\(^a\) [Gpc\(^{-3}\) yr\(^{-1}\)] | det. rate\(^b\) [yr\(^{-1}\)] | det. number\(^c\) [131 days] |
|--------------|-------------|---------------------------------------------|-------------------------------|-------------------------------|
| FS1          | NS-NS       | 0.002–0.012                                | 0.004                         | 0.004                         |
|              | BH-NS       | 0.022–0.234                                | 5.974                         | 2.151                         |
|              | BH-BH       | 74.0–121                                   | 1.418                         | 0.510                         |
|              | NS-NS       | 27.2–84.2                                  | 6.951                         | 2.502                         |
|              | BH-NS       | 220–1802                                   | 2080                          | 748.8                         |
|              | BH-BH       | 0.004–0.015                                | 0.020                         | 0.007                         |
|              | NS-NS       | 0.004–0.015                                | 0.020                         | 0.007                         |
|              | BH-NS       | 0.024–0.153                                | 4.067                         | 1.464                         |
| KK1          | NS-NS       | 0.004–0.015                                | 0.020                         | 0.007                         |
|              | BH-NS       | 0.024–0.153                                | 4.067                         | 1.464                         |
|              | NS-NS       | 0.004–0.015                                | 0.020                         | 0.007                         |
|              | BH-NS       | 0.024–0.153                                | 4.067                         | 1.464                         |
|              | BH-BH       | 1.159–12.0                                 | 507                           | 182                           |

\(^a\) Typically, merger rate density increases from low redshift to high redshift within advanced LIGO horizon. We list rate density at \(z = 0\) (local; before arrow) and at \(z = 2\) (AdLIGO horizon; after arrow).

\(^b\) Detection rate for full advanced LIGO sensitivity.

\(^c\) Number of LIGO detections per 1 years of advanced LIGO, while assuming \(p = 0.36\) duty cycle: 131 effective observation days per year.

By comparison, the Pop III BH-BH AdLIGO detection rate is much lower: for model FS1 we find a rate of \(\sim 6 \text{ yr}^{-1}\), or \(\sim 2 \text{ yr}^{-1}\) if we take into account the duty cycle of the detectors. These numbers are only 2.5 orders-of-magnitude lower than the corresponding numbers for model M10. The BH-BH merger rate density difference between the two models is much larger: 4 orders-of-magnitude (see Sec. 5.4). This is explained by the higher mass of merging BH-BH binaries formed from Pop III stars \(M_{\text{tot}} = 63.4 M_\odot\); see Belczynski et al. 2016c; Mandel 2016. This produces a small but distinct population of Pop III BH-BH mergers originating from Pop I/II stars. This small contribution \((\lesssim 1\%)\) may go unnoticed and remain hidden in the population of other BH-BH mergers. Note that Pop III BH-BH mergers reach the same maximum intrinsic mass as Pop I/II BH-BH mergers \(M_{\text{tot,max}} = 80 \sim 90 M_\odot\); see Belczynski et al. 2016c; Mandel 2016. The maximum total mass is set, for both Pop III and Pop I/II, by pair instability pulsation supernovae mass loss and by binary evolution that removes H-rich envelopes from stars that form BH-BH mergers (see Sec. 5.2 and 4 for details). Although the exact value of the total maximum mass may be uncertain, the same cutoff is expected for both Pop III and Pop I/II BH-BH mergers. Therefore, Pop III BH-BH mergers are not likely to be distinguished through their heavier mass by AdLIGO. Although the distribution of total mass for Pop III BH-BH mergers is different from that of Pop I/II BH-BH mergers (see Fig. 5), the very small number of predicted AdLIGO detections for Pop III BH-BH mergers will most likely blend into larger populations of Pop I/II BH-BH mergers.

5.5 Advanced LIGO Detection Rates

Advanced LIGO is expected to achieve design sensitivity around 2020. Following Dominik et al. 2015, we use the “AdLIGO” design sensitivity in Figure 12 and the PhenomC model for nonspinning BH binary merger waveforms to estimate the number of detected events for both Pop III and Pop I/II evolutionary models.

The results of this calculation are presented in Table 5. According to model M10, Pop I/II BH-BH mergers are expected to be detected at a rate of \(\sim 2000 \text{ yr}^{-1}\). However we should take into account the fact that the LIGO interferometers will not work simultaneously all the time. The typical duty cycle \(p\) in the first observing run O1 (i.e., the fraction of time during the run when both interferometers were operating simultaneously) was about \(p = 0.36\). Taking into account the duty cycle, the predicted rate yields about \(\sim 700\) detections in one year of actual observations. These detection rate estimates are on the high side for Pop I/II stars; other models compatible with current LIGO constraints predict smaller rates. Rates that are smaller by about one order of magnitude cannot be excluded (Belczynski et al. 2016a; Belczynski et al. 2016c; Mandel 2016). Such reduced rates of BH-BH mergers are obtained for example with increased BH natal kicks. In particular, even very high BH natal kicks cannot yet be excluded based on electromagnetic observations (Repetto & Nelemans 2015). By comparison, the Pop III BH-BH AdLIGO detection rate is much lower; for model FS1 we find a rate of \(\sim 6 \text{ yr}^{-1}\), or \(\sim 2 \text{ yr}^{-1}\) if we take into account the duty cycle of the detectors. These numbers are only 2.5 orders-of-magnitude lower than the corresponding numbers for model M10. The BH-BH merger rate density difference between the two models is much larger: 4 orders-of-magnitude (see Sec. 5.4). This is explained by the higher mass of merging BH-BH binaries formed from Pop III stars \(M_{\text{tot}} = 63.4 M_\odot\); see Belczynski et al. 2016c; Mandel 2016. This produces a small but distinct population of Pop III BH-BH mergers originating from Pop I/II stars. This small contribution \((\lesssim 1\%)\) may go unnoticed and remain hidden in the population of other BH-BH mergers. Note that Pop III BH-BH mergers reach the same maximum intrinsic mass as Pop I/II BH-BH mergers \(M_{\text{tot,max}} = 80 \sim 90 M_\odot\); see Belczynski et al. 2016c; Mandel 2016. The maximum total mass is set, for both Pop III and Pop I/II, by pair instability pulsation supernovae mass loss and by binary evolution that removes H-rich envelopes from stars that form BH-BH mergers (see Sec. 5.2 and 4 for details). Although the exact value of the total maximum mass may be uncertain, the same cutoff is expected for both Pop III and Pop I/II BH-BH mergers. Therefore, Pop III BH-BH mergers are not likely to be distinguished through their heavier mass by AdLIGO. Although the distribution of total mass for Pop III BH-BH mergers is different from that of Pop I/II BH-BH mergers (see Fig. 5), the very small number of predicted AdLIGO detections for Pop III BH-BH mergers will not allow accurate (if any) measurement of their mass distribution. These Pop III BH-BH mergers will most likely blend into larger populations of Pop I/II BH-BH mergers.

This is in tension with the conclusion reached by Hartwig et al. 2016 that gravitational waves have the potential to directly detect the remnants of the first stars, and possibly even to constrain the Pop III IMF by observing BHBH mergers with a total mass around \(M_{\text{tot}} = 300 M_\odot\). This different conclusion originates from the fact that Hartwig et al. 2016 considered a Pop III IMF that may potentially extend to \(M_{\text{sims}} = 300 M_\odot\) or even to \(M_{\text{sims}} = 1000 M_\odot\). This produces a small but distinctive population of Pop III BH-BH mergers with total mass of about \(M_{\text{tot}} = 300 M_\odot\), which would stand out from...
Pop I/II BH-BH mergers simply by the virtue of its high total mass. This is only true if Pop I/II stars have IMF that do not exceed above a mass of $M_{\text{zams}} = 300 \, M_\odot$. However, there is observational evidence that Pop I/II stars may reach such high mass: several stars in the R136 region of the Large Magellanic Cloud may have had an initial mass up to $300 \, M_\odot$. According to models M10, BH-BH massive mergers from Pop III stars can exist and evolve at low- to moderate-metallicity, forming massive BHs and BH-BH mergers from Pop III stars. Whether such very massive stars exist and can lead to formation and AdLIGO detection of several to hundreds of BH-BH mergers within a total intrinsic mass range $m_{\text{tot}} = 50 - 300 \, M_\odot$ (see Fig. 3 of Belczynski et al. 2014). If the metallicity were decreased to say $Z = 0.002$ (about 1% solar metallicity), the total intrinsic mass for these BH-BH mergers would increase. This would cause the overlap of BH-BH massive mergers from Pop I/II with BH-BH massive mergers from Pop III stars. Whether such very massive stars exist ($M_{\text{zams}} \gtrsim 300 \, M_\odot$; as to avoid pair instability supernova disruption and allow for massive BH formation) in Pop III and in Pop I/II stars still remains an open question. However, if such stars are considered in one population, they should also be considered in the other population. Therefore, the idea that Pop III stars can be investigated by means of massive BH-BH mergers needs to allow for this caveat.

We note that, while our predicted rates are considerably lower than those found by other investigations (see Sec. 6.5 for a detailed model comparison), they are consistent with those estimated by C. S. Park and colleagues (personal communication). These authors used a combination of dark matter halo merger trees (GALFORM; Cole et al. 2000) specific for Pop III star formation with some (e.g., initial binary separations) properties specific for massive Pop I stars (Sana et al. 2012) to determine the initial conditions for estimates of BH masses and BH-BH merger rates. These estimates were based on population synthesis study for Pop I stars with $Z = 0.002$; with non-zero wind mass loss and significant radial expansion of stars and without effects of pair-instability pulsation supernovae (de Mink et al. 2015). Unlike Table 5, where we listed results only for Advanced LIGO at design sensitivity, here we show event rates for all of the noise PSDs shown in Figure 12.

In the Pop I/II model M10, BH-NS and NS-NS detection rates are comparable in order of magnitude (BH-NS rates being slightly larger for all detectors); BH-BH detection rates are about two orders of magnitude higher. While a BH-NS observation may occur already during the O2 run, NS-NS detections seem to be likely only at the Advanced LIGO design sensitivity and above.

Our most optimistic Pop III model (FS1) predicts BH-BH rates comparable to the BH-NS rates in model M10, because the high mass of Pop III BHs compensates for their lower merger rate density. The number of detections for Pop III BH-BH mergers plateaus for third generation detectors such as Voyager, ET and Cosmic Explorer, essentially because all detectable binaries in the Universe have already been seen, and better noise PSDs only increase the SNR of the observed events; by contrast, the number of BH-NS and NS-NS detections in the M10 model keeps increasing as detectors are improved and more of the Universe becomes visible.

### 5.6 Binary black hole spectroscopy

After merger, two BHs settle down to a stationary (Kerr) solution of Einstein’s equations by emitting gravitational waves at characteristic complex frequencies, known at the “quasinormal mode frequencies” (“quasinormal” because the system is dissipative and the frequencies are complex: the inverse of the imaginary part corresponds to the damping time due to gravitational wave emission). In GW150914, this “ringdown” signal was observed with a relatively low SNR $\rho \sim 7$. The signal is consistent with the predictions of general relativity for a Kerr BH, but it does not allow us to...
to do BH spectroscopy (triangles). Detectable BH ringdown events (empty circles) also are much more unlikely. According to our model, the detection of a second mode requires SNRs ($\gtrsim 3$), while the high rates correspond to flat IMF. We will use the high rate model of [Kinugawa et al. 2014] for our comparison, and hence we adopt the flat IMF.

We constructed two models in order to reproduce and explain the results of [Kinugawa et al. 2014]. In model KK1 we employ initial conditions for evolution of Pop III binaries as in [Kinugawa et al. 2014], but we keep our evolutionary scheme. In model KK2 we employ initial conditions for evolution of Pop III binaries as in [Kinugawa et al. 2014], and we match (as closely as we can) the evolutionary scheme of [Kinugawa et al. 2014]. For both models we use the same SFR used by [Kinugawa et al. 2014], which we have also adopted for our models (FS1 and FS2; see Fig. 4). Also the radius evolution of the Pop III stars in our models matches closely that of [Kinugawa et al. 2014] (see Fig. 1).

Model KKI initial distributions are as follows. The primary mass ($M_1$) is drawn from a flat IMF within the range $10–100 M_\odot$. The mass ratio (secondary-to-primary) is taken from a flat distribution in the range $q_{\text{min}} – 1$ with $q_{\text{min}} = 10/M_1$. For the eccentricity distribution we adopt $f(e) = 2e$ in the range $0 – 1$, while for the orbital separation distribution we adopt $f(a) = 1/a$ in range $a_{\text{min}} – 10^3 R_\odot$, with $a_{\text{min}}$ such that stars do not overfill their Roche lobes at periastron on Zero Age Main Sequence. The binary fraction is taken to be $f_{\text{bi}} = 1/3$. We evolve the stars as described in Sec. 3.

Model KK2 uses the same initial distributions as in model KKI. However, the evolution is modified in the following way.

6 THE ORIGIN OF THE UNPHYSICALLY HIGH POP III BH-BH MERGER RATES

Since the Pop III rates that we find here are considerably lower than those found by other studies (i.e. [Bond & Carr 1984; Belczynski, Bulik & Rudak 2004; Kinugawa et al. 2014]), we have devoted a considerable effort to understand the reasons for these differences, and performed a detailed model comparison, as described below. We however note that our detection rates of Pop III BH-BH mergers are in agreement with those recently found by [Hartwig et al. 2016] (see Sec. 5.3).

6.1 Description of the models used for a comparative study

We use one of the recent studies that argues for high Pop III BH-BH merger rates and significant contribution of these mergers to advanced LIGO signal to show that such findings originate from (i) initial conditions that may not be appropriate for Pop III stars, and (ii) outdated evolutionary calculations for Pop III binaries. In particular, [Kinugawa et al. 2014] finds a merger rate density of $12–25 \text{ Gpc}^{-3} \text{ yr}^{-1}$ at small redshifts (see their Fig. 9) and an advanced LIGO detection rate at the level of $68–140 \text{ yr}^{-1}$ for Pop III BH-BH mergers. The range of the reported rates corresponds to different assumption for the Pop III IMF. The low rates correspond to Salpeter-like IMF (power-law with index of $–2.3$), while the high rates correspond to flat IMF. We will use the high rate model of [Kinugawa et al. 2014] for our comparison, and hence we adopt the flat IMF.

In Figure 14 we consider, for models M10 and FS1, the rates per year of BH-BH mergers for which we can detect the full inspiral-merger-ringdown signal (solid circles) and the ringdown signal (empty circles). We also show the (much smaller) number of detections that would allow us to do BH spectroscopy (triangles). Detectable BH ringdown signals and rates for BH spectroscopy are estimated as described in [Berti et al. 2016]. Because BH-BH merger event rates in model FS1 are two orders of magnitude lower than in model M10, ringdown detections and spectroscopic tests are also much more unlikely. According to our model, the detection of ringdown signals from Pop III binaries will require at least the implementation of squeezing. Notice that while BH merger (and ringdown) detections plateau for detectors such as ET or Cosmic Explorer and beyond, the fraction of events allowing for BH spectroscopy increases: this is because the SNR of the observed events is increasing, and no-

conversionally confirm the Kerr nature of the remnant. As first pointed out by [Detweiler 1980], with higher-SNR observations we may be able to measure more than one quasinormal mode frequency. Since all quasinormal mode frequencies in general relativity depend only on the BH mass and spin, a multi-mode gravitational wave detection would allow us to do “BH spectroscopy” — i.e., to identify these objects as Kerr BHs with the same certainty with which we identify atoms from their spectra ([Berti, Cardoso & Starinets 2009]). To quote Detweiler: “after the advent of gravitational wave astronomy, the observation of these resonant frequencies might finally provide direct evidence of BHs with the same certainty as, say, the 21 cm line identifies interstellar hydrogen.” As discussed by [Berti, Cardoso & Will 2006] and [Berti et al. 2007], the detection of a second mode requires SNRs ($\gtrsim 8$) about one order of magnitude larger than the SNRs ($\gtrsim 8$) necessary for ringdown detection.

Figure 15. Full inspiral-merger-ringdown rates (solid circles), ringdown detection rates (empty circles) and number of detections allowing us to do BH spectroscopy (triangles) for models M10 (black) and FS1 (red), and for various detectors.
(i) We adopt a constant $\lambda = 1.0$: this is a parameter that describes CE binding energy. Note that more realistic values used in our current simulations (models FS1, FS2, M10) are not constant and are much smaller ($\lambda \approx 0.1$; see Sec. 5) so the binding energy in our models is much higher ($E_{\text{bind}} \propto \lambda^{-1}$).

(ii) We use our old computation scheme of BH and NS mass (Belczynski, Kalogera & Bulik 2002) that was obtained for outdated wind-mass loss prescriptions for massive stars. The new (weaker) mass loss (Vink, de Koter & Lamers 2001; Belczynski et al. 2008; Vink 2011) and new supernova models (Fryer et al. 2012; rapid explosions) were applied in our current simulations (models FS1, FS2, M10).

(iii) We do not apply corrections that take into account pair-instability supernovae and pair-instability pulsation supernovae. Note that these supernovae disrupt the most massive stars and reduce the BH mass for high mass stars (see Fig. 2).

(iv) We do not apply natal kicks, neither to NSs nor to BHs. In all our other models considered in this study, compact objects receive natal kicks based on the formation mode. Light NSs receive average 3D kicks of about 400 km s$^{-1}$ (Hobbs et al. 2005), the most massive BHs that form through direct collapse get no natal kicks, while the heavy NSs and light BHs receive natal kicks decreasing with increasing mass of fall back material (Fryer et al. 2012).

(v) We allow stars on HG (radiative envelopes) and beyond to enter and survive CE. This allows for enhanced formation of merging double compact objects. This is in contrast with what we apply in other models; only stars beyond HG during later stages of evolution (convective envelopes) are allowed to survive CE (see Fig. 1).

(vi) Additionally, we turn off magnetic braking and set the maximum NS mass at 3 $M_\odot$ (instead of 2.5 $M_\odot$ used in our other models).

6.2 Comparison with Kinugawa et al. 2014

The results for models KK1 and KK2 are given in Table 4 (merger rate densities and detection rates), Figure 16 (BH-BH merger rate density change with redshift), Figure 17 (BH-BH merger total mass) and in Figure 18 (BH-BH merger delay time).

We note that our model KK2 resembles rather closely that of Kinugawa et al. (2014) (one with flat IMF; noted in their work as model III.f). The KK2 BH-BH merger rate density increases from 1.2 Gpc$^{-3}$ yr$^{-1}$ ($z = 0$) to 12 Gpc$^{-3}$ yr$^{-1}$ ($z = 2$) within reach of advanced LIGO. For comparison, the reported BH-BH merger rate density in model III.f is 25 Gpc$^{-3}$ yr$^{-1}$ (a factor of $\sim 2$ larger than our maximum rate density within the LIGO horizon).

The KK2 BH-BH detection rate for advanced LIGO is 507 yr$^{-1}$, while the detection rate in model III.f by Kinugawa et al. (2014) is only 182 yr$^{-1}$. This is surprising, since the average intrinsic total mass of BH-BH mergers in model KK2 ($M_{\text{tot}} = 62.8 M_\odot$; see Fig. 17) is rather similar to the one in model III.f ($M_{\text{tot}} \approx 55 M_\odot$; read off Fig. 6 of Kinugawa et al. 2014). This may result from an improper calculation of the advanced LIGO rate. The estimates by Kinugawa et al. (2014) account only for sources up to the redshift of $z = 0.28$, while the advanced LIGO design sensitivity will allow to detect massive BH-BH mergers to $z \approx 2$ (see Fig. 13). Additionally, no signal waveforms nor the projected advanced LIGO response function are used in their calculations of the detection rates; they simply count merging sources within the redshift of $z = 0.28$ (see their eq. 95). Hence in the following we will only make comparisons with their merger rate density, and ignore Kinugawa et al. (2014) estimate of the detection rate.

The factor of $\sim 2$ difference in the BH-BH merger rate density noted between models KK2 and III.f originates from the fact that Kinugawa et al. (2014) includes a BH-BH formation channel that is in tension with evolutionary studies done so far for binary stars in isolation and without rapid rotation (Tutukov & Yungelson 1993; Lipunov, Postnov & Prokhorov 1997; Belczynski, Kalogera & Bulik 2002; Voss & Tauris 2003; Postnov & Yungelson 2006; Belczynski et al. 2010b; Dominik et al. 2012; Mennekens & Vanbeveren 2014; Belczynski et al. 2016b; Eldridge & Stanway 2016). Note that Kinugawa et al. (2014) does not deal with dynamical BH-BH formation, and that their code is based on updated Hurley, Pols & Tout (2000) formulas (same as our model KK2) so they cannot model rapidly rotating stars and homogeneous evolution. Therefore, their evolutionary scenario would need to have a common envelope stage in order to bring two massive BHs within a distance small enough so that they can merge within a Hubble time. For two 30 $M_\odot$ BHs (their typical mass of Pop III BH-BH mergers) on a circular orbit one requires the orbital separation to be below 50 $R_\odot$ for the system to merge within Hubble time. Two massive stars with $M_{\text{zams}} = 40 – 100 M_\odot$ (Belczynski et al. 2016b), progenitors of such massive BHs, cannot fit on an orbit with a size below 50 $R_\odot$. So typically, they start on wide orbits (1000 – 4000 $R_\odot$; de Mink & Belczynski 2015) and then CE brings the compact remnants together. There is no published alternative for such a formation scenario for isolated and slow-to moderately-spinning stars. And yet, their major channel (36.9% of BH-BH mergers; the second most populated channel is only 16.3%; see their Table 5) does not require common envelope. The details of this evolutionary path hence remain unclear. If we look at the results of their simulations without this channel, then our results in model KK2 are very close to their model III.f. In Table 4 we show that each channel of our evolution (and in particular model KK2) requires a common envelope phase.

In addition to these differences in the evolutionary scenarios, the main reason for the discrepancies in the predicted merger rates lies in the adopted initial conditions. Kinugawa et al. (2014), and likewise our models KK1 and KK2, use thermal distribution of eccentricities and flat in log orbital separation distribution for their initial conditions. These are outdated conditions that were used in the early stages of population synthesis codes for Pop I/II stars (Belczynski, Kalogera & Bulik 2002). Additionally, it has now been demonstrated that these particular distributions do not apply even to massive Pop I stars (Kobulnicky & Fryer 2007; Sana et al. 2012; Chini et al. 2012; Kobulnicky et al. 2014; Moe & Di Stefano 2016). However, they are crucial for the production rates of BH-BH mergers (de Mink & Belczynski 2015). As we have shown here (models FS1 and FS2), these initial distributions are expected to be very different for Pop III stars. Additionally, Kinugawa et al. (2014) assume unrealistic conditions for CE, which is again crucial for BH-BH merger production. More specifically, they assume
concentrated around very early times right after the Big Bang (see Fig. 4). The distribution of the delay times can be calculated using the delays computed numerically (see Fig. 10 and Fig. 18). In evaluating the integral (2) we see that the integrand defined by the star formation is concentrated around $t_{form} = 300$ Myr. Thus we can express it as

$$R = X_{BBBH} \frac{dN}{dt} (t_{today} - t) SFR(t) .$$  

where $t$ is the cosmic time. In the case of Pop III the star formation is concentrated around very early times right after the Big Bang (see Fig. 4). The distribution of the delay times can be calculated using the delays computed numerically (see Fig. 10 and Fig. 18). In evaluating the integral (2) we see that the integrand defined by the star formation is concentrated around $t_{form} = 300$ Myr. Thus we can express it as

$$R = X_{BBBH} \frac{dN}{dt} (t_{today} - t_{form} \approx 13500$Myr$) \int dt SFR(t).$$

Therefore the current, local merger rate density of BBH-BH binaries originating in Pop III stars is due to the binaries that were formed in distant past and took about 13.1 - 13.6 Gyr to merge. In such a case one can estimate the current merger rate density in the following way. Let us first calculate the total mass density in the Pop III stars:

$$\rho_{PopIII} = \int_{0}^{T_Hubble} SFR(z(t))dt .$$

Integrating the star formation rate presented in Figure 4 we obtain $\rho_{PopIII} = 8 \times 10^6 M_\odot$Mpc$^{-3}$. The value of the delay time distribution at $\delta t = t_{today} - t_{form} \approx 13.5$ Gyr can be easily read off Figure 18 with the use of Table 4 as $\frac{dN}{dt}_{del} = n_i/(10^5 \times N)$, where $n_i$ is the number of binaries in a $10^5$ yr bin at $\approx 13.5$ Gyr as shown in Figure 18 and $N$ is the number of merging BH-BH binaries in the simulation from column 4 of Table 4. We obtain $\frac{dN}{dt}_{del} \approx 7 \times 10^{-13}$yr$^{-1}$ for KK1, and $\frac{dN}{dt}_{del} \approx 2 \times 10^{-12}$yr$^{-1}$ for KK2. Using the values of BH-BH merger formation efficiencies of $3.5 \times 10^{-5}$ for KK1, and $5.8 \times 10^{-4}$ for KK2, we obtain the local merger rate densities for the model KK1 and KK2: $R_{KK1} \approx 0.02$ Gpc$^{-3}$yr$^{-1}$, and $R_{KK2} \approx 1.1$ Gpc$^{-3}$yr$^{-1}$, quite close to the result of the detailed calculation presented in Figure 10.

This represents the fact that the local merger rate density is a result of the tail of the distribution of the delayed mergers produced at $z \approx 10$. Moreover the BH-BH production efficiency in Pop III stars is similar to the one of very low metallicity stars. This is mainly due to the fact that the Pop III IMF starts at 10 M$_\odot$ and therefore a large fraction of Pop III stars leads to formation of BHs. However the total mass of stars in Pop III is much smaller than the total mass of stars in Pop I/II. Thus the local merger rate density of Pop III mergers is suppressed in comparison to the Pop I/II stars for two reasons: smaller total mass of stars in this population, and the fact that the Pop III star formation has ceased roughly 10 Gyr ago ($z \approx 2$).

The local merger rate density of Pop III BH-BH mergers could be increased by increasing the BH-BH merger formation efficiency or by altering the delay time distribution. The highest the BH-BH formation efficiency that can ever be obtained is when all the BHs formed end up in merging BH-BH binaries. For a binary fraction of $f_{bin} = 1/3$ and with the KK1 IMF we obtain the maximum efficiency of BBH-BH merger formation of $7.5 \times 10^{-3}$, which means that BH-BH mergers are produced with the efficiency of $\approx 0.5\%$ of the maximal possible value. For model KK2 production of BH-BH proceeds at $\approx 6\%$ of the maximum value. The delay distribution can not be changed by much without tuning the initial distribution of orbital separation especially to do so.

The merger rate density of Pop I/II BH-BH binaries cannot be that easily calculated. The major contributions to the integral of equation (2) comes from two regions. The first is the recent star formation with short delay times, and the second are the long delay binaries for which the delay distribution factor is small but the SFR contributed a long stretch of time. The two contributions are roughly of the same order of magnitude. Thus the merger rate density is approximately, but not exactly, proportional to the SFR.

Using the similar arguments as above we can estimate the maximum BH-BH formation efficiency for Pop I/II stars - assuming Salpeter IMF (with $\alpha = -2.3$), $f_{bin} = 1/2$ binary fraction and ignoring the effects of binary evolution. With these assumptions we obtain the maximum BH-BH formation efficiency of $4 \times 10^{-4}$. Thus, for model M10 with the metallicity of 0.0002, the actual BH-BH formation efficiency is $3.0 \times 10^{-5}$ (see Tab. 4) which is about 10% of the maximum value. The overall efficiency is a mean value coming from averaging over 32 metallicities in model M10.

7 CONCLUSIONS

A number of recent studies exploring BH-BH and BH-NS mergers from Pop III stars have been based on evolution
BH-BH mergers from Pop III stars

Figure 16. Merger rate density for BH-BH binaries in a function of redshift for models KK1 and KK2. For comparison we also show merger rate density for Pop I/II stars: model M10. The local BH-BH merger rate density measured by advanced LIGO during O1 observations is marked. We also mark advanced LIGO horizon for its full (design) sensitivity.

Figure 17. Total intrinsic (solid lines) and redshifted (dashed lines) BH-BH merger mass for BH-BH mergers that take place within redshift of 2 (z < 2) for models KK1 and KK2. Average mass for these models is $M_{\text{tot}} = 55.8 M_{\odot}$ ($M_{\text{tot},z} = 141 M_{\odot}$) for model KK1 and $M_{\text{tot}} = 62.8 M_{\odot}$ ($M_{\text{tot},z} = 158 M_{\odot}$) for model KK2. For comparison Pop I/II BH-BH mergers (model M10) have average mass: $M_{\text{tot}} = 29.7 M_{\odot}$ ($M_{\text{tot},z} = 73.7 M_{\odot}$).

Figure 18. Delay times for BH-BH mergers for models KK1 and KK2. It is clearly seen that the delay times (from star formation to the merger) are short to intermediate; the average delay time is 192 Myr for model KK1 and 1,580 Myr for model KK2.

specific to metal free stars, but initial conditions employed in these studies were not relevant for Pop III stars (Kinugawa et al. 2014, 2016; Kinugawa, Nakamura & Nakano 2016). On the other hand, in another recent study, Hartwig et al. (2016) employed more appropriate physical initial conditions for Pop III stars, albeit the results were based on evolutionary calculations relevant for Pop I stars.

Ours is the first computation of BH-BH merger rates which simultaneously combines initial evolutionary conditions specific to Pop III stars, as derived from $N$-body simulations of binary formation in primordial halos, with binary evolution models for metal-free stars. All of the studies listed above are important steps in the process of understanding the formation of double compact objects from the first stars. The work is still in progress and many open questions about the formation and physical properties of Pop III stars remain open. In the following we present our limited set of conclusions based on the numerical simulations of formation and evolution specific to the first stars.

The initial conditions in our study were derived from cosmological, hydrodynamical simulations of dark matter halos at high redshifts, and include the initial mass function, binary fractions, separations, mass ratios and eccentricities determined via N-body simulations. The stellar evolution model updates pre-existing models to take into account limited radial expansion and lack of stellar wind mass loss from Pop III stars, and produces a realistic spectrum of Pop III black holes. We have also adopted a very optimistic star formation rate for Pop III stars, that most likely places an upper limit on the number of these stars in Universe. Therefore our conclusions, in the context of Pop III BH-BH, BH-NS and NS-NS merger rates and chances of their detections, are most likely on the high side. These are our basic conclusions.

(i) The initial conditions for the evolution of Pop III binaries are very different from those of Pop I/II binaries. In fact, no Pop I/II initial distribution should be applied in studies of Pop III binaries. For example, the Pop III initial mass function increases with star mass (increasing massive BH formation) instead of the steep power-law fall off observed for Pop I/II stars (see Fig. 5). Additionally, the initial orbital separations for Pop III binaries are depleted at separations typical for BH-BH merger formation $\sim 1000 R_\odot$ (limiting BH-BH merger formation) as compared with Pop I/II binaries (see Fig. 7).
(ii) We have considered, depending on the model, star formations in the Universe specific to Pop I/II stars and Pop III stars. Since we have adopted rather pessimistic estimates for the Pop I/II formation rate and a rather optimistic one for the Pop III formation rate (see Fig. 9), our results should be viewed as delivering an optimistic ratio of Pop III to Pop I/II BH-BH mergers. Despite this fact, only $\sim 0.3\%$ of all stars in our simulation are Pop III, while the rest are Pop I/II. This stark contrast makes it extremely difficult for Pop III BH-BH mergers to make a large contribution to the LIGO event rate.

(iii) We have estimated the formation efficiency of BH-BH mergers from Pop III binaries to be significantly, but not overwhelmingly, higher than that from Pop I/II binaries. This efficiency is a strong function of metallicity for Pop I/II stars. Pop III stars form BH-BH mergers (per unit of star forming mass) a factor of $\sim 3$, $10$, 500 times more effectively than Pop I/II binaries at metallicity of $Z = 0.0002, 0.002, 0.02$, respectively (see Tab. 4).

(iv) The Pop III binaries in the framework of our model, in which we do not consider stars with very rapid rotation, form along classical binary evolution channels that involve a common envelope phase (see Tab. 3). The combination of initial distribution of orbital separations, with CE orbital decay followed by gravitational radiation-induced inspiral, generates a steep delay-time distribution of Pop III BH-BH mergers $\propto t^{-3} - t^{-1}$ (see Fig. 10). Given that Pop III stars form at high redshifts and evolve toward BH-BH mergers with relatively short delay times, they are unlikely to make a significant contribution to the LIGO signal.

(v) The combination of all our calculations leads to a full cosmological prediction of the merger rate density and the detection chances of Pop III BH-BH mergers. The merger rate density of Pop III BH-BH systems is found at the level of $0.1$ Gpc$^{-3}$ yr$^{-1}$ (see Fig. 11) within the reach of advanced LIGO at its full projected design sensitivity ($z < 2$). For comparison, recent LIGO observations (O1) have constrained the local BH-BH merger rate ($z < 0.1-0.2$) to be $\dot{\mathcal{R}}_{\text{BH-BH}} = 9 - 240$ Gpc$^{-3}$ yr$^{-1}$ (Abbott et al. 2016). Our results strongly indicate that Pop III BH-BH mergers cannot comprise a significant share of existing and future advanced LIGO detections. However, our predicted detection rate for Pop III BH-BH mergers is not zero, and LIGO at its full design sensitivity may potentially detect a couple of such mergers per year (see Tab. 5). This needs to be contrasted with predictions of tens-to-hundreds of BH-BH mergers a year from Pop I/II stars (e.g., Belczynski et al. 2016b, de Miguel & Mandel 2016, Rodríguez, Chatterjee & Rasio 2016).

(vi) The identification of a Pop III origin of a BH-BH merger event is not straightforward, as it lacks a smoking gun signature: BH masses alone are not likely to distinguish Pop III from Pop I/II mergers in advanced LIGO era (see Sec. 5.3). However, with 3rd generation interferometers it may be possible to see a peak of the merger rate distribution at $z \approx 10-12$ which may be attributed to Pop III stars (see Fig. 11). It is also possible that stochastic gravitational wave background may provide means to identify Pop III BH-BH mergers that are forming with heavier (on average) mass and very different redshift distribution than Pop I/II BH-BH mergers. It remains to be tested whether Pop III BH-BH mergers that are formed in our simulations could be detected and identified by AdLIGO at its full sensitivity through stochastic gravitational wave background.$^2$

We note that any Pop III BH-BH merger identification would carry profound implications for our understanding of the environments in which the first stars in the Universe formed. In particular, we have shown how, if Pop III stars generally form as a result of fragmentation of multiple, less massive protostars around a more massive one on scales of tens of AU, as found e.g. by the simulations of Greif et al. (2012), then no Pop III merger should ever be detected, even by future gravitational wave detectors. However, even a single event would argue towards formation in halos with spatial scales of several thousands of AU (Stacy & Bromm 2013).

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$^2$ Data on Pop III mergers can be found at [http://www.syntheticuniverse.org](http://www.syntheticuniverse.org) and any extra data is available upon request from Chris Belczynski.
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