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On the host galaxy properties of stellar binary black hole mergers

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Abstract. We report our investigations on the host galaxy properties of stellar binary black holes (SBBHs) by implementing simple recipes for SBBH formation and merger into cosmological galaxy formation model. If the time delay between SBBH formation and merger ranges from Gyr to the Hubble time, SBBH mergers at redshift $z < 0.3$ occur preferentially in big galaxies with stellar mass $M_* > 2 \times 10^{10} M_\odot$ and metallicities Z peaking around $\sim 0.6 Z_\odot$. However, the host galaxy stellar mass distribution of heavy SBBH mergers (with total black hole mass $> 50 M_\odot$) is bimodal with one peak at $\sim 10^9 M_\odot$ and the other peak at $\sim 2 \times 10^{10} M_\odot$. The contribution fraction from metal-poor host galaxies ($Z < 0.2 Z_\odot$) to heavy mergers is much larger than that to less heavy mergers. If SBBHs were formed in the early universe, their mergers detected at $z < 0.3$ occur preferentially in even more massive galaxies with $M_* > 3 \times 10^{10} M_\odot$ and in galaxies with metallicities mostly $> 0.2 Z_\odot$ and peaking at $Z \sim 0.6 Z_\odot$.

Keywords. stars: black holes, gravitational waves, black hole physics.

1. Introduction

Gravitational wave (GW) events from the mergers of stellar binary black holes (SBBHs) are now expected to be regularly detected by the advanced LIGO (aLIGO) and VIRGO, examples include GW150914 [Abbott *et al.* (2016a)], GW151226 [Abbott *et al.* (2016b)], GW170104 [Abbott *et al.* (2017a)], GW170608 [Abbott *et al.* (2017b)], and GW170814 [Abbott *et al.* (2017c)]. Detections of those gravitational wave sources and many more in future, with precise measurements on physical parameters, offer a great tool to study the astrophysical origin of SBBHs and the abundant stellar and dynamical physics involved in, which are still not well understood, yet.

Several mechanisms have been proposed to produce SBBH GW sources. The leading mechanism is probably the evolution of massive binary stars in galactic fields in isolation [Mandel & de Mink(2016), Belczynski *et al.* (2016b)]. It is anticipated that the properties of the host galaxies of GW sources, if identified by future observations, can be used to reveal the formation mechanism for SBBHs and constrain the physics involved in the SBBH formation processes.

To identify the host galaxies of GW sources, one of the crucial ways is to find their electro-magnetic (EM) counterparts, if any, since the localization of these sources, obtained from GW signals only, is poor [Abbott *et al.* (2016c)]. Great efforts have been put into searching for EM counterparts of GW sources via broadband campaign (e.g., GW150914). However, there still seems little expectation of the detection of EM counterparts for SBBH mergers [Abbott *et al.* (2016d)]. If the host galaxy properties of GW sources can be known, the search for EM counterparts would be greatly narrowed. Therefore, it is of great importance to figure out where and when the GW sources were formed and what kind of galaxies they are hosted in at the GW detection time also by the means of searching for the EM counterparts of SBBH GW sources.

In this conference paper, we investigate the host galaxy properties of the SBBH GW sources by implementing simple SBBH formation recipes into a cosmological galaxy formation model. A simple SBBH formation model is introduced in Section 2. With this model, we show how to generate mock samples of SBBHs in section 3, with which the host galaxy properties are obtained and presented in section 4. Conclusions are given in section 5. Most of the results presented in this conference paper will be published in Cao *et al.* (2017).

2. Binary Black Holes formation and merger scenario

In general, the birth rate $R_{\rm birth}$ of single BHs with mass $m_\bullet$ per unit volume per unit time at the cosmic time t can be estimated as Abbott *et al.* (2016e), Dvorkin *et al.* (2016),

$$R_{\rm birth}(m_\bullet, t) = \int\int \dot{\psi}(Z;t)\phi(m_\star)\delta(m_\star - g_\bullet^{-1}(m_\bullet, Z))dm_\star dZ. \tag{2.1}$$

Here $\dot{\psi}(Z;t)$ is the star formation rate with metallicity Z per unit volume per unit time at the cosmic time t, $\phi(m_\star) \propto m_\star^{-\alpha}$ is the initial mass function (IMF) and the Chabrier IMF Chabrier(2003) is adopted below, δ is the Dirac-δ function, $m_\bullet = g_\bullet(m_\star, Z)$ is a function that describes the relation between the mass of a stellar remnant BH and the mass of its progenitor star and the latest version given in Spera *et al.* (2015) is adopted in this paper. The evolution time of a massive star to its remnant is usually on the order of $\leqslant 10^7$ yr and is ignored in the above equation. An SBBH may merger after a time period of $t_{\rm d}$ since its formation due to orbit decay by GW radiation. The GW event rate is then given by the convolution of the birthrate $R_{\rm birth}(m_{\bullet,1}, t)$ with the delay time distribution $P(t_{\rm d})$ and mass ratio distribution $P_q(q)$, i.e.,

$$R_{\rm GW}(m_{\bullet,1}, q; t) = f_{\rm eff}\int R_{\rm birth}(m_{\bullet,1}, t - t_{\rm d})P_q(q)P_t(t_{\rm d})dt_{\rm d}, \tag{2.2}$$

where $q = m_{\bullet,2}/m_{\bullet,1}$ is the ratio of the mass of the secondary black hole to that of the primary one, $f_{\rm eff}$ is the effective factor to form GW sources from binary stars.

With the above prescription, we can estimate the GW event rate of SBBH mergers by using the catalog of mock galaxies with detailed assembly histories given by Guo *et al.* (2011), including the star formation rate and the metallicity evolution of each mock galaxy. In this simple approach, all the physics governing the evolution of SBBHs are encoded in the three independent functions $f_{\rm eff}$, $P_q(q)$ and $P_t(t_{\rm d})$. Better estimates of the SBBH merger rate may be obtained by sophisticate binary evolution population synthesis model. However, there are still large uncertainties in the evolution models of massive (binary) stars, especially, the large uncertainties in the understanding of a number of physical processes, such as the common envelope evolution, the kick from supernova explosion, and the mass transfer, etc. [e.g., Dominik *et al.* (2013), Belczynski *et al.* (2016a), Mapelli *et al.* (2017)]. Different models may result in significantly different merger rate densities. Below we show that our simple approach can give similar merger rate density evolution compared against those obtained by using binary population synthesis codes.

Figure 1 shows the results on the merger rate density distribution as a function of redshift by adopting a reference model for $P_t(t_{\rm d})$, where $P(t_{\rm d} \propto 1/t_{\rm d}$ and $t_{\rm d} > 50\,$Myr. For the calculation, $P(q)$ is set to $\propto q$ in the range from 0.5 to 1 according to binary population synthesis model results [e.g., Belczynski *et al.* (2016a)]; $f_{\rm eff}$ is set by calibrating the local merger rate to the observational constraint of $103{\rm Mpc}^{-1}{\rm yr}^{-1}$ [Abbott *et al.*

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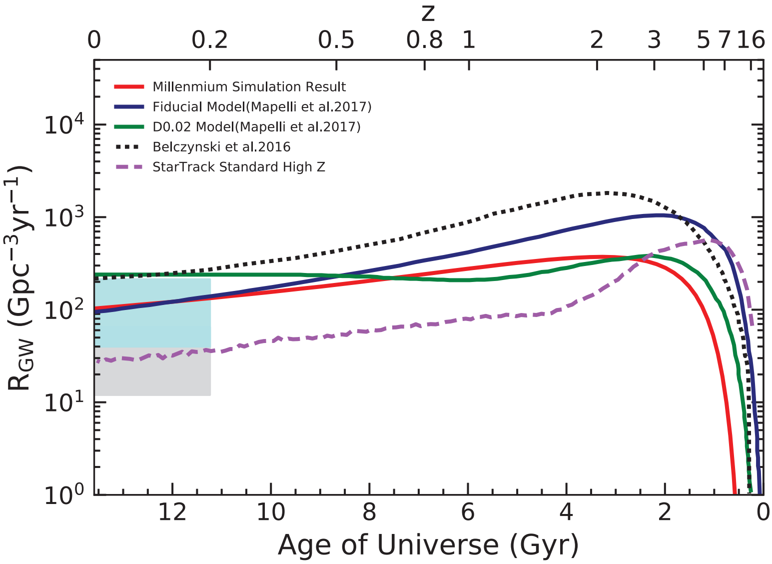

Figure 1. SBBH merger rate density as a function of the age of universe or redshift z. The red solid line represents the results obtained from the Millennium simulation galaxy catalog assuming the reference model for the time delay. The black dotted line represents the result obtained by Belczynski *et al.* (2016a) by using the extinction-corrected specific star formation rate in Madau & Dickinson (2014) and the binary population synthesis code StarTrack. The blue and green solid lines represent respectively the results from the fiducial model and the D0.02 model in Mapelli *et al.* (2017) by planting BBHs obtained from the binary population synthesis code SEVN into the Illustris simulations. The purple dashed line represents the merger rate density obtained by Dominik *et al.* (2013). The cyan and grey shaded regions represent the constraints on the merger rate density obtained from those detected GW sources by assuming two different IMF, respectively Abbott *et al.* (2017a).

(2017c)]. As seen from this figure, the merger rate density obtained by using the above simple recipes for SBBH formation and the New-Millennium cosmological galaxy catalog [Guo *et al.* (2011)] (red line) is more or less consistent with those obtained in previous works by Dominik *et al.* (2013), Belczynski *et al.* (2016a), and Belczynski *et al.* (2016a), by using binary population synthesis models. We note here that the large uncertainties in the evolution models of massive (binary) stars, especially, the large uncertainties in the understanding of a number of physical processes, such the common envelope evolution, the kick from supernova explosion, and the mass transfer etc. [e.g., Dominik *et al.* (2013), Belczynski *et al.* (2016a), Mapelli *et al.* (2017)] can lead to significantly different merger rate densities. The differences of the merger rate density estimated from our simple SBBH formation model from those estimates by using more sophisticated binary population synthesis models is comparable to the differences between those estimates in different works by using the population synthesis models.

3. Mock samples

Using the mock galaxy catalogs and the assembly and star formation history of each mock galaxy, we randomly assign SBBH merger GW events according to the probability for individual galaxies across cosmic time. We also impose that $\min[m_{\bullet,1}, m_{\bullet,2}] \geqslant 5M_{\odot}$, which is set by considering that all BHs measured dynamically have masses $> 5M_{\odot}$ [Özel *et al.* (2010), Farr *et al.* (2011)]. With these procedures, we can obtain mock catalogs

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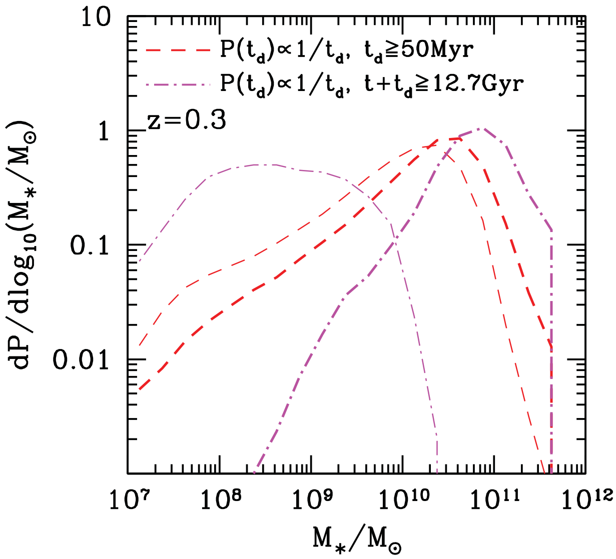

Figure 2. Stellar mass distribution of the host galaxies of binary black holes (SBBHs) at the SBBH formation time (thin lines) and merger time (thick lines). The red short-dashed and magenta dot-dashed lines show the results obtained from those time delay models $P(t_{\rm d}) \propto 1/t_{\rm d}$ with $t_{\rm d} \geqslant 50\,{\rm Myr}$, and $\geqslant 12.7\,{\rm Gyr} - t(z)$, i.e., the reference model, and the early SBBH formation model, respectively. Here $t(z) = \int_z^\infty \left|\frac{dt}{dz}\right| dz$ and 12.7 Gyr are the cosmic age at redshift z and at $z = 6$, respectively.

of SBBH GW events at any given cosmic time t (or correspondingly redshift z) for given $P_t(t_{\rm d})$ and $P_q(q)$. We generate mock catalogs of SBBH GW events at redshift $z = 0.3$, that enables the statistic studies on the properties of their host galaxies. Each GW event is characterized by the masses of the two components, i.e., $m_{\bullet,1}$ and $m_{\bullet,2} = qm_{\bullet,1}$, the merger time $t(z)$, the SBBH formation time $t(z) - t_{\rm d}$, the position and other properties (e.g., stellar mass M_*, metallicity Z_*) of its host galaxy, and the properties of its progenitor galaxy that the SBBHs formed in at the SBBH formation time $t - t_{\rm d}$.

4. Model Results

4.1. *Stellar mass distributions of SBBH host galaxies*

We extract the statistical information on their host galaxies from the mock catalogs for SBBH GW events and SBBHs. Figure 2 shows the stellar mass distribution of the host galaxies of those SBBHs at their merger time (i.e., the GW detection time $z = 0.3$) and formation time (thin lines), respectively. For the reference model, the distribution of the SBBH host galaxies at the GW detection time is shifted to higher masses compared with that at the SBBH formation time simply because of the growth of those host galaxies after the SBBH formation.

If the SBBHs were formed at early time, e.g., $z > 6$ (magenta dot-dashed lines for the early SBBH formation model), their host galaxies grew more significantly since their formation and became massive at the GW detection time.

4.2. *Host galaxies of SBBH mergers with different total masses*

SBBHs with different total masses $[M_{\bullet\bullet} = M_{\bullet,1} + M_{\bullet,2} = (1+q)M_{\bullet,1}]$ may have different formation histories. Heavy SBBHs may be formed only from metal poor binaries and

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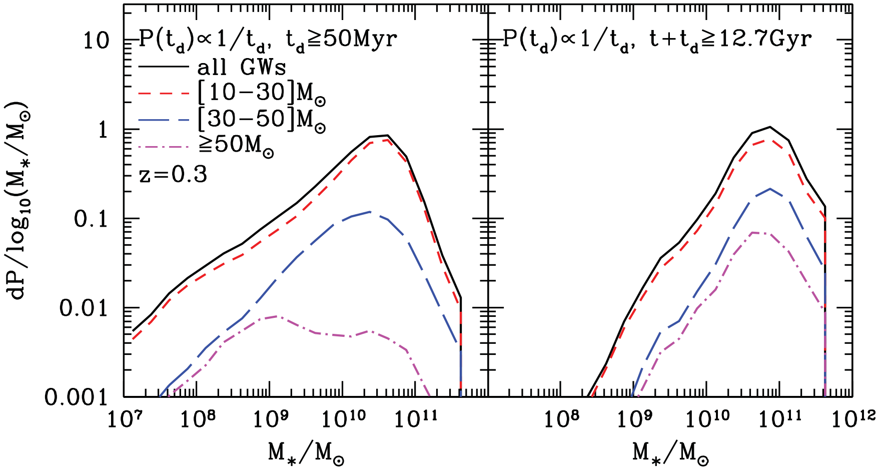

Figure 3. Stellar mass distributions of the host galaxies for SBBH mergers (at $z = 0.3$) with different total masses.

thus in metal poor galaxies at early times, therefore, they should be hosted in galaxies with different properties from those lighter SBBHs at the SBBH merger time.

Figure 3 shows the stellar mass distributions of the host galaxies of SBBH GW events with different $M_{\bullet\bullet}$ at $z = 0.3$. For the reference model, those heavy SBBHs with total mass $M_{\bullet\bullet} \geqslant 50M_{\odot}$, the host stellar mass distribution are broad and bimodal with one peak at $\sim 10^9 M_{\odot}$ and the other peak at $\sim 2 \times 10^{10} M_{\odot}$, which are corresponding to a population formed recently in small galaxies and another population formed at early time in small galaxies but merged into big galaxies later.

4.3. *Host galaxy metallicities*

Since the formation of BHs depends on the metallicity of their progenitor stars, the formation of SBBHs is also dependent on the metallicity of their progenitor binary stars and thus the metallicity of the progenitor galaxies when they formed in. However, the metallicity of the host galaxies at the GW detection time may be significantly different from that of the progenitor galaxies at the SBBH formation time.

Figure 4 shows the host galaxy metallicity distributions of those SBBHs at their merger time (thick lines) and at formation time (thin lines), respectively. The host galaxy metallicity distributions at the SBBH merger time shift to higher metallicities due to the metal enrichment after the SBBH formation.

If those SBBHs were formed at early time, e.g., $z > 6$ (the early SBBH formation model), then they were mostly formed in metal poor small galaxies. However, their host galaxies at the SBBH merger time ($z = 0.3$) have metallicities around $Z \sim 0.57Z_{\odot}$.

Figure 5 shows the metallicity distributions of the host galaxies for SBBHs with different total mass ($M_{\bullet\bullet}$) range (i.e., $10 - 30M_{\odot}$, $30 - 50M_{\odot}$, and $\geqslant 50M_{\odot}$) at both the SBBH formation time and the SBBH merger time. For SBBH mergers with total mass $M_{\bullet\bullet} \geqslant 50M_{\odot}$, they must be formed in galaxies with metallicities $< 0.2-0.3Z_{\odot}$. However, the metallicities of their host galaxies at the SBBH merger time are substantially metal richer and have a distribution skewed towarding high metallicities if those SBBHs were formed at $z \geqslant 6$.

For light SBBHs, e.g., $M_{\bullet\bullet} = 10 - 30M_{\odot}$, they can be formed in galaxies with a large metallicity range. At the SBBH merger time, their host metallicities distribute over an even larger range with broader extensions at both the high Z and the low Z

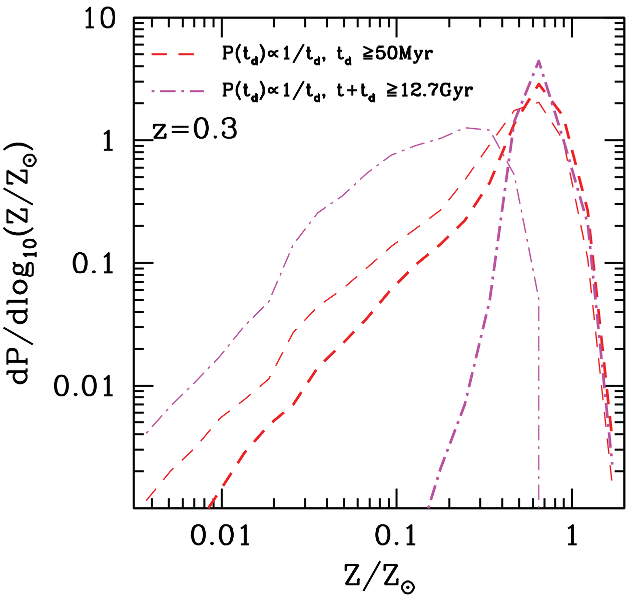

Figure 4. Metallicity distribution of the host galaxies at the SBBH formation time (thin lines) and the GW detection time or the SBBH merger time (thick lines). Legends for the lines and models are similar to Fig. 2.

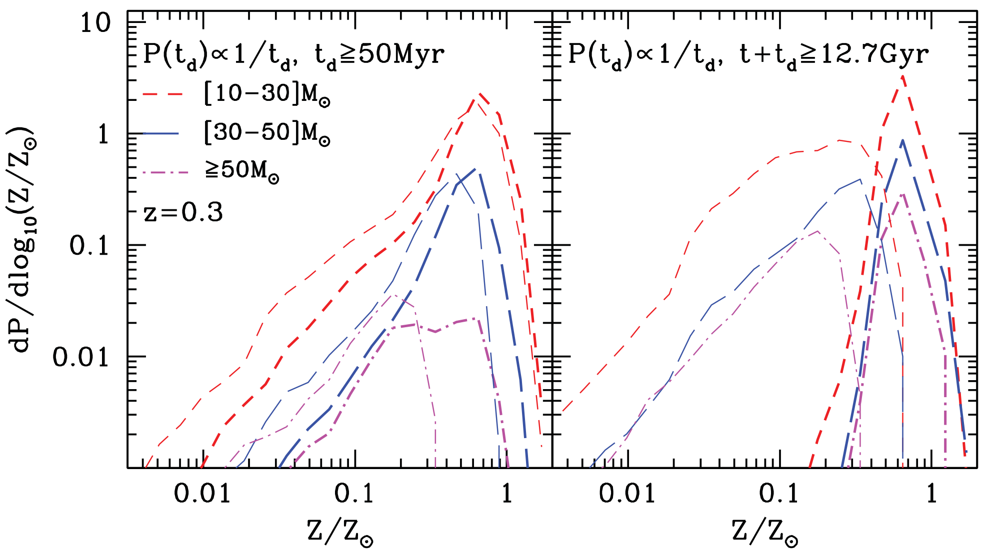

Figure 5. Metallicity distribution of those SBBH mergers with different mass ranges at both the SBBH detection time ($z = 0.3$; thick lines) and the SBBH formation time (thin lines). The red short dashed, blue long-dashed, and magenta dot-dashed lines in each panel represent the host galaxy metallicity distribution for mock SBBHs with total mass $M_{\bullet\bullet} = 10-30M_{\odot}$, $30-50M_{\odot}$, and $\geqslant 50M_{\odot}$, respectively.

ends compared with that for $M_{\bullet\bullet} \geqslant 50M_{\odot}$. For SBBHs with intermediate mass [$M_{\bullet\bullet} \in (30-50M_{\odot})$], the distributions of the host metallicities at both the SBBH formation time and the SBBH merger time are in between those for the heavy SBBHs and for the light SBBHs (see Figure 5).

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5. Conclusions

In this paper, we investigate the host galaxies of SBBH mergers, i.e., gravitational wave sources that may be detected by advanced LIGO and VIRGO, by implementing simple SBBH formation recipes into cosmological galaxy formation model using the Millennium-II simulation with a large box of side 137 Mpc, and we present a complete and thorough analysis of the properties of the SBBH host galaxy. We note here that understanding the host properties of SBBH mergers, as that done in this study and others Lamberts *et al.* (2016), O'Shaughnessy *et al.* (2017), Elbert *et al.* (2017), Schneider *et al.* (2017), is important for revealing the origin of those SBBHs and also idenfication of their EM counterparts. We summarize our main results as follows.

SBBH mergers with total mass $M_{\bullet\bullet} \geqslant 10M_{\odot}$ at low redshift ($z < 0.3$) occur preferentially in massive galaxies if the delay time between the SBBH formation and the merger is distributed in a broad range from less than Gyr to the Hubble time, and they occur preferentially in even more massive galaxies ($\sim 8 \times 10^{10} M_{\odot}$) if they were mostly formed at high redshift (e.g., $z > 6$) and have a large delay time (> 13 Gyr). For those heavy SBBH mergers ($M_{\bullet\bullet} \geqslant 50M_{\odot}$), their host stellar mass distribution is probably bimodal, with a low mass peak of $\sim 10^9 M_{\odot}$ and a high mass peak of $\sim 2 \times 10^{10} M_{\odot}$. The lower peak is mainly contributed by those SBBHs formed recently ($z < 0.5$), while the higher mass peak is mainly contributed by those SBBHs formed at early time ($z > 3.0$).

The formation of SBBHs depends on the metallicity of their progenitor binary stars. Heavy SBBHs ($M_{\bullet\bullet} \geqslant 50M_{\odot}$) were mostly formed in metal poor small galaxies with metallicities $< 0.2-0.3Z_{\odot}$. If the time delay between SBBH formation and merger covers a range from less than Gyr to the Hubble time, the host galaxy metallicity distribution of SBBH mergers detected at redshift $z < 0.3$ peaks around $0.6Z_{\odot}$ and has a long skewed wing towarding the low metallicity end ($Z < 0.2Z_{\odot}$). The host galaxy metallicity distribution of heavy SBBHs at the merger time at redshift $z < 0.3$ is ranging from $Z < 0.1Z_{\odot}$ to $\sim 1.0Z_{\odot}$, substantially broader compared with that for less heavy SBBHs. If SBBHs formed at early time, e.g., at $z > 6$, their mergers detected at $z < 0.3$ occur preferentially in galaxies mostly with metallicities $> 0.2Z_{\odot}$, because of significant metal enrichment of those host galaxies after the SBBH formation.

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References

Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2016, Physical Review Letters, 116, 061102
Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2016, Physical Review Letters, 116, 241103
Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2016, Living Reviews in Relativity, 19, 1
Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2016, APJL, 826, L13
Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2016, Physical Review Letters, 116, 131102
Abbott, B. P., Abbott, R., Abbott, T. D., *et al.* 2017, Physical Review Letters, 118, 221101
The LIGO Scientific Collaboration, the Virgo Collaboration, Abbott, B. P., *et al.* 2017, arXiv:1711.05578
Abbott, R., *et al.* 2017, arXiv:1709.09660
Belczynski, K., Repetto, S., Holz, D. E., *et al.* 2016a, APJ, 819, 108
Belczynski, K., Holz, D. E., Bulik, T., & O'Shaughnessy, R. 2016b, Nature, 534, 512

Cao, L., Lu, Y., & Zhao, Y. 2017, arXiv:1711.09190
Chabrier, G. 2003, PASP, 115, 763
Dominik, M., Belczynski, K., Fryer, C., *et al.* 2013, APJ, 779, 72
Dvorkin, I., Vangioni, E., Silk, J., Uzan, J.-P., & Olive, K. A. 2016, MNRAS, 461, 3877
Elbert, O. D., Bullock, J. S., & Kaplinghat, M. 2017, arXiv:1703.02551
Farr, W. M., Sravan, N., Cantrell, A., *et al.* 2011, APJ, 741, 103
Guo, Q., White, S., Boylan-Kolchin, M., *et al.* 2011, MNRAS, 413, 101
Lamberts, A., Garrison-Kimmel, S., Clausen, D. R., & Hopkins, P. F. 2016, MNRAS, 463, L31
Madau, P. & Dickinson, M. 2014, ARAA, 52, 415M
Mandel, I. & de Mink, S. E. 2016, MNRAS, 458, 2634
Mapelli, M., Giacobbo, N., Ripamonti, E., & Spera, M. 2017, arXiv:1708.05722
O'Shaughnessy, R., Bellovary, J. M., Brooks, A., *et al.* 2017, MNRAS, 464, 2831
Özel, F., Psaltis, D., Narayan, R., & McClintock, J. E. 2010, APJ, 725, 1918
Schneider, R., Graziani, L., Marassi, S., *et al.* 2017, arXiv:1705.06781
Spera, M., Mapelli, M., & Bressan, A. 2015, MNRAS, 451, 4086