Binary black hole remnants of first stars for the gravitational wave source

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Abstract

Using our population synthesis code, we found that the typical chirp mass of binary black holes (BH-BHs) whose origin is the first star (Pop III) is ~ 30 M$_\odot$ with the total mass of 60 M$_\odot$ so that the inspiral chirp signal as well as quasi normal mode (QNM) of the merging black hole are interesting targets of LIGO,VIRGO and KAGRA. The detection rate of the coalescing Pop III BH-BHs is ~ 180 events/yr $(SFR_p/(10^{-2.5}\ \mathrm{M_\odot/yr/Mpc^3}))\cdot([f_b/(1+f_b)]/0.33)\cdot Err_{sys}$ in our standard model where SFR_p, f_b and Err_{sys} are the peak value of the Pop III star formation rate, the binary fraction and the systematic error with $Err_{sys} = 1$ for our standard model, respectively. Furthermore, We found that the chirp mass has a peak at 30 $M_\odot$ in most of parameters and distribution functions. This result predicted the gravitational wave events like GW150914 and LIGO paper said ‘recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014)’. Thus, there is a good chance to check indirectly the existence of Pop III massive stars by gravitational wave.

Key words: gravitational wave, binary black hole, Population III stars

1. Intriduction

advansed LIGO detected the first gravitational signal GW150914 (Abbott et al. 2016). The source of the gravitational wave signal is the binary black hole merger. The Black hole masses of GW150914 are 36 and 29 M$_\odot$ (Abbott et al. 2016). The black holes of GW150914 is more massive than conventional black holes (BHs) in X-ray binaries whose masses are typicaly 10 M$_\odot$ (Remillard & McClintock 2006). In order to explain the origin of GW150914, many theories exist such as the Population II (Pop II) binary origin, the Population III (Pop III) binary origin, the globular cluster origin and so on. Especially, the Low metal field binary origin is widely accepted theory. There are two reason why the low metal field binary is widly accepted. First, there are many massive binaries and the binary fraction of massive stars are high. For example, the binary fraction of O stars in Milky way young open clusters is $69^{+}_{-}9\%$ (Sana et al. 2012). Second, if the progenitors of binary black hole are Population I (Pop I) stars, the fraction of massive is few and they lose a lot of mass due to a stellar wind mass loss. Due to strong wind, Population I stars cannot become 30 M$_\odot$ BH. Furthermore, the binary orbit becomes wide due to the wind mass loss If the progenitor is low metal stars, it possibly becomes massive BH. In the case of Pop II, they typical mass is same as Pop I, but the wind mass loss weaker than that of Pop I. So if Pop II star born as massive star, they possibly become massive BH. Furthermore, Pop III stars which are the first stars after the big bang are born as massive star. The typical mass of Pop III stars is 10-100 M$_\odot$. Furthermore, the wind mass loss is not effective due to no metal. Thus, Pop III star are easier to be massive compact BH. Our group alredy reseach the gravitational wave from Pop III binary BHs and showed that the Pop III binaries typicaly become 30 M$_\odot$ binary BHs and some of them merge at the present day. This result predicted the gravitational wave events like GW150914 and LIGO paper said ‘recently predicted BBH total masses agree astonishingly well with GW150914 and can have sufficiently long merger times to occur in the nearby universe (Kinugawa et al. 2014)’. In this talk, I talk about why Pop III binaries become 30 M$_\odot$ binary BHs and they can merge at the present day.

2. Method

We calculate the Pop III binay BHs and Pop I and II binary BHs for comparison. Pop I and Pop II stars means solar metal star and metal poor star whose metallicity is less than 10% of solar metallicity, respectively. In this talk, we consider four metallicity cases of $Z = 0$ (Pop III), $Z = 5\times10^{-3}Z_\odot$, $5\times10^{-2}Z_\odot$ (Pop II) and $Z = Z_\odot$ (Pop I). There are important differences between Pop III and Pop I and II. Pop III stars are (1) more massive,

$> 10\ \mathrm{M}_\odot$ (2) smaller stellar radius compared with that of Pop I and II (3) no stellar wind mass loss. These properties play key roles in binary interactions.

In order to estimate the event rate of binry BH mergers and the properties of binary BHs, we use the binary population synthesis code which is the Monte Carlo simulation of binary evolution. First, we choose the binary initial conditions such as the primary mass M_1, the mass ratio q, the separation a and the eccentricity e when the binary is born. These binary initial conditions are choosed by the Monte Carlo method and the initial distribution functions such as the initial mass function (IMF), the initial mass ratio function (IMRF), the initial separation function (ISF) and the initial eccentricity distribution function (IEF). We adopt these distribution functions for Pop III stars and Pop I, II stars as Table. 1. Second, we calculate the evolutions of the primary and the secondary stars. If the binary full fills the condition of binary interaction, we consider binary interactions such as the Roche lobe overflow (RLOF), the common envelope (CE) phase, the tidal effect, the supernova effect and the gravitational radiation. We treat these binary interactions as Kinugawa et al. (2014); Kinugawa et al. (2016) In this paper, we treat the binary interaction parameter such as the CE parameter $\alpha\lambda$ and the lose fraction β of transfered stellar matter during a RLOF as $\alpha\lambda = 1$, $\beta = 0$.

3. Result

We calculate the 10^6 binaries for each metallicity. Figure 1 is the total mass distribution of BH-BH which merge within the Hubble time. Black line is the first star binary. The typical total mass of Pop III BBH is 60 $\mathrm{M}_\odot$ ($\sim$30 $\mathrm{M}_\odot$-30 $\mathrm{M}_\odot$). On the other hand, in the other metallicity cases, the typical total mass is 20 $\mathrm{M}_\odot$ or so.

There are the reason why Pop III binaries become 30 $\mathrm{M}_\odot$-30 $\mathrm{M}_\odot$ Binary black holes. The Pop III whose mass is larger than 50 $\mathrm{M}_\odot$ evolves as the red giant. The mass transfer of red giant is generally unstable and it becomes the common envelope phase. Thus, they lose the envelope and they become light. Therefore, the BH mass become about 30 $\mathrm{M}_\odot$. On the other hand, the Pop III whose mass is less than 50 $\mathrm{M}_\odot$ evolves as a blue giant. In such cases, the mass transfer is stable and mass loss is not so effective. Thus, they become about 30 $\mathrm{M}_\odot$ BH. Therefore, the peak of binary BH total mass is about 60 $\mathrm{M}_\odot$ due to these two evolution path. It does not depend on the IMF and binary parameters. It only depends on the Pop III stellar evolution. Thus, the peak mass of Pop III reflects the influence of Pop III stellar evolution. On the other hand, in the case of Pop I and Pop II, all stars evolve via a red giant, so almost all binaries evolve via the similar evolution pass. Thus, the shape of Pop II binary BH mass distribution reflect the influence of IMF due to similar evolution pass. Pop I has the influence of stellar wind due to strong wind.

In this calculation, Pop III binaries tend to become massive binary BHs. Furthurmore, we can see such binarues which are born at the early universe. Pop III stars were born and died at $z \sim 10$. However, the typical merger time of compact binaries due to gravitational radiation is too long. Thus, We might see the gravitational wave from first stars as binary BH mergers.

In order to calculate merger rate, we need to know when Pop III stars were born and how many Pop III stars were born. i.e. we need the star formation rate (SFR) of Pop III stars. We adopt the Pop III SFR by de Souza, Yoshida & Ioka (2011). The peak value of the SFR is $10^{-2.5}\ \mathrm{M}_\odot/\mathrm{yr}/\mathrm{Mpc}^3$ at $z \sim 9$.

Using our population synthesis results and the SFR, the Pop III binary BH merger rate density at the present day in our standard model (IMF: flat 10 $\mathrm{M}_\odot$ $<$ M $<$100 $\mathrm{M}_\odot$) is 2.5 $\times 10^{-8}$ events/yr/Mpc^3$(SFR_p/(10^{-2.5}\mathrm{M}_\odot/\mathrm{yr}/\mathrm{Mpc}^3))\cdot([f_b/(1+f_b)]/0.33)$. The detection range of KAGRA and advanced LIGO for 30 $\mathrm{M}_\odot$-30 $\mathrm{M}_\odot$ binary BHs is $\sim$1.5 Gpc. Thus, the detection rate of Pop III BBH (GW150914 like BBH) in our standard model is $\sim$ 180 events/yr $(SFR_p/(10^{-2.5}\ \mathrm{M}_\odot/\mathrm{yr}/\mathrm{Mpc}^3))\cdot([f_b/(1+f_b)]/0.33)$ This value depends on the SFR and the binary fraction of Pop III. Since the typical mass of Pop III BBH is 30 $\mathrm{M}_\odot$, we can see quasi-normal mode (QNM) of merged binary BH. Nakano, Tanaka & Nakamura 2015 show that if S/N of QNM is larger than 35, we can confirm or refute the General Relativity (GR) more than 5 sigma level. Therefore, we might not only detect the Pop III binary BH by GW but also check GR by Pop III BH QNM. Furthermore, the mass distribution might distinguish Pop III from Pop I, Pop II. It might become the evidence of the Pop III existence. If the chirp mass distribution can not distinguish Pop III due to small SFR or so, we can confirm Pop III BHBH by redshift dependence. DECIGO which is the Japanese space gravitational wave observatory project has good sensitivity from 0.1 Hz to 10 Hz. B-DECIGO is test version. DECIGO and B-DECIGO might see such binary black holes up to redshift 30. The expected detection rate is about 10^5 events/yr. The SFR of Pop III has the peak at $z \sim 10$. Thus, it can see Pop III binary BH when they were born. Furthermore, we can check the redshift dependence of high mass binary BH mergers (See Fig. 2). B-DECIGO can measure the mass spectrum and the z-dependence of the merger rate to distinguish various models of binary BHs like GW150914, such as Pop III and Pop II BBH.

References

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Table 1: The initial distribution functions.

	Pop III	Pop I,II
IMF	flat (10 $M_\odot$ <M< 100 or 140 $M_\odot$)	Salpeter (1 $M_\odot$ <M< 100 or 140 $M_\odot$)
IMRF	flat ($10/M < M_2/M_1 < 1$)	flat ($0.1/M < M_2/M_1 < 1$)
ISF	logflat ($a_{min} < a < 10^6$ $R_\odot$)	logflat ($a_{min} < a < 10^6$ $R_\odot$)
IEF	e ($0 < e < 1$)	e ($0 < e < 1$)

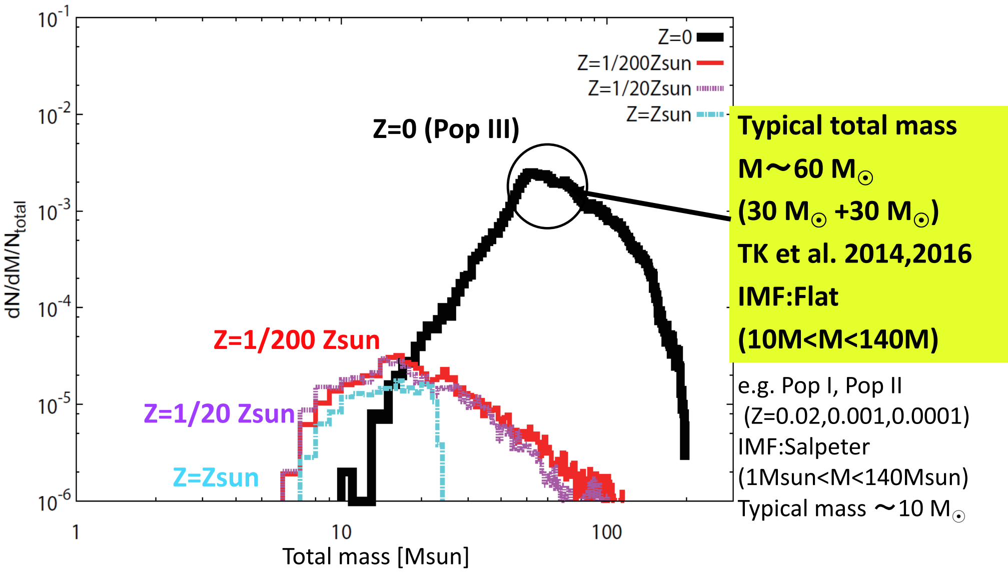

Fig. 1: The total mass distribution

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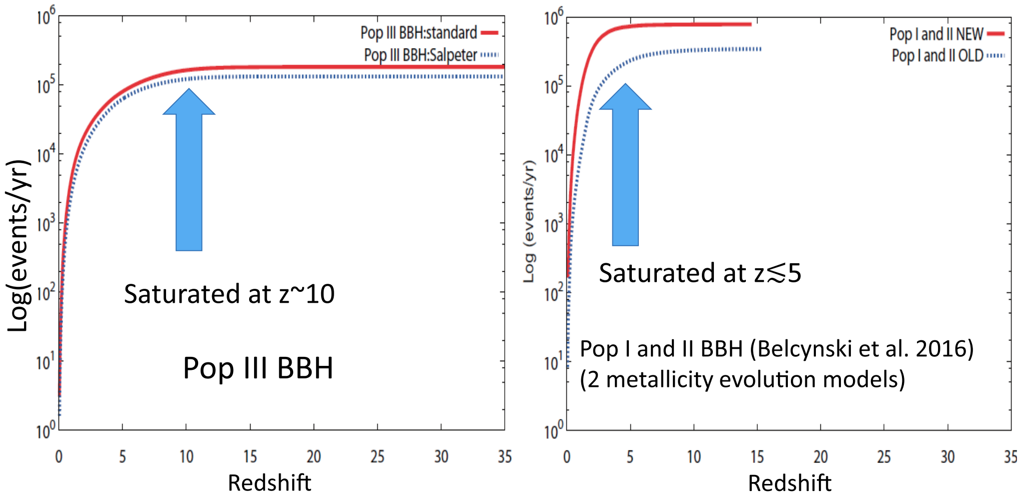

Fig. 2: The cumlative merger rate of binary BHs.