The binary population synthesis in the early universe and the detection rate of gravitational waves from the binary black holes

Tomoya Kinugawa

We perform population synthesis simulations for Population I (Pop I), Population II (Pop II) and Population III (Pop III) coalescing compact binaries which merge within the age of the universe. We habe the typical mass of binary black holes (BH-BHs) around 10 $M_\odot$ for Pop I and Pop II cases. On the other hand, we found that the typical mass of Pop III BH-BHs is $\sim$ 30 $M_\odot$-30 $M_\odot$. The inspiral chirp signal of gravitational waves and quasi-normal modes (QNMs) from Pop III BH-BHs can be detected up to z=0.28 by KAGRA, Adv. LIGO, Adv. Virgo and GEO network. Our simulations suggest that the detection rate of the coalescing Pop III BH-BHs is $\sim$1.8 $\times 10^2$ events yr^{-1} $(SFR_{\rm p}/(10^{-2.5}\ {\rm M}_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}))\cdot([f_{\rm b}/(1+f_{\rm b})]/0.33)\cdot Err_{\rm sys}$ for our standard model, where $SFR_{\rm p}$, $f_{\rm b}$ and $\mathrm{Err}_{\rm sys}$ are the peak value of the Pop III star formation rate, initial binary fraction and the possible systematic errors due to the assumptions in Pop III population synthesis, respectively. $Err_{\rm sys}=1$ corresponds to conventional parameters for Pop I stars. To evaluate the robustness of chirp mass distribution and the range of $Err_{\rm sys}$, we examine the dependence on the unknown parameters and the distribution functions in the population synthesis code. We found that the chirp mass has a peak at $\sim$ 30 $M_\odot$ in most of parameters and distribution functions as well as $Err_{\rm sys}$ ranges from 0.046 to 4. Therefore, the detection rate of the coalescing Pop III BH-BHs ranges about $8.3-720$ events yr^{-1} $(SFR_{\rm p}/(10^{-2.5}\ {\rm M}_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}))\cdot([f_{\rm b}/(1+f_{\rm b})]/0.33)$. The minimum rate corresponds to the worst model which we think unlikely. Therefore unless $(SFR_{\rm p}/(10^{-2.5}\ {\rm M}_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}))\cdot([f_{\rm b}/(1+f_{\rm b})]/0.33)\ll 0.1$, we expect the Pop III BH-BHs detection rate of at least one event per year by KAGRA. Nakano, Tanaka & Nakamura (2015) have shown that if S/N of the QNM is larger than 35, we can confirm or refute the General Relativity (GR) more than 5 sigma level. In our standard model, the detection rate of Pop III BH-BHs whose S/N is larger than 35 is 3.2 events yr^{-1}$(SFR_{\rm p}/(10^{-2.5}\ {\rm M}_\odot\ {\rm yr}^{-1}\ {\rm Mpc}^{-3}))\cdot([f_{\rm b}/(1+f_{\rm b})]/0.33)\cdot Err_{\rm sys}$. Thus, there is a good chance to check whether GR is correct or not in the strong gravity region. Furthermore, from the observation of the chirp signal of the coalescing Pop III BH-BHs,

we can determine both the mass and the redshift of the binary for the cosmological parameters determined by Planck satellite. Our simulations suggest that the cumulative redshift distribution of the coalescing Pop III BH-BHs depends almost only on the cosmological parameters. We might be able to confirm the existence of Pop III massive stars of mass $\sim 30\ M_\odot$-$30\ M_\odot$ by the detections of gravitational waves if the detection rate of the Pop III massive BH-BHs ($\sim 30\ M_\odot$-$30\ M_\odot$) dominates those of Pop I and Pop II massive BH-BHs.