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Population III binary black holes: filling the pair instability mass gap

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The first binary black hole (BH) merger has been discovered by the first detection of gravitational waves (GWs) in 2015. Since then, the number of discovered binary BH mergers have rapidly grown, and reached to about 90. However, their origins have been under debate. They can be isolated binary stars, dense cluster stars, and primordial BHs.

One of the important processes to elucidate their origins is pair instability (PI) supernovae (SNe), which proceed in the following. At the central region of a massive star with zero-age main-sequence mass of about 100 solar mass, photon radiation pressure generally exceeds gas pressure, where the adiabatic index is slightly more than 4/3. At the final phase of the star, the energy of a photon is converted into an electron-positron pair (pair creation). This decreases the adiabatic index to less than 4/3. Then, the star becomes unstable, and implodes. The implosion triggers explosive nuclear burning, and the nuclear burning finally blows off the whole star. PISNe leave no stellar remnant like a BH. Hence, it was thought that there should be a mass range without BHs (50-130 solar mass), so-called "pair instability mass gap", if merging binary BHs are formed from isolated binary stars.[1]

GW190521, which contains a 85 solar mass BH, has been reported.[2] Since it must be a BH in the pair instability mass gap, the scenario of isolated binary stars becomes inferior. However, previous studies on the scenario have not considered Population (Pop) III (or metal-free) stars. We have found that Pop III binary stars can form GW190521-like binary BHs because of Pop III peculiarity, such as weak stellar wind mass loss and small stellar radius.[3] When we consider isolated binary stars with all the metallicities from Pop III stars to Pop I stars (those with the solar metallicity), we have made clear that the primary BH mass distribution formed from isolated binary stars can be consistent with that observed by GWs (see Figure 1).[4] Especially, Pop III binary stars dominate binary BHs with BHs in the pair instability mass gap.

Recently, another scenario of isolated binary stars has been suggested, in which the pair instability mass gap can be shifted upward (say 90-180 solar mass), if the nuclear reaction rate of $^{12}C(\alpha,\gamma)^{16}O$ is 3-σ smaller than the standard one.[5] If we adopt this pair instability mass gap, we can also reproduce the observed primary BH mass distribution without Pop III binary stars. To identify these two scenarios (hereafter called fiducial and 3-σ scenarios), we propose that PISN survey will be instructive.[6] We have found that the *Euclid* space telescope will detect a few and no PISNe if the fiducial and 3-σ scenarios are correct, respectively (see Figure 2). The PISN event rate in the fiducial scenario is intrinsically larger than in the 3-σ scenario, since lower-mass stars can cause PISNe in the fiducial scenario. We will expect that the origin of binary BHs will be elucidated in the near future.

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References

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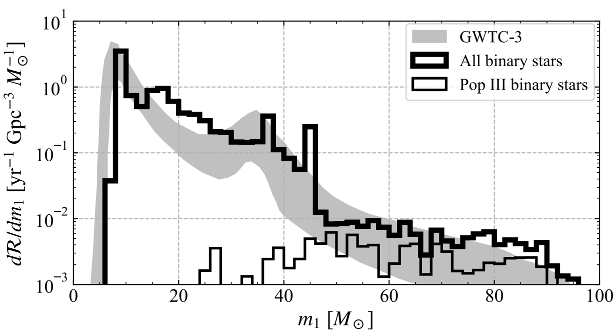

Figure 1. Primary BH mass distribution of our prediction (thick curve) and observation (shaded region. The thin curve shows Pop III contribution.

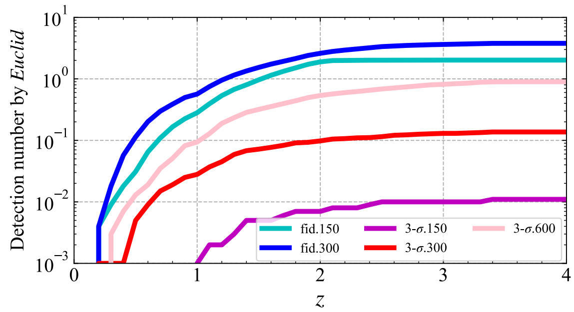

Figure 2. Detection number of PISNe by *Euclid*. The "fid" and "3-σ" in the legends indicate the results of the fiducial and 3-σ scenarios. The numbers show the maximum stellar mass we adopt.