論文の内容の要旨

Formation of supermassive stars and black holes via direct gravitational collapse of primordial gas clouds (始原ガス雲の重力崩壊による超大質量星形成およびブラックホール形成)

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Recent observations report that SuperMassive Black Holes (SMBHs) reside at the center of matured galaxies. They are the most massive compact objects in the universe and of great interest in the physical and astronomical contexts. Tremendous energy is radiated away when the gas accretes around the Schwarzschild radius of SMBHs, which are observed as "Quasars (QSOs)". This energetic phenomenon provides us valuable knowledge about the structure formation history in the early universe. We have now observed more than one hundred QSOs at $z > 6$ and the most distant QSO resides at $z = 7.541$ and the estimated mass of the SMBH is $8 \times 10^8\ M_\odot$ (ULAS J1342+0928; Bañados *et al.*, 2017). The fact that they are observed at the cosmic age of $\lesssim 0.7$ Gyr gives a clue to understand the formation history of SMBHs. Historically, Rees (1978) compiles a number of the formation channels of SMBHs known at that time. They are divided largely into two classes: the channels with and without SuperMassive Stars (SMSs) formation.

This thesis studies the formation of SMSs in the early universe as possible seeds for the observed SMBHs. How massive the first generation stars can be, has been intensely studied for the last few decades (e.g. Hirano *et al.*, 2014). The recent discovery of the atomic-cooling path suggests a promising formation channel of SMSs (e.g. Omukai, 2001; Bromm & Loeb, 2003). The cloud collapsing along this evolutionary path radiates away the internal energy by H atomic emission, not by H_2 molecular emission as in the normal primordial star formation. The atomic-cooling clouds can yield the SMSs with 10^5 – 10^6 $M_\odot$ (e.g. Latif *et al.*, 2013). Such massive stars collapse into massive BHs due to the general relativistic instability (Iben, 1963), and then grow into SMBHs with further mass accretion. This SMBH formation channel is often dubbed as "Direct Collapse (DC)" scenario.

Our main goal is to test the DC scenario in the cosmological context. In the last few years, various authors study the SMS formation under the idealized environment (Shang *et al.*, 2010). They focus on arbitrary atomic-cooling halos and artificially disable molecular cooling. However in reality, the molecular hydrogen should be destroyed due to i.e. the radiation from a nearby star-forming galaxy. To learn whether an SMS forms in realistic environments set by the cosmological initial conditions, we for the first time demonstrate the SMS formation fully consistent with the formation of galaxies which provide molecular dissociating photons. Specifically, we perform hydrodynamics simulations that start from the cosmological initial conditions, solving the transfer of radiation from the star-forming galaxies.

We have found several effects important for the SMS formation that are overlooked in the previous studies. Tidal force is one of such effects, which counteracts the self-gravity of the collapsing cloud and can prevent the cloud collapse. Since a luminous and massive galaxy is located just close to the collapsing cloud, tidal force significantly affects the cloud evolution in most of the cases. We have performed the simulations for 42 candidate clouds in the simulation box with 20 h^{-1}Mpc on a side and found that only two out of 42 candidates collapse into the protostellar cores. The two "successful" samples experience a major merger just before the onset of the cloud collapse, which transports the gas toward the cloud center where tidal force is weak. Our results indicate that the environmental effects, such as tidal field from the source galaxy, reduce the SMS formation rate by an order of magnitude, compared with the previous studies that do not consider such effects.

We have also examined the effects of the ionizing radiation coming from the source galaxy. What we have found is that the ionizing radiation has large impact on the cloud evolution when the candidate cloud is located inside the void region. Meanwhile in reality, the cloud approaches mainly along the filament that protect the cloud from the ionizing radiation. Therefore, the ionizing radiation can only have small impact on the cloud evolution since these filaments attenuate the ionizing radiation.

We further follow the cloud evolution after the protostellar cores are formed at the cloud centers. Starting from the two "successful" clouds, we perform radiation hydrodynamics simulations that follow the long-term evolution for 0.1 million years. Interestingly, tidal force still have great impacts on the cloud evolution at 10^2 – 10^4 AU scale. One cloud suffers the strong tidal force from the nearby galaxy, which yields an order of ten SMSs with 10^3–10^4 $M_\odot$ after the stellar lifetime. The other one suffers relatively weak tidal force, and that a few SMSs with 10^4–10^5 $M_\odot$ will be expected. The reason why the tidal force is important at such small scales is owing to the nature of isothermal collapse, which enhances the bar-mode perturbation during the collapse. In fact, the tidal force itself is not important at 10^2 – 10^4 AU scale. The tidal force seeds the initial bar-mode perturbation, which grows during the collapse

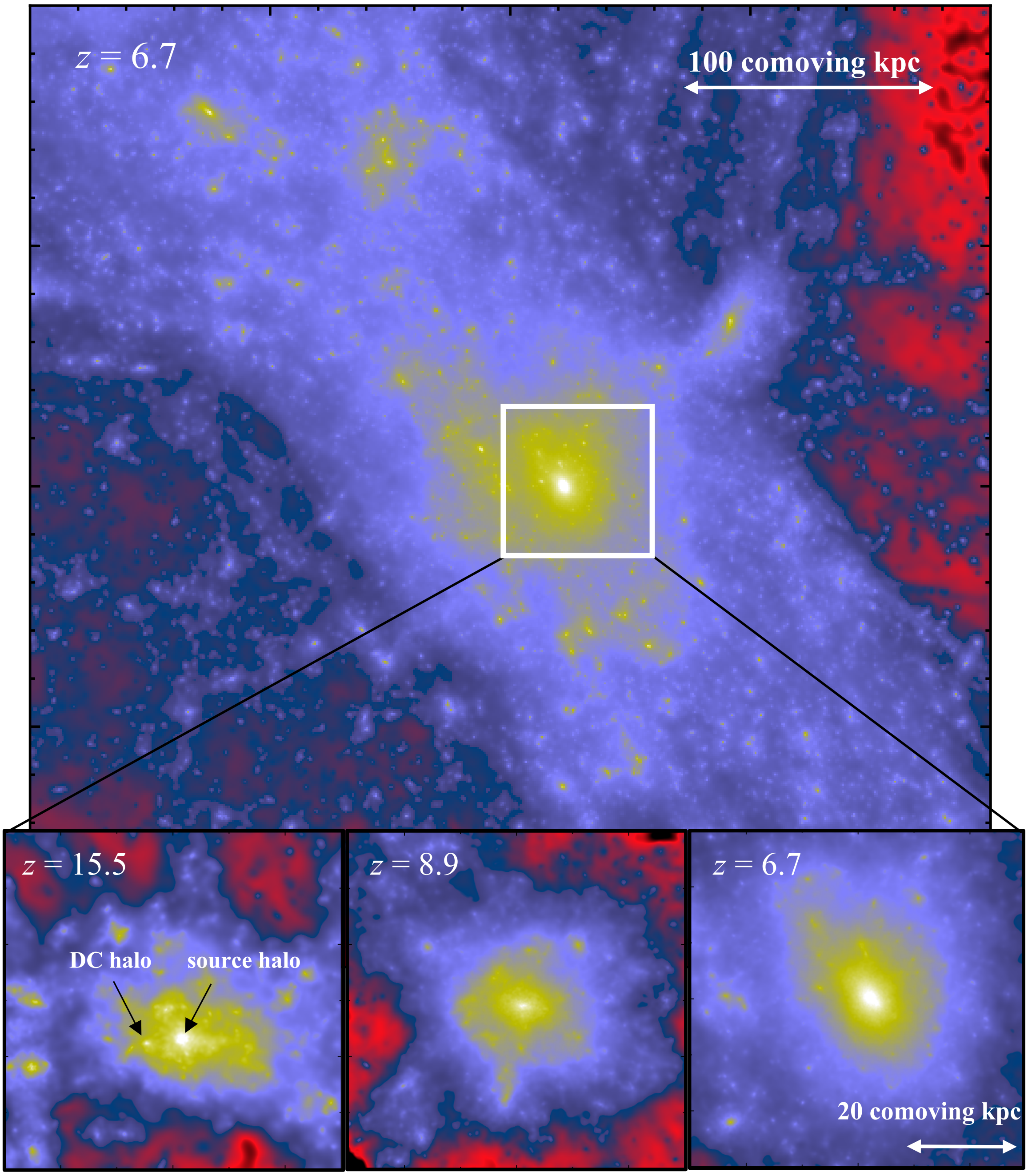

図 1　DM density distribution around the DC halo after the formation of SMSs and the remnant DCBHs. The bottom panels represent the time evolution of the density structure around the DC halo. The DC halo sinks toward the center of the massive galaxy at $z = 8.9$.

to finally cause the fragmentation of the filamentary cloud. The stellar multiplicity is enhanced by this effect. These SMSs will collapse into BHs, after they exhaust the nuclear hydrogen or during the hydrogen burning stage due to general relativistic instability.

Future gravitational wave (GW) observations can give some implications about the formation process of SMBHs. Our simulations have shown that several BH binaries will appear as a result of the cloud fragmentation. If they merge as interacting with

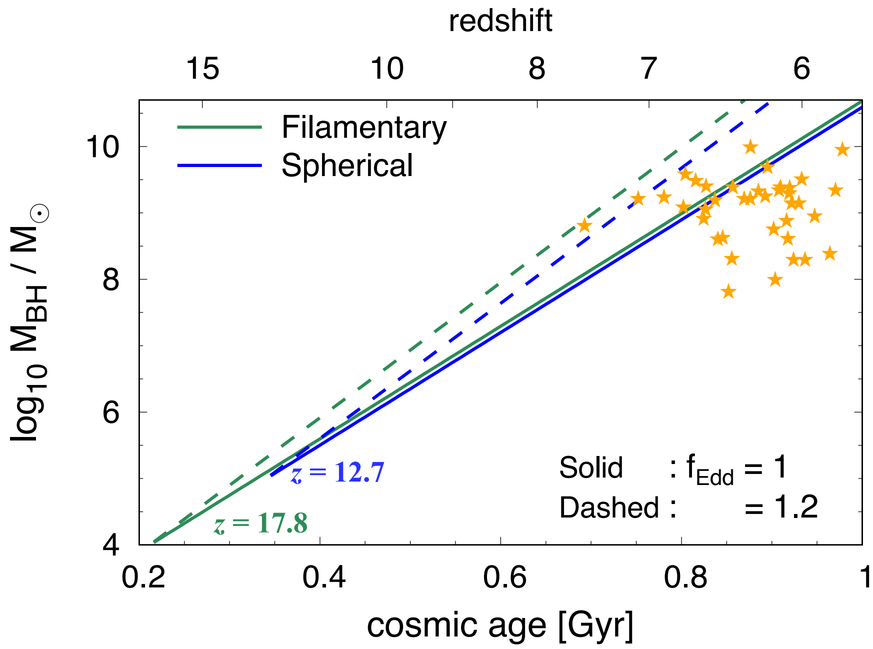

図 2 The mass evolutions of the BHs, starting from the remnant DCBHs of SMSs found in our simulations. The solid and dashed lines assume the accretion with $f_{\rm Edd} = 1$ and 1.2, respectively. Stellar symbols represent the mass and the redshift of the SMBHs at $z \gtrsim 5.5$.

the other gaseous or stellar components, we can observe the GW signals by future space GW observatories, LISA and DECIGO. We expect a number of GW signals by BH binary mergers with 10^4–10^5 $M_\odot$, if the DC scenario provides a dominant fraction of seed BHs.

These are the first examples of the seed BH formation that is predicted by DC scenario. To compare our results with the observed number density of the $z > 6$ QSOs, we should further follow the growth of seed BHs. In fact, the number density of formed SMSs in our simulations ($\sim 10^5$ Gpc^{-3}) is much larger than that of the observed $z > 6$ QSOs (~ 1 Gpc^{-3}), while the number density of SMSs we found is by an order of magnitude smaller than the previous studies. The further mass growth of such seed BHs is expected because the cloud containing the BH will fall into the UV-illuminating galaxy center, which has a plenty of gas to feed the BH. The efficient Eddington accretion allows these BHs to attain the masses of 10^9 $M_\odot$ at $z \gtrsim 6$. We should also uncover whether these massive SMBHs provide us the observable signals. If the BHs are embedded in the dense surroundings, we may not observe their existence. These two factors – the BH growth and the observability of the SMBHs – can resolve the discrepancy of the number density of SMSs and the observed SMBHs.