Early Disk-Galaxy Formation from JWST to the Milky Way
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Stellar Mergers in Dense Stellar Systems and growth of supermassive black holes

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Abstract. The rapid formation of supermassive black holes (SMBHs) at high redshifts is still a puzzle. One hypothesis is that intermediate-mass black holes (IMBHs) serve as seeds for their formation, which could arise from hierarchical mergers in dense star clusters. There are two possible pathways for IMBH formation: 1) very massive stars may form in young star clusters, such as Pop3 clusters, and evolve into IMBHs within a few million years; 2) multiple stellar-mass black holes can merge into IMBHs in dense nuclear star clusters. Detailed insights into these scenarios can be obtained through high-resolution star-by-star simulations of dense star clusters. Furthermore, upcoming observations of faint quasars, nuclear star clusters, and Pop3 stars with the James Webb Space Telescope (JWST) will offer valuable data to constrain theoretical models and deepen our understanding of the rapid formation of SMBHs.

Keywords. nuclear star clusters, supermassive black holes, intermediate-mass black holes, gravitational waves, numerical simulations

1. Introduction

Recent observations have revealed the existence of supermassive black holes (SMBHs) at extremely high redshifts (Wu et al. 2015; Bañados et al. 2018). These SMBHs, with masses on the order of $10^9 M_\odot$, have been observed as early as $z \approx 7.54$. However, the mechanisms by which these SMBHs grew to such enormous sizes in such a short amount of time remain a mystery.

There are two main scenarios that have been proposed to explain the rapid growth of SMBHs in the early universe (Inayoshi et al. 2020). The first scenario involves accretion of matter onto the SMBH at rates exceeding the Eddington limit. The second scenario proposes the existence of seed black holes with masses exceeding $10^3\ M_\odot$, which formed through a different channel than that of typical stellar-mass black holes.

Here we focus on the discussion of the formation of SMBH seeds, as understanding their formation is crucial to fully unraveling the mystery of SMBH growth in the early universe. A crucial requirement for any theoretical model is that it not only accounts for the formation of these extreme SMBHs, but also accurately reproduces the formation of the majority of normal SMBHs.

2. Formation of SMBH seeds

Various studies have focused on the formation of SMBH seeds. Depending on their mass range, SMBH seeds can form through three primary channels (Inayoshi et al. 2020):

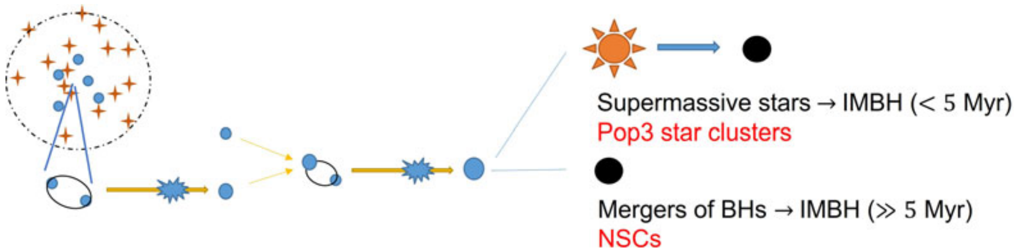

Figure 1. The fast formation of very massive stars (VMS) in young star clusters such as Pop3 clusters is driven by hierarchical mergers of main-sequence stars. On the other hand, the long-term evolution of nuclear star clusters (NSCs) can lead to the formation of intermediate-mass black holes (IMBHs) through multiple mergers of stellar-mass black holes.

• Stellar-mass black holes (BHs) (10^{1-2} $M_{\odot}$) form through the classical stellar evolution of massive stars. The detection of graviatational waves (GW) by advanced LIGO/VIRGO/KAGRA (The LIGO Scientific Collaboration et al. 2021) confirms the existence of these BHs. The growth of SMBHs from stellar-mass BHs seems natural. However, to explain the extremely-massive SMBHs at high redshift, over Eddington accretion is required.

• Intermediate-mass BHs (IMBHs) (10^{3-4} $M_{\odot}$) are predicted to form from either very massive stars (VMS) or through hierarchical mergers of stellar-mass BHs. The major environments for the production of IMBHs are dense stellar systems, including massive star clusters and nuclear star clusters (NSCs) at the galactic center. In addition, VMS at high redshift can be Population III stars.

• Heavy seeds (10^{5-6} $M_{\odot}$) are predicted to form via the rapid collapse of primordial gas in atomic-cooling halos.

The second and third channels can explain the fast formation of SMBHs at high redshift. In this section, we focus on the formation of IMBHs through the dynamical mergers in dense stellar systems. The theory of stellar dynamics suggests that the gravitational N-body system undergoes gravothermal catastrophe (Lynden-Bell and Wood 1968), which results in the rapid increase of central density of star cluster as energy transfers from central to halo. As a result, a binary must form at the center and kick out surrounding objects to prevent infinite core collapse. Such a process is called binary heating and is also an important mechanism for driving mergers of binaries. In dense stellar systems, hierarchical mergers may occur, as shown in Figure 1. Different outcomes are possible depending on their progenitors. Main-sequence stars can lead to the formation of very massive stars (VMS), while stellar-mass black holes can form intermediate-mass black holes (IMBHs). We describe these two cases in detail in the following sections.

2.1. *Very massive stars*

Young massive star clusters can undergo binary mergers, leading to the formation of VMS with masses above $10^3 M_{\odot}$ within a few million years, which can evolve into IMBHs as suggested by previous studies (Portegies Zwart and McMillan 2002). However, further research indicates that strong winds significantly reduce the mass of VMS before they evolve into BHs, resulting in a final mass only in the range of stellar masses (e.g. Köhler et al. 2015). Nevertheless, this scenario might work for extremely metal-poor population III (PopIII) star clusters. Recent hydro-dynamical simulations of PopIII star cluster formation by Sakurai et al. (2017) suggest that the high density of collapsed gas enabling VMS to form in the cluster centers with a mass up to $10^3 M_{\odot}$. The weak winds of PopIII stars preserve most of their mass, enabling the formation of IMBHs. The

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theoretical studies of PopIII star formation suggest a top-heavy initial mass function, which also help the formation of VMS (Stacy et al. 2016; Chon et al. 2021; Latif et al. 2022). In addition, PopIII stars form at redshifts $z < 10$, consistent with the formation time of SMBH seeds. Wang et al. (2021) suggests that PopIII star clusters containing IMBHs may survive until the end of the Hubble time if a mini dark matter halo protects the cluster from tidal disruption. In this case, long-term evolution may result in GW radiation from IMBH-BH mergers that could be detected by space-based GW detectors such as LISA, Tian-Qin, and Taiji.

2.2. *Mergers of stellar-mass black holes*

The secondary scenario for IMBH formation involves the hierarchical mergers of stellar-mass BHs within dense star clusters like globular clusters and nuclear star clusters (NSC) (e.g. Giersz et al. 2015; Antonini et al. 2019; Fragione and Silk 2020; Kroupa et al. 2020; Rizzuto et al. 2021; Mapelli et al. 2021, 2022; Fragione et al. 2022; Rose et al. 2022). However, for this channel to be successful, the host system must have a sufficiently high density to retain the mergers and prevent them from escaping. To achieve this, the BH recoil kick due to asymmetric GW radiation must be less than the host system's escape velocity, allowing the BH to remain in the center and grow continually. While the typical escape velocity of globular clusters may not be large enough to retain the mergers, NSCs are located in the deep potential of the galactic bulge, making them an ideal environment for IMBH growth (Antonini et al. 2019). In addition, studying the formation of SMBH seeds in NSCs is crucial to understanding the observed correlation between NSCs and SMBHs (Kormendy and Ho 2013; Neumayer et al. 2020; Greene et al. 2020).

3. Perspective

The new era of JWST offers several opportunities to enhance our understanding of SMBH and NSC formation and evolution. Firstly, JWST can detect faint quasars at high redshifts, which will aid in measuring the lower end of the SMBH mass function and constrain SMBH formation scenarios (Habouzit et al. 2022). Secondly, PopIII VMS or PopIII star clusters might be detected by JWST if they are lensed, which could provide additional constraints on the IMBH formation scenario from PopIII stars (Bovill et al. 2022; Larkin et al. 2023). Additionally, JWST's improved age determination of stellar systems will help to understand the star formation history in nearby NSCs. A recent example is the combined HST and JWST analysis of the NSC in NGC 628 from the PHANGS-JWST program, which demonstrated the potential of JWST for studying NSCs (Hoyer et al. 2023).

With the continuous improvement in computational hardware and software in recent years, theoretical modeling of SMBH formation in NSCs will also advance in the near future. N-body models for dense stellar systems can now reach the million-body region with high accuracy (Wang et al. 2016; Arca-Sedda and Gualandris 2018; Panamarev et al. 2019; Mukherjee et al. 2023). New N-body codes, such as PETAR (Wang et al. 2020), BIFROST (Rantala et al. 2022), and TAICHI (Mukherjee et al. 2023), including accurate integrators for binaries, make it possible to model NSCs with ten million bodies, where individual stars and binaries can be resolved. With high-resolution simulations, physical processes such as two-body relaxations, resonant relaxations, and stellar evolution can be self-consistently simulated to provide realistic models of NSCs that contain massive BHs. Combining observations and theoretical models will enable us to unveil the mystery of fast SMBH formation at high redshifts, comprehend the relationship between the dynamical evolution of NSCs and SMBH formation, and further improve our understanding of the star formation history in the early Universe.

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