Massive Stars Near and Far
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Formation of Supermassive Stars and the Direct Collapse to Black Holes

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Abstract. Supermassive stars represent a promising avenue for seeding the (super-)massive black holes observed in the centres of massive galaxies. In these proceedings I review the motivation on the need for supermassive stars as a progenitor pathway for seeding massive black holes. I discuss the currently understood limitations of seeds produced by less massive stars (i.e. remnants from the first generation of stars) and advocate that more massive stars - with masses up to $M_* \sim 10^5 M_\odot$ - formed under the conditions of hierarchical structure formation, in rare haloes, are the favoured pathway. Finally, I discuss some recent high resolution simulations demonstrating the formation of supermassive stars in early galaxies.

Keywords. Massive Black Holes, Early Universe, Supermassive Stars

1. Introduction

Observations point to an occupation fraction of very close to 100% for massive black holes (MBHs) in massive galaxies (Faber et al. 1997, Fan et al. 2006, Kormendy and Ho 2013). However, the origin of MBHs remains unknown. Over the past four decades many theoretical proposals have been put forward to address the origin of MBHs in galaxy centres beginning with Martin Rees in the late 1970's (Rees 1978; 1984). In Figure 1 we illustrate the most up-to-date theoretical proposals for the formation pathways of MBH seeds.

One of the main challenges presented by the detection of MBHs in galactic nuclei is their existence at very early times - less than a billion years after the Big Bang. Almost 200 high-z quasars have now been discovered at $z \geqslant 6$. This means that MBHs with masses close to, or in excess of, $M_{MBH} \sim 10^9 M_\odot$ are already in place well before the end of reionisation. The presence of MBHs at the centres of massive galaxies in the early Universe poses a challenge to our understanding of both the formation and growth of MBHs.

The main avenues to forming and growing MBHs can be broken down into *light* and *heavy* seeds. In these proceedings I will flesh out the details of each pathway making the case that *heavy* seeds - forming out of (super-)massive stars are currently favoured both theoretically and empirically based on the evidence at hand.

2. The Massive Black Holes Mass Spectrum

As noted in the Introduction MBHs display a strong correlation with their host galaxy. This relationship, originally discovered more than two decades ago, is most easily seen using the so-called M-σ relation (Magorrian et al. 1998). Initially the relationship was confined (empirically) to black hole masses in excess of $10^6 M_\odot$ and to galaxy masses above the dwarf galaxy threshold ($M_{gal} \sim 10^{11} M_\odot$). However, in more recent years MBHs in

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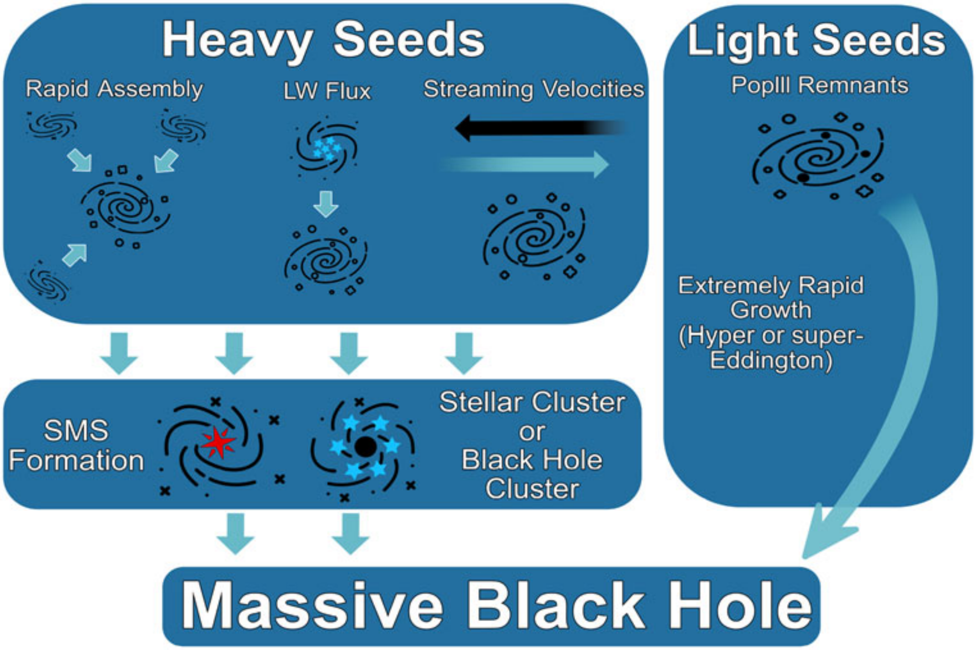

Figure 1. The formation pathways leading to both the creation of heavy and light seeds. Heavy seed pathways can lead to either the realisation of a monolithic collapse and a super-massive star or in the event of significant fragmentation the realisation of a dense stellar cluster or subsequently a black hole cluster. Light seeds are born from the remnants of the first generation of stars and are expected to have typical masses in the range $M_{BH} \sim 10^1 - 10^3 M_{\odot}$. Heavy seeds are expected to cover the range of $M_{BH} \sim 10^3 - 10^6 M_{\odot}$.

dwarf galaxies have been detected and so are beginning to populate the same relation. In Figure 2 we show a recent plot of the M-σ relation from Baldassare et al. (2020) where they were able to identify MBHs below the $10^6 M_{\odot}$ threshold.

Probing MBH masses between $M_{MBH} = 10^{4-6} M_{\odot}$ is now the next frontier in the relationship between MBHs and their host galaxies. This is the regime in which we expect *heavy* seeds to be born or for *light* seeds to reach masses of $M_{MBH} \sim 10^5 M_{\odot}$ before settling into the (dwarf) galactic centre. Identifying MBHs in dwarf galaxies at the masses of what we expect the seed masses to be does not however by itself identify the seeding mechanism. This is because as black holes accrete and grow, memory of their initial formation (i.e. seeding) is erased. Instead we must rely on the demographics of MBHs found in dwarf galaxies to try to piece together the evolutionary histories of the MBH population as a whole. However, this will be no easy task since the number of theorised pathways to forming MBHs is large with some predicting large seed masses (e.g. Regan and Downes 2018) while others predict ‘intermediate’ (e.g. Lupi et al. 2016) seed masses which grow into the *heavy* seed regime within certain environments (e.g. Stone et al. 2017, Natarajan 2021).

3. The Formation Pathways to Massive Black Holes

MBHs are expected to be seeded at high-z ($z \gtrsim 10$) in either metal-free or metal-poor environments. The demographics of MBHs inside early galaxies is currently unknown with quantitative estimates of the number densities of MBHs as a function of redshift varying by several orders of magnitude (Agarwal et al. 2012; 2014, Dijkstra et al. 2014, Habouzit et al. 2016, Wise et al. 2019). The variation can be partly explained by our lack

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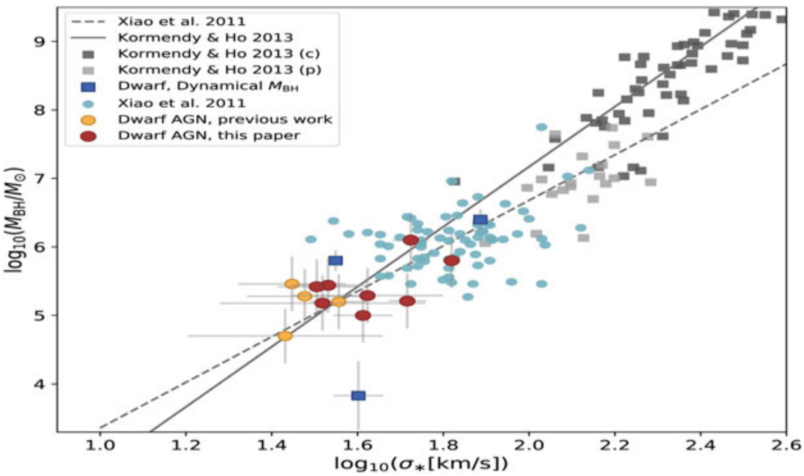

Figure 2. Massive Black hole mass vs. stellar velocity dispersion. The gray squares are from the compilation of Kormendy and Ho (2013); dark gray squares show galaxies with classical bulges and light gray squares show galaxies with pseudo-bulges. Light blue circles show data for low-mass AGN from Xiao et al. (2011). Active dwarf galaxies with stellar velocity measurements (from the Keck II Echellette Spectrograph and Imager) analysed by Baldassare et al. (2020) are shown as red circles with active dwarf galaxies with analysed by Baldassare et al. (2020) from the existing literature are shown in orange. Dwarf galaxies with dynamical BH mass estimates are shown as dark blue squares. We also show the fits to MBH-σ from Xiao et al. (2011) (dashed line) and Kormendy and Ho (2013) (solid line). Reproduced with modification from Baldassare et al. (2020).

of understanding of both the exact processes responsible and the exact environmental conditions required to seed MBHs.

The (astrophysical) seeds from which MBH grow can be broken down into *light* and *heavy* seeds. Light seeds are born from the remnants of the first generation of stars and are expected to have typical masses in the range $M_{BH} \sim 10^1 - 10^3 M_{\odot}$. Heavy seeds are expected to cover the range of $M_{BH} \sim 10^3 - 10^6 M_{\odot}$. In the following sections we will describe in detail both the formation pathways and growth prospects of *light* and *heavy* seeds. We will break the *heavy* seed formation scenario into two complementary parts. The first section will deal with the dynamical formation of a MBH seed within a dense, gaseous or stellar, environment (e.g. a dense stellar cluster, a nuclear cluster or within a dense black hole star cluster) and the subsequent formation of a MBH(s) at the cluster centre. The second section will explore the related idea of (super-)massive star formation in a similar environment and the subsequent transition of the system with one or more MBHs at the centre. Both scenarios may overlap potentially distinguished only by the degree of fragmentation at the outset.

3.1. *Light Seed Growth*

In Figure 1 we show a schematic of the pathways of both *light* and *heavy* seeds and their possible evolutionary avenues to MBH realisation. In the right hand panel we illustrate the formation of *light* seeds. These are seeds born out of the remnants of the very first stars. The mass spectrum of the first stars is unknown but there are strong reasons to suspect that the initial mass function of early stars will be top-heavy (Hirano et al. 2017). Resulting from the formation of massive stars will be a population of stellar mass black holes with masses in the range $M_{BH} \sim 10^{1-3} M_{\odot}$. If these seeds (or a small subset of them) can grow efficiently (Madau and Rees 2001) then they can explain both the high-z

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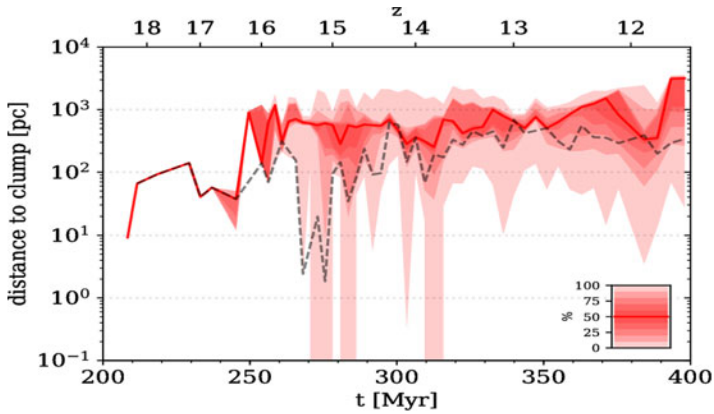

Figure 3. Distribution of distances between a black hole and a high accretability gas clump (greater than $10^{-3}\mathrm{M}_{\odot}^{-1}$) for all progenitor haloes of the halo hosting the most black holes (shown in Figure 7.) Where the shaded region extends to the bottom of the figure, some black holes exist within high accretion rate clumps - but crucially this is short lived. Values shown in red correspond to all black holes within a halo's virial radius. The black, dashed line denotes the median separation for black holes within 0.25 of the virial radius. Reproduced with modification from Smith et al. (2018)

quasars as well as the population of MBH observed across cosmic time. However, both semi-analytic models and detailed numerical calculations have shown that growing light seeds is exceedingly difficult (Alvarez et al. 2009, Milosavljević et al. 2009). In a recent investigation by Smith et al. (2018) we found that when analysing the high resolution Renaissance simulations containing over 20,000 PopIII remnant black holes that none grew by more than 10%. In Figure 3 we show the growth of the entire population of black holes from the Renaissance simulations. What we show in Figure 3 is the mean distance of all stellar mass black holes from the nearest clump from which it could accrete (and grow). On average these PopIII remnant black holes are over 100 pc from the nearest gas clump. The black holes are too small to sink to the dense inner parts of their host galaxy and as a result wander the outer regions of the core where they cannot grow.

This characteristic of black hole growth was further investigated by Pfister et al. (2019) who found that stellar mass black holes do not sink and that black hole must reach a mass of $\mathrm{M}_{\mathrm{MBH}} \sim 10^5 \mathrm{M}_{\odot}$ before they become sufficiently massive and can sink to the centre of their host galaxy.

3.2. *Heavy Seed Formation & Growth*

Given the challenges outlined above in relation to the growth of light seeds numerous research studies over the last few decades have postulated that it may be possible (or likely indeed) that more massive seeds could have driven the formation of MBHs. Initial investigations of the collapse of primordial gas clouds and the formation of heavy seeds date back to early papers by Loeb and Rasio (1994) and Eisenstein and Loeb (1995) who looked at the collapse of the central regions of haloes (albeit under highly idealised conditions) and found that seed masses up to approximately $10^6\mathrm{M}_{\odot}$ were possible under favourable conditions. Using a cosmological setup Regan and Haehnelt (2009) used the adaptive mesh refinement code Enzo (Bryan et al. 2014, Brummel-Smith et al. 2019) to model the collapse of gas within a dark matter halo at high redshift. They found that centrifugally supported disks formed with masses capable of supporting the formation of an intermediate stage en-route to MBH formation. Over the last decade rapid progress in understanding the formation pathways to MBHs via a heavy seed route has ensued.

In Figure 1 the potential pathways to heavy seed formation are outlined in the left hand panel. We begin by examining the Lyman-Werner (LW) and Baryonic Streaming Velocity channels to forming MBHs.

Emission in the LW band can readily dissociate H_2 cutting off a critical cooling route to forming PopIII stars. If this cooling channel is either cutoff or even disrupted then normal PopIII star formation is prevented and this can lead to (much more massive) star formation in more massive haloes where cooling is instead achieved via atomic hydrogen emission lines. Numerous authors have investigated this pathway over the last decade with the synchronised halo pair scenario emerging as a leading contender to produce heavy seeds (Shang et al. 2010, Dijkstra et al. 2014, Regan et al. 2017). In this scenario two haloes evolve closely separated in space and time with one halo beginning star formation first and irradiating the nearby halo and through LW irradiatiion leaving the neighbouring halo free of H_2. The neighbouring halo's gas then cools via atomic cooling (rather than molecular) and this leads to the formation of (super-)massive stars. The crucial parameter in the LW channel scenario is the level of flux required written as $J_{21,crit}$ where $J_{21,crit}$ is the critical level of flux in units of J_{21}†, required to dissociate H_2 and allow collapse via atomic hydrogen. Regan et al. (2017) found that neighbouring haloes must be separated by less than 300 pc with the receiving flux then being approximately $J_{crit} \sim 10^2$ J_{21}. Such high levels of flux are only possible due to the very tight separation of the haloes. The fine-tuned conditions for this pathway impacts on the number density of haloes that can support this particular pathway and hence it may be that this scenario cannot explain the full MBH population but maybe important for a subset of haloes hosting MBHs.

Baryonic streaming velocities originate following recombination and refers to the offset in velocities between baryons and dark matter. The mean offset is zero but fluctuations on either side of the mean, result in offsets between the baryons and the dark matter. This pathway has been extensively explored by many authors (e.g. Tanaka and Li 2014, Schauer et al. 2017, Hirano et al. 2017) in the context of heavy seed formation. Hirano et al. (2017) probed the collapse of haloes in rare regions of the Universe subject to 3σ fluctuations in the root mean squared offset between baryonic and dark matter velocities. They found that in these regions baryonic collapse inside dark matter haloes is delayed as the baryons cannot initially settle into the dark matter potential wells due to their excess kinetic energy. As a result larger inflow fluxes develop leading the formation of very masses stars with masses up to $M_* \sim 10^5 M_\odot$. Similarly to the LW pathway it is unlikely that this particular pathway can explain all MBHs but it could also be, that it can work in tandem with the LW pathway to drive the formation of very massive stars which can be the seeds for the most MBHs (Schauer et al. 2017).

Finally, the rapid assembly process relies on the hierarchical structure formation pathway as the main driver either through dynamical heating offsetting cooling (Yoshida et al. 2003, Fernandez et al. 2014, Wise et al. 2019) or through turbulent cold flows acting to pressure support the gas against collapse (Latif et al. 2022). In many ways this is the most natural pathway with simulations now focusing on the initial mass function of stars produced with this pathway. If the rapid assembly process (or a derivative of it) can produce heavy seeds then a key finding would be the continuum of heavy seed masses supported and of how the seeds produced populate galaxies as they grow and evolve over cosmic time. Regan et al. (2020b) used high resolution adaptive mesh refinement simulations to follow the collapse of single halo in an overdense region which had previously been identified as a rapidly growing halo Regan et al. (2020a). In Figure 4 we show visualisation from the high resolution simulations of Regan et al. (2020b). Using a sophisticated subgrid model for star formation they showed the formation of massive

† J_{21} is defined as 10^{-21} erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}

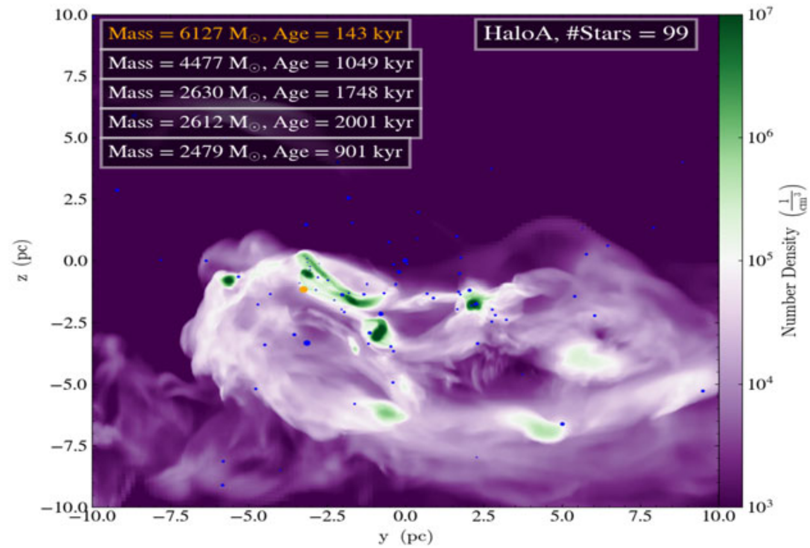

Figure 4. Visualisation of the stars in the high resolution runs of Regan et al. (2020b). Stars are marked with filled circles. The most massive star is coloured orange. Other stars are coloured blue. The stars are plotted on top of the baryonic gas density (in projection weighted by density). The most massive stars are labelled in the top left. Reproduced from Regan et al. (2020b)

stars with stellar masses $M_* \gtrsim 6000 \mathrm{M}_\odot$. This (super-)massive star will directly collapse into a MBH of approximately the same mass as significant mass loss is not expected for metal free stars (Woods et al. 2017). It should be noted however that these stars are likely at the Eddington limit (e.g. Haemmerlé 2021) and detailed analysis is still lacking in understanding the exact mass loss rates and stellar winds produced by such objects. More simulations and greater statistics are now required to probe this and other related heavy seed formation channels (e.g. Latif et al. 2022) which may ultimately both predict and explain the observed number density of MBHs.

4. Observational Guidance and Outlook

Definitive observational signatures of the seeding process responsible for the formation of MBHs is still beyond the range of current (and indeed near future) telescopes. With the seeding process existing at small mass scales at very high redshift direct, clear, evidence is likely to be very difficult to achieve in practice. Nonetheless, there are a number of avenues that can be explored that together can build up sufficient circumstantial evidence to point towards certain avenues. In this section we explore how high-z observations of quasars, low-z observations of fossil dwarf galaxies and future gravitational wave measurements can all contribute to understanding the origin of MBHs.

The best direct method to detect the seeding process of MBHs may have to await the launch of a next generation X-ray telescope. As discussed in detail by Haiman et al. (2019) they argue that to detect seed black hole massed with masses in the $10^5 \mathrm{M}_\odot$ range at $z \gtrsim 10$ requires a telescope with capabilities similar to that of the proposed Lynx mission † with flux sensitivities down to 10^{-19} ergs^{-1}cm^{-2}. While Lynx will be sensitive enough to detect these embryonic black holes a combination of JWST ‡ and the Roman telescope § will be required for investigation of the host galaxy environment through

† https://www.lynxobservatory.com/
‡ https://www.jwst.nasa.gov/
§ https://roman.gsfc.nasa.gov/

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their Optical and Near Infrared emission signatures. In additional to probing the seeding mechanisms of MBH at high-z it is also possible (and indeed a requirement) to probe the fossil remnants of heavy seeds at low-z. Dwarf galaxies may hold the key in this regard as dwarf galaxies resemble, in terms of the mass, the earliest galaxies. For dwarf galaxies that remain today some have had quiescent histories meaning that they retain information on the early Universe and of their foundation in from very early times. As a result the centres of dwarf galaxies today may host MBH that were seeded at high-z and have undergone only mild evolution since that epoch (Volonteri et al. 2008, van Wassenhove et al. 2010). More over recent detections of AGN in dwarf galaxies have resulted in the detection of tens of MBH candidates in the nuclei, as well as off-nuclear candidates, of dwarf galaxies (Mezcua 2017, Mezcua and Domínguez Sánchez 2020, Baldassare et al. 2020). Theoretically the existence of MBHs in dwarf galaxies is well founded (e.g. Dunn et al. 2018, Sharma et al. 2019) and the key now lies in understanding the demographics inside dwarf galaxies (Pacucci et al. 2021) and their connection to their high-z progenitors.

The advent of the detection of gravitational waves via the LIGO and Virgo detectors has opened up a new window into how we observe black holes (e.g. Abbott et al. 2016). While the current generation of GW observatories cannot observe MBH in the range of interest here the planned next generation of space based GW observatories † will have the capabilities to observe the mergers of MBHs out to redshifts up to $z = 20$. LISA, due for launch, in the second half of the next decade will be the premier observatory for detecting mergers of MBHs but by itself will not have the capability to directly distinguish between seeding pathways (Bellovary et al. 2019, Valiante et al. 2021). This is due to the fact the mergers will carry no information on the birth of the seeds. Instead a multi-messenger approach will ultimately be required with statistics being required from multiple different observations to piece together the full picture.

5. Conclusions

MBHs populate the centres of massive galaxies all the way down from the most massive central cluster galaxies into the regime of dwarf galaxies. Understanding both the formation pathways of MBHs and also their demographics inside galaxies remains an open question in modern astrophysics. While observations in both the electro-magnetic (EM) spectrum and gravitational wave spectrum have discovered hundreds of stellar mass black holes, and observations in the EM have detected MBH with masses in excess of $\mathrm{M_{MBH}} \gtrsim 10^6 \mathrm{M_\odot}$ - MBH detections in the window between $\mathrm{M_{MBH}} = 10^{3-6}$ remain elusive.

Here we discuss the avenues to MBH formation in the early Universe - focusing on the formation of supermassive stars as a progenitor pathway. This pathway requires more "exotic" scenarios although we argue here that such environments do arise naturally through hierarchical structure formation and look promising in terms of producing number densities that match current observational constraints. In particular for supermassive stars formed through the rapid assembly of galaxies - be that through dynamical heating induced from minor mergers or through supersonic inflows - seeds with masses in the range $10^4 \mathrm{M_\odot}$ appear quite plausible. Further work on building up the statistics of these formation pathways as well as (multi-messenger) observational signatures are now required.

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Discussion

Ralf Klessen: The pathways to *heavy* seeds could be via dense stellar clusters or SMS star formation. Which pathway do you think is more likely

Regan: I think some fragmentation is nearly inevitable in most systems and very difficult to prevent. However, it could be that after initial fragmentation some of the stars (fragments) merge with the central object as shown by Chon et al.

Kaz Omukai: Have you looked at SMS formation in metal enriched haloes

Regan: Yes we have. We looked in the Renaissance simulations to see the fraction of rapidly growing haloes that occur with some prior metal enrichment. We found that including slightly enriched haloes increases the number of candidates haloes by a factor of approximately 3. Further, study of heavy seed formation in these metal-poor, rapidly assembling galaxies would be very useful.