Supermassive black hole seeds: updates on the “quasi-star model”

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Abstract. LISA will allow us to see the infancy of the universe and gather unique constraints on an outstanding mystery: the formation of supermassive black holes. Here, I review a particular scenario, where black hole seeds are formed from direct collapse of gas at the centre of (proto)-galaxies. I will show that very massive (>10^5 M⊙) black hole seeds are possible but before confidently claim so the impact of physical ingredients, like internal rotation and super Eddington accretion, need to be fully understood.

1. Introduction

The Laser Interferometer Space Antenna (LISA) would be a unique probe for supermassive black hole (SMBH) science. In particular, it will be suited to directly detect massive black hole seeds — with masses between 10^4 − 10^6 M⊙ — at their formation epoch z > 10. This is one of my main motivations to study and try to assess the feasibility of the “direct collapse scenario”, the leading model to form massive seeds at the centre of proto-galaxies. In addition, this scenario has the appealing feature of forming seeds where we actually observe SMBHs, contrary to the population III stars scenario, where mergers of the hosting mini-haloes need to eventually deliver a black hole to the bottom of the potential of an assembling galaxy with all the contingent complications nicely detailed in this recent review [1].

The challenge however remains: how actually do black holes form in first place? The issue is two-fold: (i) how to funnel this gas towards the centre of a galaxy from galactic scales avoiding the centrifugal barrier and fragmentation into stars, and (ii) once the gas is collected how actually the gas collapses into a black hole. In this contribution I will only address the second part of the puzzle, especially reviewing my recent results, published in [2] and [3].

Formation of massive seeds requires accretion rates > 0.1 M⊙ s⁻¹ (e.g. [4, 5, 6]). There are two main proposed mechanisms that may produce such high accretion rates and make massive seed formation possible. The first channel entails a major merger between two galaxies, that has been shown to effectively funnel > 10^8 M⊙ in less than one Myr [7, 8], forming a structure which is gravitationally unstable and can directly collapse into a black hole that may retain all the mass [9, 10, 11]. This scenario however cannot explain the whole SMBH population and its entire range of observed black hole masses. Indeed major mergers are rare in the history of a galaxy and, at high redshifts considered here (z > 10), most of the galaxy mass is accreted in a secular process through cold gas streams that flow from the cosmic web into the galactic halo. These streams of dark and baryonic matter can contain substructures like dwarf galaxies, incorporating the concept of “minor mergers”. Recent numerical cosmological simulations suggest that this is
also the primary mode of SMBH growth [12]. In this scenario, the accumulated mass would first form a very massive star (MS) as nuclear reactions are ignited in their centre and, very much like in a regular massive star, its core would collapse after H exhaustion (lifetime $\sim 1$ Myr) into a black hole of maximum possible mass equal the total mass of the star: $0.1 \ M_\odot \ yr^{-1} \times 1 \ Myr \sim 10^5 M_\odot$.

2. Massive star formation as an intermediate step to seed formation

Let me now dwell more on the last scenario. The question I am interested in is: given the mass of a MS, what is the mass of the emerging black hole? The core of the MS has just a fraction of its mass. Therefore the previous question can be reformulated: after the core of the star collapses, what happens to the envelope? I believe it depends on the angular momentum re-distribution within the envelope, an important factor whose weight I came to appreciate in my last work on the subject [3]. I venture that the fate of a “slowly” rotating envelope is to follow the core to collapse directly into a black hole [3, 13]. The “fast” rotating ones will instead set as hydrostatic massive envelope around the black hole resulting from the collapse of the core: this structure is called a “quasi-star” and can foster the growth of the central black hole by super-Eddington accretion [14, 4, 15, 16, 17, 2]. In the following, I will first review the physical properties of a quasi-star (Section 3) and then physically explain the role of rotation in channelling a massive star towards either scenarios. It should then be clear what I mean by “slowly” (“fast”) rotating envelope.

![Figure 1](image1.png)  
**Figure 1.** Quasi-star envelope mass vs. black hole mass plane. Three regions are highlighted: the “growth” region, the “evaporation strip”, and the “no hydrostatic solution” region. The blue lines mark isocontours of the outflow rate $\dot{M}_{\text{wind}}$ labelled by their value in $M_\odot \ yr^{-1}$.

![Figure 2](image2.png)  
**Figure 2.** Evolutionary sequences of three quasi-stars in the envelope vs. black hole mass plane (time goes from left to right along the curves). The labels denote the assumed values for the (constant) inflow rates feeding the quasi-star envelopes.

3. The quasi-star scenario

As the core of a MS collapses into a black hole, the surrounding envelope follows the fall. However, if in the innermost region the gas has enough angular momentum to circularise outside the last stable circular orbit of the black hole and form an accretion disc, accretion energy may be
injected back into the envelope stopping its collapse. The envelope would inflate and expand until equilibrium is found, which corresponds to a surface luminosity roughly equal to the Eddington luminosity for the total mass of the envelope. This is a highly super Eddington luminosity for the black hole, by a factor equal to the envelope to black hole mass ratio. This is possible because energy is transported through most of the envelope via convection, which is not subject to the Eddington limit [14]. The embryon black hole thus grows at a highly super-Eddington pace, until it has consumed enough envelope mass that the equilibrium for a quasi-star object is not longer possible. Here the feedback from the black hole is likely to blow away the remaining envelope, leaving a bare black hole, that will eventually accrete at a more subdued pace from the pre-galactic disc. Not all combinations of envelope mass $M_*$ and black hole mass $M_{BH}$ are allowed. On the lower right corner of Figure 1 lies the parameter space where no equilibrium solutions can be found: this occurs when the mass ratio between the envelope $M_*$ and the $M_{BH}$ is equal or lower than 20.

Interestingly, [17] and [2] pointed out and study the possibility that the accretion power can even exceed the Eddington luminosity for the whole envelope, leading to mass loss from the quasi-star surface. A quasi-star is a radiation dominated object (as are all objects that emit around their Eddington limit, therefore energy losses (even slightly) above the Eddington limit unbound mass resulting in winds. We developed a self-consistent model for radiation dominated winds, valid in both the optically thin and thick regime [2]. Our main assumptions are steady state, spherical symmetry and an approximate description of the transition between the optically thick and the optically thin regimes. We find that, quite generally, the ultimate source of the wind kinetic energy is the advection energy, while the radiation energy (i.e. the radiation luminosity) remains constant. When applied to quasi-stars (with a self-consistent calculation of their envelope+wind structure), we find that very vigorous winds are blown from their surface. This can be appreciated in Figure 1, where we plot iso-contours of the mass loss rate: between 10 and 10 thousand solar masses per year can be lost by a quasi-star.

There are therefore two competing processes: the embryon black hole accretes from the inner edge of the envelope, while gas is blown from the surface. In Figures 1 the light grey strip diagonally running through the $M_*$-$M_{BH}$ plane corresponds to models where the evaporation timescale (mass of the envelope divided by the calculated mass loss rate) is shorter than the accretion timescale (mass of the black hole divided by the accretion rate). For this reason it is called the evaporation strip: the envelope is consumed by the wind before the black hole can double its mass. The white region (the growth region) in that parameter space is instead where accretion is the faster process.

In Figure 2, we plot evolutionary tracks of quasi-stars fed by an external accretion flow: the envelope acquires mass from the pre-galactic disc and loses it because of its wind and the inner black hole accretion. The quasi-star moves through a series of equilibrium states until it hits the evaporation strip, where the envelope is rapidly consumed, leaving a bare black hole. The result is quite clear: massive seeds require quasi-star envelopes that are initially very massive $\sim 10^7 M_{\odot}$ or that accrete at very high rates.

4. Rotation
A quasi-star to exist must be supplied by accretion energy. The internal rotation of the envelope sets the boundary condition for the accreting gas: are those always consistent with the existence of an accretion disc? In [3] we provide a first answer to this question. We use the so called “thermal wind equation” (e.g. [18, 19]) to model the internal rotation of a steady state and convective star, ignoring magnetic fields and turbulences. We then follow [20] by adopting a closure relation that allows one to reproduce data of the Sun’s convective zone (e.g. [21]). Given this tentative framework, the result is clear: the rotation of the gas close to the black hole’s Bondi radius is highly sub-Keplerian for a large range of parameters. We then check for each
model in the parameter space shown in Figures 1 and 2 whether the gas angular momentum would be enough for the gas to circularise outside the black hole’s innermost stable circular orbit. Surprisingly, we find that models in the “growth region” are not consistent with accretion disc formation at the centre of the envelope, while the opposite is true for models in the evaporation strip! The result is very striking, but of course our analytical modelling of the internal rotation can only be indicative. I think it is fair to say that our work proves that considering rotation (a so far neglected ingredient in MS models) in quasi-star modelling is important.

5. Discussion and Conclusions

We may now amuse ourselves and step on to more speculative grounds, by boldly taking at face value the results of the previous section and by foreseeing their full impact for SMBH formation. The above statement “models in the “growth region” are not consistent with accretion disc formation” may evoke a scenario in which, after the core of the MS has collapsed into a black hole, the envelope feels its huge gravitational pull and it does not have enough rotation to stop its quasi-radial fall. In the growth region envelopes are quite massive, therefore their direct collapse into a black hole may produce very massive \( > 10^5 \, M_{\odot} \) black hole seeds. This can only happen in rare dark matter haloes with masses between \( 10^8 \sim 10^{10} \, M_{\odot} \) at \( z > 10 \) (see figure 5 in [3]). Quasi-stars can instead form in the evaporation strip, but this implies no substantial growth for the embryos black hole, that remains of the (relatively small) size of the MS core (i.e. \( \sim 100 \, M_{\odot} \)). For a given black hole mass, the envelopes in the evaporation strip are lighter than those in the growth region, and they can form in less massive haloes. There may therefore be two populations of seeds from the direct collapse scenario which live in different halo populations: very massive seeds \( \geq 10^5 \, M_{\odot} \) and stellar size \( \sim 100 \, M_{\odot} \) seeds. The observational impact of this dychotomy would require implementing this formation scenario in a cosmological evolution framework, which will be the topic of a follow up work.

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