



# Formation of massive black holes via collisions and accretion

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**Resumen** / Para explicar la población de agujeros negros supermasivos en  $z \sim 7$ , se necesitan semillas de agujeros negros muy masivos o, alternativamente, escenarios de acreción super-Eddington a fin de alcanzar masas finales del orden de  $10^9 M_{\odot}$ . El modelo del colapso directo predice la formación de un solo objeto masivo debido al colapso directo de una nube de gas masiva. Las simulaciones en los últimos años han demostrado que este escenario es muy difícil de lograr. Un modelo realista de formación de agujeros negros debería tener en cuenta la fragmentación y considerar la interacción entre los procesos estelar-dinámicos y la dinámica del gas. Presentamos aquí una simulación numérica aplicada con el código AMUSE, realizando un tratamiento aproximado del gas. Según estas simulaciones, mostramos que se pueden formar agujeros negros muy masivos,  $10^4 - 10^5 M_{\odot}$ , dependiendo del suministro del gas y la acreción en las protoestrellas.

**Abstract** / To explain the observed population of supermassive black holes at  $z \sim 7$ , very massive seed black holes or, alternatively, super-Eddington scenarios are needed to reach final masses of the order of  $10^9 M_{\odot}$ . A popular explanation for massive seeds has been the direct collapse model, which predicts the formation of a single massive object due to the direct collapse of a massive gas cloud. However, simulations over the last years have shown that such a scenario is very difficult to achieve. Therefore, a realistic model of black hole formation should take fragmentation into account, and consider the interaction between stellar-dynamical and gas-dynamical processes. We present here numerical simulations performed with the AMUSE code, employing an approximate treatment of the gas. Based on these simulations, we show that very massive black holes of  $10^4 - 10^5 M_{\odot}$  may form depending on the gas supply and the accretion onto the protostars.

*Keywords* / black hole physics - stars: Population III - methods: numerical

## 1. Introduction

At present, more than 100 quasars are known at  $z > 5.6$  (Bañados et al. 2016; Schleicher 2018), with the currently known highest-redshift quasar at  $z \sim 7.5$ , hosting a supermassive black hole with about  $8 \times 10^8 M_{\odot}$  (Bañados et al. 2018). To explain such early and supermassive black holes, one needs to assume almost continuous Eddington accretion since redshifts  $z \sim 20$ , bursts of Super-Eddington accretion or rather massive seeds at the beginning of the accretion process (e.g. Shapiro 2005). The pathways to produce massive seeds have already been laid out by Rees (1984). These include the formation via direct collapse of a massive gas cloud into one single object and also black hole formation, via stellar-dynamical processes resulting from runaway-collisions either in stellar clusters or clusters of stellar-mass black holes.

The direct collapse seemed initially very promising, due to its capacity of producing very high-mass seeds with up to  $10^5 M_{\odot}$  (e.g. Bromm & Loeb 2003; Wise

et al. 2008; Schleicher et al. 2010; Latif et al. 2013, 2014). However, to reach the required conditions, the collapse should basically be isothermal under atomic cooling, requiring very large ambient UV fluxes (Latif et al. 2015). On the other hand, even tiny amounts of dust can already trigger strong fragmentation through the enhanced cooling (e.g. Omukai et al. 2008; Dopcke et al. 2011; Klessen et al. 2012; Bovino et al. 2016; Latif et al. 2016).

Under realistic conditions, it is then almost unavoidable for fragmentation to occur, at least initially preventing the formation of a single massive object. However, also star clusters can produce massive black holes by collisions, as discussed e.g. by Devecchi et al. (2012); Sakurai et al. (2017), showing that black holes of  $\sim 500 M_{\odot}$  are able to form. It has been established over the last years that the radii of primordial protostars can be considerably enhanced while accreting, thereby effectively behaving like red giants (Hosokawa et al. 2013; Haemmerlé et al. 2018). As known already from present-

day protostellar clusters (Baumgardt & Klessen 2011), such an enhancement of the protostellar radii increases the probability for collisions, and may favor the formation of massive objects. In the context of primordial stellar clusters, Reinoso et al. (2018) recently explored the implications of such enhanced radii for the collisions, showing that indeed both the fraction of collisions as well as the mass of the central massive object, increases significantly with protostellar radii. They also provide scaling relations that allow to infer the black hole mass as a function of the ambient condition.

The presence of gas in the first proto-cluster may have further implications. Firstly, it provides an additional gravitational potential, which enhances the velocity dispersion of the embedded stellar cluster. Secondly, the protostars may accrete and change their masses during the run-time of the simulations. The interaction between gas-dynamical and stellar-dynamical processes may thus be quite relevant for the formation of very massive objects in the first stellar clusters, however, it has hardly been considered so far. In the following, we present a set of simulations performed with the publicly available AMUSE framework\* (Pelupessy et al. 2013) to approximately account for such effects. A more detailed description of the simulations has been presented by Boekholt et al. (2018).

## 2. Numerical setup

We adopt here a simplified initial condition, where both protostars and the gas follow a Plummer distribution (Plummer 1911). In our reference model, the initial gas mass corresponds to  $10^5 M_{\odot}$ , the Plummer radius is 0.1 pc and the initial number of stars is 256, with very low masses of initially  $0.1 M_{\odot}$ . The system is thus initially gas-dominated. We also introduce a cut-off radius after which the density is set to zero. The latter corresponds to five times the Plummer radius. The gravitational interaction between the stars is modeled via the N-body code PH4 by McMillan & Hut (1996), using a fourth-order Hermite algorithm by employing the time-symmetric integration scheme developed by Hut et al. (1995). The gravitational potential of the gas cloud is described as an analytic background potential, which is coupled to the stars using the BRIDGE method (Fujii et al. 2007).

The accretion of the gas onto the stars is described by the simplified models outlined in Table 1 (Boekholt et al. 2018). Models with an infinite gas reservoir indicate that the gas is efficiently resupplied during the evolution, so that gas accreted onto the protostars is not removed from the gas (models 1-2), while it is removed in the models with a finite gas reservoir (models 3-6). In case of position-dependent accretion, we assume that the accretion rate is proportional to the gas density in the Plummer sphere. If the accretion rate is also time-dependent, we assume it to be proportional to the mass in the gas reservoir. In models 3-6, the accretion is switched off when the gas reservoir is exhausted. Our fiducial accretion rate is  $0.03 M_{\odot} \text{ yr}^{-1}$ ,

Model	Gas reservoir	Position dep. accretion	Time dep. accretion
1	Infinite	no	no
2	Infinite	yes	no
3	Finite	no	no
4	Finite	yes	no
5	Finite	no	yes
6	Finite	yes	yes

Table 1: The gas accretion models for Pop. III protostars embedded in their natal gas cloud, as presented by Boekholt et al. (2018).

as suggested through numerical simulations (e.g. Latif et al. 2013, 2014), but we also explored other values.

The stellar radii have been determined using approximate fits to the mass-radius relations given by Hosokawa et al. (2013) and Haemmerlé et al. (2018), where both prescriptions yield similar results. To model collisions, we adopt the so-called "sticky-sphere" approximation, replacing two protostars by one if the distance between two protostars becomes less than their radii. During the collision, we assume the conservation of mass, and the new radius is determined from the mass-radius parametrization. Using this setup, we follow the evolution of the system until no further collisions occur. The latter usually corresponds to a physical time of less than one million years.

## 3. Results

The results for our fiducial parameters, providing the time evolution of the mass of the most massive central object, are presented in Fig. 1 for the different accretion models (Boekholt et al. 2018). Clearly, the most optimistic models are models 1 and 2 with an infinite gas reservoir, so that the central mass can continue to grow unimpededly. Such a scenario is only feasible in case of a strong external mass supply, which needs to be transported through the protogalaxy, for instance as a result of gravitational torques. In case the gas reservoir is finite, the mass of the resulting object is lower by a factor of 2 or 3. The most conservative model with respect to the black hole mass is our model 5, with the finite gas reservoir and a time-dependent accretion rate, which is however independent of position. In this case, large fractions of the mass are accreted in the outer parts of the cluster, where they do not strongly participate in collision events. As a result, they do not contribute to the mass of the most massive object. Nevertheless, even in the most conservative scenario, the central object reaches a mass of  $10^4 M_{\odot}$ .

We have checked the dependence of these results on various parameters, as presented in detail by Boekholt et al. (2018). We found that the most crucial parameter is the initial gas reservoir. In case a gas mass of  $10^5 M_{\odot}$  is available, the results only weakly depend on other parameters, but the mass of the central massive object decreases significantly if less gas is available. The size of the cluster as well as the accretion rate, on the other hand, were found to be of minor relevance and to

\*Webpage AMUSE: <http://amusecode.org/>

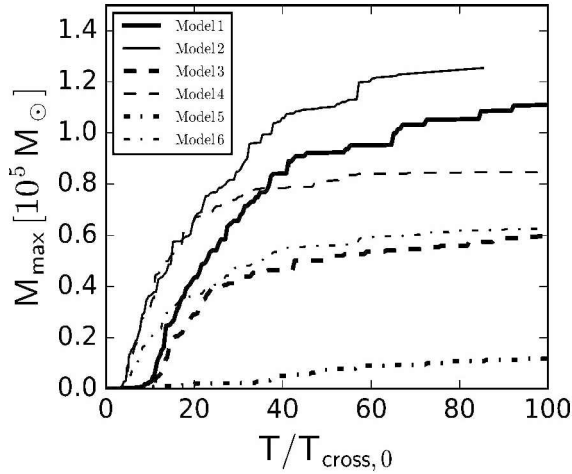


Figure 1: Time evolution of the most massive object mass. Shown are the results for the six different accretion models given in Table 1. Figure from Boekholt et al. (2018).

primarily affect the timescale until the process is completed. Therefore, the model has the advantage to potentially be robust, at least under conditions where a sufficiently large gas masses are available for accretion.

#### 4. Summary and discussion

We find that our scenario provides a potentially promising pathway for the formation of very massive black holes, with masses between  $10^4$  and  $10^5 M_{\odot}$ . Our gas-dynamical model, however, is still based on highly simplifying assumptions, considering an analytic gravitational potential and very simple prescriptions for the accretion of the protostars. For the future, it will be central to gradually relax some of the assumptions, and to explore how a detailed dynamical treatment of the gas and the accretion will affect the results. Additional uncertainties concern the geometry of the star and gas distribution, which was here assumed to be spherical. Numerical simulations frequently suggest that fragmentation will occur preferentially in flattened geometries including rotation. The presence of such an ordered velocity component could potentially somewhat alter the results presented here, as collisions may become less likely in such a case. On the other hand, the presence of gas is also expected to lead to dynamical friction, which we neglected in the simulations presented here. Such friction could further affect the motions of the stars and increase the probability of collisions.

As semi-analytic models indeed suggest that massive seeds are needed to form supermassive black holes (Valiante et al. 2016), it will be important to explore realistic formation scenarios.

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