# Growth of Seed Black Holes in Galactic Nuclei

### (NIC project chhd32, using Juwels GPU)

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## 1. Growth of Seed Black Holes

How do the massive black holes in galactic centers grow to their observed sizes, and from what mass range are their progenitors drawn? We are examining the growth of stellar-mass seed black holes into larger compact objects through runaway tidal capture (or tidal disruption, see Stone, Küpper & Ostriker, 2017, and earlier ideas in that direction by Miller & Davies, 2012) in the dense core of a nuclear star cluster (NSC). This pathway for intermediate mass black hole (IMBH) formation is a more recent, and more plausible, variant of runaway growth scenarios proposed in the past. Understanding the star cluster conditions required to form IMBHs is of great astrophysical importance, both at high and low redshift. If tidal capture runaways occur in the first galaxies (in the early universe at high redshifts z), then it is straightforward to explain the surprisingly large central supermassive black hole masses (>109 M☉) of quasars at such early times. (We note, however, that this explanation requires super-Eddington mass growth of the stellar-mass seed black holes). On the other hand, many NSCs at low redshifts, in our "local" universe may be dense and/or compact enough to be unstable to tidal capture runaways, and this process may set the bottom end of the nuclear black hole mass function.

Related IMBH formation scenarios that have received greater attention include

- (i) formation of a supermassive star through runaway collisions of main sequence stars, and the subsequent collapse (through GR instability) of the supermassive star into an IMBH (cf. e.g. Freitag, Gürkan & Rasio 2006; Gürkan, Fregeau & Rasio 2006); and
- (ii) direct formation of an IMBH through repeated and hierarchical mergers of stellar-mass black holes (cf. e.g. Davis, Miller & Bellovary 2011).

Compared to scenario (i), the tidal capture runaway we investigating requires less extreme cluster core dens (because the runaway does not need to occur in an upper n sequence lifetime of order $10^6$ yr), and also does not req extremely low-metallicity environments (as mode metallicities likely result in upper main sequence me products ``boiling away" through line-driven winds, leaving n much less massive remnants, see e.g.Glebbeek et al. 20 Furthermore, the tidal capture cross-section is larger than for direct star-star collisions.

Compared to scenario (ii), the tidal capture seems more rob since it requires lower cluster velocity dispersions (say < km/s). Gravitational Wave recoils of merging stellar mass b holes produce recoil kicks which may prevent the retentio black hole-black hole merger products; this threshold is even higher if black holes are born with high spins. But the presence of many initial (``primordial") stellar binaries and multiples may change the picture again, since close few-body encounter produce non-aligned black hole spins and increase the black hole retention rate. The core density threshold for a tidal capture runaway mayalso be lower than that for runaway compact object mergers, though this depends somewhat on the issue of compact object binarity, and therefore the uncertain subject of natal kicks.

It is therefore clear that the cluster conditions required for a tidal capture runaway are less fine-tuned than those required for other types of runaway IMBH formation, as they will occur in more loosely bound clusters with lower stellar densities. Our direct N-body models in the upcoming project period of the tidal capture runaway will, however, also be able to follow relativistic black hole mergers and help us to distinguish the critical NSC parameters, which favour tidal capture runaway or runaway relativistic mergers. We have done in the past period preliminary studies with smaller star clusters and improved stellar evolution parameters, to understand the critical conditions and parameters which support IMBH growth (Rizzuto et al. 2020, in preparation) .

At the extremely high stellar densities of up to $10^5$ $M_{\odot}/pc^3$ the evolution of stars becomes extremely complex. They evolve in time into e.g. red giants, white dwarfs, neutron stars or black holes. At any evolutionary stage they can form binaries, experience close gravitational interactions, mass overflow, or even physical collisions on extremely small spatial and temporal scales. Therefore the accurate modeling of stellar or stellar remnants orbits and the evolution of GCs as a whole is highly complex and a challenge for high-performance computations (Fig. 1). We have implemented current updated stellar evolution prescriptions in our N-body simulation code (Banerjee et al. 2019).

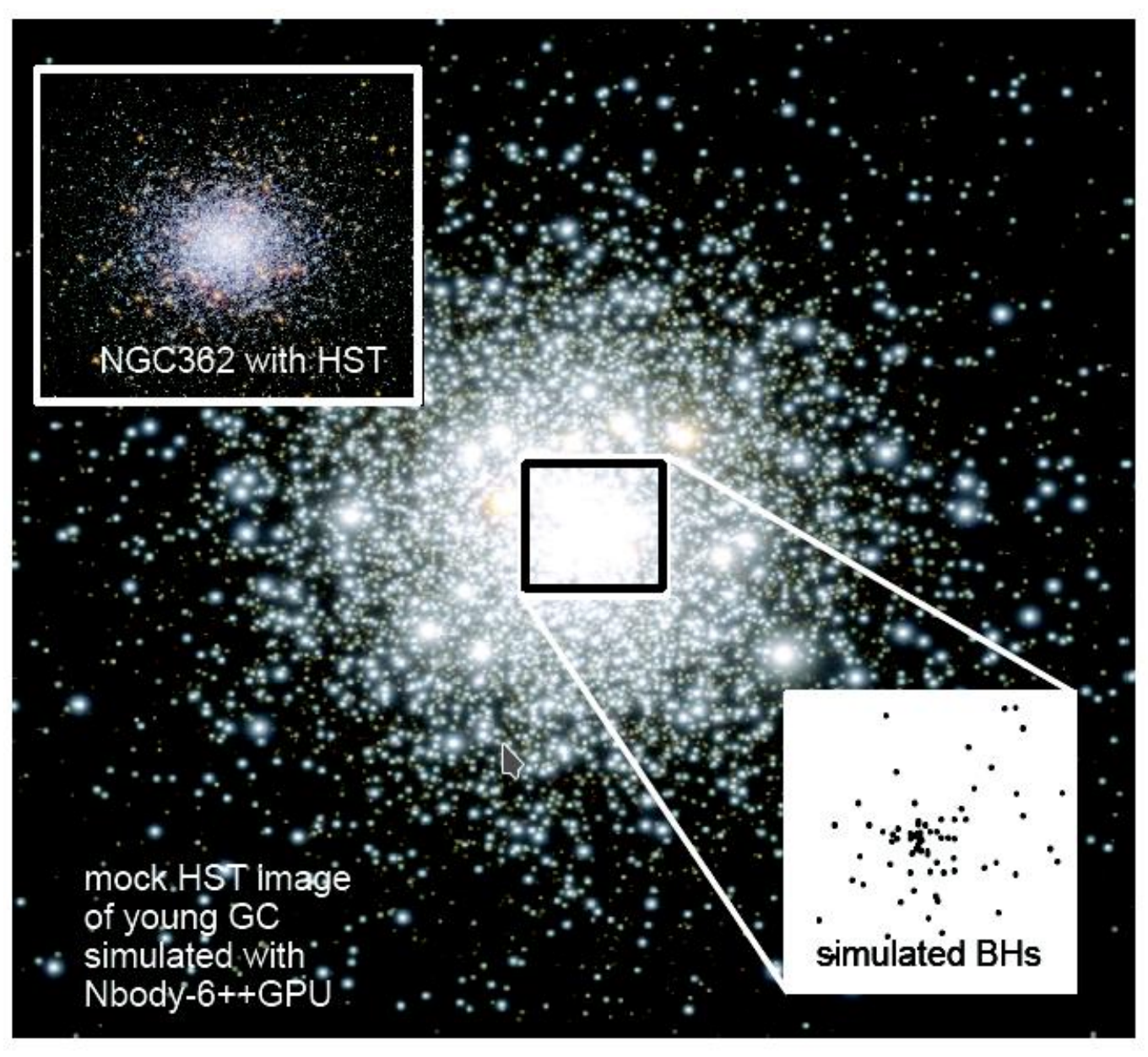

Fig 1: Simulated young globular cluster in comparison with HST observations of the old GC NGC 362. The inset show the simulated BH population in the nucleus, which is not directly observable. Here stellar mass BHs can grow by mergers to IMBHs.

## 2. Direct N-Body Code – scaling and facilities used

We use one main application code (NBODY6++GPU) in production, which has been carefully benchmarked and tested in a massively parallel version using multiple GPUs (typically one GPU per MPI process). The code uses a 4th order Hermite integration scheme and hierarchical block time steps. It also uses MPI parallelization and GPU acceleration (typically for long-distance forces) as well as OpenMP for multi-core on the CPU (for short and intermediate range forces). It is written in Fortran77 (NBODY6++) with MPI and CUDA extensions.

The strong scaling of the gravity calculation and the typical performance for V100 in comparison to older systems is shown in Fig. 2 for the older K20 systems. We use one main application codes (NBODY6++/GPU) in production, which have been carefully benchmarked and tested in a massively parallel version using multiple GPUs (typically one GPU per MPI process). The code use a 4th order Hermite integration scheme and hierarchical block time steps. It also uses MPI parallelization and GPU acceleration (typically for long-distance forces) as well as OpenMP for multi-core on the CPU (for short and intermediate range forces). It is written in Fortran77 (NBODY6++) with MPI and CUDA extensions.

Part of our simulations were executed on the Freya and COBRA systems (Fig. 2) of Max Planck Computing & Data Facility (MPCDF) in Garching with Kepler K20 and Volta V100 GPUs, and some pilot models on Juwels GPU. The strong scaling of the gravity calculation and the typical performance for V100 in comparison to older systems is shown in Fig. 2 for the older K20 systems.

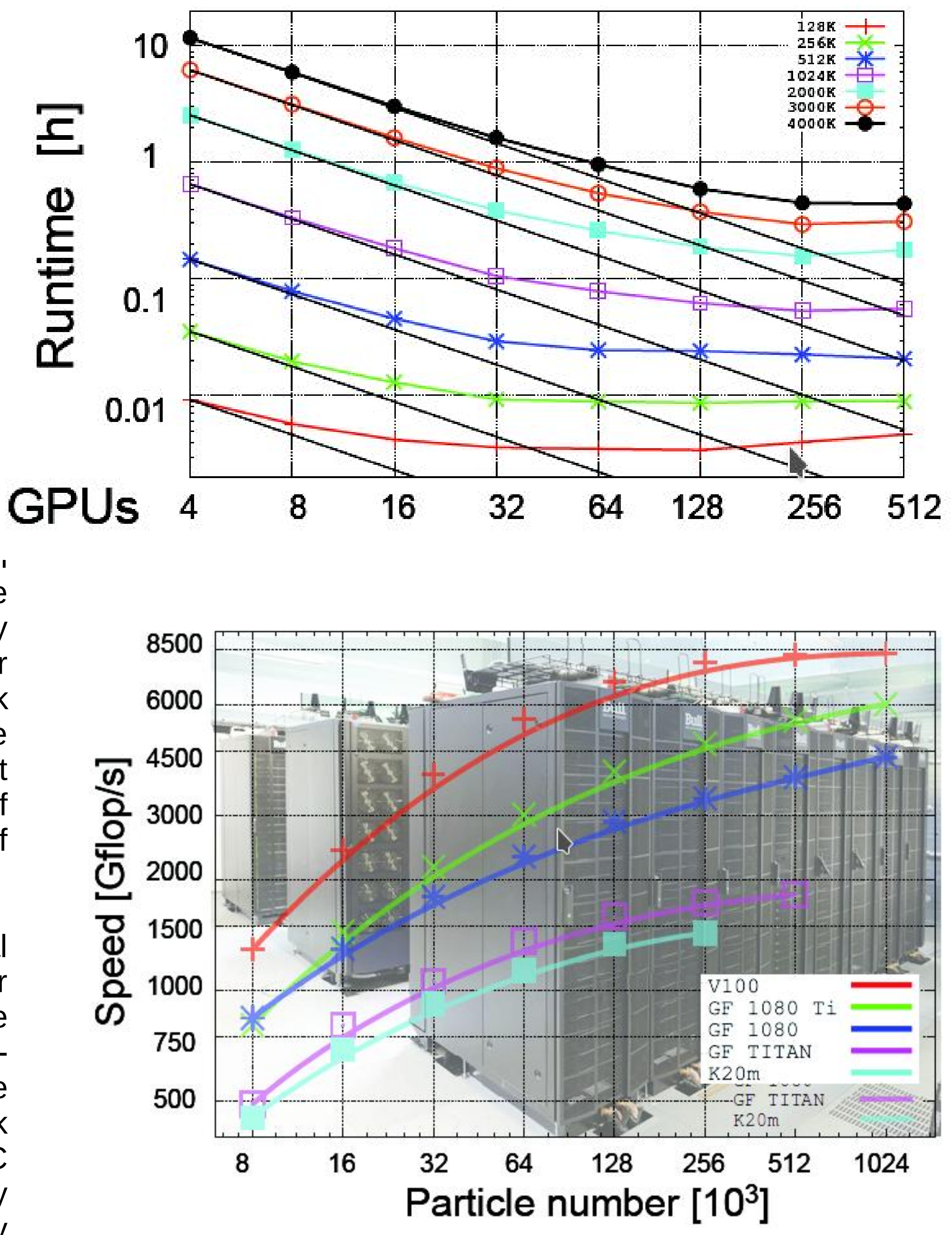

Fig. 2: **Top:** Strong scaling forP100 (Pascal) on Piz Daint.
**Bottom:** Single GPU performance of the gravity calculation for GeForce, Kepler K20, and Volta V100 GPUs for different particle numbers. A mixed precision scheme allows for higher than the max. 7.5 Tflop/s V100 double precision performance.
**Background:** the MPCDF Cobra system.

***Some References:***

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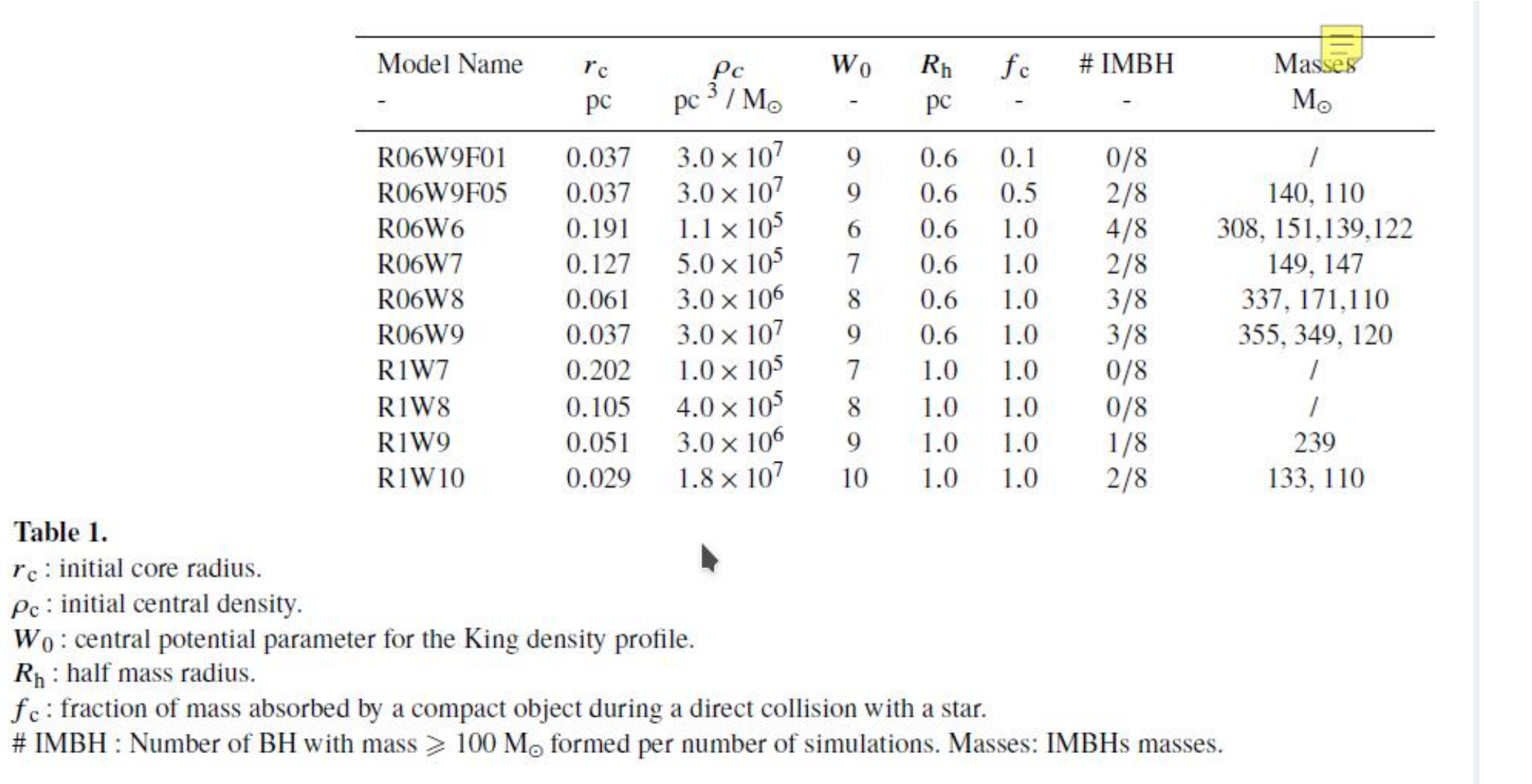
## 3. Preliminary Results – formation of IMBH

The aim of our project is to investigate the possible formation of intermediate mass black holes in dense nuclear and globular star clusters. In order to do that we use NBODY6++/GPU to simulate several GCs realization with different initial conditions (such as density concentration etc..) .

In our pilot study we have studied smaller star clusters (100k particles, instead of the targeted million body), with eight different initial models regarding central density and concentration parameter, and a variation of the fraction of mass absorbed by a compact object (black hole) in a direct collision with a normal star. The last is a completely new investigation not been done before in this kind of N-body simulations and it affects the formation of IMBH. The figures and data are preliminary and taken from Rizzuto et al. (2020, in preparation).

The Table below shows the maximum mass of an IMBH formed after 100 Myr; the Figures 3 and 4 below details (for one example)how such an object has evolved in the star cluster – by binary evolution, collisions and mergers. Note that in some cases the IMBH is ejected by energetic few-body collisions.



| Model Name | $r_c$ | $\rho_c$ | $W_0$ | $R_h$ | $f_c$ | # IMBH | Masses |
|---|---|---|---|---|---|---|---|
| - | pc | pc $^3$ / M$_{\odot}$ | - | pc | - | - | M$_{\odot}$ |
| R06W9F01 | 0.037 | $3.0 \times 10^7$ | 9 | 0.6 | 0.1 | 0/8 | / |
| R06W9F05 | 0.037 | $3.0 \times 10^7$ | 9 | 0.6 | 0.5 | 2/8 | 140, 110 |
| R06W6 | 0.191 | $1.1 \times 10^5$ | 6 | 0.6 | 1.0 | 4/8 | 308, 151,139,122 |
| R06W7 | 0.127 | $5.0 \times 10^5$ | 7 | 0.6 | 1.0 | 2/8 | 149, 147 |
| R06W8 | 0.061 | $3.0 \times 10^6$ | 8 | 0.6 | 1.0 | 3/8 | 337, 171,110 |
| R06W9 | 0.037 | $3.0 \times 10^7$ | 9 | 0.6 | 1.0 | 3/8 | 355, 349, 120 |
| R1W7 | 0.202 | $1.0 \times 10^5$ | 7 | 1.0 | 1.0 | 0/8 | / |
| R1W8 | 0.105 | $4.0 \times 10^5$ | 8 | 1.0 | 1.0 | 0/8 | / |
| R1W9 | 0.051 | $3.0 \times 10^6$ | 9 | 1.0 | 1.0 | 1/8 | 239 |
| R1W10 | 0.029 | $1.8 \times 10^7$ | 10 | 1.0 | 1.0 | 2/8 | 133, 110 |

**Table 1.**
$r_c$ : initial core radius.
$\rho_c$ : initial central density.
$W_0$ : central potential parameter for the King density profile.
$R_h$ : half mass radius.
$f_c$ : fraction of mass absorbed by a compact object during a direct collision with a star.
# IMBH : Number of BH with mass $\geqslant 100$ M$_{\odot}$ formed per number of simulations. Masses: IMBHs masses.

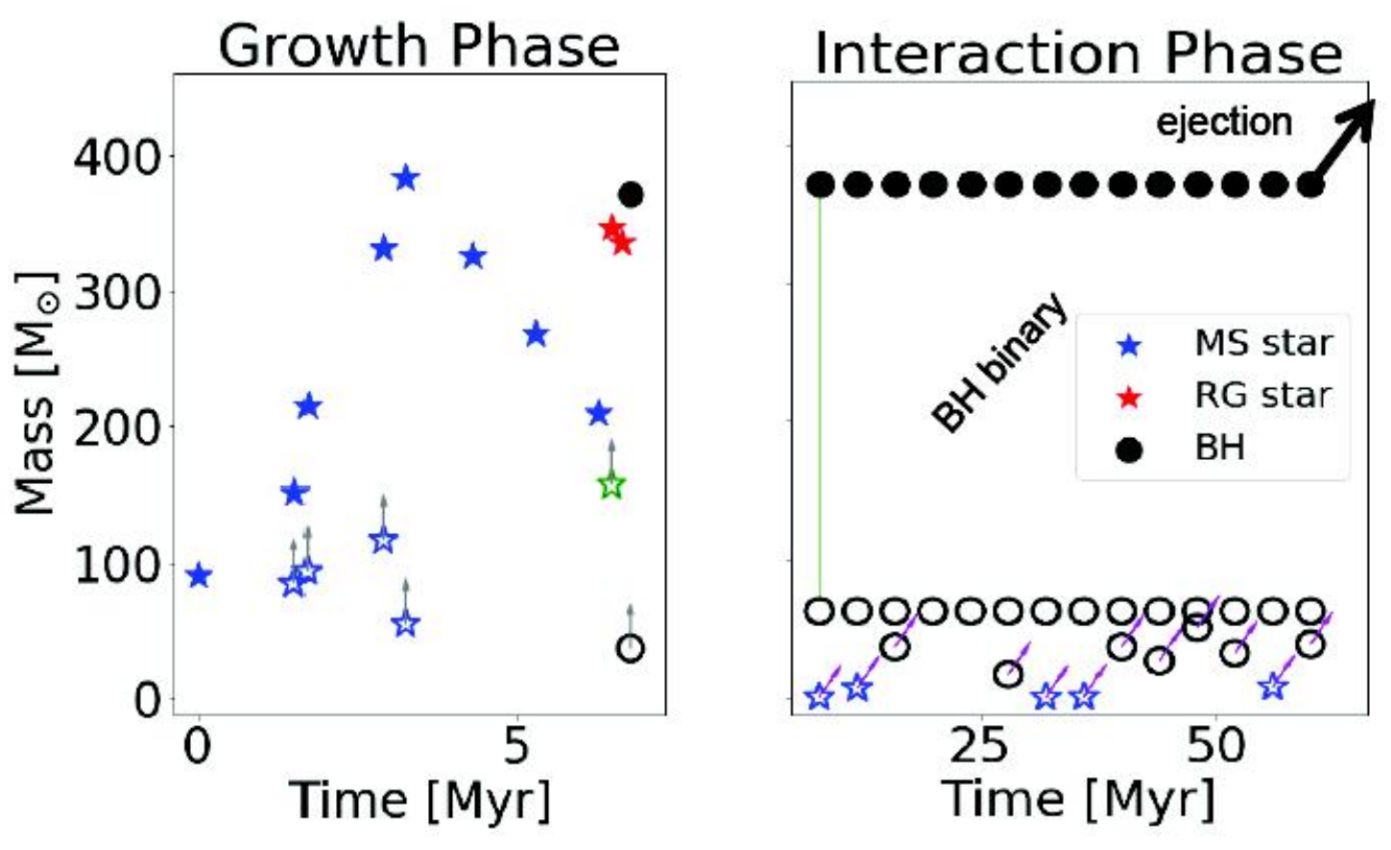


Fig. 3: Evolution of the most massive object (filled symbols) in a GC simulation with $10^5$ stars. A massive main sequence star (MS, blue) grows by mergers (upward arrows) with other MS stars and evolves into a red giant (RG, red) and a ~ 380 $M_{\odot}$IMBH after merging with a 50 $M_{\odot}$ BH (left panel). Then the IMBH forms a BH binary (green line) and interacts (diagonal arrows) with other BHs and MS stars. At the end of the interaction phase the BH is kicked out (right panel).

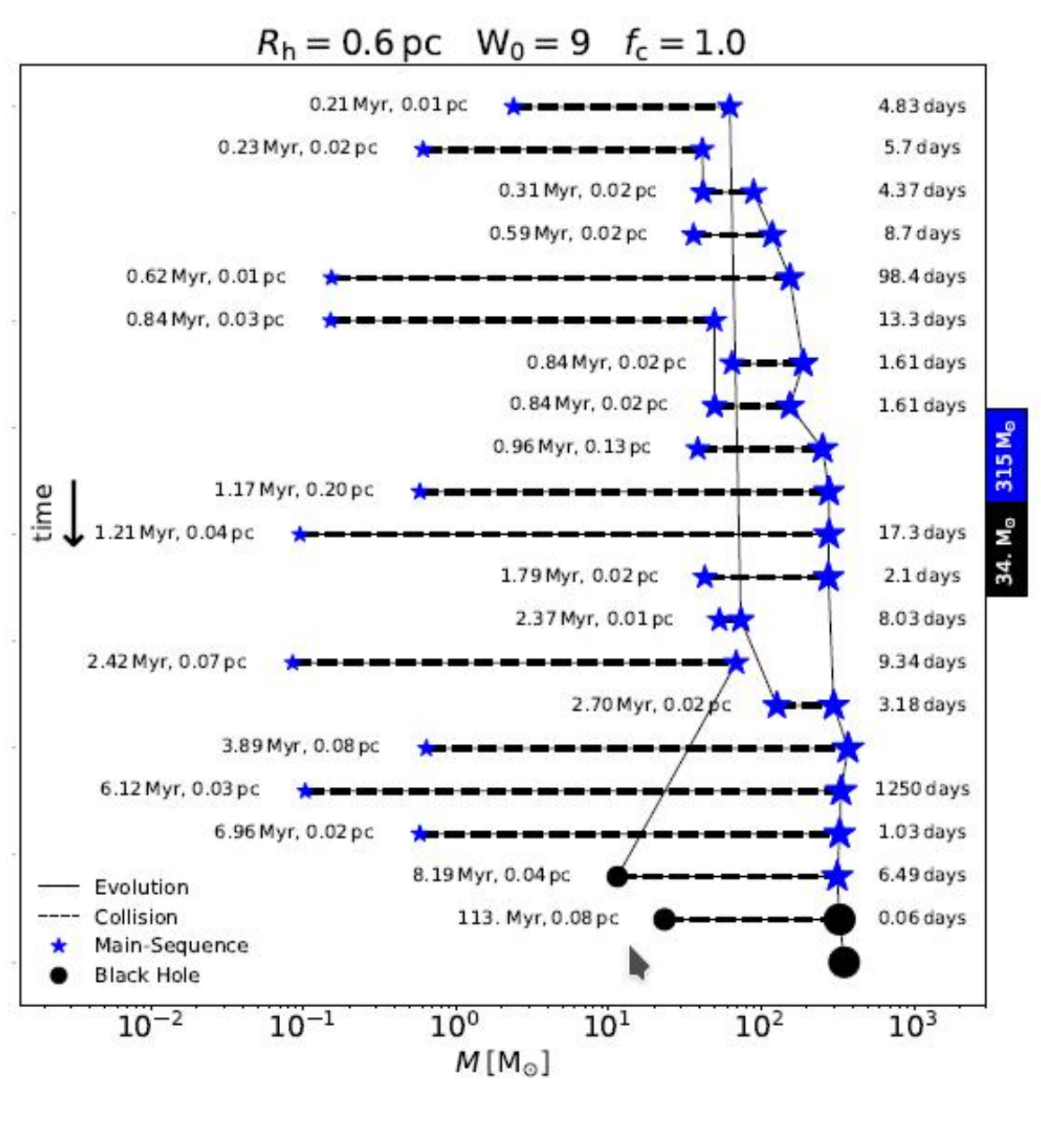


**Figure 4.** Formation and evolution of an IMBH in a simulation with $W_0 = 9$, $R_h = 0.6$ pc and $f_c = 1.0$ . A massive main-sequence star (MS, blue) grows by mergers (dashed horizontal lines) with other MS stars and evolves into ≈ 300 $M_{\odot}$ IMBH colliding with a 10 $M_{\odot}$ BH. At about 113 Myr the IMBH collide with an other BH. The two values to the left of each collision event show when and where the merger occurred. If the two colliding objects formed a binary before the coalescence the plot indicates the period and the semi-major axes. No period indicates the coalescence was hyperbolic.

## 3. Preliminary Conclusions

It is possible to form intermediate mass black holes (IMBH) in high density star clusters, and it has been shown by our direct N-body simulations. Results are preliminary in the sense that simulations are short (only few 100 Myr) and of small star clusters (100k) – with the planned project we will be able to confirm the scenario for longer times (several Gyrs) and realistic large and hot star clusters (million body). These scenarios of IMBH formation have been predicted by approximate Monte Carlo models already (MOCCA, see e.g. Morawski et al. 2018), and we hope we can confirm them in the detailed and more accurate direct N-body model.

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