News from Black Holes in Star Clusters simulated with large GPU clusters

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1. Globular Clusters & Intermediate Mass Black Holes

Globular clusters (GCs) are the oldest and densest gravitationally bound stellar systems with $10^4 - 10^6$ stars. The Milky Way contains at least 150 GCs which are distributed in a nearly spherical halo around the galactic center. GCs are found in galaxies of all types from dwarfs to the largest early-type galaxies.

At the extreme densities of up to $10^5\ M_\odot/pc^3$ the orbits of stars become highly complex. The stars evolve 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).

Modern observations have revealed the properties of GCs at unprecedented detail, shedding new light on the physics of these enigmatic astronomical objects. The discovery of gravitational waves from merging black holes of several tens of solar masses have moved GCs into the focus of astrophysical research. They provide perfect conditions for the formation of black hole binaries and subsequent mergers of the black holes.

GCs might even be the formation sites of intermediate-mass black holes (IMBHs) with several hundred to several ten thousand solar masses by merger driven black hole growth. Some recent observations seem to provide strong hints for their existence. However, their formation mechanism are unclear. The repeated collision of stellar mass black holes and other compact objects in extremely dense star clusters is one possible formation scenarios for IMBHs.

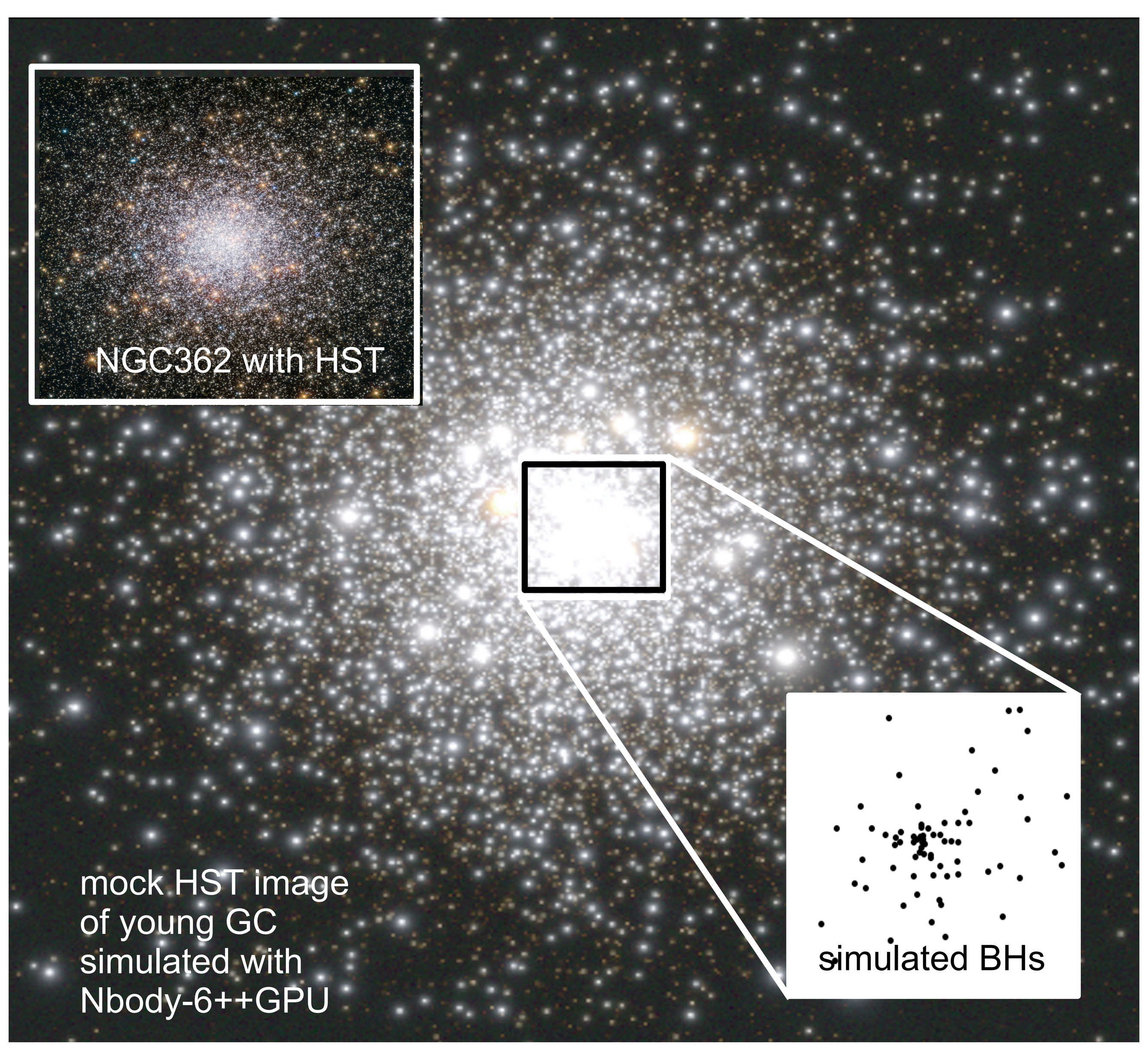

Fig 1: Simulated young globular cluster in comparison with HST observations of the old GC NGC 362. The inset show the simulated BH population in the nucleus, which is not directly observable. Here stellar mass BHs can grow by mergers to IMBHs.

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Wang, L., Spurzem, R., Aarseth, S., Giersz, M., Askar, A., Berczik, P., Naab, T., Schadow, R., Kouwenhoven, M. B. N., The DRAGON simulations: globular cluster evolution with a million stars, 2016, MNRAS, 458, 1450

Wang, L., Spurzem, R., Aarseth, S., Nitadori, K., Berczik, P., Kouwenhoven, M. B. N., Naab, T., NBODY6++GPU: ready for the gravitational million-body problem, 2015, MNRAS, 450, 4070

2. NBODY6++GPU & performance

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.,

All production runs are executed on the COBRA system (Fig. 2) of the Max Planck Computing & Data Facility (MPCDF) in Garching. The hardware configuration of this supercomputer provides to the users 64 nodes for parallel GPU computing. Each node has a total of 40 CPU cores (with Intel Skylake CPUs @ 2.4 GHz), 192 GB RAM per node, and is equipped with two NVIDIA Tesla V100-PCIE-32GB GPUs (Volta). Smaller runs are performed on the Max-Planck-Institute for Astrophysics system Freya (hosted by MPCDF) with 8 Skylake nodes with 16 Nvidia Tesla P100-PCIE-16GB GPUs and 4 Skylake nodes with 8 Nvidia Tesla V100-PCIE-32GB GPs. 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.

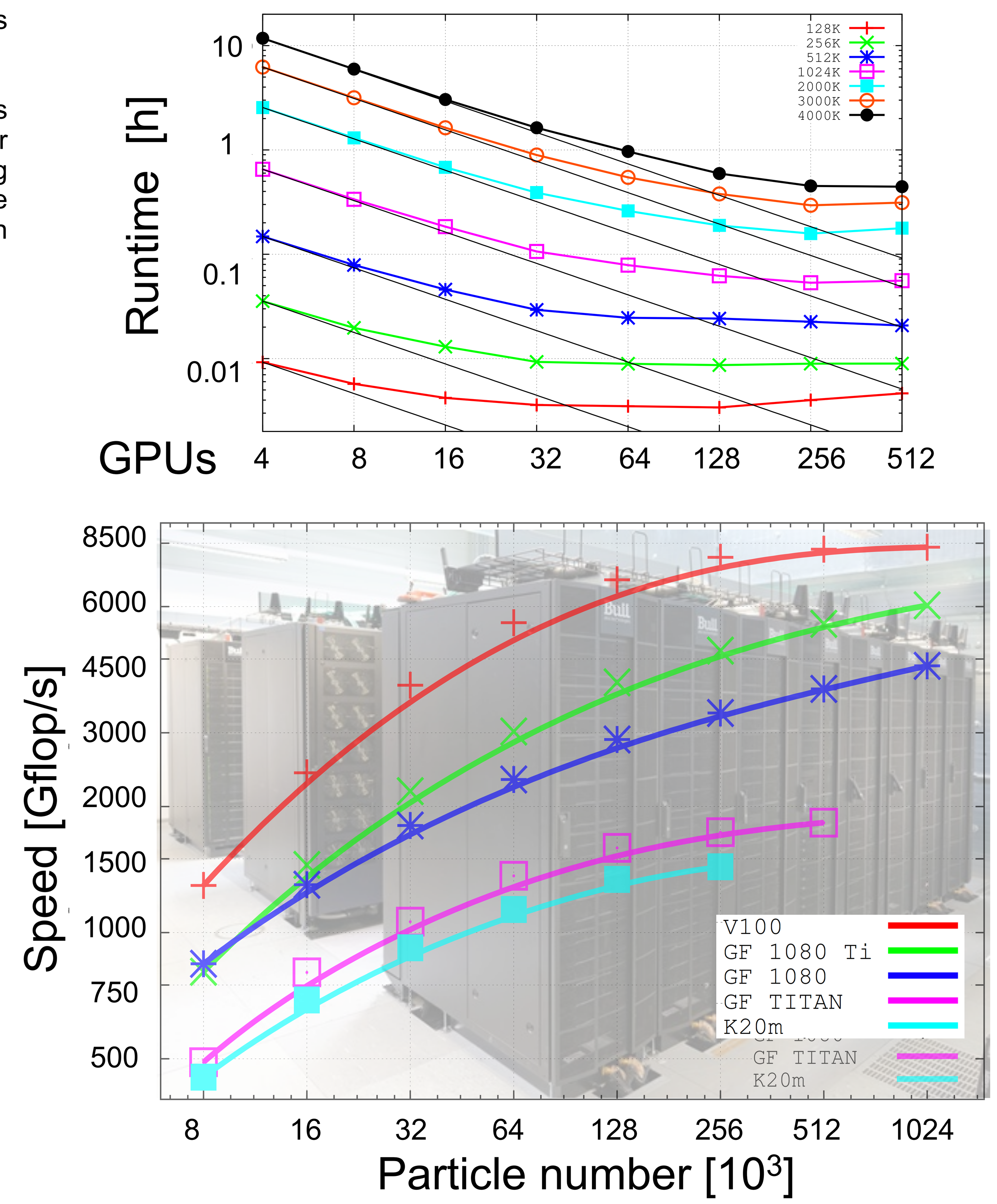

Fig. 2: *Top:* Strong scaling forP100 (Pascal) on Piz Daint. *Bottom:* Single GPU performance of the gravity calculation for GeForce, Kepler K20, and Volta V100 GPUs for different particle numbers. A mixed precision scheme allows for higher than the max. 7.5 Tflop/s V100 double precision performance. Background: the MPCDF Cobra system with128 Volta GPUs used for production runs.

3. Direct simulations of black hole growth by mergers in GCs

We use Nbody++GPU to simulate the evolution of GCs with up to 10^6 individual stars with initial masses in the range of 0.08 to 100 solar masses. The computations are performed with 8 V100 GPUs (Volta). From the beginning of the simulation, highly complex interactions and mergers between massive stars and BHs result in the rapid formation of IMBHs with several hundred solar masses. The growth phase is followed by an interaction phase with the formation of binaries and many-body encounters with stars and other black holes. After several tens of Myr the IMBH candidates are typically kicked out of the cluster and only solar mass black holes remain.

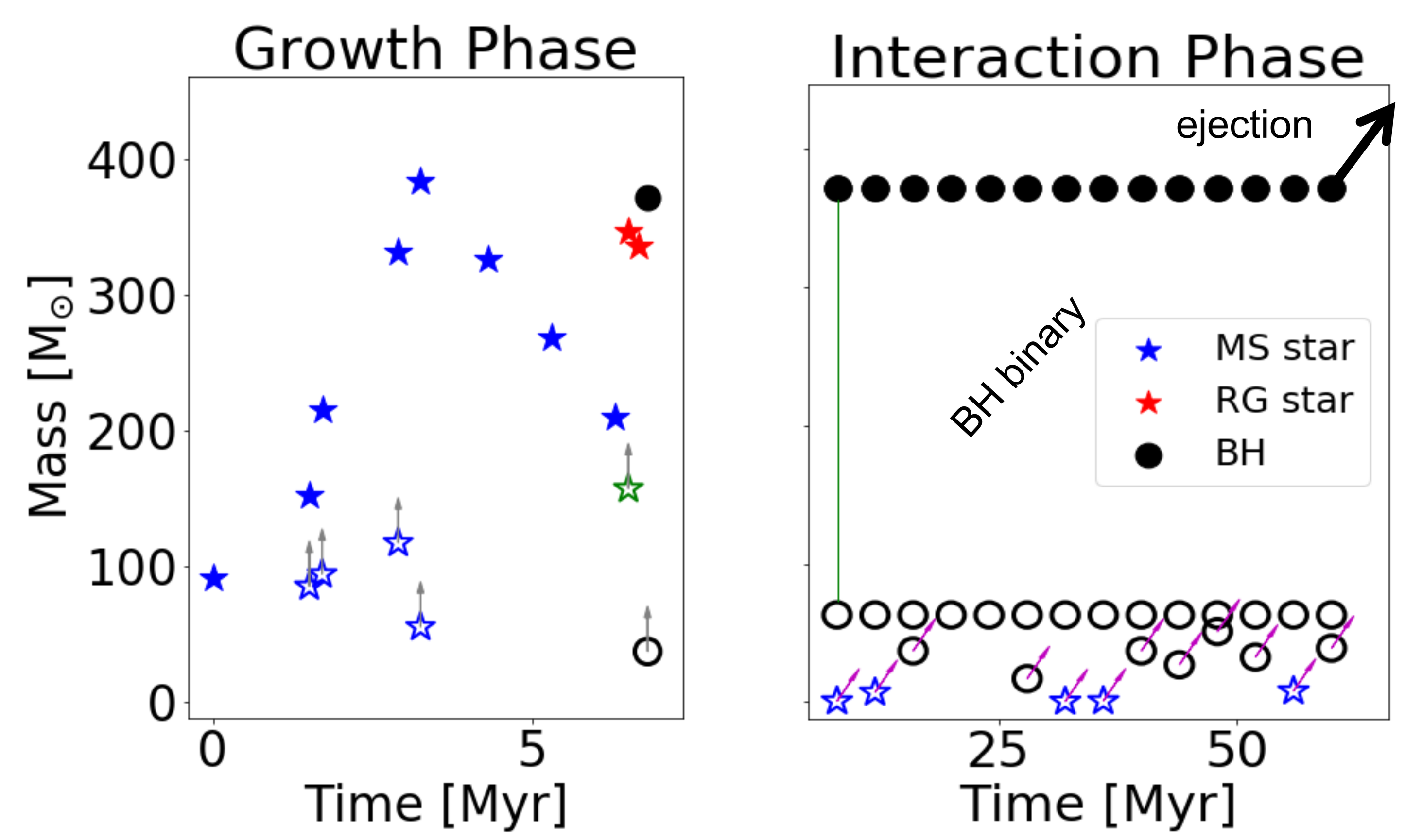

Fig. 3: Evolution of the most massive object (filled symbols) in a GC simulation with 10^5 stars. A massive main sequence star (MS, blue) grows by mergers (upward arrows) with other MS stars and evolves into a red giant (RG, red) and a ~ 380 $M_\odot$ IMBH after merging with a 50 $M_\odot$ BH (left panel). 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).

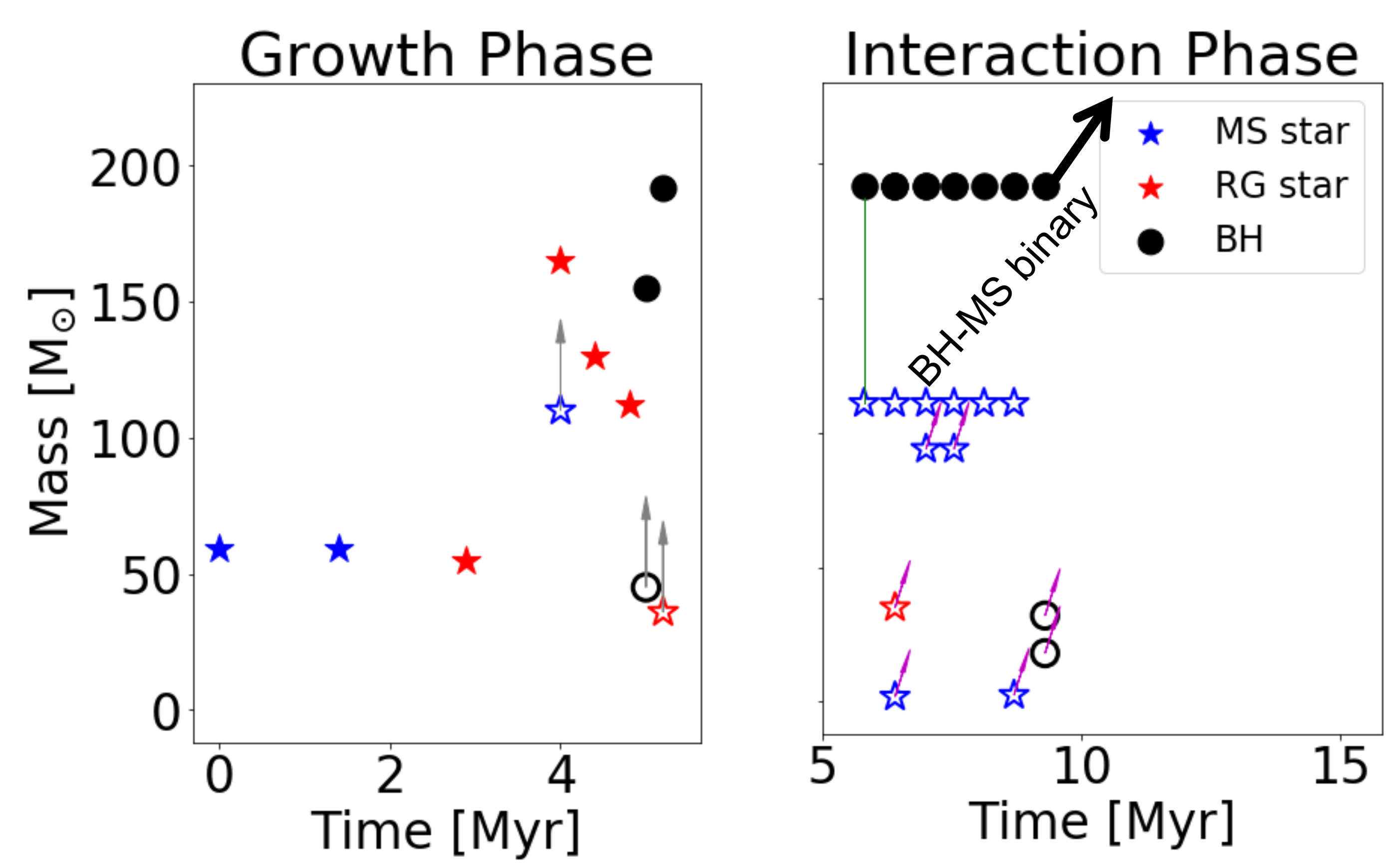

Fig. 4: Same as Fig. 3 for a massive star evolving into a lower mass IMBH in the growth phase (left panek) and forms a binary with a MS star before it is kicked out (right panel).

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