New IMBH formation scenario in dense star clusters

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Outline

1. IMBH - Formation Theories
2. IMBH - Observations
3. The new Scenario for IMBH Formation
4. Conclusions

Theory - IMBH formation processes

IMBH - formation processes

- Direct collapse of very massive first generation stars, Population III stars (Madau & Rees 2001);
- Runaway merging in dense young star clusters (Portegies Zwart et al. 2004, Gürkan et al. 2004, Freitag et al. 2006);
- The most massive globular clusters are probably stripped cores of dwarf galaxies and therefore also more likely to host central black holes - relation between BH mass and the system mass hosting BH;
- Accretion of the residual gas on stellar mass BHs formed from the first generation stars (Leigh et al. 2013);
- Slow buildup of BH mass due to mergers in dynamical interactions and mass transfer in binaries (Giersz, Leigh & Hypki in preparation). .

Theory - Direct collapse of Population III stars

- The very first generation of stars must have formed out of unmagnetized, metal-free gas (Madau & Rees 2001);
- The Population III stars are fromed with IMF extremely top heavy. Stars with masses larger than $200 - 300 M_{\odot}$ can be formed;
- Stars were formed at so called minihalos of mass about $10^5 M_{\odot}$ at redshift about 20;
- After a few Myr of evolution the most massive Population III stars will end up as a IMBH of masses larger than $150 - 200 M_{\odot}$, loosing only small fraction of mass (Fryer et al. 2001);
- There are doubts how such extremely massive BH could become members of GC consisting of Population II stars?

Theory - Runaway merging

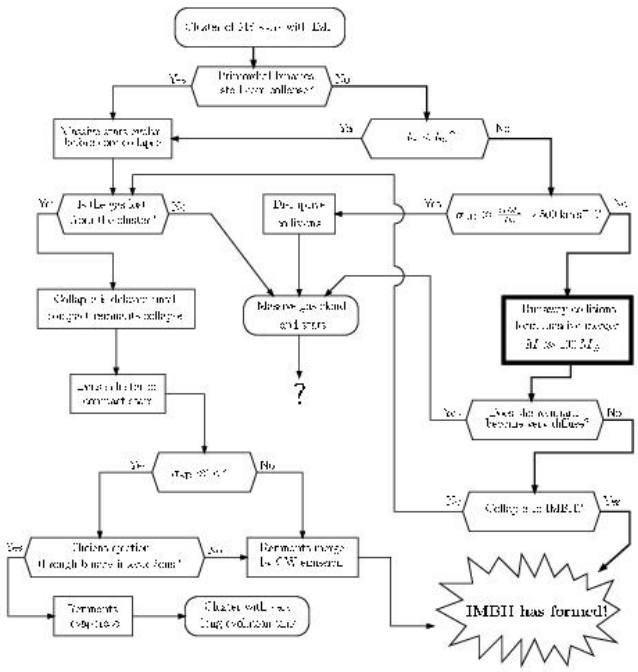
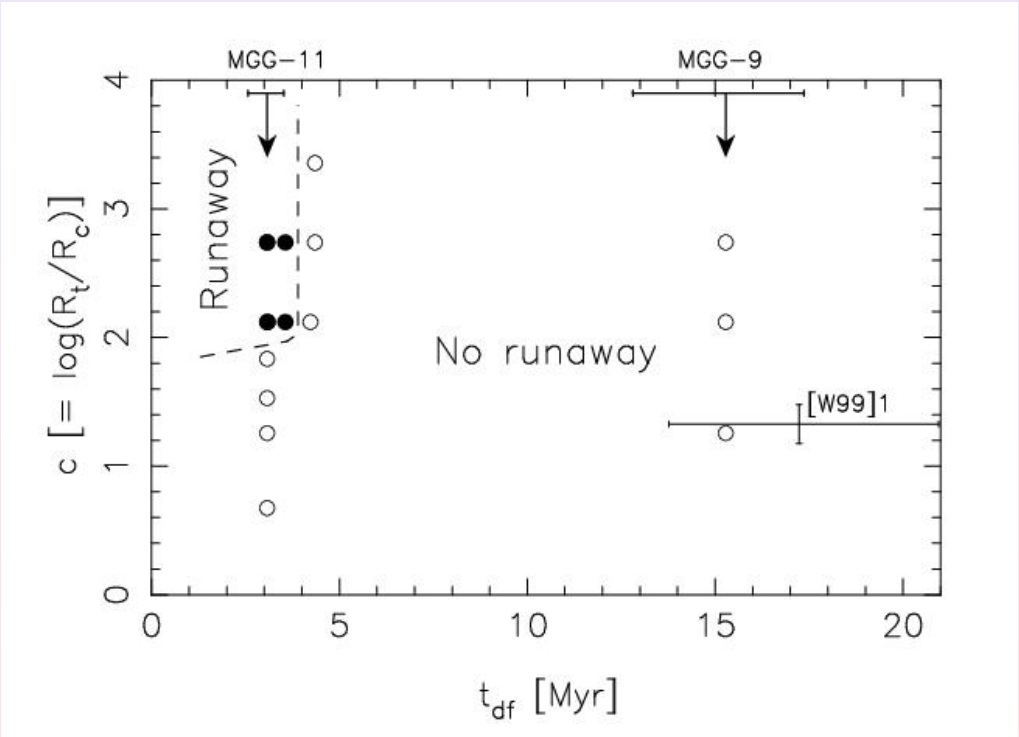


FIG. 1.—Various possible scenarios for the early dynamical evolution of a dense star cluster with a realistic IMF. The path for the formation of an IMBH through core collapse and runaway collisions (studied in this paper) is indicated by a thicker line. An alternative scenario involves successive mergers of stellar-mass BH binaries driven by a combination of dynamical interactions and gravitational radiation (*left*). For a runaway to occur, the core-collapse time t_{cc} must be smaller than the stellar lifetime t_* of the most massive stars in the cluster. High-velocity disruptive collisions, the formation of a very extended and diffuse merger remnant, or the accumulation in the cluster of gas released by stellar winds and supernova explosions could lead to the formation of a complex system containing stars embedded in dense gas clouds. The final fate of such a system is highly uncertain.

- Time scale of the mass segregation of the most massive stars (about $100M_{\odot}$) has to be shorter than the evolution time-scale for those stars;
- The velocity dispersion in the collapsed star cluster cannot be larger than a few hundred km/s;
- Collisions between stars lead to formation of very massive stellar type objects - very small mass loss;
- Formation of very massive BH.

Gürkan, Freitag & Rasio, 2004, ApJ 604, 632

Theory - Runaway merging cont.



Portegies Zwart et al., 2004, Nature 428, 724

- N-body simulations of very dense star clusters with $W_o = 9 - 12$;
- Formation of extremely massive objects - about $1000 M_\odot$;
- Formation of BH due to SN without substantial mass loss;
- Extreme initial conditions. Some observed young star clusters fulfil the conditions for runaway merging - MGG-11 in galaxy M82.

Theory - Gas Accretion onto BH

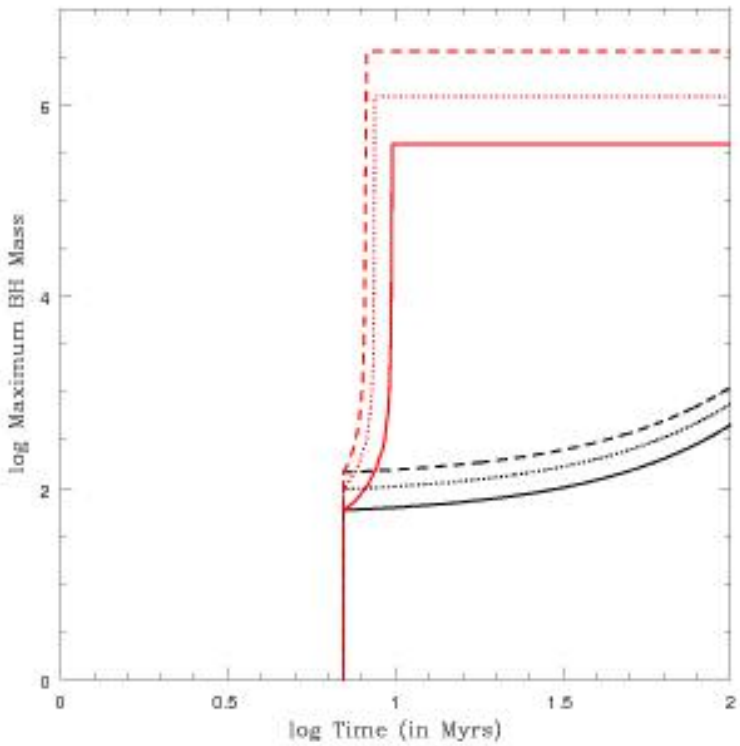


Figure 3. Mass of the most massive BH as a function of time for the case of Bondi-Hoyle (red curves) and Eddington-limited (black curves) accretion. The dashed, dotted, and solid lines correspond to an IMF upper mass cut-off of 150, 100, and 60 $M_{\odot}$, respectively.

Leigh et al., 2013, MNRAS 429, 2997

- Model proposed to explain the multiple stellar populations in GCs;
- Interactions between interstellar medium remaining after formation of the first generation stars and BHs formed from the most massive first generation stars;
- Gas accretion onto stellar mass BHs;
- Substantial increase of the BH mass and speedup of their mass segregation. Formation of the dense and massive BH subsystem. Further evolution can lead to IMBH formation.

"Direct" Observations - IMBH

X-ray emissions because of gas accretion on IMBH.

- Detection of ultraluminous X-ray sources at off-center positions in distant galaxies (eg. Matsumoto et al. 2001, Soria et al. 2010) suggests IMBH, probably originating from disrupted GCs or dwarf galaxies;
- Not confirmed detections of X-ray and radio emissions from center of G1 (Miller-Jones et al. 2012). Strader et al. 2012 - X-ray and radio emissions for several GC - very low upper limits on possible IMBHs;
- Radio and X-ray emission in NGC 6388 and ωCen - upper limits of $\sim 1500 M_{\odot}$ and 1100 - 5200 $M_{\odot}$, respectively (Cseh et al. 2010 and Lu & Kong 2011)
- Extension for lower mass of the observed $M - \sigma$ correlation for SMBH suggests that the best candidates to host IMBH are massive GCs;

"Indirect" Observations - IMBH

Global properties of a star cluster hosting IMBH.

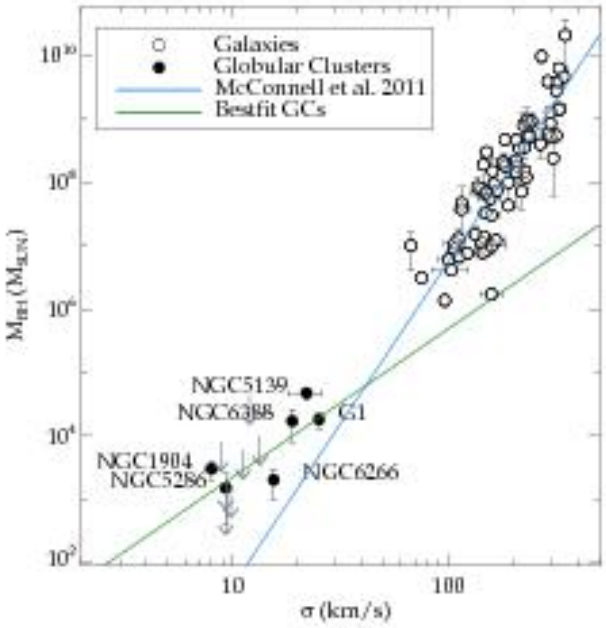


Fig. 2. $M_\bullet - \sigma$ relations of IMBHs and SMBHs in comparison. The slope of the bestfit to the GCs (green line) is by a factor of two smaller than the slope of the SMBHs in galaxies (blue line).

Lützgendorf et al. 2013

- Rising Velocity Dispersion Profile - caution, can be connected with massive evolved stars population in the core (Baumgardt et al. 2005);
- Shallow cusp in the Surface Brightness Profile (Baumgardt et al. 2005) - caution, a similar signature can give massive BH-BH binary (Hurley 2007);
- The $M - \sigma$ corelation at the lower mass end indicates a lower slope compared to the slope obtained for SMBHs by McConnell et al. (2011). Possible explanation could be connected with high mass loss of the GCs due to tidal stripping. This could lower the VD and move the GCs away from the standard relation.

MOCCA Simulations - Initial Conditions

Project with Nathan Leigh, which aims is to explain the observed correlations between custer mass and binary fraction - the larger the cluster mass the smaller the binary fraction (Milone et al. 2012) and MF power-law index and cluster concentration - the more concentrated the clusters the larger the MF power-law index (De Marchi et al. 2007).

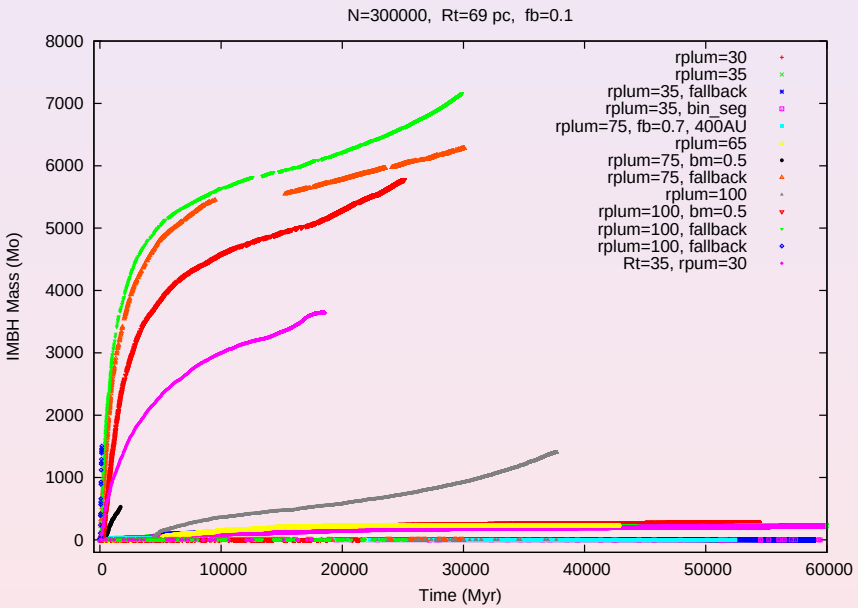
About 200 models.

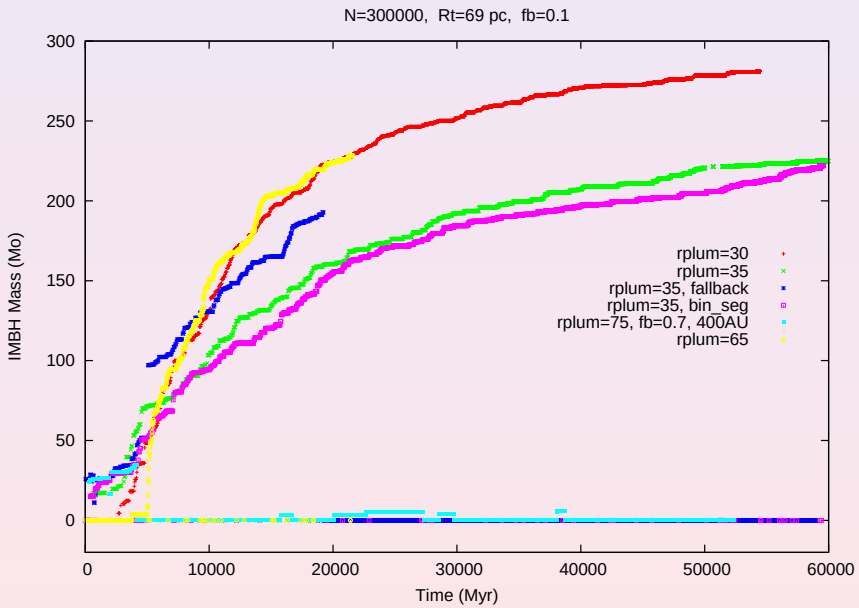
N	R_t (pc)	R_t/R_h	f_b	$a_{max}(R_\odot)$	IMF	Kicks (km/s)
$N = 5.0x10^4$ King $W_0 = 6$	38	20, 25, 30 50, 75	0.1	100 Period	IMF2, IMF3	0, 265 Fallback
$N = 1.0x10^5$ King $W_0 = 6$	38	10, 20	0.1	100 Period	IMF3 IMF2-m	265 Fallback
$N = 2.0x10^5$ King $W_0 = 6$	38	10, 20	0.1	100 Period	IMF3 IMF2-m	265 Fallback
$N = 3.0x10^5$ King $W_0 = 6$	35, 50 69	35, 50, 60 75, 100	0.1, 0.3 0.7, 0.95	100, 200 400, Period	IMF2, IMF3 IMF2-m	0, 265 Fallback
$N = 1.8x10^6$ King $W_0 = 6$	125	60, 75, 90 100, 125	0.1	100 Period	IMF2, IMF3 IMF2-m	0, 265 Fallback

Table : BH and NS kicks are the same, except mass fallback. IMF2 - Kroupa (2007), IMF3 - Kroupa (1995a), IMF2-m - modyfied by changing α_{low} and α_{high}, Period - Kroupa (1995b), Fallback - Belczynski et al. (2002)

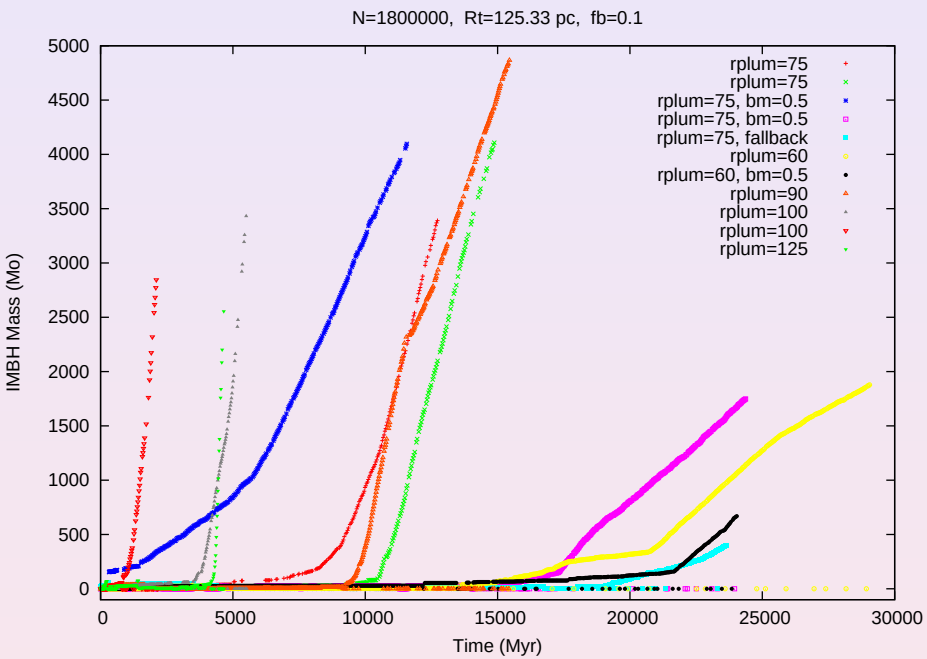
IMBH Formation

Very unexpected byproduct of the project - formation of the IMBH!!!





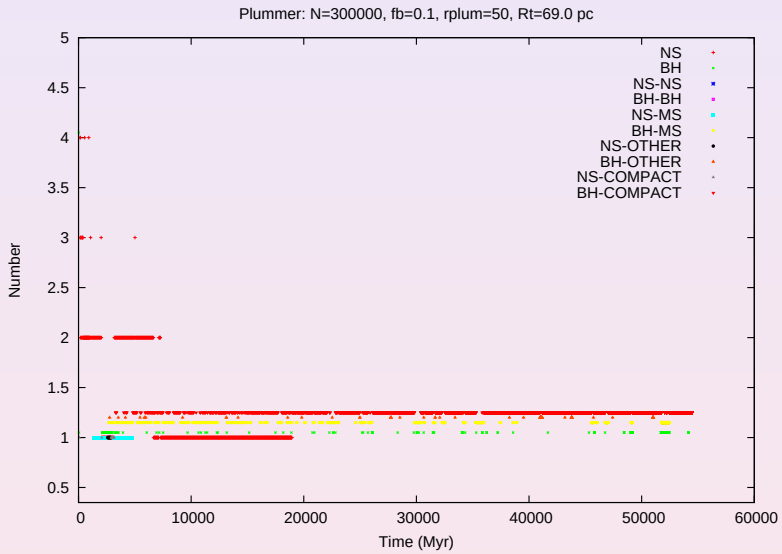
IMBH Formation cont.

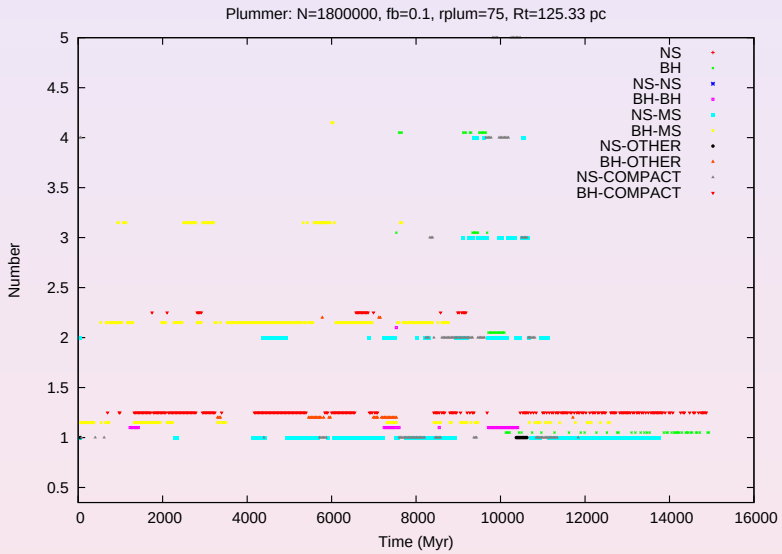


- Only a small fraction of all models show buildup of BH mass and IMBH formation. Most of N=1800000 models and only a few N=50000 models (with fallback=1) form IMBH. The larger the initial cluster mass the larger the probability of IMBH formation. The process of IMBH formation is highly stochastic;
- The larger the initial concentration the larger the probability of IMBH formation;
- The rate of IMBH mass buildup depends on the initial concentration. The larger the concentration the earlier and faster the IMBH is formed.

NS and BH Formation

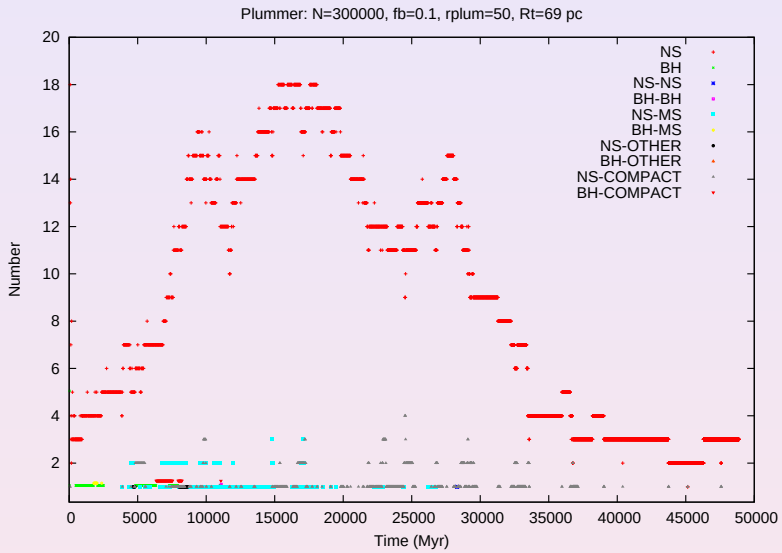
What are the processes responsible for IMBH formation?
How is it possible to form an IMBH so late during cluster evolution?

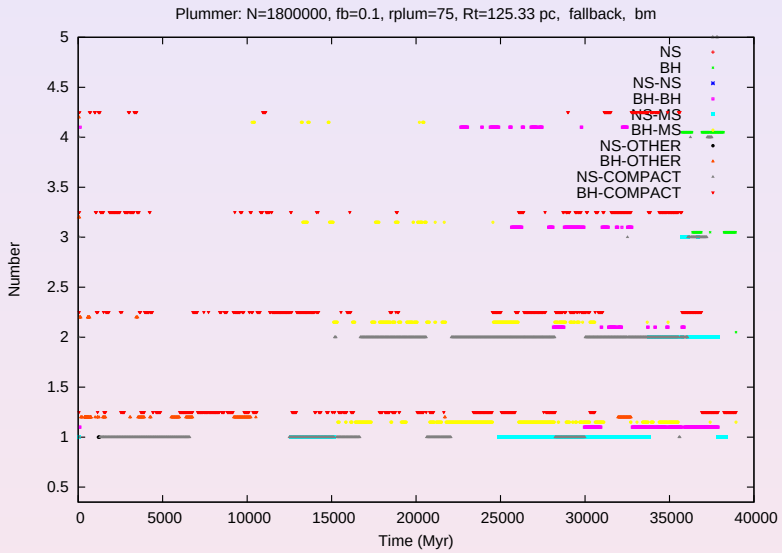




- BHs are very quickly removed from the system, because of dynamical interactions involving binaries;
- NSs and BHs are also formed late during cluster evolution, not only at the beginning as a consequence of stellar evolution of the most massive stars.

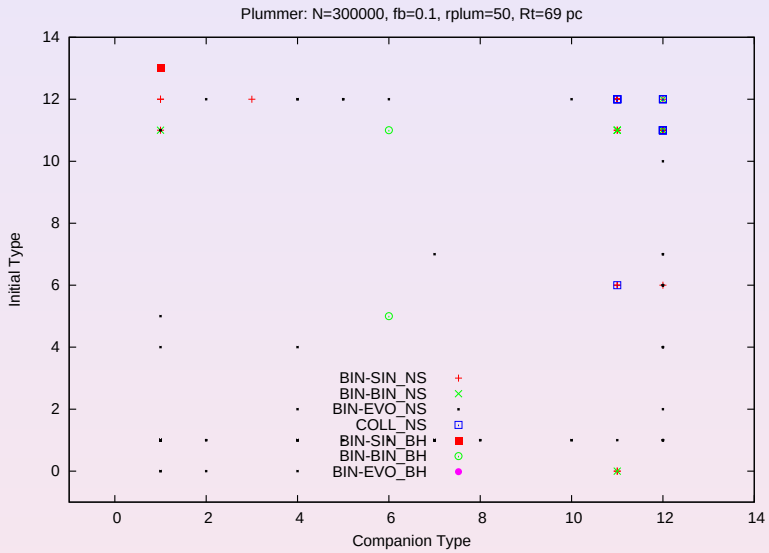
NS and BH Formation cont.

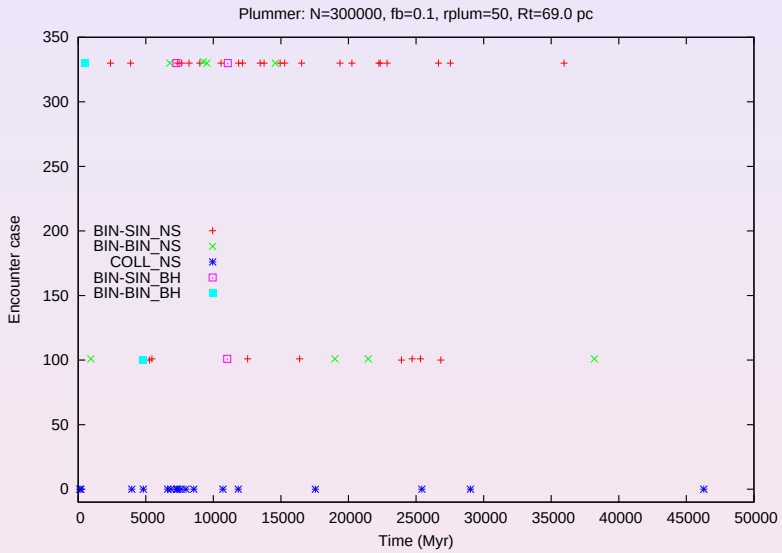




- Much larger number of NSs and BHs are formed during cluster evolution in the case of no IMBH formation than in the case of IMBH formation - larger density for no IMBH formation. The core radius is larger for IMBH formation;
- In the case no IMBH formation there is substantial number of NSs and binaries with NS and other type of companion. There are even NS-NS binaries.

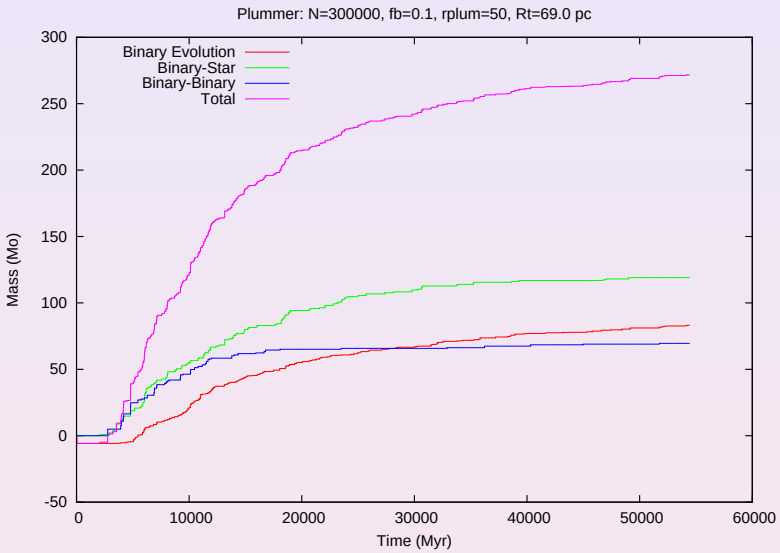
NS and BH Formation cont.

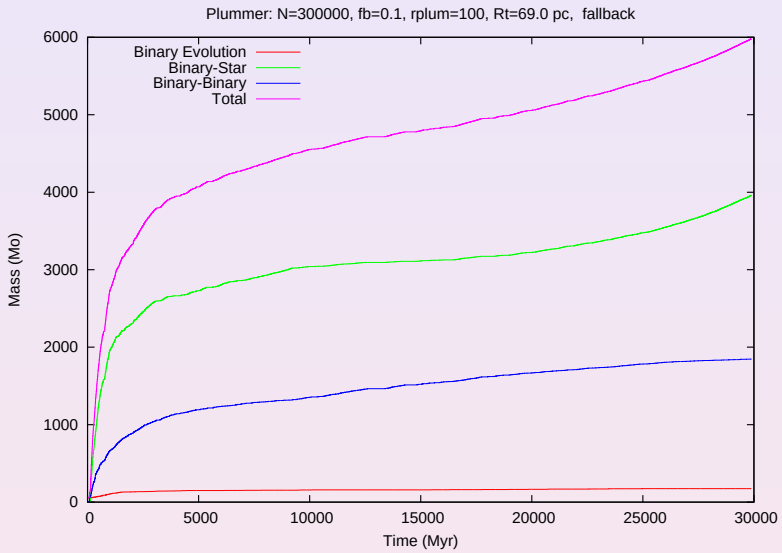




- Usually, NSs and BHs are formed in interactions between evolved and unevolved stars, including direct collisions. There are some interactions involving only WDs;
- There is a substantial number of "total mergers" (case 100) in which all interacting objects merge into one NS/BH;
- Formation of NS/BH spreads over the whole cluster evolution.

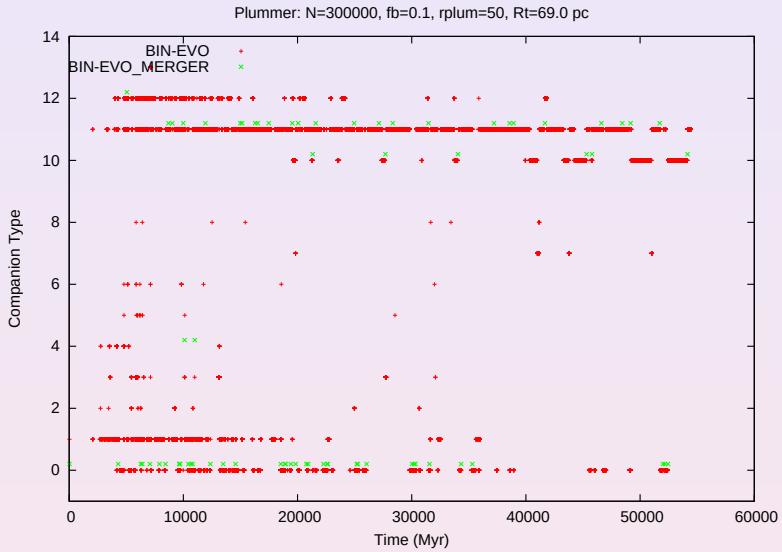
IMBH Formation - MASS

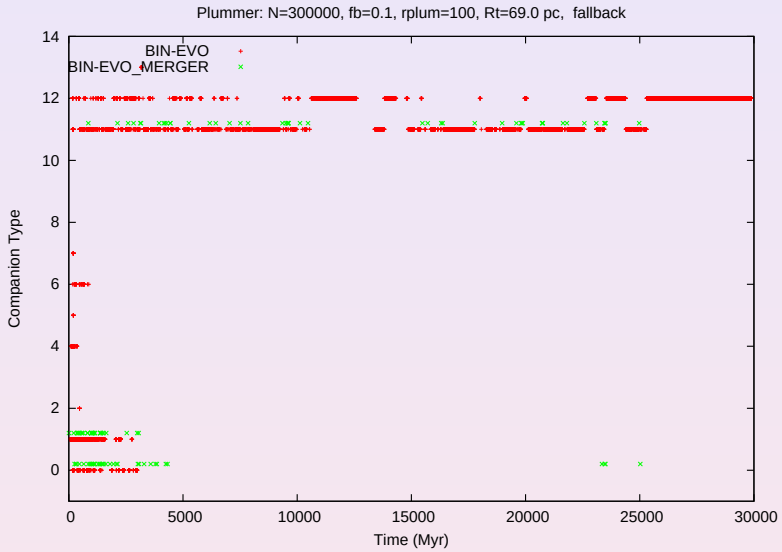




- Basically, there are two regimes of IMBH formation: very fast IMBH mass buildup starting from the very beginning of the cluster evolution (FAST), and slow IMBH mass buildup starting later in the cluster evolution (SLOW);
- For the SLOW scenario Bin-Bin, Bin-Sin interactions and Bin-Evo participate approximately equally in the IMBH mass buildup;
- For the FAST scenario Bin-Sin interactions are dominant in the IMBH mass buildup, Bin-Evo is practically negligible.

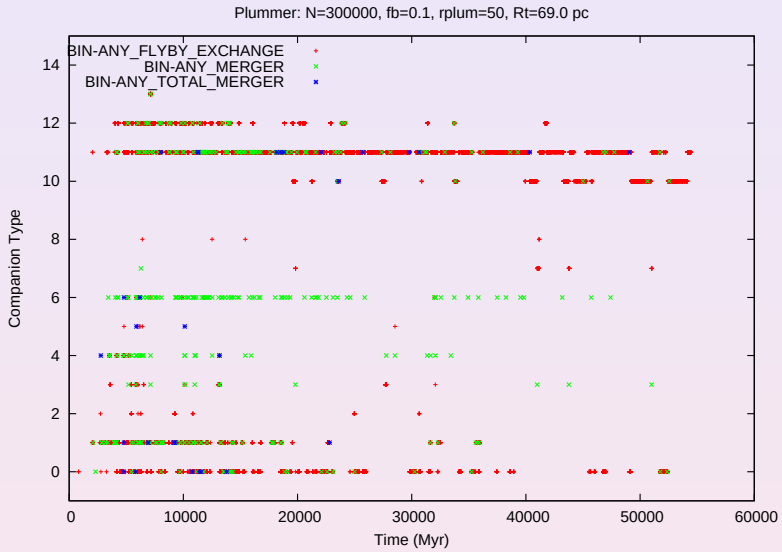
IMBH Formation - TYPE

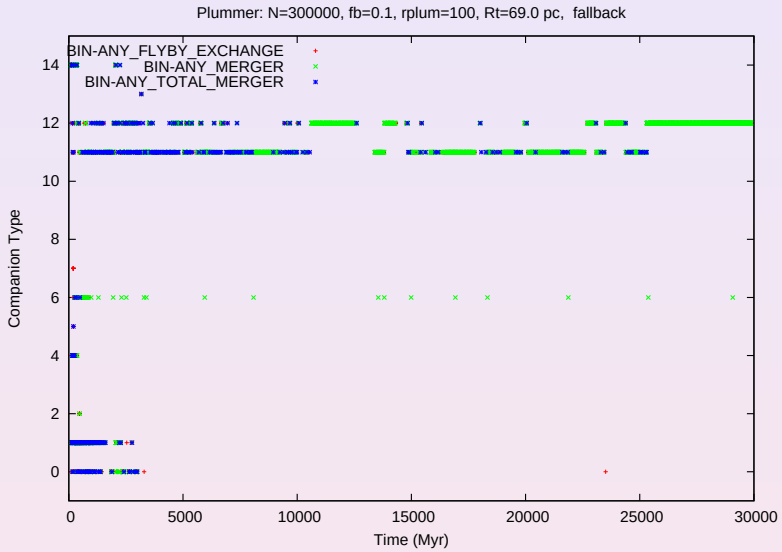




- All TYPES of companion stars take part in the evolution of binaries containing IMBH. For the SLOW scenario evolution events with unevolved stars are spread over the whole time, but for the FAST scenario only at the beginning;
- There are no mergers with O, Ne WDs! and only one IMBH-NS merger;
- For the FAST scenario there are no evolution events with He WDs.

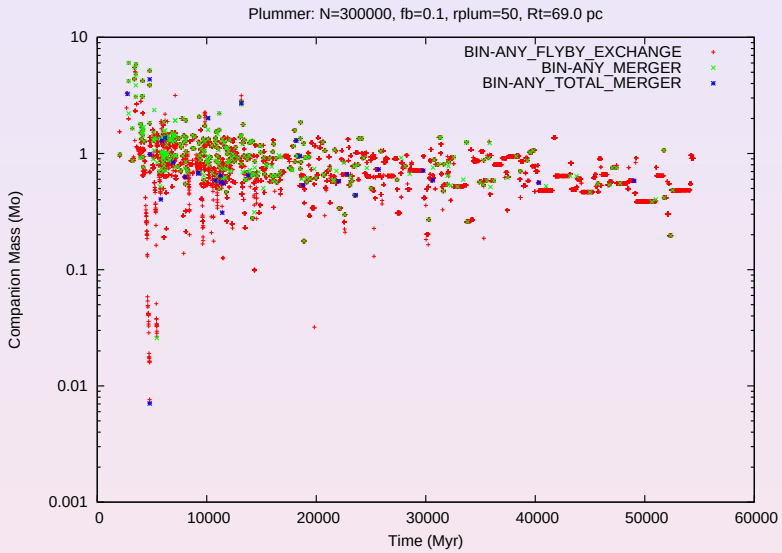
IMBH Formation - TYPE cont.

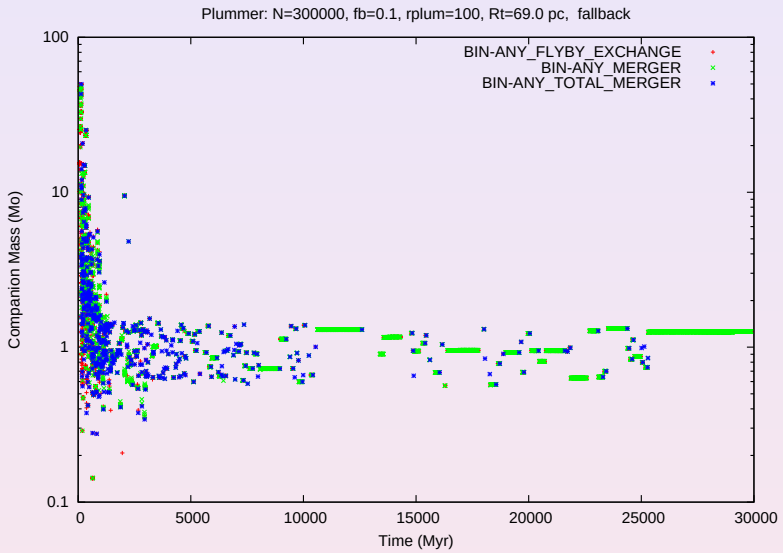




- For the SLOW scenario there is much more flybys than merger events (18054 to 350 mergers and only 30 total mergers). In the case of the FAST scenario half of all interactions is connected with mergers (5002) and total mergers (477) and half with flybys (5914).
- Because of a large number of BHs in the case of FAST scenario there are "total" binary mergers involving only BHs.

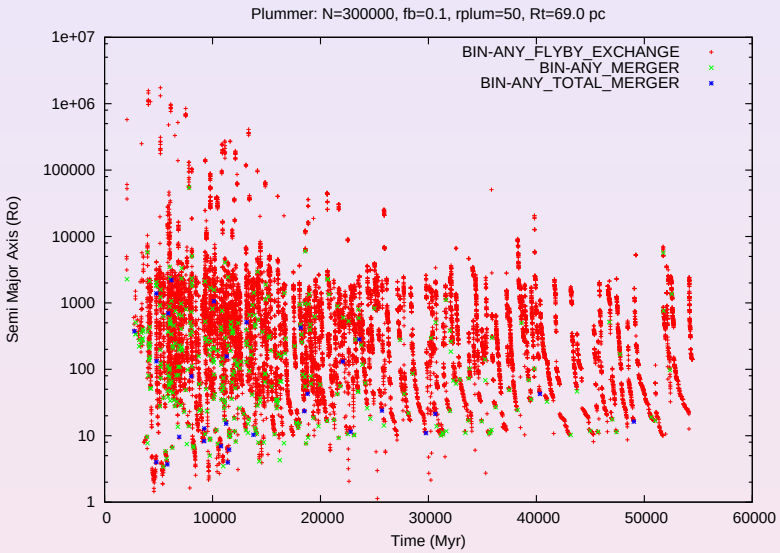
IMBH Formation - MASS

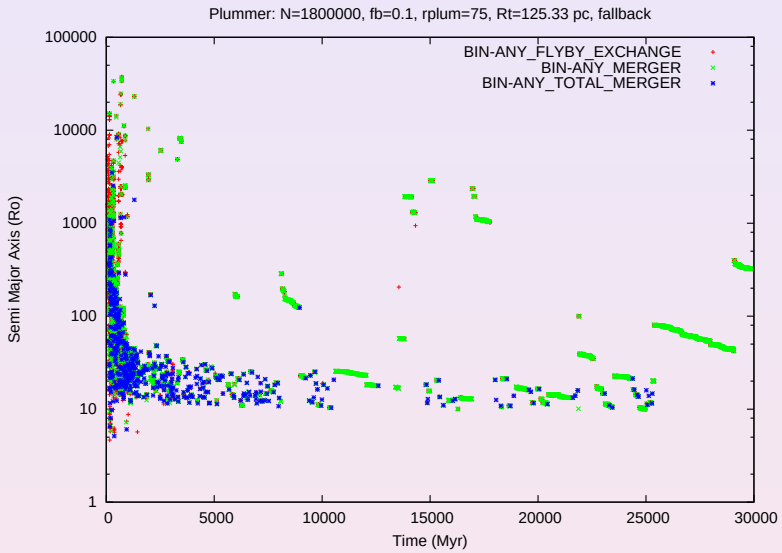




- The extremely fast increase of the IMBH mass in the FAST scenario is connected with mergers and "total" binary mergers involving massive BHs and binaries containing massive BHs - the case with mass fallback for SN kicks;
- For the SLOW scenario IMBH mass starts to buildup when there are no very massive objects - the most massive objects are stellar mass BHs, NS, WD or merged unevolved stars with masses up to a few $M_{\odot}$.

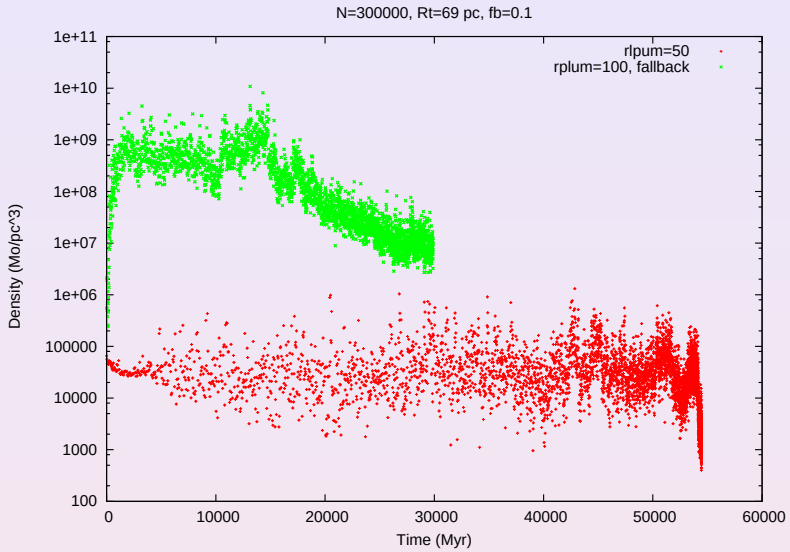
IMBH Formation - A





- For the SLOW scenario there are clearly visible binary evolution patterns - shrinkage of binary semi major axis (hardening) because of binary dynamical interactions;
- For the FAST scenario practically every dynamical interaction is connected with mergers or "total" binary mergers;
- Binary containing IMBH does not escape because it undergoes "total" binary merger before it can escape due to a dynamical interaction.

IMBH Formation - Scenario



For the SLOW scenario central densities are not extraordinary high. To form IMBH we do not need an extreme conditions.

What is the IMBH formation scenario?

- To initiate the process of BH mass growth it is needed that only one BH is left in the system after the phase of the initial SN explosions or BH is formed in dynamical interactions. Alternatively there can be more BHs in the system but in this case the density has to be extremely high $> 10^8 M_\odot / pc^3$;
- Formation of BH-any_star binary in 3-body interactions. BH is the most massive object in the system, so there is high binary formation probability. Frequently BH-MS/RG are formed;
- Dynamical interactions with other binaries and stars:
  - orbit tightening leading to mass transfer from MS companion;
  - exchanges and mergers, but binary is not destroyed;
  - "total" mergers - only BH is left. BH will very shortly form a binary which then is again involved in dynamical interactions.

Conclusions

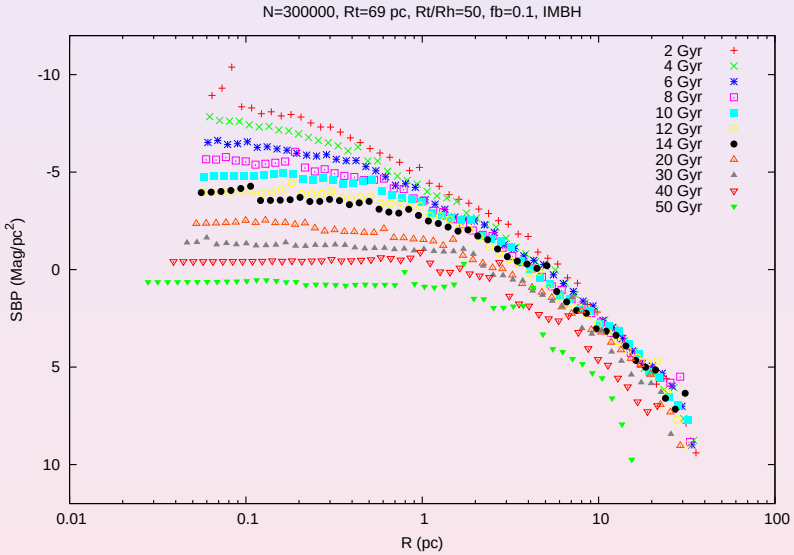
Summary

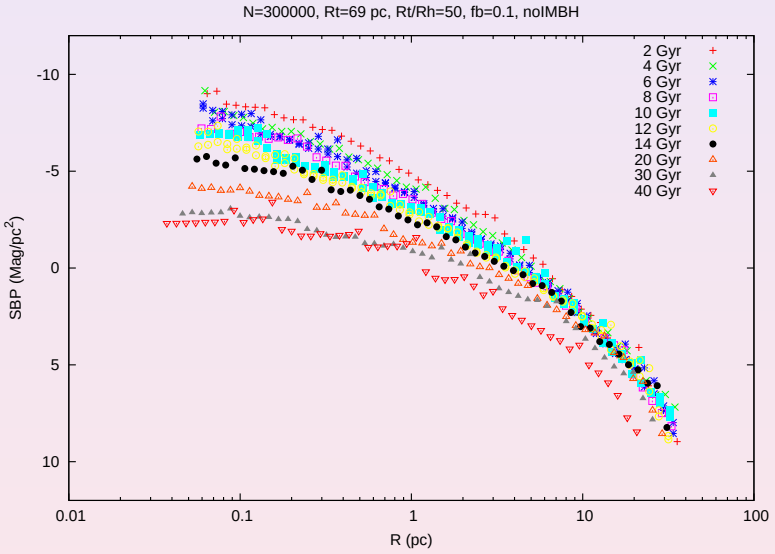
- NSs and BHs can be formed in the course of star cluster evolution due to dynamical interactions (collisions and binary interactions);
- If the system density is large enough (about $10^5 M_\odot / pc^3$) there is possibility that BH mass can buildup only because of dynamical interactions and mass transfer in binaries. That is true for the more probable SLOW scenario;
- The process of BH mass buildup and finally IMBH formation is highly stochastic;
- The rate of IMBH mass buildup strongly depends on the system density. The larger the density the higher the rate;
- There are frequent phases of mass transfer in binaries containing IMBH. Therefore, X-ray emission should be observed from such binaries.

Problems

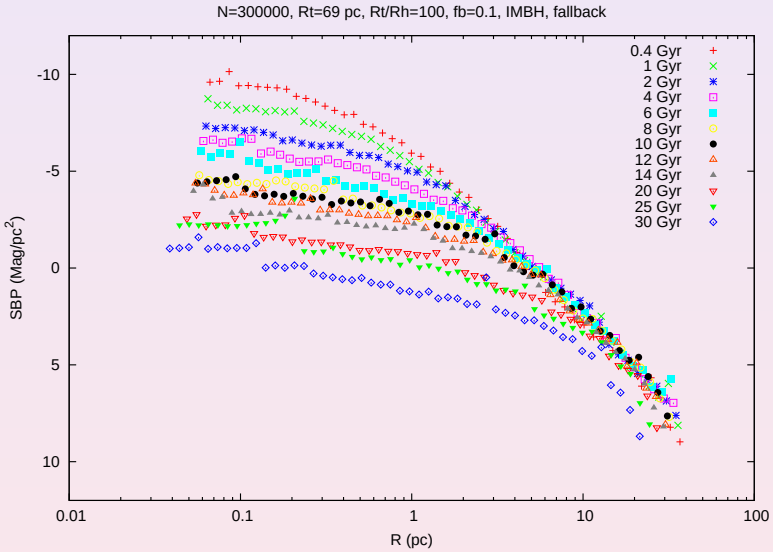
- MOCCA code is not prepared to follow the dynamical evolution of extremely massive objects (larger than a few hundred $M_\odot$). Nevertheless, the initial IMBH mass buildup should be correctly followed;
- The *Fewbody* code (Fregeau et al. 2004) seems to work properly for the extreme mass ratios - several checks were carried out;
- There are some doubts about the BSE code (Hurley et al 2000, 2002) and its ability to follow binary evolution and mass transfer in the case of extreme mass ratios and extremely massive compact objects. The mass transferred onto IMBH because of binary/stellar evolution is not dominant, so the process of IMBH mass buildup should not be disrupted even in the case of mass transfer switch off.

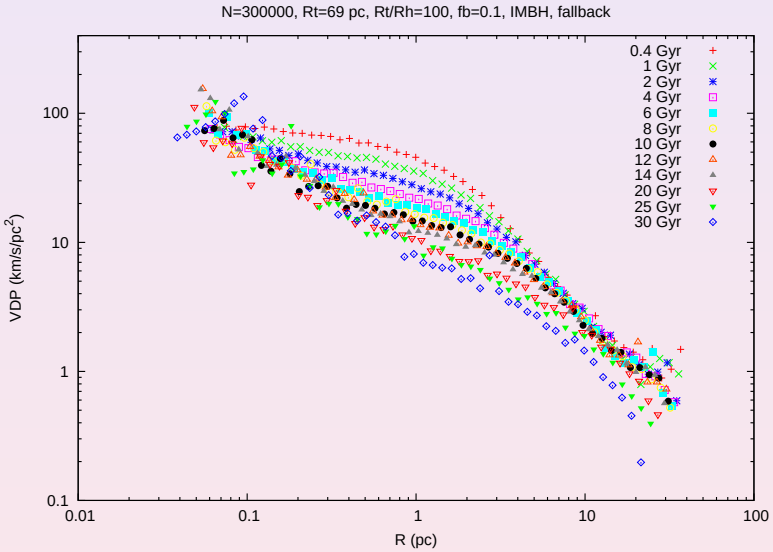
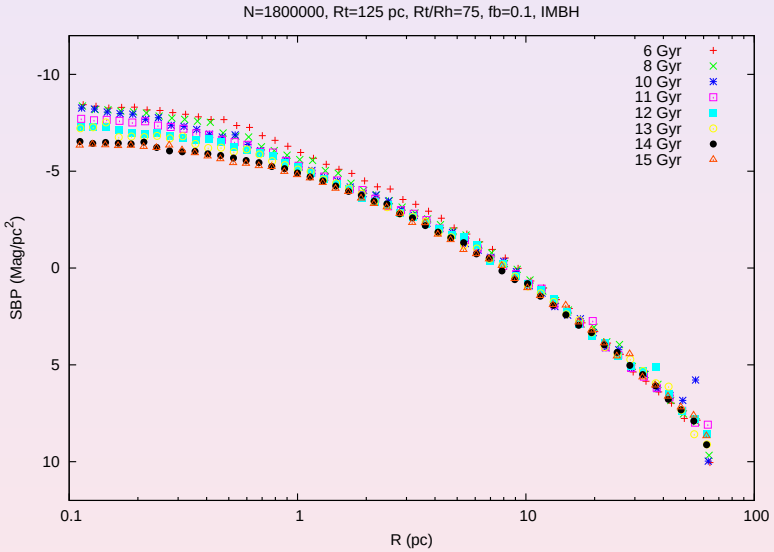
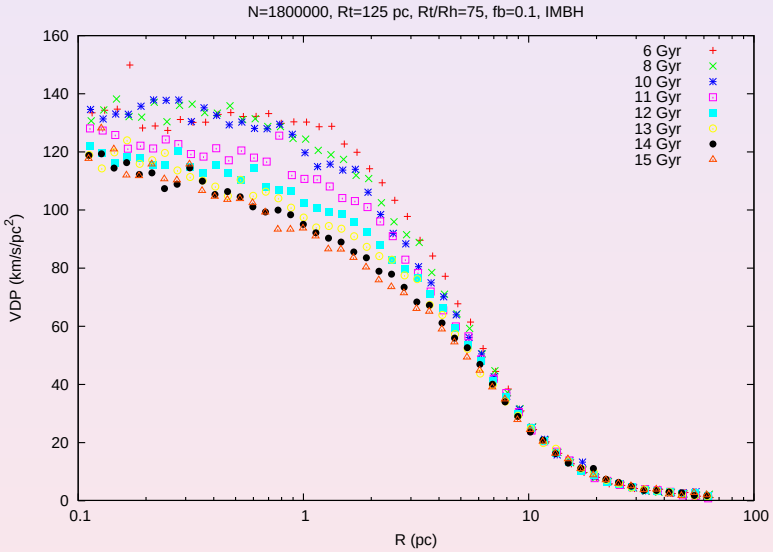
N=300000 - SBP


N=300000, Rt=69 pc, Rt/Rh=50, fb=0.1, IMBH
SBP (Mag/pc^2)
R (pc)
2 Gyr
4 Gyr
6 Gyr
8 Gyr
10 Gyr
12 Gyr
14 Gyr
20 Gyr
30 Gyr
40 Gyr
50 Gyr


N=300000, Rt=69 pc, Rt/Rh=50, fb=0.1, noIMBH
SBP (Mag/pc^2)
R (pc)
2 Gyr
4 Gyr
6 Gyr
8 Gyr
10 Gyr
12 Gyr
14 Gyr
20 Gyr
30 Gyr
40 Gyr

N=300000, $R_t/R_h = 100$, fallback - SBP and VDP





N=1800000 - SBP