Can black holes be formed in dynamic interactions in star clusters?

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Collaborators

Main Collaborators in the IMBH Project

- Nathan Leigh
- Arkadiusz Hypki
- Christoph Olczak
- Douglas Heggie

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 binary dynamical interactions and mass transfer in binaries (Leigh, Olczak, Heggie & Hypki)

"Direct" Observations - IMBH

Recently, there were observed a few candidates of stellar mass BHs in M22, M62, 47 Tuc and other clusters.

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.

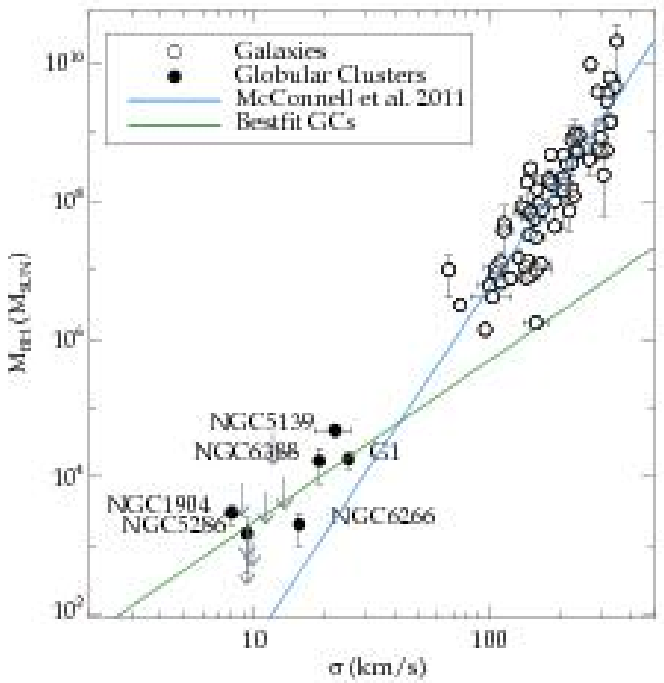


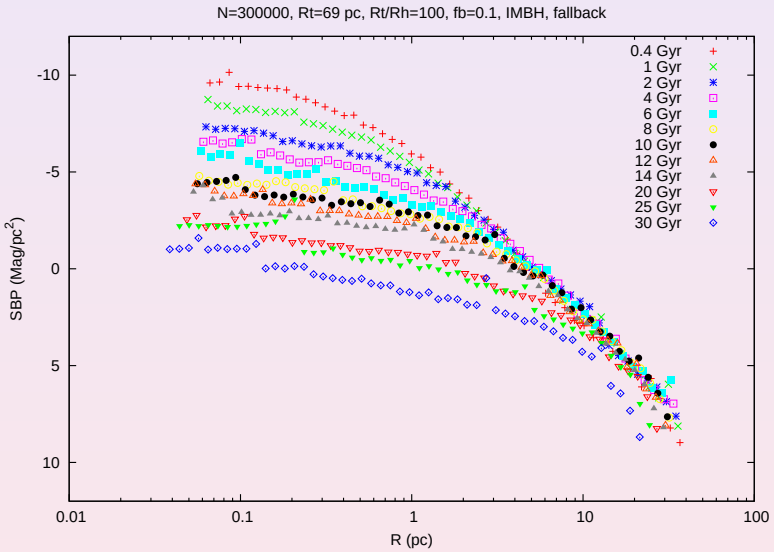
Fig. 2. $M_\bullet - \sigma$ relations of IMBHs and SMBHs in comparison. The slope of the bestfit to the GCs (green line) is by a factor of two smaller than the slope of the SMBHs in galaxies (blue line).

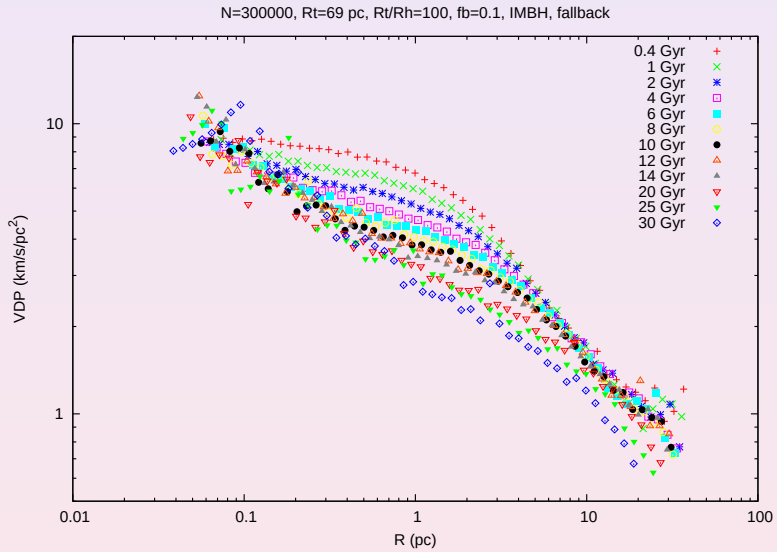
- Rising Velocity Dispersion Profile - caution, can be connected with massive evolved stars population in the core (Baumgardt et al. 2005);
- Shallow cusp in the Surface Brightness Profile (Baumgardt et al. 2005) - caution, a similar signature can give massive BH-BH binary (Hurley 2007);
- The $M - \sigma$ correlation 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.

Lützgendorf et al. 2013

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

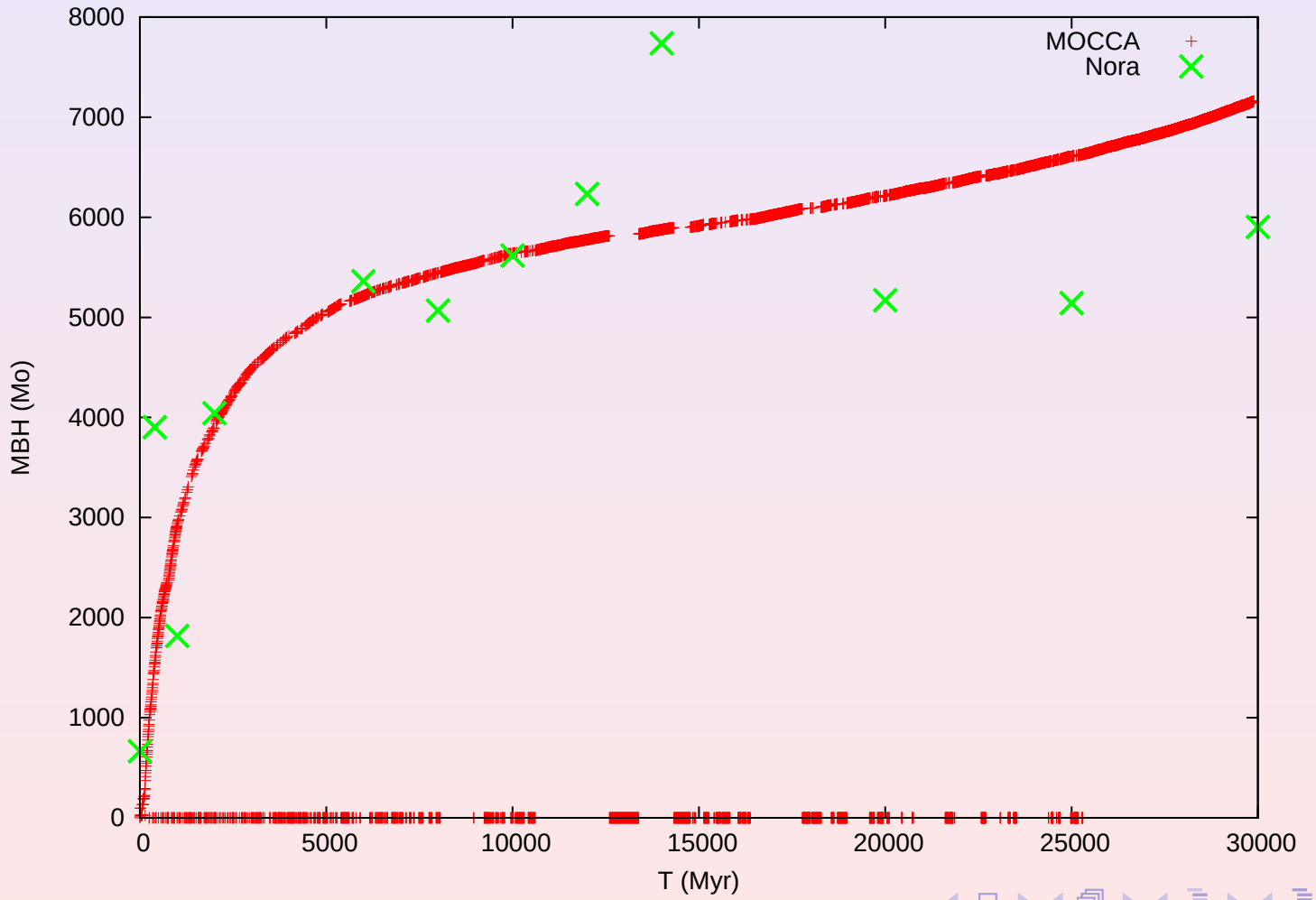
SBP and VDP for MOCCA model with IMBH formation. The flat SBP and steeply rising VDP in the center are clearly visible.





It would be interesting to apply the method used by Nora Lützgendorf to the data from MOCCA simulations and see how massive, if at all, IMBH could be detected.

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



MOCCA Simulations - Initial Conditions

- Project with Nathan Leigh, which aim was to explain the observed correlations between cluster 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).
- Project with Christoph Olczak, which aim was to check if it is possible to form low mass IMBH in dense open clusters.
- Project with Douglas Heggie, which aim is to constrain initial conditions for Omega Cen by comparison of results of MOCCA simulations with available observations.

About 300 models were run.

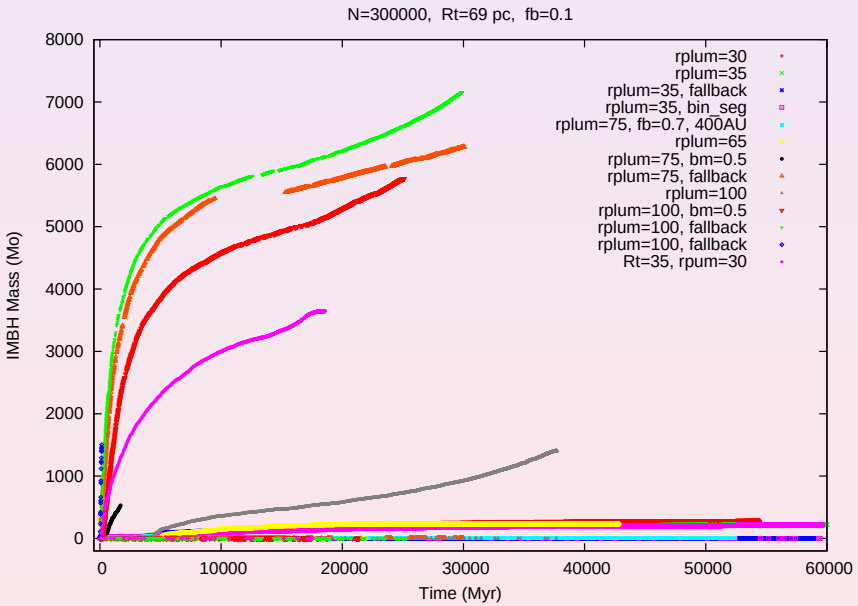
MOCCA Simulations - Initial Conditions

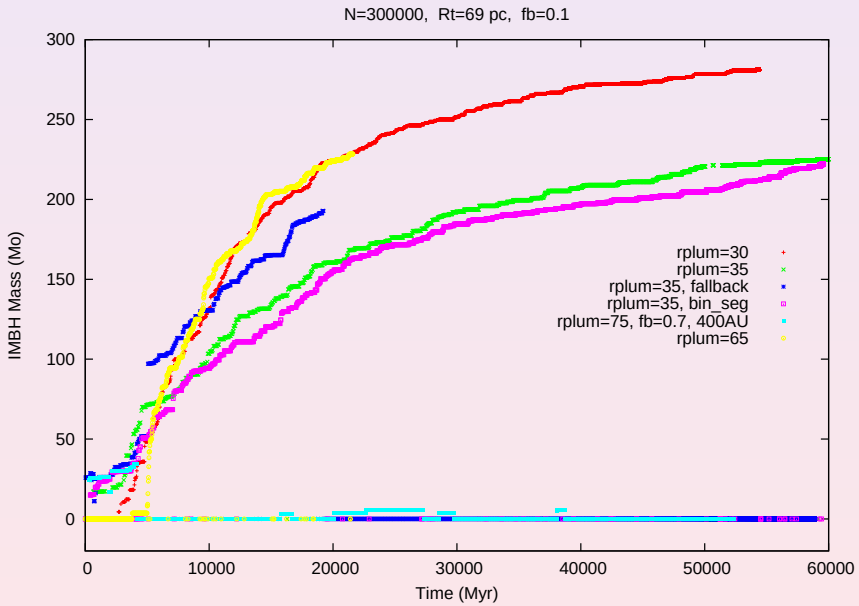
N	R_t (pc)	R_t/R_h	f_b	a_{max} (AU)	IMF	Kicks (km/s)
$N = 5.0x10^4$ King $W_0 = 6$	38	20, 25, 30 50, 75	0.1	100 Period	IMF2, IMF3	0, 265 Fallback
$N = 1.0x10^5$ King $W_0 = 6$	38	10, 20	0.1	100 Period	IMF3 IMF2-m	265 Fallback
$N = 2.0x10^5$ King $W_0 = 6$	38	10, 20	0.1	100 Period	IMF3 IMF2-m	265 Fallback
$N = 3.0x10^5$ 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
$N = 6.6x10^4$ King $W_0 = 6$	3.6	6.8	0.0, 0.1 0.95	100 Period	IMF2	190 Fallback
$N = 5.7x10^6$ King $W_0 = 10.6$ extreme density	70	52 $10^{12} M_\odot / pc^3$	0.05	50	IMF2-m	0, 190 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)

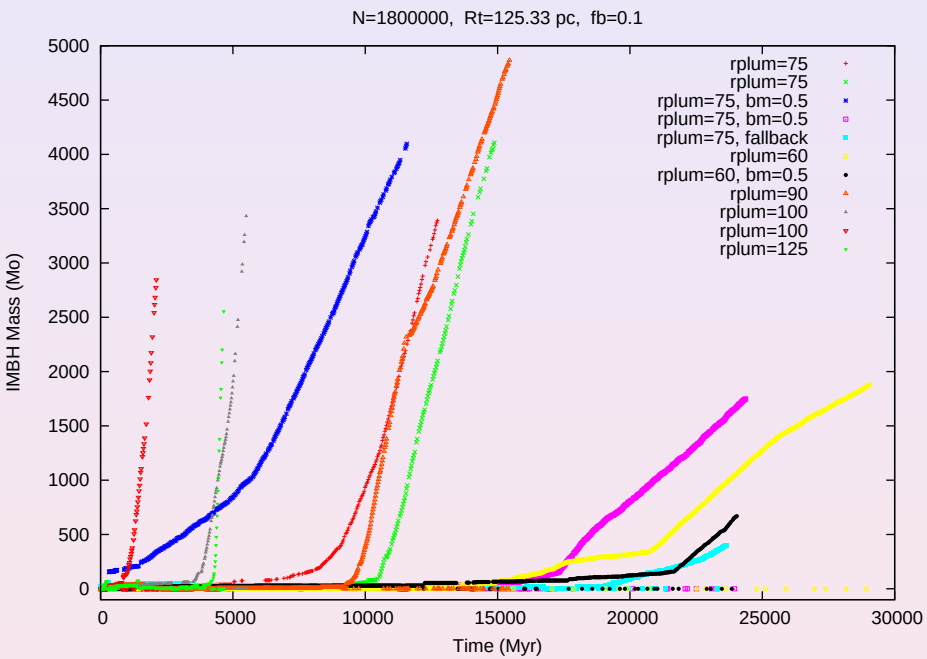
IMBH Formation

Very unexpected byproduct of the project with Nathan Leigh - formation of the IMBH!!!





IMBH Formation cont.

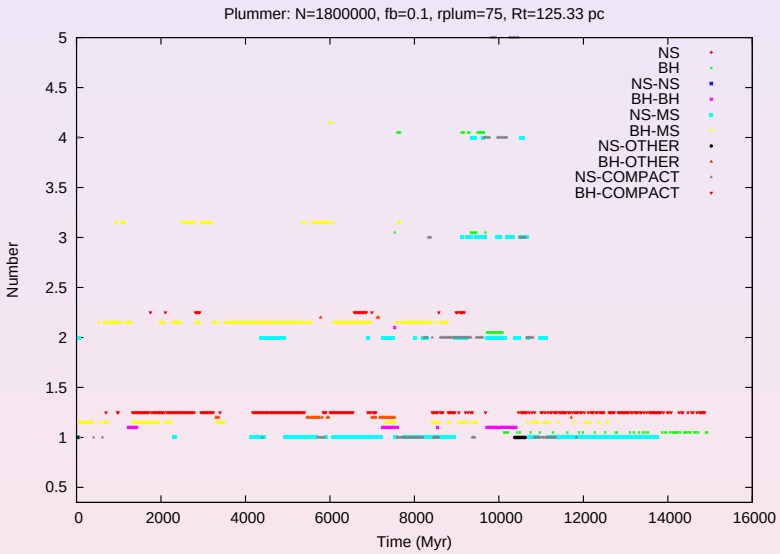


- Only a small fraction of all models show buildup of BH mass and IMBH formation. Most of N=1800000 models and only a few N=50000 models (with fallback=1) form IMBH. The larger the initial cluster mass the larger the probability of IMBH formation. The process of IMBH formation is highly stochastic;
-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

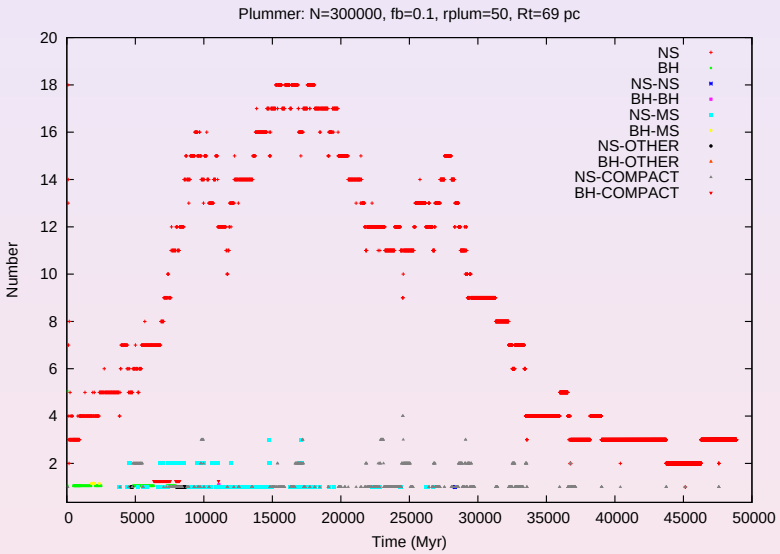
NS and BH Formation

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

IMBH formation

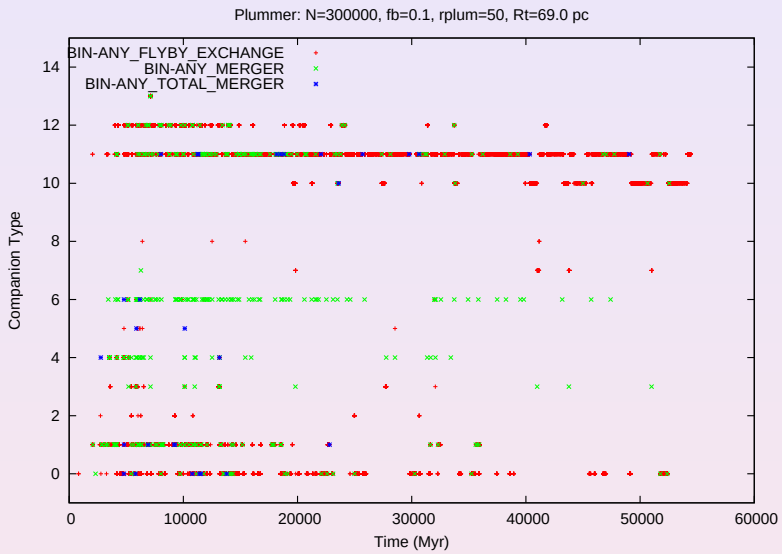


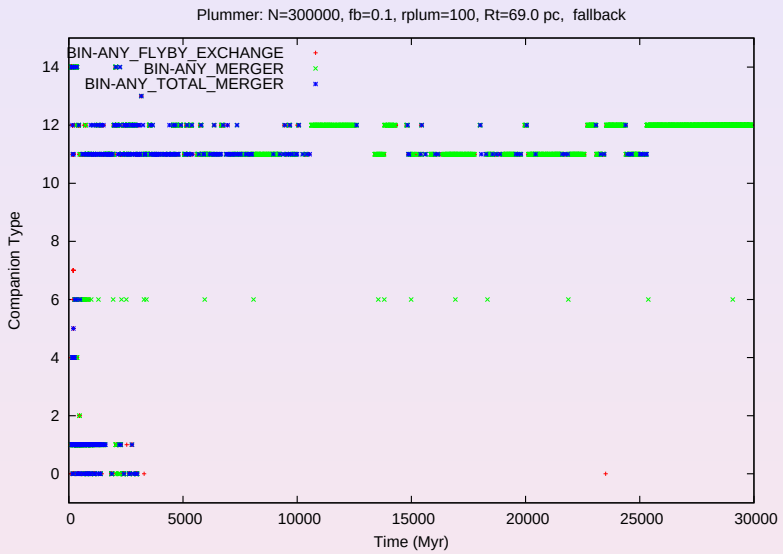
No IMBH formation



- 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;
- 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.
- 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" in which all interacting objects merge into one NS/BH;
- Formation of NS/BH spreads over the whole cluster evolution time.

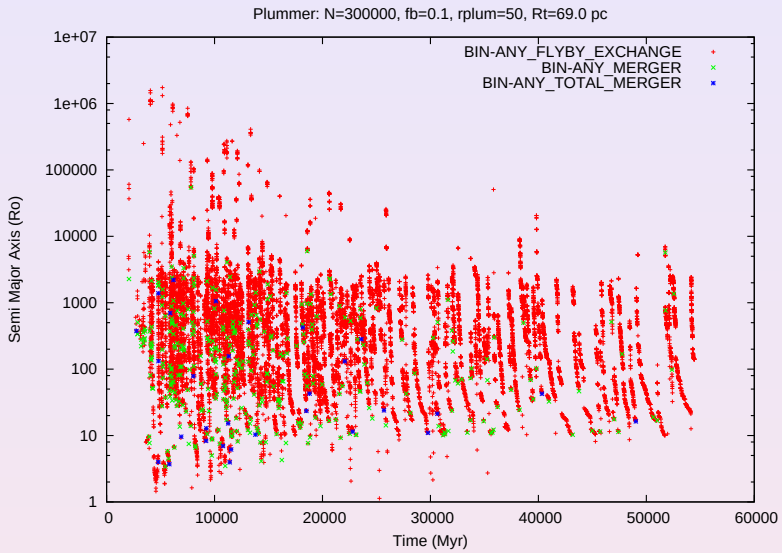
IMBH Formation - TYPE

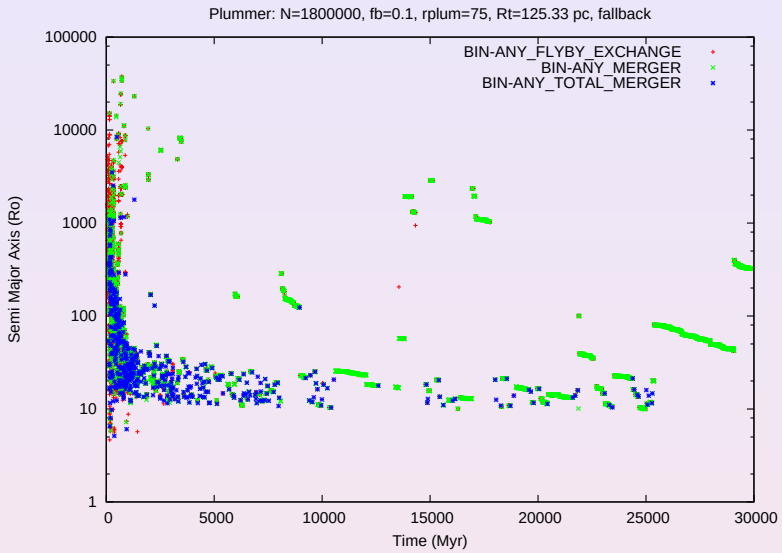




- For the SLOW scenario there are much more flybys than merger events (18054 to 350 mergers and only 30 total mergers). In the case of the FAST scenario half of all interactions is connected with mergers (5002) and total mergers (477) and half with flybys (5914).
- For the FAST scenario most of interactions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

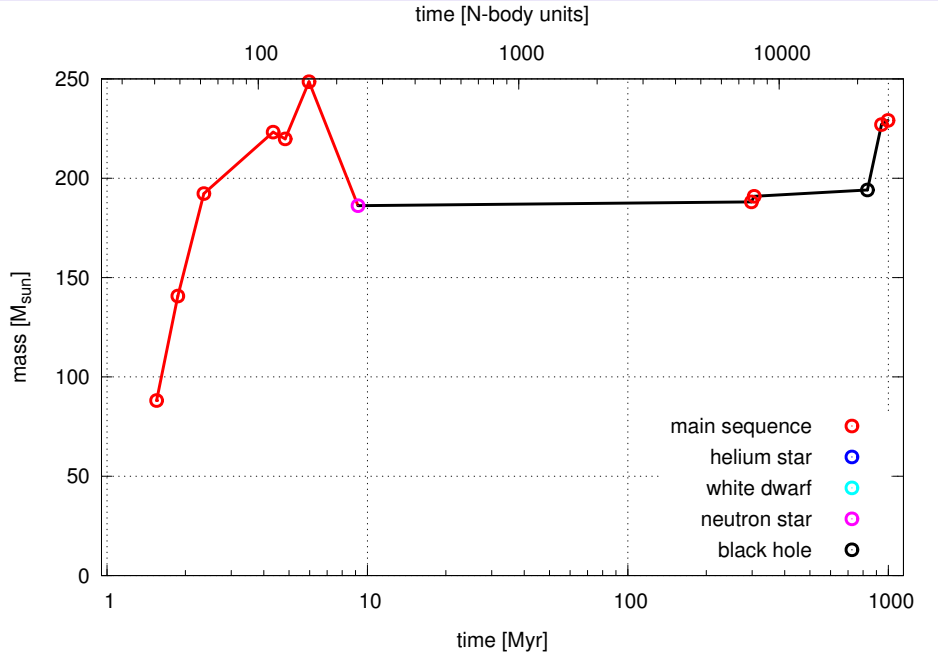
IMBH Formation - A

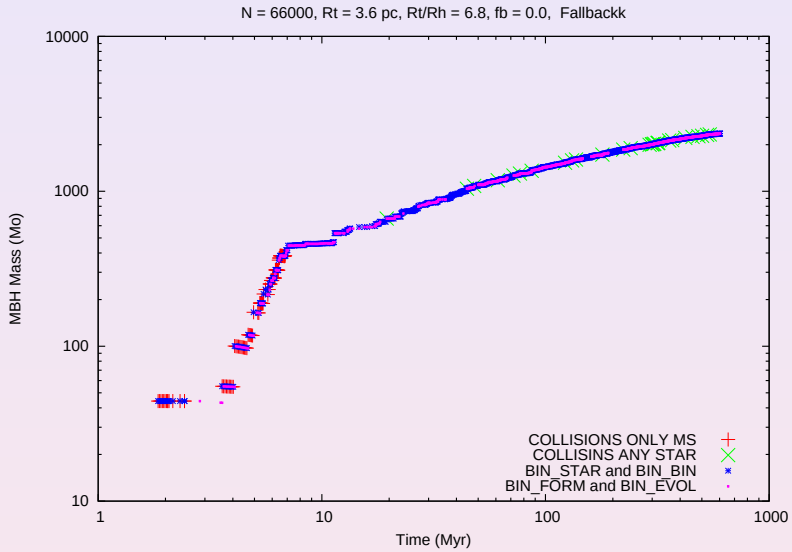




- For the SLOW scenario there are clearly visible binary evolution patterns - shrinkage of binary semi major axis (hardening) because of binary dynamical interactions;
- For the FAST scenario practically every dynamical interaction is connected with mergers or "total" binary mergers;
- Binary containing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

IMBH Formation - Dense, Open Clusters

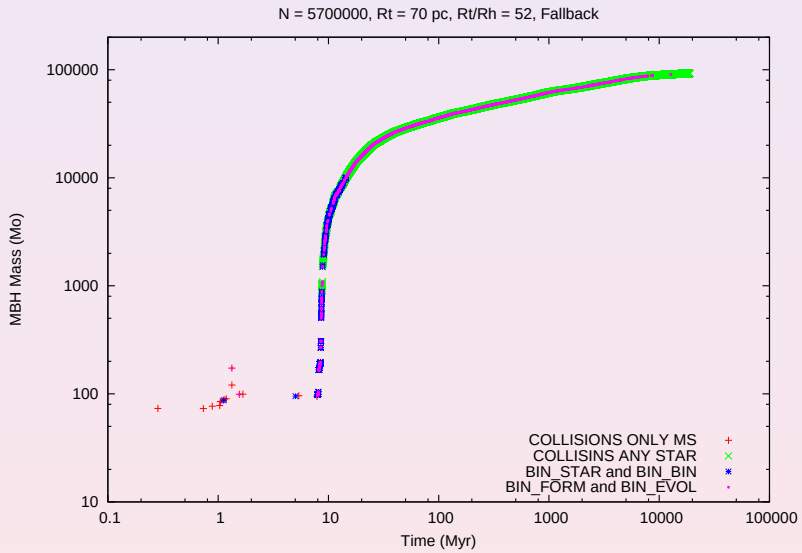


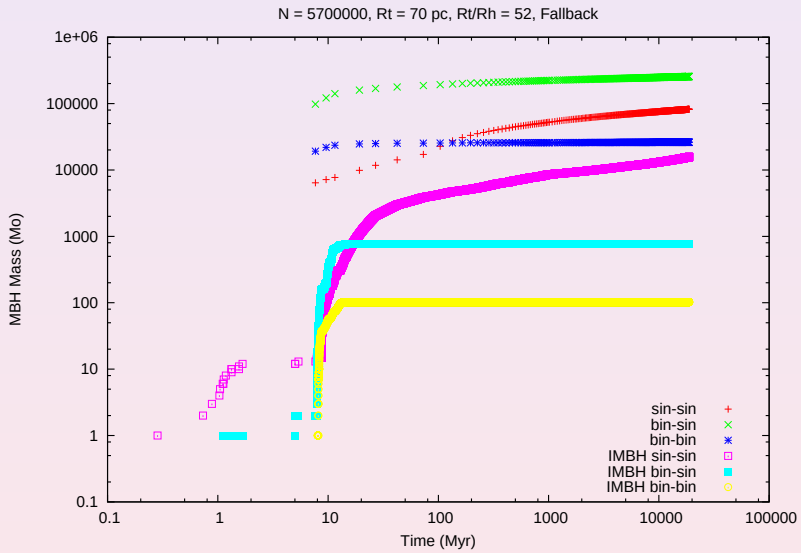


- IMBH also can be formed in small and dense, but not extremely dense, stellar systems. IMBH is also formed for models with primordial binaries;
- In N-body IMBH is formed because of frequent collisions of very massive MS stars. In MOCCA IMBH is formed mainly because of mergers in binaries, like for the cases described before for globular clusters;
- MOCCA is able to reproduce the N-body results for small N systems with very short collision time scales.

IMBH Formation - Extreme Dens Cluster - Omega Cen model

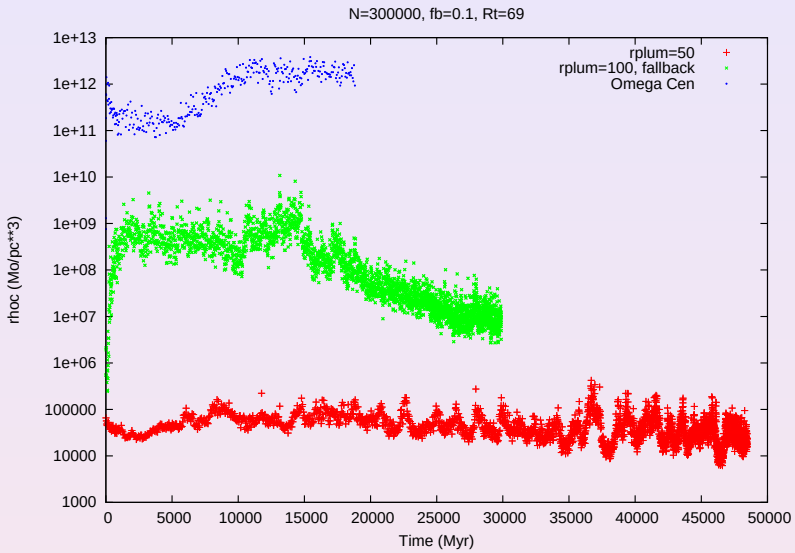
Just for curiosity's sake, to show that MOCCA copes well even for extreme models.





- Extreme large N and the central densities above $10^{12} M_{\odot}/pc^3$, but still only two days of simulations is needed!!!;
- The IMBH's mass buildup is probably unphysical when IMBH mass is greater than about $1000 M_{\odot}$, but earlier should be roughly correct.

IMBH Formation - Scenario

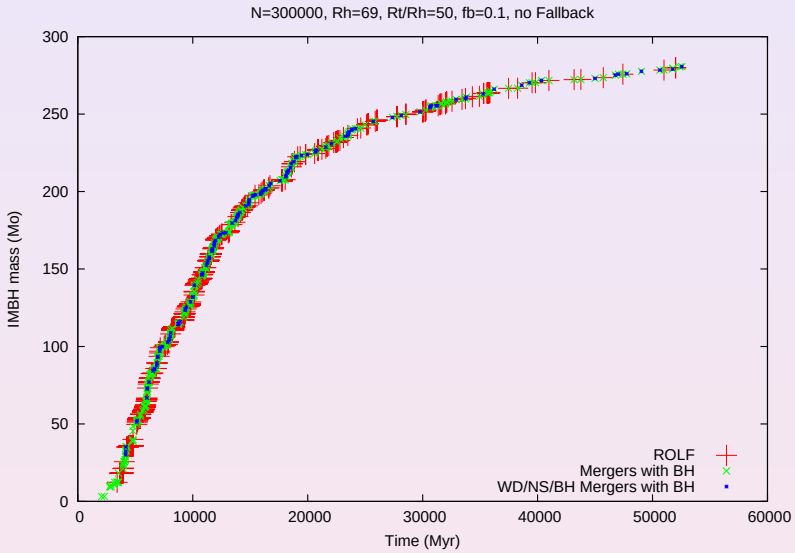


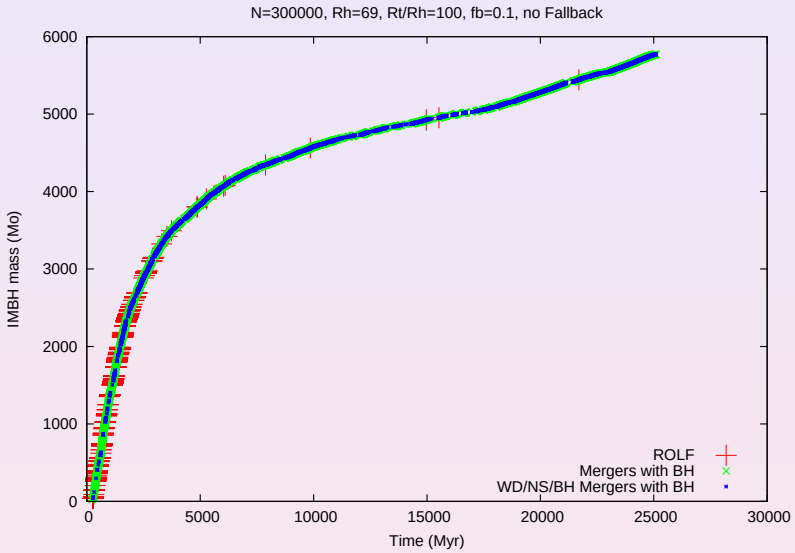
For the SLOW scenario central densities are not extraordinary high. To form IMBH we do not need an extreme conditions.

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.

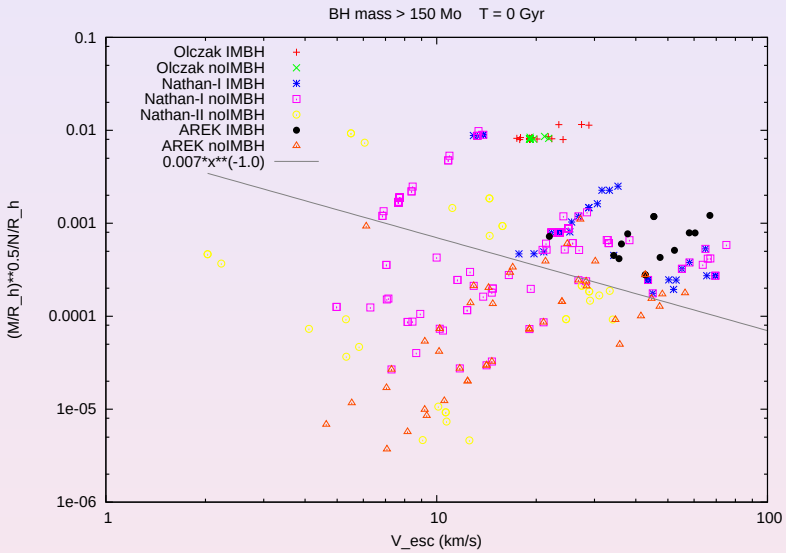
IMBH Formation - Possible Observations

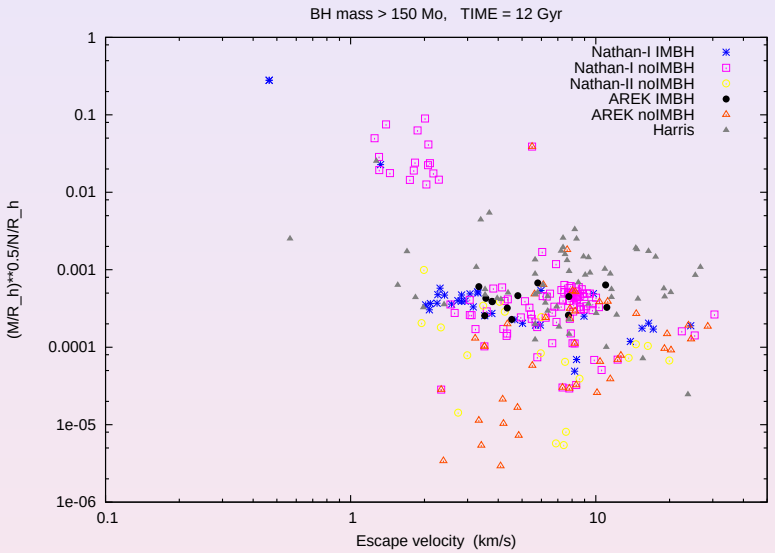




- Substantial number of events connected with mass transfer or mergers with IMBH;
- Possible observation of X-Ray and/or GR emissions;
- For FAST scenario at present there is very small probability of observation of X-Ray emission connected with mass accretion, but there is large probability of observation of GR.

IMBH Formation - Possible Conditions





- Taking average system properties, the probability of interaction of a average binary on the boundary between soft/hard binaries is proportional to $< m > /M^{1/2}/Rh^{3/2}$;
- It seems that at T = 0 there is a statistical boundary between models which can or cannot form IMBH;
- Some Galactic GCs seem to have parameters which suggests that they can contain IMBH, e.g. Omega Cen, 47 Tuc, M22, NGC6397.

Conclusions

Summary

- MOCCA code is capable to simulate evolution of star clusters from open cluster up to extremely massive and dense cluster (e.g. nuclear star cluster);
- 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 and mergers with IMBH. Therefore, X-ray and GR emissions 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.