New Scenario for IMBH Formation in Globular Clusters - Recent Developments and Observational Imprints

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Stellar Aggregates over Mass and Spatial Scales
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Collaborators

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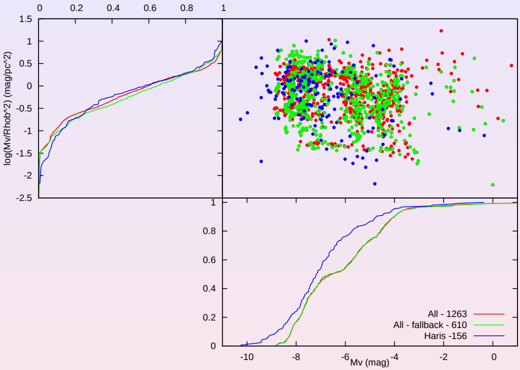
MOCCA Survey I - Initial Conditions

N	R_t (pc)	R_t/R_h	W_0	Z	f_b	Natal Kicks	Number of Models
4.0×10^4	30, 60, 120	25, 50, Filling	3.0, 6.0, 9.0	0.001, 0.005, 0.02	0.05, 0.1, 0.3, 0.95	Fallback & No Fallback	486
1.0×10^5	30, 60, 120	25, 50, Filling	3.0, 6.0, 9.0	0.001, 0.005, 0.02	0.05, 0.1, 0.3, 0.95	Fallback & No Fallback	513
4.0×10^5	30, 60, 120	25, 50, Filling	3.0, 6.0, 9.0	0.001	0.1, 0.3, 0.95	Fallback & No Fallback	166
7.0×10^5	30, 60, 120	25, 50, Filling	3.0, 6.0, 9.0	0.0002,0.001,0.005, 0.006 0.02	0.1, 0.3, 0.95	Fallback & No Fallback	619
1.2×10^6	30, 60, 120	25, 50, Filling	3.0, 6.0, 9.0	0.001	0.05, 0.1, 0.95	Fallback & No Fallback	164

Table : About 2000 models. BH and NS kicks are the same, 265 km/s, except the case of mass fallback Belczynski et al.(2002). Two segment IMF (Kroupa 2001) was used for all models, with $M_{min} = 0.08M_{\odot}$ and $M_{max} = 100.0M_{\odot}$. If the binary fraction, f_b, is equal to 0.95 then binary parameters are chosen according to Kroupa (1995) (eigenevolution, mass feeding algorithm), otherwise eccentricity distribution is thermal, mass ratio distribution is uniform and semi-major distribution is uniform in logarithm, between $2(R_1 + R_2)$ and 100 AU. R_t - tidal radius, R_h - half-mass radius, W_0 - King model parameter, Z - cluster metallicity. For each initial number of objects different combinations of parameters are used to generate the initial model. The number of models with different metallicities are as follows: 63, 831, 487, 64 and 503 for Z = 0.0002, 0.001, 0.005, 0.006 and 0.02, respectively.

MOCCA Survey I - Initial Conditions



Models for the Survey were not selected to match the observed Milky Way GCs. Except for few bright (massive and intermediate mass) Galactic GCs, the agreement with the observational properties of Galactic GCs is quite good. Despite this agreement, any combination of global observational properties of GCs cannot be used to clearly distinguish between different cluster models because there is a strong degeneracy with respect to the initial conditions.

It can be assumed that the Survey cluster models are representative of the MW GC population.

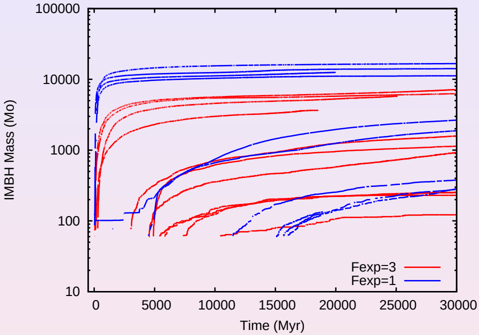
IMBH Formation

Scenarios for IMBH formation:

- Direct collapse of very massive first generation stars, Population III stars (Madau & Rees 2001);
- Runaway merging of massive main sequence stars in very dense young star clusters (Portegies Zwart et al. 2004);
- Accretion of residual gas on stellar mass BHs formed from the first generation of stars (Leigh et al. 2013);
- Buildup of BH mass due to mergers in dynamical interactions and mass transfer in binaries.

There are a lot of indirect observations suggesting presence of IMBHs in nearby galaxies or Milky Way GCs. They are based on the detection of strong X-ray or radio emissions at of-centre positions in distant galaxies, not confirmed X-ray or/and radio emissions in some Galactic GCs or on kinematical and spatial structures of central parts of GCs. There is no FIRM observational confirmation of IMBH presence in GCs.

IMBH Formation



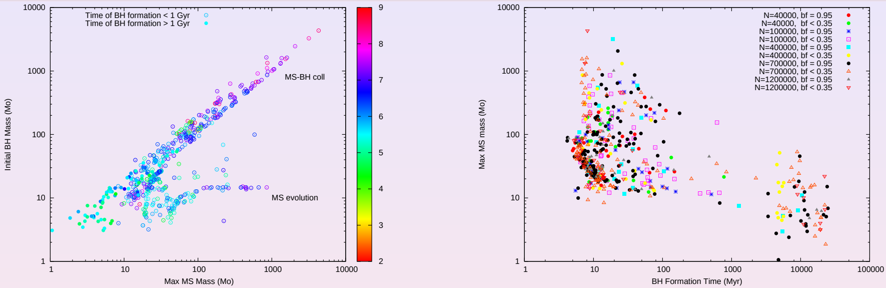
- The process of IMBH formation is highly stochastic. The larger the initial cluster concentration, the earlier, faster and with higher probability an IMBH will form. IMBHs were formed in 462 models out of 2000 models, even in low N models, for N = 40000 and 100000;
- Two variants of the new scenario for IMBH formation. The SLOW and FAST scenarios. They occur later or earlier in the cluster evolution and require smaller or extremely large central densities, respectively;
- IMBH formation does not strongly depend on details of mass accretion onto BH and the detailed structure of a star after physical collision with another star.

IMBH Formation cont.

- There are two possible variants of the IMBH formation scenario: SLOW and FAST.
  - SLOW scenario - either a single BH is left after the early phase of SN explosions, or a single BH is formed via mergers or collisions during dynamical interactions - usually around the core collapse time - central density larger than about $10^5\ M_\odot/pc^3$;
  - FAST scenario - several dozen/hundreds BHs remain in the system after the early phase of SN explosions, and form a dense central subsystem. The central density must be extremely high (greater than $10^8\ M_\odot/pc^3$) for an IMBH to form. Alternatively, all BHs are quickly and efficiently removed from the system via dynamical interactions. If at least one remains, then the SLOW scenario is followed.
- Initial mass buildup of IMBH progenitors.
  - If the cluster density is large enough the collisions between MS stars lead to the formation of very massive, MS like stars (hundreds of $M_\odot$). If such a star collides with a BH then a very massive BH (IMBH) is formed, if not, it will form a very massive BH, because of stellar evolution. Next, the BH in three-body interactions forms a binary.
  - If the density is lower a stellar mass BH, formed because of stellar evolution, creates a binary via a three-body interaction.
- Dynamical interactions with other binaries and stars:
  - orbit tightening leading to mass transfer from MS/RG/AGB companions;
  - exchanges and collisions, leaving the binary intact;
  - *total* collisions during dynamical interactions or mergers induced by the gravitational radiation - only the BH is left. Then the single BH forms a new binary via another three-body interaction. The process is repeated. Because of the total collisions, BH mass can steadily increase and BHBHs are not kicked out from the system.

The SLOW scenario, does not require any specific conditions, unlike other scenarios.

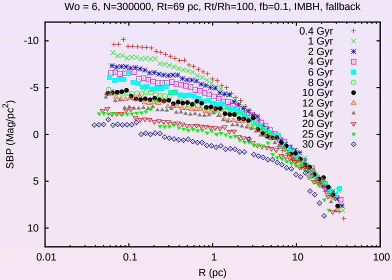
MS –> BH Mass



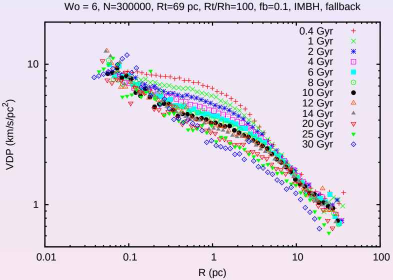
- Clearly visible different branches of BH formation: runaway MS mergers and collisions with BH, runaway MS mergers and stellar evolution;
- Less dense models form lower mass BH, which later in the course of evolution will substantially grow. Very massive BHs are preferentially formed for very dense models at the very beginning of the cluster evolution;
- The initial mass of BH which will form an IMBH is smaller for models which form IMBH late in the cluster evolution. Only low mass MS stars are available;
- Low N clusters can form IMBH only at the beginning of the cluster evolution - interesting conclusion for observers.
- There is no visible correlation between cluster metalicity and the mass of BH, which will later form an IMBH. Also the mass of BH does not depend strongly on the initial binary fraction and the details of SN kicks This are rather unexpected conclusions.

Spatial and Kinematic Properties

IMBH Formation - SBP

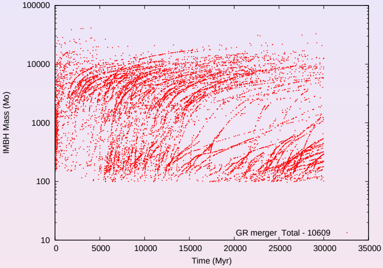


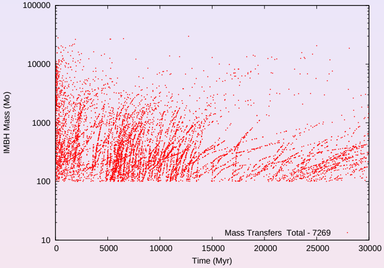
IMBH Formation - VDP



- Development of flat SBP with a large core radius and a steeply rising VDP toward the cluster centre is clearly visible;
- The IMBH begins accreting mass almost immediately, eventually increasing its mass to 7000 $M_\odot$;
- The Jeans' model fitted to the simulated VDPs and SBPs shows a good agreement with IMBH mass from the MOCCA simulation;
- Motion of the IMBH is significant, particularly for IMBH masses less than about a few hundreds of $M_\odot$. The off-centre positions of massive IMBHs can alter the structure of the underlying cluster potential, and hence influence the orbits of cluster stars;
- The presence of an IMBH will show a clear signal in the VDP for IMBH masses larger than about $1000 - 2000\ M_\odot$.

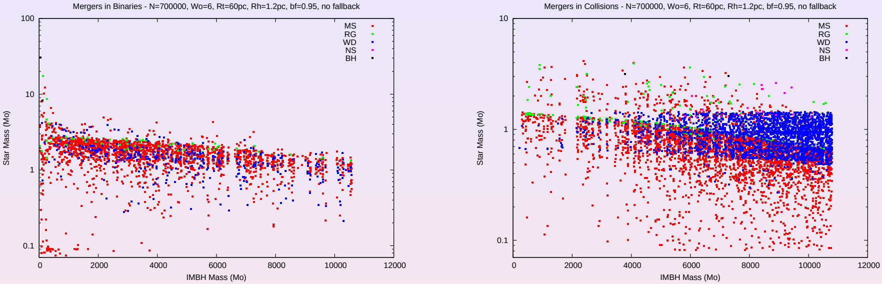
GR and Mass Transfer Events





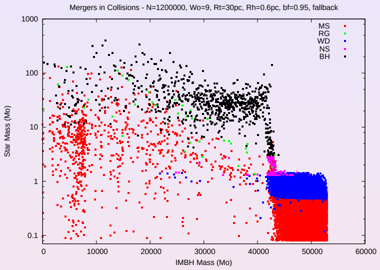
- A clearly visible pattern of IMBH mass buildup for both GR and Mass Transfer events;
- At around $3 - 5$ Gyr and around $15 - 20$ Gyr there is a smaller rate of IMBH mass buildup
- For masses between about $500 - 5000\ M_\odot$ and for times larger than about 15 Gyr there are less models which buildup the IMBH mass;
- For Mass Transfer events for IMBH masses larger than about $5000\ M_\odot$ there is a clearly visible deficit of such events;
- The most numerous and mostly contributing to the build up of IMBH mass are mergers with IMBHs - mergers during direct physical collisions of two separate stars or mergers in binaries during dynamical interactions. There is about 2.5 million of such events.

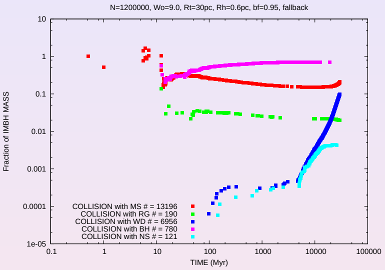
IMBH - TDEs



- The IMBH was formed at about 2 Gyr in the SLOW scenario. At 12 Gyr the IMBH mass was about $8000\ M_{\odot}$. There are 2836 and 6726 mergers in binaries and collisions, respectively;
- Interactions with binaries are more important than collisions in the first phase of IMBH mass buildup;
- When the mass of IMBH becomes large enough, about $4000\ M_{\odot}$, collisions are more important than interactions with binaries;
- For larger IMBH masses, about $8000\ M_{\odot}$, collisions between IMBH and WD are the most frequent;
- If TDEs for MS and WD have different observational signatures, then WD TDEs should be preferentially observed at positions off-center of galaxies.

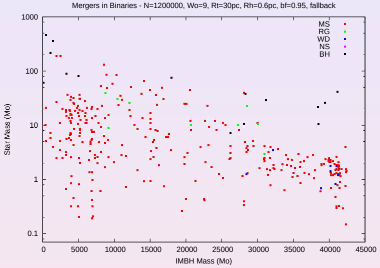
IMBH - TDEs Extreme Case

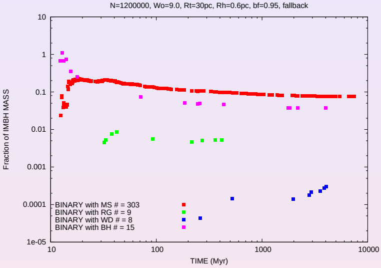




- Model more suitable for a Nuclear Star Cluster than for a GC. At T = 25 Myr the IMBH mass is already about 8000 $M_\odot$ and the mass of about 35000 $M_\odot$ is achieved at about T = 1 Gyr. The accretion rates are about $3.2x10^{-4} M_\odot / yr$ and $3.5x10^{-5} M_\odot / yr$, respectively;
- Collisions with other massive BHs are responsible for the initial IMBH mass build up. Always the mass of BHs colliding with the IMBH is much smaller than the IMBH mass - the GR kicks are reduced and the IMBH can be retained in the system;
- For more than 1 Gyr very massive IMBH coexists with very massive BHs subsystem;
- For times comparable with the Hubble time, collisions between IMBH and WD are the most frequent.

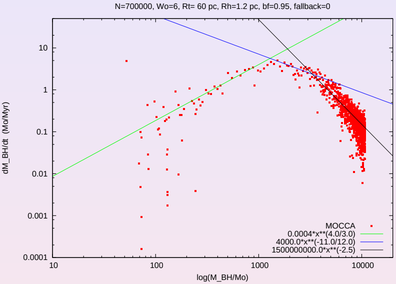
IMBH - TDEs Extreme Case con.

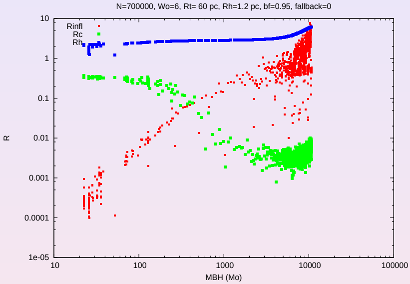




- TDEs in binaries are very much less frequent than TDEs connected with collisions of single objects;
- At the beginning, mergers with other massive BHs are responsible for the IMBH mass build up in binaries. Then massive MS stars take over;
- For times much smaller than the Hubble time TDEs in binaries become unimportant;
- If one can treat this model as a model of low-mass NSC, and if it is PHYSICAL then rescaling it to a larger masses a SMBH of mass about $10^6 M_\odot$ can be formed in a time of few tens of Myr !!!.

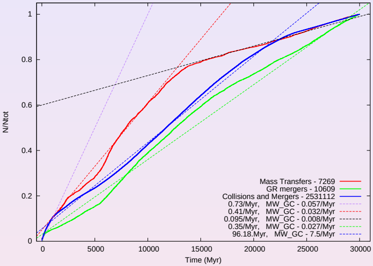
IMBH - Theory and Simulations

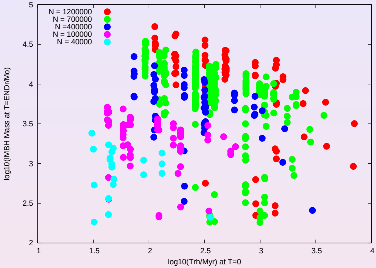




- Very good agreement with theoretical predictions (Stone, Küpper and Ostriker 2016) for the IMBH mass buildup. Green line - BH Brownian motions and full loss-cone. Blue line - empty loss-cone. Black line - ?;
- The observed agreement is rather unexpected. The theoretical predictions were derived under assumption of tidal captures and disruptions by IMBH. These effects are not included yet in the MOCCA code; Probably interactions with binaries behave similarly to tidal interactions - larger cross-section. Later, collisions become more and more important;
- The changes between different regimes happen when the core radius is comparable to the IMBH influence radius and the influence radius is comparable to the half-mass radius, respectively.

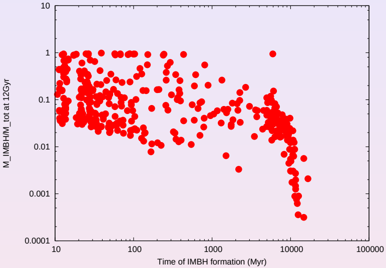
Rate of “Observational” Events

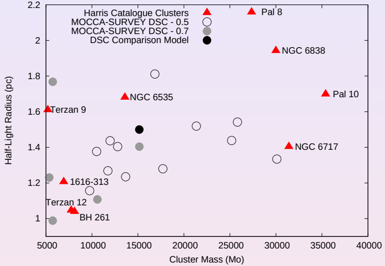




- The cumulative distributions for GRs, Mass Transfers or Mergers/Collisions can be roughly approximated by straight lines;
- Assuming that simulated models are representative for the population of real GCs we can estimate the rate of occurrence of particular types of events - the numbers are very small. There is a rather small chance to observe them;
- An IMBH can be formed even in very small N clusters provided that the initial half-mass relaxation time is smaller than about 200 Myr. An interesting observational conclusion. Maybe to look for IMBHs in star cluster we should get interest in YMSC?;
- These findings seem to agree with results of Breen & Heggie (2013) - substantial number of BHs can be kept only in the system with half-mass relaxation time larger than about 1 Gyr. Such environments are not suitable for IMBH creation.

IMBH - Dark Cluster



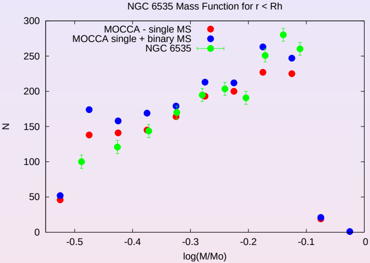


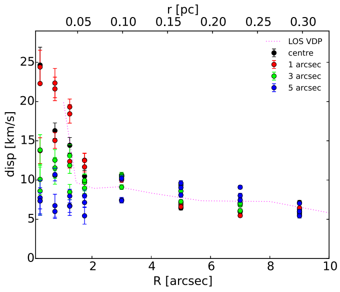
- The mass ratio between the IMBH mass and the total cluster mass for the majority of models is of the order of several hundredths. There are clearly visible “DARK CLUSTERS” and the tail of just formed IMBHs with very low mass. The spread of the mass ratios is substantial for 12 Gyr;
- Dark Clusters should have very large M/L of the order of over a dozen, deficiency of low mass stars and rising VDP in the center. Their galactocentric distances should be small (a few kpc) to efficiently tidally strip the clusters;
- It seems that the NGC 6535 is a very good candidate for a Dark cluster.

IMBH - Dark Cluster con.

Left Panel: Mock observation of the Dark Cluster model wit an 8-meter class telescope (FOV:2.73 x 2.73 arcmins). The image was created using COCOA software (Askar et al. 2016a) an 12 Gyr MOCCA snapshot for the cluster model. The RGB image was obtained by combining synthetic observations in the I, V and B filters. The model was projected at a distance of 6.8 kpc in order to compare it with NGC 6535.
Right Panel: Hubble Image of NGC 6536 from 4 different filters (FOV: 3.31 x 3.28 arcmins).

IMBH - Dark Cluster con.





- Very good agreement with observed MF for NGC 6535 (Halford & Zaritsky 2015) - strong deficiency of low mass stars;
- Integrated-light velocity dispersion profiles obtained by the SISCO code (Bianchini et al. 2016) for the mock observations of the model snapshot at 12 Gyr with different position of the cluster center. A small displacement may lead to the disappearance of raising VDP. Good agreement with observed proper motion VDP (Watkins et al. 2015) - observations not close enough to the cluster center;
- If NGC 6535 harbors an IMBH then it may be possible to detect it with IFU observations;
- We have applied for observational time on two IFU instruments (ARGUS and SYNFONI) on ESO VLT telescope to observe NGC 6535 and check whether it may be harboring an IMBH.

Conclusions

Summary

MOCCA code is capable to simulate evolution of star clusters from open clusters up to nuclear star clusters;

If the system density is about $10^5 M_\odot/pc^3$ the BH mass can build up only because of dynamical interactions and mass transfer in binaries - SLOW scenario. For the FAST scenario even larger densities are needed (about $10^8 M_\odot/pc^3$). The mass buildup starts from the very beginning;

The process of IMBH formation is highly stochastic and 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 - small expected rate; TDEs are the most probable to observe. For MW GCs the rate is expected to be about 10 per Myr, but for the local Universe the rate can be substantial. TDEs can be observed at positions off-centre of galaxies;

Dark Clusters and YMSC are most promising for an IMBH search.

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;

MOCCA code is not prepared to follow physical processes connected with the loss-cone effect;

The *Fewbody* code (Fregeau et al. 2004) seems to work properly for the very large mass ratios - several checks were carried out, never for a mass ratio larger than $10^4 - 10^5$;

There are strong 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 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;

Amount of accreted on IMBH mass from dissolved/collided object is very uncertain, probably substantially less than 50%;