Intermediate Mass Black Holes and the Evolution of Star Clusters
Lecture VIII

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Star Cluster Dynamics and Evolution

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Why are IMBHs so important?

- A missing link between stellar-mass black holes (BH) and supermassive BHs (SMBH)
- Observational confirmation of the existence of IMBHs would have an important impact on a number of open astrophysical problems related for e.g. to:
  - formation of SMBHs and their host galaxies,
  - origins of ultraluminous X-ray sources and tidal disruption events in nearby galaxies,
  - detection of gravitational waves (GR).
- Globular clusters (GC) are a natural site for IMBH formation. Proximity of GCs makes it possible to directly observe kinematical and structural imprints of IMBHs.

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-center positions in distant galaxies, not confirmed X-ray or/and radio emissions in some Galactic GCs or on kinematical and spatial structure of central parts of GCs.

There is no FIRM observational confirmation of IMBH presence in GCs

Theory - IMBH formation processes

- Direct collapse of very massive first generation stars, Population III stars (Madau & Rees 2001).
  - The very first generation of stars must have formed out of unmagnetized, metal-free gas;
  - Stars were formed at so called mini halos of mass about $10^5\ M_\odot$ at redshift about 20;
  - The Population III stars are formed with IMF extremely top heavy. Stars with masses larger than $200 - 300\ M_\odot$ can be formed;
  - 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).
  - How could such extremely massive BHs become members of GCs consisting of Population II stars?.

Theory - IMBH formation processes

- Runaway merging of massive main sequence stars in very dense young star clusters (Portegies Zwart et al. 2004, Freitag et al. 2006).
  - Time scale of the mass segregation of the most massive stars (about $100\ M_{\odot}$) has to be shorter than the evolution time-scale for those stars, otherwise massive stars will evolve before they will start to collide;
  - The velocity dispersion in the collapsed star cluster cannot be larger than a few hundred km/s - otherwise collision will disrupt stars;
  - Frequent collisions between stars lead to the formation of very massive stellar type objects - amount of the mass loss depends on the cluster metallicity;
  - Formation of BH due to SN usually without substantial mass loss;
  - Well tailored initial conditions are needed to initiate the runaway merging process - very concentrated clusters.

Theory - IMBH formation processes

- Accretion of the residual gas on stellar mass BHs formed from the first generation stars (Leigh et al. 2013).
  - 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 leads to a substantial increase of BH masses and a speedup of their mass segregation and finally, to the formation of a very massive BH, an IMBH seed;
  - Residual gas removal takes a few Myr, so there is not enough time and not enough residual gas to build very massive BHs.
- The most massive globular clusters are probably stripped cores of dwarf galaxies and therefore also more likely to host central very massive BHs. It is believed that Omega Cen is such a GC;

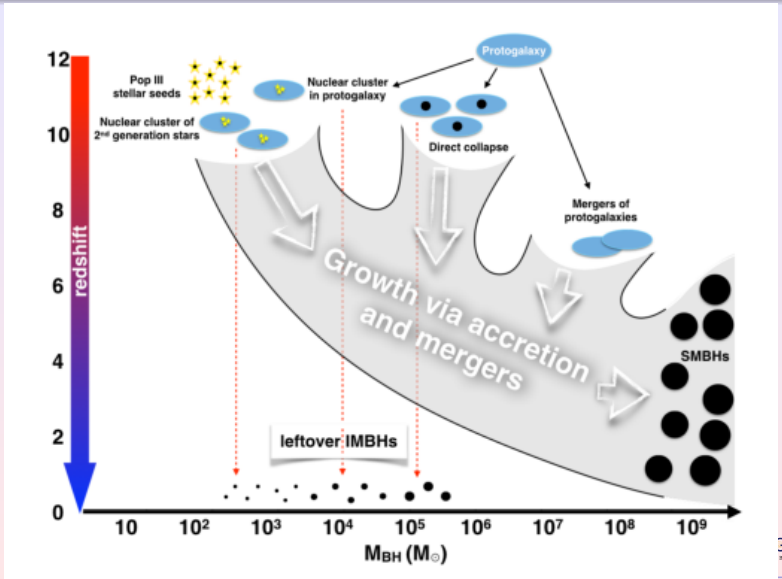
Theory - IMBH formation processes

- Buildup of BH mass due to mergers in dynamical interactions and mass transfer in binaries, Giersz et al. 2015
  - There is no need for any special conditions to initiate the process of IMBH mass buildup, but process is extremely stochastic

The new scenario of IMBH formation is based on an analysis of about 2000 simulations (Survey I) with different masses, concentrations, metallicities, initial binary populations, binary fractions and SN kicks.

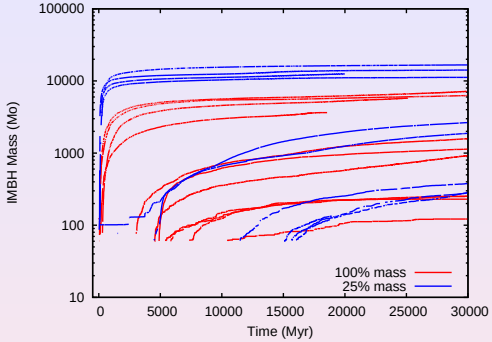
Old SNe treatment - smaller BH masses. Smaller influence of BH Subsystem on cluster evolution

Theory - IMBH formation processes



Credits: Mezuca 2017

Simulations - IMBH Formation



There are two scenarios for IMBH formation. The SLOW and FAST scenarios. They occur later or earlier in the cluster evolution and require smaller or very large central densities respectively.

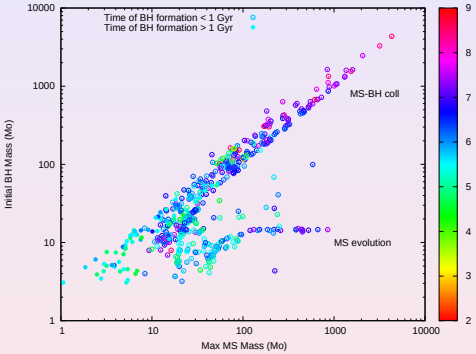
The process of IMBH formation is highly stochastic. The larger the initial cluster concentration, the earlier, faster and with higher probability an IMBH will form.

Simulations - IMBH Formation

- 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;
  - FAST scenario - several dozen 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 formation of very massive MS 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 stellar mass BH, because of stellar evolution. Next, BH in three-body interactions form a binary.
  - If the density is lower a BH forms directly 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 in tact;
  - *total* collisions during dynamical interactions or mergers induced by the emission of gravitational waves - in this case, the binary is destroyed and only a BH is left. The single BH then forms a new binary via another three-body interaction, which is free to undergo subsequent dynamical interactions with other single and binary stars, and the process repeats. In this way, the BH mass steadily increases.

It is worth noting that the presented scenarios for IMBH formation in GCs, in particular the SLOW scenario, do not require any specific conditions, unlike other scenarios proposed in the literature.

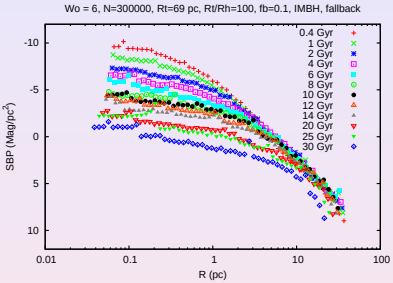
MS –> BH Mass



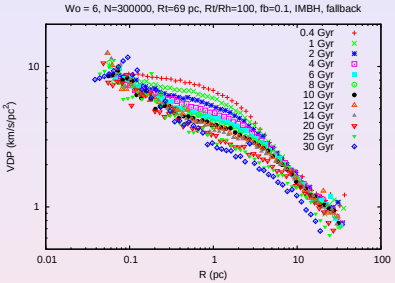
- Clearly visible different branches of BH formation: runaway MS mergers and collisions with BH, runaway MS mergers and stellar evolution;
- Less dense models form lower mass BH, which later in the course of evolution will substantially grow. Very massive BHs are preferentially formed for very dense models at the very beginning of the cluster evolution
- Small N clusters can form IMBH only in the SLOW scenario

Spatial and Kinematic Properties

IMBH Formation - SBP

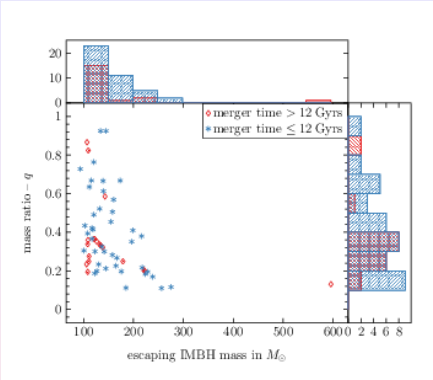


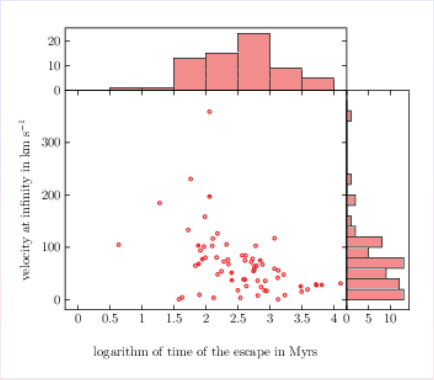
IMBH Formation - VDP



- Development of flat SBP with a large core radius and a steeply rising VDP toward the cluster center
- The IMBH begins accreting mass almost immediately, eventually increasing its mass to about 7000 $M_\odot$
- IMBH masses can be successfully recovered using Jeans equation for MOCCA snapshots

Escaping IMBHs



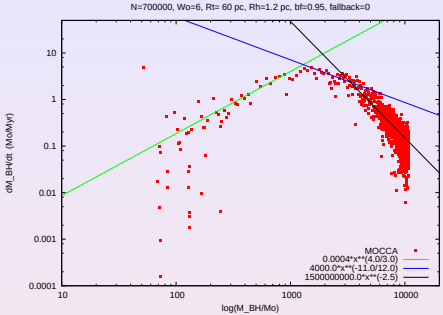


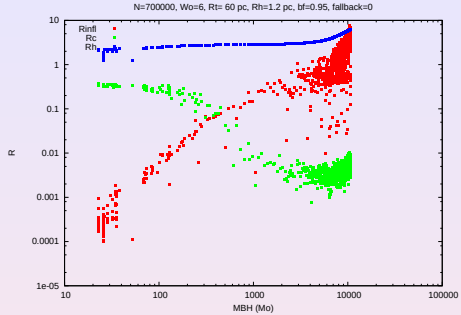
Credits: Maliszewski et al. 2022

IMBH seeds can be kicked out from the system due to dynamical interactions. Kicks happen usually at the beginning of cluster evolution in the presence of BHS.

The intruder does not have to be very massive, and the interaction does not have to be strong

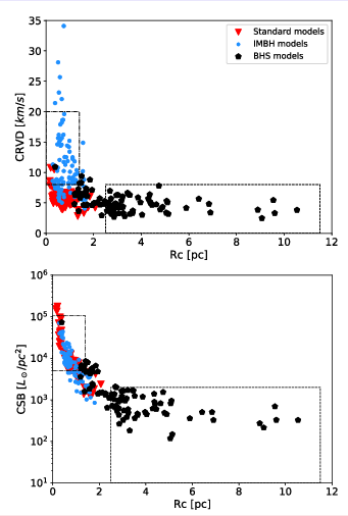
IMBH - Theory and Simulations



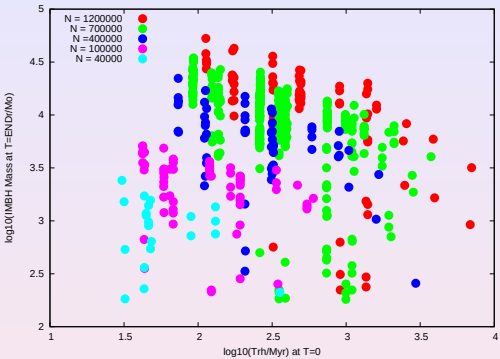


- Very good agreement with theoretical predictions (Stone, Küpper and Ostriker 2016) for the IMBH mass buildup. Green line - BH Brownian motions and full loss-cone. Blue line - empty loss-cone. Black line - ?;
- The changes between different regimes happen when the core radius is comparable to the IMBH influence radius and the influence radius is comparable to the half-mass radius, respectively.

IMBH Simulations and Observations



Credits: Leveque et al. 2021



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

GCs with IMBH have large CSB and VD

Short Summary

- IMBHs are a missing link between stellar mas BHs and SMBHs
- The most probable site for IMBH formation is a dense and massive star cluster
- Generally, there a two scenarios for IMBH formation in star clusters:
  - FAST - at the very beginning for very dense systems
  - SLOW - after BHS removal and core collapse
- IMBHs can be kicked out from star clusters due to dynamical interactions
- The rate of IMBH mass buildup depends on the ratio between Influence Radius and characteristic cluster radii: R_h and R_c
- Star clusters with IMBHs have larger CSB and VD than other type of clusters