Galaxies collisions in galaxy cluster core: formation of tidally stripped dwarf galaxies and massive black holes merging

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ABSTRACT

In this work we investigate the coalescing process of several galaxies moving inside the core of a galaxy cluster with mass $M_{cl} \cong 10^{14}\, M_\odot$ using direct N-body simulations at high resolution. We found that mutual interactions between galaxies drive the formation of a massive central system (MCS), whereas, on the other hand, tidal forces drive the formation of a population of small galaxies, possibly connected with the "Ultra Compact Dwarfs" (UCDs), observed in several clusters core. Moreover, we investigated how a population of super massive black holes (SMBHs) evolve and interact during and after the galaxies collisions. If two merging galaxies host a central SMBH, it is widely thought that the two SMBHs form a binary system (SBHB). However, it is currently unclear the fate of the SBHB if another galaxy hits the merging product in which the SBHB is harbored. We ran 100 simulations by varying the configuration of SMBHs population. We found that in 39% of the cases, the SBHB merges within 100 Myr from the MCS formation. These results can be related to the so called "final parsec problem", by which the hardening of a massive SBHB is limited because of a decrease in the efficiency of SBHB-star scattering. Our results suggest that the problem disappears even in consequence of a collision involving at least three galaxies, with a non-negligible probability.

NUMERICAL METHOD

Variable	Value
M_{cl}	$9.2 \times 10^{13}\, M_\odot$
N	1048576
$N_{galaxies}$	240

To simulate the dynamical evolution of the cluster model we used a modified version of the direct N-body code **HiGPUs**[1], that runs on a hybrid platform hosting GPUs. Each particle moves according to the equation of motion:

$$m_i \ddot{\vec{r}}_i = \sum_j \frac{m_i m_j}{r_{ij}^3} \vec{r}_{ij} + \vec{F}_{ext}$$

Modelling the galaxies: The galaxies mass are distributed following[2,3] $f(M_g) \propto M_g^{-1}$. Each galaxy has been modelled according to the so-called Dehnen model with $0.2 < \gamma < 1.74$. The galaxy scale radius r_g is related to the galaxy half mass radius r_h.

$$\rho(r) = \frac{(3-\gamma)M_g}{4\pi r_g^3} \left(\frac{r}{r_g}\right)^{-\gamma} \left(1+\frac{r}{r_g}\right)^{-4+\gamma}$$

$$r_h = \frac{1}{2^{1/(3-\gamma)} - 1} r_g$$

Modelling the cluster: We placed the galaxies in the space according to a King profile[4] with $\varrho_0 = 1.47 \times 10^{-3}\, M_\odot$, $r_c = 0.1$ Mpc, $r_{cut} = 3.85$ Mpc. The presence of r_{cut} ensures that the cluster mass distribution converges to a finite value.

$$\rho_{cl} = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1} \frac{1}{\cosh(r/r_{cut})}$$

Modelling the super massive black holes: to assign the SMBH masses we use the correlation between BH and galaxy mass[5].

$$\mathrm{Log}\, M_{BH} = \alpha\, \mathrm{Log} \left(\frac{M_g}{10^{11.3}}\right) + \beta$$

$$\alpha = 1.37 \qquad \beta = 8.47$$

The evolution of the SMBHs population follows three steps:

- **HiGPUs** This code is used to perform high resolution simulations. After around 5 Gyr of the evolution, we get the positions of the 21 merging galaxies centre of mass.
- **CODEs** With this semi-analytical code[6] we followed the trajectory of the galaxies up to the formation of the first super massive black hole binary.

$$r(t) = r_0 \left(1 - \frac{t}{\tau_{DF}}\right)^{0.57}$$

- **ARGdf** This code allows strong collision treatment through the AR scheme[7]. We performed 100 simulations to investigate the binary evolution.

RESULTS

Massive Central System

We followed the orbits of the central galaxies, which are are efficiently affected by dynamical friction, which drags them toward the cluster centre (Fig. 1).

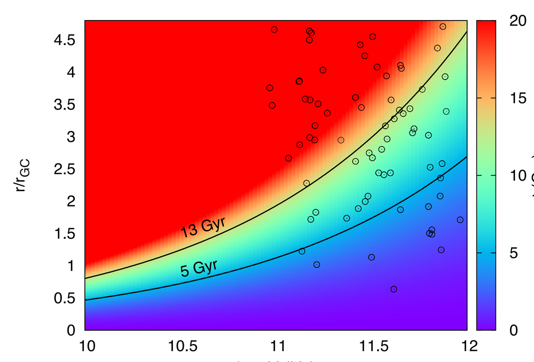

Fig. 2. Surface map of dynamical friction time scale at varying M_g and r.

Our results show that a sequence of 21 merging and collisions drives the formation of a massive central system (MCS), according to a semi-analytical estimate (Fig. 2).

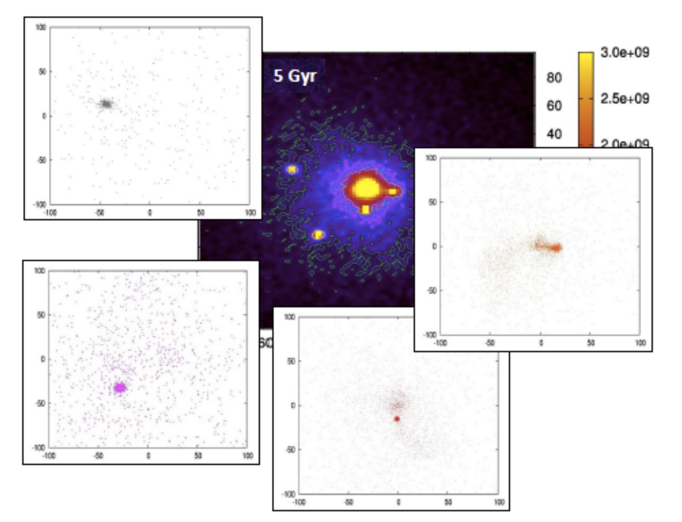

Fig. 2. Surface density map of the largest merging product formed in all the simulations. The bright spots located around the central spot are tidal debris of galaxies that move around the cluster centre, as indicated in the 4 panels.

$$\rho_{MCS} = \frac{3M_{MCS}}{4\pi r_{MCS}^3} \left(1 + \frac{r}{r_{MCS}}\right)^{-4}$$

$$M_{MCS} = 3.3 \times 10^{12}\, M_\odot$$
$$R_{MCS} = 4\, \mathrm{kpc}$$
$$R_h = 15.5\, \mathrm{kpc}$$

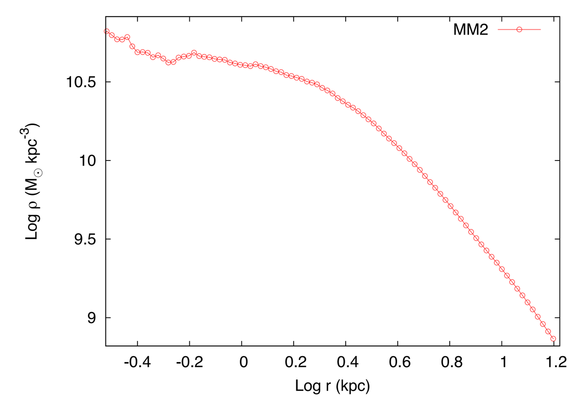

Fig 3. Density profile of the MCS formed in the cluster central regions.

QR code: movie of the MCS formation

Tidal stripping

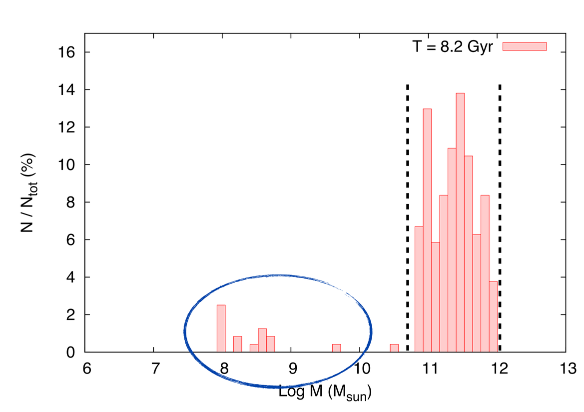

Fig 4. Mass distribution of all galaxies at T=8.2 Gyr. It is evident the formation of a small fraction of galaxies with masses 10^8-$10^{10}\, M_\odot$

In our simulations, the tidal force acting on the infalling galaxies induces a strong mass-loss, leading to the formation of a group of galaxies with a mass in the range (10^8-10^{10}) $M_\odot$, smaller than the minimum value allowed for our initial galaxy models (Fig. 4). These results can be related to the possible nature of the UCDs[8,9], although masses of stripped galaxies found in our runs are clearly greater that the UCDs expected ones. Moreover, it has been stressed here that the initial galaxies mass considered at the beginning of the simulations plays a crucial role in the tidal stripping process.

SMBH interactions

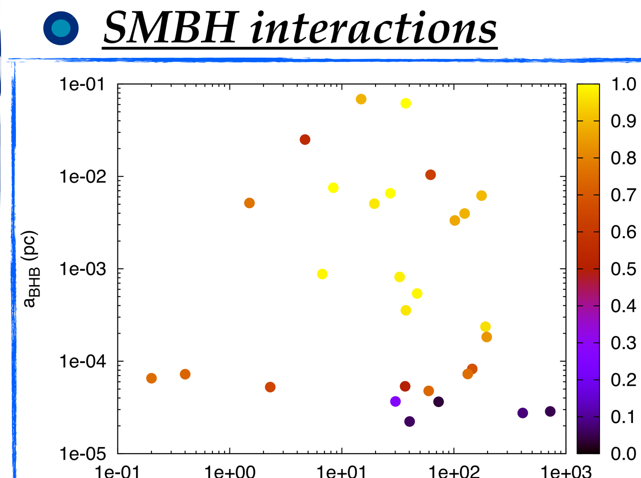

Fig 5. Time at which a SBHB coalesces in all the simulations performed as a function of its semi-major axis. The color coded map represents the BHB eccentricity.

Dynamical interactions between SMBHs affect significantly their evolution, leading to merging events of highly eccentric binaries within 300 Myr in the 39% of the studied cases[10,11].

- **15%** the coalescence occurs between the original BHB components;
- **16%** the primary merge with another SMBH;
- **4%** the coalescence occurs between the original secondary and another SMBH;
- **4 %** the merging occurs between two SMBHs different from the BHB component.

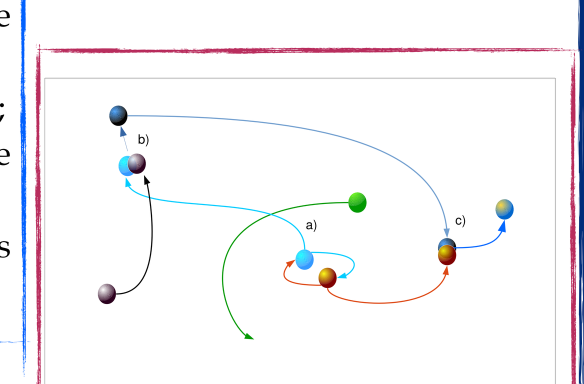

Fig 5. Phase a) SBHB is broken up; phase b) secondary merges with another SMBH; phase c) the resulting SMBH comes back, binds to the original primary and merges with it.

In the 4% of the cases, there are at least two mergings event.

CONCLUSIONS

- By using direct N-body simulations we studied the evolution of the innermost region of a mid-weight galaxy cluster composed of 240 galaxies.
- We found that around 21 galaxies reach the cluster core within 5 Gyr, driving the formation of a massive central system with a well defined density profile and for which we evaluated the structural properties (mass, half mass radius and velocity dispersion profile). These values are in agreement with semi-analytical estimates.
- Tidal forces induces the formation of a population of tidally stripped galaxies with a mass two orders of magnitude smaller than the minimum mass allowed. These results may be related to UCDs, observed in several clusters core.
- Assuming that each galaxy contains a SMBH, we used a modified version of the well known AR scheme to perform a set of simulations, following the evolution of a population of SMBHs residing in the centre of galaxies forming the MCS. In particular we followed the merging phase from the formation of the first SBHB.
- Our results show that in 39% of the cases, the SBHB merges within 100 Myr from the MCS formation. In 35% of these cases, the merging occurs between one of the original component of the SBHB and an infalling SMBH. The SBHB stalling problem disappears, with high probability, in consequence of a collision involving at least three galaxies.

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