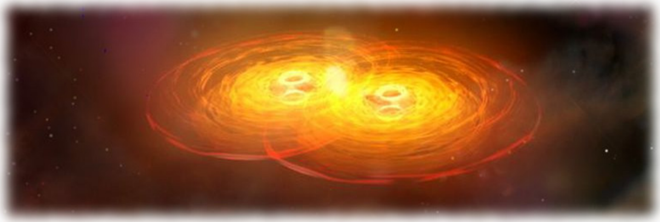

Dynamics of Massive Black Hole Binaries in Galactic Merger Remnants

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Modelling and Observing Dense Stellar Systems
Kobe, Japan
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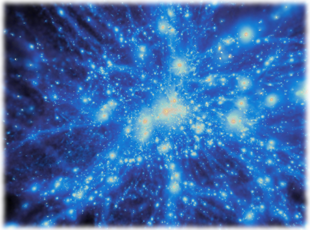
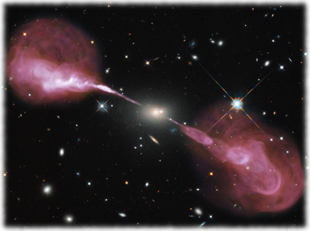
if you have Questions/Advices/AnyThingElse please e-mail me at elisa.bortolas@studenti.unipd.it :)

Cosmological merger paradigm

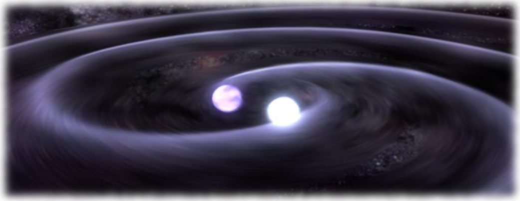


Massive black holes in galactic nuclei



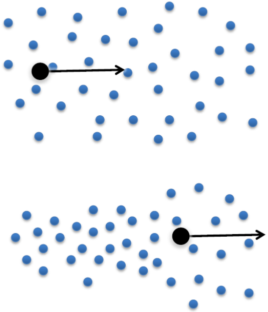
$\Rightarrow$ Formation of a large number of massive BH binaries along the cosmic time

Coalescence via gravitational waves (GW) emission?

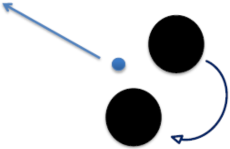


Massive binary evolution

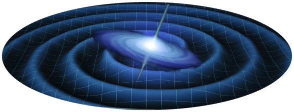
Dynamical friction driven inspiral



Slingshot ejection mechanism



GW emission (at $\sim 10^{-2}$ pc separation)



Is the slingshot ejection mechanism efficient in bringing the binary to GW emission stage?

$\Longrightarrow$ Final parsec problem!

Possible solution to the final parsec problem

$\Longrightarrow$ oversimplified assumption of sphericity

BUT

Is the final parsec problem REALLY solved?

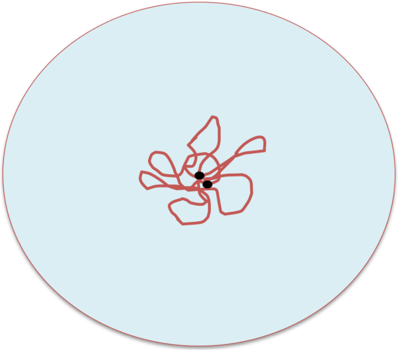
Some other aspects have to be investigated:

- Brownian motion of the binary
- Triaxiality evolution
- Eccentricity evolution

Brownian motion of the binary CoM (1)

- Real galaxies contain about 10^{11} particles
- Direct summation codes can integrate max 10^6 particles
- This limit in resolution brings to an increased Brownian motion of the binary CoM:

$\longrightarrow$ increased number of intersected stellar orbits!



Brownian motion of the binary CoM (2)

Merritt D., 2001, ApJ, 556, 245

- Single black hole: *energy equipartition* with the surrounding stars is expected

$$M_{bin} < V_{bin}^2 > = m_* < v_*^2 >$$

- black hole binary: further effects come into play
  BUT the wandering is still dominated by distant encounters

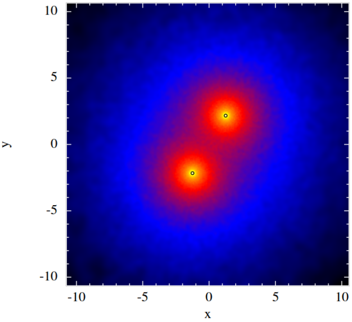
It can be shown that for real galactic nuclei

$$\Delta r_B \sim r_{GW} \ll \Delta r_{B,simulations}$$

$$\Delta r_B \propto N^{-0.5}, \text{ but } N_{real} \gg N_{simul}!$$

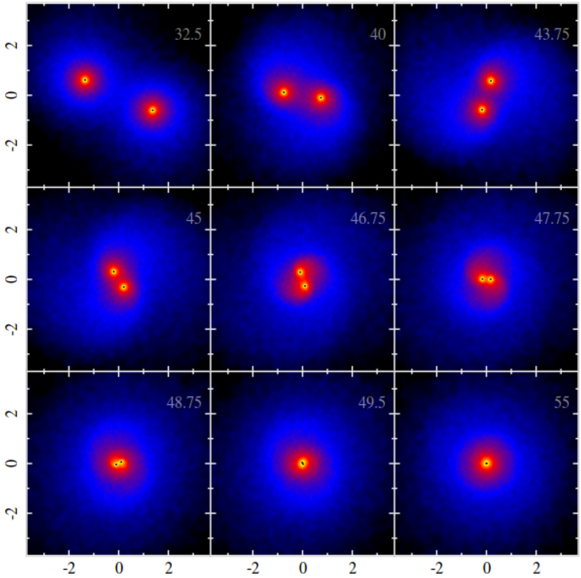
Simulations outline

- Dehnen's models, inner slope $\gamma = 1,\ 1.5$
- black hole masses $M_{BH} = 0.005 M_{gal}$
- initial elliptical orbit $e = 0.5$, $a = 5r_0$

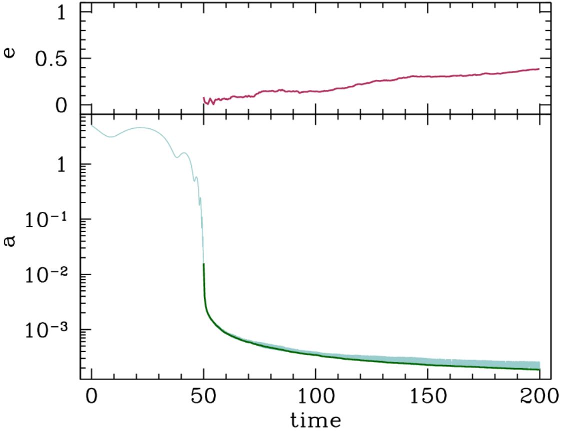


- Integrator: HiGPUs (Capuzzo-Dolcetta, Spera et al, 2013)
  - GPU runs
  - direct summation
  - sixth order Hermite scheme with block timesteps

N = 8k, 16k, 32k, 64k, 128k, 256k, 512k (1M)


32.5
40
43.75
45
46.75
47.75
48.75
49.5
55
-2
0
2

Binary evolution

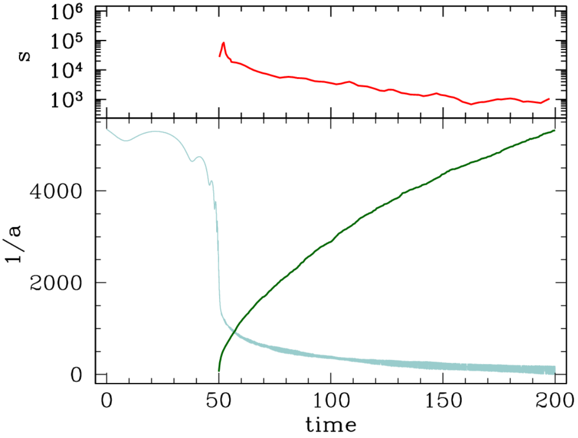


- binary separation
- orbital parameters
  - a
  - e
  - $1/a$
- hardening rate

$$s = \frac{d}{dt}\frac{1}{a}$$

$\rightarrow$ for different values of N!

Binary evolution



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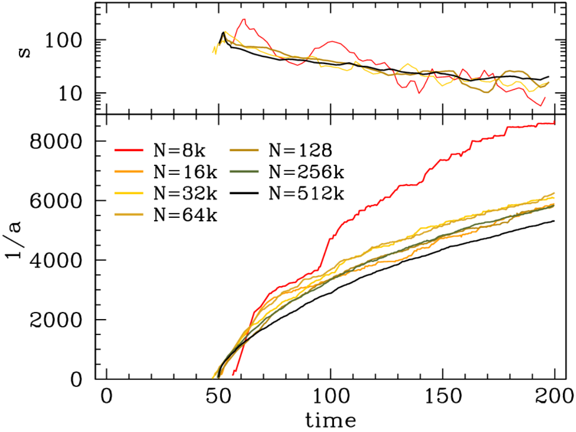

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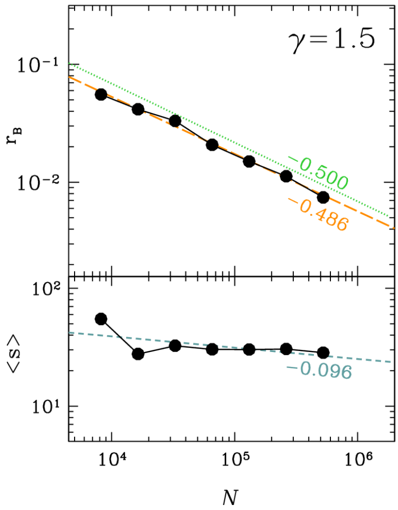
$\rightarrow$ for different values of N!

Binary Brownian motion dependence on N

The time-averaged displacement r_B between the binary CoM and inner system CoM (50% innermost stars) has been computed.



- The Brownian motion is considerably smaller than the scale-radius of the system
- it follows the expected behaviour $r_B \propto N^{-1/2}$
- the hardening rate instead has a weak or *absent* dependence on N
  $\rightarrow$ *especially excluding the low-N realizations*

$\Longrightarrow$ **Less probable artificial binary shrinking due to resolution effects**

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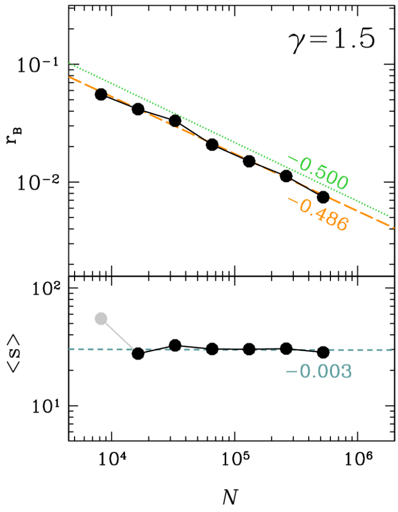

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Triaxiality evolution of the remnant

The merger remnant shows a certain amount of *triaxiality/non-sphericity*

- presence of centrophilic orbits
- more stars can interact with the binary
- nuclear scale gravitational torques

$\Longrightarrow$ triaxiality is believed to play a crucial role in bringing the binary to the GW-emission phase

We are analysing the triaxiality

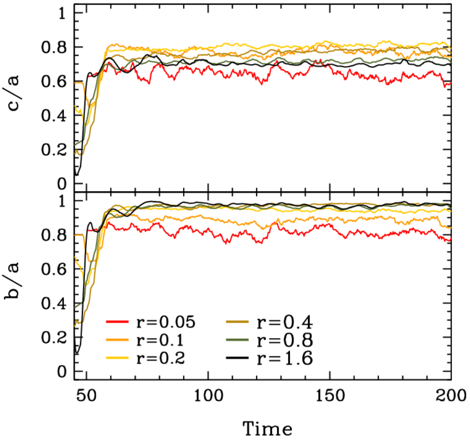
- evolution in time
- at different radii
- varying the initial conditions of the merger (orbit, inner slopes of the initial galaxies...)

The triaxiality has been computed following the procedure described by Katz (1991) and Antonini et al. (2009) and implemented by A. Gualandris.

(EB, A. Gualandris et al., in preparation)

Triaxiality evolution of the remnant (PRELIMINARY)

Evolution of the axis ratios in time for $\gamma = 1$:

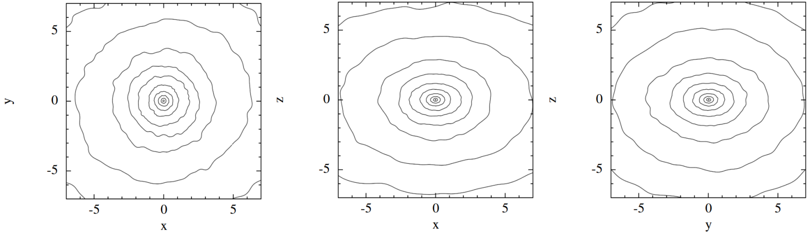


- limited evolution of the axis ratios in time
- steeper initial models and lower initial orbital eccentricities lead to axisymmetric and more regular models

(EB, A. Gualandris et al., in preparation)

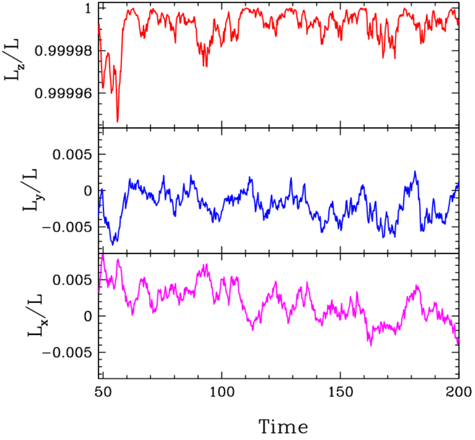
Triaxiality evolution of the remnant (PRELIMINARY)

The models are actually flattened in the plane *xy* of the initial merger



but does the remnant rotate??

Angular momentum analysis (PRELIMINARY)



- Computation of the cumulative stellar angular momentum for the 80% of the innermost stars

The remnant rotates in the plane of the merger!!
This result is valid in all the simulations performed so far.

Summary

- the Brownian motion of the binary seems not to affect its hardening rate
- the binary evolution does not affect considerably the shape of the outer remnant
- the remnant shows triaxiality and rotates in the merger plane
- even a mild triaxiality suffices to keep the binary shrinking (in agreement e.g. with Vasiliev et al., 2015)

Work in progress...

- Dependence of the eccentricity at the formation of the binary on the initial conditions of the merger (paper in preparation)


Thank you!