GRAVITATIONAL WAVE RECOIL IN ANALYTICAL AND NUMERICAL GALAXY POTENTIAL

Majda Smole, Miroslav Micic, Ana Mitrasinovic

Astronomical Observatory, Belgrade
msmole@aob.rs

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Introduction

- Hierarchical growth of structure $\Rightarrow$ galaxy mergers $\Rightarrow$ formation of BH binaries
- Interactions with stars and gas lead to binary hardening.
- Once the separation between BHs becomes $\lesssim 10^{-3}$ pc gravitational wave radiation will efficiently extract angular momentum and energy from the binary system, causing rapid BHs merger.
- Any asymmetry in the binary system will lead to asymmetric emission of gravitational wave radiation and BH recoil.

- Kick velocity depends on the mass ratio of BHs, the spin magnitude and orientation with respect to the binary orbital plane.

- Full numerical relativity simulations have shown that kick velocities can be as high as $\sim 4000\ \mathrm{km/s}$.

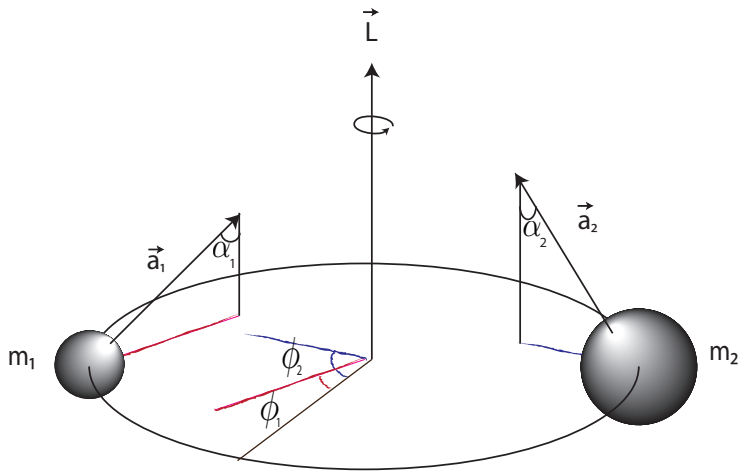


Figure: Geometry of a BH binary sistem.
Source: Guedes et al. (2011).

Recoiling BHs in static and evolving DM halo potential

- Integrate trajectories of recoiling BHs in a static and evolving (van den Bosch et al. 2014) DM halo with $M_{\rm halo} = 10^{12}\,{\rm M}_{\odot}$
- In evolving potential DM halo grows ~ 2 order of magnitude from $z = 7$ to $z = 0$

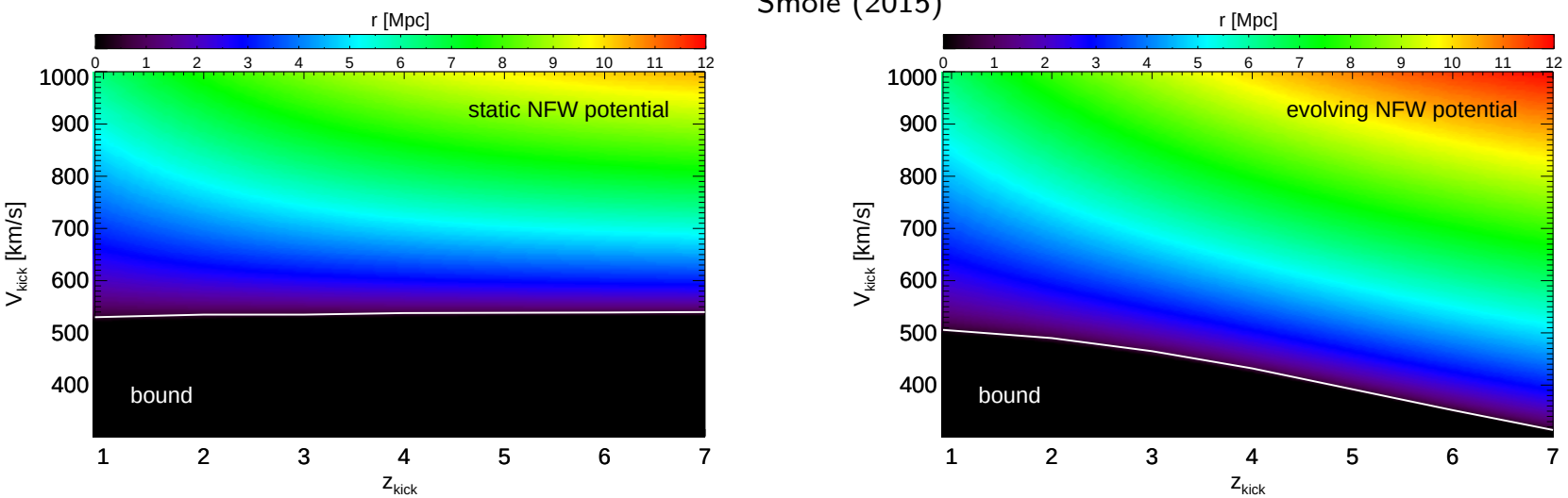


Figure: Distance of a kicked BH from a host halos centre at $z = 0$ as a function of $v_{\rm kick}$ and $z_{\rm kick}$. Smole (2015)

Galaxy models

- We follow trajectories of recoiling BHs in analytical and numerical potential of galaxies whose components are: DM halo, bulge and disc.
- Galaxies with masses $10^{12}\,\mathrm{M}_{\odot}$ and $10^{11}\,\mathrm{M}_{\odot}$ formed in:
  1. major (1:1) mergers
  2. minor (1:10) mergers

  whose central BH has mass of:
  1. $M_{\mathrm{BH}} = M_{\mathrm{gal}}/10^5$
  2. $M_{\mathrm{BH}} = M_{\mathrm{gal}}/10^3$
- Analytical models of merger remnants - galaxies properties are defined by its central BH mass and by scaling relations.
- Numerical models - simulate mergers of progenitor galaxies in order to produce remnant galaxies with the similar characteristics to those in analytical models.

Galaxy models

- Numerical merger remnants:
  1. generate initial conditions for each pre-merger galaxy model - `GalactICS` code
  2. evolve galaxy in isolation in order to test stability of each galaxy component
  3. simulate galaxy merger
  4. place a BH in the merger remnant centre and follow the recoiling BH trajectory
- N-body `GADGET-2` code (Springel 2005)
- Each progenitor galaxy is represented with $N = 10^6$ particles
- Galaxy escape velocity $\longrightarrow$ kick velocity necessary for a BH to return to its host centre after $\gtrsim 10$ Gyr.

Results

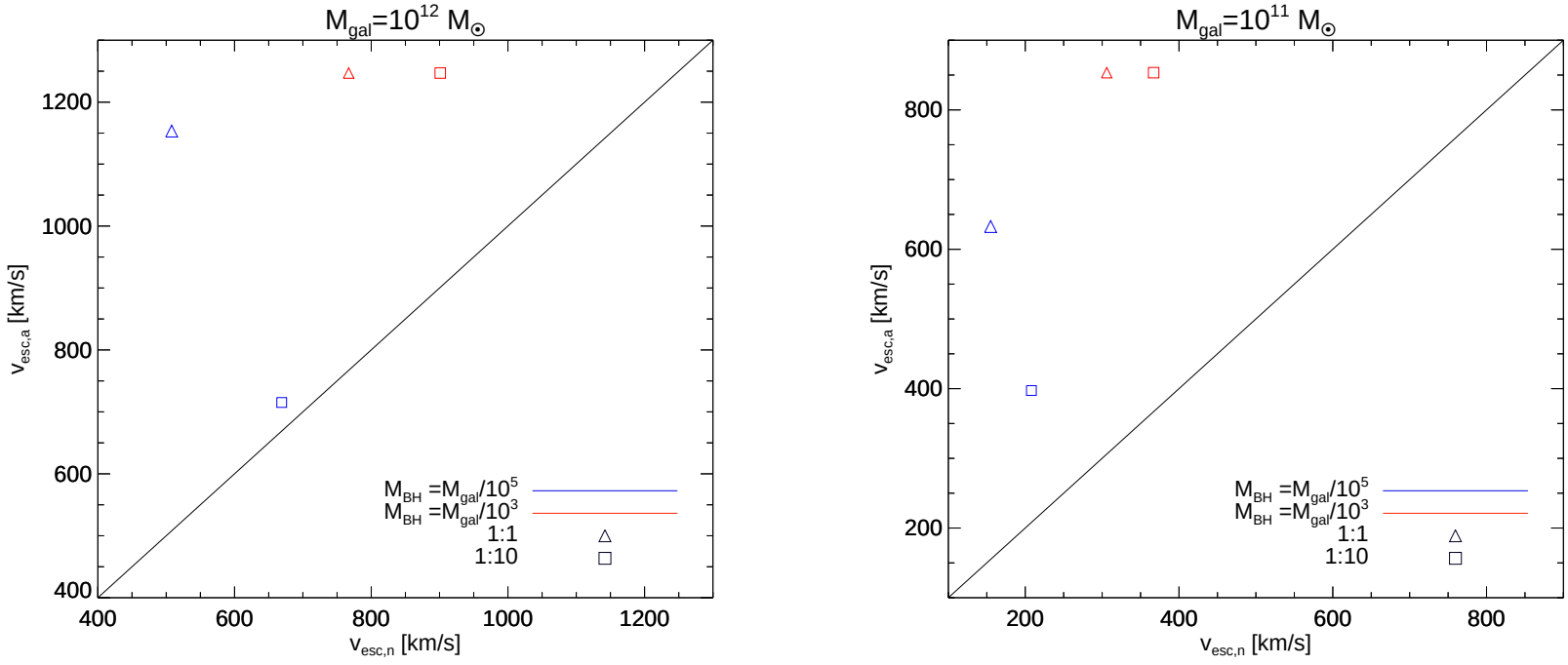
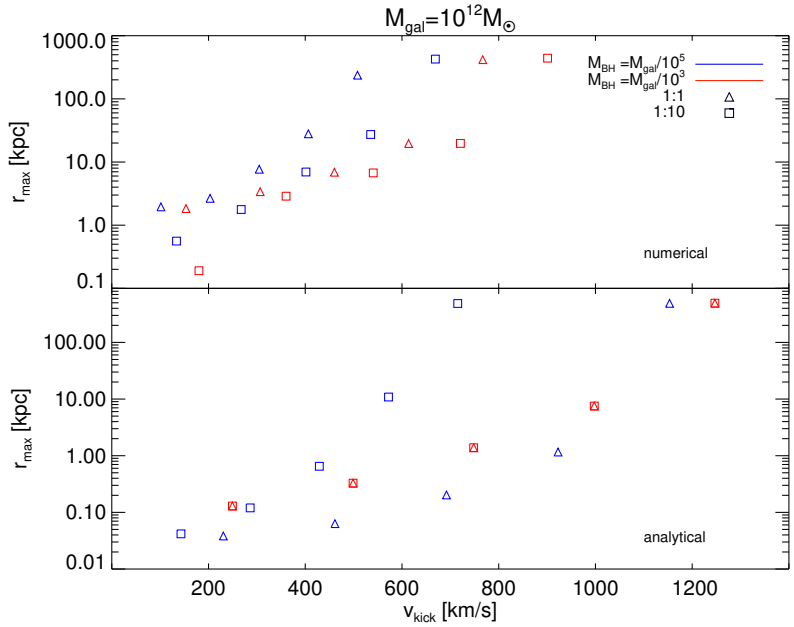


Figure: Escape velocities from galaxies in analytical models as a function of their escape velocities in numerical models.

Results



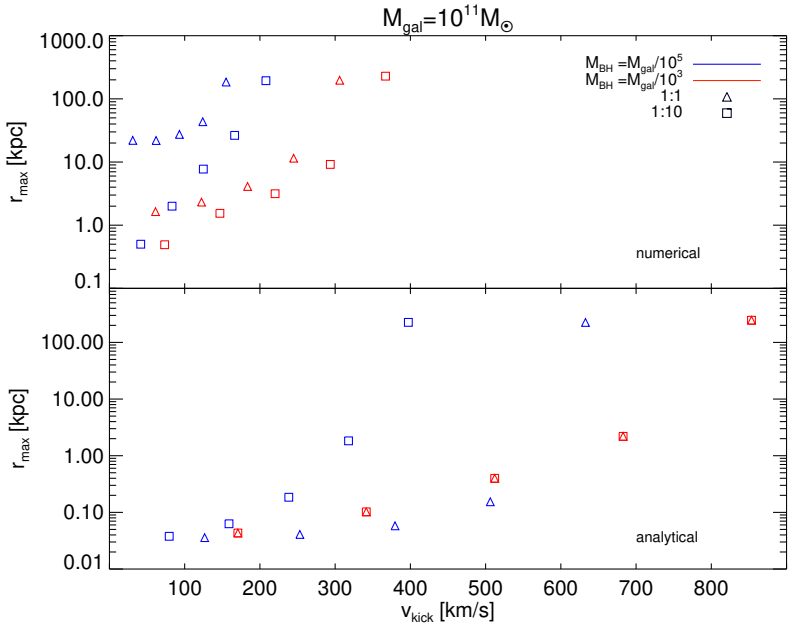


Figure: Maximal separation of a recoiling BH from the galaxy centre over 10 Gyr, as a function of kick velocity, $v_{\mathrm{kick}} = 0.2, 0.4, 0.6, 0.8, 1.0 \times v_{\mathrm{esc}}$.

Summary

- $v_{\rm esc}$ in numerical models are $\lesssim 75\%$ lower compared to those in analytical models $\longrightarrow$ in numerical models BH ejection occurs before virialization finishes.
- Increasing BH mass from $M_{\rm BH} = M_{\rm gal}/10^5$ to $M_{\rm BH} = M_{\rm gal}/10^3$ results in $\lesssim 75\%$ higher $v_{\rm esc}$ $\longrightarrow$ dynamical friction force increases with BH mass.
- BHs on bound orbits can reach greater apocentric distances in numerical models, which could increase the number of offset AGN compared to analytically based predictions.

Influence on SMBH growth

- At hight redshifts BHs primarily grow through mergers with other BHs and through episodes of gas accretion.
- Gas accretion is triggered by major mergers.
- Major merger remnants in numerical models have the lowest escape velocities $\longrightarrow$ this could affect formation of SMBHs if BH mergers are the dominant growth mode.
- However, BH kick amplitudes strongly depend on the binary characteristics and BH spin parameters.