Cosmological History of Massive Black Hole Interactions in Triples

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1. Introduction

In the currently favored cold dark matter model (e.g. Spergel et al. 2006), galaxies form hierarchically from small building blocks. Since all nearby galaxies with stellar bulges are observed to host nuclear massive black holes (MBH), the formation of MBH binaries seems to be inevitable along the hierarchy. If the binary coalescence timescale exceeds the time between galactic mergers, we expect triple MBH systems to form as well. Triple MBH systems produce a range of phenomena and signatures that are qualitatively different from those of MBH binaries. (1) MBHs can be ejected at speeds comparable to or exceeding the galactic escape speed, producing a population of wandering MBHs. (2) Three-body interactions can enhance the MBH merger rate, leading to quick coalesces.

We simulate a large number of such triple interactions, with initial conditions constrained by the detailed merger history of dark matter halos and central MBHs. When two galaxies hosting MBHs merge, the black holes that were initially embedded in the galactic nuclei of the colliding galaxies form a binary system in the center of the merger remnant due to dynamical friction. The coalescence time-scale of a MBH binary in a stellar background can be long enough for a third BH to fall in and interact with the central binary, following a subsequent galaxy merger.

2. Triple Black Holes in a Hierarchical Universe

The merger history of DM halos and associated MBHs is followed through Monte Carlo realizations (based on the extended Press-Schechter formalism) of the merger hierarchy from early times to the present. During the merger of two halos, the `satellite' - and its MBH - spirals in on the dynamical friction time-scale. The efficiency of dynamical friction decays when the MBHs get close and form a hard binary. The time-scale for merging of an equal mass binary can be much longer than the Hubble time. If a halo hosting such a “stalled” binary then experiences a merger with another halo with an embedded MBH, the third MBH can reach the core of the galaxy, where the pre-existing binary is located, within a dynamical friction timescale, forming a MBH triple system.

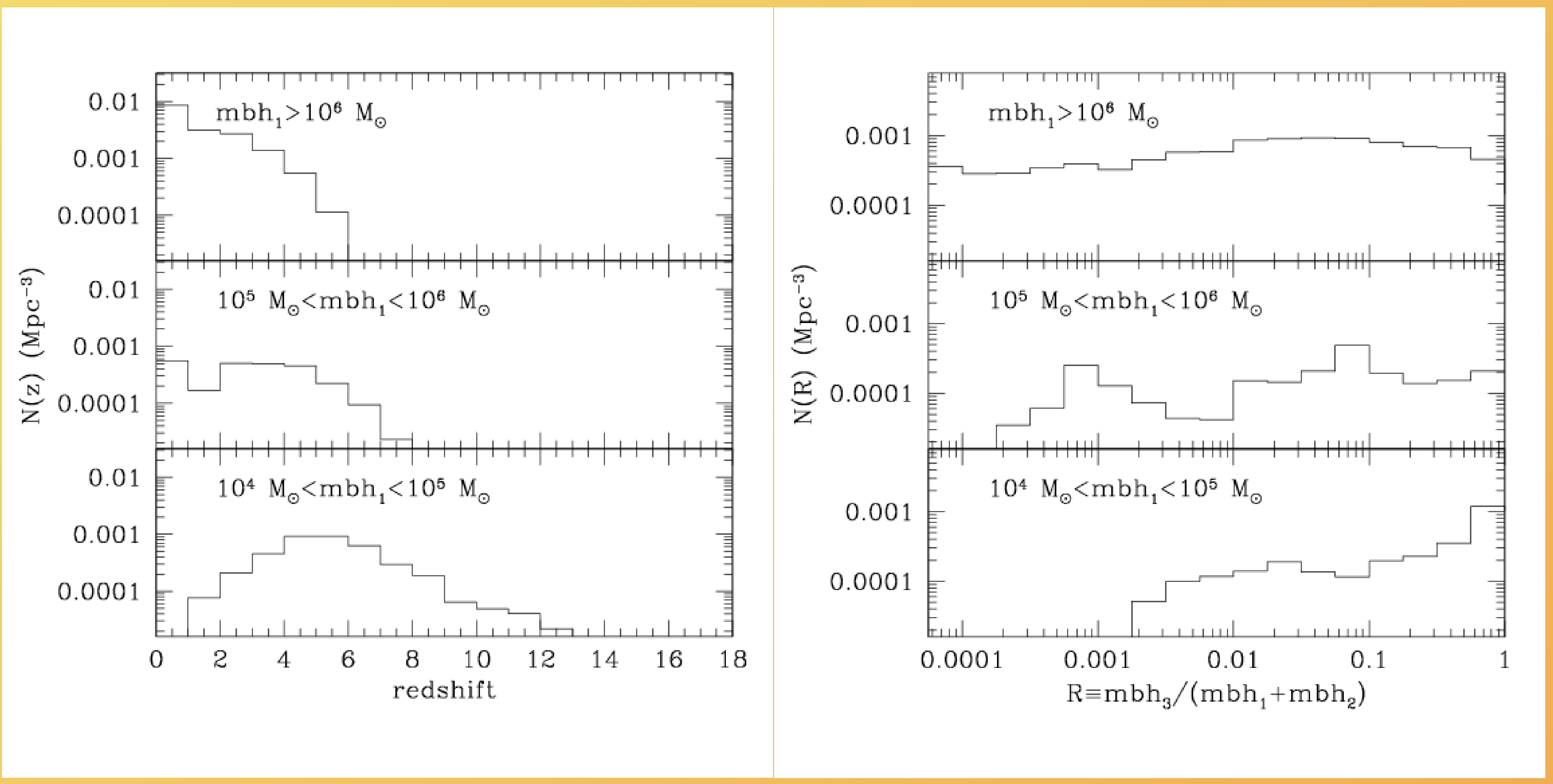
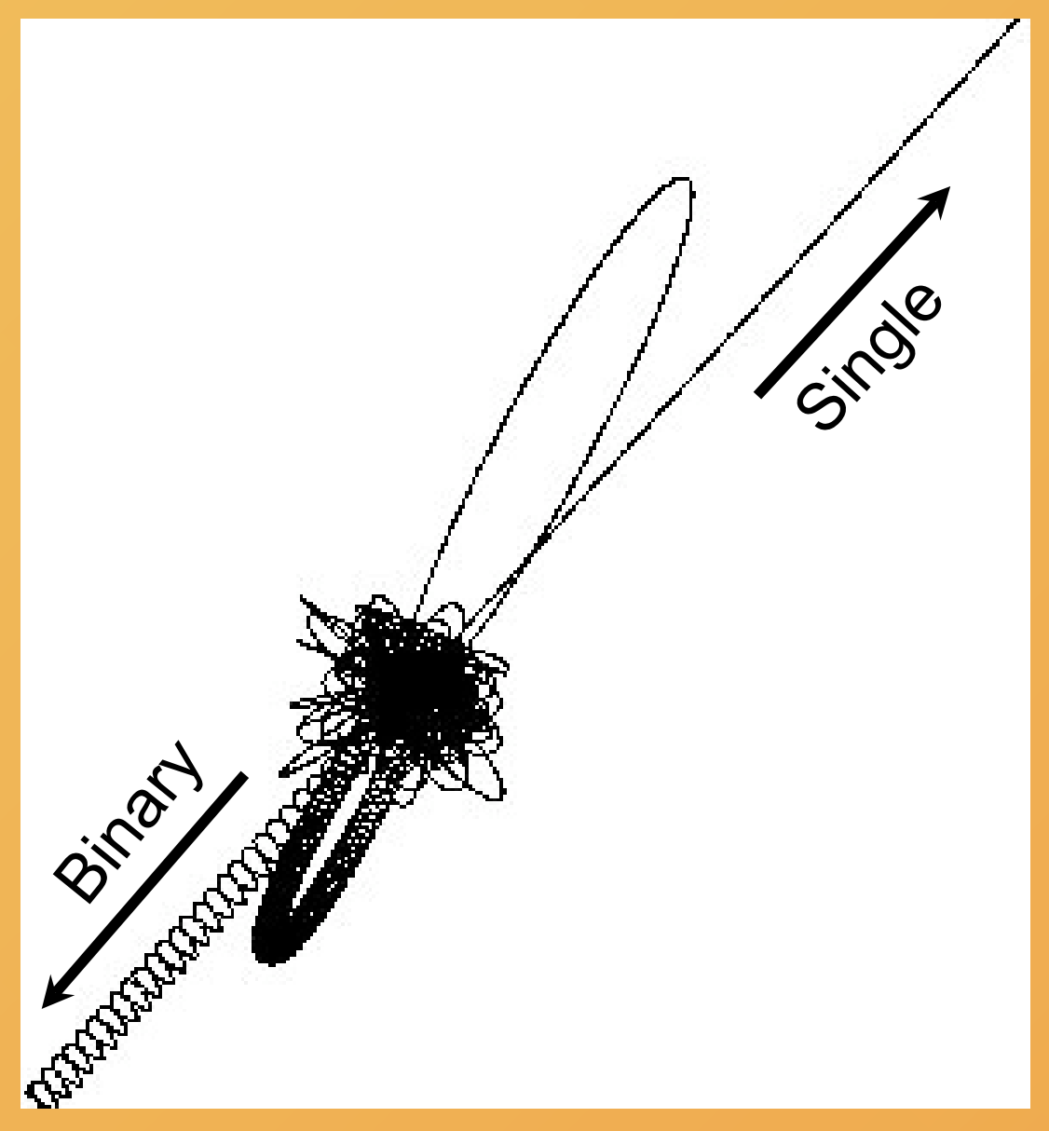


Fig. 1: Distribution and properties of triple black holes formed by galaxy mergers. For three different black hole mass ranges, the redshift distribution of MBH triples (left panel) and their mass ratio distribution (right panel) are shown.

3. Evolution of Triple Black Holes in Galactic Centers

When the third MBH reaches the core of the galaxy, it forms an outer binary, with the stalled inner binary. Once the semi-major axis of outer binary shrinks to the chaotic unstable region (Mardling & Aarseth 2001), a strong three-body interaction takes place. The most likely outcome of such an interaction is the ejection of the lightest body, recoil of a (possibly new) binary, and an enhancement of the binary eccentricity, which can eventually lead to accelerated coalescence.

Fig 2: Dynamical evolution of a typical unstable triple (equal mass case). Once the in-spiraling third black hole gets so deep into the center that its distance to the binary black hole becomes comparable to the binary separation, the three black holes start to interact strongly on a much shorter time-scale than the dynamical friction time scale. This figure illustrates such a strong dynamical interaction, showing the orbits of the three black holes. Eventually the triple disrupts into a single and binary.



4. Coalescence in Triple Encounters and Final-State Binaries

A third MBH enhances the gravitational radiation rate in several ways: (a) direct energy extraction from the binary through repeated three-body interactions, (b) allowing the binary to encounter more stars by moving it about the nucleus and scattering stars into the loss cone, (c) thermalization of the eccentricity during chaotic encounters and high-amplitude eccentricity oscillations through Kozai resonance, (d) return of ejected MBHs on nearly radial orbits to form a new high-eccentricity binary with the coalesced binary remnant and (e), in about 5% of the cases, eccentricity growth and forced hardening of the inner binary through a mean motion resonance with the outer binary. The latter mechanism is analogous to the so called “convergent migration” of giant planets (see e.g. Lee & Peale 2002). We find that the combination of these effects is often sufficient to cause coalescence of one or more MBH pairs during the repeated three-body encounters. For MBH systems with masses $>10^7$ M_{sun} the original binary pair coalesces in more than 75% of cases, and in 10 to 15% of the cases the new system formed from the third MBH and the binary remnant also coalesces (Hoffman & Loeb 2006). The high efficiency of coalescence in triple encounters guarantees a significant MBH merger signal for LISA even if other energy extraction mechanisms fail.

Fig. 3: Distribution of coalescence times for the original binary (upper panel), and new binary (lower panel) formed by the third MBH and coalesced binary remnant, for MBHs.

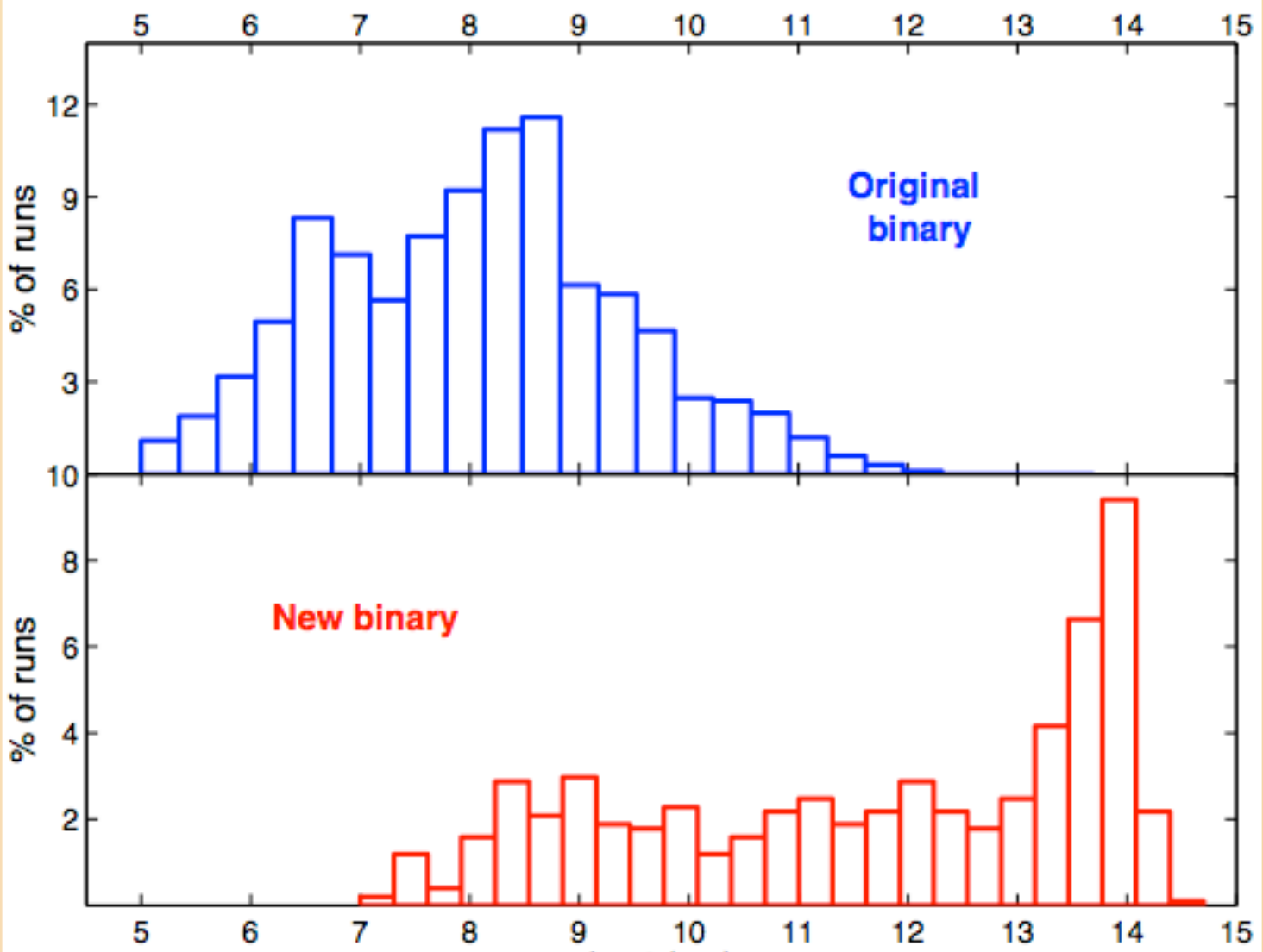
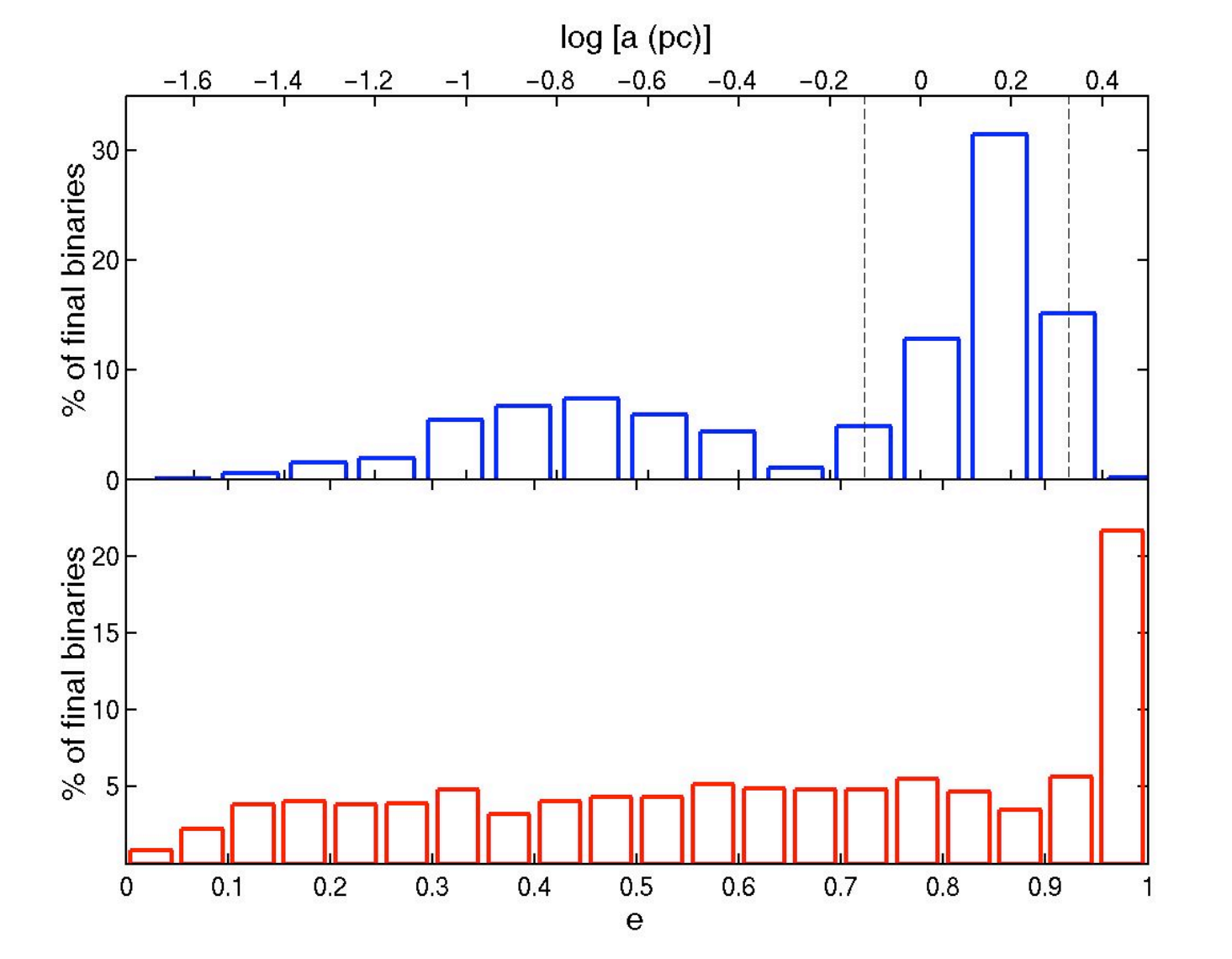


Fig. 4: Distribution of parameters of ``final state'' binaries resulting from repeated three-body encounters between MBHs



Triple encounters often end in coalescence for MBH systems, guaranteeing a high cosmic coalescence efficiency and thus a high detection probability with LISA

5. Wandering Black Hole Binaries - Observational Signatures

When the binary recoil velocity is larger than ~0.1 v_{esc}, the binary can be left wandering in the galaxy halo - leaving the center devoid of a central MBH for times comparable to the Hubble time (Madau & Quataert 2005). A population of wandering binaries is created. If these binaries coalesce through emission of gravitational radiation, they would be recognized among possible LISA sources as off-center binaries. Wandering binaries can also affect the correlations between central MBH and host bulge - possibly leading to MBHs deviating (from below) from the standard correlation. As the binary spends long times in low-density external regions, accretion onto the MBHs is likely suppressed. In the early universe, when the MBHs are less massive, the binary recoil velocities can even be large enough to leave the remnant merger galaxy entirely, If these binaries coalesce, they could be detected as free-floating MBH binaries with LISA.

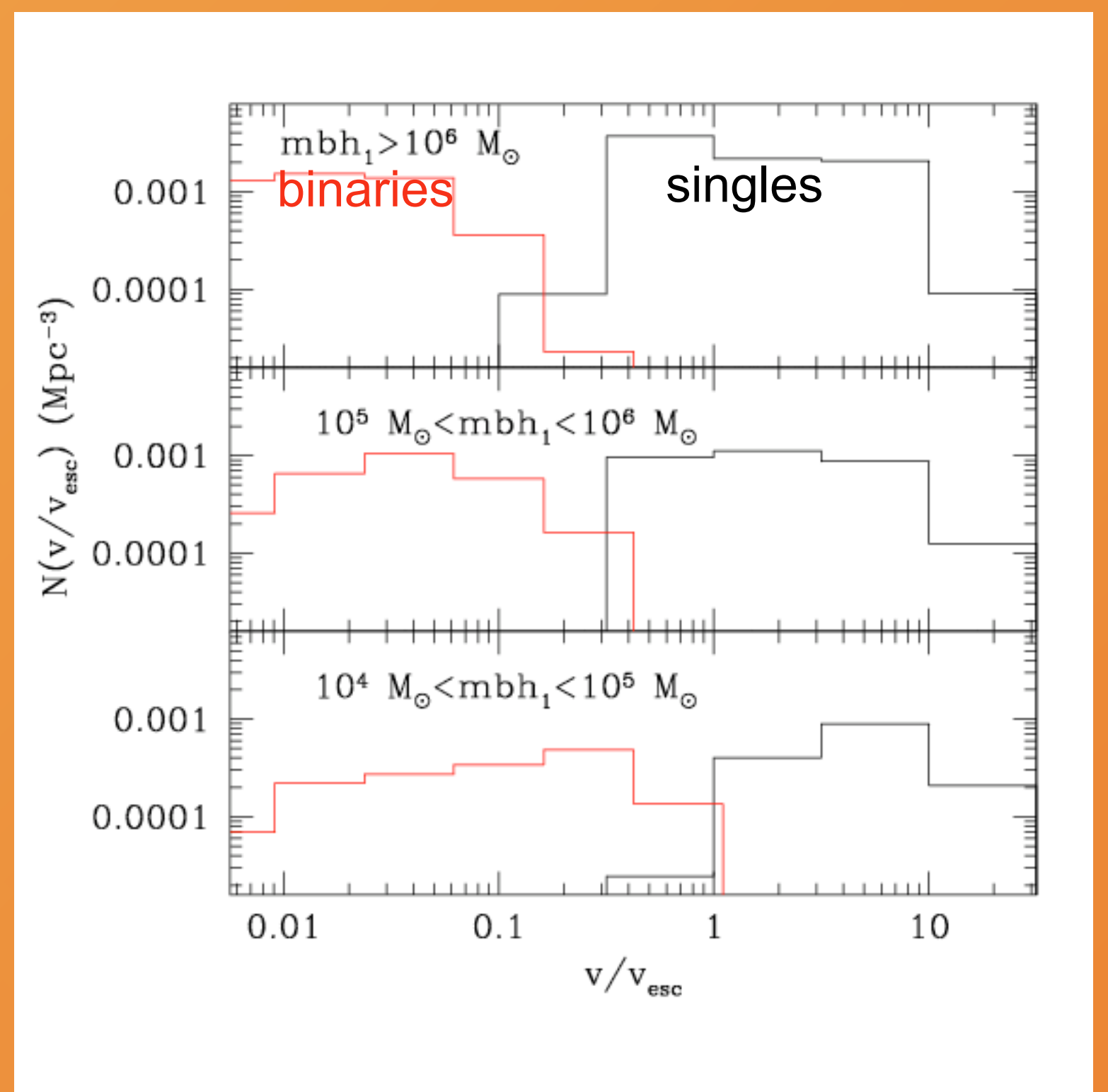


Fig. 5: Distribution of recoil velocities for binaries (red) and single MBHs (black), after one counter, in three MBH mass ranges.

Free-Floating MBH binaries are commonly found in the early universe and could be detected with LISA

References

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