The Role of Primordial Kicks on Black Hole Merger Rates

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Primordial stars are likely to be very massive $\gtrsim$ 30Msun, form in isolation and likely will leave black holes as remnants in the centers of their host dark matter halos in the mass range $10^6 - 10^{10}$Msun. Such early black holes have been speculated to be the seed black holes for the many supermassive black holes found in galaxies in the local universe. If they exist, their mergers with nearby supermassive black holes may be a prime signal for long wavelength gravitational wave detectors. We distinguish cases in which the black holes are born in the center of high redshift dark matter halos and are endowed with or without intial kick velocities. The central distributions of early black holes in present day galaxies is reduced if they are born even with moderate kicks of tens of km/s. The modest kicks allow the black holes to leave their parent halo which consequently leads to dynamical friction being less effective on the lower mass black holes as compared to their parent halos. Therefore, merger rates may be reduced by more than an order of magnitude. Using analytical and illustratory cosmological N–body simulations we quantify the role of natal kicks of black holes formed from massive metal free stars on their merger rates with supermassive black holes in present day galaxies. Our results also apply to black holes ejected by the gravitational slingshot mechanism. A powerful instrument for studying massive black holes will be LISA.

1. MOTIVATION

It is firmly established that most of the galaxies have super-massive black holes at their centers. Ab initio numerical simulations of the formation of the first luminous objects in the current structure formation models find metal free stars to form in isolation and to may have masses $30 - 300$ Msun [1], [2], [5]. This suggests that a large population of primordial black holes could be an end product of such pregalactic star formation [10]. Since they form in rare high-σ density peaks [7], [11] relic massive black holes would be predicted to cluster in the cores of more massive halos formed by subsequent mergers. It has been suggested [15] that clustering of these massive black holes could aid in the formation of supermassive black holes that are indirectly observed in the nuclei of nearby luminous galaxies. The core collapse of the primordial massive stars can lead to fragmentation and production of two or more compact objects (black hole or neutron star). Their coalescence under gravitational radiation may give the resulting black hole or neutron star a significant kick velocity [6], which may explain those observed in pulsars. The most probable kicks come from coalesce of binary black holes through mergers of dark matter halos at high redshifts [9], [12]. LISA can study much of the last year of inspiral, and the waves from the final collision and coalescence of massive black hole binaries, whenever the masses of the black holes are in the range $3 \times 10^4 - 10^8$ Msun [8].

2. IMBHs TRAJECTORIES AND KICKS

In our numerical simulations we use GADGET (GAlaxies with Dark matter and Gas intEracT), a code written by Volker Springel [14]. Periodic box of 14.3 comoving Mpc, ΛCDM universe with Ω_M=0.3, Ω_Λ=0.7 and h=0.7 from redshift z=40 to z=1, refined field: sphere of 2 Mpc comoving radius. 4.9×10^6 high-resolution particles (softening length 2 kpc comoving) for the simulation and 2.0×10^6 low-resolution particles (softening length 4 kpc comoving) in the rest of the box. The mass of each high resolution particle in these simulations is 8.85×10^5 Msun and the mass of each low-resolution particle is 5.66×10^7 Msun. Analysis is performed by P-GroupFinder [13]. We used this code to define dark matter halos and to identify black holes as the most bounded particles in their host halos. Density plots were made with codes provided by Naoki Yoshida. Fig 1: (SIM1): At redshift z=8.16 we identified 2869 dark matter halos with mass in range 10^7 Msun $\lesssim M \lesssim 10^{10}$ Msun. We selected the same number of MBHs from their centers. By connecting particles' coordinates through 33 snapshots we obtained MBHs trajectories from redshift z=8.16 to redshift z=1.00. From 2869 MBHs at z=8.16, 1958 of them can be found inside primary halo at z=1.00. Fig 2: We add this presumed kick velocity with a random direction to a gadget velocity taken from the snapshot at redshift 8.16, for every particle identified as tracing the location of a presumed pop III intermediate mass black hole. This leads to Fig 1 (SIM2a and SIM2b). Fig 3: IMBHs in more massive host halos demand larger kicks in order to escape. As a result, some of them stay captured in their host halo gravitational potential. Notice the fundamental difference between simulations SIM1 and SIM2. In the case without the kicks, black holes embedded in sub–halos reach the center of the primary halo, and the location of the presumed supermassive black hole, through dynamical friction, and the main contribution to this procces is from the total mass of their halos which remain mostly bound through our simulation.

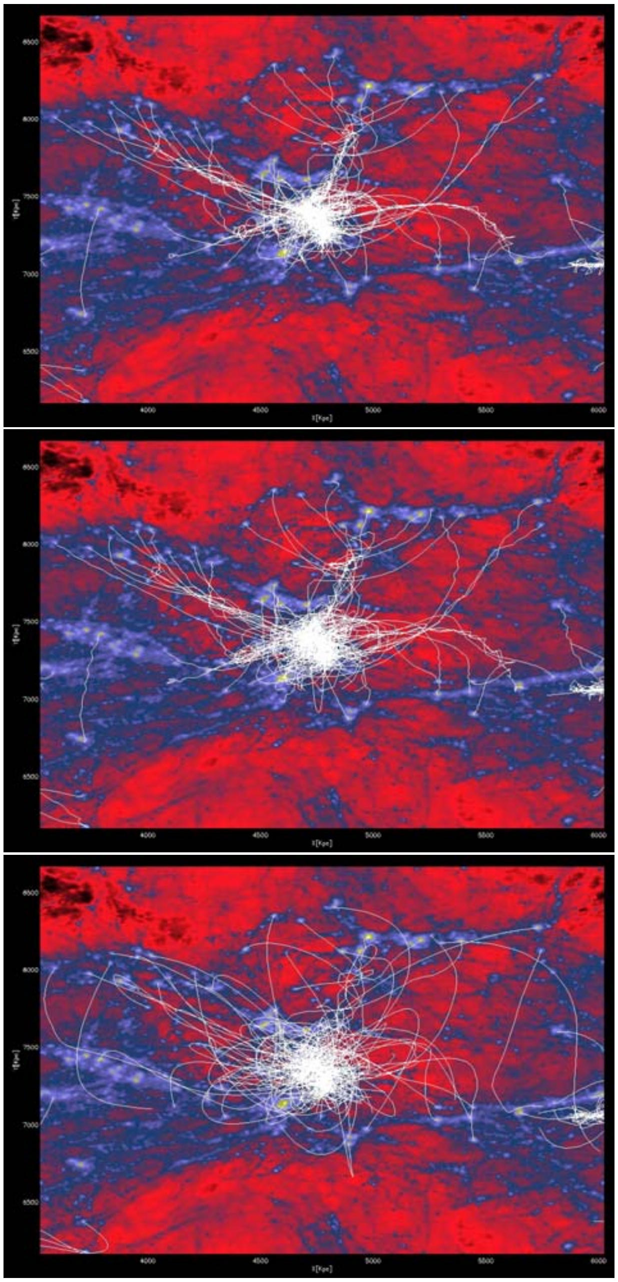

Figure 1: Sample of hundred IMBHs selected from most massive host halos at z=8.16 and their trajectories from z=8.16 to z=1 overploted on 2D density projection. Density peaks in yellow correspond to host halos centers and to the positions of their IMBHs. top : no kick case (SIM1); middle (SIM2a): case of [0,150] km/s kick centered at 75km/s and bottom (SIM2b): case of [125,275] km/s kick centered at 200km/s. With large kicks IMBHs overcome the host halos gravitational potential resulting in change of their trajectories.

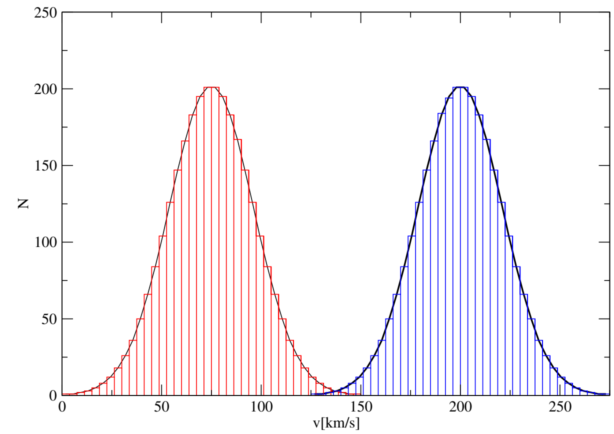

Figure 2: Binned black holes' kick velocities chosen from analytical distribution (overploted as thin for [0,150] km/s kicks centered at 75 km/s and as thick for [125,275] km/s kicks centered at 200 km/s).

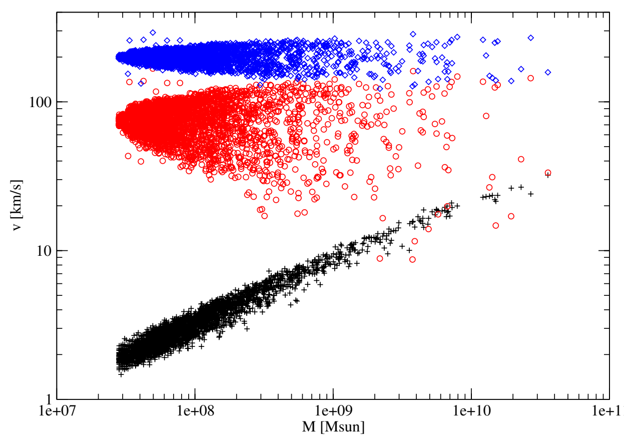

Figure 3: Black holes' escape velocity as a function of halo mass as pluses, calculated from gravitational potential of host halo set consisting of 2869 members. Black holes' velocity relative to their host halos' velocity reduce to assigned kicks: [0,150] km/s centered at 75 km/s repesented as circles and [125,275] km/s centered at 200 km/s represented as diamonds. Lower mass host halos have lower maximum escape velocities enabling their IMBHs to escape.

3. ANALYTICAL EXPECTATIONS

Clustering of massive black holes at the centers of dark matter halos leads to their growth into the population of intermediate mass black holes (IMBH) at the centers of merging dark matter halos. The early stages of merger are driven by hierarchical cold collapse of the sub–halos into the primary halo forming the Galaxy. Subsequent dynamical evolution of the IMBH population occurs through dynamical friction.

We assume that IMBHs embedded in their parent sub–halos experience dynamical friction acting collectively upon the entire compact sub–halo containing the IMBH, at least until tidal stripping significantly reduces the effective sub–halo mass to that of the central mass only [16]. The primary halo is well approximated by a singular isothermal sphere. The frictional force on a host-halo [4] of mass M moving on a circular orbit is:

$$F = -0.428 ln\Lambda \frac{GM^2}{r^2}, \tag{1}$$

Trivially, taking the time derivative of the expression L=rv_c, and substituting into equation (2) gives an upper bound on the timescale for dynamical friction to bring the sub–halo and associated IMBH to the primary halo center. Solving, subject to the initial condition r(0)=r, one finds that the sub–halo would reach the center after a time:

$$t_{fric} = \frac{1.17}{ln\Lambda} \frac{r^2 v_c}{GM}. \tag{2}$$

Assuming that dynamical friction is efficient in bringing sub–halo to the center of the primary halo, from the equation (3), we can calculate the radius r_{sink} at which sub–halo has to be, in order to sink to the center in less then the Hubble time for given velocity dispersion and sub–halo mass. If every sub–halo carries one IMBH at its center, then the merger rate for IMBHs will be function of number of sub–halos inside r_{sink}. If kicks at higher redshifts supply IMBH with velocity enough for IMBH to escape its sub–halo, the expected number of IMBHs at $r \lesssim r_{sink}$ will be smaller and this will lead to significant decrease in IMBH merger rates. Stoping the growth of IMBH through gas accretion by ejecting them into lower dark matter density regions, changing x-ray population predictions [3].

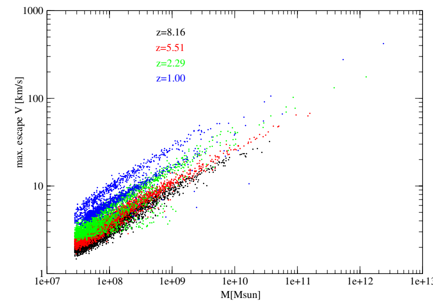

Figure 4: All dark matter halos in our simulations. Maximum escape velocity (corresponds to central gravitational potential) of dark matter halos at different redshifts as a function of dark matter halos' masses. Gravitational potential of the same mass halos increases at lower redshifts wich, together with IMBHs free fall, results in reaching the primary halo at z=1 for almost all of the kicked IMBHs, see Fig 6.

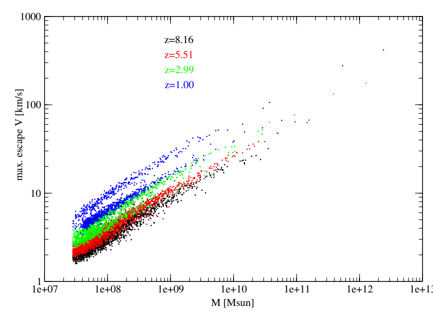

Figure 5: Data after removing substructures. Maximum escape velocity (corresponds to central gravitational potential) of dark matter halos at different redshifts as a function of dark matter halos' masses. As the number of substructures increases with redshift, the dark matter halos with mass $\lesssim 10^9$ Msun start showing dispersion in their maximum escape velocity. This is due to tidal effects in the outer regions of primary. Dispersion disappears after removing substructures. At redshifts z=1 and z=2.99 data splits into two streams as the result of major merger at redshift z=3.

4. POST-MERGER EVOLUTION

We find that significantly more black holes get at the center of the primary halo when they are embeded in their dark matter sub–halos. But a number of mergers to the center occur even in the presence of kicks. Comperable numbers of black holes reach primary halo in both cases since the gravitational potential of dark matter halos increases with redshift (Fig 4 and Fig 5). Fig 6. shows number density of the IMBHs inside primary halo, from SIM1, SIM2a and SIM2b. Although the total number of black holes differs from SIM1 by 0.7% for SIM2a and 8.3% for SIM2b, there is a decrease in the number of IMBHs at SIM2 for the inner 10% of the primary halo.

We calculate a radius (r_{sink}) which IMBHs have to reach in order to merge to the center in less then the Hubble time for two cases. First, when the IMBHs are inside sub–halos of minimum mass 10^7 Msun (SIM1), and second when IMBH has been ejected from its parent sub–halo (SIM2). In the first case, IMBHs inside 10^7 Msun will merge to the center if they are at less then r_{sink}=$r_{vir}/30$ when the halo collapse virialises. We find that a little over 4% of the IMBHs formed are at radii less then r_{sink}. So for this model we predict that in the absence of kick, 83 IMBH reach the center to coalesce with the central SMBH (or the seed SMBH formed in the sub–halo that became the center of the

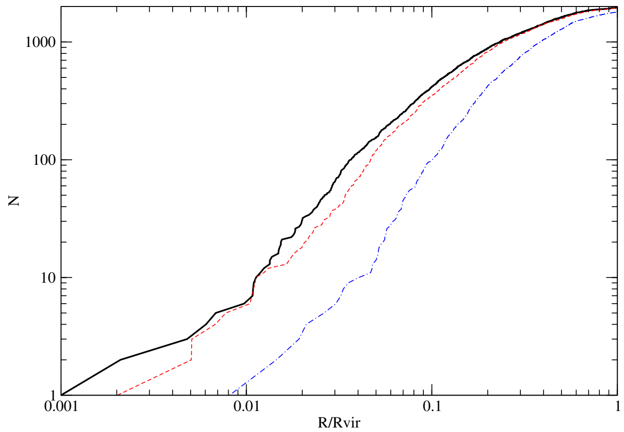

Figure 6: Number of black holes as a function of primary halo radius. No kick case (thick); [0,150] km/s kick centered at 75 km/s (dash) and [125,275] km/s kick centered at 200 km/s (dash-dot). Although the number of IMBHs entering primary halo is comparable in all three cases, the difference in their interior distribution is well pronounced.

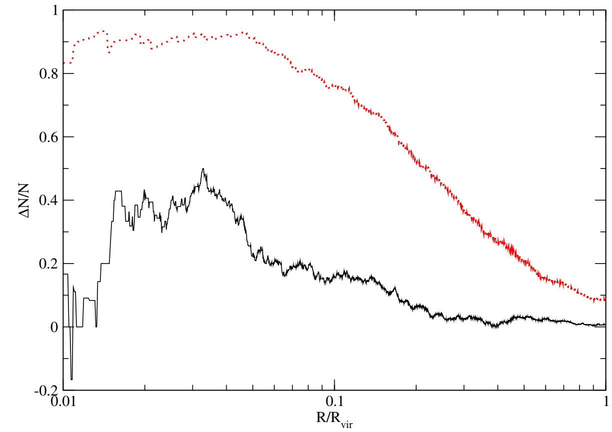

Figure 7: Fraction of SIM1 black holes in SIM2a and SIM2b as a function of radius. Thick line for [0,150] km/s kicks centered at 75 km/s and dots for [125,275] km/s kicks centered at 200 km/s.

primary halo). More generally, this predicts $O(10^2)$ IMBH mergers per Milky Way like halo over a Hubble time, even for the cases shown here where only halos with masses $\gtrsim 2.83 \times 10^7$ Msun were allowed to form black holes. In the second case, the kicked IMBHs have a significantly flatter spatial distribution, partly because they have decoupled from their parent sub–halos, so there are fewer inside $1/30r_{vir}$. Fig 6. shows that there are 2.21% of IMBHs from SIM2a and 0.95% of IMBHs from SIM2b inside this radius. Fig 7. shows the ratio of IMBHs with kicks and IMBHs with no kicks. There is a large drop in the central population of IMBHs with kicks. This can be seen also in density plots Fig 8. IMBHs in SIM2 have to be at radii less then r_{sink}=$r_{vir}/100$. Only 1/4% of the SIM2a IMBHs are inside this radius. That is, under the same assumptions but allowing for natal kicks, only about 4 to 5 IMBH merge with the central SMBH over a Hubble time, a factor of 20 lower merger rate. In the SIM2b there are no IMBHs inside $r_{vir}/100$ except for the one originating from the ancestor of primary halo at redshift z=8.16.

These numbers can increase since, in reality, σ is lower at small radii so t_{fric} is also smaller. The merger of 83 IMBHs in SIM1, leads to formation of 7.34×10^7 Msun SMBH inside dark matter halo with velocity dispersion $\sigma = 157$ km s^{-1}. We note that primary halo is not actually spherical and if a halo is triaxial, then some fraction of the IMBHs can "walk" into the inner halo ($r \ll 10^{-2}r_{vir}$) region on time scale $\sim 10t_{orbital}$ due to centrephilic box or boxlet orbits [17], [18], at which point dynamical friction becomes effective in bringing the IMBH to the halo center. Also, some of

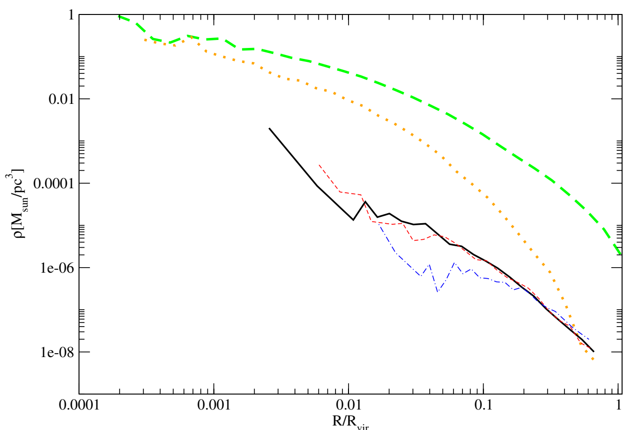

Figure 8: Density of the primary halo at z=1 (thick dash) and its most massive progenitor from z=8.16 (dots) as a function of radius. Also, density in hosted black holes for no kick (thick); [0,150] km/s kick centered at 75 km/s (dash) and [125,275] km/s kick centered at 200 km/s (dash-dot).

the MBHs are being assigned with kick velocities that directed them toward center. Due to this, some additional IMBHs from SIM1 and SIM2 could reach orbits in the center of HALO 1. Kicks are also responsible for ejecting IMBHs from gas enriched regions of the halos. Since gas accretion is one of the main mechanisms for black hole growth, dumping black holes into regions of lower gas densities would prevent formation of AGNs which would lead to decrease in their numbers. Gas accumulates where the gravitational potential wells are deepest. It is also where dark matter densities are highest. Therefore we may get a crude estimate

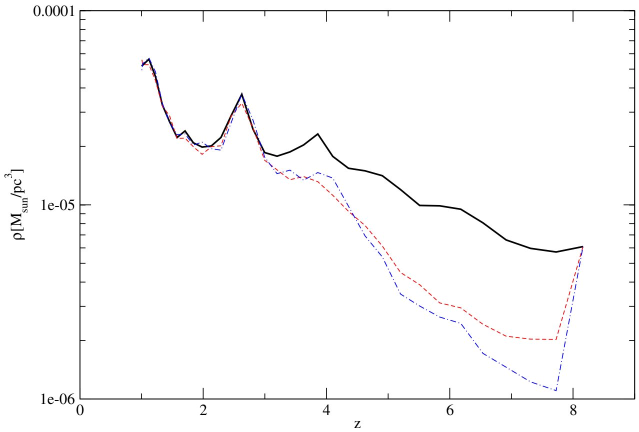

Figure 9: Local density of dark matter traced by black holes as a function of redshift. No kick (thick); [0,150] km/s kick centered at 75 km/s (dash) and [125,275] km/s kick centered at 200 km/s (dash-dot). Ejection of IMBHs from gas enriched regions of galaxy infuences AGNs formation rates, reduces their numbers and their contribution to ionizing background.

of the ability of IMBHs to accrete gas by tracing the dark matter density at their positions. Fig 9. shows average local density of dark matter traced by our set of IMBHs vs. redshifts. At z=8.16 the kicks are assigned. IMBHs are being ejected from their host halos into the regions with lower density (dash and dash-dot from z=8.16 to z=7.75). From z=7.75 to z=2.80 kicked IMBHs are in the environment 1-6 times less dense then in the no-kick case. This might suppress formation of AGNs. Notice that around z=3.00, the average IMBHs in all three cases start tracing similar density distributions. This implies that for $z \gtrsim 3$, the contribution of faint AGNs to the ionizing background would be decreased if kicks of IMBHs were important.

5. DISCUSSION

We have performed and analyzed high-resolution collisionless simulations of the evolution of structure in a ΛCDM model. We have followed the formation and evolution of dark matter halos and by assuming that each halo is a host of one IMBH we studied the formation of SMBH. We focused on two cases where in the first IMBHs together with their host halos merge through dynamical friction and second when IMBHs are endowed with an initial kick which in many cases lead to ejection from their host halos. Already analytically it is clear that the dynamical friction will act more efficiently on the host halos then on the much lower mass black holes formed within them. Our illustrative calculations highlight some of the expected differences in the density distribution of the final distributions of black holes which may by quite different even in the presence of the modest kick velocities we have imposed. The flatter spatial distribution of MBH with kicks can be due to dynamical friction but it can also be influenced by numerical noise. In order for dynamical friction to work in numerical simulations, the density of the background - parent halo density, has to be more resolved. Larger resolution gives smaller softening lengths for particles and smaller softening lengths give more realistic dynamical friction. At the current resolution of our simulation, dynamical friction can not be efficiently realised in the model because the background density of parent halos is not resolved well enough. Nevertheless, it seems that even at current resolution, our simulations are able to account for effects of dynamical friction. Subsequent papers will track the dynamical evolution of the subhalos and IMBH at late times, using higher resolution simulations and semi-analytic implementations of dynamical friction [4]. A little over 4% of MBHs merge at the center in less then Hubble time and if this is the dominant way of creating SMBH then it is efficient even if the MBHs are ejected from their parent halos, with merger numbers only reduced by a factor of two or so for modest kicks. It is also possible that kick velocities have been underestimated in our simulations. The value of median kick of 150km/s may be increased to more then 1000km/s according to some authors [9], [12], which would also greatly enhance the effects introduced here, reducing the number of mergers to negligibly small. LISA observations should strongly constrain any natal kick on IMBHs formed from very massive Pop III stars in low mass proto-galactic sub-halos. Currently we are running a followup simulation together with SCF code that evolves our structures from redshift z=1.0 to z=0.0. We are also studying globular clusters formation and kinematics through our simulation.

6. Acknowledgments

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