

HOW DID THE IMBHs FORM THAT GREW TO BE THE MASSIVE BLACK HOLES  
FOUND TODAY IN MOST GALACTIC CENTERS?

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Many theoretical studies have been carried out to try and determine the processes in early galaxies that led to the massive black holes (MBHs) found at the centers of most medium and large sized galaxies. Four main types of scenarios have been considered. In the first, run-away collisions of roughly  $10 M_{\odot}$  black holes in dense clusters in the centers of early galaxies formed Intermediate Mass Black Holes (IMBHs) with masses above  $100 M_{\odot}$ , and these later grew by accretion events and galaxy mergers to more than  $10^5 M_{\odot}$ . In the second, the near absence of metals in Pop III stars led to the initial mass function for the first stars being tilted toward higher masses. If enough very massive stars were formed, their early evolution would have led to IMBHs being formed in supernova explosions in many galaxies. In both cases, growth at sub-Eddington rates could have led to the MBH masses of roughly  $10^5$  to  $10^8 M_{\odot}$  seen in the local universe.

On the other hand, starting from fairly low mass IMBHs at redshifts of 10 or so makes it difficult to explain the growth of the roughly  $10^{10} M_{\odot}$  supermassive BHs seen in quasars at redshifts as high as 7. Thus either super-Eddington accretion or an alternate mechanism to produce perhaps  $10^4$  or  $10^5 M_{\odot}$  IMBHs initially have been suggested. A particular mechanism is the rapid loss of angular momentum in some large galactic nuclei so that the start of star formation is delayed, and quasi-stars can form that evolve into the suggested very large IMBHs.

At some point in the process of galaxy evolution, mergers will start to take place between pairs of galaxies that both contain IMBHs or more massive MBHs in their centers. If dynamical friction brings both BHs to the center of the new galaxy and they merge in much less than a Hubble time, the resulting gravitational wave signals will carry information on how the IMBH and MBH masses built up with time at redshifts up to about 10. Because of the apparent close relationship between galaxy evolution and MBH evolution, it is expected that gravitational wave observations in space can help to understand the nature of the relationship better.

From the gravitational wave observations, the spins of the merging BHs as well as their masses and the luminosity distance of the event would be determined. Knowing the spins is important because it gives valuable information on how the mass of the BHs has built up. For random accretion events, the BH spins are expected to be fairly small. However, if the plane of the galaxy has strong influence on the orientation of the accretion events, a high BH spin is likely to be produced. Thus, the spin determinations can help to understand the accretion processes.

Many estimates have been made for the expected rates of IMBH-MBH and MBH-MBH mergers for the different scenarios for initial formation of IMBHs and MBHs. While the rates at redshifts of about 10 have large uncertainties, even the more pessimistic rates are a few events per year that would give signals strong enough to be observed clearly with the evolved LISA (eLISA) mission that is now being investigated as a candidate for an ESA-led large mission under the ESA Cosmic Vision Programme. NASA participation in such a mission could considerably enhance the scientific returns from the mission.