Probing Massive Black Hole Populations and Their Environments with LISA

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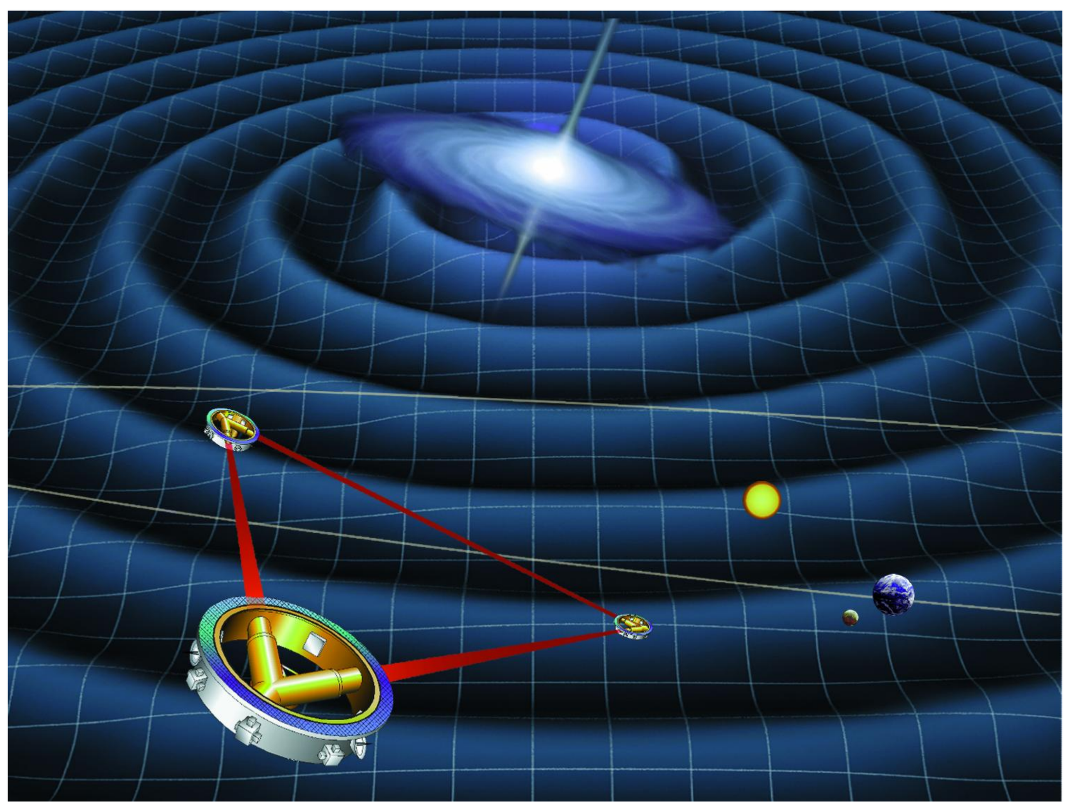
Abstract

ESA and NASA are moving forward with plans to launch LISA around 2030. With data from the Illustris large-scale cosmological simulation, we provide analysis of LISA detection rates accompanied by characterization of the merging massive black holes and their host galaxies. Massive black holes of total mass $\sim 10^6 - 10^9 M_\odot$ are the main focus of this study. Using a custom treatment for the binary massive black hole evolutionary process, we evolve Illustris massive black hole particle mergers from ~kpc scales until coalescence to achieve a merger distribution. With the Illustris output as a statistical basis, we Monte Carlo synthesize many realizations of the merging massive black hole population across space and time. We use those realizations to build mock LISA detection catalogs to understand the impact of LISA mission configurations on our ability to probe massive black hole merger populations and their environments throughout the visible universe.

Finding Massive Black Holes with Gravitational Waves

Gravitational waves (GW), like electromagnetic waves, live on a spectrum spanning many orders of magnitude in frequency. Ground-based observatories like aLIGO are sensitive to stellar mass objects in their latest stages of evolution at about 10^2 Hz. In order to detect massive black hole (MBH) binaries, the LISA space-based GW detector is needed. LISA covers a large fraction of the GW spectrum with a peak sensitivity around 10^{-3} Hz. LISA is also sensitive to stellar mass black hole, white dwarf, and neutron star binaries, along with Extreme Mass Ratio Inspirals (EMRI). [1] [2]

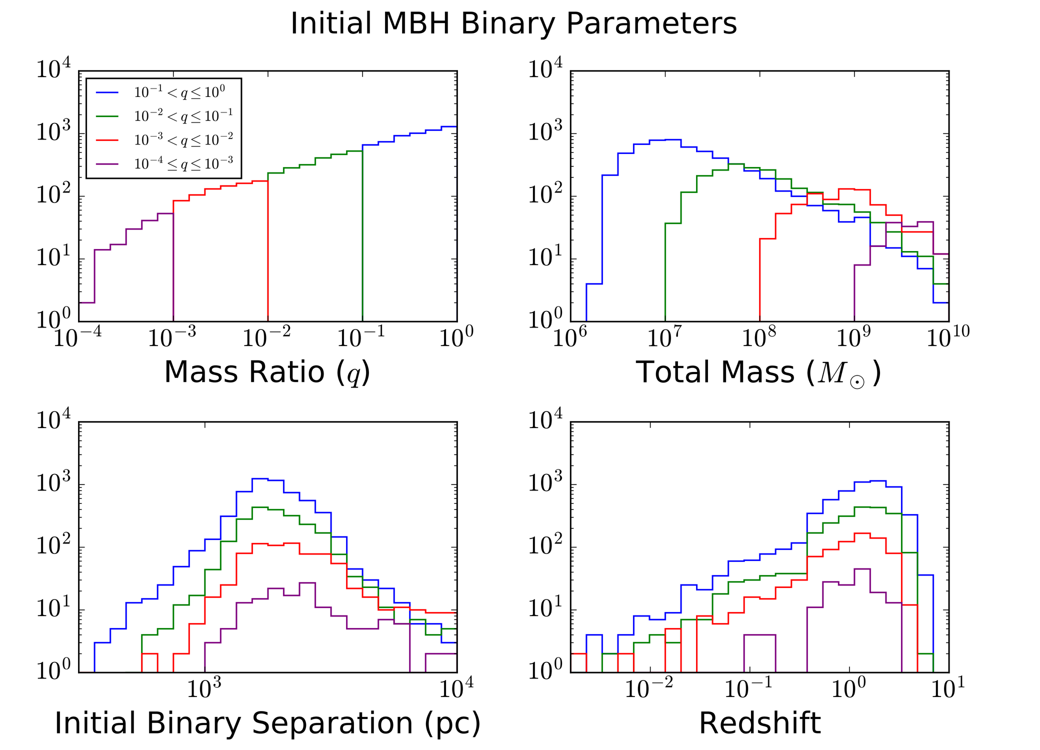


Monte Carlo Synthesis from Illustris Output

Illustris is a suite of large cosmological simulations following the evolution of dark matter, gas, stars, and massive black holes from $z = 137$ to $z = 0$ in a cube with side length 106.5 cMpc. We analyze the highest resolution simulation, Illustris-1 [3]. From this simulation we find the properties of all black holes participating in mergers, including the particles and properties of their host galaxies. After making certain cuts for details of each host galaxy's structure and black hole mass ($M >= 10^6 M_\odot$), the statistics of the remaining $\sim 10^4$ mergers become the input for our Monte Carlo synthesis [4].

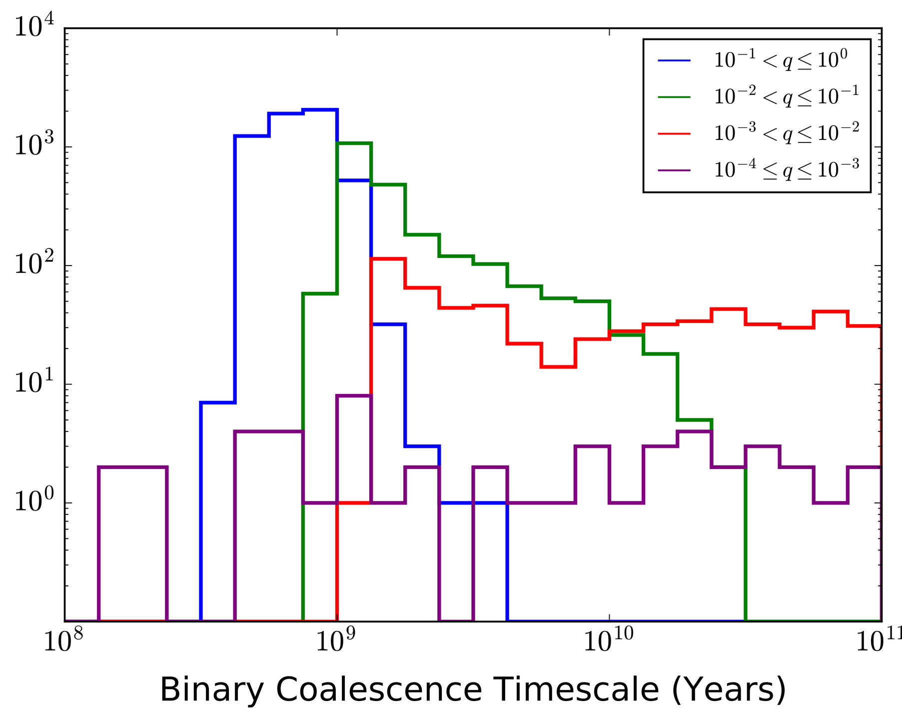
Illustris MBH Binaries

- In Illustris, two MBHs become one when separated by the MBH simulation smoothing length. These events occur at separations of ~kpc and form the basis for our Monte Carlo analysis.
- A kernel density estimate is built from the parameters extracted from Illustris, and then used for resampling.
- Binaries are sampled and then evolved using an improved formalism for dynamical friction inspiral times by Dosopoulou and Antonini 2017. [5].



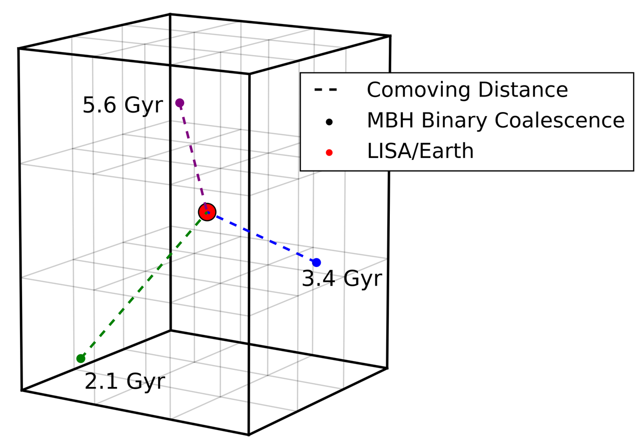
MBH Binary Evolution

- Large scale orbital decay begins as the two host galaxies merge and ends when the the secondary MBH reaches the primary's influence radius.
- Dynamical friction evolves the binary from the influence radius to about the hardening radius.
- Binary hardening occurs until gravitational waves become the primary process for the dissipation of orbital angular momentum and energy [6].
- Gravitational waves evolve the binary to coalescence.



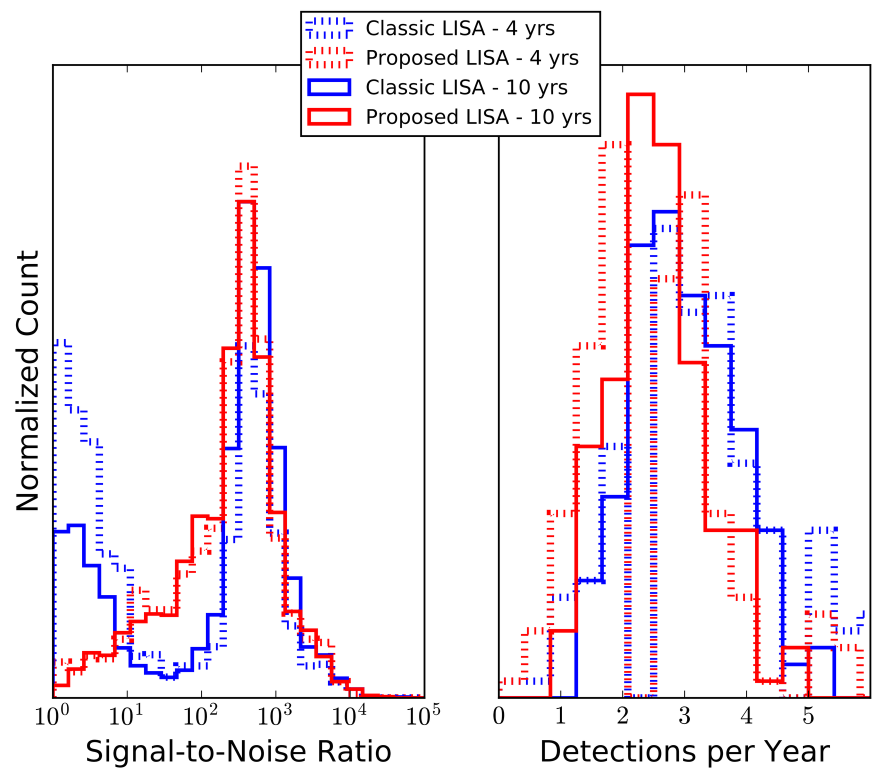
Monte Carlo Sampling

- Cubes of equal volume to the Illustris simulation volume are tiled in three dimensions out to comoving distances at high redshift.
- Binaries are drawn from our kernel density estimate of the Illustris MBH merger population within each cube assuming periodic boundary conditions.
- These Monte Carlo draws involve binary parameters for study including a time of merger and a comoving distance relative to LISA.
- Gravitational wave arrival times are determined by $t_{GW} = t_m + t_e + t_{LTT}$, where t_m, t_e, and t_{LTT} are the time of binary formation, binary evolution to coalescence, and light travel time, respectively.

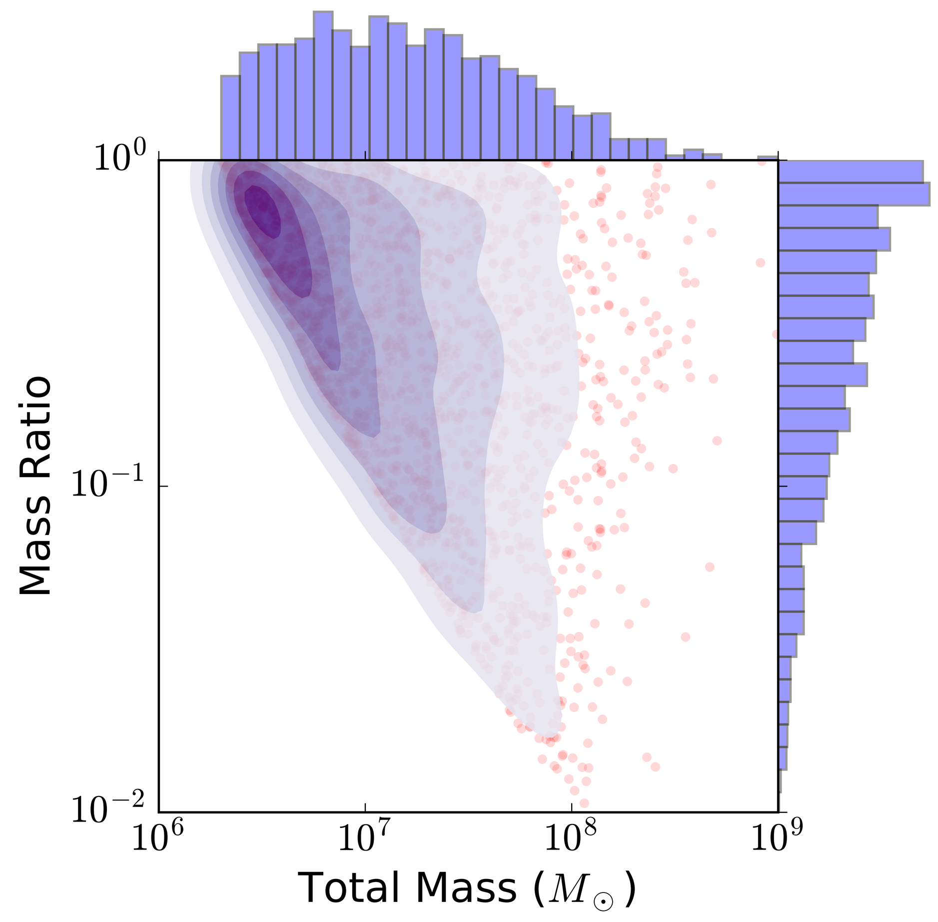


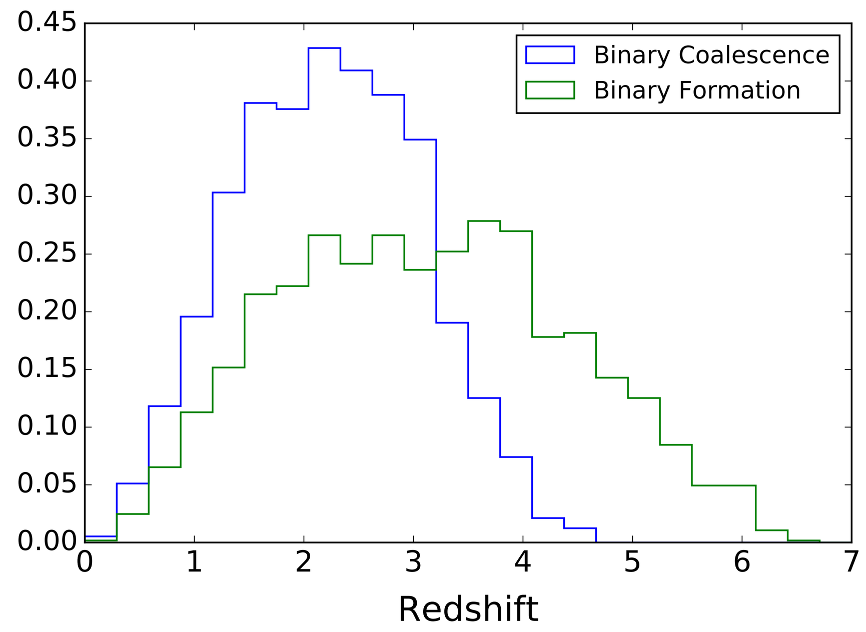
Simulation Output

- Initial analysis includes expected detection rate and signal-to-noise ratio (SNR) predictions.
- This helps define the scope of LISA's science performance, and how mission design affects that performance.

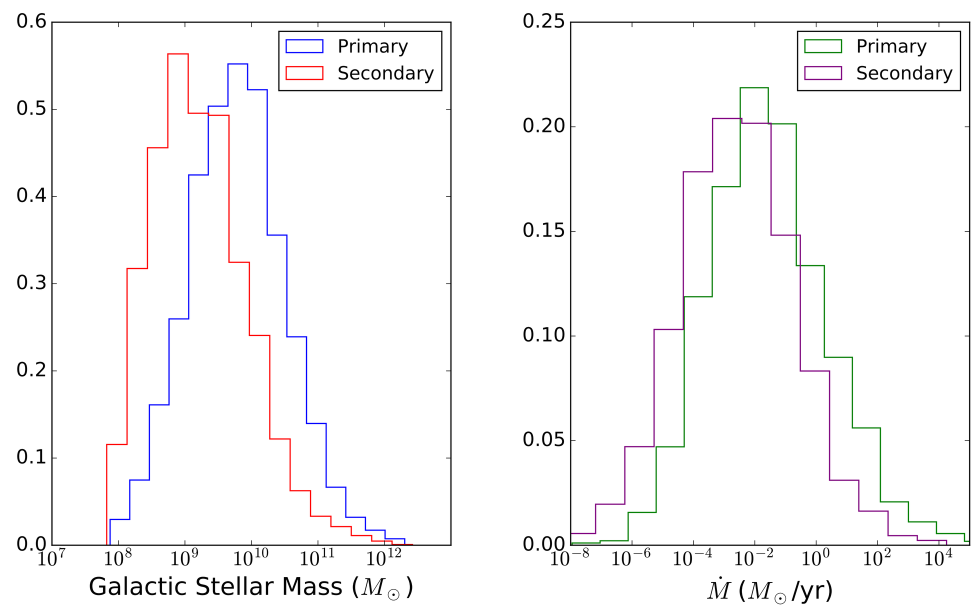


- We examine the main binary parameters of interest: total mass, mass ratio, and redshift.





- Future work will examine the influence of galactic masses and density profiles on the LISA detection rate.
- Any parameter from Illustris can be included in the KDE and analyzed in the simulation output.



Acknowledgements

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References

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