Gravitational Wave Astronomy as a Probe of Cosmic Evolution

Laura Blecha, Cole Miller, Sean McWilliams, John Baker

Gravitational wave (GW) observations will provide a unique opportunity to study the development of strongly gravitating objects at all redshifts, including objects with heavily obscured or underluminous electromagnetic (EM) signatures. This will enable the exploration of cosmic evolution at all epochs.

- **Development of present-day structure, $z < 1$:** GW observations can provide precise quantitative details about the population of black holes in this period, particularly at low frequencies and large separations where a sizable number of loud sources and an unresolvable stochastic background are expected. Masses and spins may be precisely measured through extreme mass-ratio inspirals (EMRIs) of compact objects into massive black holes (MBHs). Additionally, GW observations of MBH mergers will provide a valuable opportunity for multi-messenger studies. Simultaneous EM observations of low-redshift MBH mergers will provide unprecedented details about the gas environment and accretion physics of merging MBHs, in addition to directly addressing the contentious question of how much MBH accretion is triggered by galaxy mergers at $z < 1$.

- **Hierarchical structure formation epoch, $1 < z < 6$:** Observations of luminous quasars at $z > 6$ demonstrate that MBHs undergo rapid growth at these early times, with most observable MBH mergers occurring in this epoch. EM searches for binary MBHs (with parsec-scale or smaller separations) are limited by spatial resolution limits and by the requirement that both MBHs be simultaneously active; thus far, only one bound binary MBH has been confirmed. Direct BH mass and spin measurements via EM signatures, which are challenging in the local Universe, are impossible at higher redshifts. In contrast, GW observations of MBH mergers will uniquely provide precise quantitative details about the merging BHs masses, spins, and recoil velocities, independent of whether the BHs are actively accreting or obscured. These observations will be critical in understanding the assembly process of MBHs and their co-evolution with galaxies from early times.

- **Early galaxy formation and the first black holes, $6 < z < 20$:** Various theories suggest that ~ 100 M$_\odot$ BH seeds may form via the collapse of the first stars, which then grow via rapid accretion, or that larger ($\sim 10^4$ M$_\odot$) BH seeds may form via direct collapse of gas in massive dark matter halos. In either case, these seeds must form and accrete efficiently in order to produce the 10^9 M$_\odot$ MBHs observed as quasars at $z \sim 6$ - 7. GW observations of mergers between BH seeds at very high redshift will provide insights into their growth history and constrain the possible models for seed formation.

- **Epoch preceding reionization, $z > 20$:** In addition to gravitational radiation from the earliest black hole seeds, there are prospects for observing GWs from the electroweak and quark-hadron phase transitions, and from inflation on a scale many orders of magnitude different from what can be probed with the cosmic microwave background. Given the significant uncertainties during this epoch, and the need to rapidly form the 10^9 M$_\odot$ MBHs observed as quasars at $z \sim 6$ - 7, GWs provide an unparalleled opportunity for discovery.