Prospects for Multimessenger Observations of Massive Black Hole Binaries with LISA and Electromagnetic Observatories

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Abstract

LISA is expected to observe gravitational waves (GWs) emitted from the inspiral and merger of massive black hole binaries (MBHBs) [1]. Multimessenger observations with LISA will enable advances across astrophysics impossible with only GW or electromagnetic (EM) observations [2]. Using the Illustris-TNG cosmological simulations, we investigate the number and characteristics of galaxies within the LISA localization region as it shrinks over time as the MBHB approaches merger [3]. We also investigate the feasibility of simultaneous EM observations of MBHBs with an array of observatories.

Number of Galaxies in the LISA Localization Region

Building the localization volume in Illustris-TNG:

- Use the "on the fly" luminosity distance & sky localization fits from Mangiagli et al. (2020) [4]
- Extend simulation snapshots in z and the sky localization plane until they cover the full sky localization volume

Counting the galaxies:

- Knowledge of central MBH/potential MBHB mass can lower the number of potential host galaxies significantly

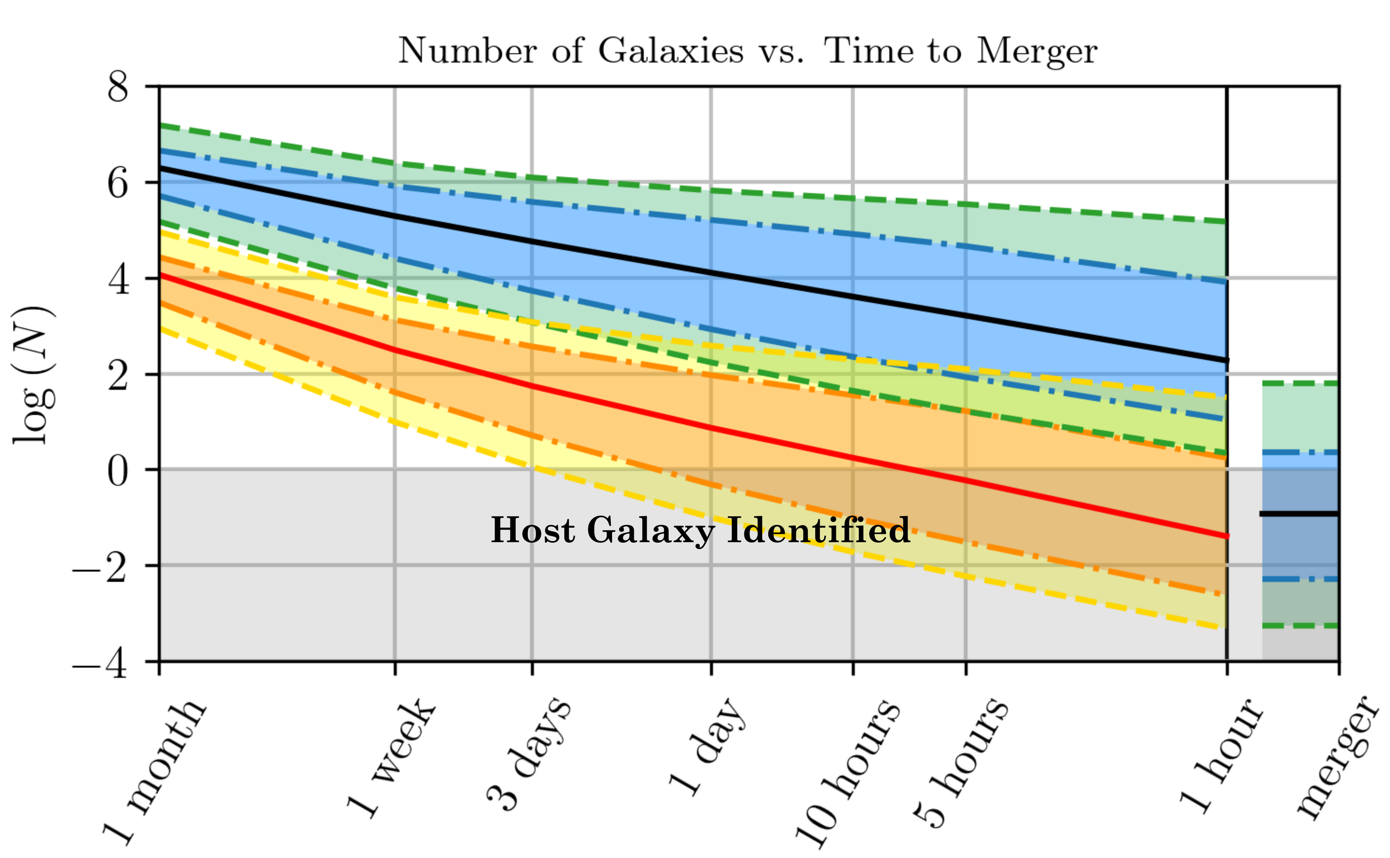

Figure 1: The number of galaxies in the LISA localization region for $3{\times}10^6 M_\odot$ MBHB at z = 0.3 as a function of time to merger. The black is median values when averaging over mass ratio, time to coalescence, spin, inclination, and sky positions; the blue region is the 68th percentile, and the green region is the 95th percentile. The break at merger results from rescaling different waveforms for the merger signal. Warm colors indicate when we apply a central MBH/potential MBHB mass uncertainty cut assuming a mass ratio of 1. LISA will detect GWs from this system ~one month before merger. **The median number of galaxies falls to tens of thousands days before merger to hundreds hours before merger; at merger, the galaxy should be identified.**

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Galaxy Properties in the LISA Localization Region

The LISA localization region is dominated by **gas rich, dim, $\sim 10^{10} M_\odot$ galaxies with low-mass central MBHs and low stellar masses & magnitudes** (solid lines in figures below). Galaxies hosting $3{\times}10^6 M_\odot \pm \Delta M_{\rm bin}$ MBHs (where $\Delta M_{\rm bin}$ is MBHB mass uncertainty) have **narrower distributions** of stellar masses, magnitudes, and SFRs, and are **preferentially gas rich** (dashed lines).

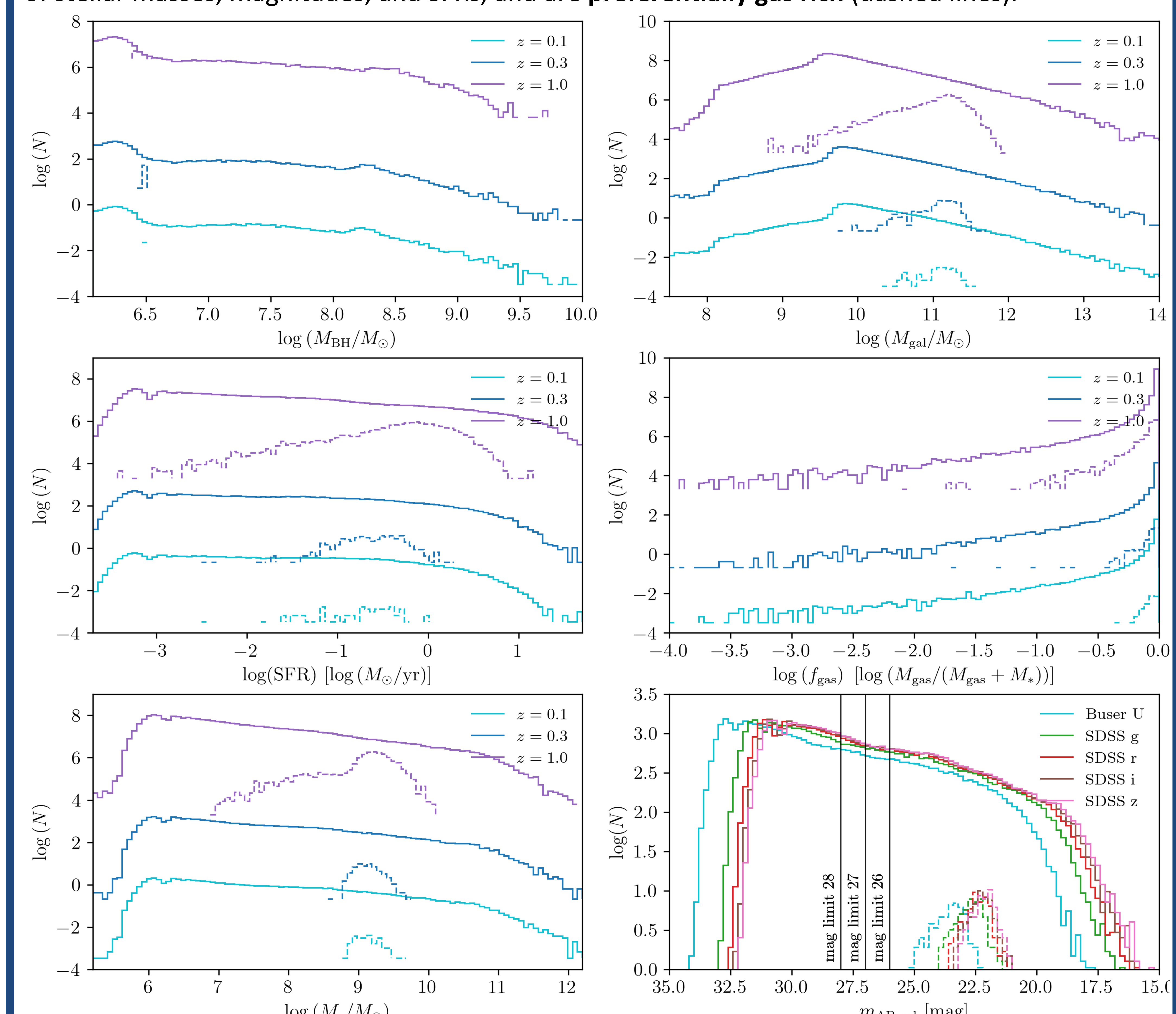

Figure 2: Distributions of properties for galaxies enclosed in the LISA localization volume calculated for a $3{\times}10^6 M_\odot$ MBHB at z = 0.1 (cyan), 0.3 (blue), and 1.0 (purple). These properties include central MBH mass (top left), total mass (top right), star formation rate (middle left), gas fraction (middle right), stellar mass (bottom left), and stellar magnitudes (bottom right, z = 0.3 only). The dashed lines show the distributions after applying the uncertainty around central MBH/potential MBHB mass. In the stellar magnitudes plot, we show the distributions of apparent magnitudes in the Buser U and SDSS g, r, i, and z bands, and indicate magnitude limits of the Roman Space Telescope for hour-long point-source exposures.

Works Cited

[1] Amaro-Seone et al. 2017, ESA. [2] Piro et al. 2022, MNRAS, 521, 2577. [3] Springel et al. 2018, MNRAS, 475, 676. [4] Mangiagli et al. 2020, PRD, 102, 084056. [5] Mangiagli et al. 2022, PRD, 106, 103017. [6] Lops et al. 2023, MNRAS, 519, 5962. [7] Dong-Páez et al. 2023, A&A, 676, A2. [8] Izquierdo-Villalba et al. 2023, A&A, 677, A123. [9] Bardati et al. 2024, ApJ, 961, 34.

Considering Observability of AGN-Like Emission

Observability will depend on:

- Telescope capabilities (FoVs, sensitivities, wavelength coverage, slew & response times, other technical aspects)
- Likelihood galaxies host MBHBs of target mass based on galaxy properties
- Likelihood AGN-like emission associated with an MBHB is above both a limiting flux/magnitude & host galaxy emission
- See Piro et al. (2022) [2], Mangiagli et al. (2022) [5], Lops et al. (2023) [6], Dong-Páez et al. (2023) [7], Izquierdo-Villalba et al. (2023) [8], Bardati et al. (2023) [9]

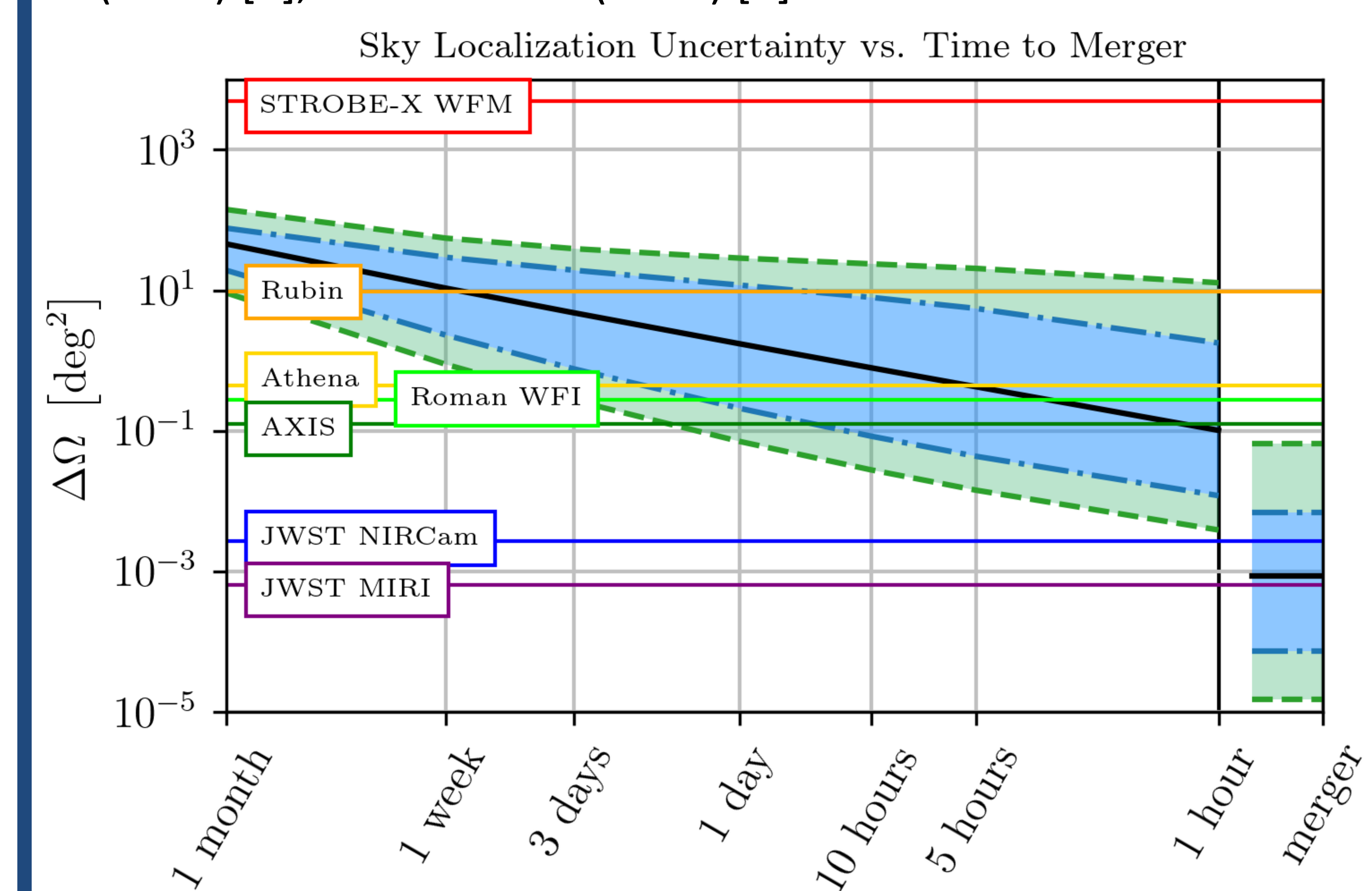

Figure 3: The sky localization uncertainty $\Delta\Omega$ for $3{\times}10^6 M_\odot$ MBHB at z = 0.3 as a function of time to merger. Colors are the same as in Figure 1, with horizontal, colored lines indicating the FoVs of various observatories. Of the seven observatories shown, STROBE-X WFM and Rubin are the only ones with sufficiently large FoVs to detect an EM precursor to the merger for the specified system without tiling observations weeks and days prior to merger. Athena, Roman, and AXIS may be able to encompass the full $\Delta\Omega$ without tiling observations in the hours before. Sensitive telescopes with small FoVs like JWST could be used for follow-up observations once the host galaxy is identified $\Delta\Omega$ is sufficiently small.

Conclusions and Future Work

The number of galaxies in the LISA localization region may initially be on the order of millions but decreases considerably as the MBHB approaches merger. The sky localization uncertainty similarly shrinks as the MBHB approaches merger and may become small enough for certain telescopes to fully encompass it in their FoVs prior to merger. Galaxies in the LISA localization region have a wide range of properties, but knowledge of the central MBH/potential MBHB mass can narrow this range. Our future work will prioritize galaxies in the LISA localization region for observation based on their properties associated with MBHBs and the likelihood that AGN-like emission from accreting MBHBs within them can be observed by a suite of observatories.