Multimessenger Observations of Merging Massive Black Holes with Roman and LISA

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Abstract

The Laser Interferometer Space Antenna (LISA) is expected to observe the gravitational radiation emitted from the inspiral and merger of massive black hole binaries (MBHBs) with mass $\sim 10^4 - 10^7 M_{\odot}$[1]. Multimessenger observations with LISA and electromagnetic (EM) observatories such as Roman will enable advances across astrophysics which are impossible with only gravitational wave (GW) or EM observations [2]. Here we consider the synergy between the two observatories and the ability of Roman to detect MBHBs before LISA is launched as well as simultaneously with LISA in mid-2030s.

Roman Observations of Massive Black Hole Binaries Before LISA

Roman's High Latitude Time Domain (HLTD) Survey will have sufficiently high cadence (about 5 days), depth (about 26-27 mag per visit), and footprint (about 19 deg^2 for the wide tier and 4 deg^2 for the deep tier) to detect many Active Galactic Nuclei (AGN) during the initial years of the mission. Some fraction of these are bound to be accreting MBHBs, which may exhibit quasi-periodic modulation in their light curves with periods of one to a few weeks. Should this signal be distinct enough, **Roman will be able to detect MBHBs with mass as low as $3\times10^5 M_{\odot}$ in the local universe and $10^7 M_{\odot}$ MBHBs up to a redshift of z~1.** This is illustrated in Figure 1 which shows the detectability of MBHBs in different bands as a function of redshift. MBHB systems with this range of orbital periods and masses are precursors to LISA sources (they will evolve into LISA sources on time scales < 10^4 years). Their detection by Roman would uniquely constrain the LISA population of MBHBs and their merger rates.

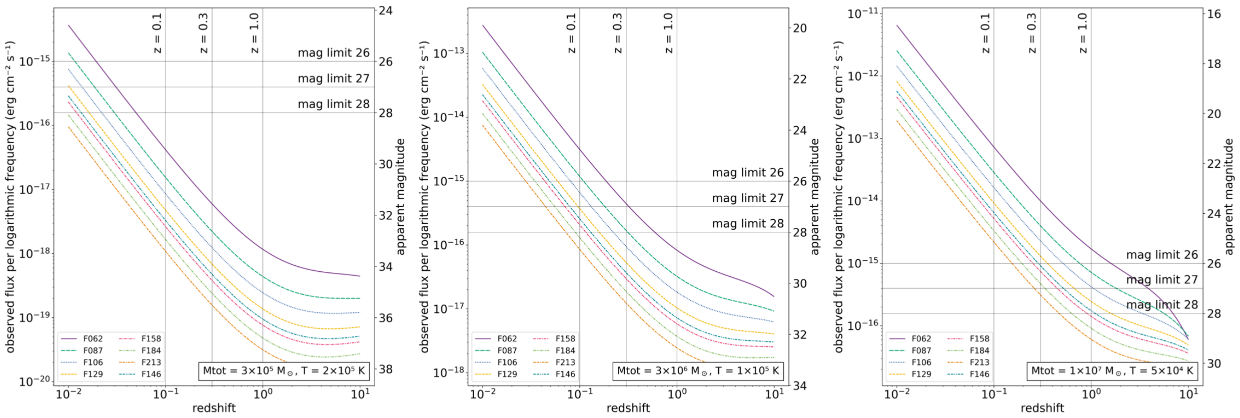

Figure 1: Roman's HLTD Survey sensitivity to the emission from MBHB systems with mass $3\times10^5 M_{\odot}$, $3\times10^6 M_{\odot}$, and $10^7 M_{\odot}$. For the purposes of this calculation, the spectrum of each source is modeled as blackbody emission from the minidisks associated with the two MBHs in the system, characterized by the temperature marked in the figure. The colored lines mark the observed flux per logarithmic frequency (apparent magnitude) in each of Roman's filters.

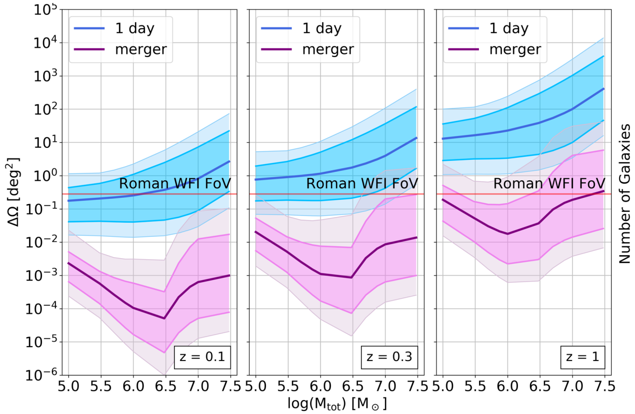

Figure 2: The LISA sky localization error as a function of MBHB mass for redshifts of 0.1, 0.3, and 1.0 calculated with the time-varying LISA error volume parametric fits presented in [4].
The central blue (1 day prior to merger) and purple (merger) lines represent the median sky localization error defined by the distribution of MBHBs with the same redshift and mass but varying mass ratios, spins, locations and orientations on the sky. The dark blue and dark purple regions represent the 68 percentile of the distribution and the light blue and light purple represent the 95 percentile of the distribution.

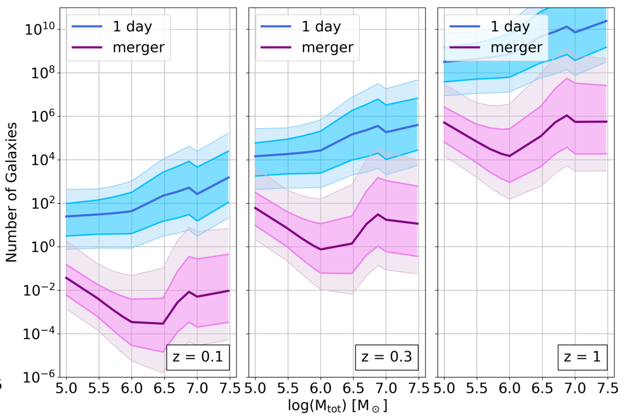

Figure 3: The number of galaxies within the full LISA error volume (encompassing LISA's sky localization error and luminosity distance error) as a function of MBHB mass for redshifts of 0.1, 0.3, and 1.0. The density of galaxies in the LISA error volume has been determined from the cosmological simulation Illustris-TNG100 [5]. We require that each candidate host galaxy has mass at least 100 times larger than the mass of the merging MBHB under consideration and neglect lower mass halos. The central blue (1 day prior to merger) and purple (merger) lines represent the median number of galaxies, and the light and dark regions represent the same percentiles of the distribution as described for Figure 2. Where the number of galaxies falls below 1 (for example, at z=0.1 at merger), the host galaxy has been concretely identified.

Simultaneous Multimessenger Detection of MBHBs by Roman and LISA

If Roman achieves a lifetime of 10 years or longer it is likely to operate contemporaneously with the LISA GW observatory. In this scenario, Roman's Wide Field Instrument (WFI) could be used for direct electromagnetic follow-up of the GW sources detected by LISA, in cases where LISA's localization uncertainties are not much larger than the WFI field of view. For example, Figure 2 shows that **more than 50% of MBHBs with total mass below $10^6 M_{\odot}$ detected by LISA at z = 0.1 will have their position on the sky determined with sufficient precision to also be in the field of view of WFI 1 day before they merge. For MBHBs at higher redshifts (z ≤ 1), the WFI will fully enclose the LISA uncertainty region on the sky for most MBHBs with mass less than $10^7 M_{\odot}$ at the time close to the merger** (i.e., within an hour from merger). Figure 3 shows that in some of these cases (at z < 0.3), the number of galaxies enclosed within the WFI field of view will be ~1-100, providing a high likelihood for identification of the MBHB host galaxy, even in the absence of characteristic AGN emission. At higher redshifts, the number of potential host galaxies in the LISA error volume becomes very large. Identification of host galaxies may still be possible in this case if their accreting MBHBs exhibit distinct quasi-periodic AGN emission. The opportunity to characterize MBHB host galaxies would provide invaluable information about their properties and would allow Roman to play a major role in multimessenger discoveries.

Conclusions

Our preliminary analysis shows that Roman may have strong synergies with the LISA observatory. Before LISA is launched Roman's HLTD Survey may detect MBHBs which are LISA precursors and in such way place unique constraints on the population of LISA MBHBs and their merger rates. In mid-2030s, Roman WFI may be able to provide a simultaneous coverage of merging MBHBs detected by LISA. Particularly, for sources at redshift z<0.3, Roman may be able to uniquely identify and characterize the merger host galaxies and play a major role in multimessenger discoveries.

Works Cited

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