Roman Core Community Survey White Paper

Title: Massive Black Hole Binaries as LISA Precursors in the High Latitude Time Domain Survey

Abstract: *With its capacity to observe* $\sim 10^{5-6}$ *faint active galactic nuclei (AGN) out to redshift* $z \approx 6$*, Roman is poised to reveal a population of* $10^{4-6}\,\mathrm{M}_\odot$ *black holes during an epoch of vigorous galaxy assembly. By measuring the light curves of a subset of these AGN and looking for periodicity, Roman can identify several hundred massive black hole binaries (MBHBs) with 5-12 day orbital periods, which emit copious gravitational radiation and will inevitably merge on timescales of* 10^{3-5} *years. During the last few months of their merger, such binaries are observable with the Laser Interferometer Space Antenna (LISA), a joint ESA/NASA gravitational wave mission set to launch in the mid-2030s. Roman can thus find LISA precursors, provide uniquely robust constraints on the LISA source population, help identify the host galaxies of LISA mergers, and unlock the potential of multi-messenger astrophysics with massive binaries.*

Name of Survey: High Latitude Time Domain Survey
Scientific Category: Supermassive black holes and active galaxies
Additional scientific keywords: Gravitational waves, Supermassive black holes, High-luminosity active galactic nuclei, Low-luminosity active galactic nuclei, Quasars

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1. Introduction and Background

Massive black holes (MBHs) in the $\approx 10^6 - 10^{10}\mathrm{M}_\odot$ range are present in the nuclei of most, and perhaps all, nearby galaxies [1]. In hierarchical structure formation models, galaxies are built up by mergers between lower-mass progenitors. Each merger event is expected to deliver the nuclear MBHs [2, 3], along with a significant amount of gas [4], to the central regions of the new post-merger galaxy. The inevitable conclusion is that massive black hole binaries (MBHBs) should form frequently in galactic nuclei over cosmic time-scales, and that this should often take place in gas-rich environments. These MBHBs are both a fundamental product of galaxy formation and evolution, and the prime targets of gravitational wave (GW) experiments, from the space-based GW detectors LISA, TianQin, and Taiji [5–7], to pulsar timing arrays [8–12]. The combination of GW and EM detections of the same population of compact MBHBs will open windows to a range of new science, from understanding the astrophysical environments and host galaxies of MBHBs over cosmic time, to understanding binary evolution, accretion, and emission [13].

The pair of MBHs from the kpc scale of a galactic collision must be dragged down to several orders of magnitude smaller separations to become a genuine gravitationally bound binary, and to eventually merge due to GW emission. This requires efficient dissipation of orbital energy and angular momentum transport by stellar and gas torques. The time to merger can be as short as 100 Myr or as long as (or exceed) the age of the Universe, depending on the geometry of the encounter, the morphology of the interacting galaxies, and a variety of inherently stochastic astrophysical processes [14]. Tracking the late stages of this long journey to coalescence, through detecting the light produced by the accretion onto MBHBs, is key to assessing the existence of merging systems. Hydrodynamical simulations have recently reached a consensus that the emission from MBHBs, when surrounded by dense nuclear gas, should be just as bright as from single MBHs, all the way to the merger [15]. Additionally, binary emission is strongly modulated on the orbital period of the binary, either due to hydrodynamical effects, or due to relativistic Doppler modulations [16].

There is, indeed, empirical evidence for pairs of MBHs in galactic nuclei, as expected from galaxy mergers. A few active MBH pairs (so-called dual AGN) have been resolved at projected separations of $0.1 - 1$kpc in the optical [3, 8] and X-ray bands [17]. A compact MBHB at a projected separation of ~ 7 pc, discovered in the radio [18], is a candidate gravitationally bound system. Some even more compact, spatially unresolved gravitationally bound MBHB candidates have been identified through indirect observational techniques relying on quasi-periodicities in light-curves, spectral features such as double-peaks or velocity offsets of emission lines, or spatial structures of optical emission lines and of radio jets and lobes (see [16, 19] for recent comprehensive reviews). Of particular relevance to Roman, several hundred bright quasars have been identified with significant optical periodicities [20–23]. Identifying quasars with periodic variability can nevertheless be challenging, particularly when the MBHB orbital periods are relatively long compared to the available observational baselines, and the incomplete knowledge of the underlying variability of AGN can lead to false detections [24]. To mitigate the risk of false detections, it is thus crucial to be able to detect as many as possible orbital cycles, something that Roman's High Latitude Time Domain Survey (HLTDS) will be capable of doing for the short-period ($\sim 5 - 12$ days) MBHBs that are inspiraling due to the emission of GWs.

The purpose of this white paper is to argue that Roman can make a major contribution to this field by discovering a population of compact MBHBs that are guaranteed LISA precursors. This can be achieved in a search, in an entirely new regime, for faint AGN with short periods, at a combination of depth, cadence, and survey area that is unique to Roman. Periodicity is perhaps the most robust EM signature distinguishing unresolved compact binaries from solitary MBHs. Identifying these sources will lead to unprecedented robust constraints on the LISA population. Roman will also allow us to characterize the properties of host galaxies of LISA precursors prior to LISA's launch. This will be crucial to help identify the hosts of the future LISA MBHB mergers, as we expect LISA's sky localization errors to be generally be too poor ($\sim 1-10\,\mathrm{deg}^2$; [25]) to identify a unique host galaxy [26]. Indeed, recent theoretical investigations indicate that LISA binaries are preferentially hosted in disk-dominated, gas-rich, and star-forming dwarf galaxies [27] that Roman can identify.

More broadly, the combination of GW and EM detections of the same population of compact MBHBs will open windows to a range of new science, from understanding the astrophysical environments and host galaxies of MBHBs over cosmic time, to understanding binary evolution, accretion, and emission (see a review in the Astro2020 Decadal Survey white paper on multimessenger astrophysics [13]).

2. The Unique Contributions by Roman

Fig. 1 demonstrates Roman's unique synergy with LISA. This figure shows, in the gray contours, the distribution of MBHB mergers in total binary mass and redshift expected to be detectable by LISA, as predicted by the semi-analytical population model of [28]. This distribution depends on model assumptions, such as the nature of the MBH seeds – i.e. whether the $\sim 10^{5-6}$ $\mathrm{M}_\odot$ MBHs grow from $10-100$ $\mathrm{M}_\odot$ stellar-mass black holes, or result from the rapid direct collapse of gas (the latter case is shown in Fig. 1). Given a sufficient number of detections, LISA will be able to probe the contributions from these different channels. Most importantly, the MBHs probed by LISA have low masses, closer to the "intermediate" [29, 30] than to the "supermassive" range. For reference, in Fig. 1 we also show, in the purple contours, the black hole mass and redshift-distribution of the $\approx 750,000$ AGN presently cataloged in the Sloan Digital Sky Survey (SDSS) [31, 32]. These AGN are powered by MBHs with masses that are much higher, and redshifts that are much lower than those of the expected LISA population. While there exist a small number of nearby, low-luminosity AGN with low black hole masses comparable to those in the LISA band [3, 33], and JWST and other instruments can also detect high-z quasars overlapping with this mass range, they are too few in number and lack sufficient time-domain data for a systematic search for the rare short-lived binaries among this population. A handful of inactive MBHs in the same low-mass range have also been detected through kinematics, but their binarity is unknown.

In contrast, the blue contours in Fig. 1 show the distribution of *all AGN* expected to be above the detection threshold of Roman, when all of the data from the HLTDS are co-added. These contours were computed by extrapolating the empirically measured quasar luminosity function (LF), as compiled by [34], to lower black hole masses and higher redshifts. The extrapolation methods and numerical choices are detailed in [35]. For the Roman survey, in the top panel, we assume a solid angle of 19 deg^2 and a co-added detection threshold of 30 mag in the F087 filter (this corresponds, for example, to 36 separate data points, each with an effective depth of 28 mag), which yields a total of $\sim 10^6$ AGN. To convert to BH mass, we assume 10% of the Eddington luminosity in the F087 band. For reference, for a 10^5 $M_\odot$ MBH at $z = 2$, the luminosity of $0.1L_{\rm Edd}$ corresponds to 30 mag.

As Fig. 1 illustrates, a sufficiently deep Roman survey is sensitive to the same black hole masses as LISA (albeit somewhat lower redshift). We note that this capability is unique to Roman's depth – for example, the Legacy Survey of Space and Time (LSST) by the Vera C. Rubin Observatory will have a ~ 4 magnitude shallower co-added depth (~ 26 mag in the i band, closest to Roman's F087), and will accordingly probe nearly $\sim$two orders of magnitude higher black hole masses [36]. As a result, Roman's HLTDS has the unique capability to discover essentially the same population of MBH binaries as LISA, but at somewhat earlier stages of their merger, with larger separations.

However, depth is not the only necessary ingredient to accomplish this. First, in order to search for periodicities, the effective depth is reduced for two reasons: (i) the AGN needs to be detected at each visit, not just in the full survey co-add, and (ii) its variability needs to be measured (for example, measuring 10% flux variations requires ≈ 2.5mag deeper photometry than a mere detection). Imposing these more stringent effective photometric limits leaves us with $\approx 550,000$ AGN, shown in the bottom panel of Fig. 1. This bottom panel adopts a sensitivity threshold of 28 mag in the F087 filter, and assumes that 10% of the band flux is variable, effectively assuming a luminosity of $L = 0.01L_{\rm Edd}$ in the F087 band.

In order to search for the compact MBHB LISA precursors, identified by their periodical variability among these AGN, solid angle and cadence are also critical. To be a guaranteed LISA precursor, an MBHB needs to be sufficiently compact to be safely in the GW-driven regime, where the inspiral time is at most 10^{4-5} years, and where the binary cannot be disrupted (although circumbinary gas disk torques could still be a significant contribution and affect the inspiral time; [37]). As a result, these short-lived sources will constitute a small fraction of all AGN (requiring a minimum solid angle), and will have short periods (also requiring a minimum cadence).

To illustrate these points, we note that the ≈ 300 MBHB candidates, identified among large time-domain surveys of bright quasars based on their periodicity [20–23], remain controversial. This is primarily because all AGN are known to be variable, and stochastic red noise (the so-called "damped random walk"; [38]) can mimic periodicity when only a few cycles are observed. The existing large time-domain surveys are shallow, and the masses of the periodic MBH candidates are $\approx 10^9$ $M_\odot$. These heavy binaries inspiral very rapidly. The GW inspiral time scales with chirp mass (the combination $M_{\rm chirp} \equiv (M_1 M_2)^{3/5}/(M_1+M_2)^{1/5}$ of the masses of the individual MBHs) as $t_{\rm GW} \propto M_{\rm chirp}^{-5/3}$, and the scaling with an orbital period is even steeper; $t_{\rm GW} \propto P_{\rm orb}^{8/3}$. For an equal-mass binary with $\approx 10^9$ $M_\odot$, source redshift $z \approx 2$, and observed orbital period of $P_{\rm orb} = 1-5$ years, the GW inspiral times are $\sim 10^{3-5}$ years. As a result, shorter-period binaries are too rare to be found in these surveys. Because of this, the existing MBH binary candidates only cover at most a few cycles and remain possible to attribute to red noise, as mentioned in the Introduction.

The combination of its depth, solid angle, cadence, and the total duration will allow Roman's HLTDS to extend the search for periodic AGN to an entirely new regime. Taking 10^5 $M_\odot$ and $z = 1$ as the approximate black hole mass and redshift corresponding to a typical Roman AGN that can be identified as periodic (see Figs. 2 and 3 below), MBHBs with this mass inspiral in $\approx 10^{3-5}$ years if their observed orbital periods are $P_{\rm orb} = 5-12$ days. Such short periods will allow the detection of a large number of cycles and securely rule out fake periodicity caused by red noise.

In particular, red noise cannot mimic periodicity when more than ≈ 10 cycles are measured [24], requiring a total of 4 months of observation time for a 12-day observed period. We note that, depending on mass ratio and circumbinary disk properties, the dominant optical/IR periodicity from hydrodynamical modulations by a binary could appear on timescales a few times longer than the orbital period [39]. Roman's light curves will need to be carefully analyzed for the presence of multiple periods – this would help probe the binary system's parameters if more than one period is detected but would require longer baselines if only the longer periods are visible in the data.

In the GW-driven regime, discovering several dozen or more sources with a range of periods will allow a novel test of the GW inspiral time, since the number of sources should scale with their period as $P^{8/3}$ – while deviations from this scaling could be used to study the torques from circumbinary disks [37]. Most importantly, identifying this short-period MBHB population will provide a unique synergy between Roman and LISA: these sources are guaranteed precursors to LISA events, and will yield robust, model-independent constraints on the LISA merger rate.

Finally, how many periodic AGN might Roman's HLTDS be able to identify? One approach is to model the merging MBH population, building on hierarchical galaxy formation models, calibrated to observations, such as the empirically determined black hole-galaxy mass scaling relations. A sequence of parallel quadratic scaling relations, which track the evolution of galaxies toward increasingly bulge-dominated morphologies, has been established and can be a key ingredient in such modeling [40]. A simple quick way to obtain an upper limit on this number, without such modeling, is to assume that AGN are often activated by mergers, so that a fraction $f_{\rm bin} \sim 1$ of all AGN correspond to MBHB mergers. In this case, the number $N_{\rm bin}$ of binaries with a particular orbital period, and corresponding inspiral time $t_{\rm GW}$, is simply given by the fraction of AGN 'caught' at this stage: $N_{\rm bin} = [t_{\rm GW} \,/\, t_{\rm Q}] f_{\rm bin} N_{\rm AGN}$, where $t_{\rm Q} = 10^{7-8}$ years is the typical quasar lifetime [41] and $N_{\rm AGN}$ is the total number of AGN in a survey. In our fiducial case, Roman's survey will contain $N_{\rm AGN} \approx 10^5$ AGN whose periodicities could be measured, so that inspiral times of 10^{3-5} years will yield $(10-1000) f_{\rm bin}$ binaries with observed periods of 5-12 days for $t_{\rm Q} = 10^7$ years, and $(1-100) f_{\rm bin}$ binaries if $t_{\rm Q} = 10^8$ years. This simple approach yields approximately the correct fraction $\sim 10^{-3}$ of binary candidates among the bright quasars that have been searched to date (~ 300 candidates among 300,000 quasars). On the other hand, it likely represents an upper limit, because if all present candidates were real, they would, in the simplest models, overpredict the stochastic GW background at nHz frequencies [42].

The results of the actual calculations of these numbers, i.e. using the quasar LF, assuming a quasar lifetime of $t_{\rm Q} = 10^7$ years, and including the GW inspiral time at a fixed observed period as a function of binary mass and redshift, are shown in Figs. 2 and 3. Fig. 2 shows the distribution of Roman AGN with an orbital period of 6 days (top) or 12 days (bottom), assuming a single-visit depth of 28 mag in a 19 deg^2 survey. As the figure shows, these periodic sources preferentially sample lower masses and redshifts among the Roman AGN population. These biases, compared to the parent population of all Roman-detected AGN, are caused by the strong dependence of the GW inspiral time on chirp mass and orbital time. In particular, at a fixed observed period, more massive binaries, as well as binaries at higher redshift (and therefore with shorter rest-frame periods) inspiral more rapidly and are correspondingly rarer. Conservatively excluding black holes with masses below $10^5\ M_\odot$ (since the existence and abundance of these intermediate-mass systems is less well understood), we find a total of 348 ($P_{\rm orb}$=6 days) and 2012 ($P_{\rm orb}$=12 days) periodic sources. Fig. 3 shows the same result, except for a shallower depth of 27 mag, reducing the numbers by a factor of 3-4, to 102 ($P_{\rm orb}$=6 days) and 531 ($P_{\rm orb}$=12 days) sources.

3. Survey Parameter Considerations

The fiducial survey, discussed in the previous section, assumes a depth of 28 mag in the F087 filter (for each single data point in the light-curve), a solid angle of 19 deg^2, a total observation time of at least 4 months, and sufficient cadence to identify 5-12 day periods, i.e. of order 5 days. At least three different filters would be ideal in order to compare the light-curves in different bands, and help distinguish periodic binary variability from other possible sources of AGN periodicity. While variability itself will be the most efficient way to select AGN to begin with [43], having colors may also help this selection, especially if, using external space-based data, the host galaxies can be resolved and subtracted.

In general, the considerations driving survey specifications for MBHB science are as follows:

- **Depth.** This is a primary consideration: the depth needs to be sufficient to detect faint AGN, corresponding to black hole masses in the LISA regime. Since we require identifying periodicities (not just detecting an AGN), this depth requirement is for each individual visit, and needs to be at least $27-28$ mag in the F087 filter. This is the closest among Roman's filters to the LSST *i* band considered in the analysis in [35]. The depth requirement is set by assuming black holes emit a luminosity of $L=0.1L_{\rm Edd}$ in the F087 band, of which 10% is variable (effectively requiring a depth corresponding to $L=0.01L_{\rm Edd}$).

- **Solid Angle.** The choice of solid angle is driven by ensuring that we have a sufficiently large sample of AGN among which the rare compact binaries, with inspiral times of 10^{3-5} years, will be represented. This necessitates a total sample size of at least 10^5 AGN, requiring a solid angle of $\gtrsim 5$ deg^2. The number of objects scales simply linearly with survey size.

- **Cadence.** The choice of cadence is driven by ensuring that periodicities as short as 5 days can be inferred from the time series. Naively, this requires a cadence of 5 days or more frequent. In principle, however, the Nyquist frequency can be beaten if the sampling is irregular, therefore, more sparse sampling is tolerable, as long as the observations are not placed at regular intervals. Finally, a single (or at most a few) long contiguous chunks of data are preferred over many separate campaigns spread over a longer baseline. Long gaps make the modeling of the red noise harder, which will increase the false detection rate.

- **Total duration.** The total duration is driven by requiring the detection of at least 10 cycles – for the 12-day period binaries, this requires at least 4 months of total coverage. Longer durations would improve sensitivity to longer periods and would significantly increase the total sample of periodic AGN (since the number increases as steeply as $P_{\rm orb}^{8/3}$ for binaries in the purely GW-driven regime).

- **Sky Location.** In principle, any location on the sky is acceptable. However, it would be useful to choose areas already covered by the deepest existing optical and infrared fields, such as COSMOS or Subaru's SHELLQs surveys, which already contain data on faint AGN. In particular, with Roman's restriction of being within 36 deg of the poles, there are several deep multi-wavelength observations near the South Galactic Pole. Of specific interest is the deep multi-wavelength GOODS-S field, which includes Hubble Deep and Ultradeep, Chandra Deep, Spitzer Deep, and will include LSST Wide and Deep, as well as Euclid Deep observations. The CANDELS team has published recent multi-wavelength catalogs for GOODS-S [44, 45] and specific deep AGN catalogs may be available in the near future. The locations of the LSST deep drilling fields would be other good possibilities.

- **Filter choices.** The filter choices are primarily driven by the need to distinguish periodic fluctuations caused by MBHBs from other sources of AGN periodicities. The low-mass AGN are expected to be bright in the F087 filter, and two additional bands would allow the construction of color-color diagrams. Measuring the chromaticity of the periodic variability can then be compared to theoretical predictions for binaries [46]. The more the filters are spread over wavelength (to obtain larger 'lever arms' in color-color space), the better. Color-color diagrams could possibly help with AGN selection but would likely require external space-based data to resolve and subtract the host galaxy.

4. Summary and Conclusions

The fiducial baseline HLTDS, planned around the requirement to search for Type Ia SNe, consists of 6 months of observing time, spread over 2 years, with a cadence of 5 days, in three filters, covering 5 deg^2, to a depth of $\sim$26 mag.

This turns out very similar to the requirements outlined here for a search for periodic, faint AGN containing MBHBs that are LISA precursors. The specification where we most significantly push on the above baseline survey is depth: single-visit exposures need to reach 27-28 magnitudes in order to detect faint AGN with black hole masses in the LISA band (10^{5-6} $M_\odot$). On the other hand, a somewhat sparser cadence can be tolerated, as long as the sampling is irregular in time (to beat the Nyquist frequency).

With the detection of a small population of LISA precursors, Roman can make a major contribution to GW and multi-messenger science with massive black hole binaries. There are additional ways in which Roman can contribute to GW science, which we list in the Appendix for completeness.

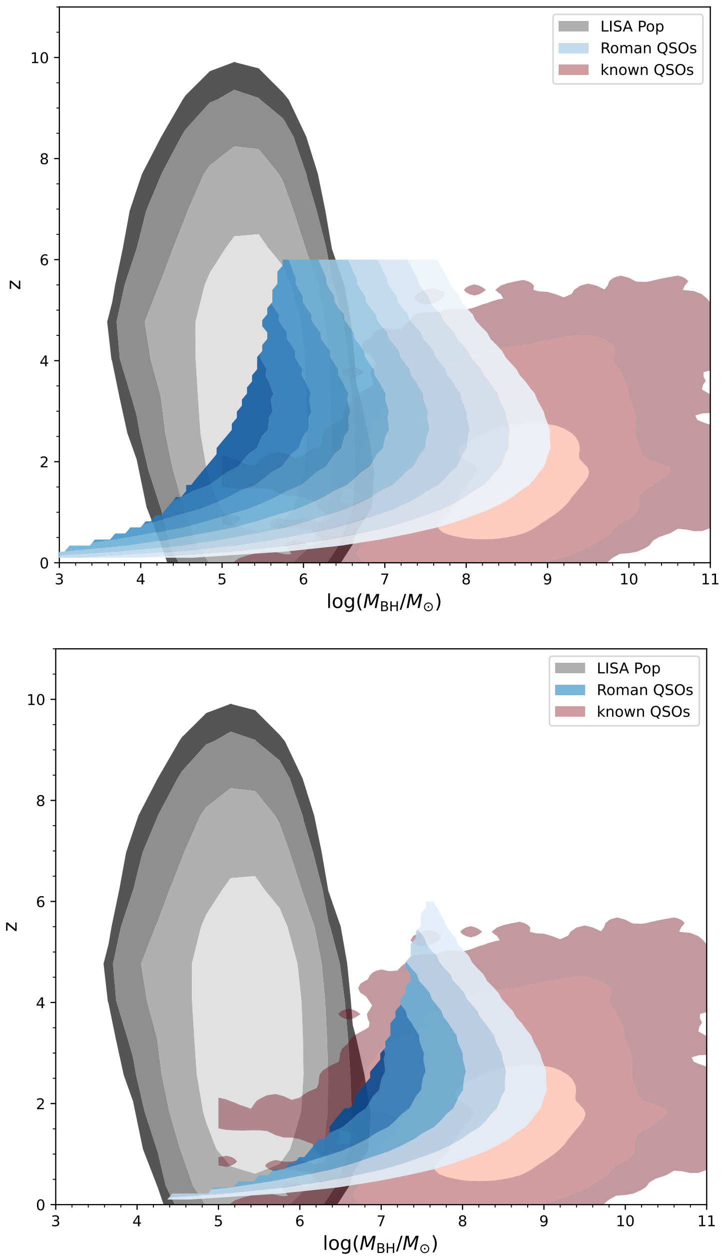

FIG. 1. **Top panel:** *The distribution of massive black hole binary mergers expected to be detectable by LISA (a total of* ~ 92 *sources shown by gray contours on the left; from the source population model in [28]), together with the distribution of currently known quasars (contours on the right; from the SDSS catalog of 746,256 AGNs), as well as the AGN expected to be above the detection threshold by Roman, in a survey reaching a total co-added limit of 30 mag in the F087 band, covering 19 deg*^{2} *(*$\approx 10^6$ *sources in blue contours with masses above* 10^5 $M_\odot$*; based on the extrapolation of the optical quasar luminosity function following [35]). The figure illustrates that the current observed AGN population is too massive and low-redshift compared to black holes probed by LISA, but Roman will be able to catalog up to approximately* 10^6 *black holes with masses and redshifts similar to those expected from LISA.* **Bottom panel:** *A subset of the faint Roman AGN are sufficiently bright to construct a light-curve and measure their variability. This panel shows, in blue contours, the mass- and redshift distribution of the approximately 500,000 AGN that can be detected in individual visits down to 28mag, along with their 10% flux variations. These AGN retain significant overlap with the masses of the LISA sources at low redshifts.*

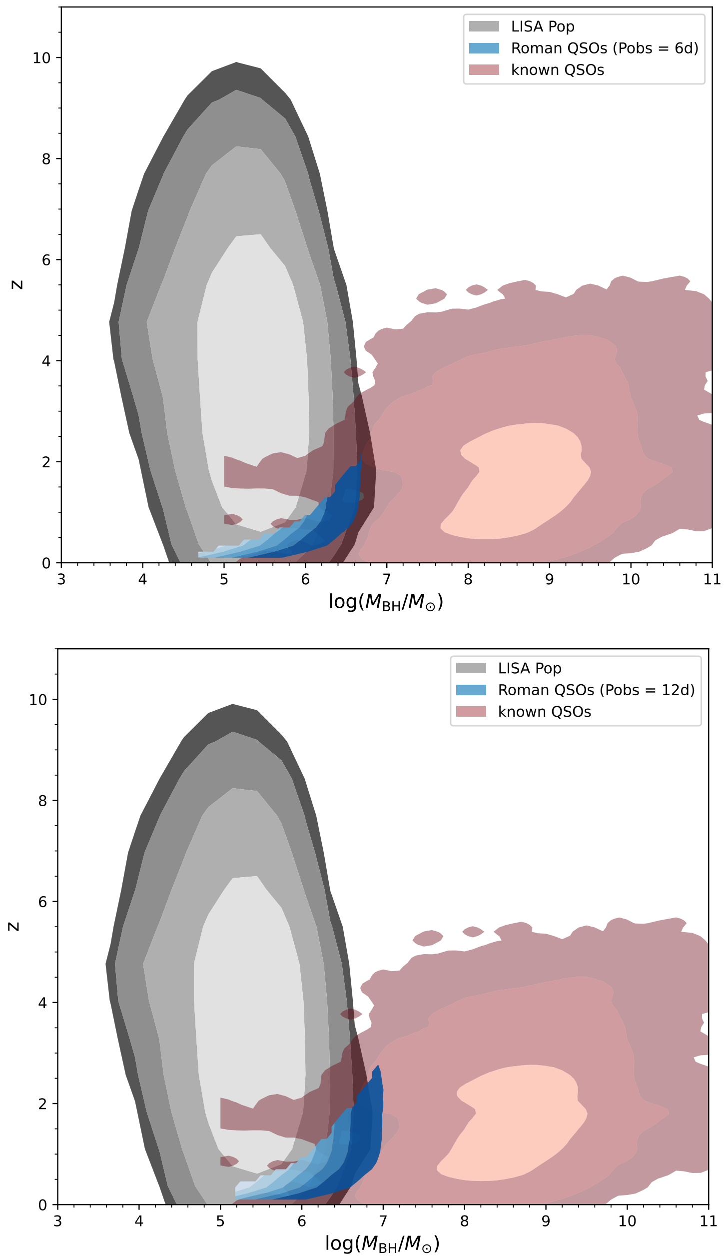

FIG. 2. *The distribution of Roman AGN with an orbital period of 6 days (top) or 12 days (bottom), assuming single-visit depth of 28 mag in a 19 deg*^{2} *survey. The GW inspiral time of these sources are* $\sim 10^4$ *yrs and* $\sim 10^5$ *yrs respectively. At these short inspiral times, they represent a small fraction of the total Roman AGN population from Fig.1, yielding 348 (P=6 days) and 2012 (P=12 days) sources that are* **guaranteed** *LISA precursors.*

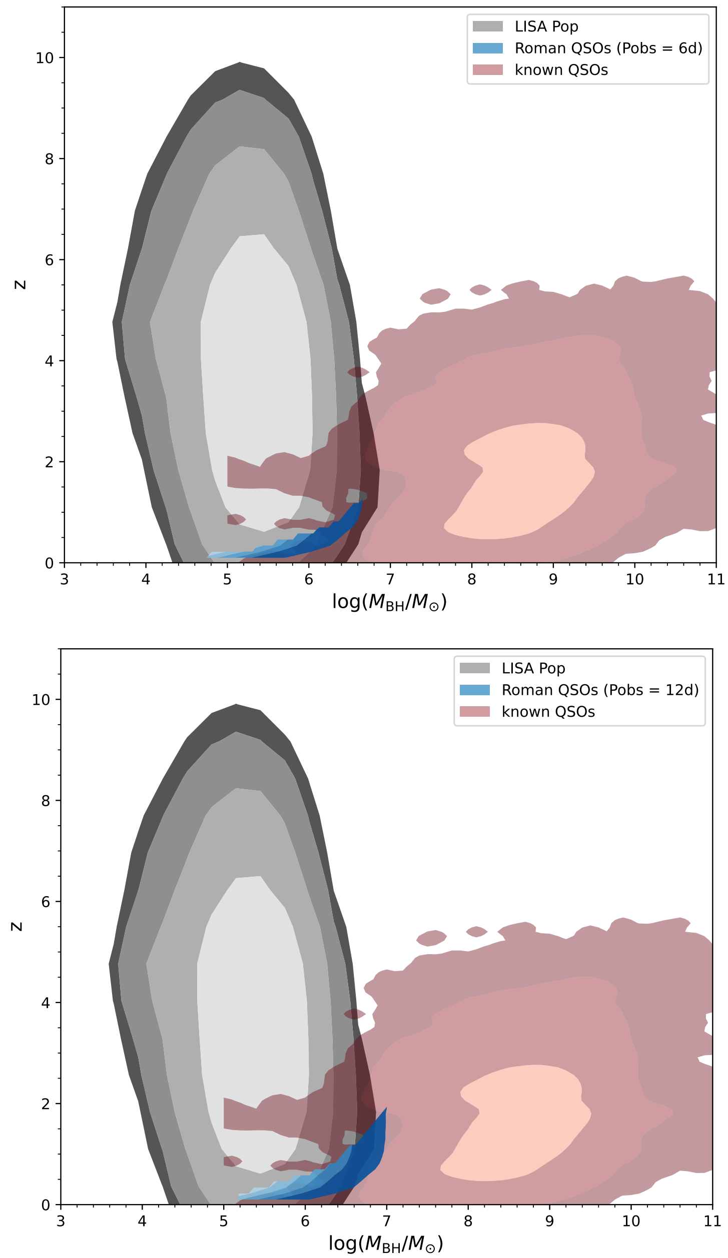

FIG. 3. *Same as Fig. 2 but assuming a shallower 27-mag single-visit sensitivity; this reduces the detectable sample of LISA precursors by a factor of 3-4 to 102 (P=6 days) and 531 (P=12 days).*

Appendix: Additional GW Science with Roman

The survey design above should allow the identification of LISA pre-cursors. There are other ways in which Roman can contribute to GW science with a survey similar to the one proposed here, as well as with its other Core Community Surveys and even beyond. Here we list these additional possible science investigations, and note some of the modifications they would require to the baseline survey above.

(i) LIGO sources in AGN disks. From the observation of stellar-mass binary black holes (BBHs) by LIGO and Virgo, we can infer a merger rate of $10-100\,\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$ [47], where it is estimated that 25 % to 80 % of these binaries form in AGN disks [48]. LIGO will see BBHs out to a distance of 2.5 Gpc from its fifth observing run (O5; starting around 2025) [47]. Assuming that Roman's HLTDS will use six months of aggregate telescope time, we anticipate around $80-2,620$ BBHs in AGN disks to merge during this period. After the BBH merges, the remnant black hole gets gravitationally kicked [49] and its motion through the gas of the AGN disk triggers a bright flare that is briefly comparable to or can exceed the AGN background in the near-infrared and optical [50, 51]. The flare becomes detectable around $20-500$ days after the GW event and lasts for days to months. Candidates for such events have been identified by LIGO/Virgo and the Zwicky Transient Facility, including GW190521 and ZTF19abanrhr [52], as well as a handful of additional coincident flares [53]. We anticipate that in the best case, tens of BBHs residing in AGN disks will merge in the area observed by the Roman Space Telescope but in the worst case, no event might be detected. If Roman extends the duration of the HLTDS – in particular, after 2026 when LIGO, Virgo, and KAGRA should further improve their detection distance – it might be able to detect hundreds of these AGN flares.

(ii) Self-lensed binaries. In addition to Doppler-induced modulations in the lightcurves of accreting MBHBs, there is a general relativistic effect that could also be detectable by Roman. If a massive binary is observed close to edge-on, the foreground BH's Einstein ring eclipses the background BH, resulting in a gravitational lensing (or self-lensing flare; SLF) event which can enhance the observed emission substantially and serve as strong evidence for an MBHB, see [54–57]. An extensive study by [58] showed that up to a hundred SLFs could be detected by LSST, which raises the question if Roman could find additional SLFs on shorter time scales.

Given a binary mass range of 10^5-10^6 $\mathrm{M}_\odot$, a mass ratio range of $q=0.1-1$, an orbital period range of $P_{\mathrm{orb}}=6-12$ days, and assuming that the light from the secondary is lensed by the primary, an SLF, with $\geq 34\%$ magnification, has a $1-5\%$ probability for orbital alignment and a corresponding lensing timescale of approximately 0.5% to 2.5% of the orbital period (hours). Considering finite source-size effects, maximum magnifications may reach from $\sim 10\times$ to $250\times$, though at a lower probability for such optimal alignment [59]. So if $\gtrsim 100$ binaries are observed, then at least one should be aligned favorably for strong self-lensing.

However, the cadence may need to be increased from the fiducial value in order to capture these short-duration SLFs. For binary mass $10^6\mathrm{M}_\odot$, $P=6$ days, and $q=0.1$, the duration of a SLF is ~ 0.14 days. The probability of capturing a flare is approximately the ratio of SLF time to orbital time, times the number of samples per orbit, times the number of orbits sampled. Given two samples per orbit (3-day cadence), at random phases, and 20 cycles in 4 months, one is left with a 95% chance of sampling the SLF. In this case, the probability for favorable alignment is

$\sim 5\%$, so for 100 binaries in the sample, there could be multiple lensing systems increasing the likelihood of sampling the flare in one of them. If a periodic signal is identified with Roman, then targeted, high-cadence follow-up could test for the existence of flares since their relative phase in the light curve is predicted by the model.

(iii) Partial tidal disruption events. The survey envisioned above would also enable the discovery of periodic flares from partial tidal disruption events (TDEs; [60]), which would be relevant for understanding the population statistics of extreme mass-ratio inspirals (EMRIs), another prime class of targets for LISA.

(iv) Synergy with pulsar timing arrays. Pulsar Timing Array (PTA) experiments are expected to detect a gravitational-wave background sourced from the cosmic merger history of supermassive black hole binaries with $M \gtrsim 10^8$ $M_\odot$. This detection can begin to constrain the abundance of MBHs at the high-mass end. Combined with the determination of the number density lower-mass MBHs in the Roman survey, this will yield a constraint on the slope of the (super)massive black hole mass function over the whole range of $10^6 - 10^9$ $M_\odot$.

(v) Galactic-scale dual AGN. Roman's High Latitude Wide Area Survey, with its unprecedented combination of sensitivity, spatial resolution, area, and NIR wavelength coverage, will revolutionize the study of galactic-scale dual AGN. The science opportunities and technical requirements on the discovery and characterization of SMBH pairs down to sub-kpc scales are summarized in a separate white paper [61].

(vi) Astrometric GW detection. Roman may be able to partner with LISA in yet another important way: by acting as a GW detector of individual MBHBs and their stochastic GW background, in the complementary microhertz range [62, 63]. The Galactic Bulge Time Domain (GBTD) survey will be particularly suitable for this purpose given its high cadence of observations (15 minutes) and high observed stellar density, coupled with Roman's high relative astrometric precision. The GBTD survey requirements necessary for the detection of GWs by Roman are described in a separate white paper [64].

(vii) Simultaneous multimessenger detection of MBHBs by Roman and LISA. It is worth noting that Roman may be able to make a unique contribution to the detection of inspiraling and merging MBHBs beyond the bounds of its Core Community Surveys. However, there is an impact on Core Community Surveys, in that this would require flexibility to interrupt ongoing surveys for target-of-opportunity observations. Specifically, 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, we estimate that about 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 out to higher redshifts ($z \leq 1$), the WFI will fully enclose the LISA uncertainty region on the sky for MBHBs with mass less than $10^7\,M_\odot$ at the time close to the merger (i.e., within an hour from merger). In many of these cases, the number of galaxies enclosed within the WFI field of view will be $\sim 1 - 100$, providing a high likelihood for identification of the MBHB host galaxy. The opportunity to characterize MBHB host galaxies would provide invaluable information about their properties and would be a unique opportunity for Roman to play a major role in multimes-

senger discoveries. For these types of detections, Roman's ability to follow up LISA sources will depend on its ability to process LISA alerts in real-time and react to updates that provide improved localization of MBHBs on the sky (i.e., localization that will land within the WFI field of view). They will also depend on Roman's agility: the ability to interrupt any other ongoing observations and slew to the location of interest in time to catch the two MBHs in the final act of merging.

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