

Super Massive Black Hole binaries with Kilometer-Baseline Interferometry

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Introduction: MBHBs are key to the most important open questions in galaxy and MBH evolution

Super massive black holes (SMBHs) are believed to reside within every galaxy, both influencing each other in their evolution. However, this co-evolution is not yet well constrained, starting from early BH seeding and the first galaxies to even more nearby systems [1, 2]. Given the hierarchical structure formation paradigm of galaxy formation, massive black hole binaries (MBHBs) are expected to form frequently in galaxy mergers. In the 2040s, E-ELT, LISA and other then-operational facilities will start to constrain the larger separation dual AGN population and the actual merging of SMBHs respectively [4]. However, the scale of 10s of pc down to milli-pc, where MBHBs become a bound binary, will not be resolved beyond some nearby sources, leaving larger uncertainties in our model [10]. A future ESO Kilometre Baseline Interferometer (KBI) would uniquely probe this very important scale of the “last pc problem” and associated physical processes – up to high redshift where merger rates and BH accretion rates are higher and galaxies are more gas rich (see Fig. 1).

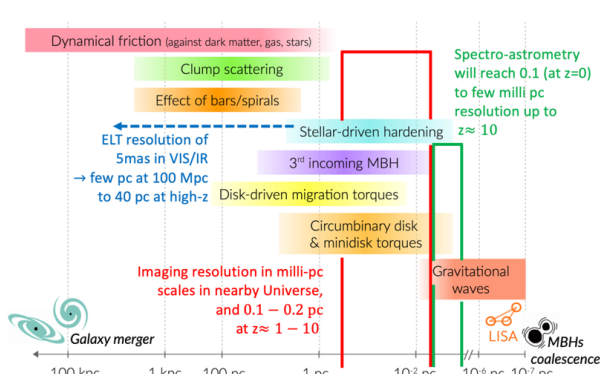


Figure 2: Representative scales of physical processes involved in MBHBs. KBI's resolution uniquely probes the sub-pc scales up to high-z in between envisioned world-leading facilities in the 2040s (assuming 10km baselines at $2\mu\text{m}$). Adapted from [3].

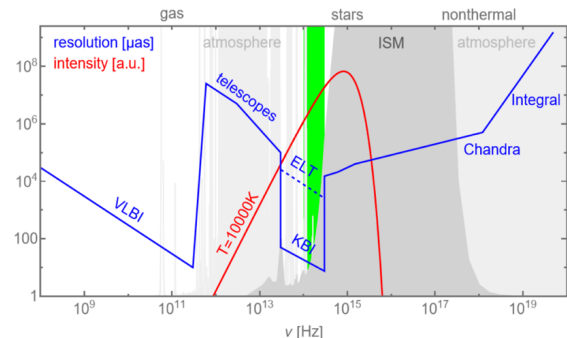


Figure 1: Nominal imaging resolution as a function of observing frequency (blue line), with atmospheric extinction in light gray, typical dust extinction in dark gray, and black-body emission of a $T=10000\text{K}$ source in red. The green band marks the NIR bands around $1-2\mu\text{m}$. Spectro-astrometry will enable KBI to resolve even smaller structures down to $0.1\mu\text{as}$.

The case for kilometre baseline interferometry

VLBI radio interferometry delivers the highest angular resolution so far and can detect MBHBs on pc scales [5]. These measurements are mostly constrained to the BHs jets and lower redshift and VLBI is already reaching limitations with earth-size baselines. KBI would be operated in a sweet spot in the optical/near-infrared (NIR) where radiation can pass through earth's atmosphere, where necessary AO can reach high Strehl ratios, and where emission from hot dust and broad lines in the vicinity of MBHBs is expected. Apart from kilometre baselines, larger collecting areas of the individual telescopes and higher throughputs are necessary to not be limited by surface brightness.

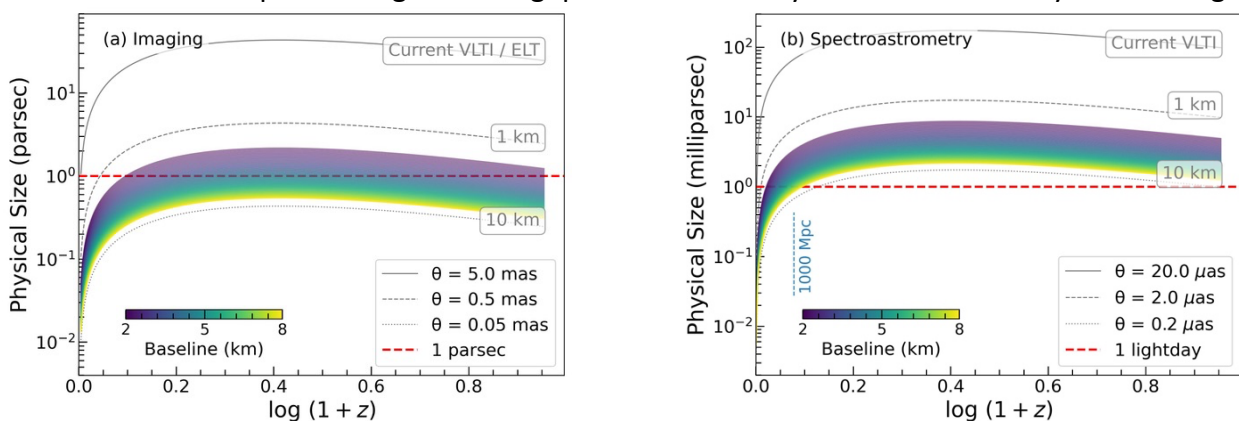


Figure 3: Physical resolution as function of redshift for different telescopes/arrays in the 2040s. Note that the peak occurs around $z \approx 1 - 2$, KBI will resolve milli-pc at high z. Left/a: Imaging resolution $\vartheta = \lambda/2B = \lambda/2D$ for $2\mu\text{m}$. Right/b: Similar but for spectro-astrometry mode (phase referenced differential astrometry across the spectrum of the object), in milli-pc.

As illustrated in Fig. 3, KBI would resolve pc to sub-pc scales throughout the Universe in pure imaging, something that no other facility in the 2040s will be capable of. Using spectro-astrometry, KBI would even reach milli-pc scales in a broader range of redshifts. These calculations are simple order of magnitude estimates.

Expected state of the field in the 2040s

With the advent of LISA onwards of the mid 2030s, we will know much more about SMBH mergers and a new potential for multi-messenger astronomy at high z will emerge [3]. Large galaxy surveys such as EUCLID are expected to reveal dual/multiple AGN [6], which can then be confirmed with IFS observations (JWST, E-ELT, VLT).

In between those scales, lie the pc to sub-pc MBHBs. Advancements in time domain astronomy and spectroscopic surveys (e.g. LSST, SDSS-V Black Hole Mapper) will likely reveal a larger number of sub-pc MBHB *candidates*, for example through moving broad lines (time dependent velocity offset due to binary orbit) [7, 8]. With the highest achievable spatial resolution with VLTI/GRAVITY+ and ELT, we expect to find some pc scale MBHB sources at $z \lesssim 0.3$, but milli-pc scale MBHBs, which are the main sources of the nano-Hertz GW, will remain illusive [9; ~ 10 yr time series needed].

Many of the rates and timescales associated with multiple AGN, MBHBs and SMBH mergers are so far hardly constrained. Therefore, the probability of observability of some specific science cases below is hard to predict right now – this would really be uncharted territory.

KBI will constrain galaxy and BH evolution models by resolving MBHBs up to high z

- 1. Resolving the central parsec of AGNs across the observable Universe with kilometer-baseline optical interferometry.** KBI will deliver an unprecedented and transformative capability: resolving the central ~ 1 pc region of AGNs across essentially the entire observable Universe. With baseline lengths of order 5-10 km, such an interferometer achieves angular resolutions of a few tens μas , sufficient to spatially resolve the immediate environments of SMBHs from the local Universe to the highest accessible redshifts. In contrast, even ELTs, despite large collecting area, are fundamentally limited by single-aperture diffraction and can resolve 1 pc scales only at low redshift ($z \lesssim 0.3$). KBI therefore provides the only viable path to allowing the direct identification and characterization of bound MBHBs in AGNs over cosmological volumes. This capability makes it possible to establish the demographic properties of SMBH binaries, thereby setting critical boundary conditions for binary evolution models that determine the nanohertz gravitational-wave background. Building on the proven efficiency of continuum interferometric observations with VLTI/GRAVITY+, kilometer-baseline interferometry will enable large, statistically powerful samples of AGNs, transforming SMBH binary studies into a population-level, cosmological science – putting constraints on MBH formation and seed populations [1, 2, 4, 9].
- 2. Directly probing GW-emitting MBH with kilometer-baseline interferometry.** KBI combined with sub- μas spectro-astrometry enables spatial resolution of ~ 1 milli-pc scales out to distances of ~ 1 Gpc ($z \approx 0.2$), and few milli-pc even to high- z (!). This capability allows direct electromagnetic probing of MBHBs at separations where GW emission starts dominating the orbital evolution, directly overlapping with the source populations targeted by pulsar timing arrays (PTAs) in the nanohertz regime and by LISA at millihertz frequencies [e.g., 14, 9]. Measuring the occurrence rates, separations, and orbital properties of sub-pc and milli-pc MBHBs out to high z provides critical constraints on the stochastic gravitational-wave background and individual merger rates, while enabling genuine multi-messenger studies that connect spatially resolved accretion and dynamical signatures with gravitational-wave signals. Such synergies are widely recognized as essential for fully understanding massive black hole growth and binary evolution across cosmic time [1, 14]. If very close binaries are detected, a prediction of a merger seen by LISA might even be possible, connecting these two regimes and observing the birth of a quasar [14, SI 2.3].

3. Understanding fundamental sub-pc physics in binary galactic nuclei. The unprecedented resolution of KBI will for the first time enable us to resolve and study the physical processes that dominate in the pc to milli-pc regime of MBHBs [3, 4, 13, 14]. Dynamically resolving hot gas and dust around MBHBs allows to directly probe essential physics, such as gas torques and orbital hardening (see Fig.1). Galaxies in the early Universe are much more gas rich, more compact and have less deep gravitational potentials, which might influence the time scales related to gas-driven torques and accretion disk dynamics. Probing these scales/physics will fill an essential gap in our models in the 2040s.

Similar to GRAVITY+, KBI will be able to dynamically resolve the BLR of MBHBs [11], but down to lower luminosity systems (smaller BLR) and up to higher redshifts where MBHB fractions might be higher due to frequent galaxy merging. We will also start to resolve out the dust torus even at low- z , so the coherent continuum flux comes from the accretion disk. This means we can observe the three-disk system (mini-disks + circumbinary disk see [13]) of some MBHBs through the variability of the spectroastrometry photocenter to test theoretical predictions, and study the morphology/dynamics/temperature of this system and its ties to binary parameters (maybe even BH spin alignment) and BLR structure or even outflows/feedback.

Other possible venues in the sub-parsec nuclear regime

Also, KBI will enable spatially resolved imaging of the outer regions of the broad-line region (BLR), with particular sensitivity to accretion-driven outflows and feedback processes that regulate black hole growth and its coupling to the host galaxy, extending current studies to less luminous, more distant sources [12]. At the highest angular resolutions, spectro-astrometric measurements will track variability in the inner BLR on dynamical timescales, providing a new avenue to probe the geometry and kinematics of gas in the immediate vicinity of the black hole and offering a powerful, indirect constraint on black hole spin.

Lower mass MBHBs, or intermediate mass black hole (IMBH) binaries could be detected in larger numbers by LISA, although this regime is particularly poorly constrained. KBI can reveal the presence of IMBHs in galactic nuclei through their dynamical perturbations of the BLR velocity field and photocenter shifts, and would thus open venues for studying such IMBHs and their binaries in the early Universe to constrain early BH evolution.

Summary

By the 2040s, astronomy will enter a mature era of multi-messenger observations, driving major breakthroughs in our understanding of black hole growth and evolution. KBI will enable the systematic study of large samples of pc- and sub-pc massive black hole binaries, providing the essential electromagnetic counterpart to gravitational-wave signals detected by pulsar timing arrays and LISA. With its unparalleled spatial resolution, KBI is uniquely complementary to ELTs, extending binary black hole studies from the local Universe to cosmological distances. Together, these capabilities will establish a coherent, population-level picture of black hole binaries across the entire observable Universe and put strong constraints on galaxy and black hole evolution models.

References

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