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Supermassive Black Hole Binaries in the Multi-messenger Context of Ground and Spaceborne VLBI*

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Abstract

Evidence of a gravitational wave background suggests the existence of a population of sub-parsec supermassive black hole binaries (SMBHBs), with characteristic angular separations on the order of 1–10 μ as. Spaceborne extensions of Very Long Baseline Interferometry (VLBI) and the next-generation ground arrays introduce the possibility of directly imaging these SMBHBs. In this work, a binary spectral energy distribution model is used to predict the detectability of SMBHBs with ground and spaceborne VLBI. We consider the Black Hole Explorer (BHEX), a proposed spaceborne VLBI mission, as our primary case study. We explore the detectable SMBHB parameter space and identify distinguishable binary signatures in the visibility domain. We find that for a flux-density-limited sample, ground array observations are more effective at detecting a wider region of the binary parameter space, with $M_{\text{tot}} \gtrsim 10^9 M_{\odot}$ systems detectable out to redshift $z = 0.075$ and beyond, depending on mass ratio. Conversely, inclusion of a spaceborne element such as BHEX, offering finer angular resolution ($\sim 6 \mu$ as) and sampling of the (u, v) plane not limited by Earth rotation synthesis, will provide significant benefits in constraining binary properties.

An illustrative Fisher analysis shows improvements in characterisation of the separation and position angle of SMBHBs by a factor of ~ 4 . Near-future ground and/or spaceborne VLBI may achieve the first direct observation of a SMBHB, contributing significantly to multi-messenger studies of such systems with pulsar timing arrays and observations across the electromagnetic spectrum.

Unified Astronomy Thesaurus concepts: [Supermassive black holes \(1663\)](#); [Very long baseline interferometry \(1769\)](#); [Space observatories \(1543\)](#); [Submillimeter astronomy \(1647\)](#); [Galaxy mergers \(608\)](#)

1. Introduction

Pulsar timing array (PTA) observations provide evidence for a nanohertz gravitational wave background (GWB), suggesting the existence of a population of supermassive black hole binaries (SMBHBs) with sub-parsec separations (Antoniadis et al. 2022; Agazie et al. 2023a; Xu et al. 2023; EPTA Collaboration and InPTA Collaboration et al. 2024). Begelman et al. (1980) first described the formation and evolution of

SMBHBs, and suggested the possibility of observing such systems with Very Long Baseline Interferometry (VLBI).

At the time of writing, there has been no conclusive, direct electromagnetic observation of a sub-parsec SMBHB. Various forms of indirect evidence have been proposed, such as: optical, ultraviolet (UV) and radio oscillations (e.g., Graham et al. 2015; D’Orazio et al. 2015; Charisi et al. 2016; Liu et al. 2019; Chen et al. 2020; Liao et al. 2021; O’Neill et al. 2022); astrometric oscillations with VLBI (Gurvits et al. 2025); and binary signatures on relativistic jet behavior, particularly for the most studied candidate OJ287 (Britzen et al. 2018; Traianou et al. 2025; Valtonen et al. 2025, and references therein). See D’Orazio et al. (2024) for a more in-depth review of such observational methods. Recently, the NANOgrav collaboration have also presented a search for continuous GW sources in the 15 yr PTA data set (Agarwal et al. 2026; Veronesi et al. 2026). Although none of the sources are

* Contribution for the PASP special issue on BHEX.

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statistically significant yet (two identified with $1 < \text{Bayes Factor (BF)} < 4$), this method holds promise for future binary candidate identification.

The next generation Event Horizon Telescope (ngEHT) will push angular resolution close to the limit of what is possible from the ground (Ayzenberg et al. 2025). With observations at ~ 345 GHz, and inclusion of more ground antennae, its angular resolution will approach $15 \mu\text{as}$, $\sim 25\%$ improvement over the achieved to date EHT results (EHT Collaboration et al. 2019). D’Orazio & Loeb (2018) predict that with these capabilities, a few SMBHB systems may be detectable out to $z \leq 0.2$. Ground-based VLBI is fundamentally limited in angular resolution by the Earth’s diameter and opacity of its atmosphere at THz frequencies. It has long been recognised that a spaceborne system could remove these limits, and also achieve rapid and dense coverage in the (u, v) plane. Two dedicated spaceborne VLBI (SVLBI) missions have flown at the time of writing: VSOP-HALCA (Hirabayashi et al. 1998) and RadioAstron (Kardashev et al. 2013), in addition to two ad-hoc experiments, TDRSS-OVLBI (Levy et al. 1986) and LOVELX (Hong et al. 2025).

The black hole Explorer (BHEX) is a proposed spaceborne extension to ground-based arrays, observing at submillimetre wavelengths and aiming to achieve the finest angular resolution to date, $\sim 6 \mu\text{as}$ (Johnson et al. 2024). BHEX will detect and measure characteristics of the photon rings that are predicted to exist in images of black holes, with M87* and Sgr A* as the primary targets. BHEX will also aim to resolve black hole shadows in additional SMBH targets (Zhang et al. 2025) and to perform studies of AGN and relativistic jets in unprecedented detail.

The enhanced angular resolution of BHEX, and improving sensitivity of ground-based arrays, warrants an investigation into the possibility of performing the first direct detection of a sub-parsec SMBHB with VLBI. In our previous work, we preliminarily constrained the binary detection capabilities of BHEX, and demonstrated its ability to measure the relative position of the secondary component with respect to the primary, with in-beam relative astrometry (Hudson et al. 2026). A post-Newtonian (PN) orbit fitting approach was also developed and used to show that with only three annual observations, BHEX could constrain the semimajor axis and eccentricity of low inclination binaries with observed orbital periods $P_{\text{obs}} \leq 10$ yr, to within 0.06 dex of their true values.

Here, we extend this work to evaluate binary detection prospects with ground and space VLBI using a binary spectral energy distribution (SED) model. We constrain the detectable binary parameter space, in terms of total mass (M_{tot}), redshift (z), mass ratio ($q = m_2/m_1$), and orbital parameters. These results can also be used to perform initial down-selection of binary candidate lists, and understand the inherent observational bias that will exist in future SVLBI surveys of SMBHBs. We note a high level synergy between

the prospective VLBI observations of SMBHBs and their gravitational-wave (GW) signal. Together, these two observational techniques create a new field of multi-messenger studies.

The binary SED and toy image model is presented in Section 2. In Section 3, we predict the likely visibility response of a VLBI array to a binary structure, and identify unique, detectable signatures in the signal. Section 4 includes an evaluation of the detectable binary parameter space with ground and SVLBI arrays. In Section 5, we develop a framework based on a Fisher analysis to evaluate how accurately a given array can characterize binary properties. Finally, in Section 6, we evaluate the multi-messenger context of VLBI observations of SMBHBs, with particular reference to PTAs.

For all calculations, we adopt a flat Λ CDM cosmology using the Planck18 realisation in *astropy* (Planck Collaboration et al. 2020).

2. Image Model

In recent years, the EHT has presented the first images of the SMBHs M87* and Sgr A* on an event horizon scale (EHT Collaboration et al. 2019, 2022a). The shadow features observed are primarily formed by synchrotron emission fed by energy from the accretion disc and modified by the strong gravitational field close to the black hole. Tiede & D’Orazio (2025) present a SED model, consisting of similar emission mechanisms, but in the context of SMBHBs. The binary advection-dominated accretion flow (BADAF) model is built of linear contributions from a circumbinary disc (CBD) and from individual minidisks around each black hole. In the context of SMBHB observations with VLBI, we consider accretion regime IV (Tiede & D’Orazio 2025), where all three discs are hot, generally optically thin advection-dominated accretion flows (becoming optically thick at low frequencies and/or small radii where synchrotron self-absorption begins, see Figure 2). We choose this regime so that both minidisks are bright at VLBI observing frequencies, allowing their relative positions to be tracked over time. The BADAF model is built upon the `LLAGNSED`⁸ model of Pesce et al. (2021), used to calculate single black hole ADAF SEDs. This is a purely disc-based model and does not yet include any jet contribution. The model therefore describes emission from the inner accretion flow close to the black hole, rather than the partially self-absorbed core associated with the base of a relativistic jet, typically observed in VLBI.

2.1. Model Parameters

The model sets an accretion rate ($\dot{m}_0$) onto the CBD at scales large compared to the binary semimajor axis, in units of

⁸ <https://github.com/dpesce/LLAGNSED>

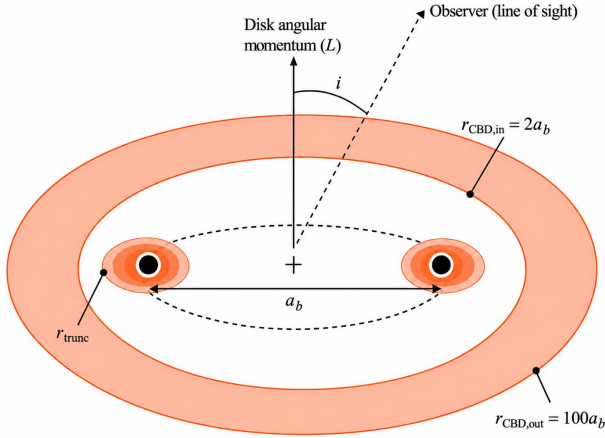


Figure 1. Diagram illustrating key SMBHB model geometric properties (not to scale). Following Tiede & D’Orazio (2025), the outer CBD diameter is fixed to $100a_b$, where a_b is the semimajor axis of the binary. Each minidisc extends out to the tidal truncation radius, where $r_{\text{trunc}} = 0.27 q^{\pm 0.3} a_b$ (Paczynski 1977; Roedig et al. 2014). We assume that the angular momentum of the minidisks is aligned with the angular momentum of the CBD and that the binary orbit is circular.

Eddington rate. An accretion splitting function between the binary components is then assumed of the form, $\lambda(q) = m_2/m_1$, from Kelley et al. (2019) using data originally generated by Farris et al. (2014). This function is used as a phenomenological model of binary accretion behavior that emulates the preferential secondary accretion generally seen in hydrodynamic simulations (see, Clyburn & Zrake 2026). Mass loss is accounted for by a simplified correction factor of the form $(r_s/1/r_{\text{trunc},1})^s$, applied to $\dot{m}_1$ before calculating the SED, and equivalently for minidisc 2. Here, r_s is the Schwarzschild radius and we take the notional value $s = 0.3$. We adopt the same gas pressure to magnetic pressure ratio ($\beta = 10$) as Tiede & D’Orazio (2025). Inclination (i) of the CBD is set to 0° for the detectability analysis and given a separate treatment in Section 4.3. We set $q = 0.05$ as the minimum mass ratio for the parameter exploration as beyond this exists a transition to a regime where the secondary black hole and its smaller minidisc act as a perturbation within the disc of the primary, at which our approximation of a linear combination of three discs breaks down (D’Orazio et al. 2016). Figure 1 illustrates the key geometry of the SMBHB model.

As stated above, the BADAF model does not yet include jet components, though Tiede & D’Orazio (2025) demonstrate how the addition of a jet component emanating from the primary black hole produces a broadband spectrum consistent with that observed for the binary candidate PG1302–102. Modelling jet launching introduces a plethora of additional parameters to the binary SED, including those defining the emission characteristics, but also the viewing geometry of the

system. There is also remaining uncertainty in the dynamics behind jet launching. In Section 4.5 we briefly consider the implications of adding one or two jets to the model, but further evaluation of the impact to SMBHB detectability is left for future work.

Here, as in Hudson et al. (2026), for the binary image model we assume the superposition of two components, with circular Gaussian brightness distributions. The Gaussian assumption is adopted as a general depiction of an unresolved/partially resolved radio source. Fitting Gaussians to visibility data is a common approach in VLBI observations (e.g., Fomalont et al. 1999; Gómez et al. 2022). It also enables analytic evaluation of detectability. The position of these components is defined by their separation (calculated from the system’s observed orbital period and redshift), and an angle, measured east of north.

Figure 2 depicts an approximate radial luminosity profile generated from the BADAF model as a function of $\dot{m}_0$ and rest-frame frequency. The profile is calculated for a single accretion flow around a black hole with mass, $m = 10^9 M_\odot$. The binary period ($P_{\text{rest}} = 10$ yr) and mass ratio ($q = 0.1$) are only used to calculate the tidal truncation radii (r_{trunc}) and therefore do not impact the radial luminosity curves. At each radius, the model calculates the local synchrotron self-absorption (SSA) turnover frequency, $\nu_c(r)$, as the frequency at which the optically thin synchrotron luminosity equals the self-absorbed blackbody luminosity. For a specified rest-frame frequency, the SSA radius, r_{SSA} , is then obtained by solving $\nu_c(r_{\text{SSA}}) = \nu_{\text{rest}}$. Emission at this frequency is treated as optically thick at radii $r < r_{\text{SSA}}$ and optically thin at radii $r > r_{\text{SSA}}$. The dashed vertical lines show approximate half-light radii of the minidisc emission calculated from this radial luminosity model. The sharp turnover approximately marks the transition between optically thick and optically thin synchrotron emission and is associated with the radius r_{SSA} at which $\tau_\nu \simeq 1$. For $\dot{m}_0 = 10^{-5}$, the estimated half-light radius is approximately $0.75r_{\text{SSA}}$ at 86 GHz, with the two radii becoming similar at higher accretion rates. We therefore conservatively set the full width at half maximum (FWHM) of each Gaussian component in the image model to $2r_{\text{SSA}}$. Because the estimated half-light radii are typically smaller than r_{SSA} across the parameter space considered here, this prescription produces broader Gaussian components than would be obtained by matching the FWHM directly to the estimated half-light radius. Broader components retain less correlated flux on long baselines and therefore provide a conservative assumption for VLBI detectability. This choice also allows for uncertainty in the radial luminosity prescription and for departures of the true brightness distribution from an ideal Gaussian. For any systems with $r_{\text{trunc}} < r_{\text{SSA}}$, we set the FWHM to $r_{\text{trunc}} = 0.27 q^{\pm 0.3} a_b$.

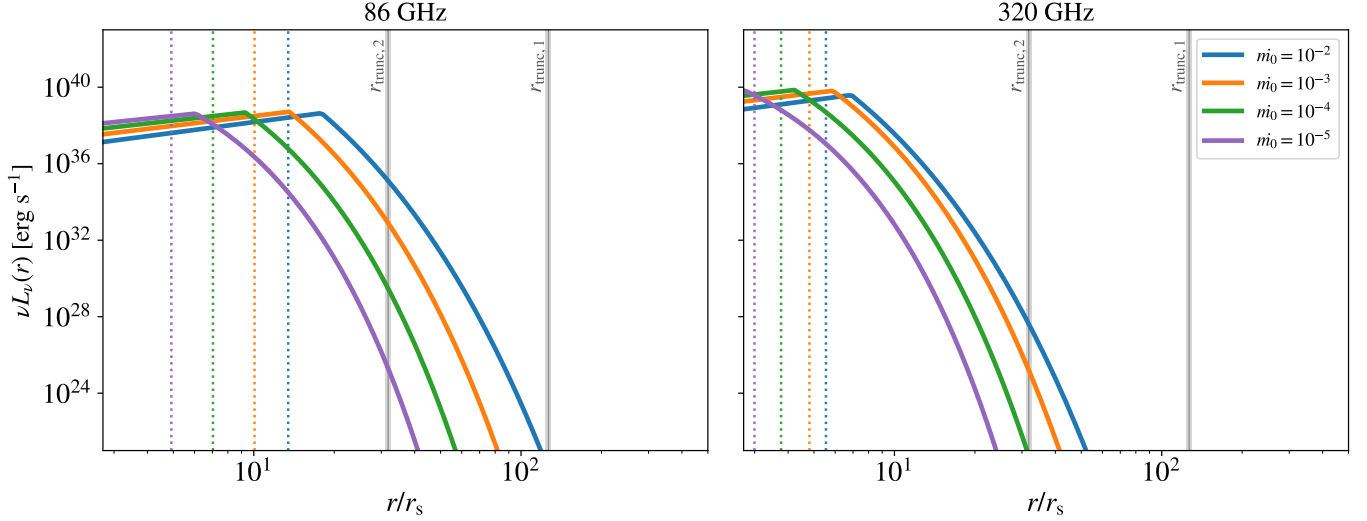


Figure 2. Radial luminosity profile of either primary or secondary minidisc plotted as a function of Schwarzschild radii (r_s) from a single, $m = 10^9 M_\odot$ black hole, at the specified rest-frame frequency and outer accretion rates. Rest-frame orbital period ($P_{\text{rest}} = 10$ yr) and mass ratio ($q = 0.1$) are only used to calculate the tidal truncation radii (r_{trunc}) of each minidisc, shown in the vertical grey bands. The vertical dashed lines depict the approximate half-light radius for each accretion rate.

2.2. (Sub)millimetre Emission

Figure 3 depicts the total flux (F_{tot}) from binary systems across redshift (z), total mass (M_{tot}), mass ratio (q), outer accretion rate ($\dot{m}_0$) in units of Eddington rate, and observed orbital period (P_{obs}) from Earth. For circular binaries, the dominant GW emission occurs at twice this orbital frequency. F_{tot} is the zero-baseline flux density of the compact binary model evaluated at the central observing frequency. Two observing frequencies (ν_{obs}) are considered: 86 and 320 GHz, notional values within the bands supported by the BHEX receivers. 320 GHz is the highest frequency of BHEX and is therefore the frequency at which the finest angular resolution is achieved (Johnson et al. 2024). When comparing the binary detection performance to ground arrays such as the ngEHT, we use this value rather than the commonly considered 345 GHz. Indicative thermal noise-limited sensitivities are provided for ground and space baselines, noting that this plot shows total flux density, and not the correlated flux density on a given VLBI baseline. Thermal noise (σ_{th}) is calculated as

$$\sigma_{\text{th}} = \frac{1}{\eta_q} \sqrt{\frac{\text{SEFD}_1 \text{SEFD}_2}{2 \Delta\nu \tau}}, \quad (1)$$

where SEFD is the system equivalent flux density of the antenna, η_q is the quantisation efficiency, $\Delta\nu$ is the observing bandwidth and τ is integration time. Appendix A provides the array characteristics used in these calculations. It is assumed that Frequency Phase Transfer (FPT) is used to maintain coherence across long integration times of ~ 10 minutes at 320 GHz (Rioja et al. 2023; Issaoun et al. 2025). For the sensitivity on the baseline to the spaceborne radio telescope, a baseline between BHEX and ALMA is assumed (86 GHz:

0.48 mJy, 320 GHz: 1.09 mJy), and for the ground, ALMA and LMT (86 GHz: 0.04 mJy, 320 GHz: 0.14 mJy). P_{obs} and ν_{obs} are converted to the rest-frame as a function of redshift, before calculation of the SED.

The modelled SED is reasonably flat across the narrow (sub) millimetre band of interest for VLBI, illustrated by the small variations in total flux density between the 86 and 320 GHz columns. The primary benefit in observing at a lower frequency is the increased baseline sensitivity that can be achieved. This will be traded-off with the reduction in angular resolution in Section 4.3. Increasing outer accretion rate has less of an impact than would perhaps be intuitively expected. For the primary and secondary components, the SED shifts upwards and right with increasing $\dot{m}_0$, as can be seen in Figures 3 and 4 in Tiede & D’Orazio (2025). In Figure 3, for each binary system the regime of accretion is checked, and any that are not in region IV are excluded. The effect of this can be seen as $\dot{m}_0$ approaches 10^{-2} where lower mass ratio systems begin to enter the thin disc accretion regimes that produce little (sub)millimetre emission.

As expected, primary and secondary contributions are approximately equal for $q = 1$. For lower mass ratios, a trade-off exists between preferential secondary accretion and mass. At $q = 0.1$, at lower accretion rates, this trade-off balances such that the secondary’s total flux density is similar to the primary’s. At $q = 0.05$, the lower mass of the secondary results in significantly lower luminosity. As this figure shows the total flux density, we will delay comments on detectability until Section 4.3, where the correlated flux density on a specific baseline is calculated.

Near the critical accretion rates (where solutions start becoming thin), the CBD itself may generate potentially detectable (sub)millimetre emission. We do not plot the CBD

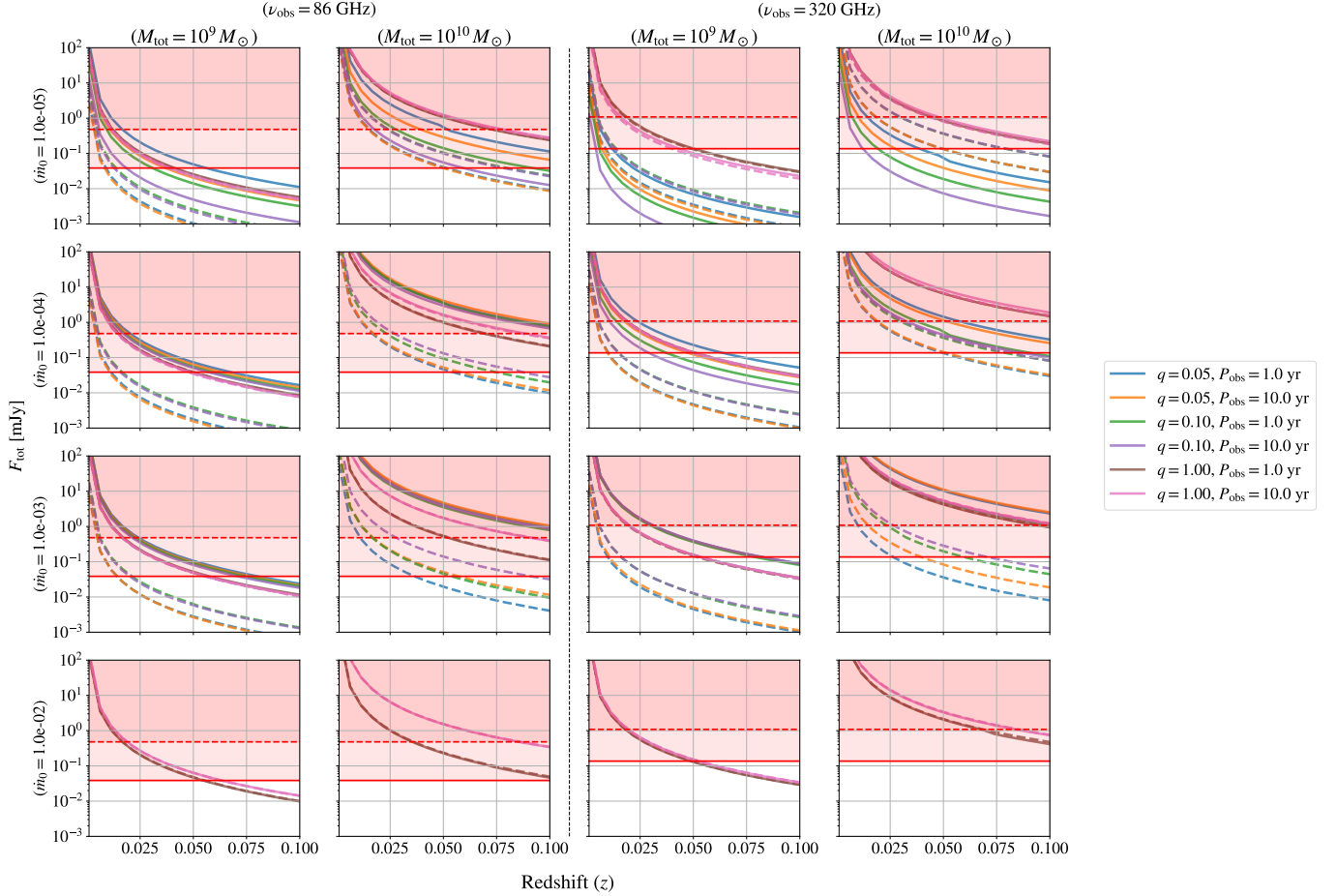


Figure 3. Total flux density across redshift calculated using the BADAF model. The independent contributions of the primary (solid lines) and secondary (dashed) black holes are shown, consisting mainly of synchrotron emission. Indicative thermal noise for a ground (solid red) and space (dashed red) baseline are also illustrated.

contribution on Figure 3 for clarity, but Figure 4 depicts the relationship between its luminosity and various model parameters, in the rest-frame. The CBD is also more sensitive to accretion rate and orbital period than the minidisks, as varying P_{obs} (and M_{tot}) will change the semimajor axis (a_b) and therefore the CBD geometry. For the remainder of this work, we neglect the CBD contribution, as more work is required to understand the sensitivity of this feature to the model parameters (e.g., the assumed $2a_b$ inner and $100a_b$ outer diameters of the disc). It is also only potentially detectable at the lowest redshifts and highest masses and accretion rates.

Over the small P_{obs} range of our interest (see discussion in Section 4.2), the ratio of luminosities $L_{\text{MD1}}/L_{\text{MD2}}$ does not vary greatly. The inner edge of each minidisc is set at the innermost stable circular orbit (ISCO) and as such, the region of peak (sub)millimetre emission (close to the horizon) is relatively constant with the size of the minidisc.

3. Visibility Domain Signatures

A VLBI array samples the noise-corrupted visibility function of a target source by correlating the signals received at spatially separated antenna, which corresponds to the Fourier transform of the sky image. The separation between the antenna can be very large (including spaceborne elements), enabling the finest angular resolution of all astronomical techniques. With sufficient sampling in visibility versus projected baseline space, properties of a source observed with VLBI can be estimated from the correlated visibilities. VLBI requires sufficiently compact structure in the source, such that the correlated flux density on a baseline is detectable.

Fang & Yang (2022) model a binary as the superposition of two point sources. Our image model consisting of binary Gaussian components can be easily reduced to the point source model by setting $\sigma_i = 0$ in the following equation. The

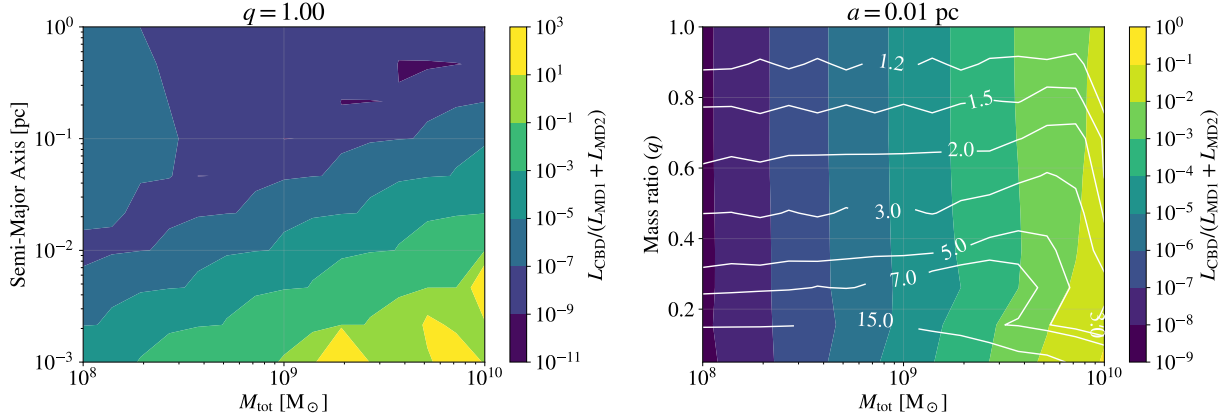


Figure 4. Ratio of CBD luminosity to the total minidisc luminosity in the rest-frame, across mass ratio and separation. Rest-frame frequency (ν_{rest}) set to 320 GHz, and outer accretion rate ($\dot{m}_0$) set to 10^{-4} . White contours on the right panel depict the ratio $L_{\text{MD1}}/L_{\text{MD2}}$.

visibility response $V(u, v)$ of a binary Gaussian source is

$$V(u, v) = \frac{F_{\text{tot}}}{1+f} [\exp(-2\pi^2\sigma_1^2 b^2) + f \exp(-2\pi^2\sigma_2^2 b^2) \exp(-2\pi i \mathbf{b} \cdot \boldsymbol{\rho})], \quad (2)$$

$$b^2 = u^2 + v^2, \quad (3)$$

where $F_{\text{tot}} = F_1 + F_2$, the sum of the two Gaussian components' total flux densities, $f = \frac{F_2}{F_1}$ is the flux density ratio, σ is the standard deviation of each Gaussian component, $\mathbf{b}$ is the baseline vector in units of wavelength, $\boldsymbol{\rho} = \rho (\sin(\phi), \cos(\phi))$ is the angular separation vector of the two components, and ϕ is the position angle of $\boldsymbol{\rho}$, measured east of north. The FWHM is related to the Gaussian standard deviation by $\theta = 2\sigma \sqrt{2 \ln 2}$. The indices 1 and 2 describe the primary and secondary black holes, respectively. This is the superposition of two Gaussian components with the primary fixed to the origin of the image reference frame (Thompson et al. 2017). This is practically achieved during the model fitting process, such that the primary becomes the phase reference (Hudson et al. 2026).

As performed in Hudson et al. (2026), modern model fitting techniques, such as those provided in `eht-imaging`⁹ (Chael et al. 2018), determine the combination of the binary parameters that most closely match the visibility data. However, it is useful to consider the theoretical basis of such model fitting in order to derive requirements for observations that provide strong constraints on binary features.

Figure 5 depicts the normalised visibility amplitude response ($|V|/F_{\text{tot}}$) of binary systems with varying characteristics, across the range of expected projected baseline lengths for BHEX, observing with a ground array comparable to the ngEHT. A projected space baseline length range of 20–35 $G\lambda$ is used, the maximum baseline occurring when the ground station is on the other side of the Earth to the spacecraft (i.e., $B = r_{\text{orb}} + 2R_E$, where $r_{\text{orb}} = 20,200$ km is

the orbital altitude of BHEX), at 320 GHz. Ground baselines are calculated assuming a range of projected antenna separations from ~ 250 km (NOEMA-PV baseline) up to the Earth's diameter. Plotted as a dashed line is the response of a single Gaussian source of the same total flux density and a FWHM equal to the average of the two components.

In general, increasing the FWHM of the Gaussian components increases the rate of drop off of the visibility amplitude with baseline length. Reducing the ratio f decreases the amplitude modulation between minima and maxima. The top-left panel can be considered analogous to a near-equal mass binary. The limits of angular resolution can be seen in the lack of minima on BHEX baselines of the 2 μs separation system. The bottom-left panel illustrates a scenario where a smaller secondary over-accretes compared to the primary. The primary in the bottom-right panel would be in the region of event horizon-scale imaging for the ngEHT and BHEX. The inclusion of a secondary with a tenth of the angular size does however produce a noticeable impact on the response, but on baselines where the visibility amplitude will have reduced to 10% of F_{tot} .

For amplitude only measurements, restricted to a single baseline orientation (γ) or radially averaged measurements, a degeneracy exists between the separation vector and angular sizes of the Gaussians, as both produce quadratic suppression of the visibility across baselines. For unresolved or partially resolved Gaussian sources, the separation can be estimated from the position of nulls through $\mathbf{b} \cdot \boldsymbol{\rho} = n + \frac{1}{2}$ (see Appendix B for derivation of this expression). However, as f or σ_i increases, the oscillations are suppressed such that clear minima may not be detectable. In this regime, without clear oscillatory behavior, a single Gaussian, or more complicated structure, can mimic a binary. Observations across baseline orientations breaks this degeneracy as the suppression of a single Gaussian, even on short baselines, is not a function of γ (see Appendix B). Table 1 summarises the binary features that can be determined from visibility data, along with the baseline regions they apply to.

⁹ <https://github.com/achael/eht-imaging>

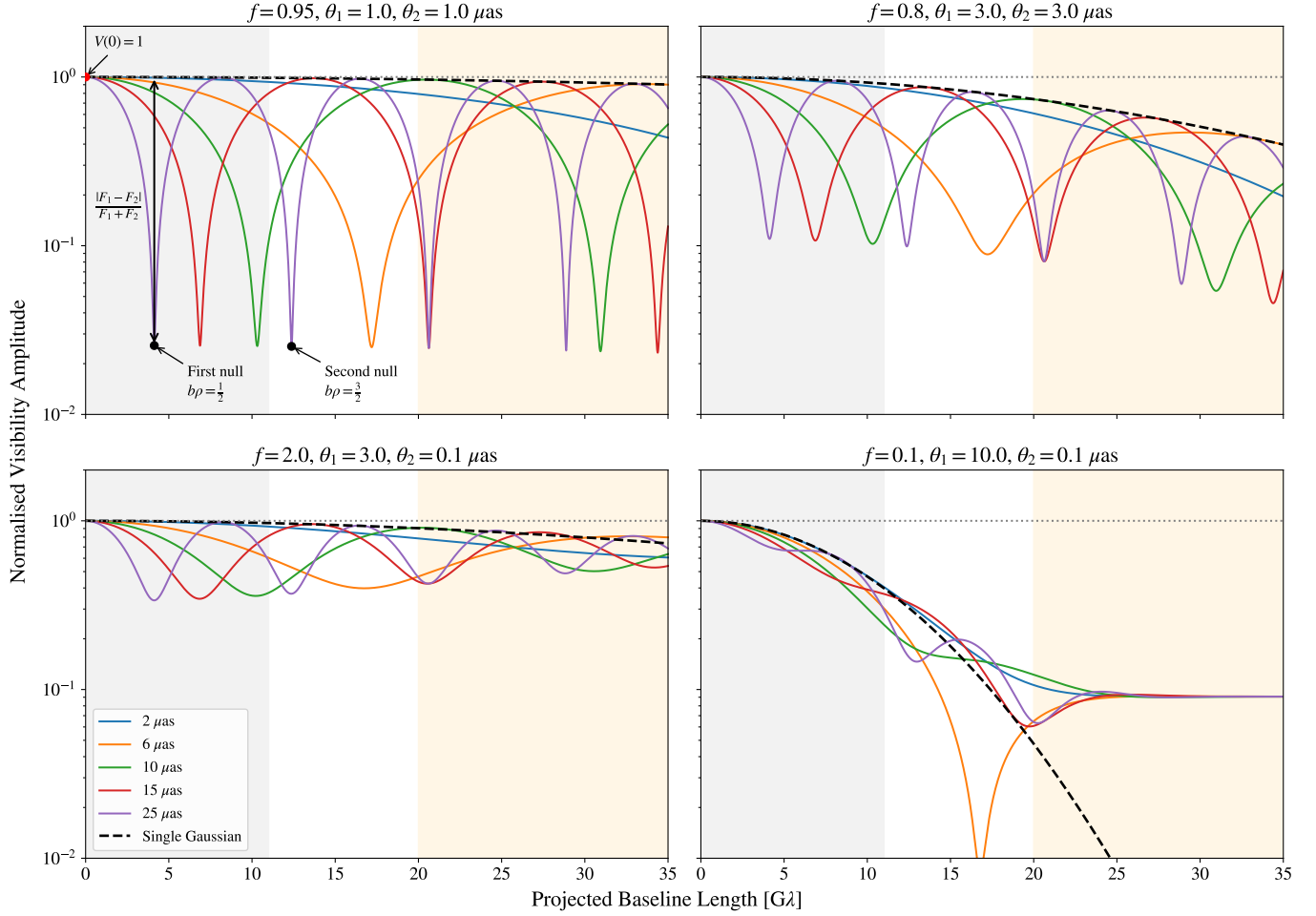


Figure 5. Visibility amplitude response of binary systems with varying flux density ratio $f = \frac{F_2}{F_1}$, angular separation and FWHM (θ) of each component. The grey shaded region depicts the region of projected baseline covered by the ground array. The orange shaded region shows the ground-space baseline regime for BHEX, when observing a source near-perpendicular to the orbital plane (such as M87*). The white region is the unsampled baseline lengths assuming this particular geometry.

Table 1
Binary Parameters Encoded in Visibility Data, Across Baseline Regimes

Visibility Feature	Expression	Binary Property	Baseline Regime
Zero-baseline amplitude	$ V(0, 0) = F_{\text{tot}}$	F_{tot} (Total flux density)	Short
Null condition	$\mathbf{b} \cdot \boldsymbol{\rho} = n + \frac{1}{2}$	ρ and ϕ (Separation and position angle)	All, unresolved components
Modulation depth	$\frac{ V _{\text{min}}}{ V _{\text{max}}} \approx \frac{ F_1 - F_2 }{F_1 + F_2}$	f (Flux density ratio)	All, unresolved components
High-baseline envelope	$\exp(-2\pi^2 \sigma_i^2 b^2)$	θ_i (FWHM of minidisc i)	Long, partially resolved
Angular anisotropy	$b^2 \rho^2 \cos^2(\gamma - \phi)$	ρ and ϕ	Short

SVLBI is particularly powerful at constraining such models as it has the ability to sample a wide range of spatial scales, as the baseline vector evolution is no longer constrained by the diameter of and rotational rate of the Earth. The characterization described here can in theory be performed as a non-imaging study on a single baseline (although this wouldn't

enable the use of closure phases, as discussed in the next section, or the use of FPT on baselines with stations that cannot observe in both an upper and lower band). Imaging studies require very dense (u, v) coverage and as such, a dense ground array, which introduces significant scheduling and cost complications. For a mission such as BHEX, observations with

the full ground array could be reserved for the primary science objectives (e.g., photon ring detection, imaging studies of jets), while preliminary, non-imaging binary investigations could be performed with a more limited array. The challenge for binary detection with BHEX is the need for there to be sufficient flux density on the space baselines to enable detection with the relatively small antenna of the spaceborne element.

4. Detectability of SMBHB with VLBI

In Hudson et al. (2026), synthetic data simulations of BHEX observations were performed on a small number of toy binary systems to demonstrate the efficacy of the orbit fitting methodology. Using the VLBI synthetic data simulation and model fitting software packages `eht-imaging` and `ngeht-sim`,¹⁰ a binary Gaussian model was fit to visibility amplitudes and closure phases to determine the accuracy to which the system could be characterized. Closure phases are measurements around triangles of three baselines that cancel out many station-based errors (Chael et al. 2018). A chi-squared test was also used to determine whether the binary morphology was distinguishable from a single, best-fit Gaussian component. Here, we apply a similar process, but using an analytic model for visibility calculation in order to assess detectability across a wider range of binary parameter space.

4.1. Requirements for Detection

The following requirements are set for detectability, inline with those used by D’Orazio & Loeb (2018) and refined in our previous work (Hudson et al. 2026):

1. Both components are sufficiently bright in the (sub) millimetre to be independently detectable on ground or space baselines.
2. The binary morphology can be confidently distinguished from that of a single, best-fit Gaussian.
3. P_{obs} is short enough such that detection of orbital motion is possible over human lifetime.

We note that morphologies other than a single Gaussian-like component could mimic a binary visibility response. For a real detection, many other scenarios will have to be rejected to build confidence that what has been observed is indeed a SMBHB. For a preliminary evaluation of binary detectability, the single Gaussian structure has been selected as the null hypothesis to be rejected because:

1. For scenarios where one component is out-shone by the other (e.g., high accretion splitting fraction), a key

question is whether the dimmer component can be distinguished from the primary;

2. A single Gaussian is a simple representation of an unresolved source.

4.2. Angular Resolution

The diffraction-limited, nominal angular resolution (θ_{res}) of a VLBI array is given by λ/B_{max} , where λ is the observing wavelength and B_{max} is the maximum baseline length projected in the direction of the source. Requirement 2 defined above will set a minimum array angular resolution necessary to sufficiently resolve the binary system, such that it can be confidently distinguished from other source types.

D’Orazio & Loeb (2018) set the requirement that the source must have an angular separation at least that of the array resolution, as a preliminary metric for detectability. In Hudson et al. (2026), we found that under specific noise assumptions, binary parameters could be constrained on angular scales smaller than the nominal array angular resolution, a manifestation of the effect known in imaging interferometry as super resolution. Specifically, in Hudson et al. (2026) we found that BHEX could confidently distinguish a binary structure (and estimate separation and position angle of the binary) from the best-fit, single Gaussian, down to separations of $\sim 2 \mu\text{as}$.

Figure 6 depicts the angular separation of binary systems across redshift, for different P_{obs} . Also shown are the nominal array resolutions of BHEX and the ngEHT, at the observing frequencies of interest (recalling that super resolution may enable binaries with separations less than the angular resolution to still be detected). This figure can be used to associate the systems plotted on Figures 3 and 7 with an angular separation, and evaluate whether the binary population is likely to be flux- rather than angular resolution-limited. Table 2 provides the angular separations for the example binary systems in Figure 7 at two redshifts. As discussed in Section 2, the ratio of minidisc luminosities does not change greatly with P_{obs} . We do, however, set a maximum P_{obs} of 10 yr in Figures 3 and 7 because, in Hudson et al. (2026), we demonstrated accurate orbit reconstruction over only a few years of BHEX and ngEHT observations up to this limiting orbital period (Requirement 3 above).

Some of the parameter combinations shown in Figure 6 are less likely to exist than others. For example, population estimates from PTA data suggest that it is unlikely that the most massive systems ($\sim 10^{10} M_{\odot}$) at $P_{\text{obs}} \lesssim 6.3 \text{ yr}$ are prevalent in the GWB (Agarwal et al. 2026). This is discussed further in Section 6.

4.3. Detectability

Using the BADAF SED and our image model, we can calculate the complex visibilities on a given VLBI baseline and assess the parameter space detectability against

¹⁰ <https://github.com/Smithsonian/ngehtsim>

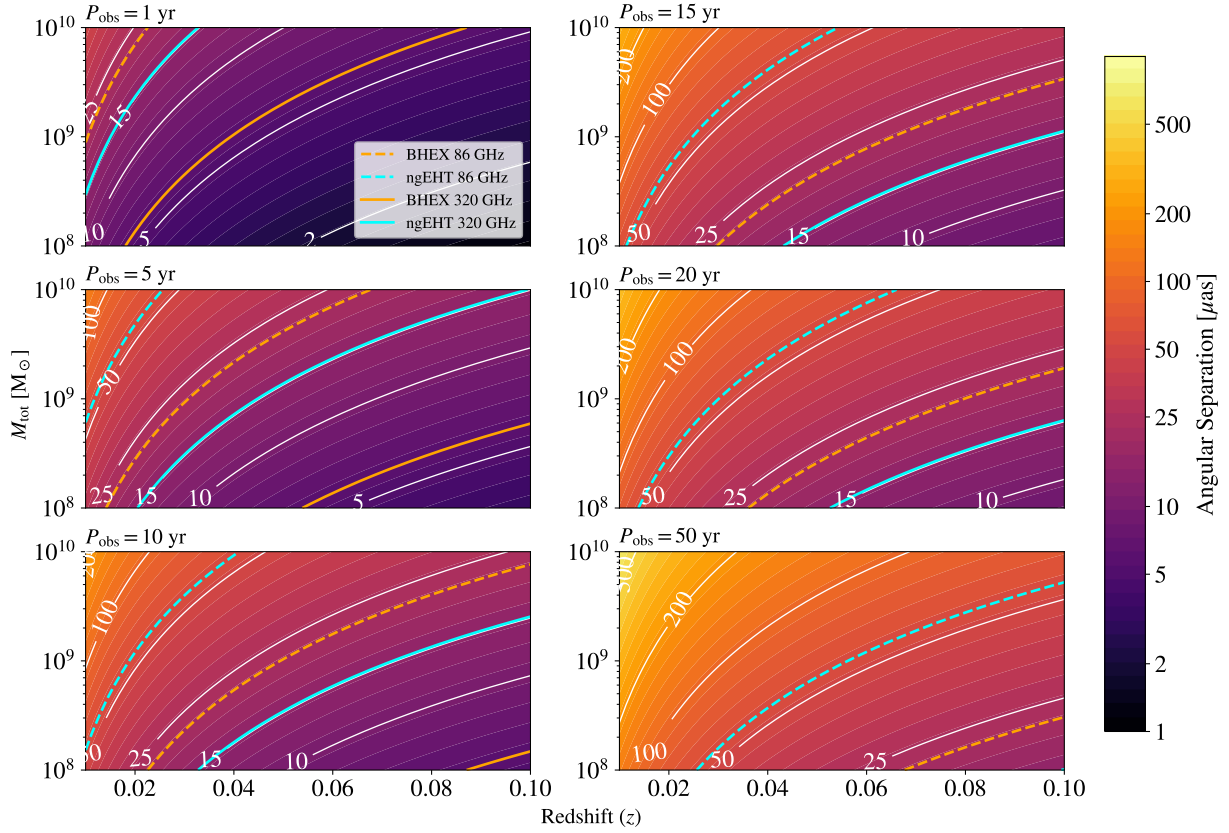


Figure 6. Angular separation of binary systems as function of total mass, redshift and observed orbital period. Nominal angular resolution of BHEX and ngEHT also indicated.

Table 2

Angular Separation for Example Systems Depicted in Figures 3 and 7

Total Mass	Observed Period	Redshift	Angular Separation
$10^9 M_\odot$	1 yr	0.025	$9.16 \mu\text{as}$
		0.100	$2.39 \mu\text{as}$
	10 yr	0.025	$42.50 \mu\text{as}$
		0.100	$11.08 \mu\text{as}$
$10^{10} M_\odot$	1 yr	0.025	$19.73 \mu\text{as}$
		0.100	$5.14 \mu\text{as}$
	10 yr	0.025	$91.56 \mu\text{as}$
		0.100	$23.86 \mu\text{as}$

requirements 1 and 2, defined above. Visibilities consist of amplitudes and phases, the latter of which are described by the complex part (see Equation (2)). While phase and closure phase information contains additional constraints on source morphology, their practical use depends sensitively on array geometry, phase calibration, atmospheric stability, and the details of the model-fitting approach. Here we consider only the visibility amplitudes in the preliminary assessment of SMBHB detectability. This is a deliberately conservative

choice as we cannot make use of the additional constraints provided by phase information.

Our metric for determining whether a given binary system is detectable is as follows:

1. The correlated flux density is detectable above the thermal noise with a minimum signal-noise ratio (SNR) requirement (notionally set to five).
2. The visibility data enables a binary Gaussian to be confidently distinguished from a single Gaussian model.

The thermal SNR of each visibility measurement is defined as

$$\text{SNR}_{\text{th},j} = \frac{|V(u, v)_j|}{\sigma_{\text{th},j}}, \quad (4)$$

where $|V(u, v)_j|$ is the visibility amplitude and $\sigma_{\text{th},j}$ is the thermal noise on baseline j . Only measurements satisfying $\text{SNR}_{\text{th},j} > 5$ are retained. We also set a requirement of having at least five usable visibility measurements before attempting to distinguish the binary source structure. Following Hudson et al. (2026), we include additional sources of uncertainty in the visibility amplitude error budget: a fractional uncertainty to

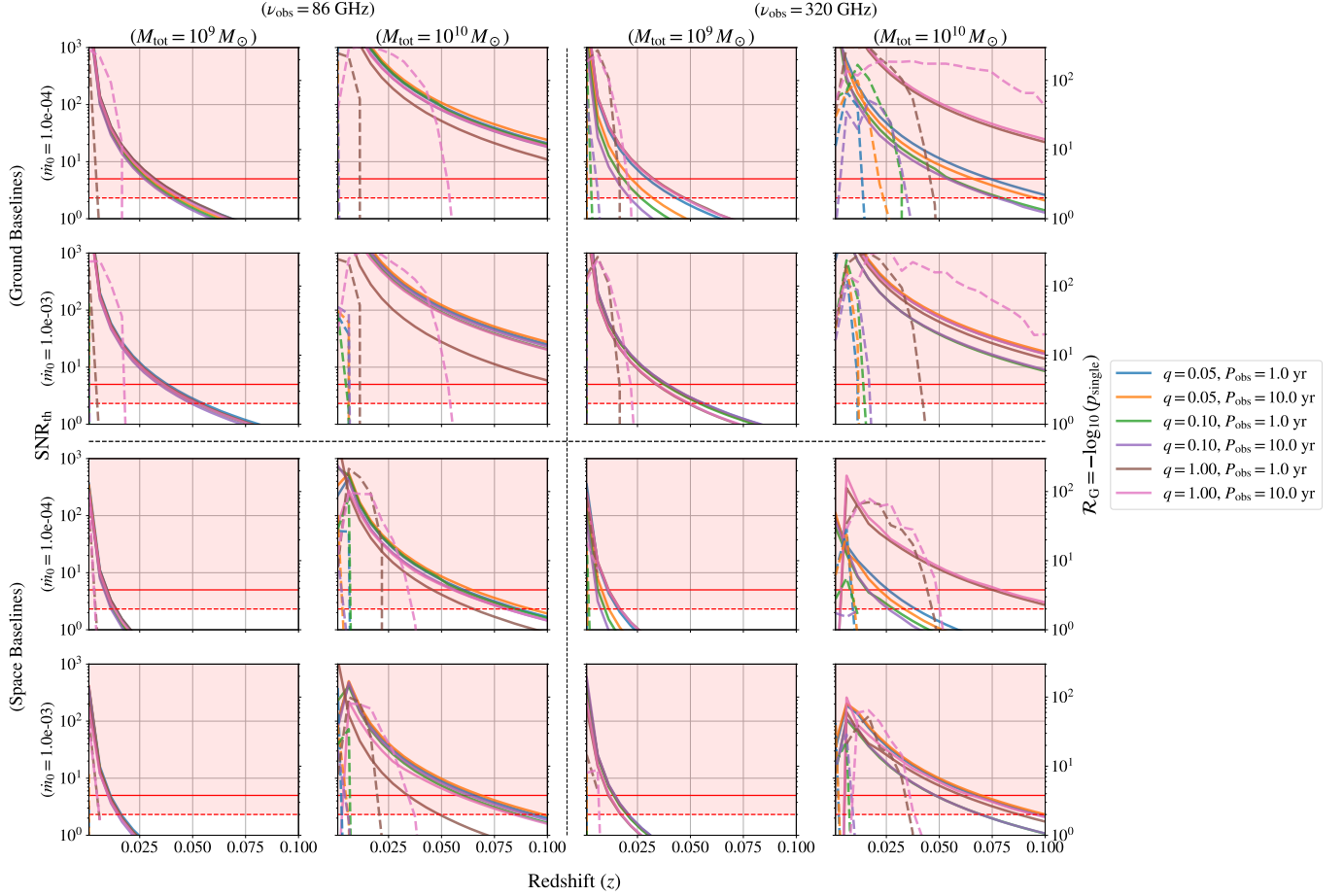


Figure 7. SMBHB detectability on VLBI baselines. Solid lines/left axes: SNR_{th} of the baseline with the fifth-highest correlated flux density. Dashed lines/right axes: $\mathcal{R}_G$ representing the confidence of rejecting a best-fit, single Gaussian model. ALMA—LMT is assumed for ground baselines, and ALMA—BHEX for space baselines.

account for systematic errors (f_{sys}) and a fractional model-discrepancy term (f_{model}). We adopt $f_{\text{sys}} = 0.1$, in line with the upper limit demonstrated by the EHT (EHT Collaboration et al. 2022b). The model-discrepancy term accounts approximately for departures of the compact components from ideal Gaussian brightness distributions. We notionally set this to $f_{\text{model}} = 0.1$. Treating these contributions as independent uncertainties, the total uncertainty on visibility amplitude A_j is

$$\sigma_j^2 = \sigma_{\text{th},j}^2 + (f_{\text{model}} A_j)^2 + (f_{\text{sys}} A_j)^2. \quad (5)$$

A single, circular Gaussian model is fitted to the visibility data (see Appendix C for detail on the model fitting). We calculate the chi-squared (χ_G^2) of the best-fitting single Gaussian model and the associated p-value (p_{single}). We adopt the requirement $p_{\text{single}} < 0.01$ for detectability of binary structure, requiring rejection of the best-fit single Gaussian with greater than 99% confidence. In general, detecting binary structure requires detecting the oscillations in the visibility response (see Figure 5). Therefore, increased sensitivity and

sampling across the projected baseline range promotes more confident rejection of single Gaussian models.

Figure 7 depicts the SMBHB detectability assessment on VLBI baselines. The shaded red region depicts the detectable parameter space according to our requirements above. Plotted in solid lines is the SNR_{th} of the fifth-highest correlated flux density, corresponding to our need for five visibility measurements above $\text{SNR} = 5$. The dashed lines show p_{single} , plotted as $\mathcal{R}_G = -\log_{10}(p_{\text{single}})$, with our requirement of at least 99% confidence equivalent to $\mathcal{R}_G \geq 2$.

Observations on a single baseline are considered, with 12 observations-per-night (as is intended for BHEX) across four nights. Uniform coverage of the projected baseline length within the range depicted in Figure 5 is assumed. Uniform baseline angle coverage across 180° is assumed for space baselines, and 45° for ground baselines, an approximate representation of the (u, v) coverage limits imposed by ground synthesis. The same stations are assumed for the ground as in Section 2. The binary is fixed at a position angle of 45° .

The correlated flux density of a binary Gaussian decreases with baseline length, as shown in Figure 5. The rate of this drop off depends strongly on the binary parameters, and is particularly evident for systems with high contrast between the primary and secondary components, in terms of flux density and angular size. As such, binaries of low mass ratio are perhaps unsurprisingly the hardest to distinguish from a single Gaussian model. The drop off in correlated flux density also means that in general, there is less flux density on the longest BHEX baselines and therefore the ground-space baseline has access to less of the binary parameter space than the ground baselines.

With this model, the most massive binaries ($M_{\text{tot}} = 10^{10} M_{\odot}$) are detectable and distinguishable as binary sources out to $z = 0.1$ on ground baselines, for equal mass ratio systems ($q = 1$) at $P_{\text{obs}} = 10$ yr. The space baseline can detect the same system out to $z = 0.05$. As total mass decreases to $M_{\text{tot}} = 10^9 M_{\odot}$, the detectable region reduces to $z < 0.025$ for ground baselines, and $z < 0.01$ for space baselines. Naturally, confirming binary structure is a more stringent requirement than detecting some correlated flux density above the thermal noise. Furthermore, Figure 7 depicts the evolution of a baseline between only two antenna to show the difference between a space and ground baseline. A larger array of N stations forming $N(N - 1)/2$ baselines, and evolving over time, would more strongly constrain the binary nature. For some parameter sets, we also see a similar insensitivity to m_0 as in Section 2, although a higher accretion rate generally makes detecting low q systems easier. As was found in Section 2, detecting any correlated flux density (solid lines in Figure 7) on the baseline is more achievable at 86 GHz due to the increased baseline sensitivity. However, 320 GHz is more favourable for distinguishing a binary source (dashed lines), due to the finer angular resolution providing access to smaller scale structure. The benefits of BHEX resolution can also be seen here. Although the space baselines have access to less of the parameter space, their ability to distinguish a $q = 1.0$, $P_{\text{obs}} = 1$ yr binary is as good as the ground baselines due to the improved angular resolution. Naturally, BHEX would become more beneficial for resolving binaries as the orbital period is decreased for the same total flux density.

At very low redshift in Figure 7, oscillation in the SNR lines can be observed where in some cases they quickly rise to a maximum and then drop off with redshift. This is an artifact of our requirement that detections above the noise floor occur on at least five baselines (and we plot the fifth highest SNR), and incomplete sampling of the projected baseline space. This is particularly prevalent for BHEX.

As the size of the Gaussian components increases as redshift decreases, there is significant drop-off in correlated flux density (see Figure 5), making it harder to detect the system on long baselines.

Correlating these results with Figure 6, we find the population to be flux- rather than angular resolution-limited, in agreement with D’Orazio & Loeb (2018). This is demonstrated by the larger detectable parameter space of the ground baselines compared to the space baselines in Figure 7. Because of this, increased sensitivity is more valuable for binary detection than finer angular resolution (within the limits of the binary parameter space explored here), making ground baselines more powerful for this activity than space baselines. Conversely, the opposite is true for characterization of the source, as is discussed in Section 5.

4.4. Inclination Effects

For systems with small separations, the orbital velocities of the black hole components can approach relativistic speeds. D’Orazio et al. (2015) demonstrate that the light curve variability of PG1302–102 can be explained by relativistic Doppler boosting of the emission from an unequal-mass binary. In this section, we assess whether this phenomena will have a significant impact on the parameter space of binaries that could be detectable with VLBI.

Figure 8 shows the Doppler factor (D) and associated boost in observed flux density, for a system with $M_{\text{tot}} = 10^9 M_{\odot}$, for varying inclination and semimajor axis, assuming a flat radio core with a spectral index, $\alpha = 0$. For inclined orbits, at any given time one of the black holes will have a velocity component in the line-of-sight (LOS), boosting emission. As Figure 8 shows, this effect approaches an order of magnitude increase in flux density for separations $\sim 10^{-4}$ pc and $i > 80^\circ$. Hudson et al. (2026) determined that BHEX could confidently detect binaries down to $\sim 2 \mu\text{as}$. At $z = 0.001$, a 10^{-4} pc system has an angular separation of $4.8 \mu\text{as}$. At $z = 0.005$, this has dropped below $1.0 \mu\text{as}$, and out of BHEX detectability. A 10^{-4} pc binary has an angular separation $> 2 \mu\text{as}$ out to $z = 0.025$ (~ 100 Mpc).

Therefore, an order of magnitude Doppler boost will only apply to BHEX-observable binaries in the very local universe, for the most massive and highly inclined systems. For binaries out to higher redshift, a factor of 2 increase in flux density (and therefore SNR) may be expected due to Doppler boosting. Although in theory this has the potential to increase detectability of one component, it of course also reduces the flux density of the other. However, it is conceivable that for a short P_{obs} , observation at one epoch may show the component moving towards the observer, while at a later epoch, when the true anomaly has progressed, the other component may instead be detectable. This would result in a time changing visibility structure that reflects not only the change in projected orbit on the sky, but an orbital phase-correlated change in relative brightness, as controlled by our parameter f in Table 1 and Figure 7.

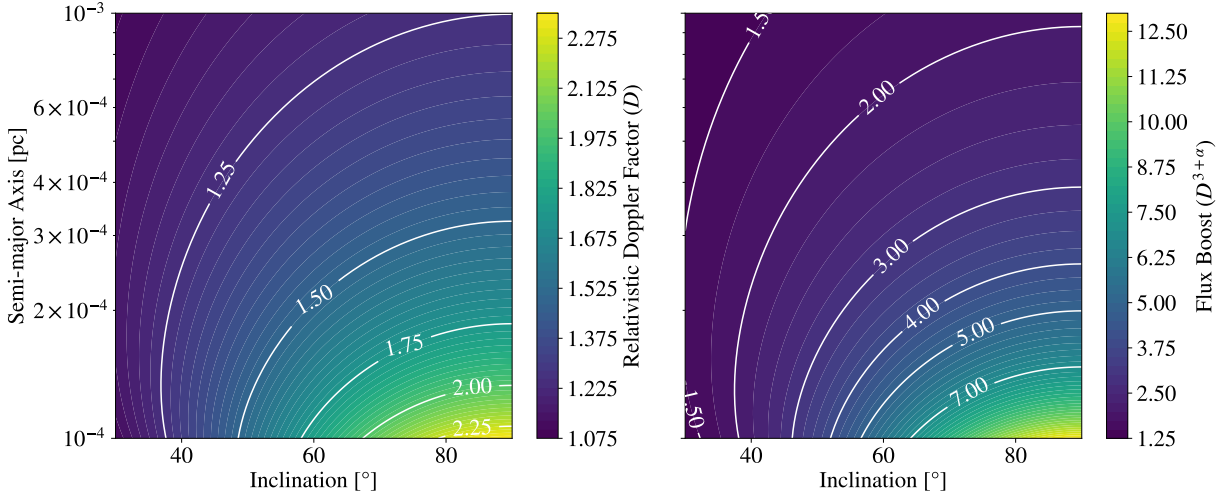


Figure 8. Doppler shift factor (left) and effective flux density boost (right), assuming $\alpha = 0$, consistent with compact radio cores observed at (sub)millimetre wavelengths. Total binary mass $M_{\text{tot}} = 10^9 M_{\odot}$.

The periodic modulation caused by the Doppler boost effect is a key signature in the identification of binary candidates from optical and ultraviolet surveys (D’Orazio et al. 2015). Davis et al. (2024) evaluate the prospects of the Rubin Observatory’s Legacy Survey of Space and Time (LSST) for identification of SMBHBs. They determine that the orbital period of the binary can be reliably recovered roughly 70% of the time, although a conservative estimate of the false-positive detection rate is $\sim 40\%$ of isolated, single quasars. Therefore, while such surveys hold promise for binary candidate identification and characterization, it is likely that consideration alongside other multi-messenger signals will be required to isolate a strong and small enough selection of systems for follow-up VLBI observations (see Section 6).

Subtler variability caused by Doppler boost in VLBI observations could be predicted from variability in optical data of the same system, assuming the two bands trace emission close to the same black hole. Taking a standard $\alpha_{\text{opt}} = -0.5$, the ratio of amplitude of brightness modulation is $(3 - \alpha_{\text{opt}})/(3 - \alpha) \simeq 1.17$. Interestingly, this method could also be applied to unresolved SMBHB systems as a means of providing additional binary candidate evidence. However, such variability is likely to be small (on the order of 10’s %) and therefore difficult to isolate from intrinsic source variability for all but the closest, most inclined systems (see Figure 8 and Kelley et al. 2021).

As well as Doppler boosting, inclination will affect the projected separation of the SMBHB, as viewed from the Earth. As inclination increases, the angular separation compared to a face-on orbit will decrease when either of the black hole components is nearest the observer. For example, a system with a $10 \mu\text{as}$ face-on separation would have a minimum separation of $\sim 7 \mu\text{as}$ at $i = 45^\circ$, and $\sim 1.7 \mu\text{as}$ at $i = 80^\circ$, tending towards zero as $i \rightarrow 90^\circ$. This will of course affect the

visibility signature of the system when observed at these positions and make it more difficult to confirm binary structure. Although Doppler boosting will increase the flux density of the approaching black hole, the reduced separation will make resolving two, distinct components more difficult if the separation is less than the array’s nominal resolution. The interplay of these effects for VLBI detectability requires more exploration and we leave this for future work. However, the reader is referred to the synthetic data simulations performed by Hudson et al. (2026) which included a highly inclined test case, but without the Doppler boosting effect.

4.5. Jet Launching

The BADAF SED model does not include jet components for either the primary or secondary black holes. As such, the analysis performed to this point only considers emission close to the event horizon, as is the case for unjetted sources.

Adding jet emission could simply increase the correlated flux density of the source, largening the detectability regions shown in Figure 7. However, this depends on the angular scale of the observation, and the distance between the core and the jet base. Kim et al. (2018) examined the base of the M87* jet at the scale of single Schwarzschild radii. Jets emanating from this close to the core would be visible in the image for some of the parameter space explored in this work, however much uncertainty remains around this phenomenon.

Jetted black holes may also bring into view binaries where the cores are not detectable on their own, as might be the case for OJ287 (Valtonen et al. 2025). Gutiérrez et al. (2024) discuss the possibility of dual jet launching from sub-parsec binaries and potentially detectable signatures of a binary source.

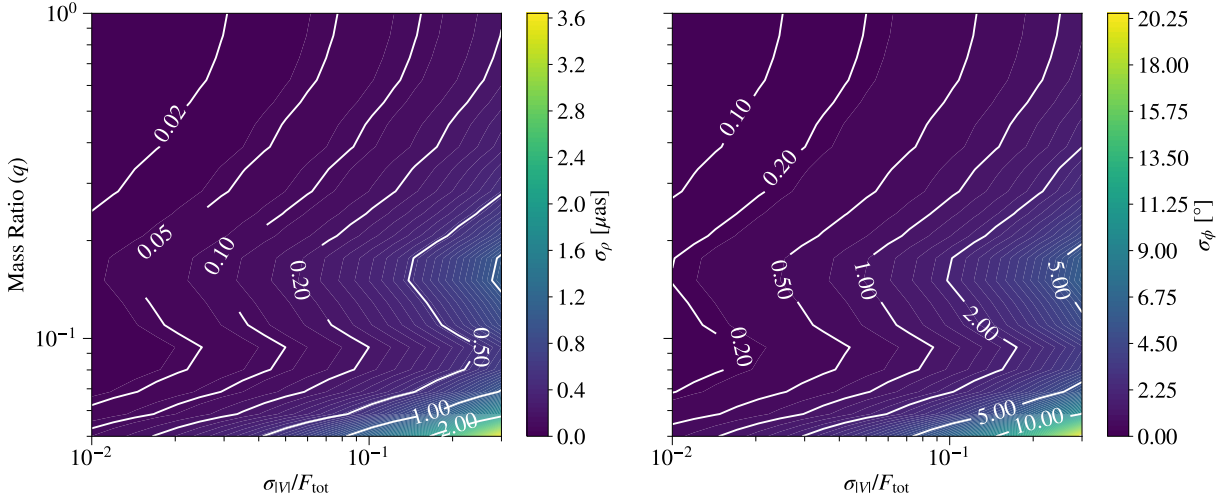


Figure 9. Uncertainty (1σ) from Fisher analysis on angular separation (left) and position angle (right) of an example binary system with $\rho = 6 \mu\text{as}$, $\phi = 45^\circ$, $M_{\text{tot}} = 10^9 M_\odot$ and $z = 0.01$. Observations by BHEX and a ground array over four nights with 12 observations-per-night.

More work is required to understand the relationship between jet launching and the black hole, particularly in the context of sub-parsec binaries, in order to explore a sensible jet parameter space in evaluation of VLBI detectability.

5. Binary Characterization

As discussed in Hudson et al. (2026) and highlighted in Requirement 3 above, a major piece of evidence in confirming a SMBHB detection is observation of orbital motion. This requires observation of the candidate source over sufficient time to first detect relative motion between the components. Once sufficient samples of the binary motion have been captured, an orbit can be reconstructed and its goodness-of-fit used to reject other possible relative motion models (e.g., linear relative motion). See Hudson et al. (2026) for a more detailed treatment of this issue, and evaluation of the minimum number of observations required to discern curved orbital motion between two components.

The orbit fitting methodology developed in Hudson et al. (2026) requires samples of the relative position of the secondary component with respect to the primary. The accuracy with which this can be estimated heavily impacts the accuracy and confidence with which an orbit can be fitted. In Hudson et al. (2026) we performed a preliminary evaluation of the impact of measurement noise and model misspecification on the estimate of the secondary position, using synthetic data simulations with `nghtsim` and `eht-imaging`. Here, we present a generalised, analytical approach that can be used for parameter space exploration.

The ability of VLBI observations to constrain specific binary parameters can be evaluated using a Fisher information analysis. A Fisher analysis is a statistical method used to measure the amount of information an observable random

variable (i.e., visibility V) carries about an unknown parameter. Formally, the Fisher information matrix is the variance of the gradient of the log-likelihood function. We focus specifically on the visibility amplitudes (as discussed in Section 4.3), but this could be extended to include phase information. We note again that using only visibility amplitudes is a conservative assumption, as the phase will also carry a binary signature that in some cases may be stronger than that in the amplitude data. In Appendix D, we derive the following form of the discrete Fisher matrix for binary visibility amplitudes,

$$F_{ij} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \frac{\partial |V_k|}{\partial p_i} \frac{\partial |V_k|}{\partial p_j}. \quad (6)$$

Where V_k are measured visibilities on baseline k , assuming constant variance of the measurement $\sigma_{|V|}$. p is the parameter set describing the binary appearance (see Appendix D). The full Fisher matrix for separation (ρ) and position angle (ϕ) is assembled in Appendix D and the expressions for calculating the uncertainty in these parameters are also provided.

Figure 9 depicts these uncertainties as a function of mass ratio (q) and Gaussian noise variance ($\sigma_{|V|}$). This is for an example $6 \mu\text{as}$ separated binary (on the edge of nominal BHEX angular resolution), with a 45° position angle. We assume the same baseline coverage as for Figures 5 and 7. A larger ground array consisting of eight locations is considered for this analysis, including BHEX as the spaceborne element. We also make the simplifying assumption that $\sigma_{|V|}$ is common across all baselines, so that we can isolate the effect of improving angular resolution by adding a spaceborne element such as BHEX. The Fisher matrix is a function of flux density ratio (f) between the two black hole components. For Figure 9, we use the BADAF model and the accretion splitting

function presented earlier to calculate f for a system of $M_{\text{tot}} = 10^9 M_{\odot}$, at $z = 0.01$, across varying mass ratio (q). The non-monotonic behavior visible in Figure 9 at $q \sim 10^{-1}$ is due to the accretion splitting function which reaches its maximum at this point.

In Hudson et al. (2026), we demonstrated that semimajor axis and eccentricity could be estimated to within 0.06 dex from three annual observations of a binary with $P_{\text{obs}} < 10$ yr. The average relative astrometric uncertainty in this analysis (from *ngchtsim* model fitting) was $\sim 0.6 \mu\text{as}$. Considering the example in Figure 9, with an extensive ground array and four nights of observations, the relative position of the secondary with respect to the primary can be characterized to within this uncertainty for $q > 0.05$, depending on the specific noise conditions. This approach allows for easier exploration of the whole binary parameter space, without the need to run expensive synthetic data simulations.

As described in Hudson et al. (2026), the accuracy with which the relative position between two sources within the same FOV can be constrained is dependent on the number of individual baseline measurements. Figure 9 is representative of the performance achievable by a BHEX observation with a full ground array. On a single ground baseline (taking the LMT—ALMA baseline assumed earlier), the ρ and ϕ uncertainty worsens by approximately a factor of ~ 6 and ~ 10 , respectively, to that in Figure 9. Adding BHEX to this single baseline, reduces the uncertainties by a factor of ~ 4 , in ρ and ϕ . This shows the benefit of improved angular resolution on the ability of the array to constrain key binary parameters.

We note that the uncertainties derived from the Fisher analysis provide an idealised, lower limit on the ability of a VLBI array to characterize binary systems. We can compare these uncertainties to those from synthetic data simulations to assess how representative the Fisher analysis is of real observations. Table 1 of Hudson et al. (2026) provides 1σ uncertainties on the separation estimates from synthetic data simulations with *ngchtsim*. For the $10 \mu\text{as}$ separation, 10% +5 mJy noise case, Hudson et al. (2026) finds $\sigma_{\rho} = 0.13 \mu\text{as}$. Although the treatment of noise is not identical between these two approaches, for an equivalent binary system, we estimate $\sigma_{\rho} = 0.115 \mu\text{as}$ from the Fisher analysis.¹¹

When considering how to include observations of binary candidates in the BHEX schedule, single baseline observations could be used for initial down-selection of binary candidates, with follow-up observations with a more complete ground array to sufficiently constrain separation and position angle to the level needed to perform orbit fitting.

¹¹ We convert the 10% +5 mJy noise case from Hudson et al. (2026) to $\sigma_{|V|}/F_{\text{tot}} = 0.24$ for comparison with our Fisher analysis method. This assumes an average sensitivity across the array of 5 mJy for an $F_{\text{tot}} = 50$ mJy source, combined in rms with the 10% fractional noise, with 5 mJy (i.e., 10% of 50 mJy) flat noise added to this.

6. SMBHB Imaging in the Multi-messenger Context

The subset of SMBHBs studied here, which are amenable to VLBI imaging, has a strong overlap with the population inferred from recent PTA measurements of a GWB (Agazie et al. 2023b). Using the population synthesis model of Chen et al. (2019); Agarwal et al. (2026) decompose the GWB into expected numbers of SMBHBs as a function of M_{tot} and P_{obs} (see Figure 10 with conversion from GW frequency to P_{obs} performed assuming circular orbits). The population model suggests that systems of $9.5 < \log_{10}(M_{\text{tot}}/M_{\odot}) < 10$ at $P_{\text{obs}} \lesssim 6.3$ yr are not supported by the data. Therefore, the $P_{\text{obs}} = 1$ yr systems in Figures 3 and 7 at $M_{\text{tot}} = 10^{10} M_{\odot}$ may not exist within the observable redshift range. However, for $8.5 < \log_{10}(M_{\text{tot}}/M_{\odot}) < 9.5$, the model suggests the existence of $\gtrsim 10^4$ sources at $P_{\text{obs}} = 10$ yr, and $\sim 10^2$ sources at $P_{\text{obs}} = 1$ yr.

The predicted total flux densities of SMBHB sources using the BADAF model do not change greatly with angular separation (see Figure 3). Therefore, the detectability evaluation performed above can be broadly extrapolated to other P_{obs} , up to a few 10's of years. The wider separations at a given redshift will impact the visibility response (and therefore the dashed lines of Figure 7, in general making binary confirmation easier), but Figure 6 can be used to determine the angular separation of a given system and relate it to the parameter combinations depicted in Figure 7. For example, a $10^9 M_{\odot}$ system with $P_{\text{obs}} = 20$ yr at $z = 0.1$ has an equivalent angular separation to a $P_{\text{obs}} = 10$ yr at $z = 0.06$. This system can then be found on Figure 7 at this redshift to assess likely detectability.

Beyond the GWB, detection of a resolved SMBHB with PTAs (a single system above the noise) is expected in the next few to 10's of years. Population models conditioned on the GWB estimate that there is a 51% chance of finding such a source in the next 10 yr, and a 14% chance that it is localised to within a few hundred square degrees (Veronesi et al. 2026). Realisations find such sources in the range $z = 0.01$ – 1 , with the majority at $z < 0.2$ (encompassing our detectable redshift). Masses are predicted to be $9 \lesssim \log_{10}(M_{\text{tot}}/M_{\odot}) \lesssim 10.5$, with P_{obs} ranging from 5–30 yr (2–12 nHz).

With the definition of “well localised” still relatively poor (a few hundred square degrees, containing 100,000's of galaxies), a method for identifying a small number of candidate systems in electromagnetic observations is still required before VLBI observations. However, with the high chance for false-positives (see discussion on periodic variability signatures in Section 4.4) in current methods for binary signature identification, a degree of luck, or improved models of binary signatures and their identification methods, will be required in achieving the first indisputable multi-messenger detection of a SMBHB in the near future.

7. Discussion

Using an ADAF supermassive black hole binary SED model, we have shown that there could exist systems which are directly observable with ground and SVLBI out to $z \sim 0.1$. We have used BHEX as an example of future SVLBI, and a ground array representative of the near-future performance of the ngEHT. We find that ground-ground baselines provide access to the largest volume of binary parameter space, due to their enhanced sensitivity. Lower frequency observations (e.g., 86 GHz), also increase the detectable parameter space for the same reason. Conversely, the fine angular resolution provided by spaceborne systems such as BHEX offers significant benefits for source characterization.

VLBI detectability is heavily dependent on the total mass and mass ratio of the SMBHB. Even on ground baselines, systems with $q = 0.05$ are only detectable and confidently distinguishable as a binary structure out to ~ 0.025 redshift. On ground-space baselines, $q = 1.0$ systems are detectable out to $z = 0.1$ for $M_{\text{tot}} = 10^{10} M_{\odot}$, but not confidently distinguishable from a single Gaussian model. This requirement limits the detectable redshift range to $z = 0.05$, reducing to $z \sim 0.01$ for $M_{\text{tot}} = 10^9 M_{\odot}$. Doppler boosting exhibited by inclined systems may increase the detectable parameter space for some systems (the flux density boost approaches an order of magnitude increase for separations $\sim 10^{-4}$ pc and $i > 80^\circ$), but the same effect will also reduce the brightness of the receding black hole. However, it is possible that for observations over long epochs, each component may be detectable at different times, as a function of the phase of the binary orbit. Of course, the challenge will then be model fitting to time-dependent visibilities, but with the constraint that the relative brightness should follow the orbital phase. We explored the parameter space down to a minimum mass ratio $q = 0.05$, beyond which the accretion flow experiences a transition away from our assumed disc model. This low q case may present other detectable signatures but we defer their exploration to future work when models of such systems exist.

As in D’Orazio & Loeb (2018), we find the SMBHB population to be flux- rather than angular resolution-limited. Although this reduces the benefit of a spaceborne system such as BHEX (offering reduced sensitivity compared to ground baselines), the finer resolution may still enable observation of some systems unresolvable by the ground. Also, the inclusion of a spaceborne element enables significantly better estimates of binary parameters to be extracted from the visibility data, which is important for orbit reconstruction, a key piece of evidence in confirming that what has been observed is indeed a SMBHB (Hudson et al. 2026). In the example provided, using a Fisher analysis, the accuracy of angular separation and position angle estimates were found to improve by a factor of ~ 4 with a spaceborne element, compared to ground-only observations.

The BADAF SED model does not include any jet components. As discussed briefly in Section 4.5, the inclusion of jets may largen the detectable binary parameter space by simply increasing the flux density of the sources. Alternatively, on larger angular scales, jet components may make binaries observable where the cores would not be detectable on their own, as may be the case for OJ287 (Valtonen et al. 2025).

A number of assumptions are inherent in the BADAF SED model that should be noted. A specific accretion splitting function is assumed, as are the values for the mass-loss correction factor slope (s) and the gas to magnetic pressure ratio (β). Although Tiede & D’Orazio (2025) find that the model is not particularly sensitive to variation in some model parameters (see their Appendix A), the emission characteristics will of course be impacted by the other assumptions. As a preliminary evaluation of parameter sensitivity, in Appendix E we have tested the effect of different s and β values on the detectable binary parameter space. Beyond SED model parameter variations, increasing the model misspecification error (f_{model}) to 20% results in only a slight reduction in the maximum redshift at which the binary is distinguishable from a single Gaussian. It does however reduce the value of $\mathcal{R}$ at z below this maximum, by just under an order of magnitude. See Tiede & D’Orazio (2025) for more discussion on the BADAF SED model, and recommendations for next steps. In general, more work is required using full hydrodynamical simulations to assess the likely (sub)millimetre radio emission from SMBHB.

This work deals with a theoretical population of SMBHBs bright in the (sub)millimetre. However, as highlighted by Hudson et al. (2026) and D’Orazio & Loeb (2018), the challenge is in identifying candidate sources for future observation. VLBI is not suited to survey-like observations due to the very small field of view, and the computation required to perform correlation for even a small fraction of this. Therefore, VLBI requires specific targets well localised on the sky to perform observations.

Multiple methods have been proposed for the identification of candidate SMBHB systems, including periodic modulation in optical and ultraviolet surveys discussed above (D’Orazio & Charisi 2023; Davis et al. 2024). Monitoring of radio loud AGN variability carried out by the Owens Valley Radio Observatory (OVRO) is also particularly relevant given its observations at GHz frequencies (Molina et al. 2026; Readhead et al. 2026). However, intrinsic variability of blazar flares still accounts for the majority of the observed periodicity, with only one candidate (PKS 1309+1154) having a significance of $>2\sigma$. The Event Horizon and Environs (ETHER) database is building a library of SMBHB candidates identified using these methods, with ongoing observations with ground-based VLBI (Ramakrishnan et al. 2023). It is envisaged that the approach used in this paper could be

applied to the down selection of ETHER’s large candidate list to help with identifying promising systems.

A strategy for SMBHB candidate observation could consist of the following:

1. Candidate identification: Broad identification of a sky region containing SMBHB from PTA data, with subsequent down-selection using existing methods for identifying binary signatures in electromagnetic observations (e.g., ETHER database). Further down-selection by predicting detectability with the SED model approach used in this work.
2. Ground radio campaign: Confirmation of detectable flux densities at GHz frequencies of interest (e.g., ~ 86 , ~ 230 and ~ 345 GHz for the EHT, ngEHT and BHEX).
3. Ground VLBI campaign: For those sources with confirmed, detectable (sub)millimetre flux densities, observe with a ground VLBI array.
4. SVLBI campaign (e.g., BHEX): (a) In the best case scenario, if the ground VLBI observations show two compact sources and/or jets, follow-up with BHEX observations to tightly constrain relative positions for subsequent orbit fitting; or (b) If the source is still unresolved at the scale of likely binary separation, follow-up with BHEX observations at $>2\times$ finer resolution than the ground. Due to the competition for space instrument time, it is likely this would only be possible for candidates with very strong additional evidence supporting the binary claim.
5. Multi-epoch monitoring: In the case of finding a candidate with two distinct sources, observe with ground and/or SVLBI regularly with a cadence of ~ 6 months/1 yr (depending on expected P_{obs}), to enable orbit fitting as demonstrated by Hudson et al. (2026).

8. Conclusions

Observation of a sub-parsec supermassive black hole binary (SMBHB) and detection of its orbital motion would be the first direct evidence of such systems existing. Very Long Baseline Interferometry (VLBI) is the only astronomical method capable of meeting this objective. Beyond conclusive proof of their existence, characterization of a population of sub-parsec SMBHBs would enable evolutionary models across the binary life cycle to be constrained. Combining such measurements with gravitational wave (GW) observations, such as those performed by pulsar timing arrays (PTAs), would broaden our understanding of galactic evolution on a cosmological scale through multi-messenger astronomy.

We have developed an approach for assessing the detectability of SMBHBs with VLBI, and evaluated the prospects of current and near-future arrays. Using an unjetted, binary SED model, we have shown that SMBHB systems could be

detectable out to $z \sim 0.1$ with ground and SVLBI, under a range of accretion, total mass, mass ratio and orbital conditions. SVLBI, such as that proposed for the black hole Explorer (BHEX), is particularly beneficial for characterizing the properties of such sources, even though it is unlikely to significantly increase the size of the detectable population.

SMBHB observation is not a defined science objective of BHEX and as such, the spacecraft has not been designed with this activity in mind. However, strong binary candidates (e.g., OJ287) are already included in the BHEX target list. Beyond this, SMBHB observation may be an intriguing tertiary activity for the mission, if promising candidate sources can be identified before launch.

Looking to the future, a SVLBI mission specifically designed with SMBHB observation as a primary objective (with sensitivity comparable to that offered by ground arrays) would be a system with unprecedented capabilities, able to tackle some of the most pressing questions in astronomy.

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Software: Astropy (The Astropy Collaboration et al. 2013, 2018, 2022), BADAF (Tiede & D’Orazio 2025), LLAGNSED (Pesce et al. 2021).

Appendix A VLBI Array Properties

Here we define the properties of the observing sites used in the above analysis to evaluate VLBI detectability. SEFD is a key metric in describing the performance of a radio telescope, defined as the strength of a hypothetical incoming signal that would double the receiver’s system temperature. The SEFD of a radio antenna is given by

$$\text{SEFD} = (2k_B T_{\text{sys}}) / (\eta_a A_{\text{geom}}). \quad (\text{A1})$$

Where T_{sys} is the system temperature, η_a is the antenna efficiency, and A_{geom} is the effective receiving area of the antenna. While the latter are geometric properties or a consequence of the specific antenna design used, T_{sys} is heavily impacted by weather (for ground sites), environmental noise, and the receiver properties.

At the time of writing, BHEX will have a 3.4 m monolithic antenna, with a surface accuracy of $\sim 40 \mu\text{m}$, observing across two frequency bands, with a bandwidth of 8 GHz, dual-polarisation. The remaining properties defining the SEFD of

the instrument are as specified in Hudson et al. (2026), and the reader is referred to Johnson et al. (2024) for more information.

As in Hudson et al. (2026), we calculate the SEFDs of BHEX (low-band: 19,200 Jy, high-band: 39,800 Jy), ALMA (low-band: 65 Jy, high-band: 160 Jy) and LMT (low-band: 170 Jy, high-band: 865 Jy) using `ngehtsim`. We take the average SEFD across a simulated night of observations, assuming median weather conditions.

Appendix B Visibility Domain Features

In this section we provide the derivations of the equations in Table 1. This is standard interferometric theory, but rarely presented in the context of binary Gaussian sources, specifically. From Equation (2), at zero baseline $\mathbf{b} = 0$,

$$|V(0, 0)| = F_{\text{tot}}. \quad (\text{B1})$$

The phase term in the binary Gaussian visibility is given by $\exp(-2\pi i \mathbf{b} \cdot \boldsymbol{\rho})$. We can write the dot product explicitly as $(\mathbf{b} \cdot \boldsymbol{\rho} = b\rho \cos(\psi - \phi))$, where ψ is the baseline orientation angle and ϕ is the binary position angle. Considering the case where a baseline is aligned with the separation vector ($\psi = \phi$), constructive interference occurs when $2\pi b\rho = 2\pi n$, giving $b = \frac{n}{\rho}$. Therefore, the spacing between successive maxima is

$$\Delta b = \frac{1}{\rho}. \quad (\text{B2})$$

Destructive interference occurs when $2\pi b\rho = (2n + 1)\pi$. More generally when,

$$\mathbf{b} \cdot \boldsymbol{\rho} = n + \frac{1}{2}. \quad (\text{B3})$$

This links baseline vector to binary separation vector, and enables the angular separation and position angle of the source to be estimated from samples of successive nulls (n). Taking the square of the amplitude in the regime where both Gaussian components remain unresolved,

$$|V|^2 = F_1^2 + F_2^2 + 2F_1F_2 \cos(2\pi \mathbf{b} \cdot \boldsymbol{\rho}), \quad (\text{B4})$$

the maximum occurs when $\cos = +1$: $|V|_{\text{max}} = F_1 + F_2$. The minimum occurs when $\cos = -1$: $|V|_{\text{min}} = |F_1 - F_2|$. Therefore,

$$\frac{|V|_{\text{min}}}{|V|_{\text{max}}} = \frac{|F_1 - F_2|}{F_1 + F_2}. \quad (\text{B5})$$

As the two Gaussians become resolved, each contributes a damping of visibility amplitude with baseline length, suppressing the contrast between maximum and minima. In such cases, the separation vector and Gaussian sizes must be fitted simultaneously, with model fitting techniques.

In the short baseline regime, we can substitute the dot product into the phase term and perform a Taylor expansion,

under the assumption of small b , such that,

$$\cos(2\pi b\rho \cos(\gamma - \phi)) \approx 1 - 2\pi^2 b^2 \rho^2 \cos^2(\gamma - \phi), \quad (\text{B6})$$

The binary separation introduces an anisotropic quadratic curvature whose amplitude depends on baseline position angle. In contrast, the short baseline suppression of a circular Gaussian depends only on b^2 and FWHM. Therefore, with sufficient baseline orientation coverage, intrinsic circular source size and binary separation can remain distinguishable even without sampling multiple visibility minima and maxima.

Appendix C Gaussian Best Fit Approach

The following single, circular Gaussian model is used in our assessment of binary detectability, defined by the total flux density (F_G) and FWHM (θ_G),

$$|V_{G,j}| = F_G \exp \left[-\frac{\pi^2 \theta_G^2 b_j^2}{4 \ln 2} \right]. \quad (\text{C1})$$

The best-fitting parameters are obtained by minimising

$$\chi_G^2 = \sum_{j=1}^{N_{\text{use}}} \frac{[|V_j| - |V_{G,j}|(\hat{F}_G, \hat{\theta}_G)]^2}{\sigma_j^2}, \quad (\text{C2})$$

where j is the baseline, N_{use} is the number of useable baselines' visibility data above the thermal SNR requirement and σ_j is the total uncertainty on visibility amplitude.

As the single Gaussian model has two fitted parameters, the number of degrees of freedom is $\nu = N_{\text{use}} - 2$. The probability of obtaining a value at least as large as the measured χ_G^2 under the single Gaussian hypothesis is

$$p_{\text{single}} = P(\chi_\nu^2 \geq \chi_G^2) = 1 - F_{\chi_\nu^2}(\chi_G^2), \quad (\text{C3})$$

where $F_{\chi_\nu^2}$ is the cumulative distribution function of the χ^2 distribution, with ν degrees of freedom.

Appendix D Fisher Information Analysis

The complex visibility of a two-component circular Gaussian binary can be written as

$$V(b, \gamma) = A_1(b) + A_2(b) \exp[-i\psi(b, \gamma)]. \quad (\text{D1})$$

A_1 and A_2 are the baseline-dependent attenuated flux densities, defined as

$$A_1(b) = F_1 \exp(-2\pi^2 \sigma_1^2 b^2), \quad (\text{D2})$$

$$A_2(b) = F_2 \exp(-2\pi^2 \sigma_2^2 b^2), \quad (\text{D3})$$

and the relative binary phase is

$$\psi(b, \gamma) = 2\pi b\rho \cos(\gamma - \phi). \quad (\text{D4})$$

In an amplitude-only treatment, the observable is the visibility amplitude,

$$|V| = (A_1^2 + A_2^2 + 2A_1A_2 \cos \psi)^{1/2}. \quad (\text{D5})$$

We assume independent Gaussian errors on the measured visibility amplitudes,

$$|V_k|^{\text{obs}} = |V_k(\mathbf{p})| + n_k, \quad (\text{D6})$$

where $\mathbf{p}$ is the model parameter vector and n_k is real Gaussian noise with variance $\sigma_{|V|}^2$. The log-likelihood is therefore

$$\ln \mathcal{L} = -\frac{1}{2\sigma_{|V|}^2} \sum_{k=1}^N [|V_k|^{\text{obs}} - |V_k(\mathbf{p})|]^2 + \text{const.} \quad (\text{D7})$$

The corresponding Fisher matrix is

$$F_{ij} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \frac{\partial |V_k|}{\partial p_i} \frac{\partial |V_k|}{\partial p_j}. \quad (\text{D8})$$

For the k th baseline,

$$|V_k| = (A_{1,k}^2 + A_{2,k}^2 + 2A_{1,k}A_{2,k} \cos \psi_k)^{1/2}. \quad (\text{D9})$$

The derivatives with respect to the separation magnitude and position angle are

$$\frac{\partial |V|}{\partial \rho} = -\frac{A_1 A_2}{|V|} \sin \psi [2\pi b \cos(\gamma - \phi)], \quad (\text{D10})$$

$$\frac{\partial |V|}{\partial \phi} = -\frac{A_1 A_2}{|V|} \sin \psi [2\pi b \rho \sin(\gamma - \phi)]. \quad (\text{D11})$$

The amplitude-only Fisher matrix elements are therefore

$$F_{\rho\rho} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left[\frac{A_{1,k} A_{2,k}}{|V_k|} \right]^2 [2\pi b_k \cos(\gamma_k - \phi)]^2 \sin^2 \psi_k, \quad (\text{D12})$$

$$F_{\phi\phi} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left[\frac{A_{1,k} A_{2,k}}{|V_k|} \right]^2 [2\pi b_k \rho \sin(\gamma_k - \phi)]^2 \sin^2 \psi_k. \quad (\text{D13})$$

The covariance between the separation and position angle is captured by the off-diagonal Fisher matrix element,

$$F_{\rho\phi} = F_{\phi\rho} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left[\frac{A_{1,k} A_{2,k}}{|V_k|} \right]^2 \times [2\pi b_k \cos(\gamma_k - \phi)] [2\pi b_k \rho \sin(\gamma_k - \phi)] \sin^2 \psi_k. \quad (\text{D14})$$

We therefore form the two-parameter Fisher matrix and covariance for the binary geometry,

$$\mathbf{F}_{\rho\phi} = \begin{pmatrix} F_{\rho\rho} & F_{\rho\phi} \\ F_{\phi\rho} & F_{\phi\phi} \end{pmatrix}, \quad (\text{D15})$$

$$\mathbf{C}_{\rho\phi} = \mathbf{F}_{\rho\phi}^{-1} = \frac{1}{F_{\rho\rho}F_{\phi\phi} - F_{\rho\phi}^2} \begin{pmatrix} F_{\phi\phi} & -F_{\rho\phi} \\ -F_{\rho\phi} & F_{\rho\rho} \end{pmatrix}. \quad (\text{D16})$$

The marginalised one-sigma uncertainties on ρ and ϕ are therefore

$$\sigma_\rho = \sqrt{\frac{F_{\phi\phi}}{F_{\rho\rho}F_{\phi\phi} - F_{\rho\phi}^2}}, \quad (\text{D17})$$

$$\sigma_\phi = \sqrt{\frac{F_{\rho\rho}}{F_{\rho\rho}F_{\phi\phi} - F_{\rho\phi}^2}}. \quad (\text{D18})$$

The same Fisher formalism can be used to calculate the diagonal matrix elements for the remaining source parameters. These diagonal terms quantify the conditional information in each parameter when the remaining parameters are held fixed. For the total flux densities ($F_{1/2}$), and angular widths ($\sigma_{1/2}$), these expressions are

$$F_{F_1 F_1} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left\{ \frac{[A_{1,k} + A_{2,k} \cos \psi_k] \exp(-2\pi^2 \sigma_1^2 b_k^2)}{|V_k|} \right\}^2, \quad (\text{D19})$$

$$F_{F_2 F_2} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left\{ \frac{[A_{2,k} + A_{1,k} \cos \psi_k] \exp(-2\pi^2 \sigma_2^2 b_k^2)}{|V_k|} \right\}^2, \quad (\text{D20})$$

$$F_{\sigma_1 \sigma_1} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left\{ \frac{4\pi^2 b_k^2 \sigma_1 A_{1,k} [A_{1,k} + A_{2,k} \cos \psi_k]}{|V_k|} \right\}^2, \quad (\text{D21})$$

$$F_{\sigma_2 \sigma_2} = \frac{1}{\sigma_{|V|}^2} \sum_{k=1}^N \left\{ \frac{4\pi^2 b_k^2 \sigma_2 A_{2,k} [A_{2,k} + A_{1,k} \cos \psi_k]}{|V_k|} \right\}^2. \quad (\text{D22})$$

A full multi-parameter characterization would require the off-diagonal terms involving F_1 , F_2 , σ_1 , and σ_2 to be included and the complete Fisher matrix to be inverted.

Appendix E Dependence on Model Parameters

Increasing s corresponds to higher mass loss and therefore reduces the effective accretion rate used in calculating the SED. Higher values of β weaken the magnetic field and consequently the synchrotron emission, the primary contribution to the detectable emission at (sub)millimetre wavelengths. Figure E1 depicts a subset of the detectable parameter space for variations in s and β . The default values (as assumed in Figure 7) are shown in black. As expected, lower s increases the detectable parameter space. Whereas increased s or β significantly reduces the redshift across which the assumed binary can be detected. As stated by Tiede & D’Orazio (2025), we leave investigation of magnetically dominated (i.e., $\beta < 1$) and other parameter variations for future study.

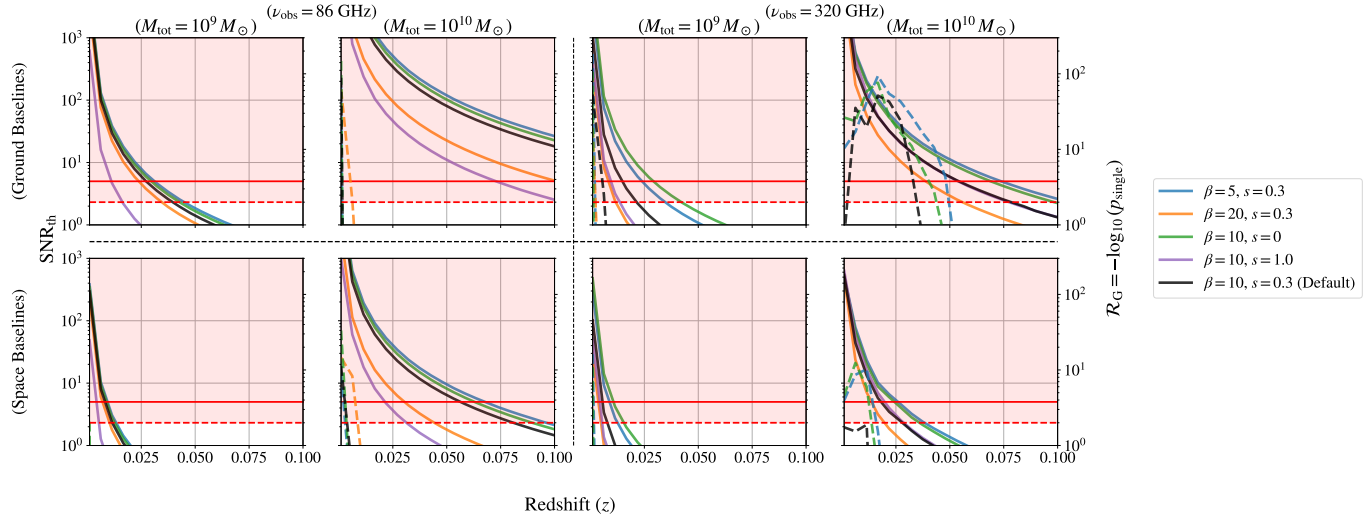


Figure E1. Detectability evaluation as shown in Figure 7 but varying the slope of the mass-loss correction factor (s) and the gas pressure to magnetic pressure ratio (β). Illustrated for a $q = 0.1$ system with $P_{\text{obs}} = 10 \text{ yr}$ at $m_0 = 10^{-4}$.

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