Direct observation of supermassive black hole binaries with ground/spaceborne VLBI

HERA 2026, Warsaw
22nd Sept 2026

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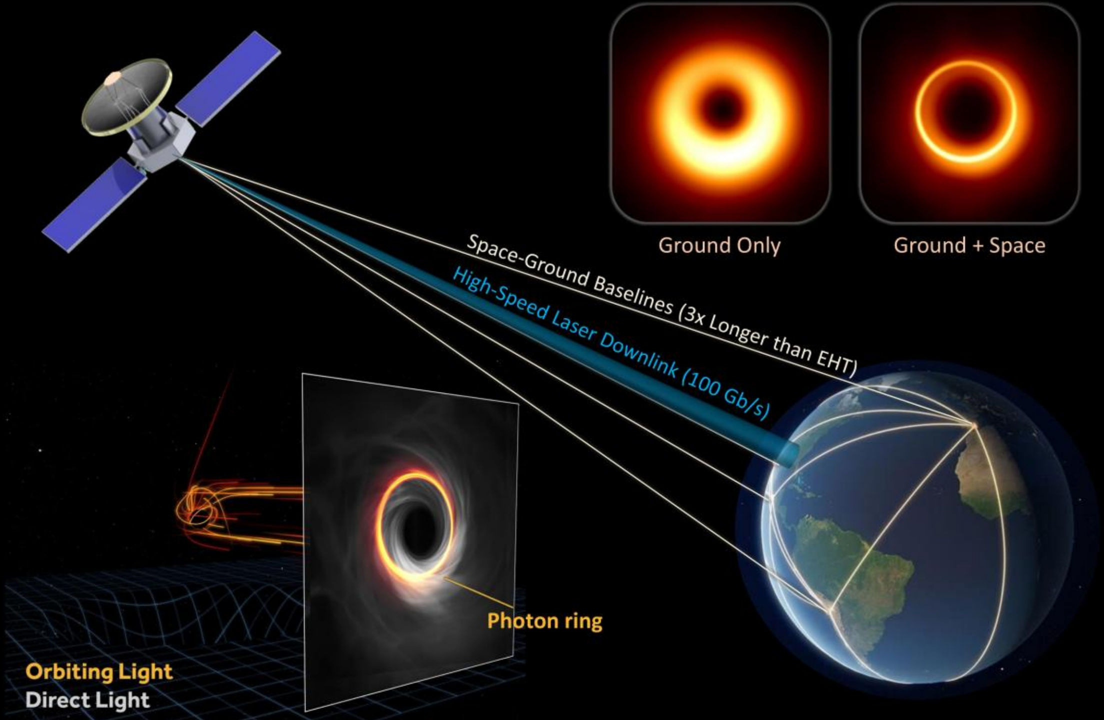
Black Hole Explorer (BHEX)

The Black Hole Explorer will achieve the finest angular resolution in history and see a black hole's "photon ring" for the first time

- Designed to fit within a NASA Small Explorers Mission
- Proposal submitted in Sept 2026

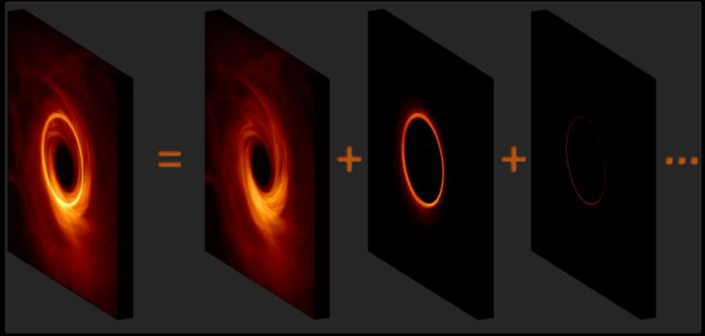


Science Goals

Discover a black hole's photon ring

Make direct measurements of a black hole's mass and spin

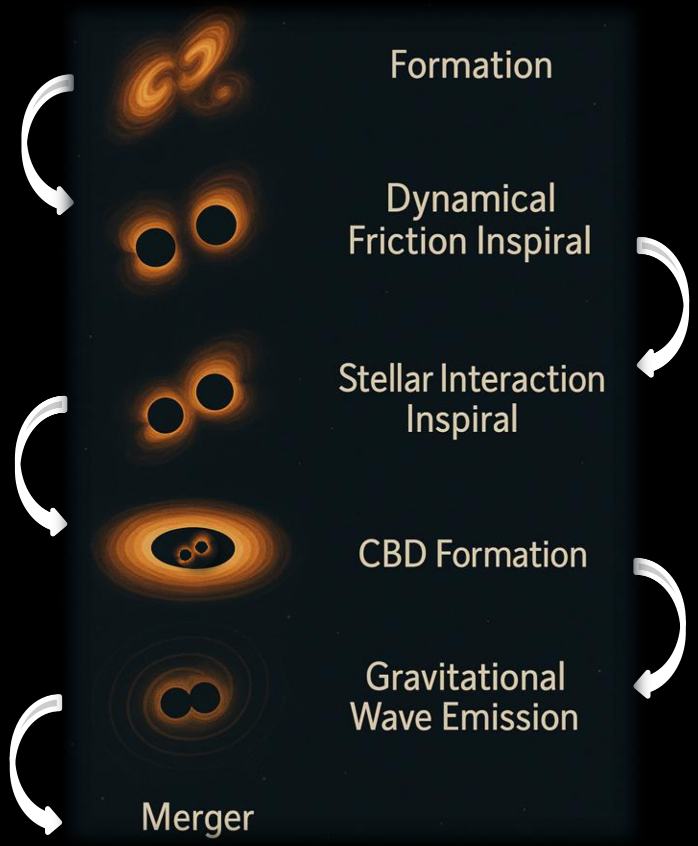
Reveal the shadows of *tens* of supermassive black holes



Johnson et al. 2024, arXiv:2406.12917

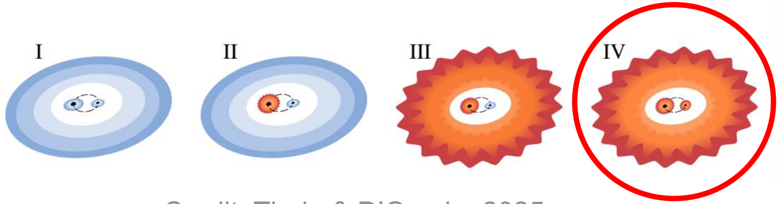
Supermassive Black Hole Binaries (SMBHB)

- PTA evidence for a nanohertz gravitational wave background points to a population of SMBHBs
- EM candidates remain ambiguous: Quasi-periodic oscillations (QPOs), jet perturbations, astrometric oscillations, etc.
- <u>mm/sub-mm VLBI can probe *μ*as-scale structure</u>
- *Can present / near-future VLBI arrays detect this population?*

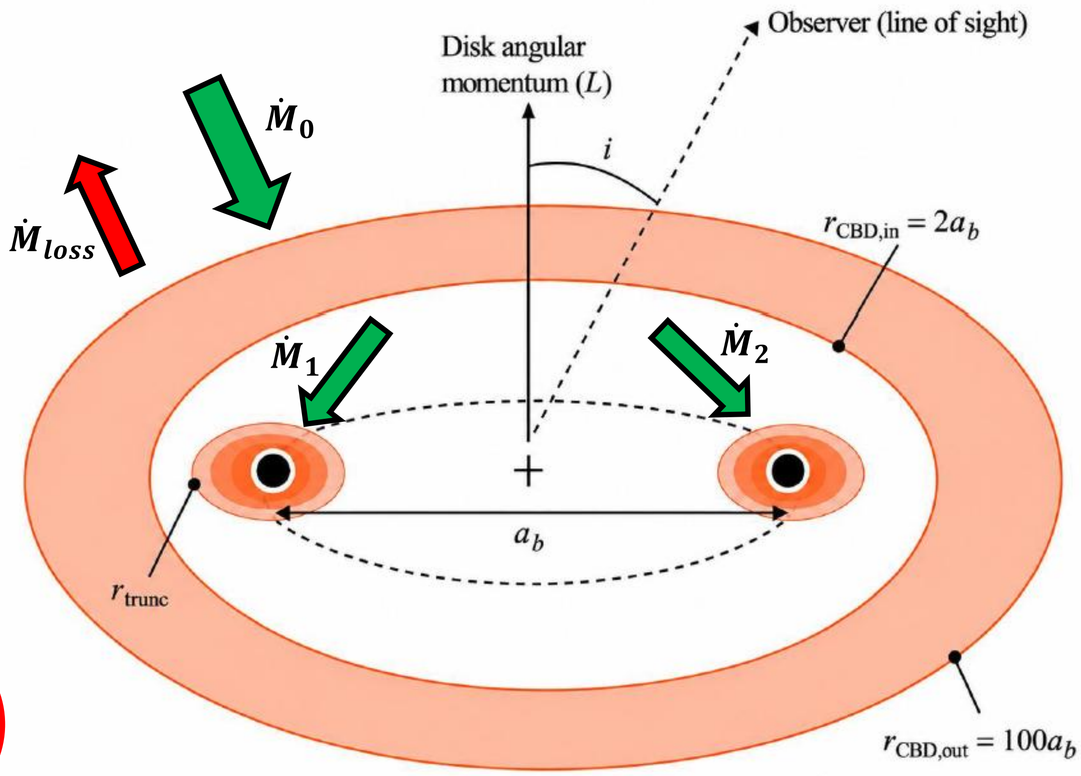


SED Model

- Unjetted minidiscs + circumbinary disc
- Accretion regime IV where discs are ADAFs with strong sub-mm emission
- ADAF modelled using LLAGNSED (*Pesce et al, 2021*)



Credit: Tiede & D'Orazio, 2025



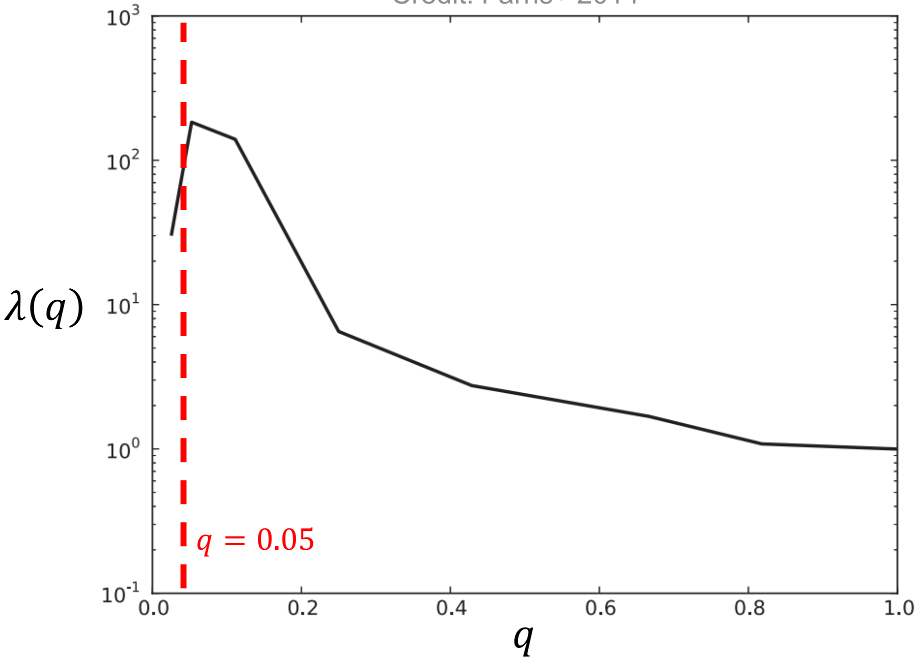
Fiducial Model Assumptions

- Mass ratio: $q = M_2 / M_1 > 0.05$
- Circular, face-on (*inclination* = 0°), coplanar discs
- Radiative efficiency: $\eta = 0.1$
- Gas-magnetic pressure ratio: $\beta = 10$
- Mass-loss slope: $s = 0.3$

$$\left(r_{s,1}/r_{\mathrm{trunc},1}\right)^{s}$$

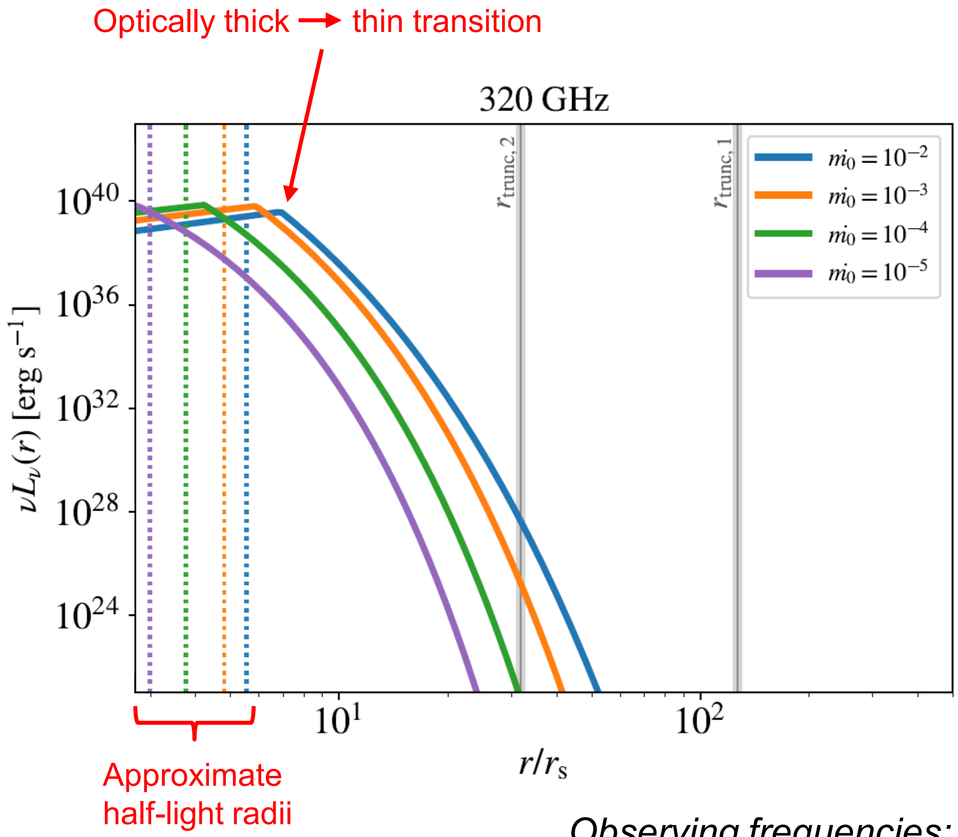
- *Other parameters consistent with Pesce et al, 2021*

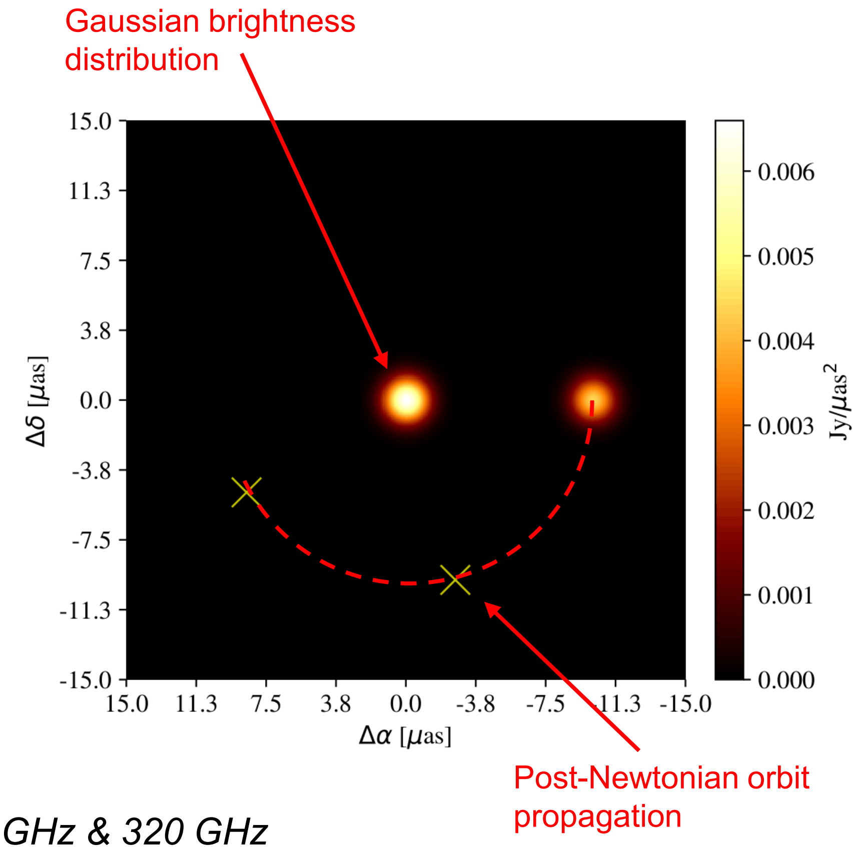
Credit: Farris+ 2014



$$\lambda(q) = \frac{\dot{M}_2}{\dot{M}_1}$$

SED → VLBI Image Model





Observing frequencies: 86 GHz & 320 GHz

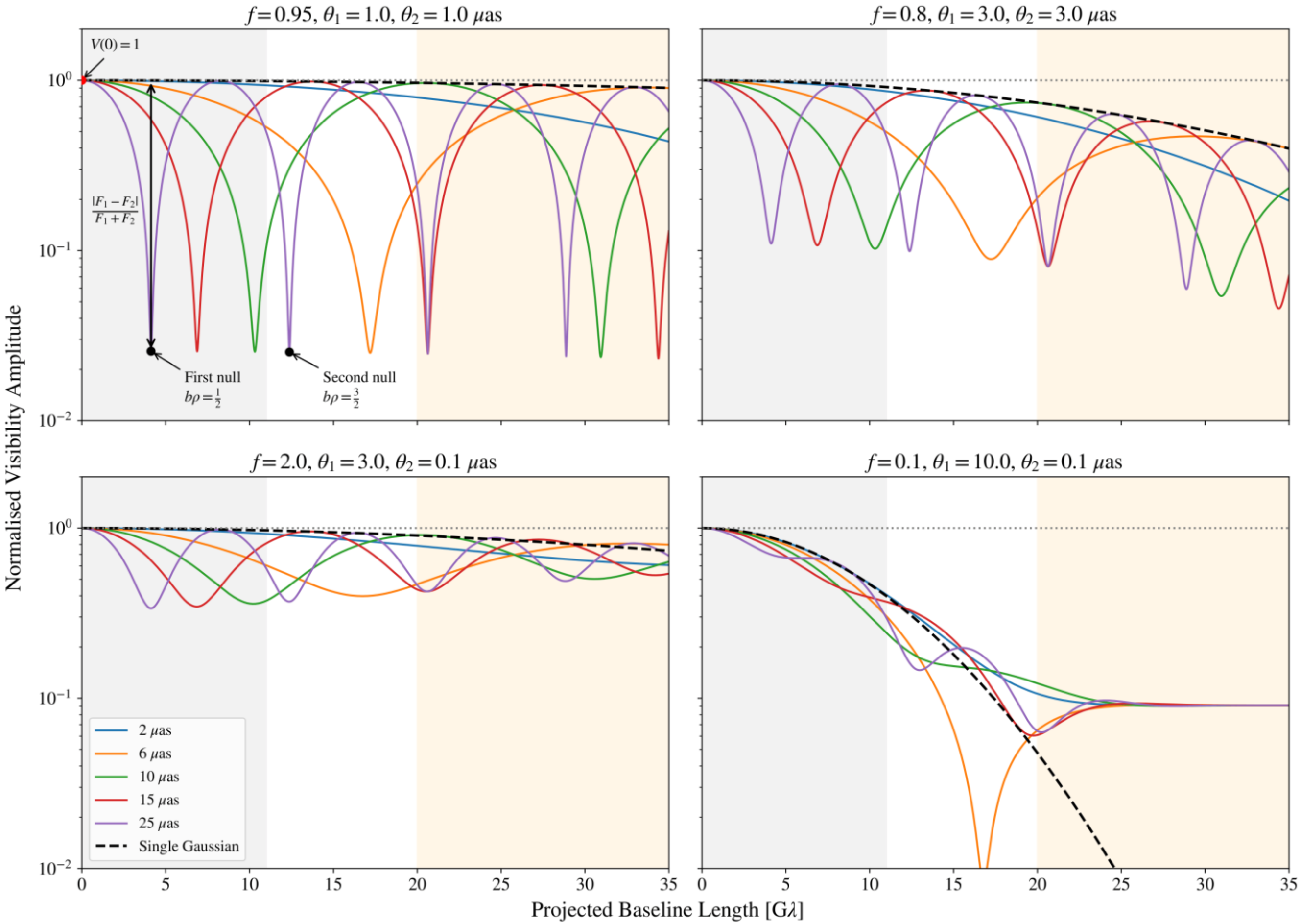
VLBI Binary Signatures

- VLBI samples the complex visibility function of a source
- Binary structure produces characteristic signatures in visibility amplitude

Null spacing → *Binary separation*

Modulation depth → *Flux density ratio*

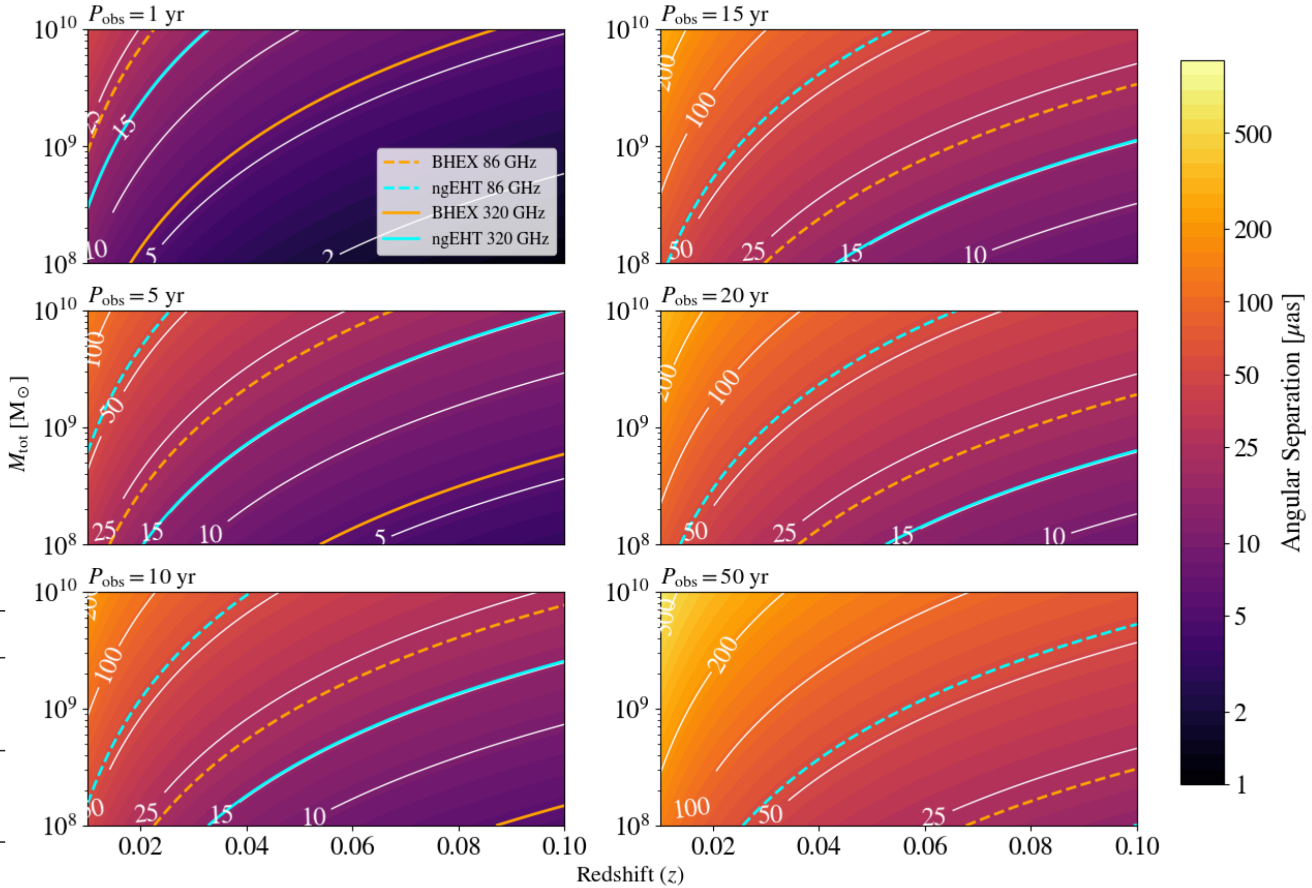
- Binary candidates can be identified without image reconstruction



Angular Resolution

- Requirement: sufficient angular separation
- VLBI can *super-resolve* binary structure below the nominal angular resolution
- Some high-mass systems out to $z \sim 0.1$ within resolution of ground/SVLBI

$M_{\rm tot}$	$P_{\rm obs}$	z	**Separation**
$10^9\ M_\odot$	1 yr	0.025	9.16 μas
		0.100	2.39 μas
	10 yr	0.025	42.50 μas
		0.100	11.08 μas



Detectability - Noise Model

- Consider visibility amplitudes:

  → Conservative as we lose potentially useful phase information

  → Ignore factors affecting phase measurement

Thermal noise

Visibility amplitudes

$$\sigma_j^2 = \sigma_{\mathrm{th},j}^2 + (f_{\mathrm{model}} A_j)^2 + (f_{\mathrm{sys}} A_j)^2$$

Model discrepancy: 10%

Systematic errors: 10%

- Detection requirements:

1. Correlated flux density above SNR of 5 (on at least five baselines)

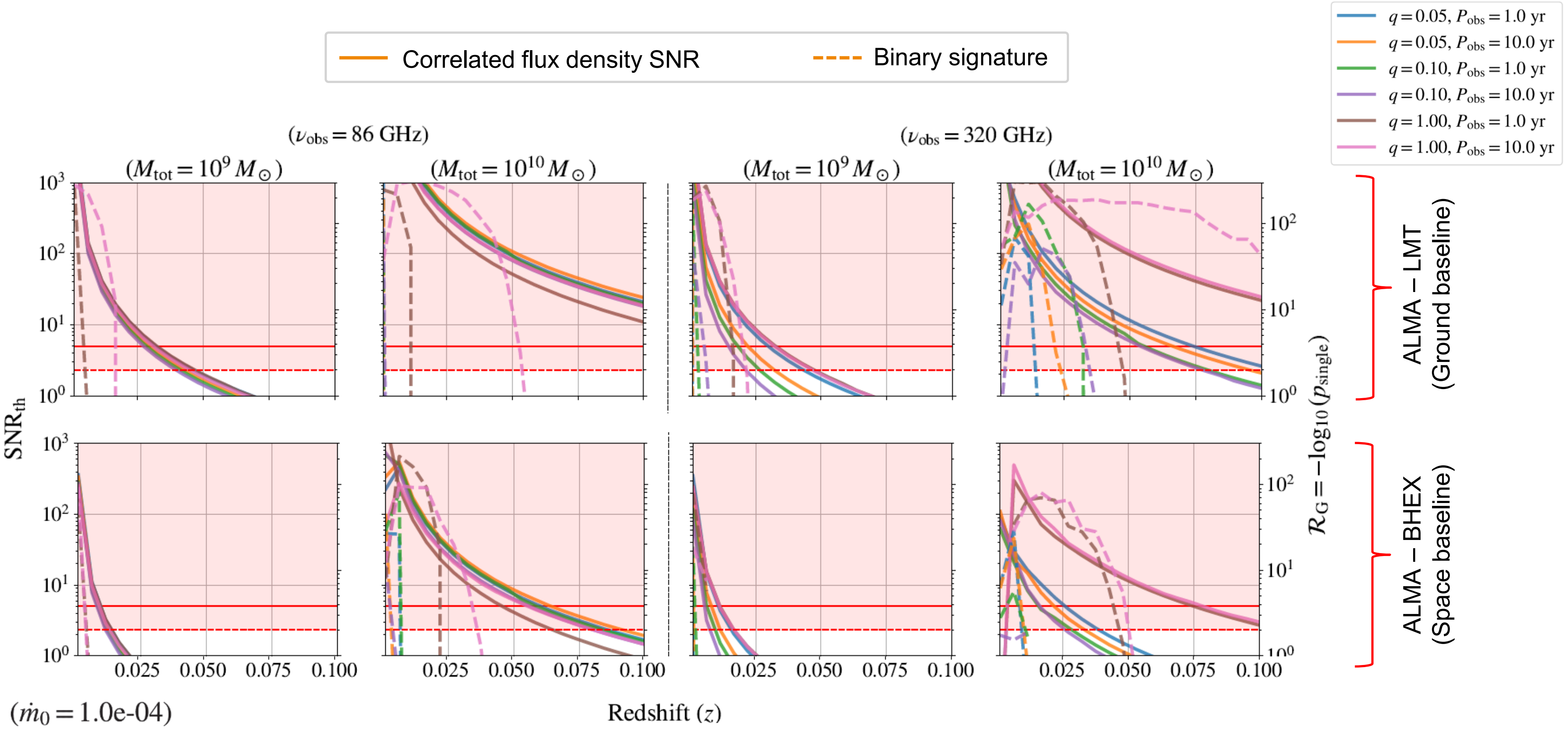
$$\mathrm{SNR}_{\mathrm{th},j} = \frac{|V(u,v)_j|}{\sigma_{\mathrm{th},j}} > 5$$

2. Single Gaussian model can be rejected with >99% confidence

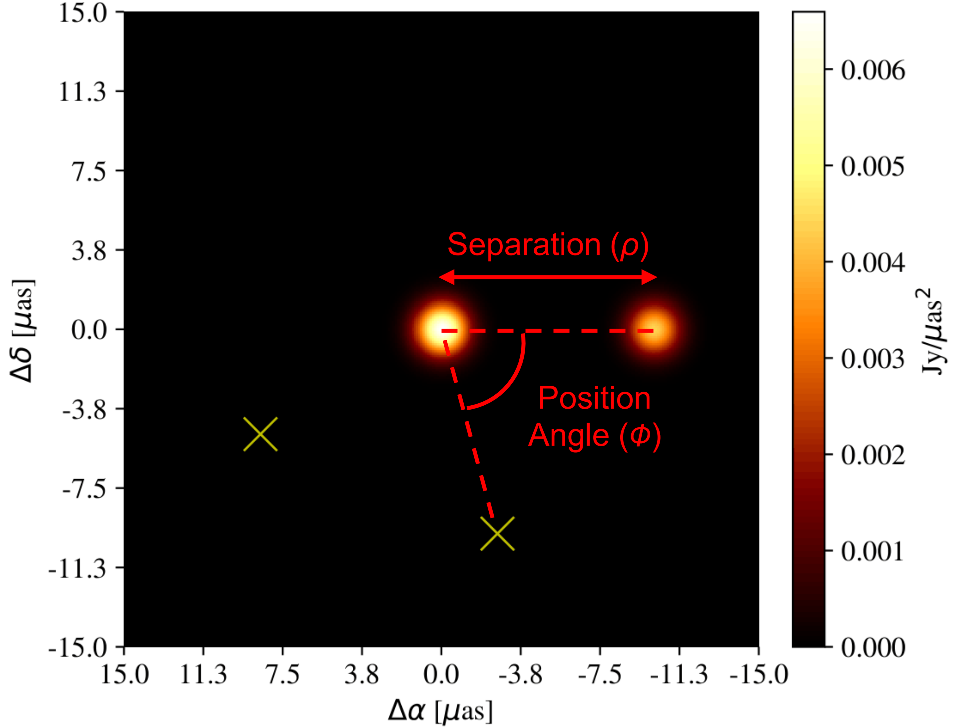
$$p_{\mathrm{single}} = 1 - F_{\chi^2_\nu} < 0.01$$

Single Gaussian best-fit

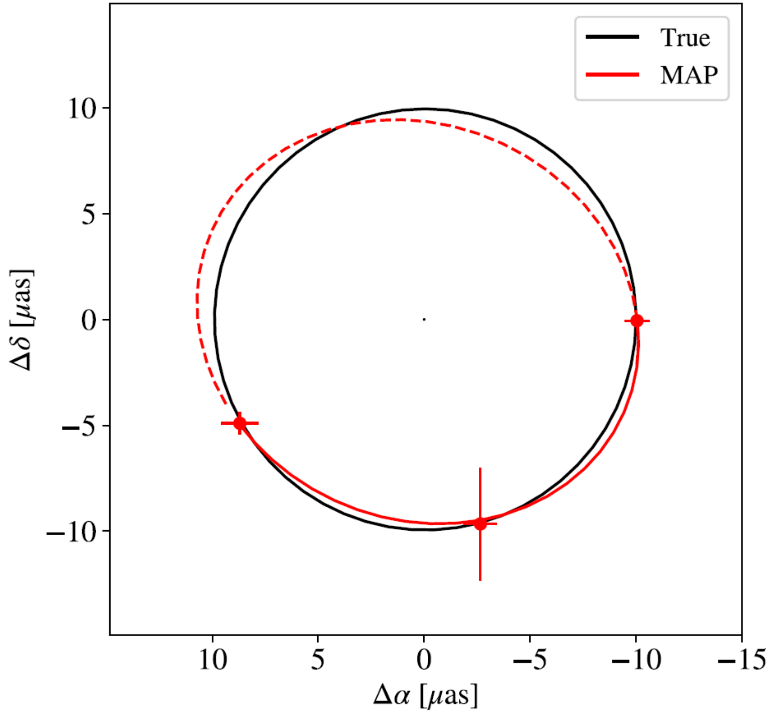
Detectability



Testing Orbital Motion

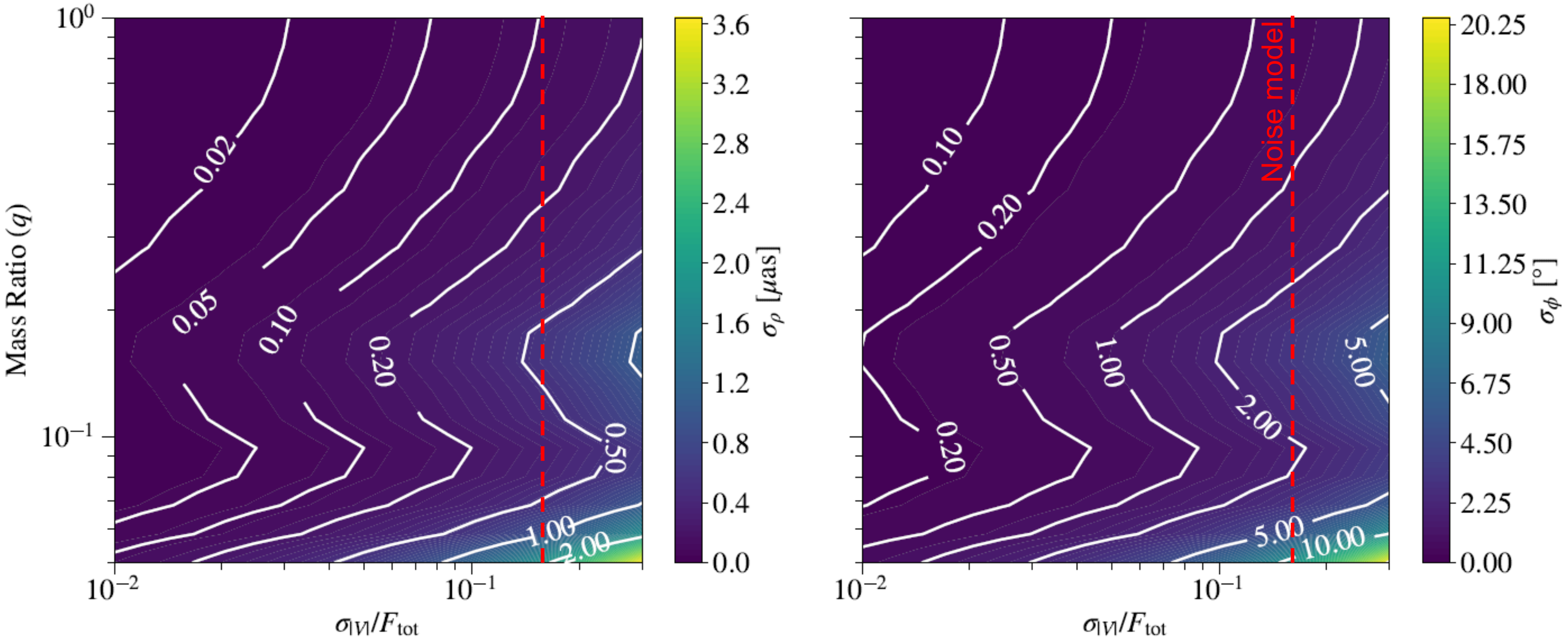


Hudson+ 2026, A&A



BHEX can constrain semi-major axis and eccentricity to within 0.06 dex for P_{obs} < 10 yr

$10^9\ \mathrm{M}_\odot$, 6 μas separation, 45° position angle



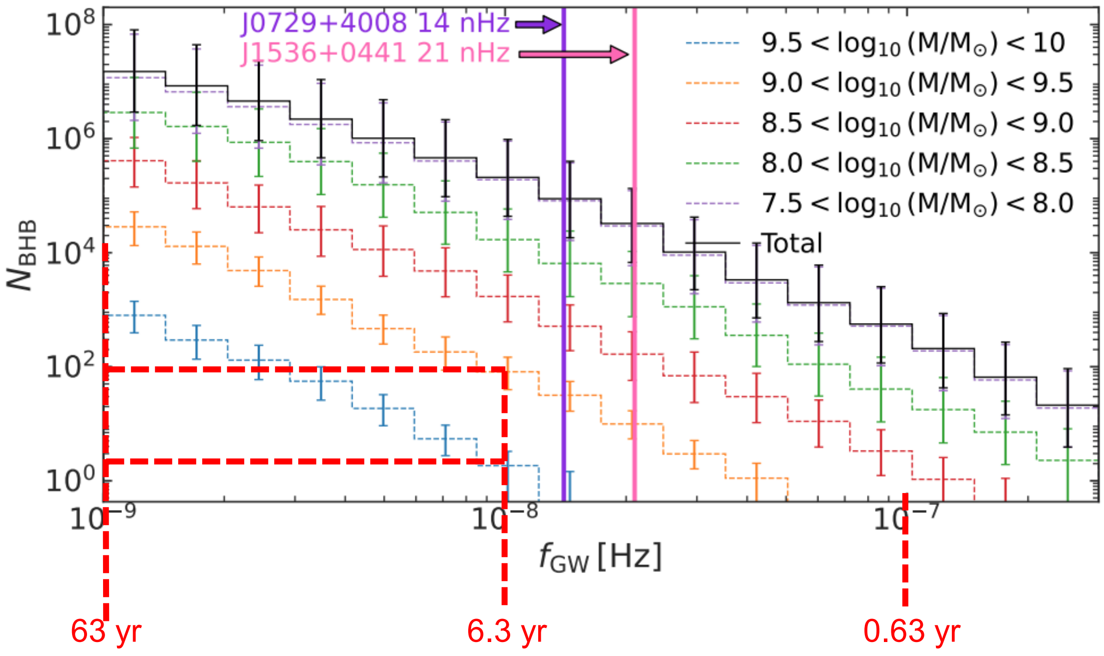
Adding BHEX reduces the uncertainties in separation and position angle by a factor of ~4

PTA Populations

- $10^2 – 10^6$ **systems with** $M_{TOT} > 10^9\ M_\odot$
- **51%** probability of identifying a single GW source in < **10 years** (Veronesi et al. 2026)
- **14%** probability of localisation to a few hundred deg^2
- Likely redshift range: z **= 0.01 – 0.2**
- Likely orbital period: P_{obs} **= 5 – 30 yr**

→ *Overlaps the VLBI parameter space considered here*

Credit: Agarwal+ 2026



Observing Strategy

1. PTA localisation:
Broad sky region

↓

2. EM candidate down-selection:
E.g., ETHER, SED modelling

↓

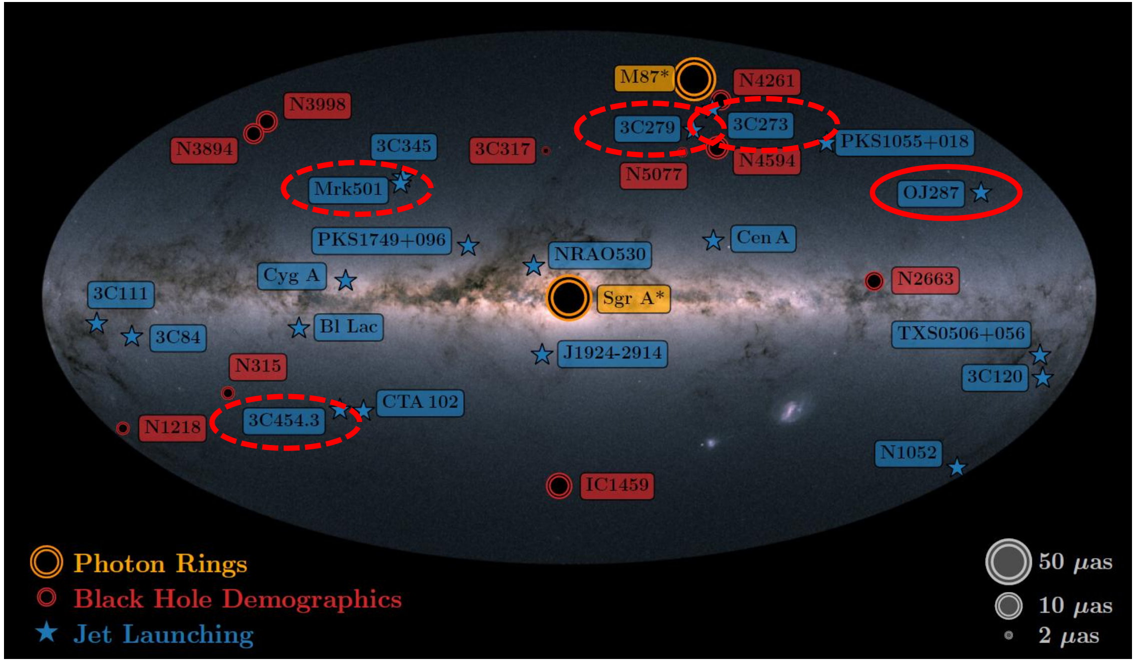
3. Ground mm-VLBI:
Detect compact flux / binary structure

↓

4. SVLBI (BHEX):
Resolve & constrain properties

↓

5. Multi-epoch monitoring:
Test orbital motion



Credit: BHEX AGN and Demographics Teams
Demographic sample from ETHER (see Zhang+)

Conclusions & Next Steps

- Conclusions:

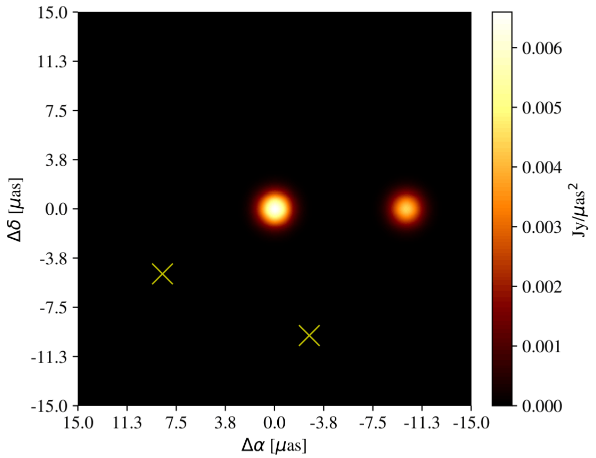
a) SMBHBs with $M_{tot} \geq 10^9 M_\odot$ detectable out to $z \sim 0.1$ (depending on mass ratio)

b) For a flux-density-limited population, ground VLBI probes a larger detectable population than BHEX

c) SVLBI substantially improves binary characterisation once a candidate is detected

- Next steps:

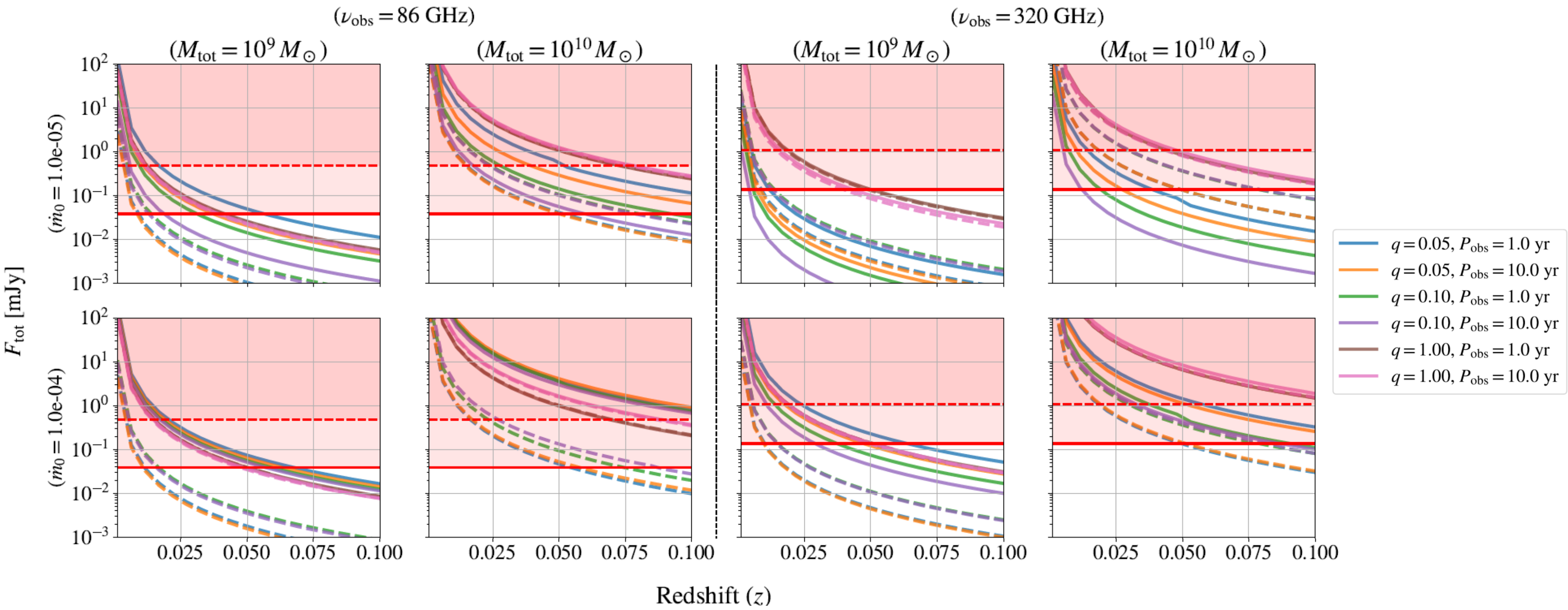
1. Population estimate updates – using new SED model and GW background
2. Candidate source identification
3. Future spaceborne VLBI



Hudson et al. 2026, PASP BHEX Special Issue

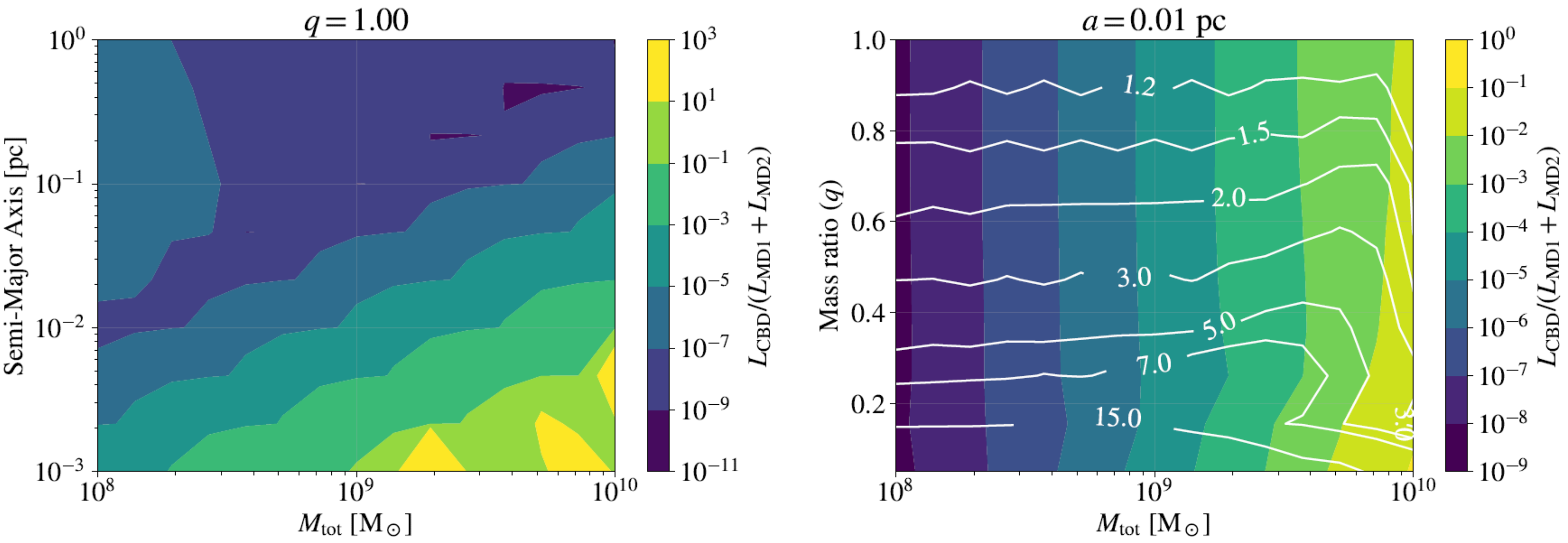
Backup Slides

Total Flux Density

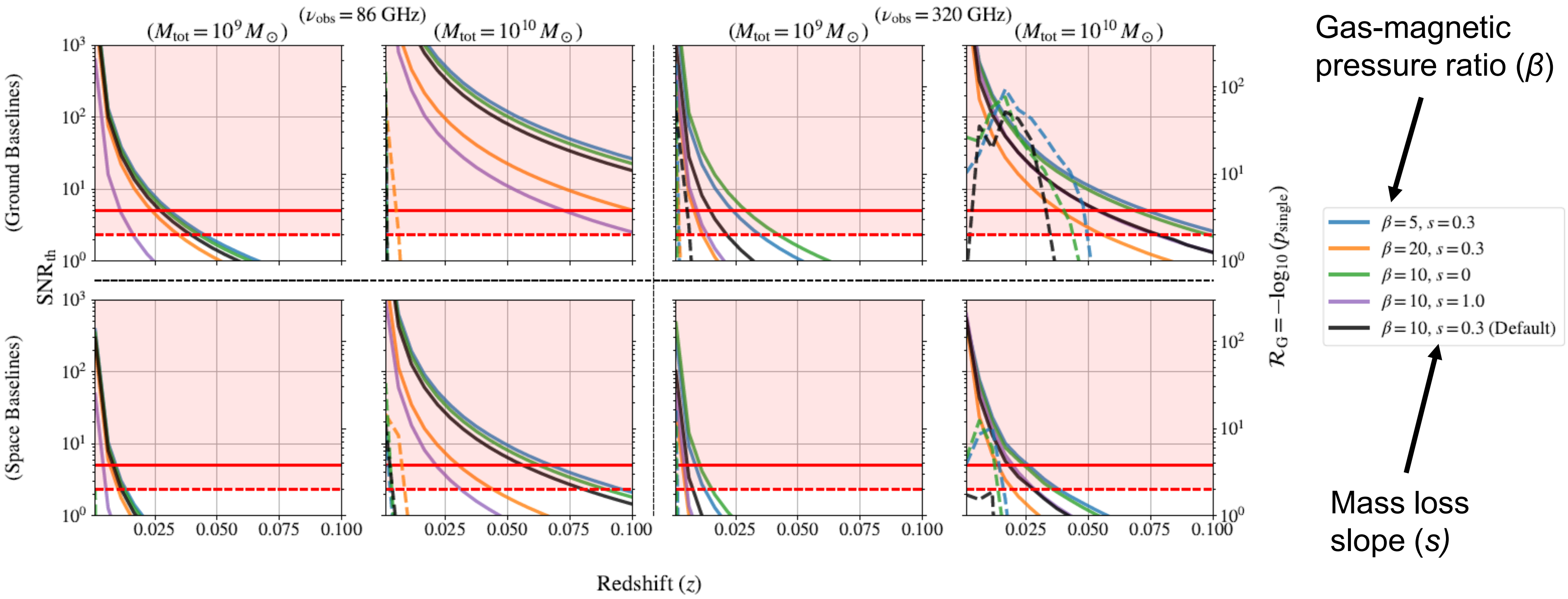


—/-- Primary / secondary black hole's F_{TOT} — ALMA – LMT thermal noise - - - ALMA – BHEX thermal noise

Circumbinary Disc Emission?



Sensitivity to Model Parameters

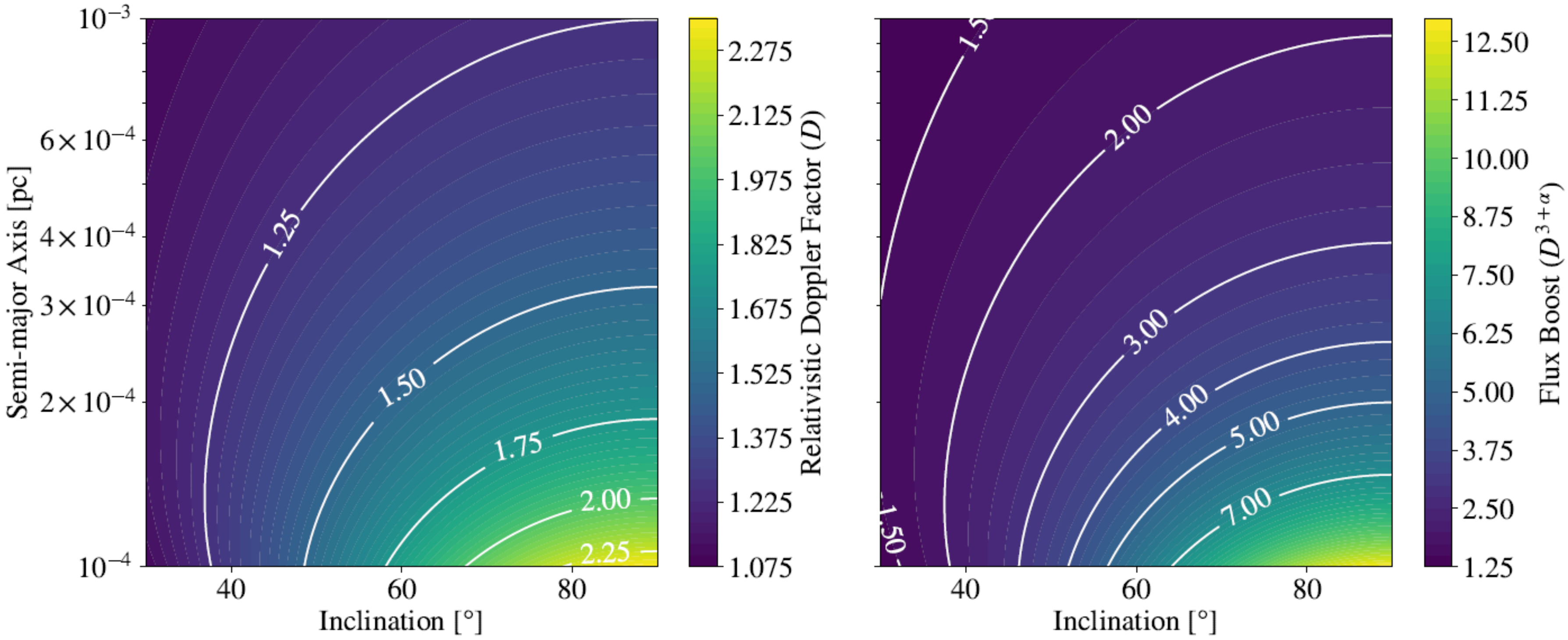


Gas-magnetic pressure ratio (β)

Mass loss slope (s)

Inclination Effects

$10^9\ M_\odot$, α = 0 (flat radio core)



System Characterisation: Fisher Analysis

- How well can binary separation (ρ) and position angle (ϕ) be constrained?

- Assumptions:
1. Common measurement noise ($\sigma^2_{|V|}$) across baselines (assume average 5 mJy)
2. 12 observations-per-night, across 4 nights (7 ground locations + BHEX)

- Validity test: ρ and ϕ uncertainties within ~10% of results from *ngehtsim* simulation of BHEX observations of same binary system

No. of scans

Baseline length & angle

Relative Phase

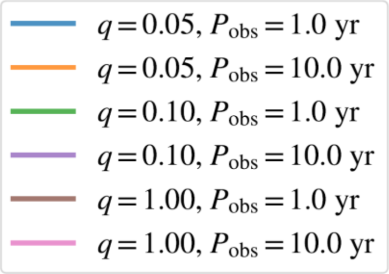
$$F_{\rho\rho} = \frac{1}{\sigma^2_{|V|}} \sum_{k=1}^{N} \left[\frac{A_{1,k} A_{2,k}}{|V_k|} \right]^2 \left[2\pi b_k \cos(\gamma_k - \phi) \right]^2 \sin^2 \psi_k$$

$$\mathbf{F}_{\rho\phi} = \begin{pmatrix} F_{\rho\rho} & F_{\rho\phi} \\ F_{\phi\rho} & F_{\phi\phi} \end{pmatrix}$$

$$\sigma_\rho = \sqrt{\frac{F_{\phi\phi}}{F_{\rho\rho} F_{\phi\phi} - F^2_{\rho\phi}}}$$

$$\sigma_\phi = \sqrt{\frac{F_{\rho\rho}}{F_{\rho\rho} F_{\phi\phi} - F^2_{\rho\phi}}}$$

Total Flux Density

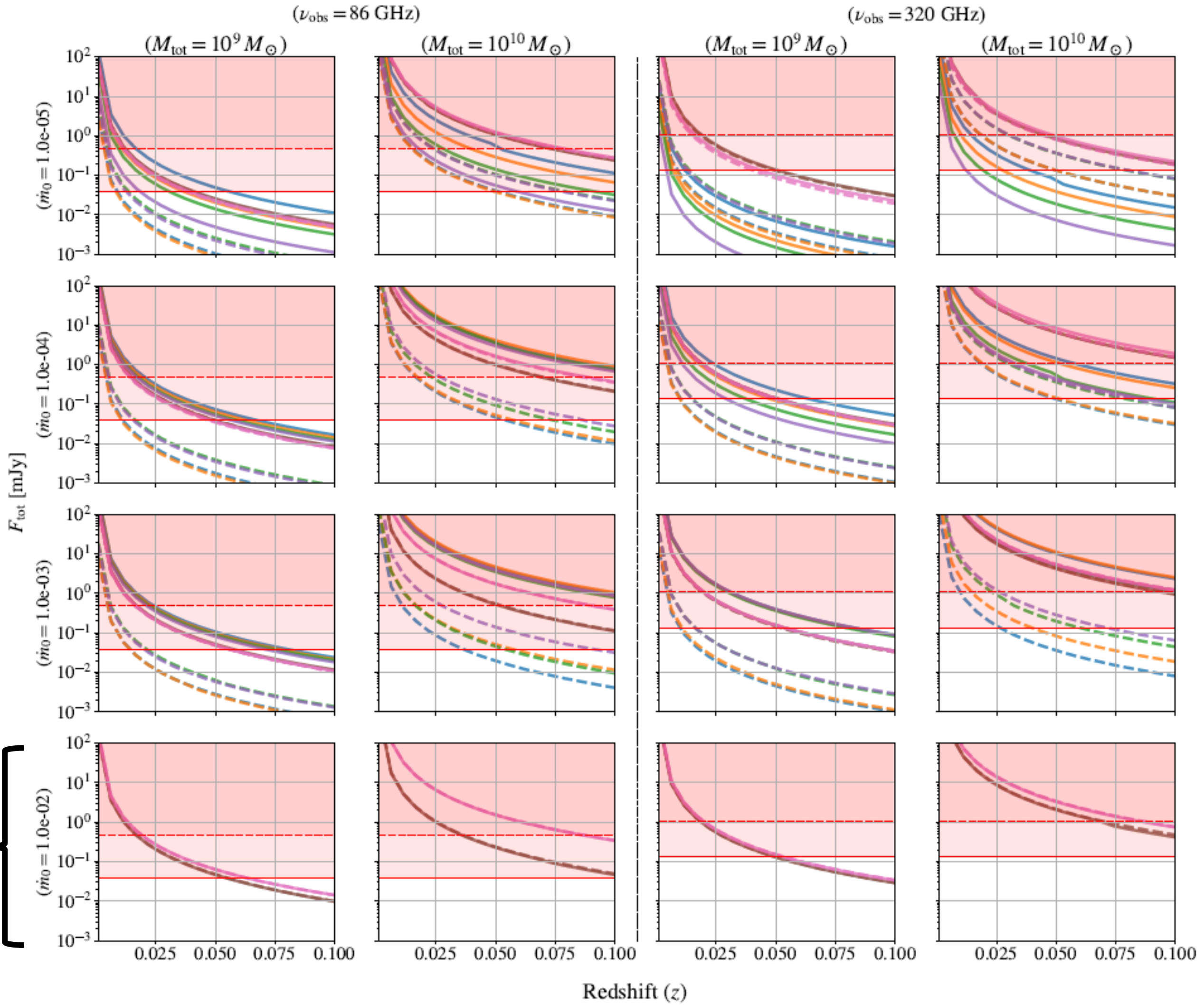


(*Solid/Dashed Lines*) Primary / secondary black hole's $F_{\rm TOT}$

(*Solid red)* ALMA – LMT thermal noise

(*Dashed red)* ALMA – BHEX thermal noise

Accretion solutions at low *q* enter regime III (one hot, one cold disc)



Detectability

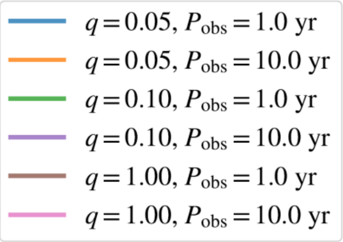
- Requirements for detection:

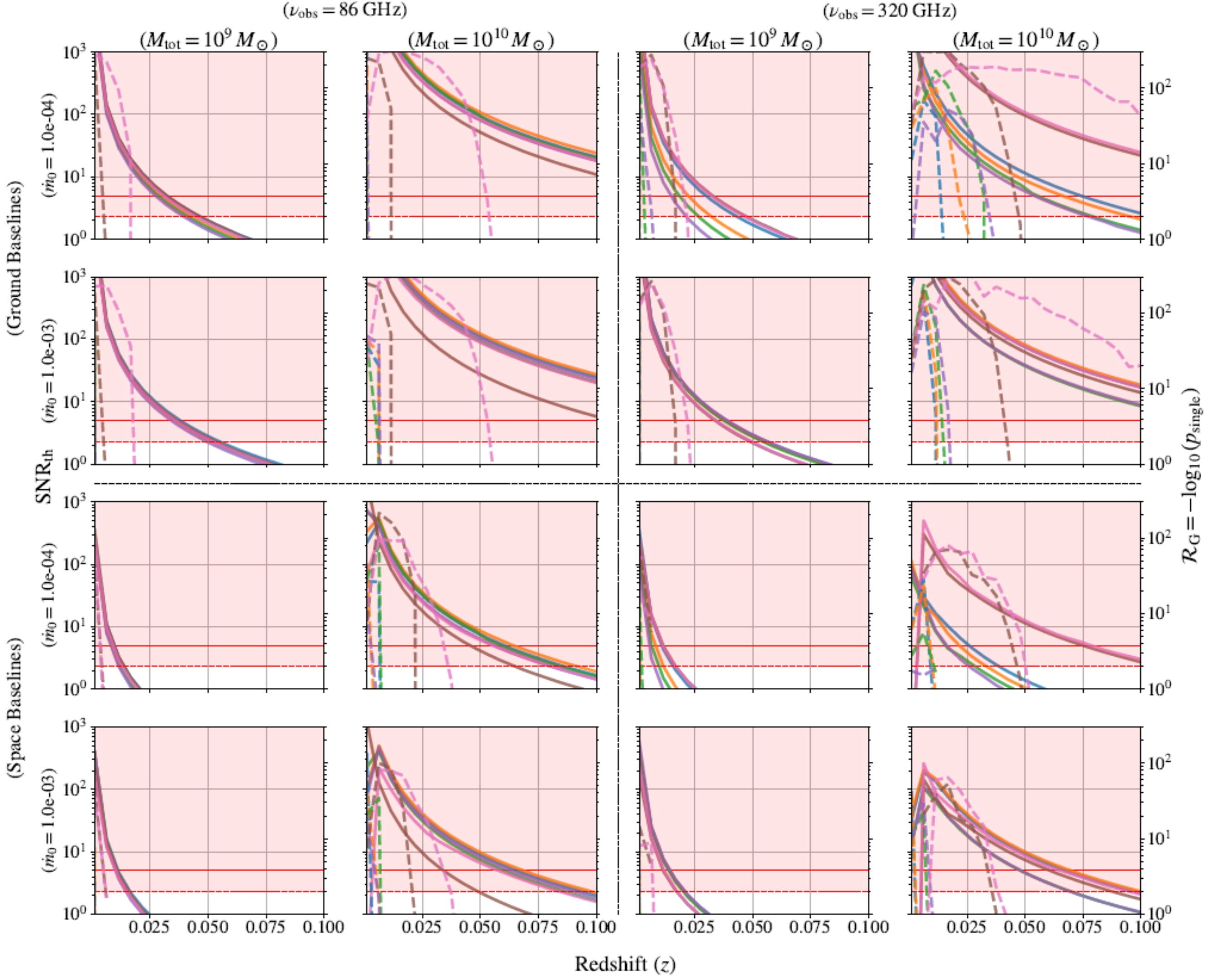
1. (*Solid lines*) Correlated flux density detected above thermal noise

$$\mathrm{SNR}_{\mathrm{th},j} > 5$$

2. (*Dashed lines*) Binary signature is distinguishable from single Gaussian model

$$p_{\mathrm{single}} < 0.01$$





Ground baseline: LMT & ALMA

Space baseline: BHEX & ALMA