


# Constraining black hole formation with VLBI astrometry

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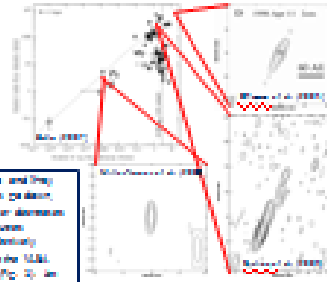
## Constraining black hole formation with VLBI astrometry

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### Hard and quiescent black hole X-ray binaries

- Produce compact, steady flat-spectrum jets
- Radio and X-ray emission correlated as  $L_{\text{radio}} \propto L_{\text{X}}^{0.7}$
- Quiescent radio jets unresolved on VLBI scales
- Persistent (at least faint), compact sources
- Ideal astrometric targets

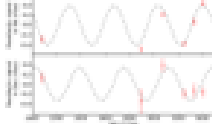


In the radio and X-ray luminosities, galactic (or galactic distance) and the sources become effectively similar under M82. **Figure 1: An example with 1.**


**Fig. 1 Radio/X-ray correlation in BH**

### The parallax of a stellar-mass black hole

- V404 Cyg: most luminous quiescent stellar-mass BH
- 0.3 mJy (unresolved) radio source
- 2 Jy (Eddington) only 16 arcmin away
- 3 Galactic epochs + 30000 epochs
- VERA + GMRT phased VLA, 512 Mbps recording



**Fig. 2 Parallax signal in V404 Cyg**




**Fig. 3 Measured parallaxes with VERA Cyg**

### Distances to X-ray binaries

- Distances typically uncertain to 50% or more
- Accurate distances needed to get true luminosities

**Implications:**

- Given horizon: Black hole quiescent luminosities are systematically lower than neutron star luminosities at the same orbital period (a good proxy for mass accretion rate), providing evidence for advection through an event horizon in black hole systems (Fig. 3)
- Nature of ULXs: Quantifying the peak accretion luminosity of stellar mass black holes and the factor by which they can exceed  $L_{\text{Edd}}$  will determine whether ULXs can be explained by super-Eddington stellar-mass black holes, or whether intermediate-mass black holes are required
- Black hole spin: Efforts to measure black hole spin, based on fitting the X-ray spectra of black holes in the thermal-dominant state during outbursts, require good distance estimates to get accurate results
- Neutron stars: Accurate distances to neutron star systems with (Eddington-limited) Type IX-ray/bursts will improve radial determinations, constraining NS equation of state. One candidate NS system identified to date.



**Fig. 4 Variation of BH and NS quiescent luminosities with orbital period (V404 Cyg circled in red)**

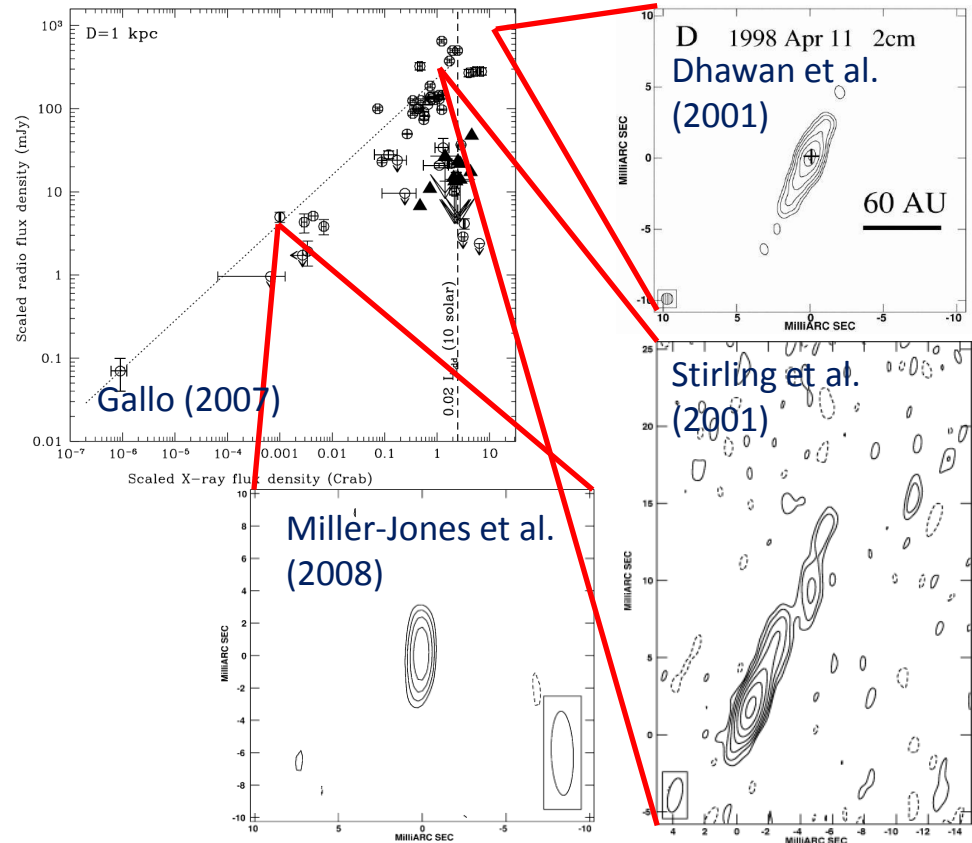
### Black hole proper motions

- 5 black holes with measured proper motions to date
- Highest-mass BH show smallest peculiar velocities
- Most massive BH form by direct collapse (no SN)
- Low-massive black holes form via fallback or proto-neutron star in a supernova explosion
- Increase sample size to provide observational constraints on SN mass cut-off in black hole formation
- 4 additional candidate BH sources identified thus far

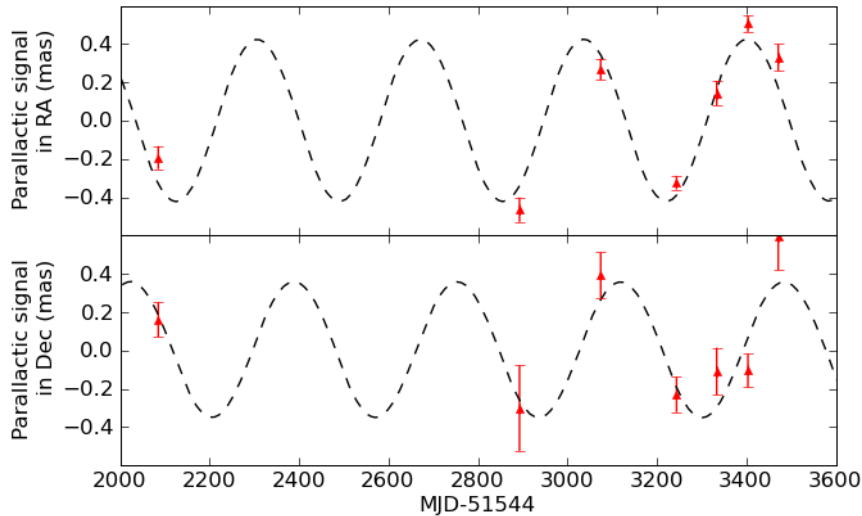
Name	Site (GHz)	$\mu_{\alpha}$ (mas/yr)	$\mu_{\delta}$ (mas/yr)	Proper motion (mas/yr)	Reference
3C 220.6	220.6	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	Chaloun et al. (2005)
3C 220.6	220.6	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	Chaloun et al. (2005)
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# X-ray binary astrometry

- Hard state/quiescent sources pointlike, persistent radio emitters => ideal astrometric targets
- Distances typically uncertain to 50%
- Distances needed for:
  - Accurate luminosities
    - Event horizons
    - ULXs
  - Fitting BH spin



# A parallax to a stellar-mass black hole



- Brightest BHXB in quiescence
- 0.3mJy radio source
- Parallax and proper motion
- Closer than found by other, model-dependent methods

- Reconstruct full 3D space velocity, Galactocentric orbit
- Peculiar velocity gives constraints on natal kick
- Sample of BH kicks to probe BH formation

