The proper motion and parallax of a black hole X-ray binary

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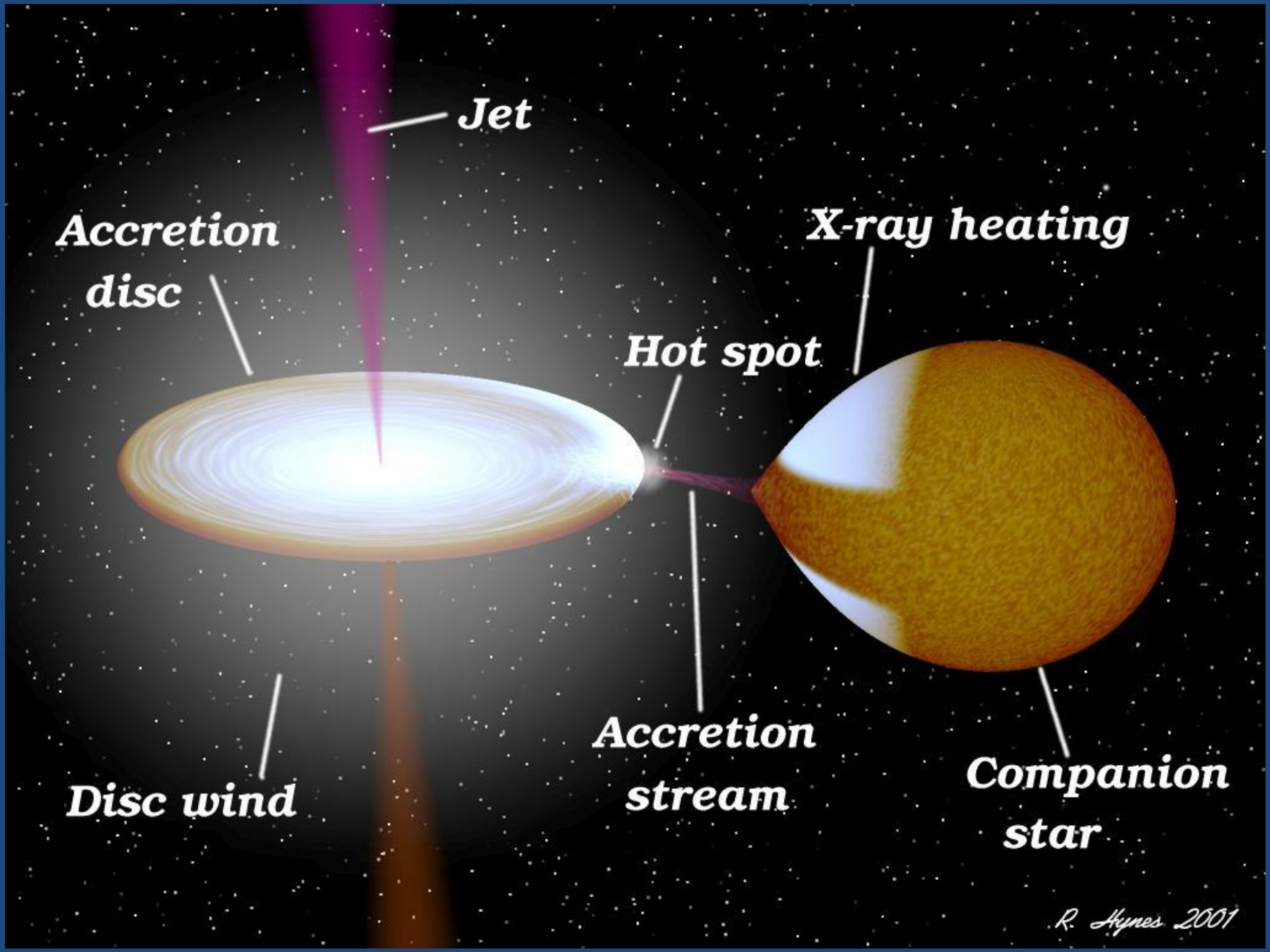
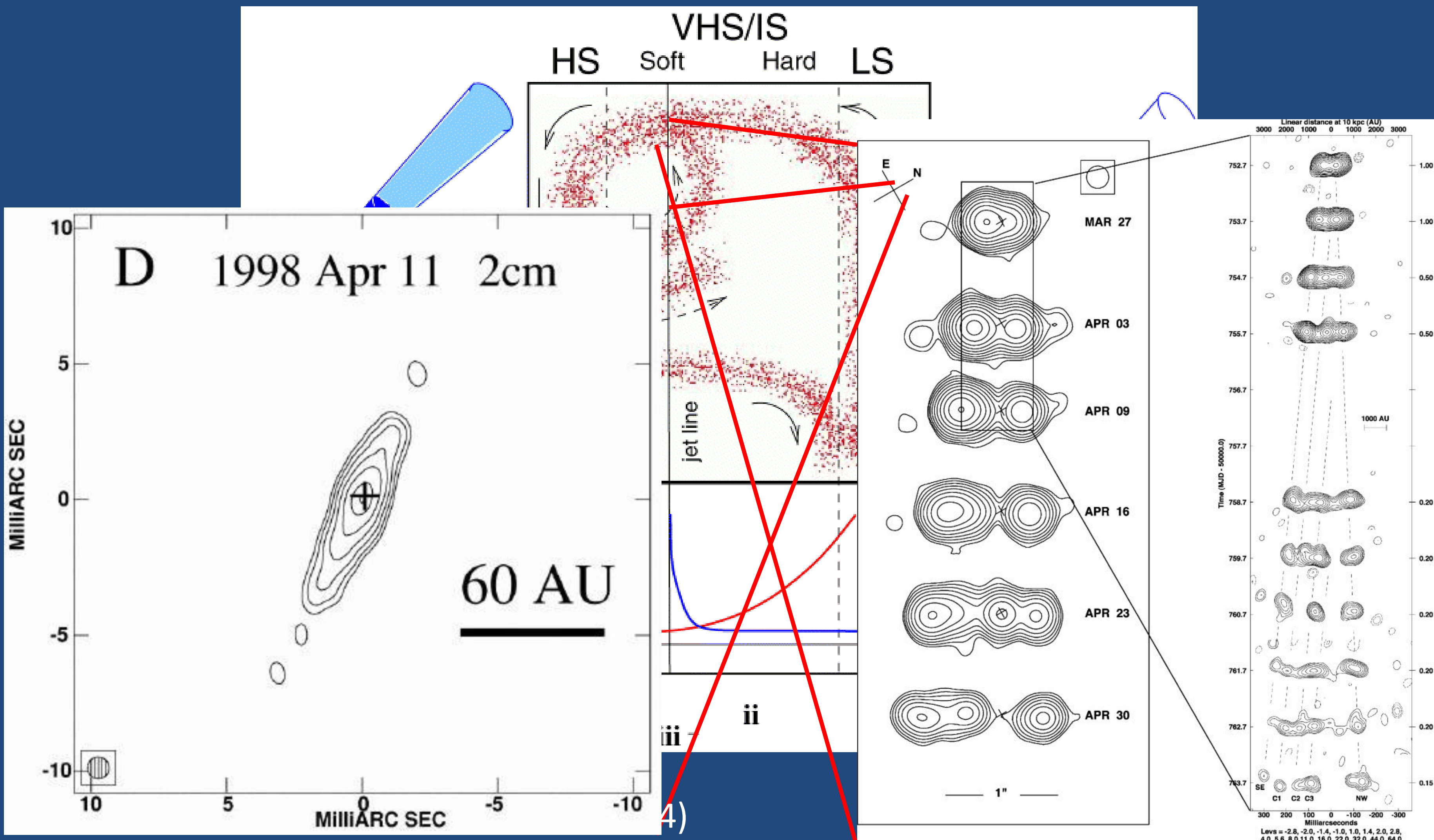
X-ray binary systems

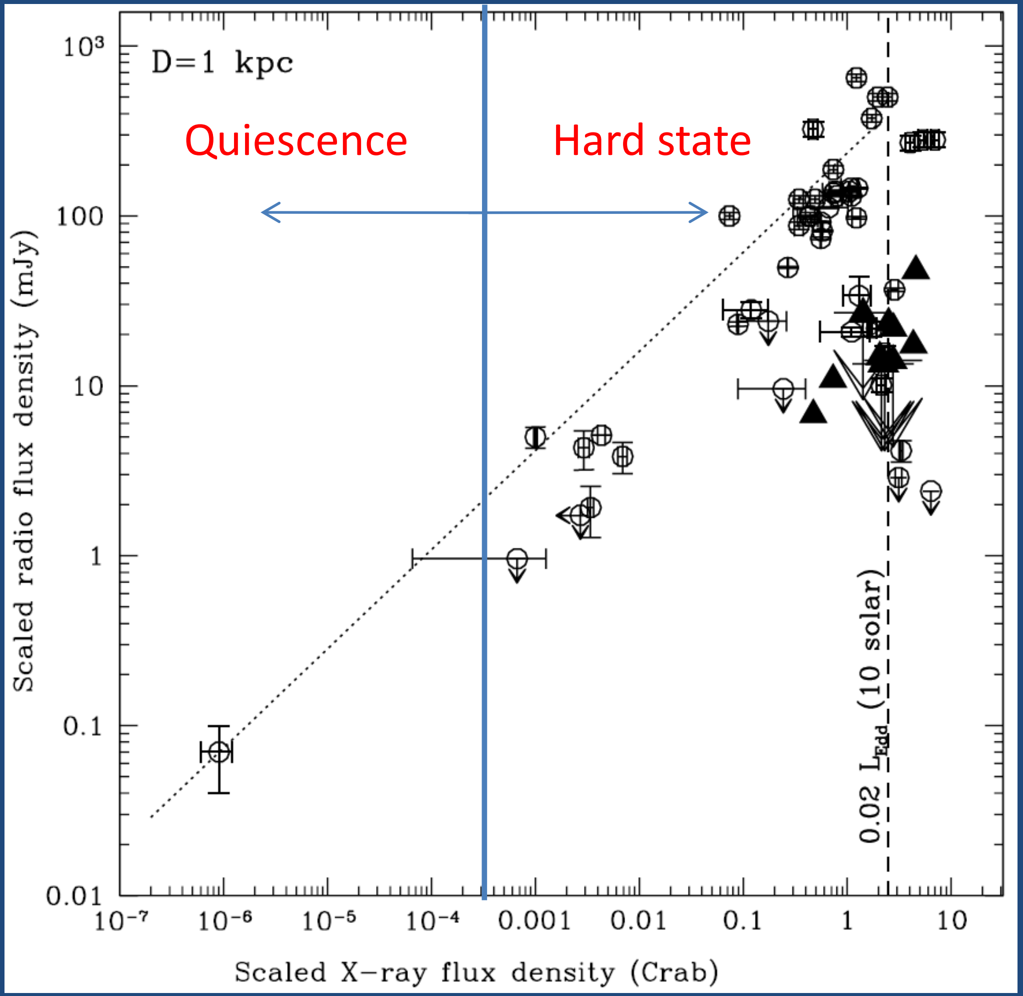


State diagram for black holes (aka “the turtle head”)



Quiescent BH systems

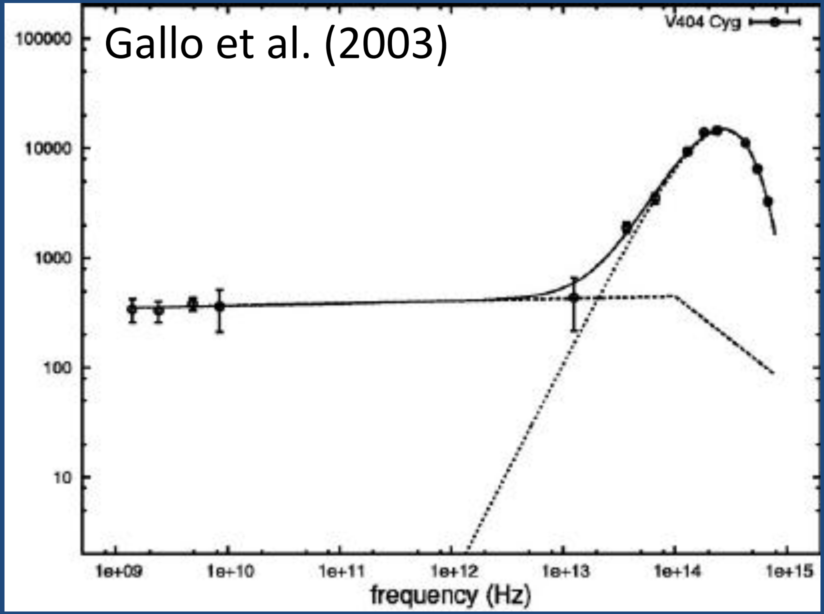
- $L_x < 10^{33.5}$ erg/s ($L_x/L_{Edd} < 10^{-5.5}$)
- Advantages of quiescent systems:
  - Persistent sources
  - No confusing structure



Gallo (2007)

Proof of concept: V404 Cyg

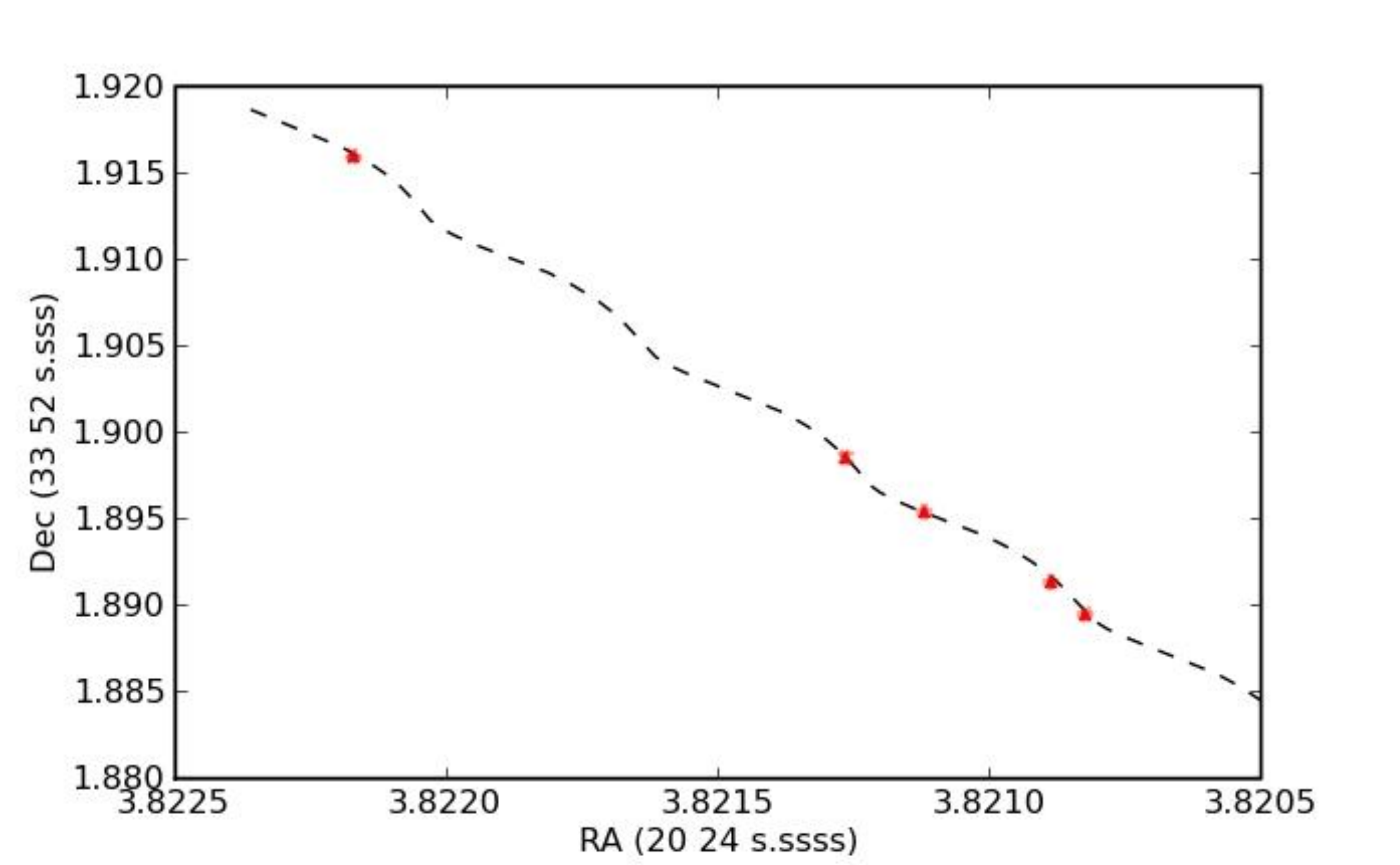
- Most luminous black hole XRB in quiescence
- High mass function: f(M) = 6.08 ± 0.06 M_0
- Black hole + K0 subgiant
- M_{BH} = 12 ± 2 M_0
- M_d = 0.7 ± 0.2 M_0
- P_{orb} = 6.5 d
- Radio properties:
  - Flat spectrum (0.3mJy)
  - Unresolved in quiescence



An accurate distance

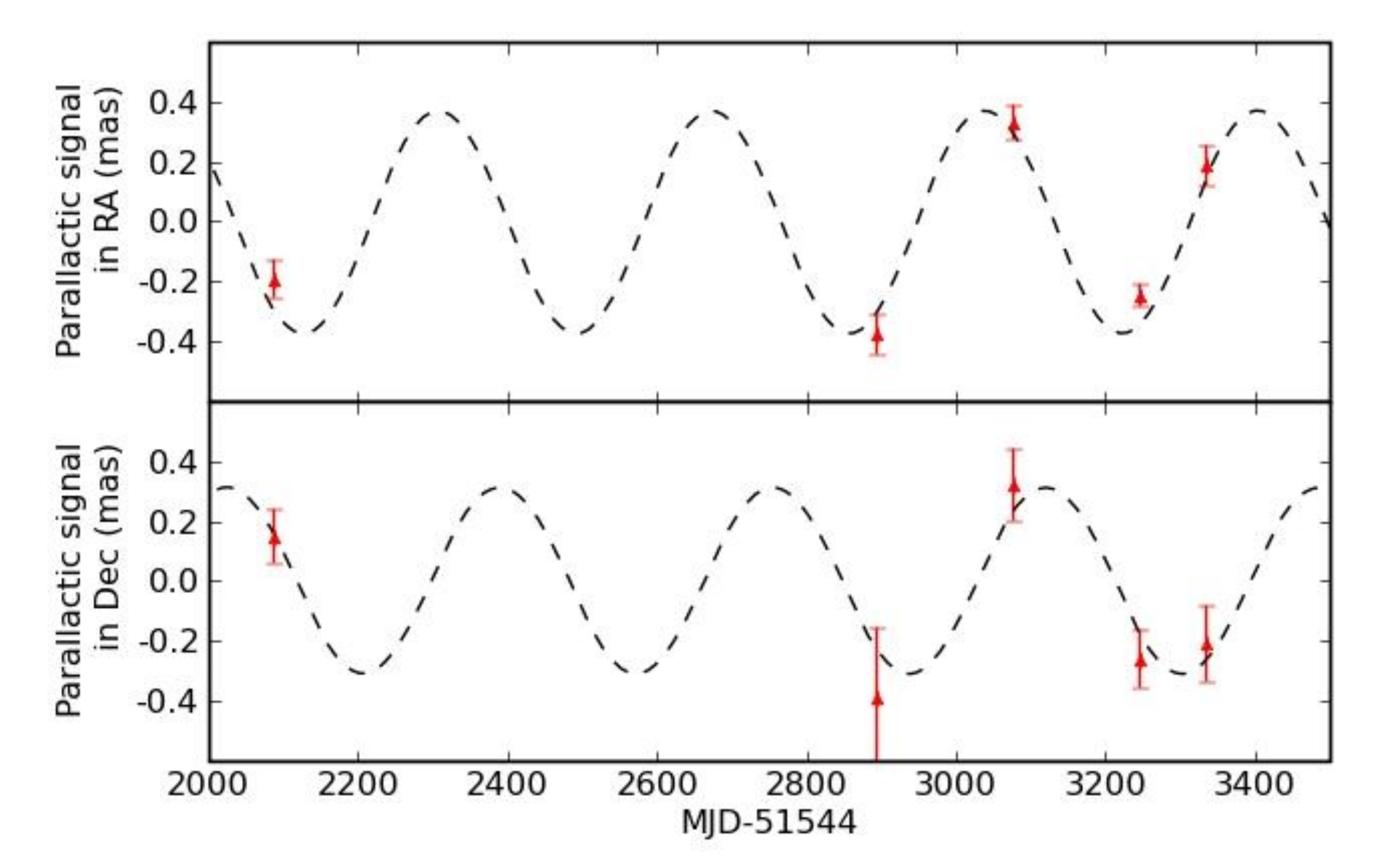
- Distance is fundamental
- Trigonometric parallax is the ONLY model-independent method of distance estimation
- V404 Cyg: $d = 4^{+2}_{-1.2}$ kpc
- 5 HSA epochs to measure a parallax
  – VLBA+GBT (+phased VLA)
  – November 2008 – November 2009
  – First two epochs taken and reduced
  – Three archival datasets

A parallactic distance



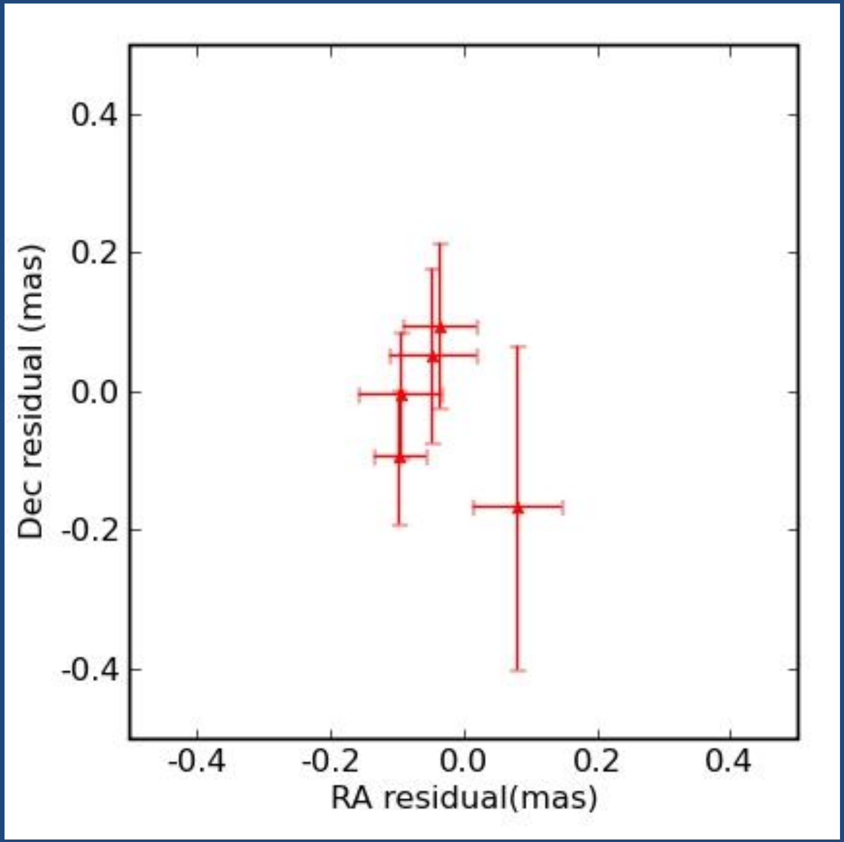
- $\mu_{\alpha} \cos \delta$ = -5.03 ± 0.03 mas/yr
- μ_{δ} = -7.62 ± 0.04 mas/yr

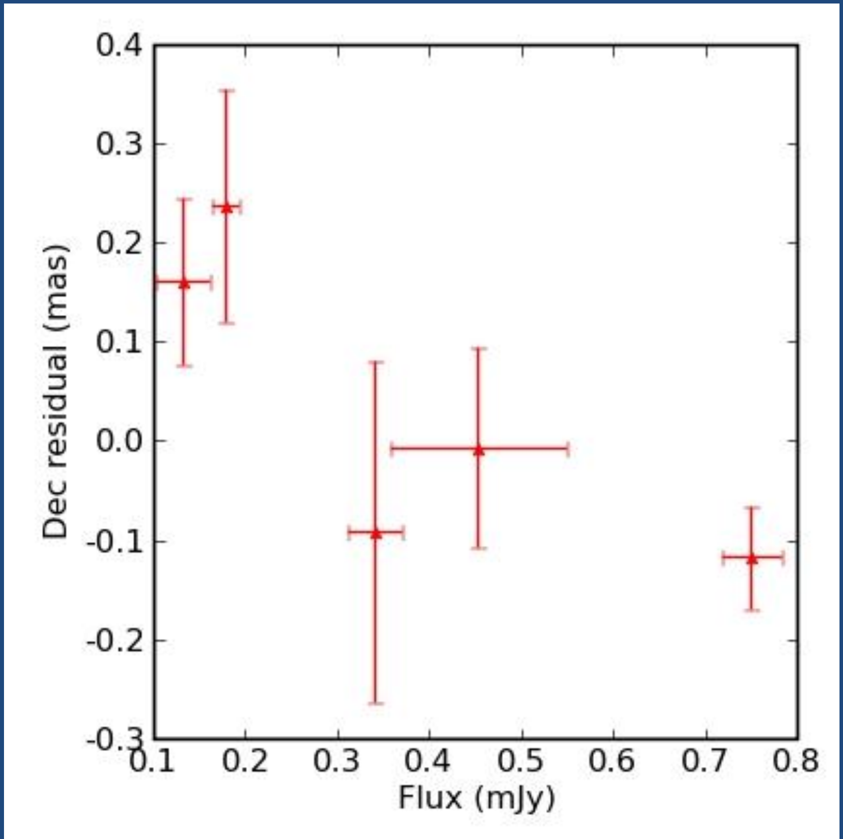
A parallactic distance



- d = 2.69 ± 0.27 kpc

Residuals

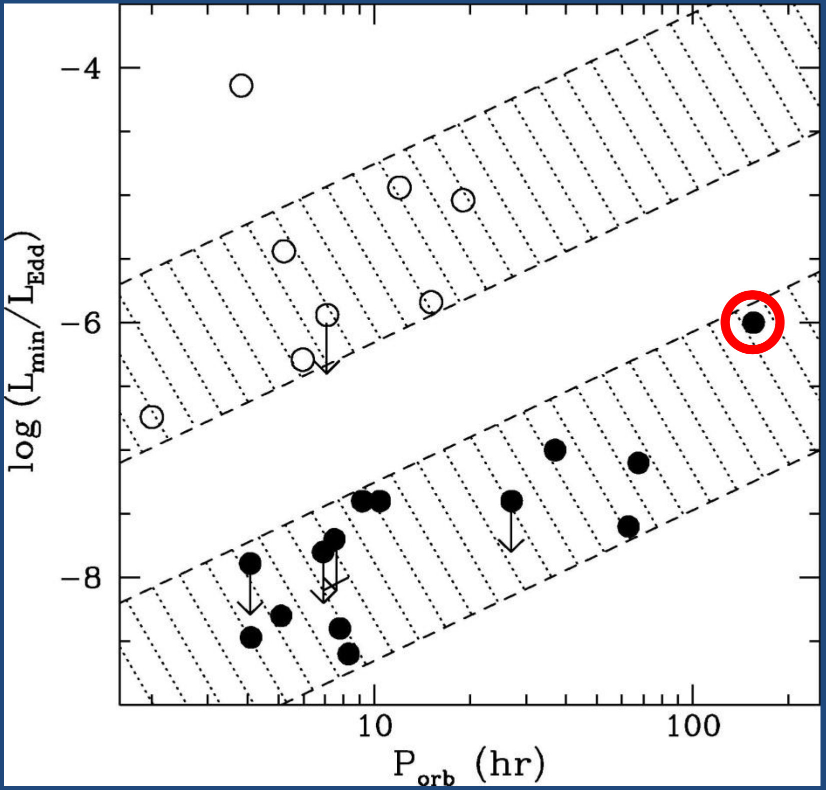




- Residuals appear to line up along a preferred axis
- Offset is greater when source is brighter

Implications of an accurate distance: I. Event horizons

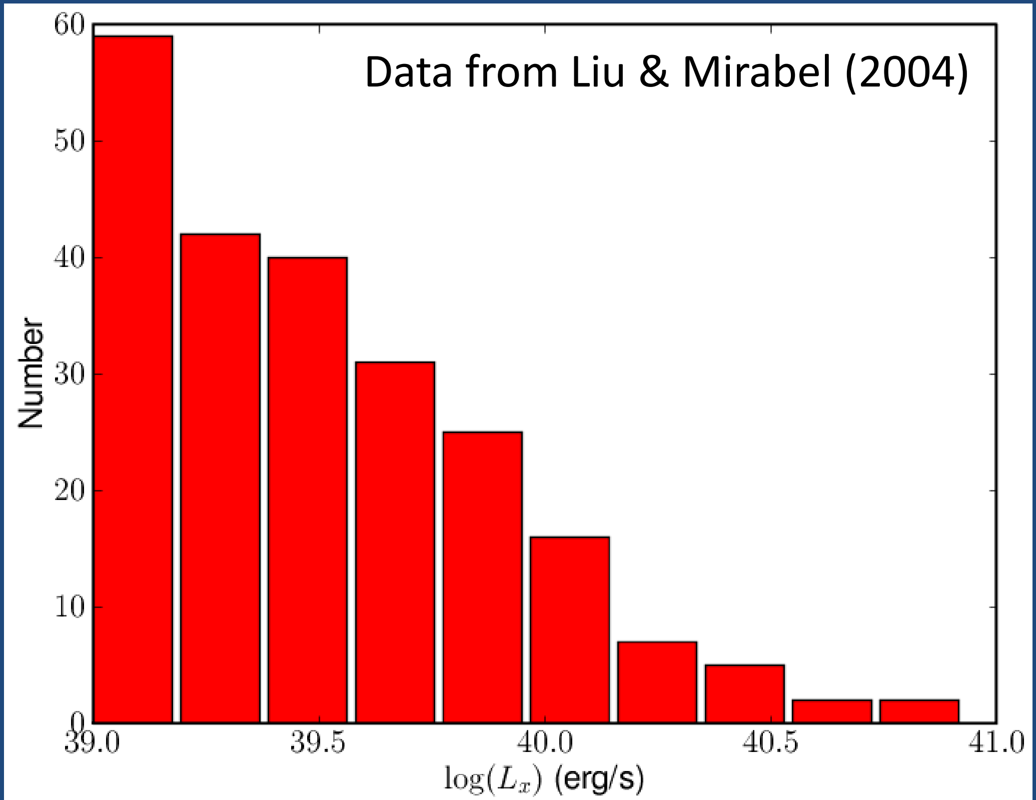
- Quiescent BH fainter than NS
- Energy advected through event horizon
- Compare at same $\dot{M}$
- *d* needed for accurate *L*



Narayan & McClintock (2008)

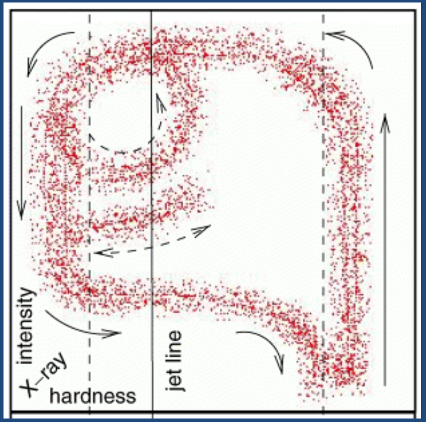
Implications of an accurate distance: II. Nature of ULXs

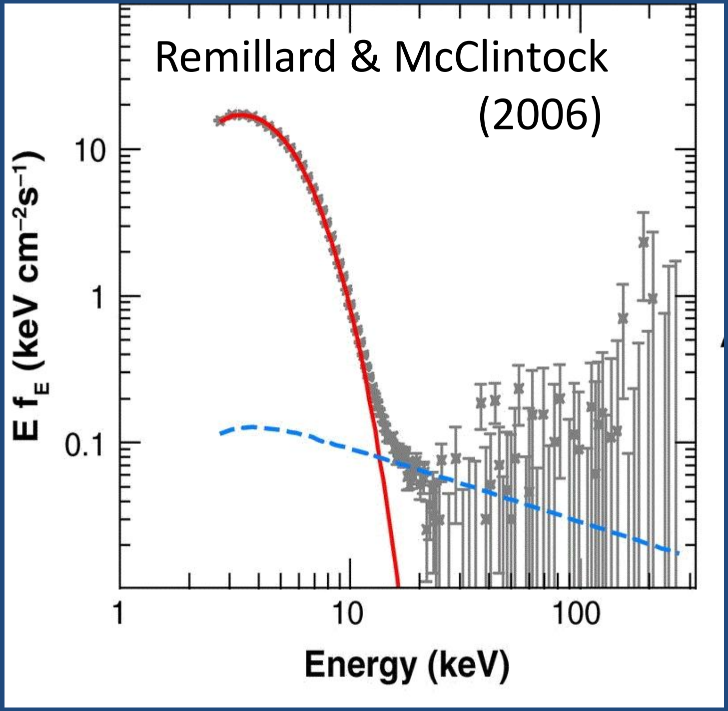
- Maximum luminosity in outburst
- V404: $L_x = 5.6 \times 10^{38}$ erg/s (1-40 keV) = 0.4 L_{Edd}
- No longer a ULX

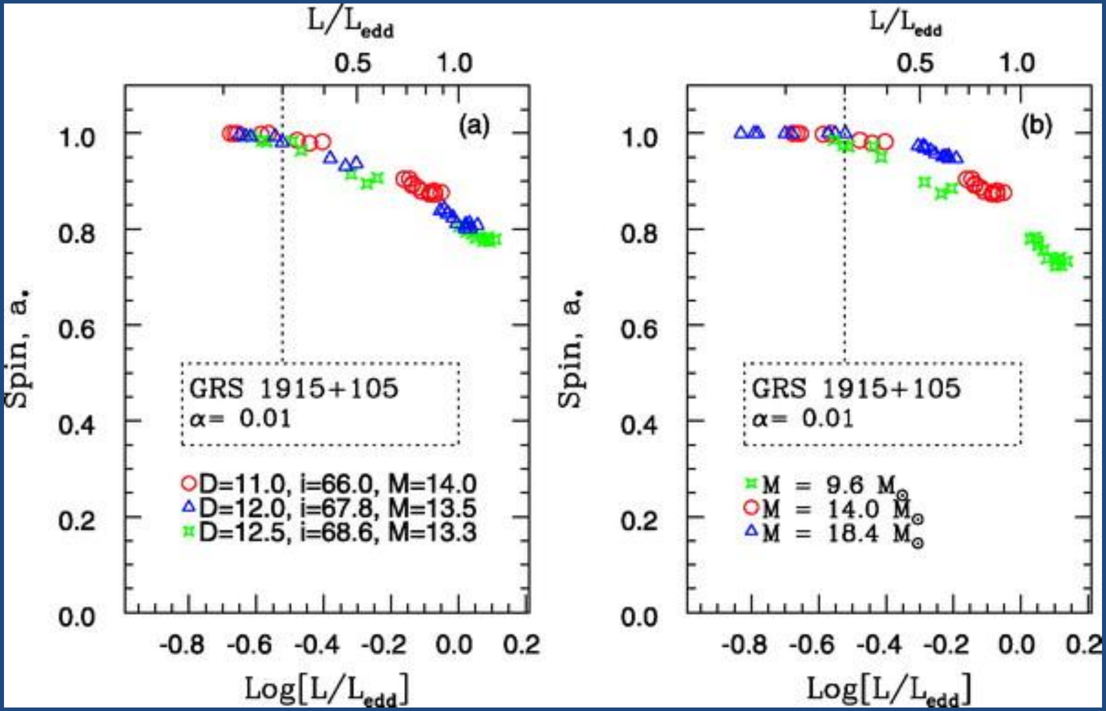


Implications of an accurate distance: III. BH spin

- Fit thermal dominant (soft) state
- M_{BH}, *i*, *d* required





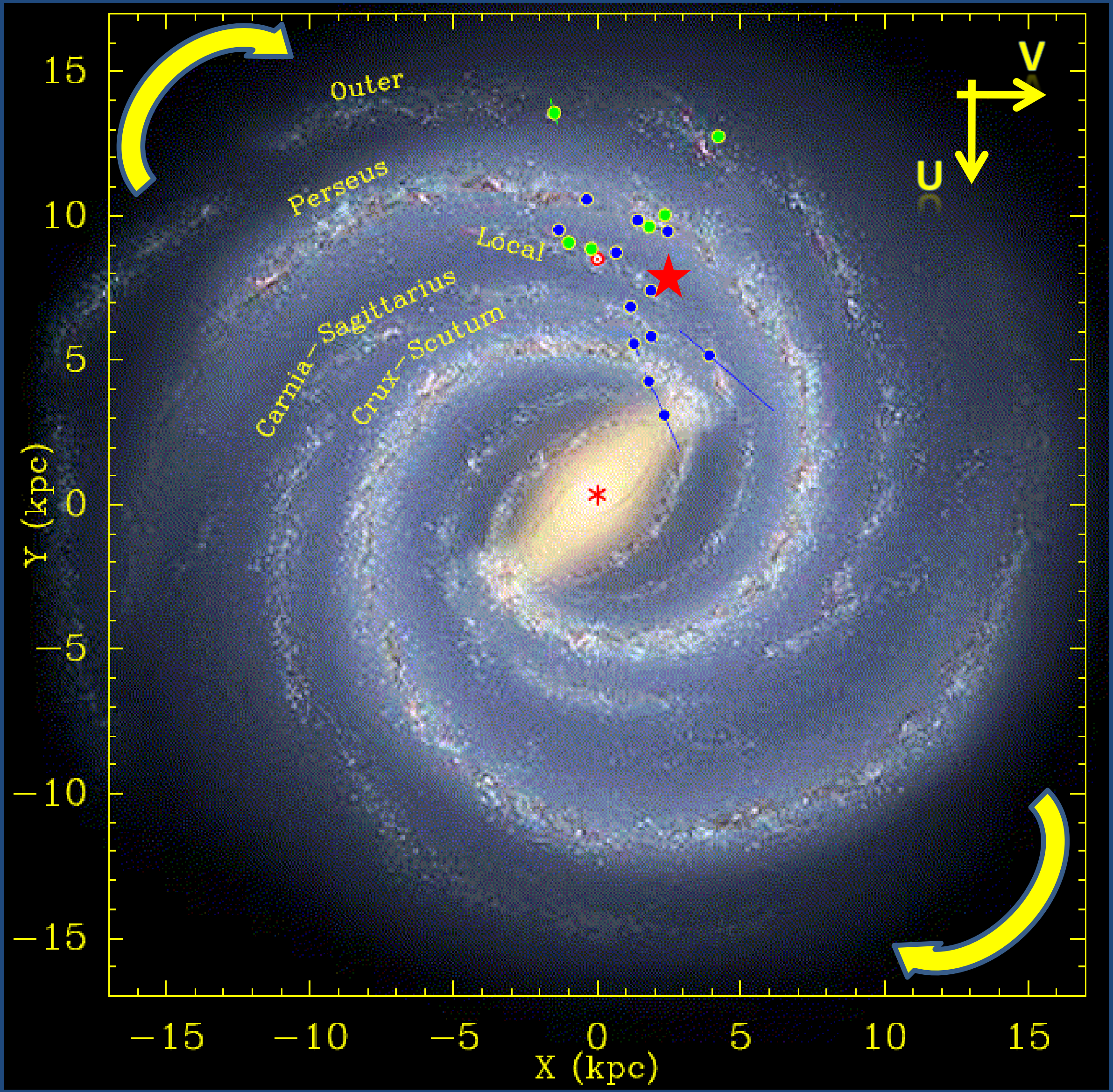


McClintock et al. (2006)

Implications of an accurate distance: IV. BH formation

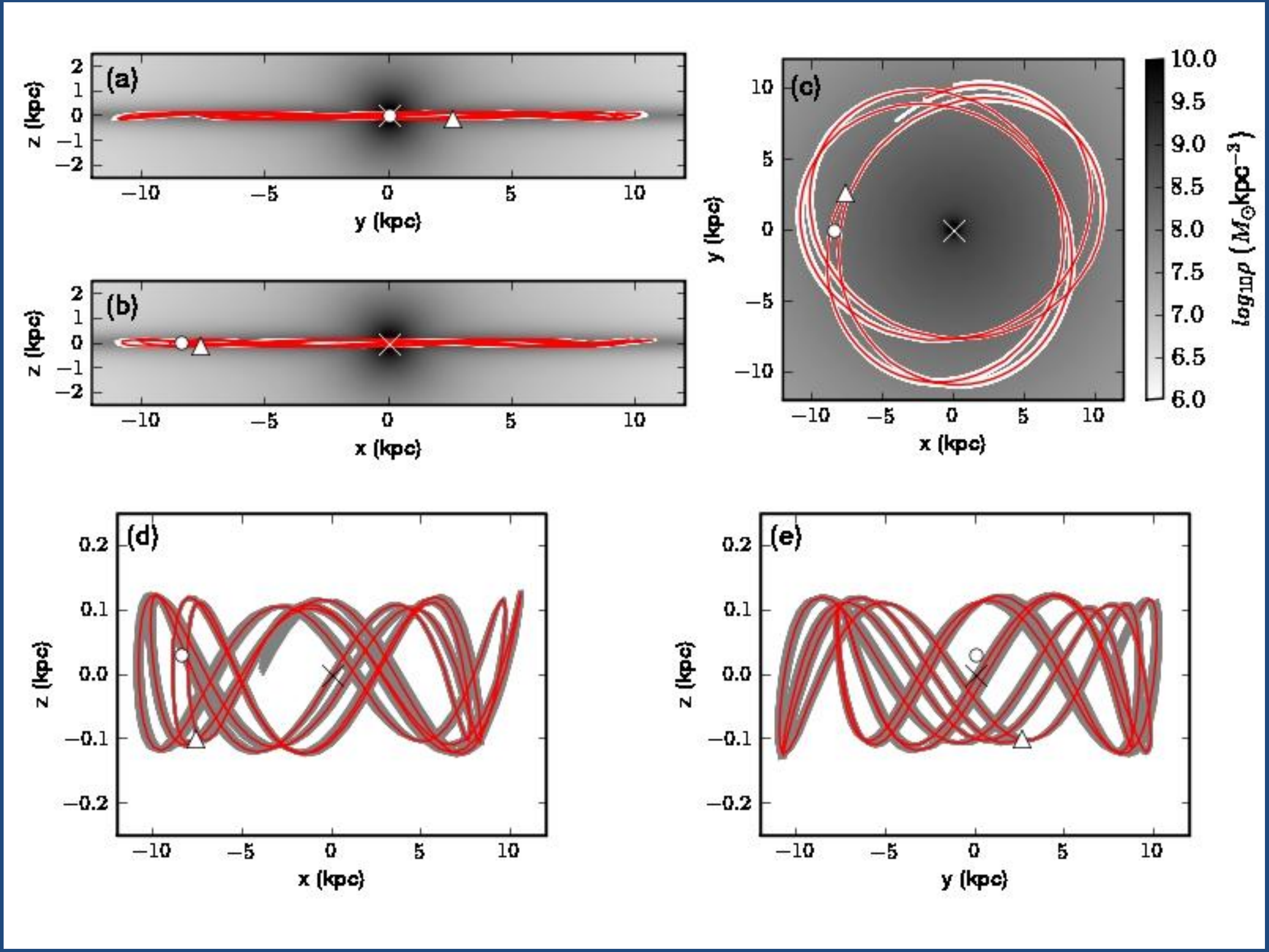
- μ, v_r -> full 3D space velocity
- d, (*l*, *b*) -> expected space velocity
- Observed Galactic space velocity components (LSR):
  - U = 121 ± 10 km/s
  - V = -29± 4 km/s
  - W = 4 ± 1 km/s
- Expected:
  - U_C = 82 km/s
  - V_C = -13 km/s
  - W_C = 0 km/s
- Peculiar velocity: 43 ± 10 km/s

Source position



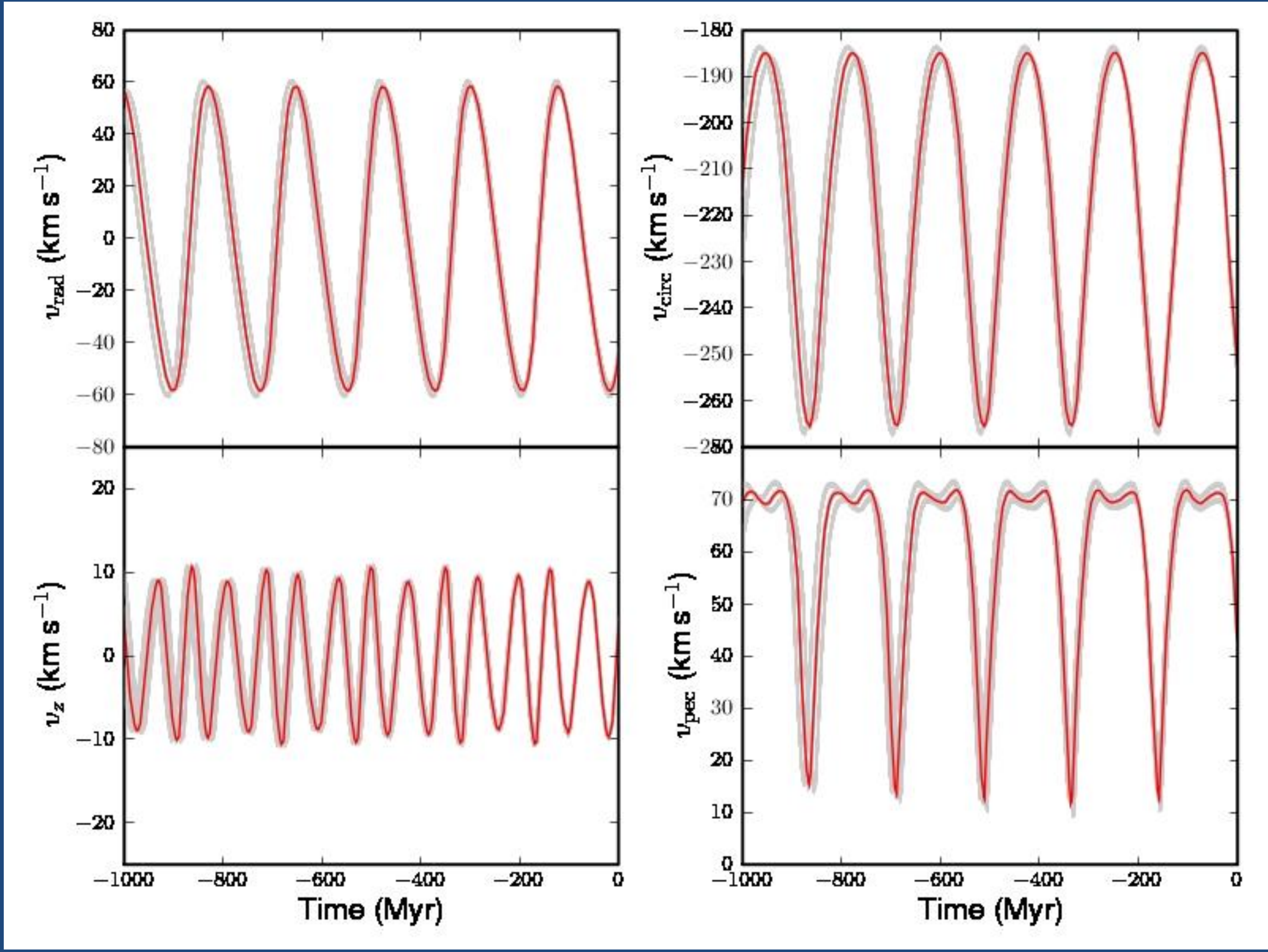
Reid et al. (2009)

Galactocentric orbit



Miller-Jones et al. (2009)

Peculiar velocity

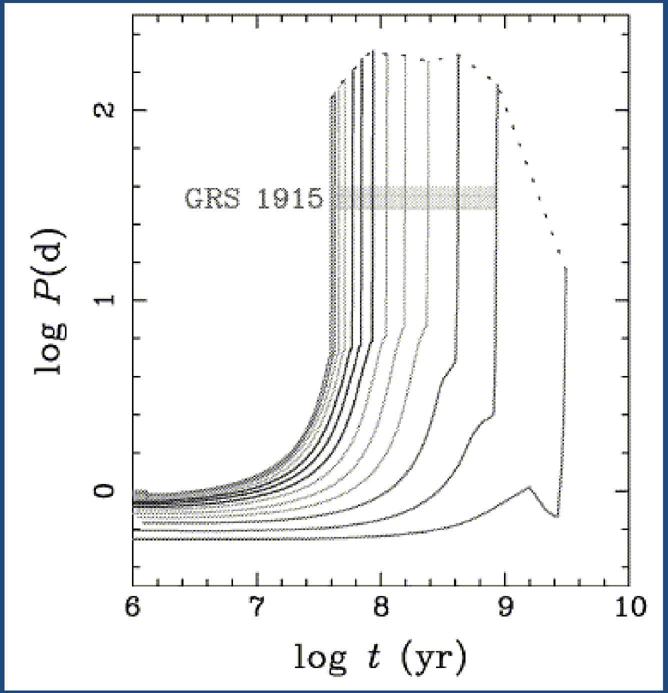


How to get a non-zero peculiar velocity

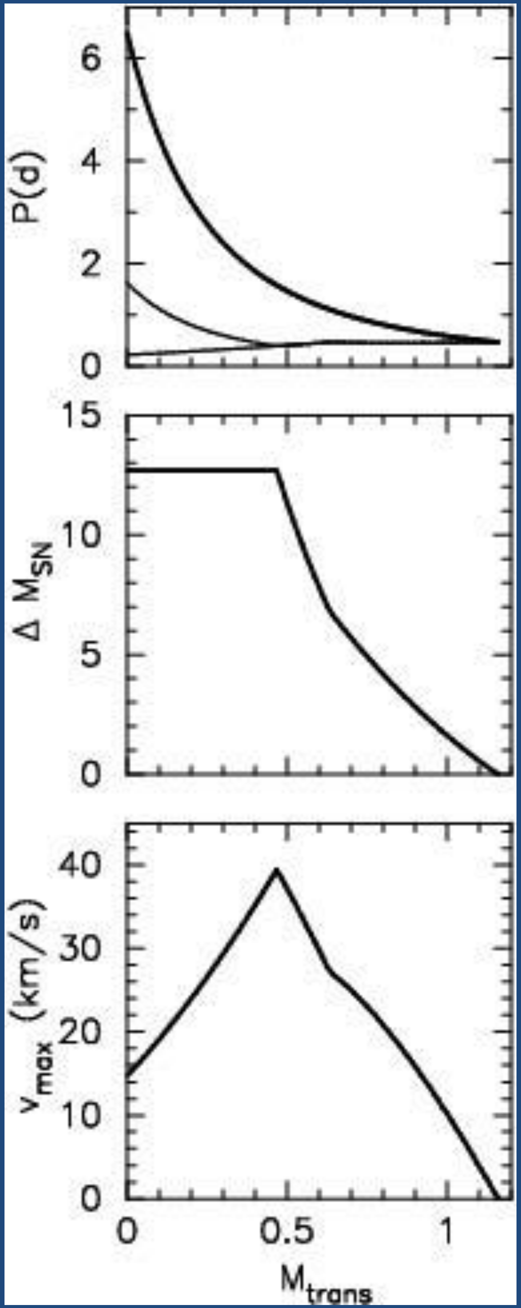
- Rocket acceleration by jets
- Three-body interactions
- Scattering from spiral arms/molecular clouds
- Supernova kick:
  - Symmetric
  - Asymmetric

Scattering

- Donor star has M=0.7±0.3Mo
- Evolves on nuclear timescale
- 0.8 Gyr to reach P_{orb} of 6.5d
- 3-5 Galactic orbits in that time
- ~1-2 solar masses transferred
- F0-F5 stars show a velocity dispersion ~22km/s

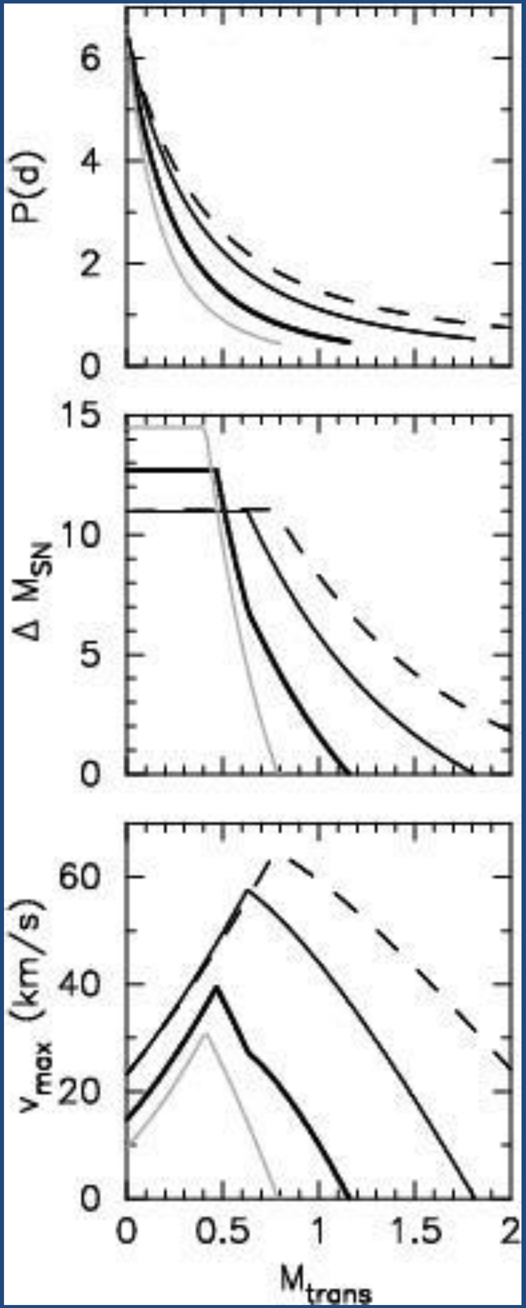


Podsiadlowski et al. (2003)



Blaauw kick

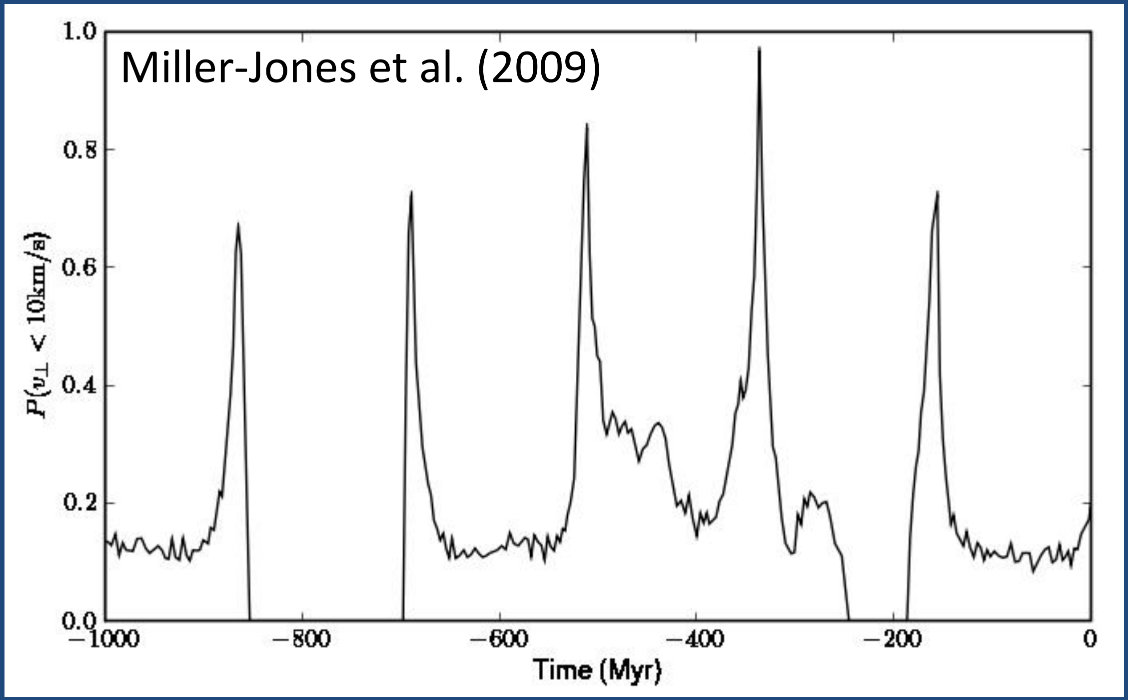
- Recoil following ejection
- $\Delta M \leq 0.5\ (M_1+M_2)$
- Corresponds to v_{max}
- Mass transfer lengthens period
- $P \propto (Mm)^{-3}$



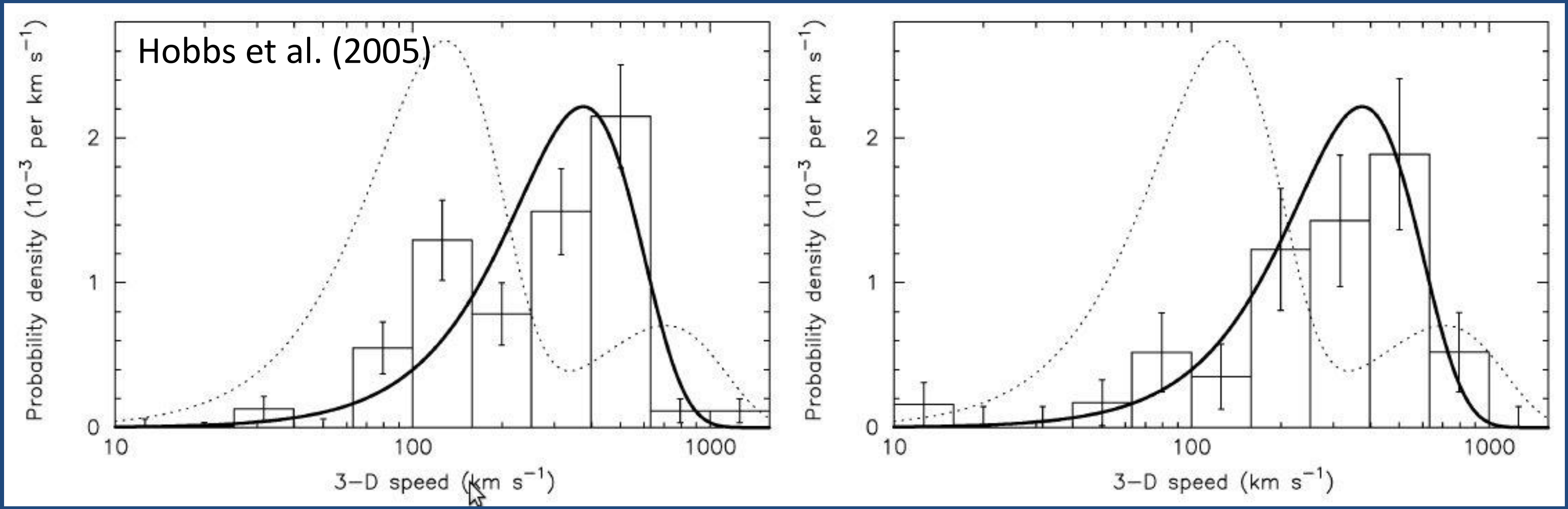
Miller-Jones et al. (2009)

Asymmetric kick

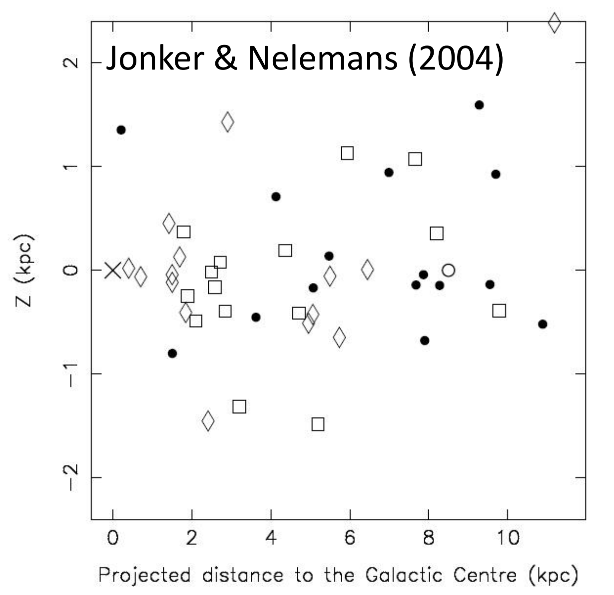
- Common in NS systems
- Can be out of orbital plane
- Component of v_{pec} out of orbital plane unlikely to be dispersion



Comparison of NS and BH XRBs



- Pulsar mean birth speed 400 km/s
- Up to 1000 km/s
- Asymmetric kicks required
- rms BH z-distances similar
- K-S test shows P = 90%



Black hole formation

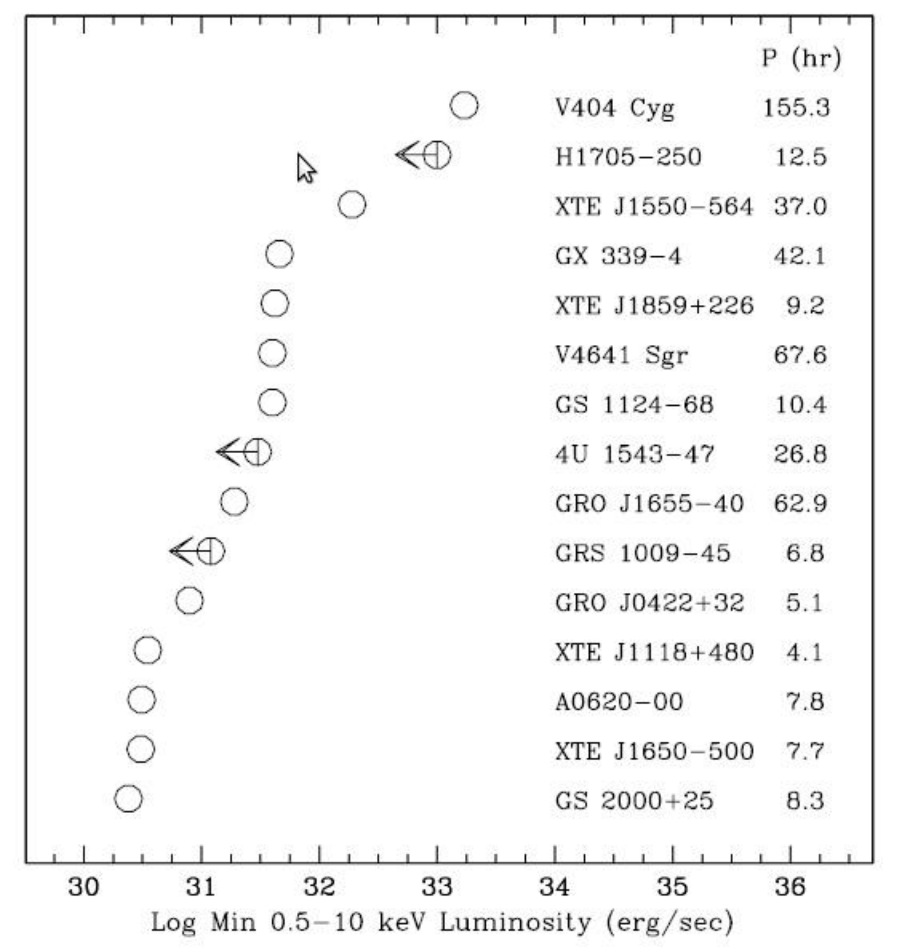
- Direct collapse
  - Most massive progenitors (25-35 M_{solar})
  - No explosion
- Formation of NS followed by delayed fallback
  - NS kick mechanisms should apply

BHXB proper motions

Source	MBH (Msolar)	Proper motion (mas/yr)	Peculiar velocity (km/s)	Reference
GRO J1655-40	6.0-6.6	5.2 ± 0.6	113 ± 20	Mirabel et al. (2002)
XTE J1118+480	6.5-7.3	18.4 ± 2.0	160 ± 25	Mirabel et al. (2001)
Cygnus X-1	6.9-13.2	8.3 ± 0.3	31 ± 26	Mirabel & Rodrigues (2003)
V404 Cyg	10.1-13.4	9.1 ± 0.1	43 ± 7	Miller-Jones et al. (2009)
GRS 1915+105	10.0-18.0	6.8 ± 0.1	$30 \pm 7\ ^{+103}_{-0}$	Dhawan et al. (2007)

Candidate quiescent systems

- 15 of 40 BHCs have quiescent X-ray detections
- Predict L_R with correlation
- Minimum luminosity at 6-8h
- Minimum radio flux: 60μJy(d/1kpc)



Gallo et al. (2008)

Looking forward

- 22GHz VLBA receiver system already upgraded
- VLBA bandwidth to be increased: more sensitivity
- 10μJy/beam in 8h
  - Many more Galactic BH X-ray binaries accessible
- Better than the HSA for astrometry
  - Reduced slew time
  - Larger FOV -> in-beam calibrators
- <10μas astrometry on a 1mJy source
  - Accurate parallactic distances to all Galactic XRBs
- Further possible upgrades

Conclusions

- Quiescent BH are good astrometric targets
- *d* = 2.7kpc for V404 Cyg
- Most accurate distance to a stellar-mass black hole
- Source proper motion is 9.2 mas/yr
- Peculiar motion consistent with a supernova kick, but could be explained by scattering
- VLBA upgrades will allow more geometric distance determinations over the coming years