Optical and Infrared Studies of X-ray Binaries in the Gaia Era

Jerome A. Orosz

San Diego State University

My Connection to Jeff

- Circa 2003, Jeff became extremely interested in measuring the spins of stellar mass black holes. He assembled a large team, and I was thrilled to be invited.

Chronological List of Team Members

CfA	Year
Jeffrey McClintock	2004.3
Ramesh Narayan	2004.3
Rebecca Shafee	2005.1
Mark Reid	2006.7
James Steiner	2007.2
Manuel Torres	2007.2
Jifeng Liu	2007.2
Lijun Gou	2007.9

Elsewhere	Year
Jerome Orosz (SDSU)	2004.3
Li-Xin Li (MPI)	2004.3
Ronald Remillard (MIT)	2005.2
Shane Davis (IAS)	2005.3
Danny Steeghs (UK)	2005.9
Charles Bailyn (Yale)	2006.2
Ken Ebiswa (ISAS)	2008.1
+ several others	

Leaders
Full-time
Occasional

This effort to measure spin requires a 50-50 mix of theory & observation.

My Connection to Jeff

- Circa 2003, Jeff became extremely interested in measuring the spins of stellar mass black holes. He assembled a large team, and I was thrilled to be invited.
- To measure the black hole spin, you need the distance to the source…

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Outline

- How can good distances and proper motions be of use in the study of the Galactic X-ray binary population?

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Outline

- How can good distances and proper motions be of use in the study of the Galactic X-ray binary population?
  - Black hole and neutron star masses.
  - Black hole spins.
  - X-ray binary populations and constraints on formation scenarios.

Two Classes of X-ray Binaries

- **High Mass X-ray Binaries (HMXBs):**
  - **Have a massive O- or B-type companion, where $L_{opt} \approx L_x$.**
  - **Mass transfer is via a stellar wind.**
- **Low Mass X-ray Binaries (LMXBs):**
  - **Have a low mass companion (typically a solar mass or less).**
  - **Mass transfer is via Roche lobe overflow.**
  - **In persistant sources, $L_x >> L_{opt}$ always.**
  - **In transient sources, $L_x < L_{opt}$, except for occasional flares.**

Dynamical Masses

- **The donor star is a single-lined spectroscopic binary…**

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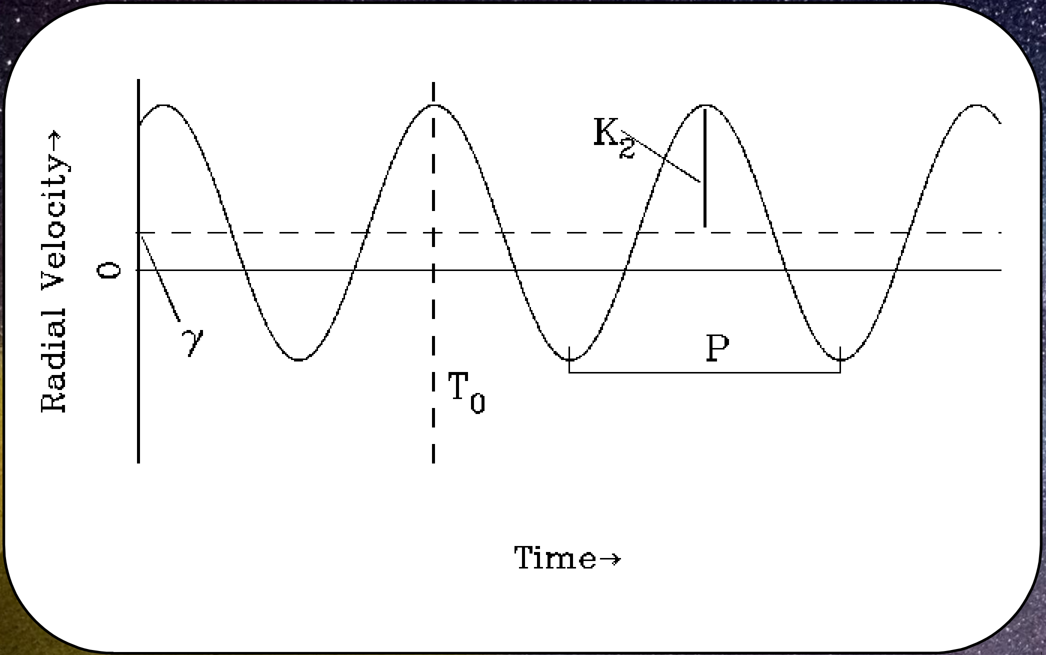
Dynamical Masses



- Circular orbit, period P and separation a:

$$V_2 = \frac{2\pi a}{P}\left(\frac{M_1}{M_1 + M_2}\right)$$

where M_2 is the donor star mass.

- Kepler's Third Law:

$$P^2 = \frac{4\pi^2 a^3}{G(M_1 + M_2)}$$

- Define $K = V_2 \sin i$, combine the above to get:

$$f(M_1) \equiv \frac{PK_2^3}{2\pi G} = \frac{M_1^3 \sin^3 i}{(M_1 + M_2)^2} \geq M_1$$

- The optical mass function is a lower limit on the mass of the compact object.

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- The optical mass function is a lower limit on the mass of the compact object.

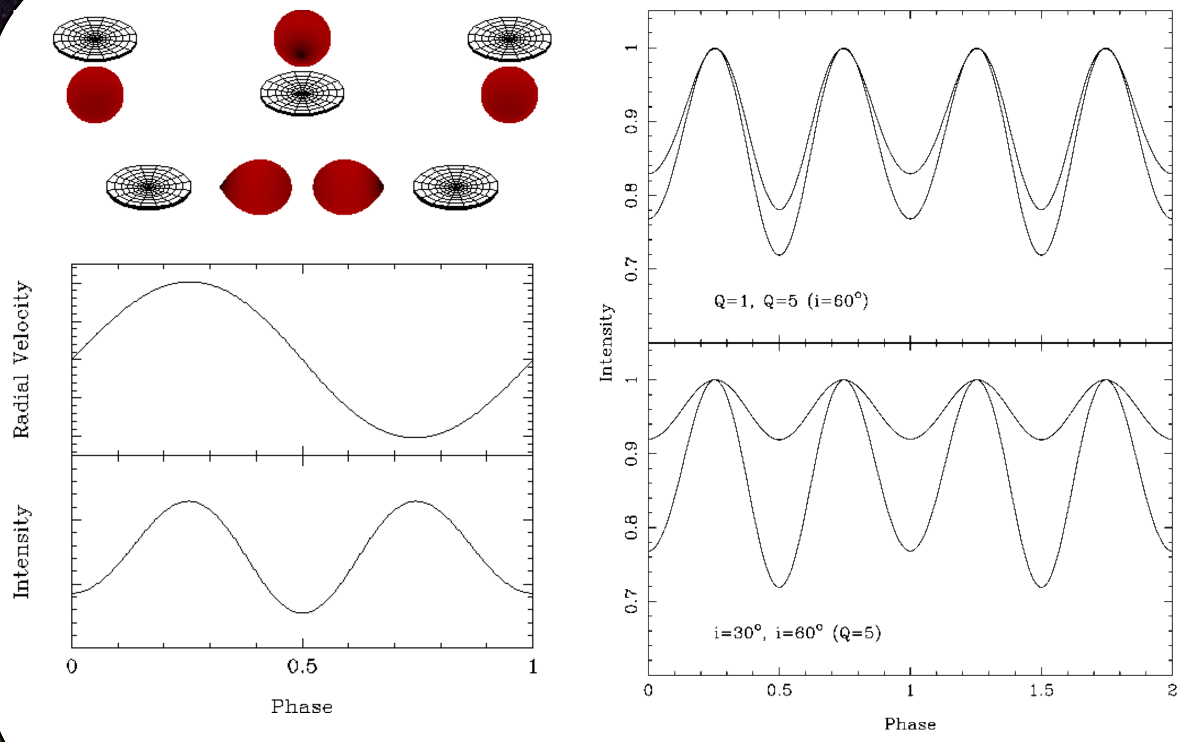
- To get the actual mass of the compact object (and that of the donor star), we need to find the orbital inclination i and the mass ratio $q \equiv M_2/M_1$.

- The rotational velocity of the donor is (for synchronous rotation):
$$V_{\rm rot} = \frac{2\pi R_L}{P}$$
where R_L is the radius of the Roche lobe.

- Hence:
$$\frac{V_{\rm rot} \sin i}{V_2 \sin i} = \frac{V_{\rm rot} \sin i}{K_2} = \frac{R_L}{a}\left(\frac{M_1 + M_2}{M_1}\right) = \frac{R_L}{a}(1+q)$$

- Thus, the observed rotational velocity of the donor gives a measurement of the mass ratio of the binary.

Dynamical Masses



- **Ellipsoidal modulations seen in the light curve can be modeled to get the inclination.**

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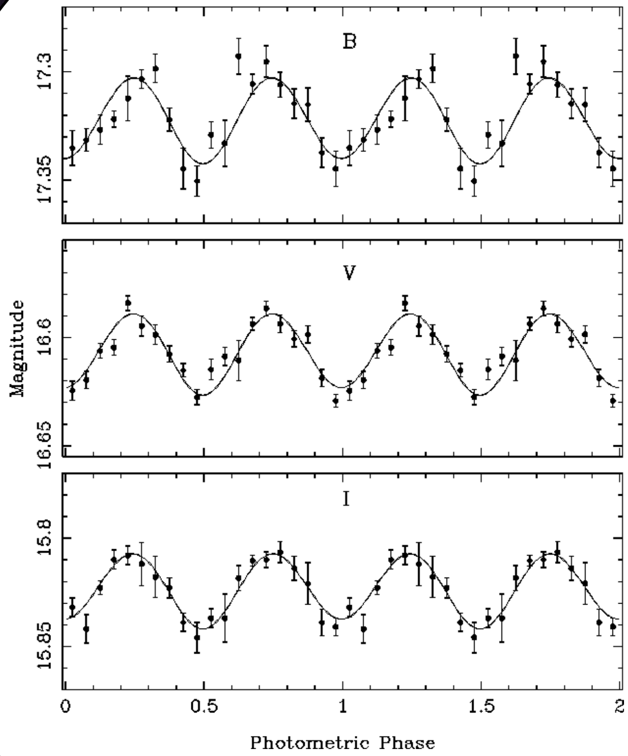
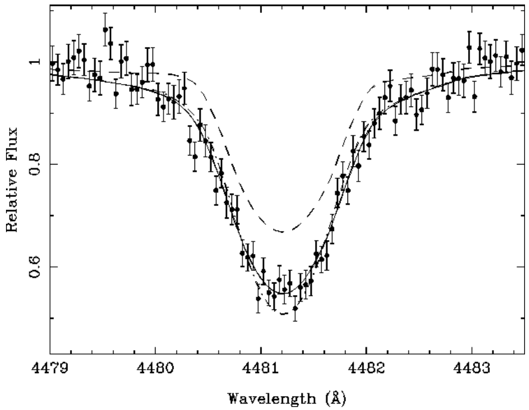
Dynamical Masses





- **Ellipsoidal modulations seen in the light curve can be modeled to get the inclination.**
- **Here is 4U 1543-47:**
  - **P = 1.123 days**
  - **f(M) = 0.22 ± 0.02 M_o**
  - **i = 20.7 ± 1.1 degrees**
  - **V_{rot} = 46 ± 2 km/sec**

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Dynamical Masses

- The donor star is a single-lined spectroscopic binary…
- Take K_2, i, and q, solve for M_1, M_2, and a.

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Dynamical Masses

- The donor star is a single-lined spectroscopic binary…
- Take K_2, i, and q, solve for M_1, M_2, and a.
- **We can calculate the distance**:
  - Find the donor star radius R_2 (use a and R_L).
  - Using T_{eff}, find L_2
  - Using model atmospheres, compute bolometric corrections.
  - Using the apparent magnitude, find the distance modulus (apply reddening corrections, use IR bands if possible).

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Dynamical Masses

- **What if we knew the distance independently?**

Dynamical Masses

- **What if we knew the distance independently?**
  - **Use *d*, the apparent magnitude, and extinction to find L_2**
  - **Use L_2 and T_{eff} to find R_2**
  - **Use the R_2 constraint as another prior and include it in the likelihood function: $\chi^2_{tot} = \chi^2_{photo} + \chi^2_{RV} + \chi^2_{R2}$**

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Dynamical Masses

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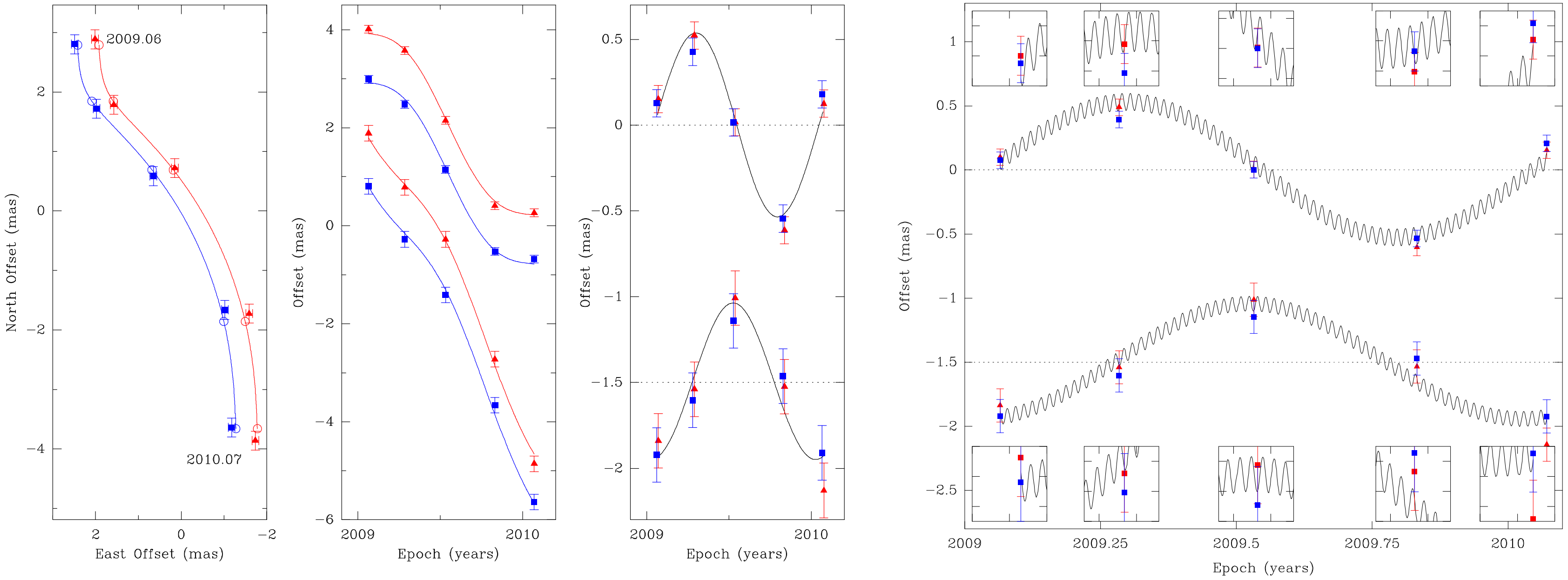
  - **This was done for M33 X-7 (*d*=840±20 kpc, Orosz et al. 2007, LMC X-1 (*d*=48±1 kpc, Orosz et al. 2009), and Cyg X-1 (*d*=1.86±0.12 kpc, Reid et al. 2011).**

Dynamical Masses



- (t)There is a ≈2σ detection of the orbital motion in the VLBI observations (a_x=0.18±0.09 AU, Reid et al. 2011).

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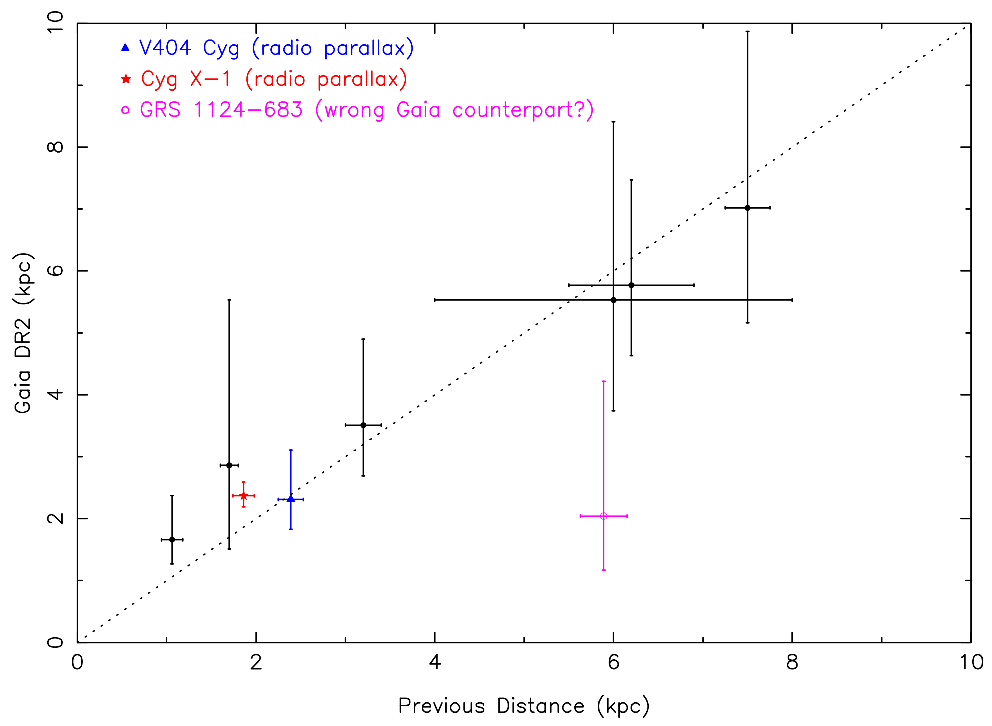
Distance Measurements



- Gandhi et al. (2018) compared Gaia DR2 distances with previous distance measurements for a sample of 24 BHs.
- The agreement is generally OK…

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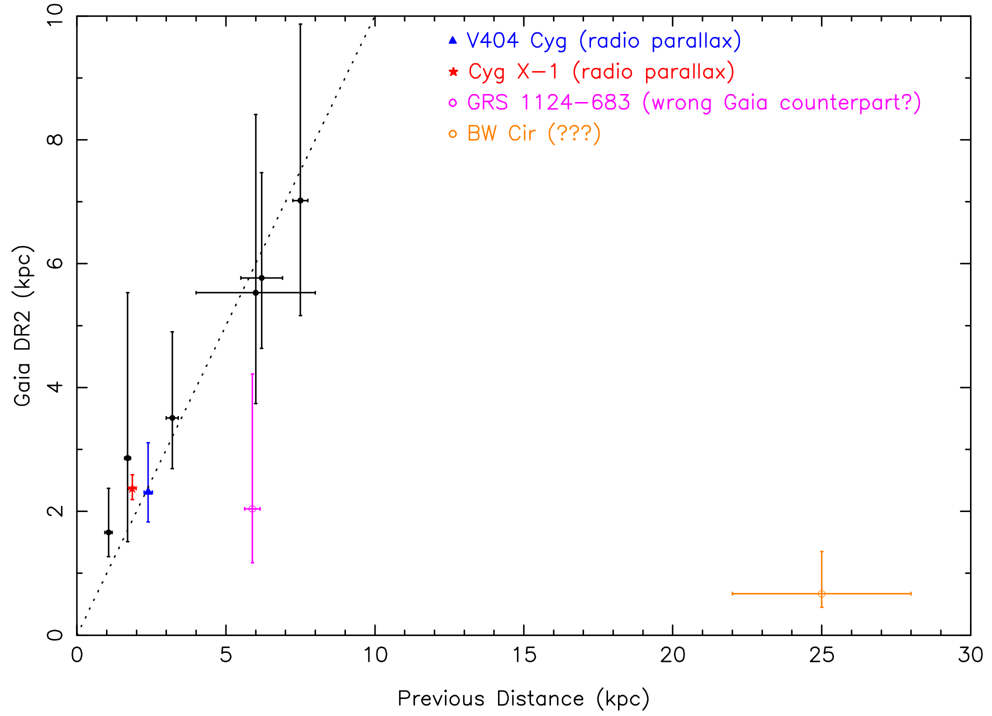
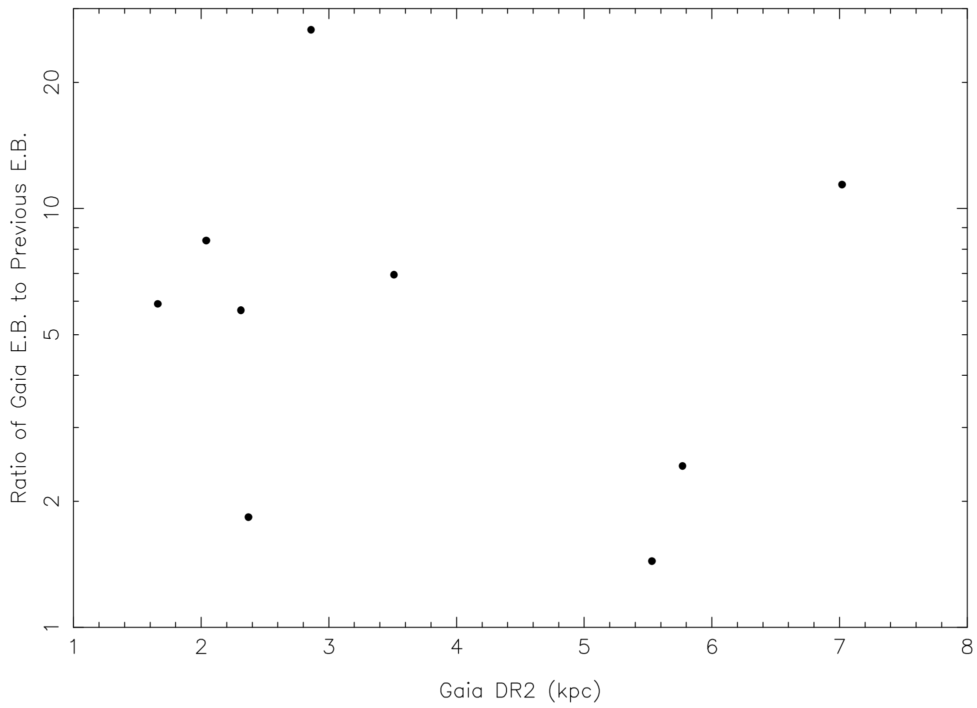
Distance Measurements



- Gandhi et al. (2018) compared Gaia DR2 distances with previous distance measurements for a sample of 24 BHs.
- The agreement is generally OK, except for BW Cir.

Distance Measurements



- **Gandhi et al. (2018) compared Gaia DR2 distances with previous distance measurements for a sample of 24 BHs.**
- **The DR2 uncertainties are a factor of a few to several times more than previous uncertainties.**

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Distance Measurements

- As it stands now, the Gaia distance measurements to the black hole X-ray binaries don't help constrain the mass measurements. Need to reduce the uncertainties by a factor of ≈5 in order to help.
- The radio parallax distance to Cyg X-1 is 1.86±0.12 kpc, and the Gaia distance is 2.37±0.22 kpc. Note that the Gaia measurement does **not** include the "wobble" corrections.
- The final Gaia catalog presumably will have smaller parallax uncertainties, but probably not a factor of ≈5 smaller (???).

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Distance Measurements

- In spite of the relatively large uncertainties, the Gaia parallax measurements provide a good check on potential systematic errors.

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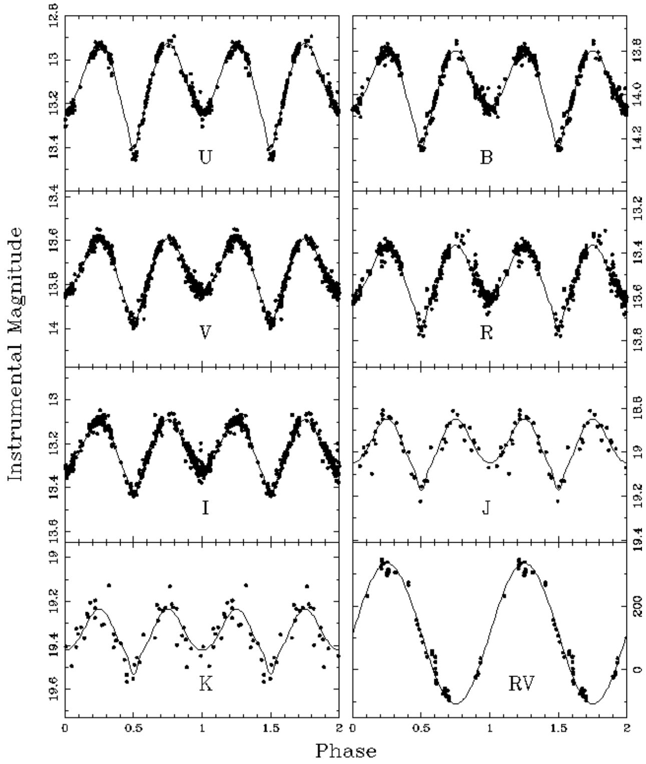
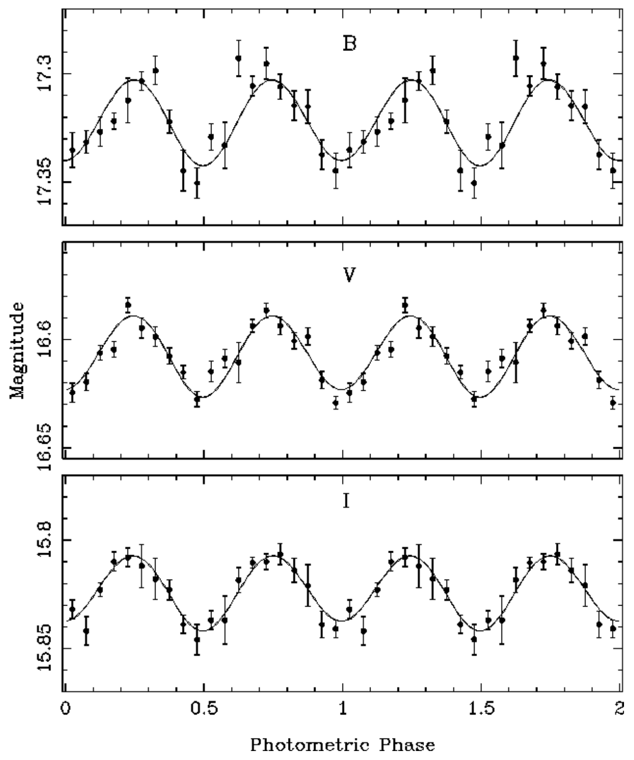
Distance Measurements



- **V4641 Sgr has textbook ellipsoidal variations, good model fits.**
  - **Gaia: 5.77±1.70 kpc**
  - **Previous: 6.2±0.7 kpc**

Distance Measurements



- Same for 4U 1543-47.
  - Gaia: 7.02±2.85 kpc
  - Previous: 7.5±0.5 kpc

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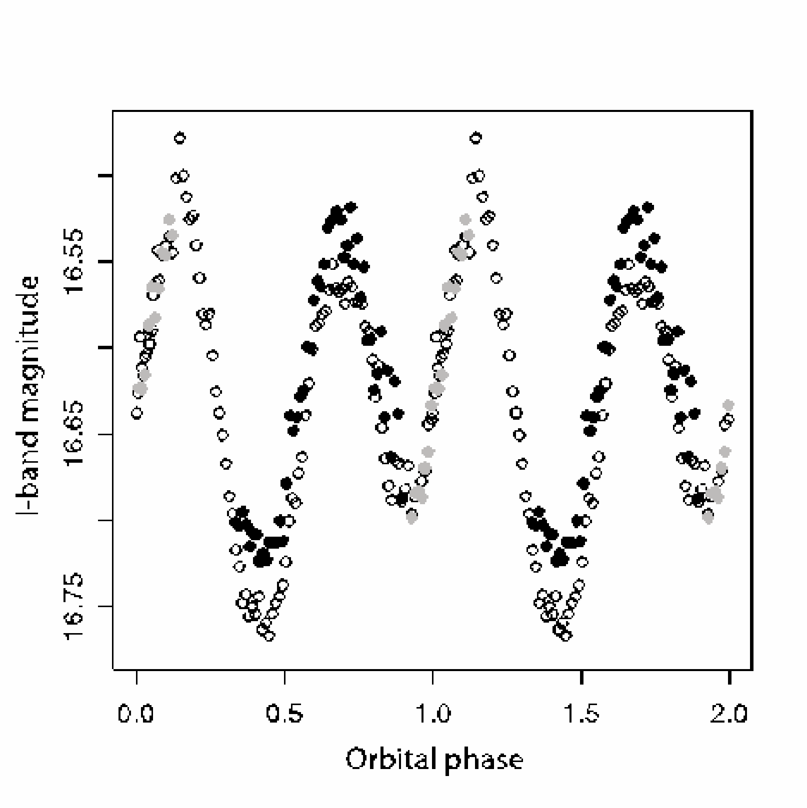
Distance Measurements



- However, A0620-00 has asymmetric quiescent light curves (Cantrell et al. 2010).

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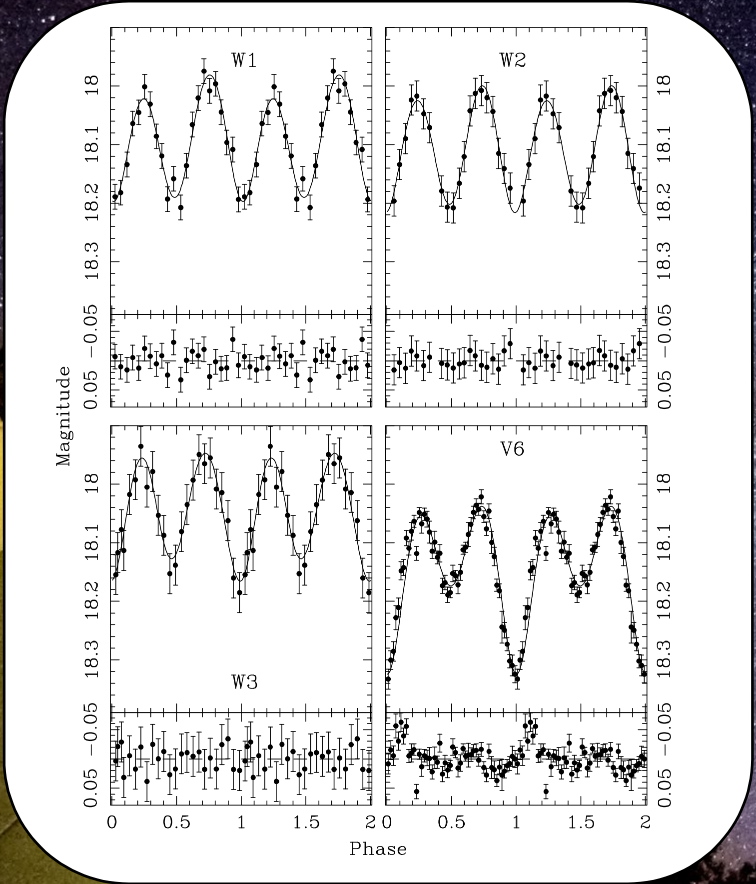
Distance Measurements



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- The asymmetries were modeled as spots on the accretion disk.

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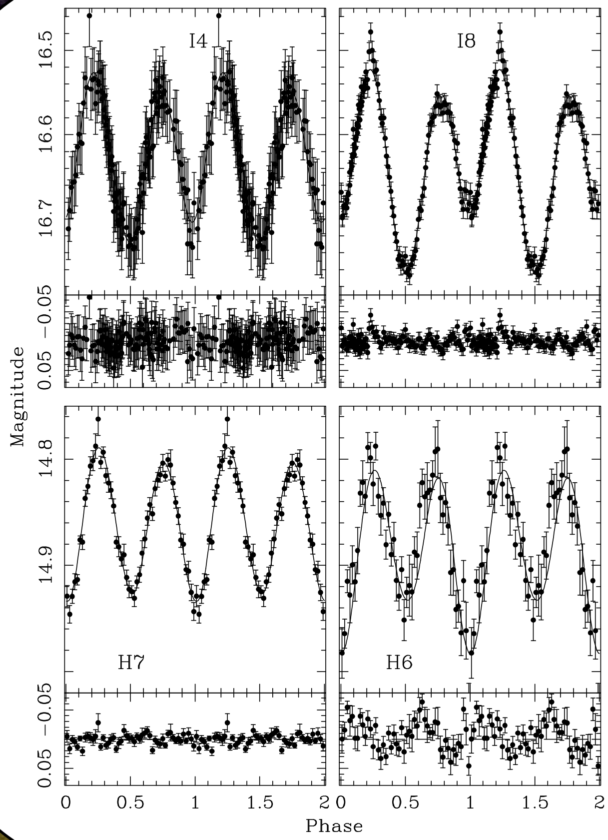

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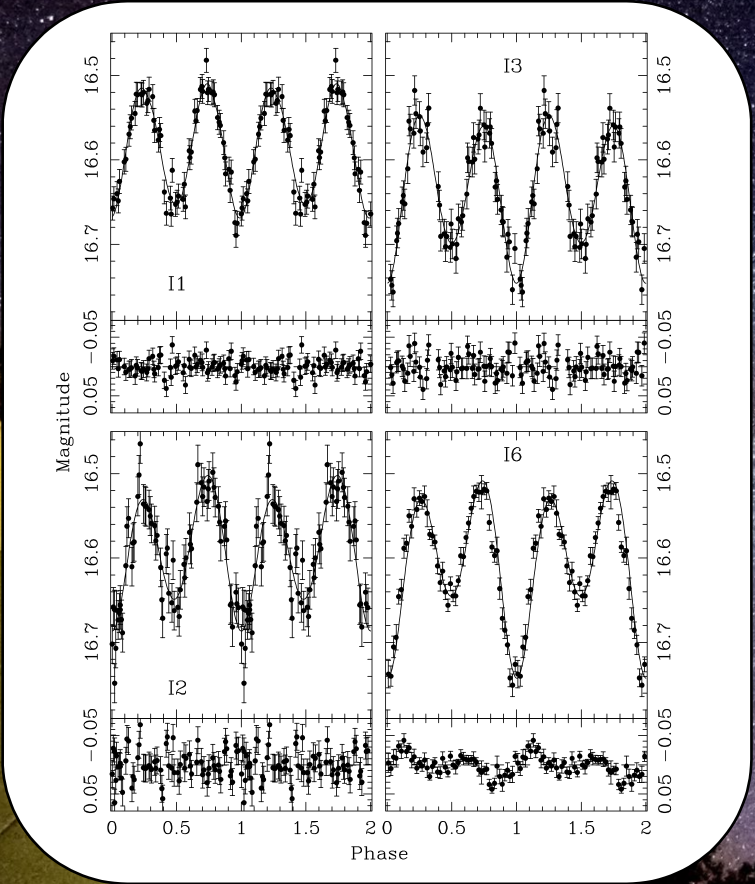

- **However, A0620-00 has asymmetric quiescent light curves (Cantrell et al. 2010).**
- **The asymmetries were modeled as spots on the accretion disk.**
  - **Gaia: 1.66±0.71 kpc**
  - **Previous: 1.06±0.12 kpc**

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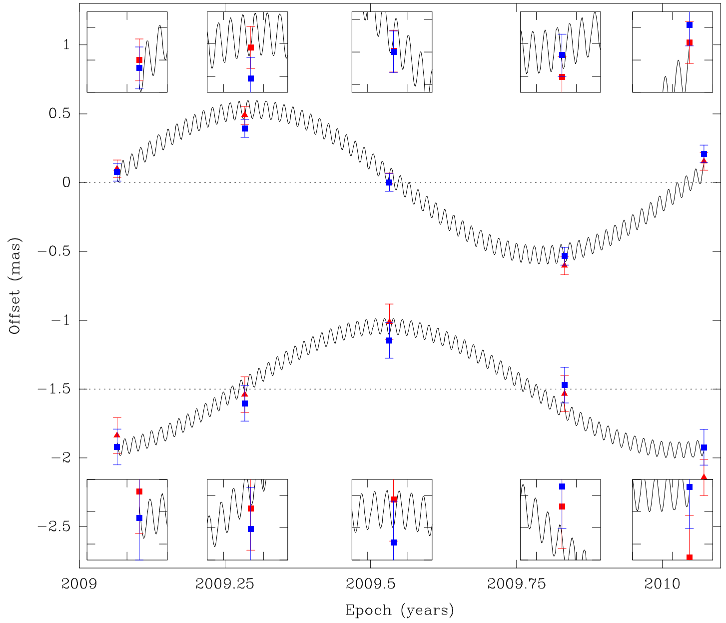
Dynamical Masses



- For Cyg X-1, imagine if the parallax errors were ≈5 times smaller. We would have a secure astrometric orbit for the black hole.
- Gaia could potentially provide an optical astrometric orbit (although with larger uncertainties).
- Direct mass ratio measurement!

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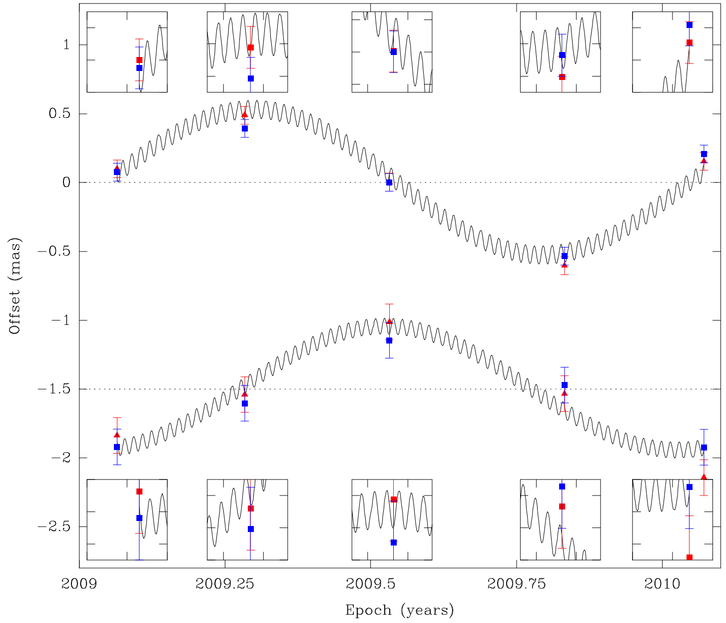
Dynamical Masses



- **A survey with ngVLA could potentially find systems like Cyg X-1 but with longer periods, and hence much lower X-ray luminosities, via the wobble (Maccarone et al. 2018).**

Black Hole Spin

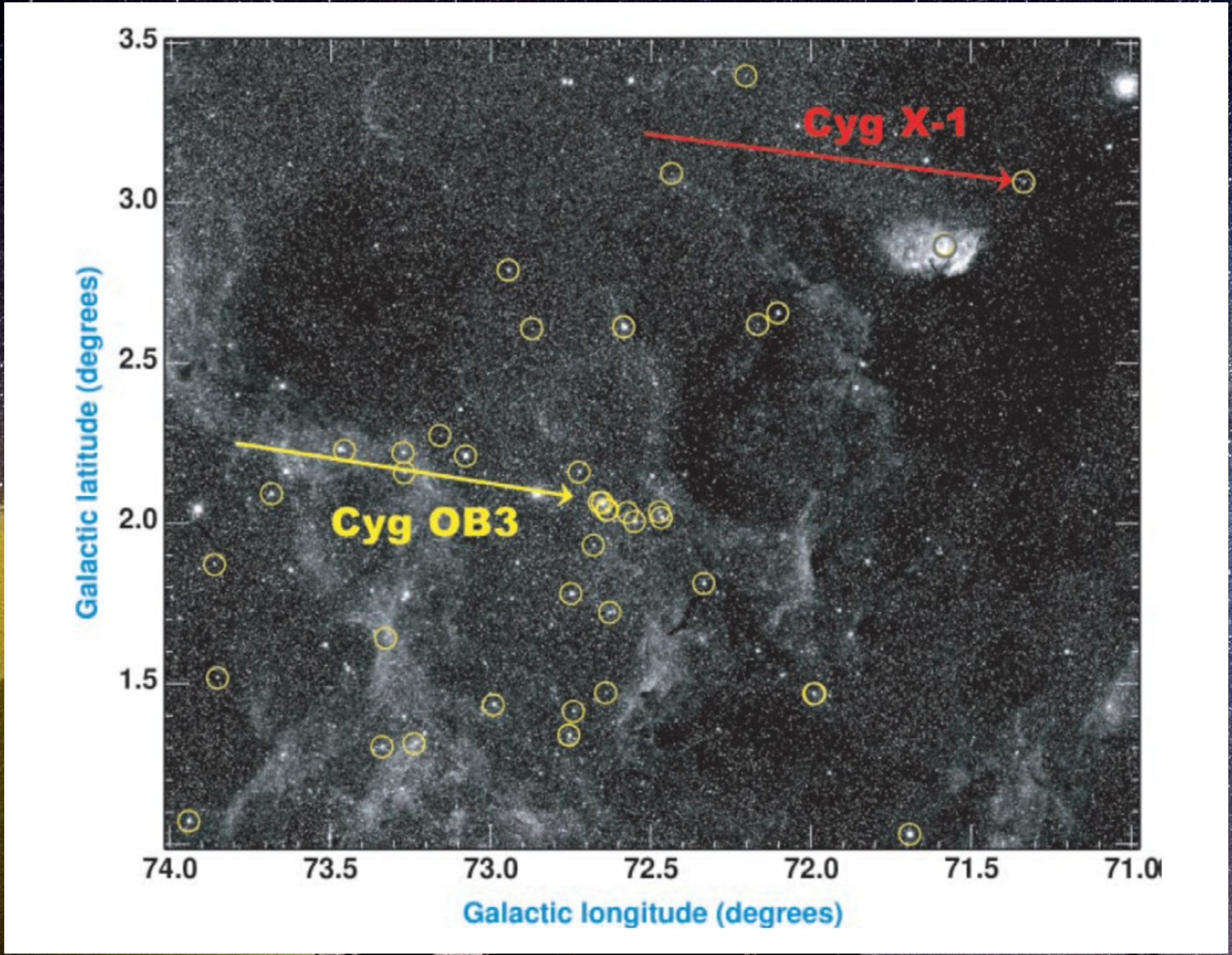
- You need the distance (among other things) to measure the spin of the black hole.

Black Hole Spin

- **You need the distance (among other things) to measure the spin of the black hole.**
- **Having uniformly measured distances for all of the sources in your sample has never hurt anyone.**

Black Hole Kinematics

- Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.



- Mirabel 2017

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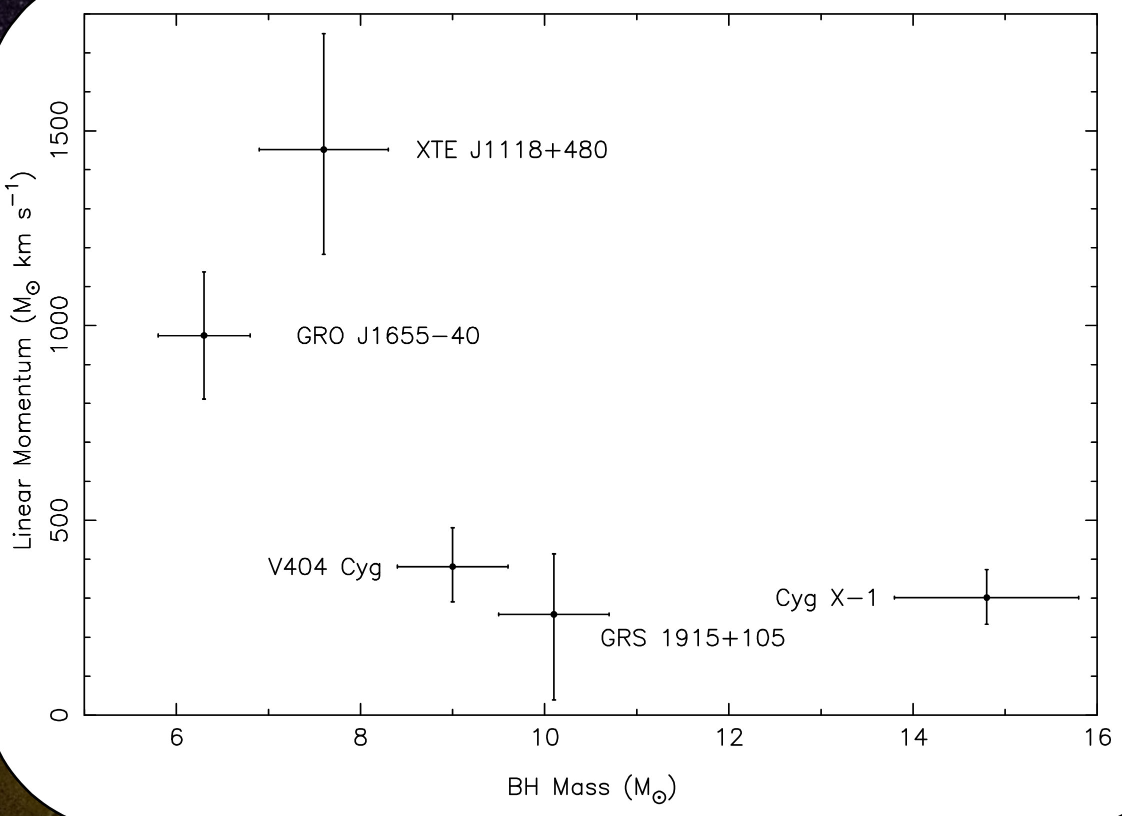
Black Hole Kinematics

- Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.
- Cyg X-1 is co-moving with Cyg OB3. It also has almost no "peculiar" velocity, indicating no "kick" at birth (Reid et al. 2011). The BH probably formed by implosion.

Black Hole Kinematics



- **These 5 BH X-ray binaries have peculiar velocities measured (Mirabel 2017).**

Black Hole Kinematics

- Proper motion measurements (in addition to parallax) gives you 3D space motions, which can help constrain formation scenarios.
- GRO J1655-40 and XTE J1118+480 have large linear momenta (similar to typical neutron stars). These BHs probably formed by infall onto a proto-neutron star.

Black Hole Kinematics

- **White & van Paradijs (1996) showed BH X-ray binaries have a smaller dispersion in the z-distance from the plane, compared to neutron star systems.**

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- Jonker & Nelemans (2004) found no differences in the distributions, suggesting no differences in the kick velocities.

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- **This suggests BH systems received fewer “kicks” compared to neutron stars.**
- **Jonker & Nelemans (2004) found no differences in the distributions, suggesting no differences in the kick velocities. Better distances wouldn’t hurt here either.**

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Summary

- Good distance measurements to X-ray binaries can help constrain the mass measurements if the uncertainties are small enough.
- Presently, the Gaia distances are too uncertain to help in this regard.
- Regular monitoring observations with ngVLA could provide useful distance and proper motion measurements for a number of X-ray binaries.

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