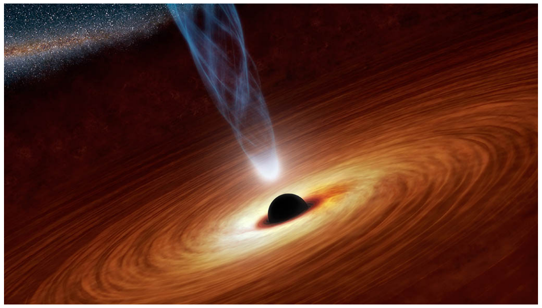
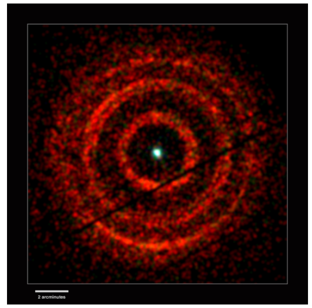
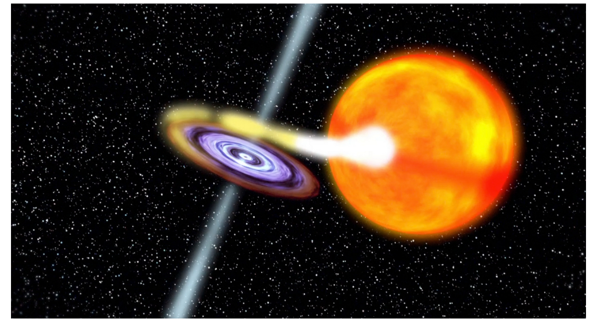






The Spin Rates of Black Holes

John Tomsick

Space Sciences Laboratory/UC Berkeley

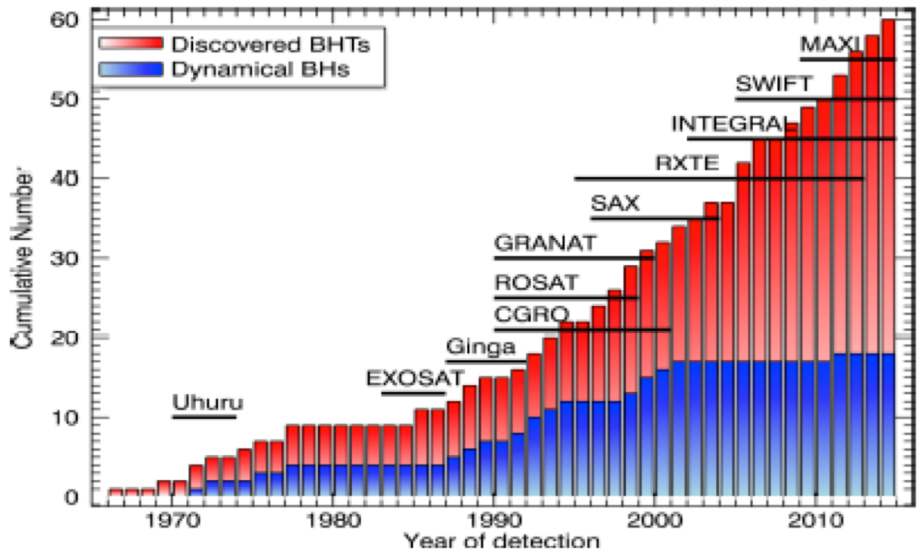
September 2018

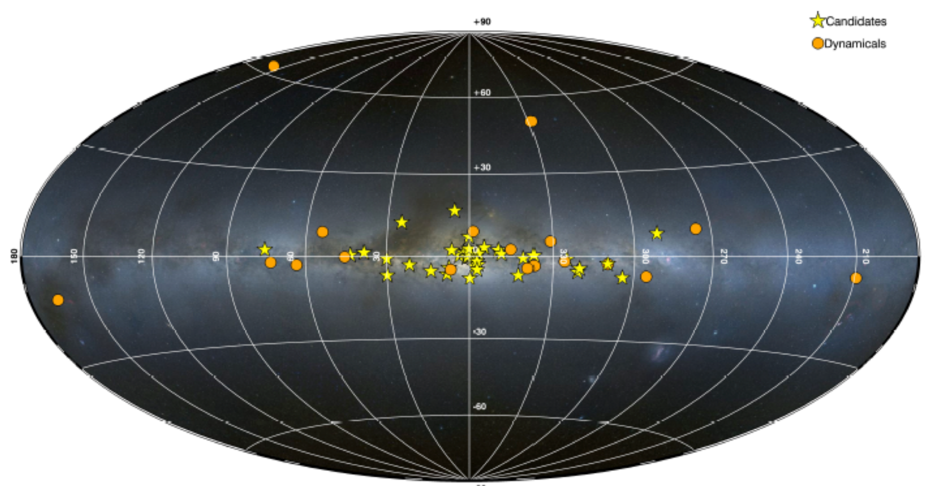
Outline

- Black hole X-ray binaries
- Measuring BH spin with X-rays
  - X-ray timing method
  - Thermal method
  - Reflection method
    - The *Nuclear Spectroscopic Telescope Array (NuSTAR)*
- Measuring BH spin with Gravitational Waves
  - LIGO/Virgo detections of BH-BH mergers
- Comparison and Discussion

Black hole binaries over time and in space

- Steady increase in the number of known BH transients in our Galaxy
  - Currently 60
- Mostly at low Galactic latitude with a couple exceptions
  - XTE J1118+480 is about 1.7 kpc away

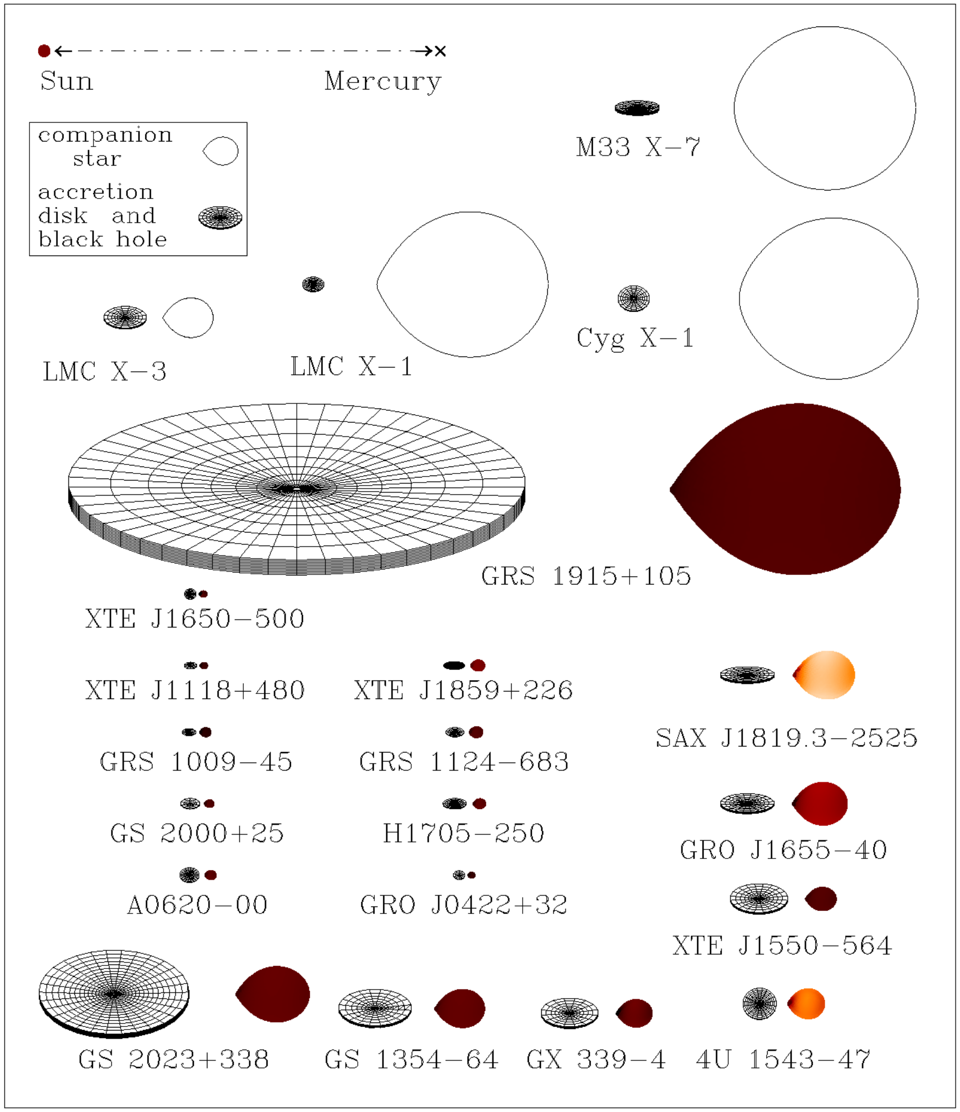




BlackCAT: Corral-Santana+16

Dynamically confirmed black holes

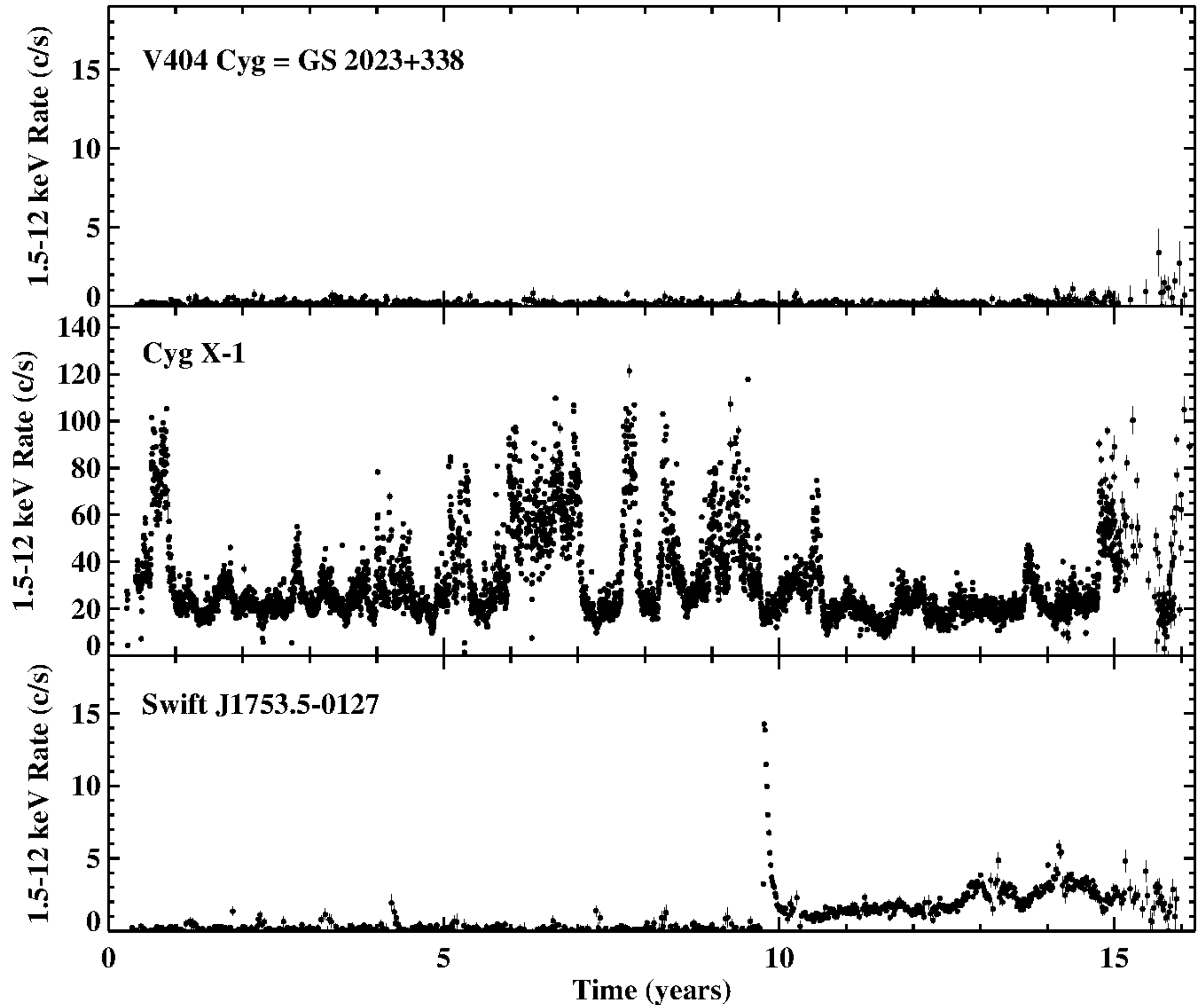
- 21 compact objects in binaries with masses >3 M_{sun}
- Orbital period range:
  - 4 hours to 34 days
- Figure indicates:
  - size of orbit
  - companion temperature and size
  - inclination



McClintock+14

Long-term soft X-ray light curves

- Very large range of activity
- Many systems with zero outbursts in 16 years
  - e.g., V404 Cyg
- Some persistent systems
  - e.g., Cyg X-1
- Some systems with long-term outbursts
  - e.g., Swift J1753.5-0127



Full mission (16 year, 1995-2012) *RXTE*/ASM light curves

Long-term soft X-ray light curves

- Very large range of activity
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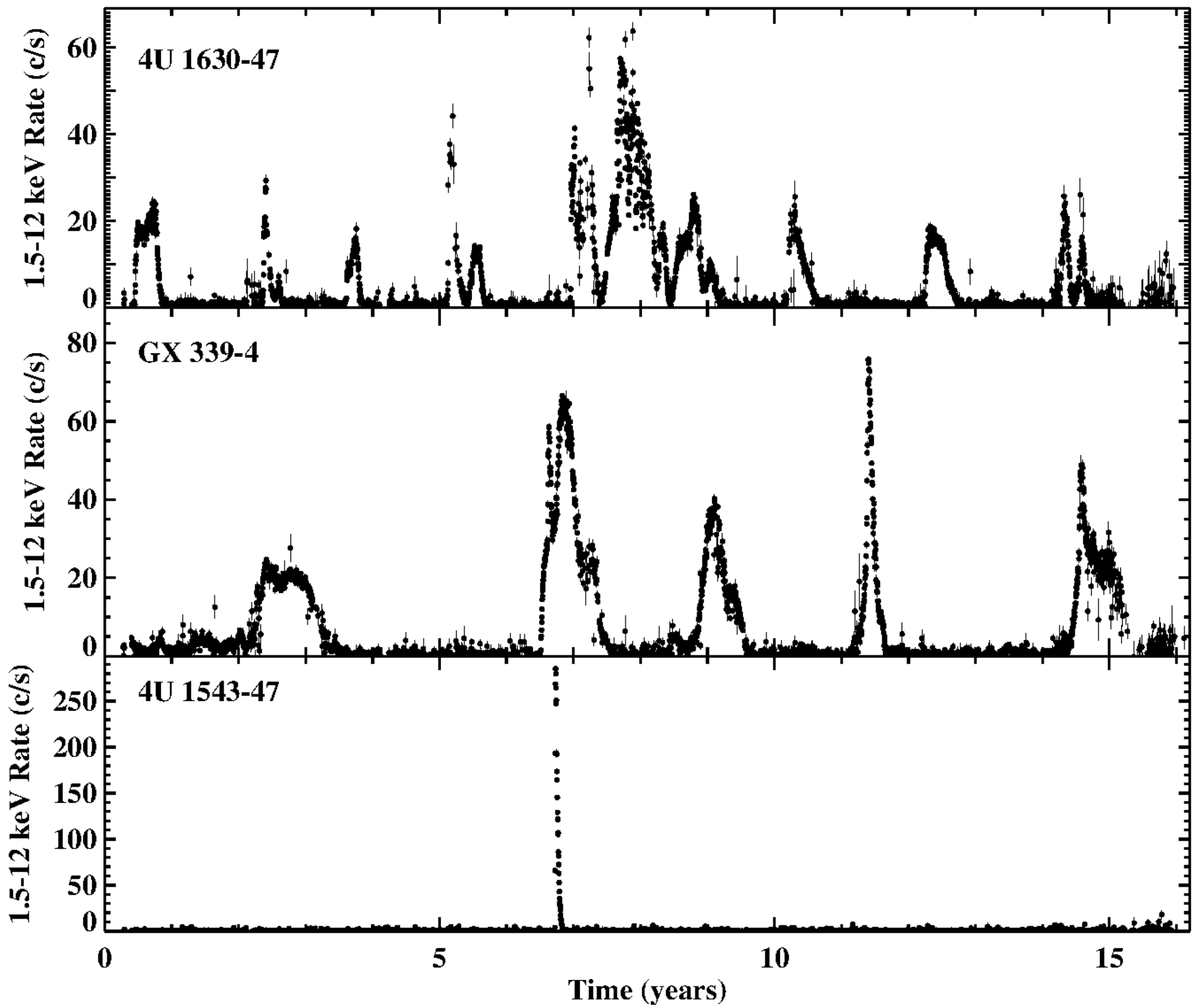
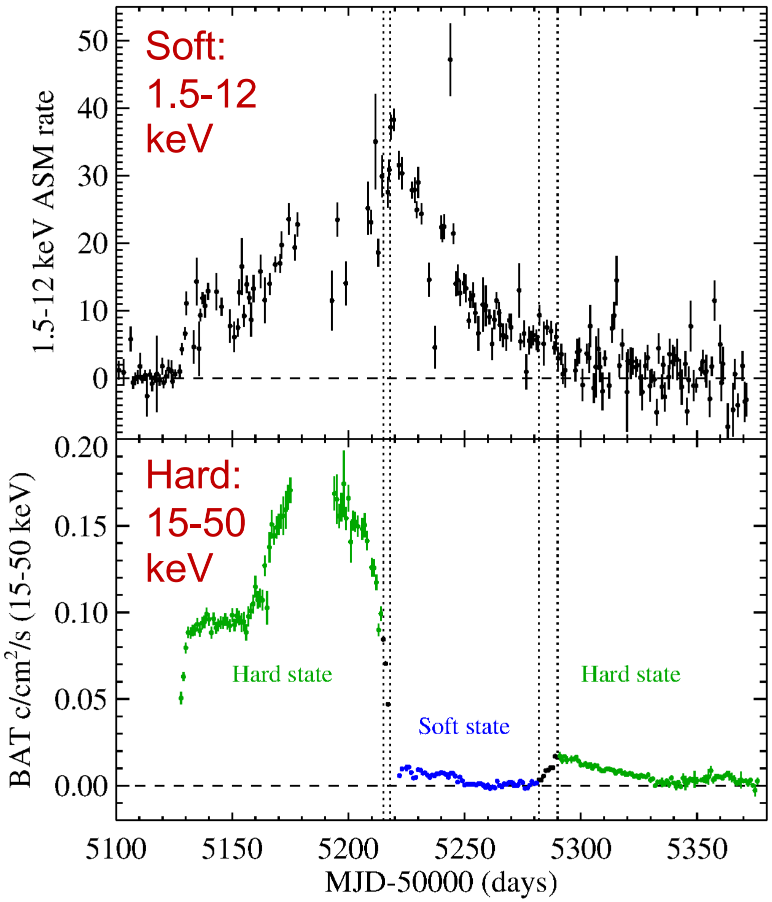
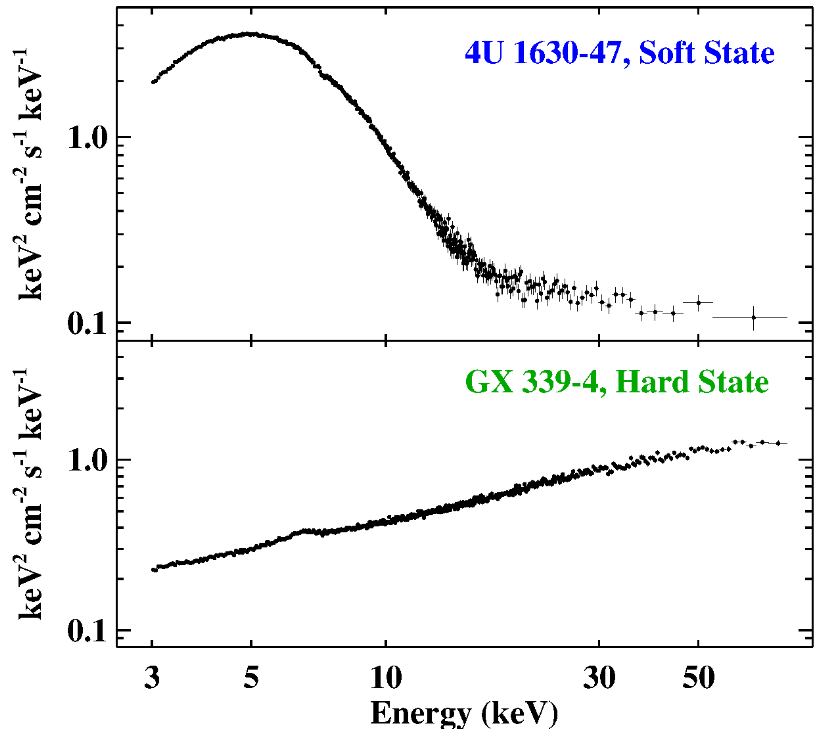


Full mission (16 year, 1995-2012) *RXTE*/ASM light curves

Changes in Energy Spectra (spectral states)



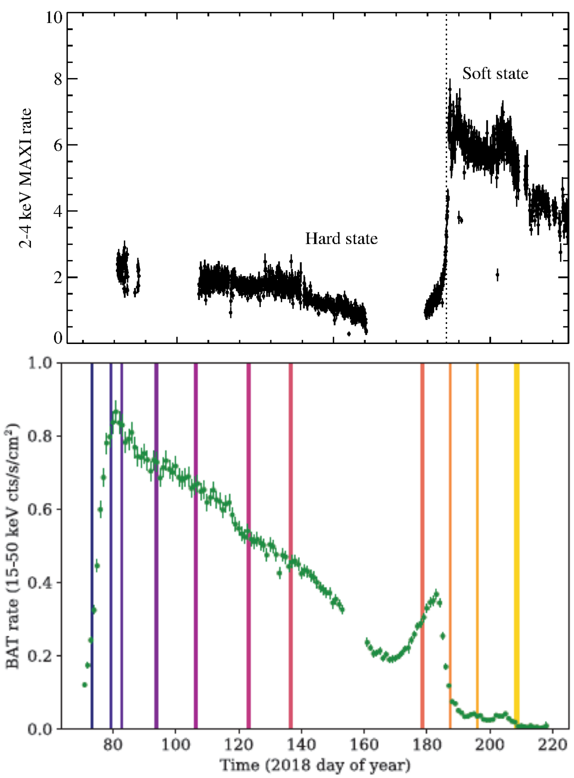


3-79 keV *NuSTAR* spectra (King+14; Fuerst+15)

- Sudden transitions during an outburst from XTE J1752-223

- Soft state: ~1 keV thermal plus power-law
- Hard state: Γ ~ 1.4-1.8 power-law

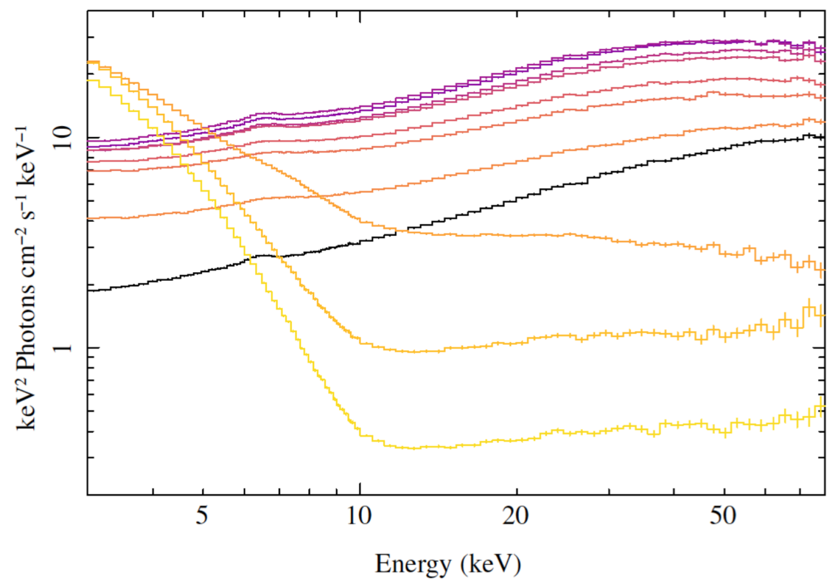
A Recent Example



Soft X-rays:
2-4 keV

Hard X-rays:
15-50 keV

Fabian et al., in prep.



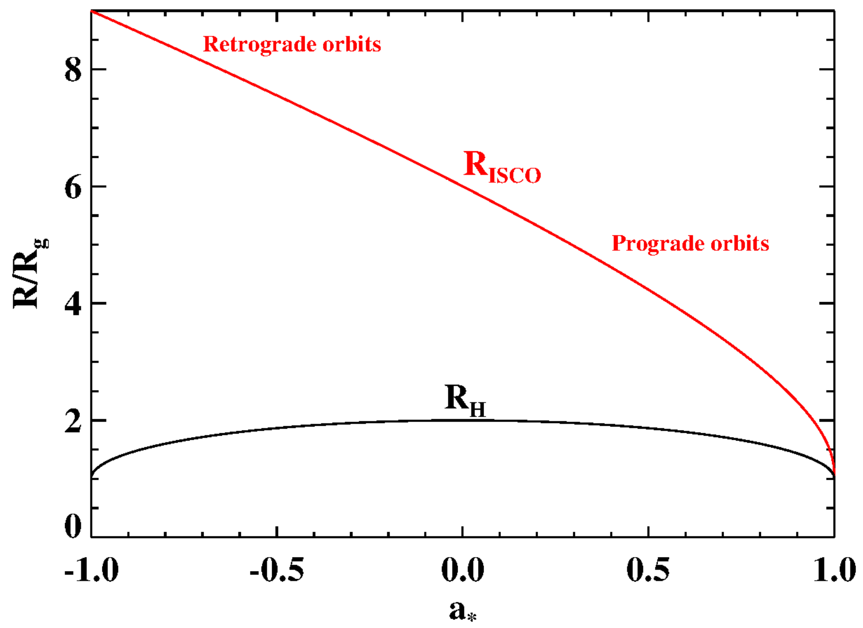
- New: MAXI J1820+070
  - Very bright source
  - >100 day hard state
- 3-79 keV *NuSTAR* spectra
  - Hard state: $\Gamma \sim 1.4$-1.8 power-law
  - Soft state: ~1 keV thermal plus power-law

BH spin definitions and radii

- Characterized by:
  - Mass: M
  - Spin: $a_* = Jc/GM^2$

  (Charge: Q=0 assumed)
- $-1<a_*<1$

  (solutions for R_H are imaginary outside this range)
- R_{ISCO} depends strongly on a_*



- R_{ISCO} = innermost stable circular orbit
- R_H = event horizon

(in units of
R_g = gravitational radius = GM/c^2)

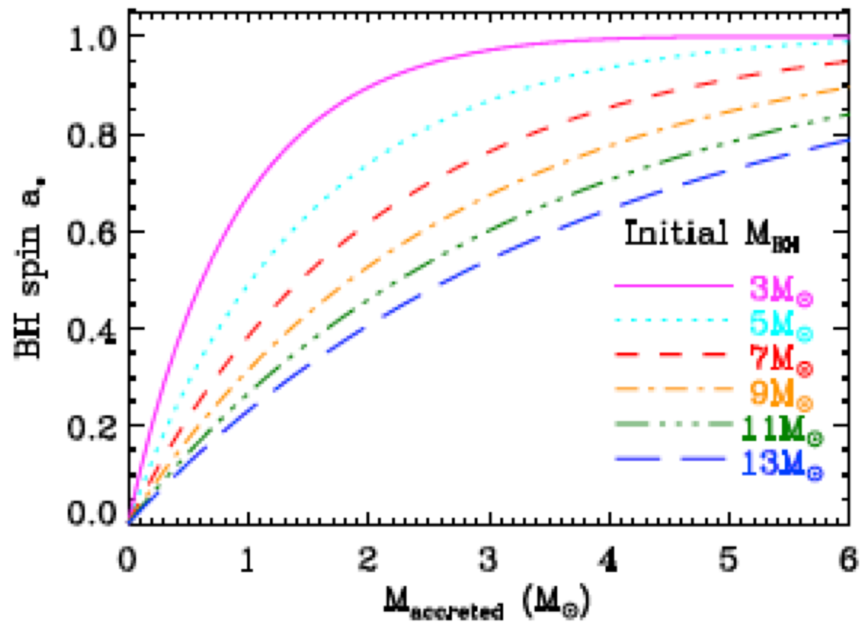
Why measure BH spin?

- How are relativistic jets powered and launched?
- To probe the strong gravity in the inner disk
- What do BH spins tell us about their formation and evolution?

HMXBs accrete for <10^7 years

- Even at ~10^{-7} M_{sun}/year, the spin does not change very much
- BHs in HMXBs are likely born with their current spin

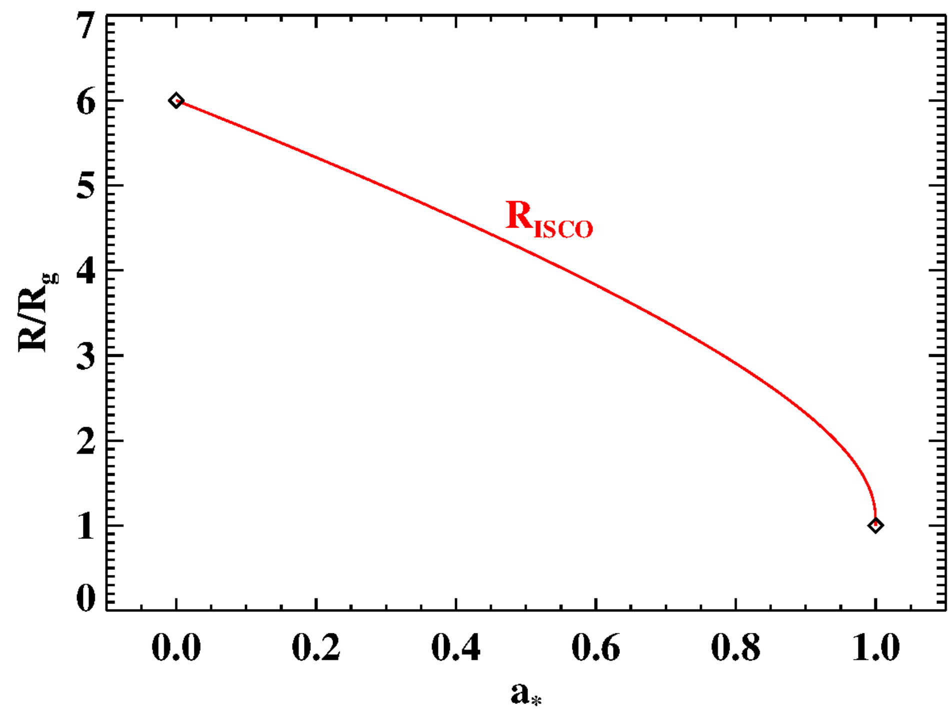
LMXBs have lifetimes of ~10^9 years, but there is not enough mass to significantly change the spin unless the BH mass starts off being very low



Fragos & McClintock (2015)

Measuring BH spin for BH binaries

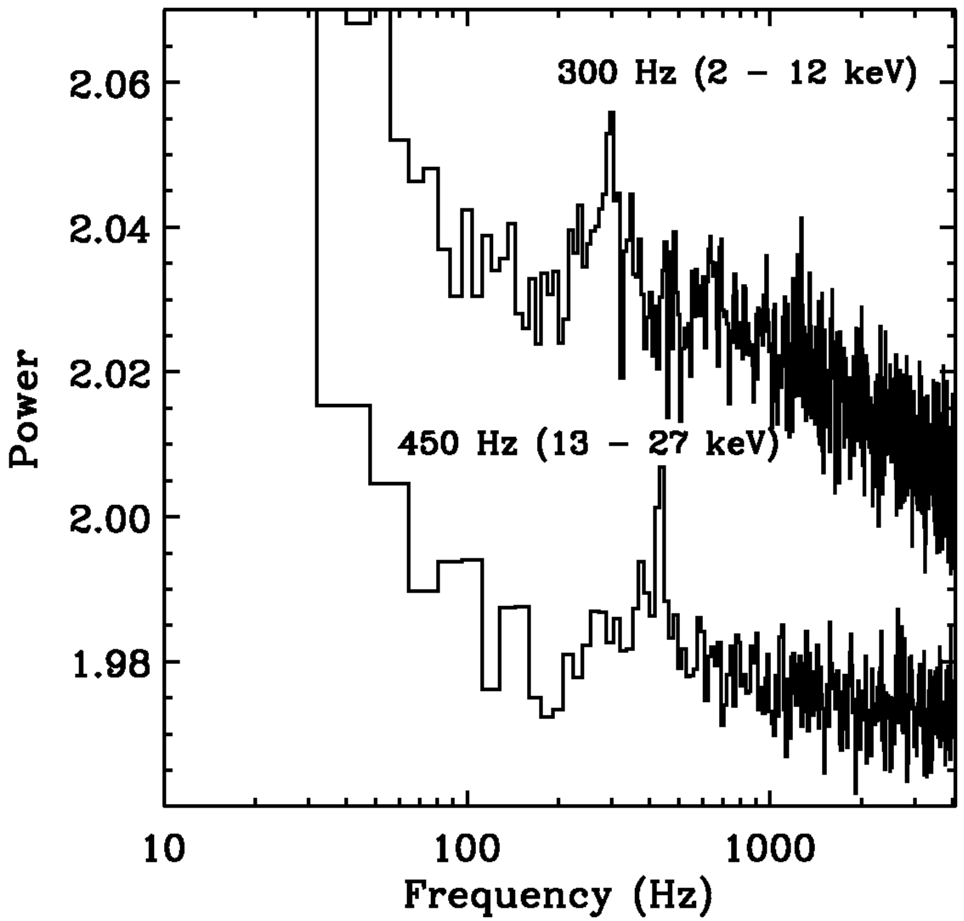
- All three X-ray methods for measuring a_* rely on constraining the inner radius of the accretion disk (R_{in})
- If R_{in}<$6R_g$, we immediately constrain a_* since $R_{ISCO} \leq R_{in}$

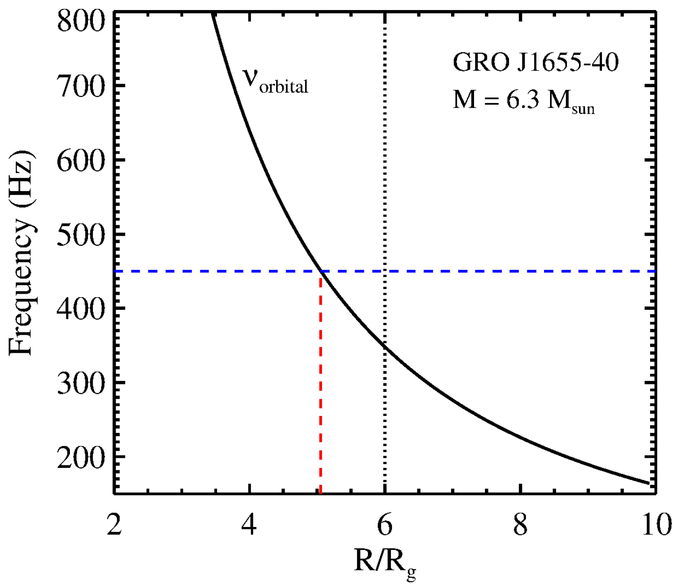


Example:

- Measure R_{in} = 5 R_g
- $R_{ISCO} \leq 5\ R_g$
- $a_* \geq 0.29$
- Lower limit on a_*

X-ray Timing: High Frequency Quasi-Periodic Oscillations (QPOs)



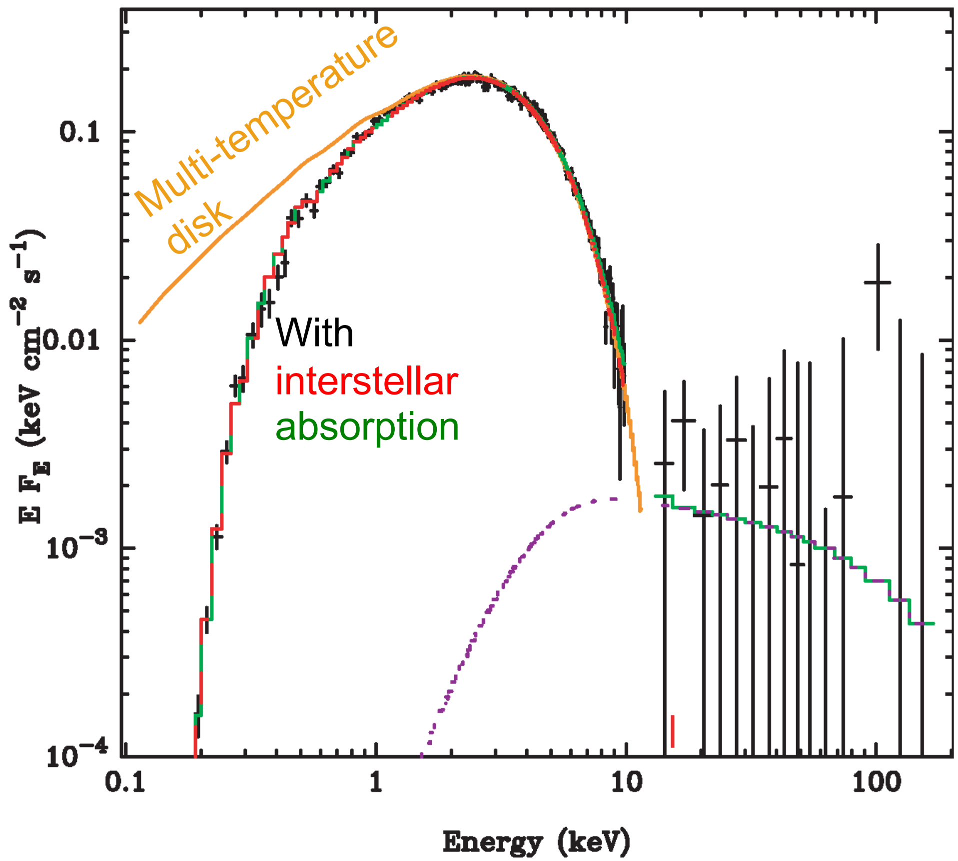


- 450 Hz signal seen by *RXTE*

- 450 Hz signal for GRO J1655-40 proves that the BH must be spinning (Strohmayer 2001)
- $a_* > 0.29$

Modeling spectra to constrain BH spin: Thermal

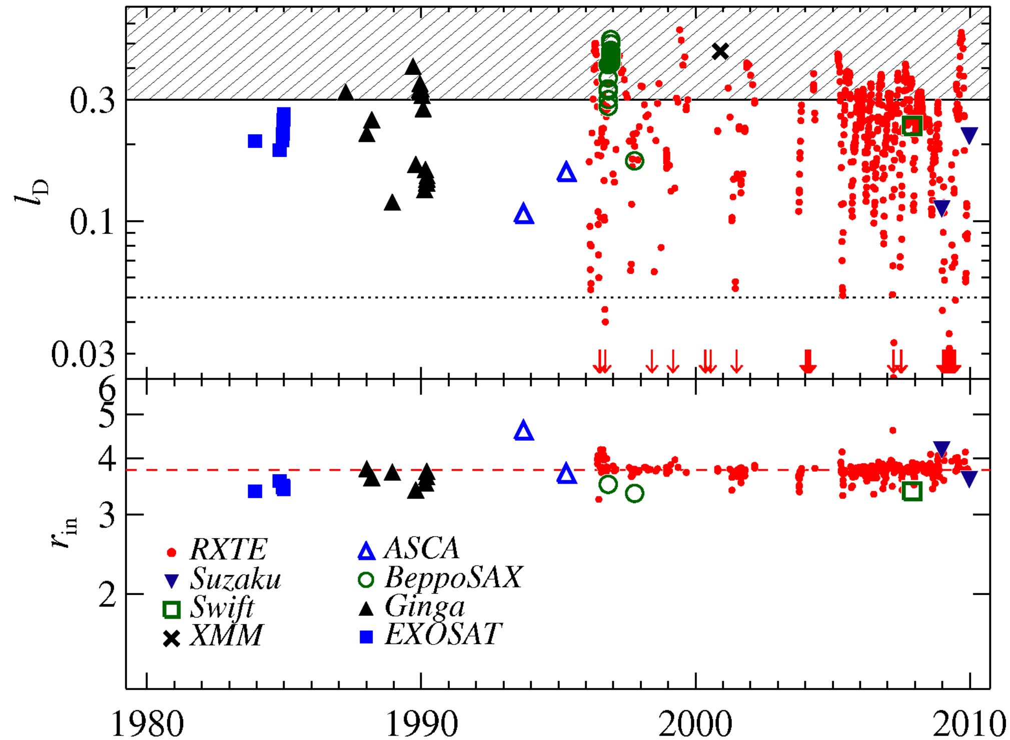
- Measuring a_* by modeling the thermal component
  - Free parameters are R_{in} (a_*) and dM/dt
- Concept is simple, but you need to know:
  - M_{BH}
  - Source distance
  - Inner disk inclination



Modeling the LMC X-3 thermal component (Davis+06; Steiner+10; Steiner +14 McClintock+14)

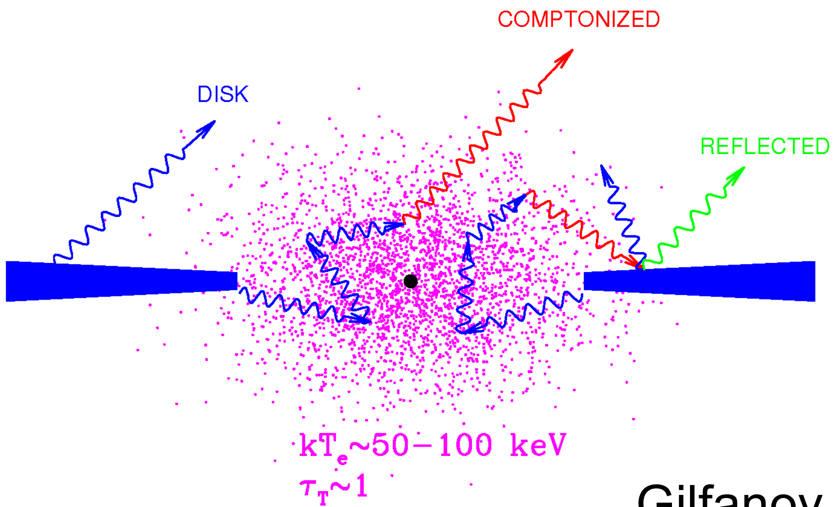
Stability of R_{in}

- For LMC X-3, R_{in} stayed in a very narrow range while the source luminosity varied by a large factor
- Suggests that R_{in} reached R_{ISCO}
- $M_{BH} = 7.0 \pm 0.6\ M_{sun}$ gives:
  - $R_{in} = 5.2^{+1.0}_{-0.7}\ R_g$
  - $a_* = 0.25^{+0.20}_{-0.29}$
  - Steiner+14

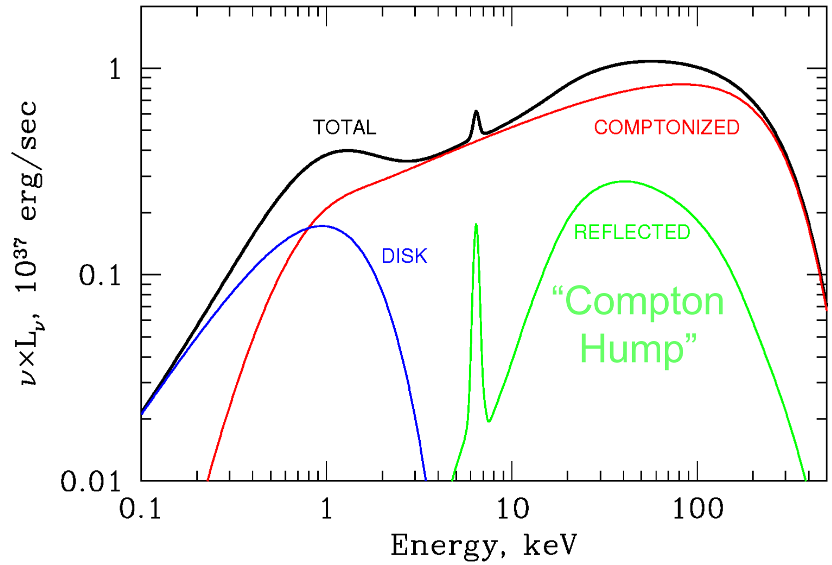


LMC X-3 luminosity and R_{in}, ***assuming*** a BH mass of 10 M_{sun} (Steiner+10)

Emission components (direct and reflected)

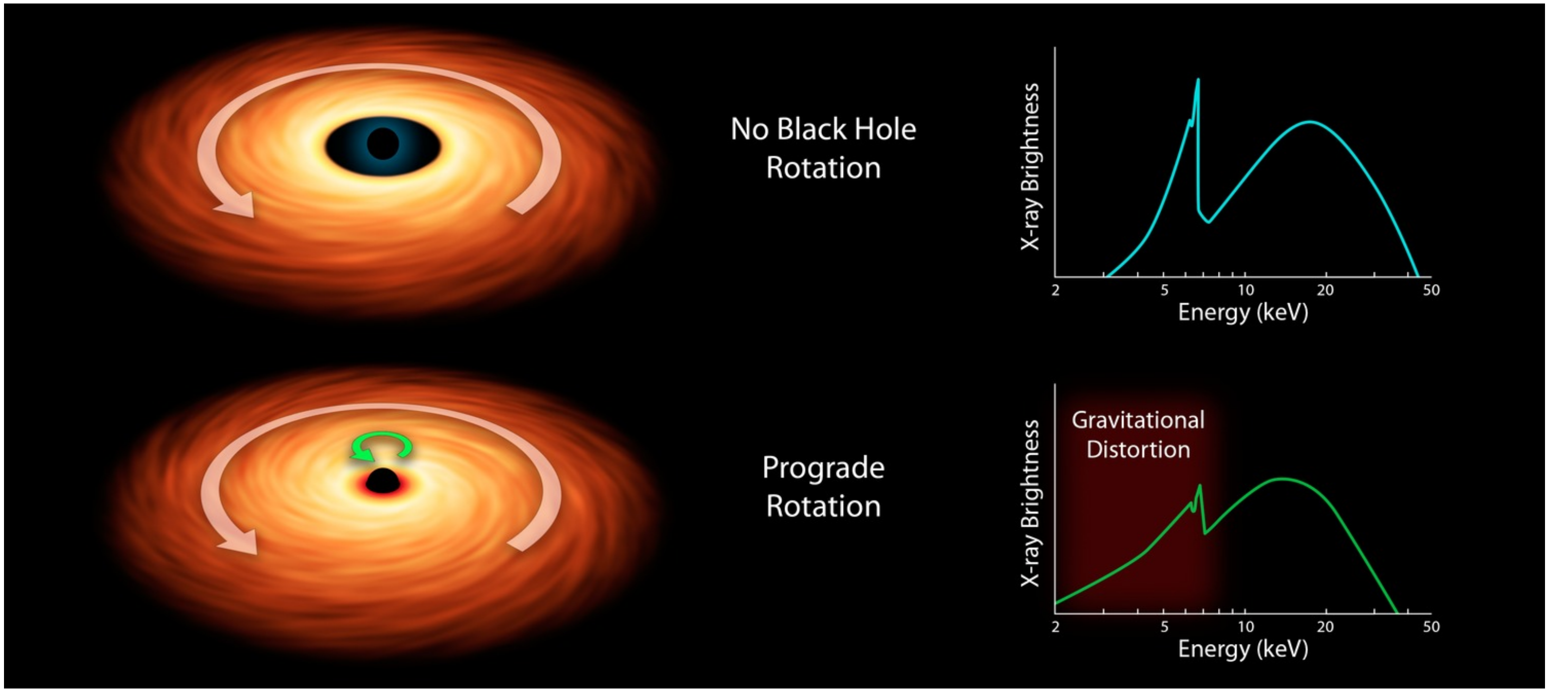


Gilfanov 2010



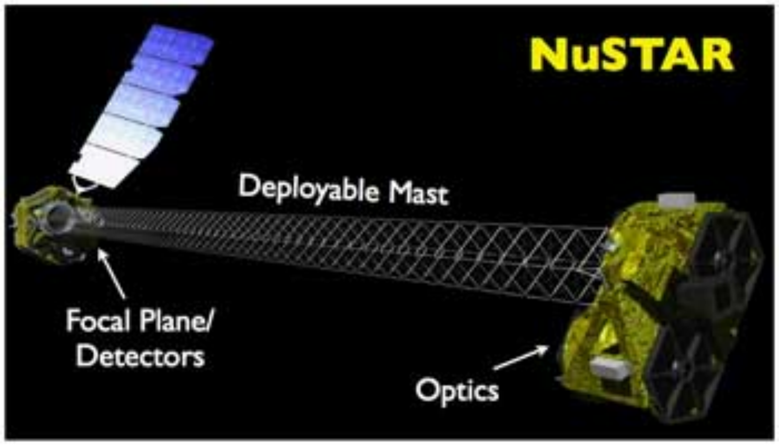
- Direct components
  - Thermal blackbody emission from the disk
  - High energy component from the "corona"
- Reflection signatures include:
  - Iron emission line (fluorescence from disk material)
  - Iron absorption edge (absorption in disk material)
  - Compton hump (scattering off disk material)

Using reflection to measure BH spin



- Model reflection component to measure R_{in} and constrain or measure a_*
- Critical region of the spectrum a few to ~50 keV

The Nuclear Spectroscopic Telescope Array



- Harrison+13
- Hard X-ray optics
- 10 meter deployable mast
- CdZnTe detectors

Energy Range:	3-79 keV
Angular Resolution:	58 arcsec (HPD) 18 arcsec (FWHM)
Sensitivity (3σ, 1 Ms):	2×10^{-15} erg/cm^2/s (6-10 keV) 1×10^{-14} erg/cm^2/s (10-30 keV)
Field of View:	12 x 12 arcmin
Spectral Resolution:	400 eV at 6 keV 900 eV at 60 keV
Effective Area:	900 cm^2 at 9 keV 100 cm^2 at 60 keV
Throughput	**~400 events/s/module (limited by deadtime but there is no pileup)**

Reflection measurements with NuSTAR

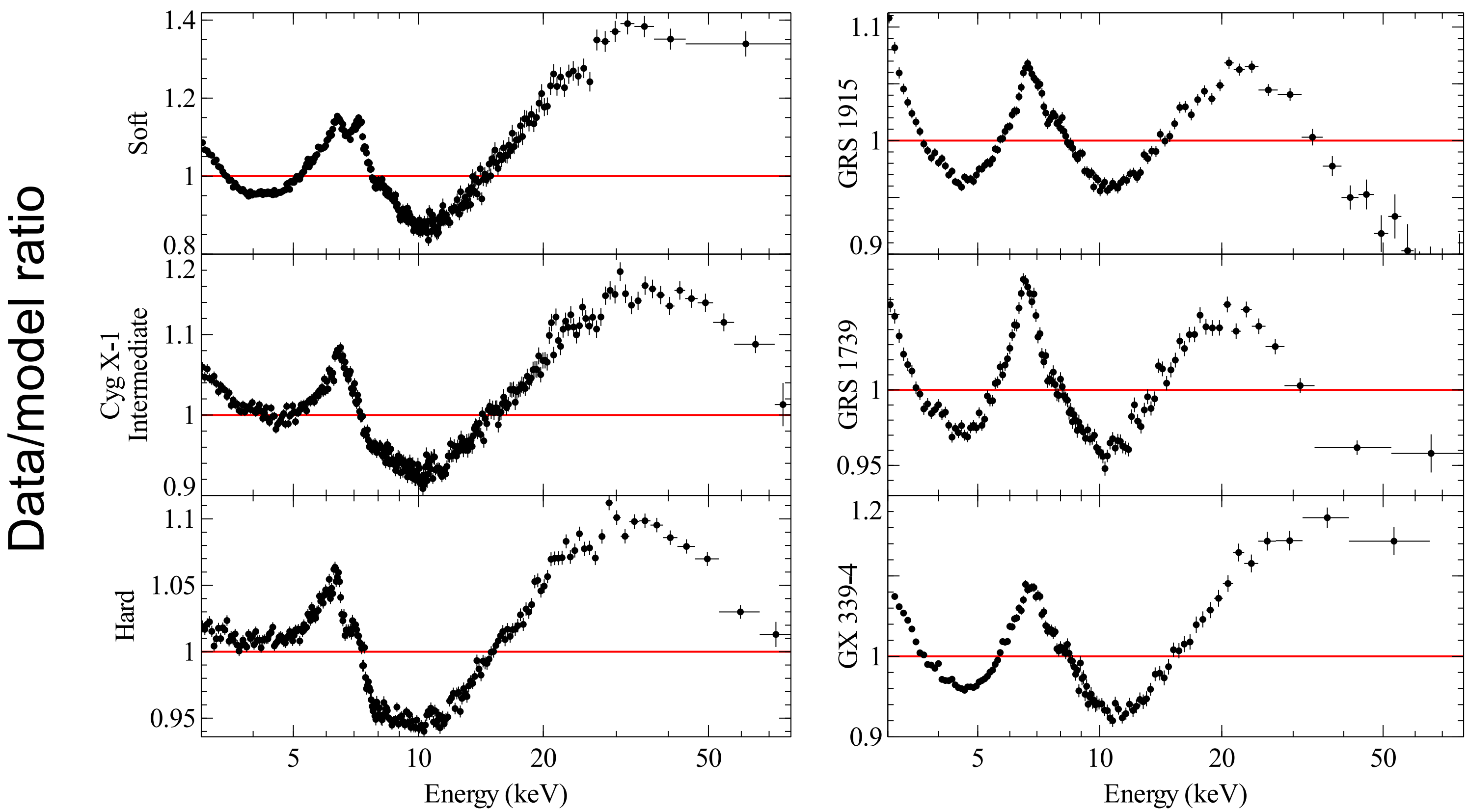


Figure credit: Michael Parker

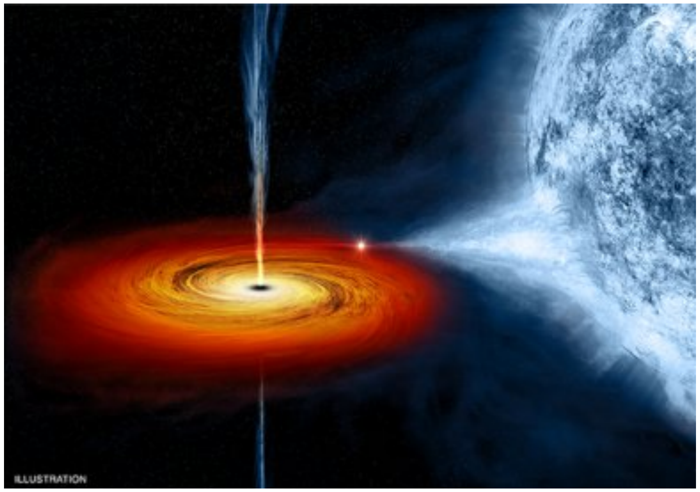
Results published in:

- Miller+13
- Tomsick+14
- Miller+15
- Parker+15
- Walton+16
- Parker+16
- Tomsick+18

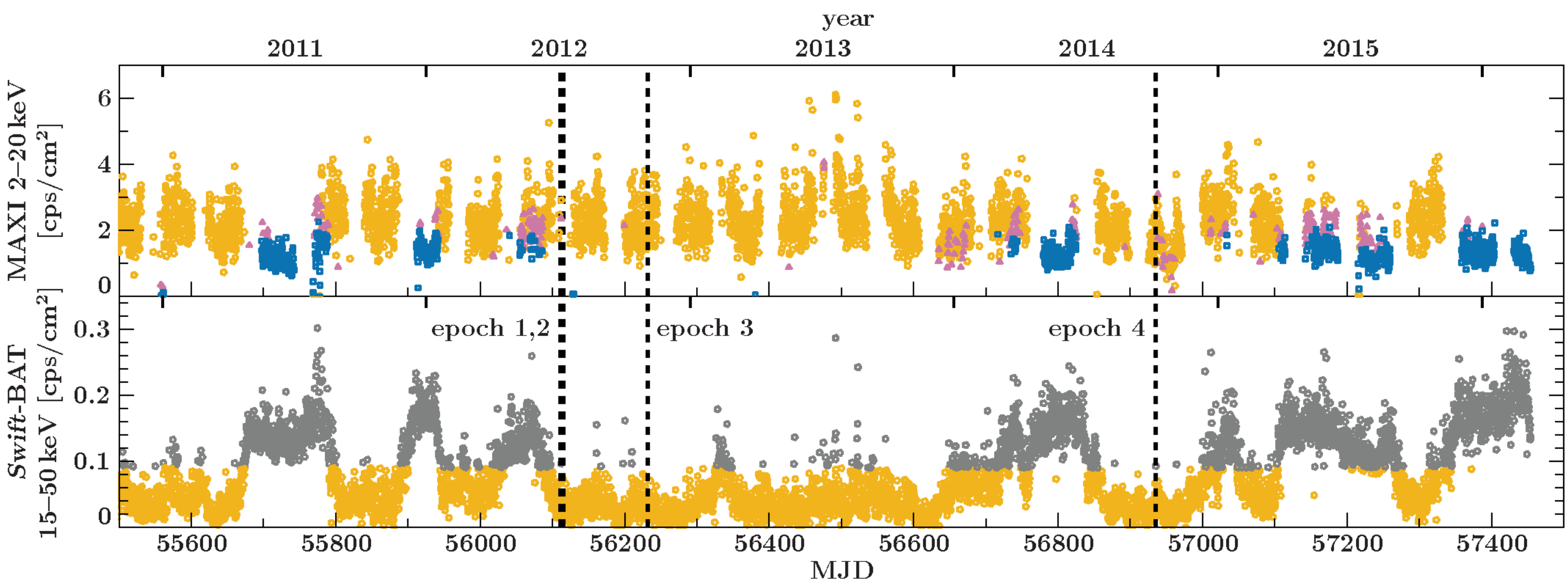
- Residuals to a power-law continuum model

Cyg X-1

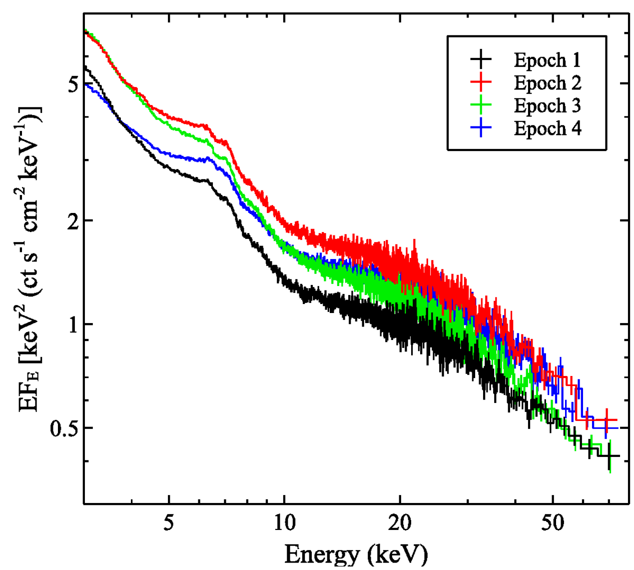
- Binary parameters from Orosz+11
  - P_{orb} = 5.6 days
  - $M_{BH} = 14.8 \pm 1.0\ M_{sun}$
  - $M_{opt} = 19.2 \pm 1.9\ M_{sun}$ (HMXB)
  - $i = 27.1^o \pm 0.8^o$
- Parallax distance measurements
  - $d = 1.86^{+0.12}_{-0.11}$ kpc (Reid+11)
  - $d = 2.37 \pm 0.18$ kpc (Gaia2)
- Bright with strong X-ray emission since its discovery in the 1960s



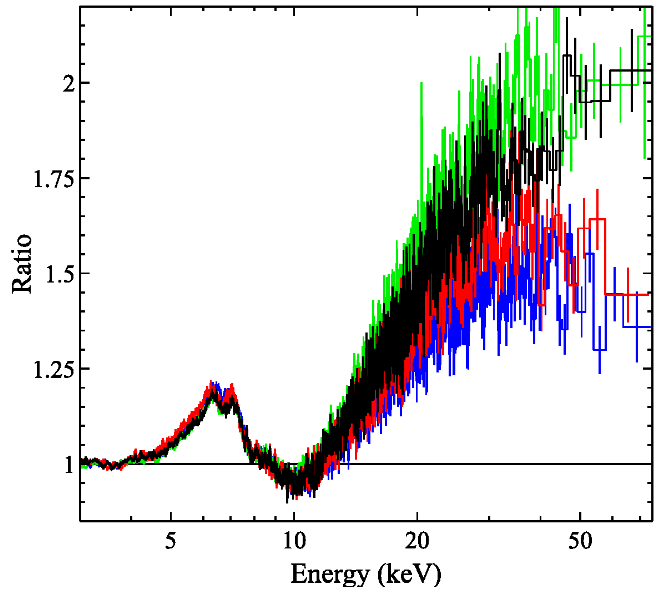
Cyg X-1 light curves and spectra



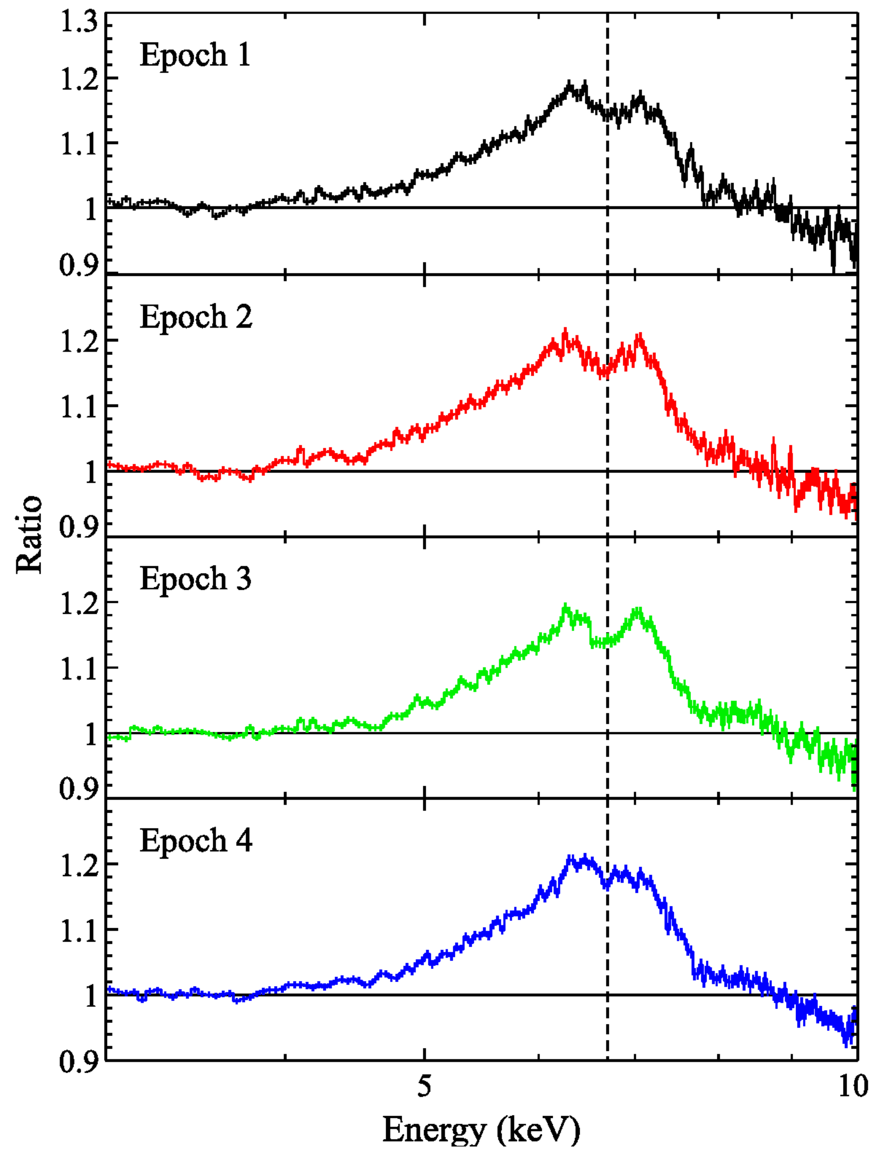
- Four observations of Cyg X-1 in the soft state (Walton+16)



Cyg X-1 spectra: model-independent look



- Dip at 6.7 keV due to absorption by stellar wind
- All profiles show red wing due to gravitational redshift



Orbital phase

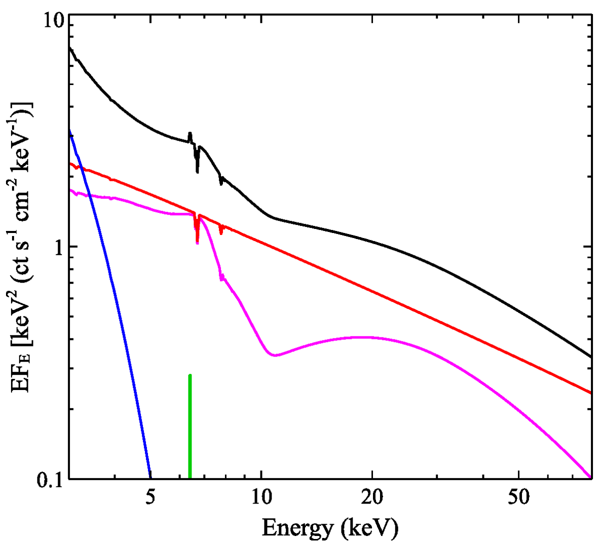
0.26-0.37

0.97-0.09

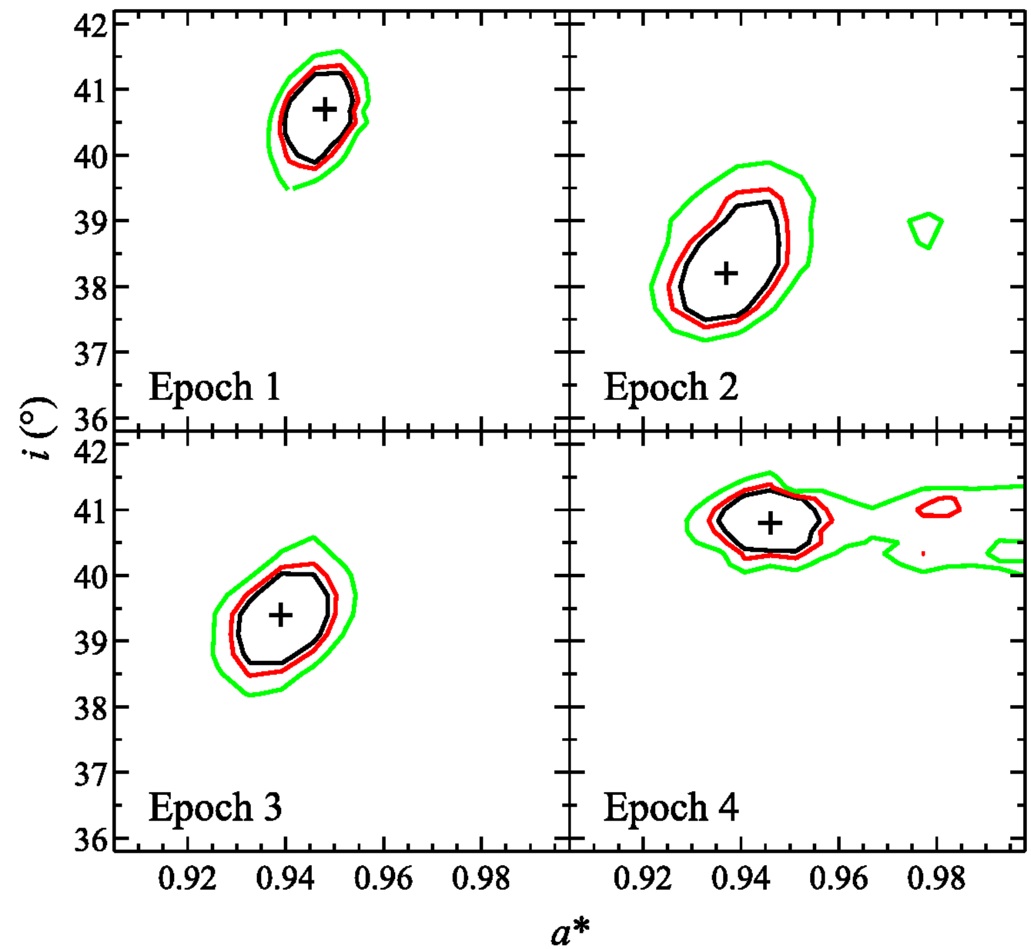
0.85-0.99

0.49-0.59

Applying reflection model to Cyg X-1 soft state spectra: BH spin and inclination constraints



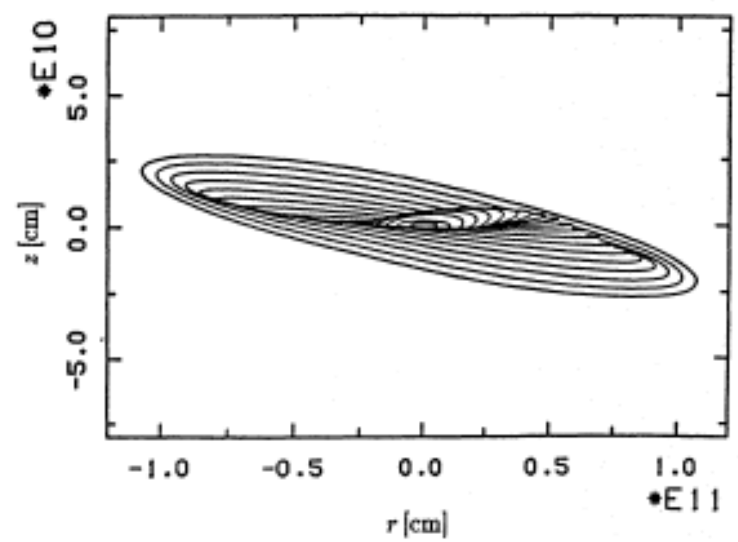
- $0.93 < a_* < 0.96$
- $37° < i < 42°$
  - Inner disk inclination



Walton et al. 2016

Warped disk?

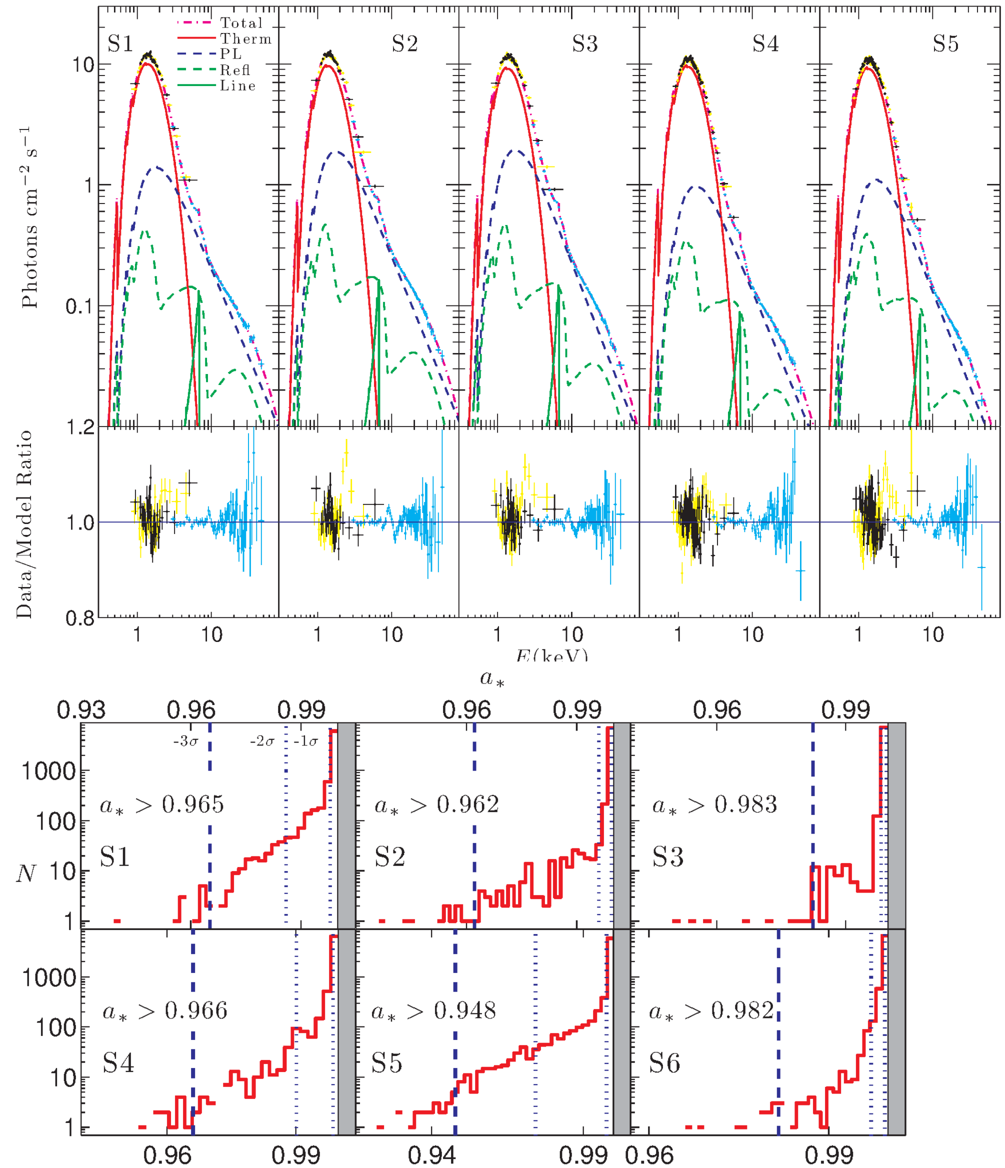
- From three *NuSTAR* studies
  - i > 40º (Tomsick+2014)
  - i = 45.3º±0.4º (Parker+2015)
  - 37º<i<42º (Walton+2016)
- These are significantly higher than the measured binary inclination (27.1º±0.8º)
- Possible misalignment between the BH spin axis and the orbital angular momentum vector



- Warped disk calculation by Schandl & Meyer (1994)
- See also King & Nixon (2016)

Cyg X-1 thermal method

- $a_*>0.983$
  - i = 27.1º (binary)
  - Gou, McClintock, Remillard, et al. 2014
- $a_* \sim 0.96$
  - i = 40º (Walton+16)
- With the higher inclination, the thermal agrees better with the reflection (0.93-0.96)



BH spin with NuSTAR reflection measurements

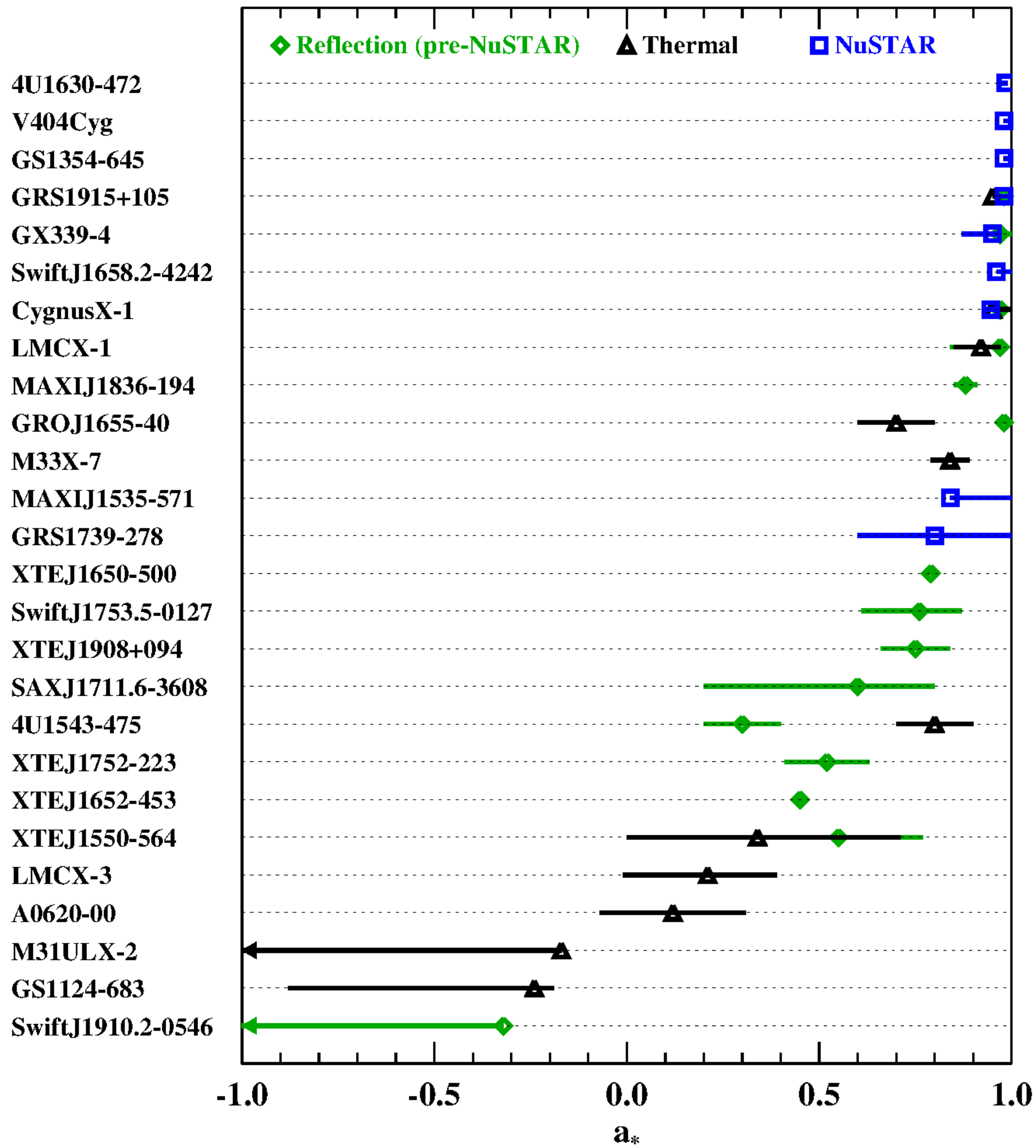
Source Name	Spin Parameter	Reference
GRS 1915+105	0.98 ± 0.01	Miller et al. 2013
4U 1630-47	$0.985^{+0.005}_{-0.014}$	King et al. 2014
GX 339-4	$0.95^{+0.02}_{-0.08}$	Parker et al. 2016
Cyg X-1	0.93-0.96	Walton et al. 2016
GS 1354-645	>0.98	El-Batal et al. 2016
V404 Cyg	>0.98 (if i>50º)	Walton et al. 2016
GRS 1739-278	0.8 ± 0.2	Miller et al. 2015
MAXI J1535-571	>0.84	Xu et al. 2018
Swift J1658.2-4242	>0.96	Xu et al. 2018

BH spin for X-ray binaries

- Spins for 26 systems
- Good agreement between methods in most cases
- Mostly (but not exclusively) high spin

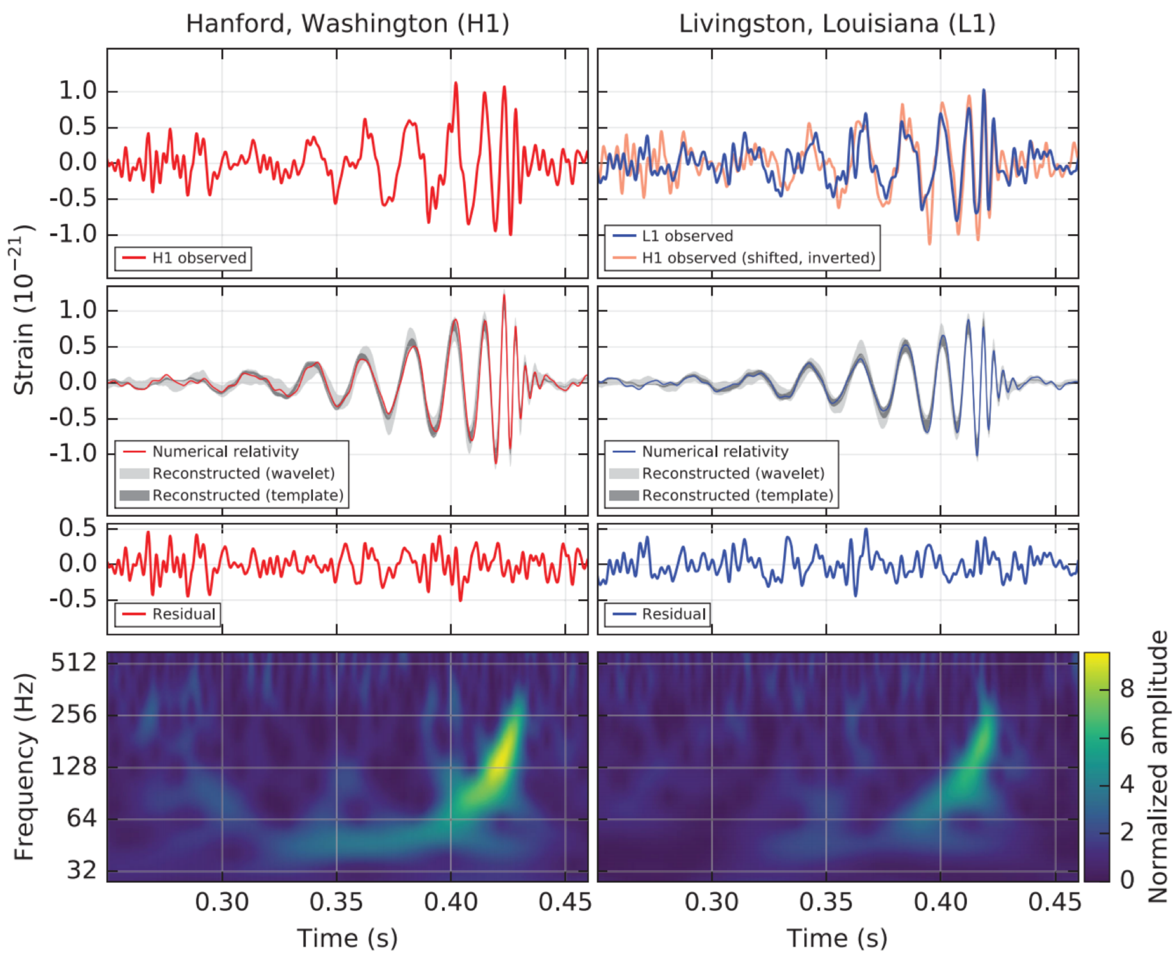
References:

- Miller & Miller 2015
- Middleton 2016
- *NuSTAR* refs



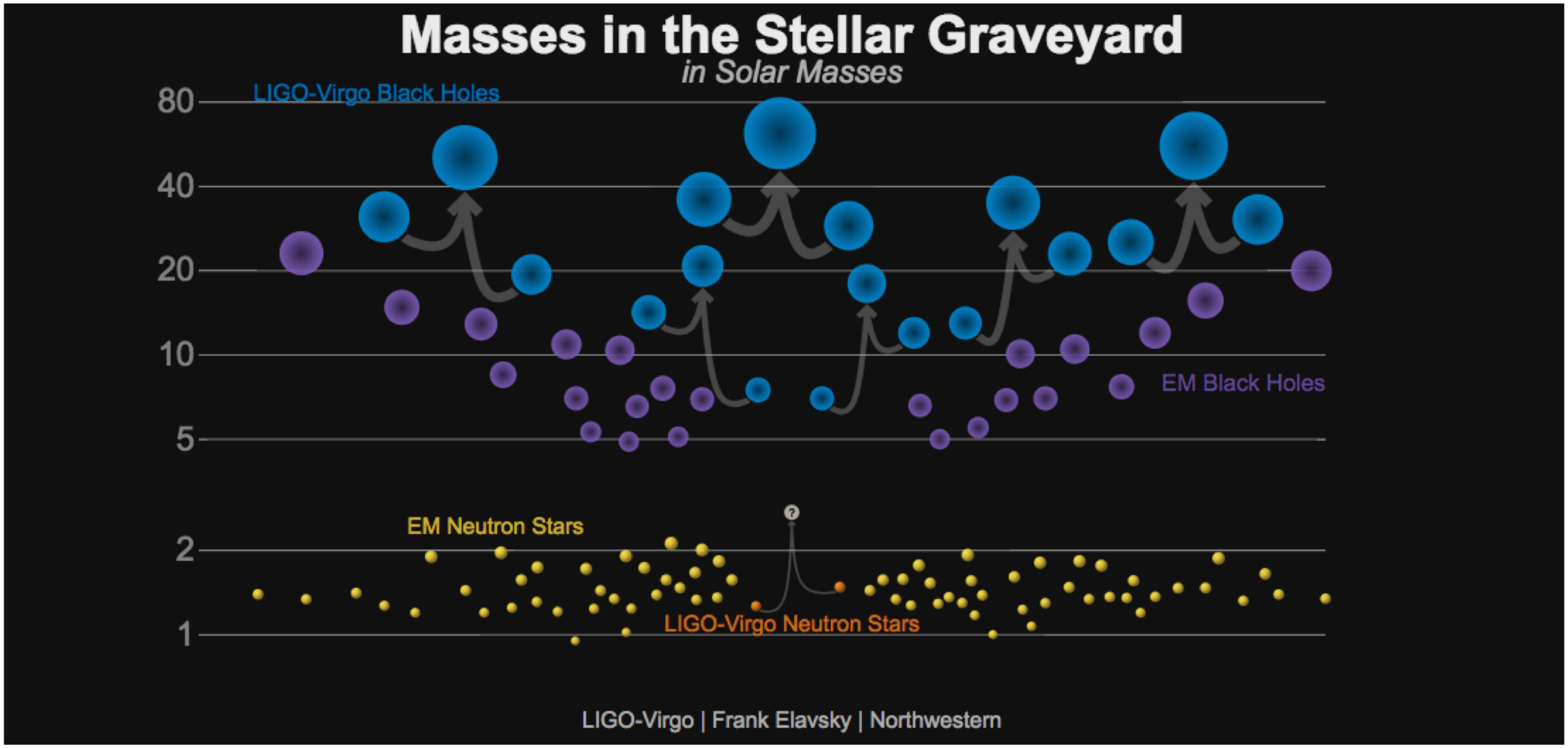
Gravitational wave measurements

- GW 150914
- Merger of 36 and 29 M_{sun} BHs
- Wow!



Abbott+16

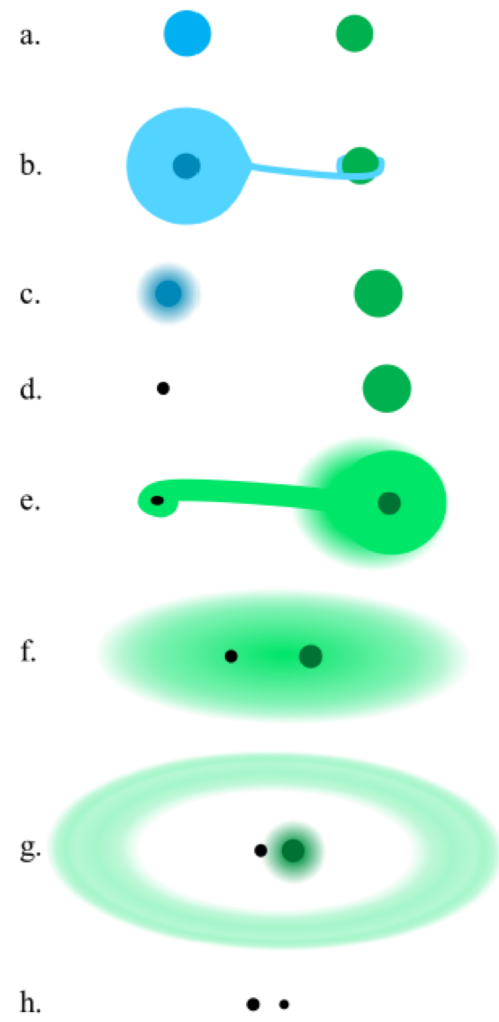
Gravitational wave measurements - masses



- Six BH-BH mergers reported during LIGO O1 and O2 runs
- Are X-ray binaries the main progenitors of BH-BHs?

BH-BH formation: X-ray binary scenario

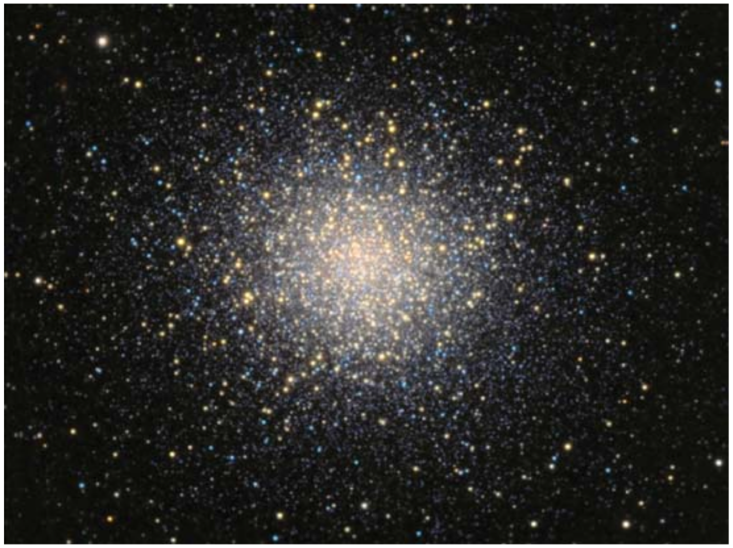
- This scenario can include 2 high-mass X-ray binary (HMXB) phases
- BH/Wolf-Rayet binaries
  - IC10 X-1
  - NGC 300 X-1
  - Cyg X-3 (BH?)
  - Candidates
    - CG X-1 (Esposito+15)
    - NGC 253 (Hornschemeier+18)



Mandel & Farmer (2018)
See also Belczynski+16

BH-BH formation: Capture scenario

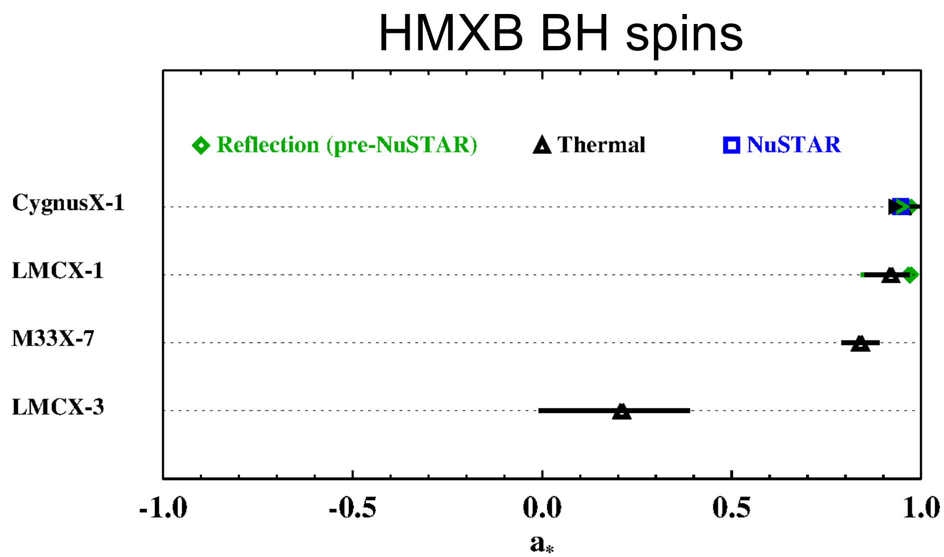
- Likely BHs in GCs
  - NGC 4472 (Maccarone+07)
  - 47 Tuc (Miller-Jones+15)
  - M22 (Strader+12)
  - M62 (Chomiuk+13)
- BH-BH merger predictions vs. actual
  - O1: 0.2-2 vs. 3 detections
  - O2: 3-45 vs. 3 detections
  - Rodriguez+16a

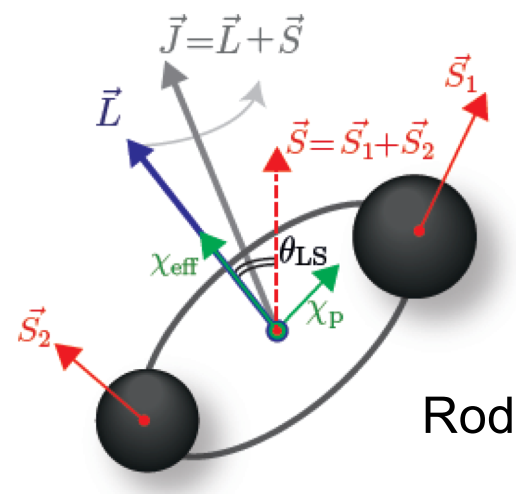


www.britannica.com
(generic globular cluster)

BH spins and X-ray binary vs. capture scenarios

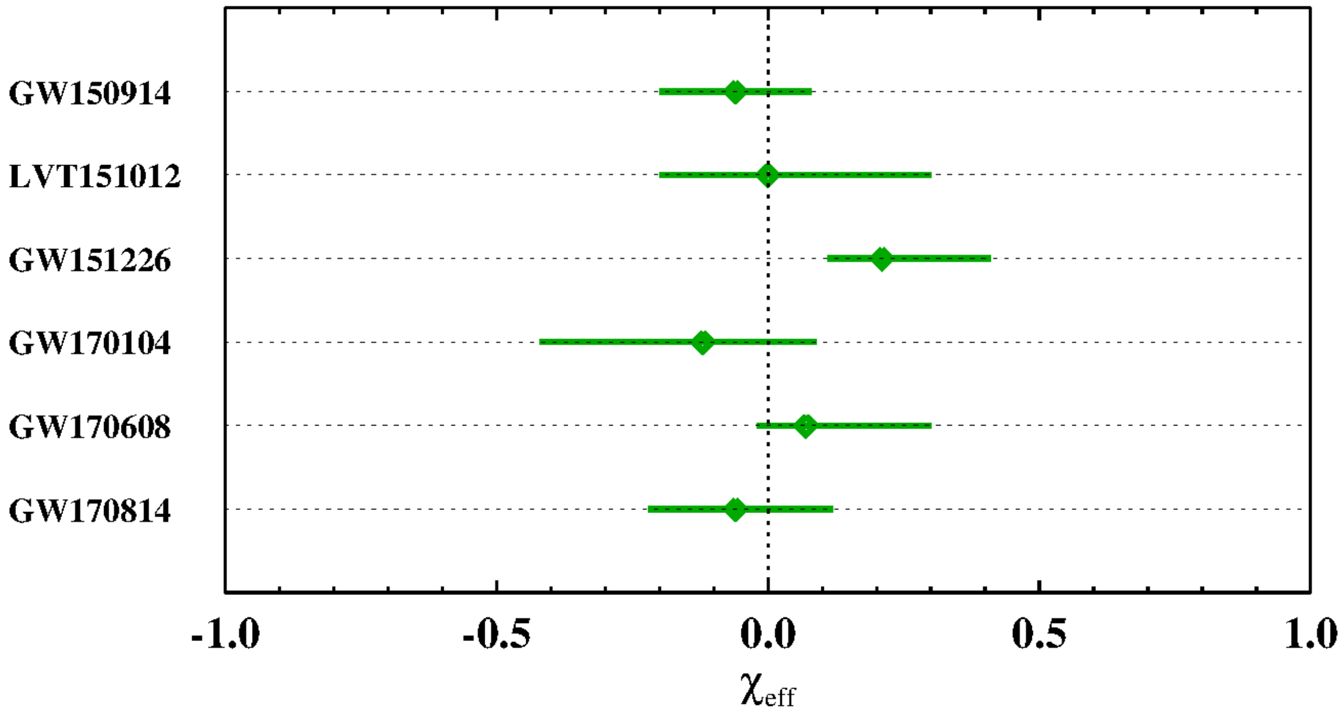
- X-ray binary predictions
  - High spins
  - Expect tendency to align with **L**
- Capture prediction
  - Isotropic spin directions





Rodriguez+16b

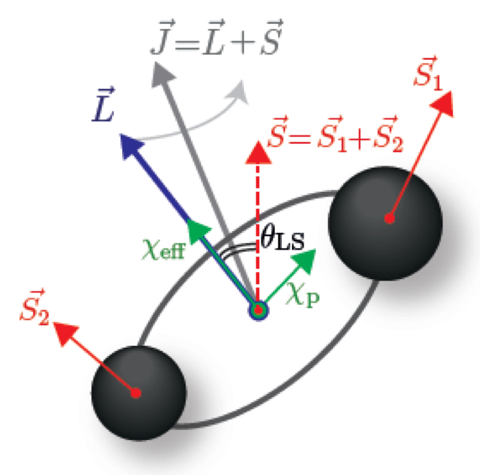
Effective spins from LIGO GW detections



Abbott+16
Abbott+17

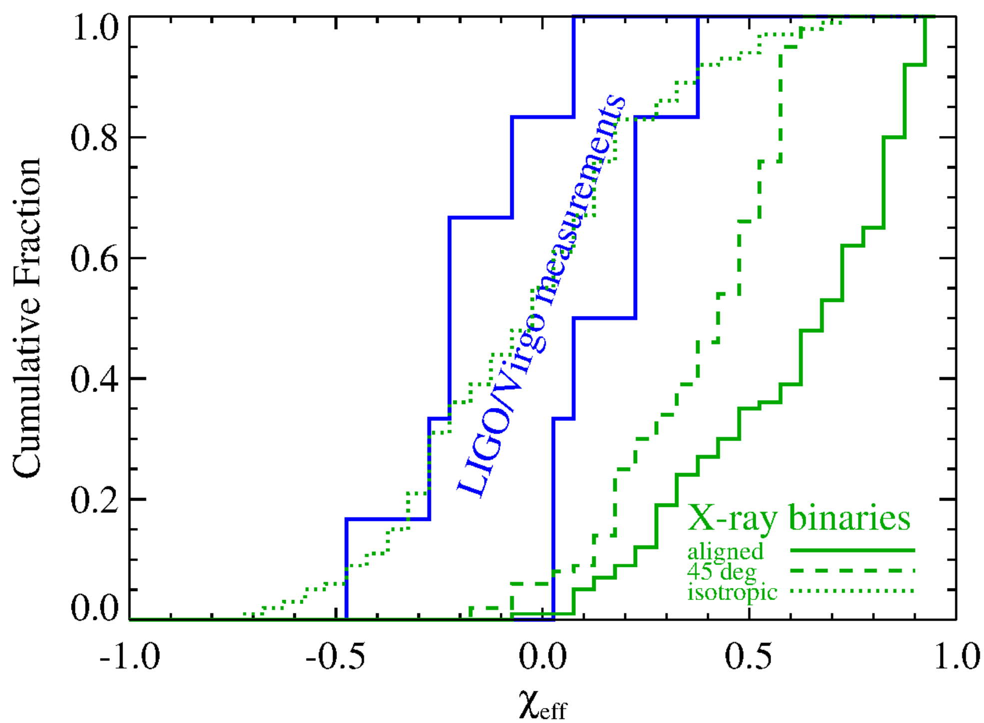
90% confidence errors

- $\chi_{eff} = (M_1\, a_1 \cos\theta_1 + M_2\, a_2 \cos\theta_2) / (M_1+M_2)$
- $\theta_{1,2}$ = angles between **L** and $\mathbf{S}_{1,2}$



χ_{eff} Comparison: BH-BH and X-ray binaries

- To compare, calculate possible χ_{eff} distribution from X-ray binary (XRB) a_* values
- For the aligned case, $\chi_{eff,XRB} >> \chi_{eff,BH\text{-}BH}$
- Also, looked at two other cases:
  - $\theta_1 = \theta_2 = 45$ deg
  - Isotropic θ's (not expected for XRBs)



Cumulative χ_{eff} distribution for:

- the actual BH-BH measurements and
- Values calculated by combining random pairs of X-ray binary spins

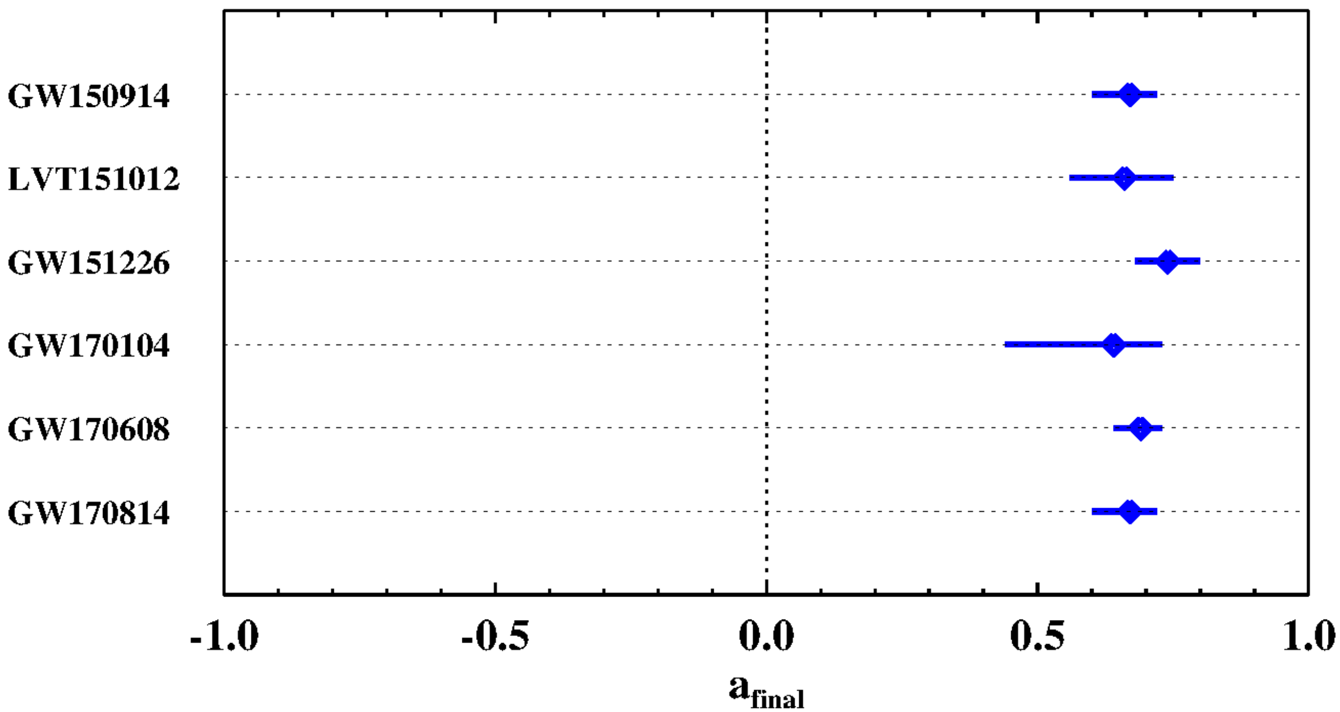
BH spin distribution – take away

- Looking like there is not a great match between the spins of BHs in X-ray binaries and BH-BHs
- Possible reasons
  - BH-BHs may be *mostly* from captures
  - XRBs may produce BH-BHs with misaligned spins (see, e.g., Piran & Hotekezaka 2018)
  - Selection effects?
  - Systematics?

Selection effects/systematics

- Selection effects for BH-BHs
  - Higher mass BHs may form with lower spin (Belczynski+17)
- Selection effects for X-ray binaries
  - Higher spin leads to stronger reflection
- Systematics for X-ray binaries
  - Reflection models depend on input physics
  - Thermal method depends on inner disk inclination

Spin of BH after LIGO mergers



Abbott+16
Abbott+17

90% confidence errors

- Measured values as expected if $M_1 \sim M_2$
- Final spin from orbital angular momentum

BH spin techniques and future possibilities

- X-ray timing and HFQPOs
  - Need a mission like RXTE but larger
- Thermal technique
  - Need more sources with known distances, BH masses, and inner disk inclinations (nearby galaxies?)
- Reflection
  - Need to continue to improve the models
- Gravitational waves
  - Expecting more BH-BHs; looking forward to the first BH-NS
- X-ray polarization is another possibility