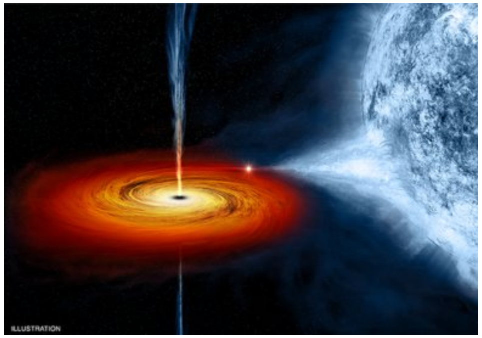

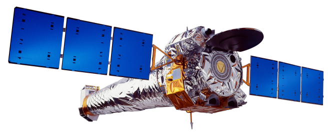

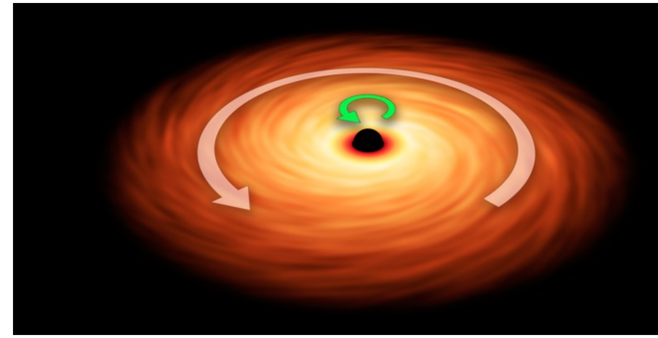

Hard X-ray observations of Galactic sources: the HMXB population and black hole spin

John Tomsick

Space Sciences Laboratory

UC Berkeley

SSL

UC Berkeley

Are HMXBs the progenitors of BH-BH binaries (BBH)?

- Massive binary evolution has two HMXB phases
  - However, we don't know of very many BH-HMXBs
  - Motivates searches for HMXBs
- BH spin should not change very much from formation to merger
  - HMXB spins should match BBH spins
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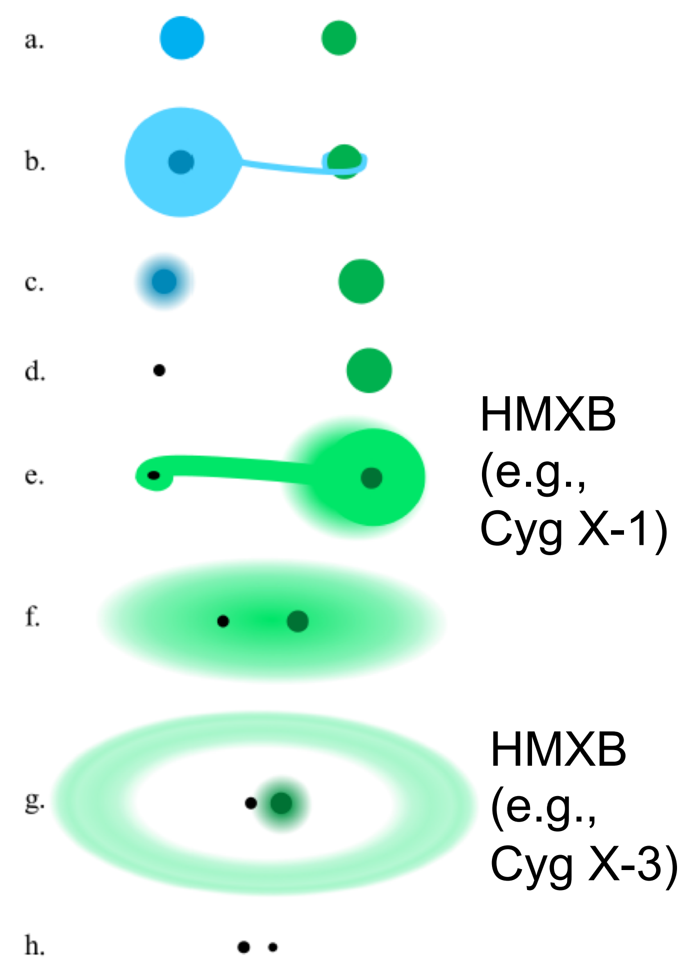

Mandel & Farmer (2018)
van den Heuvel 1976, 2018

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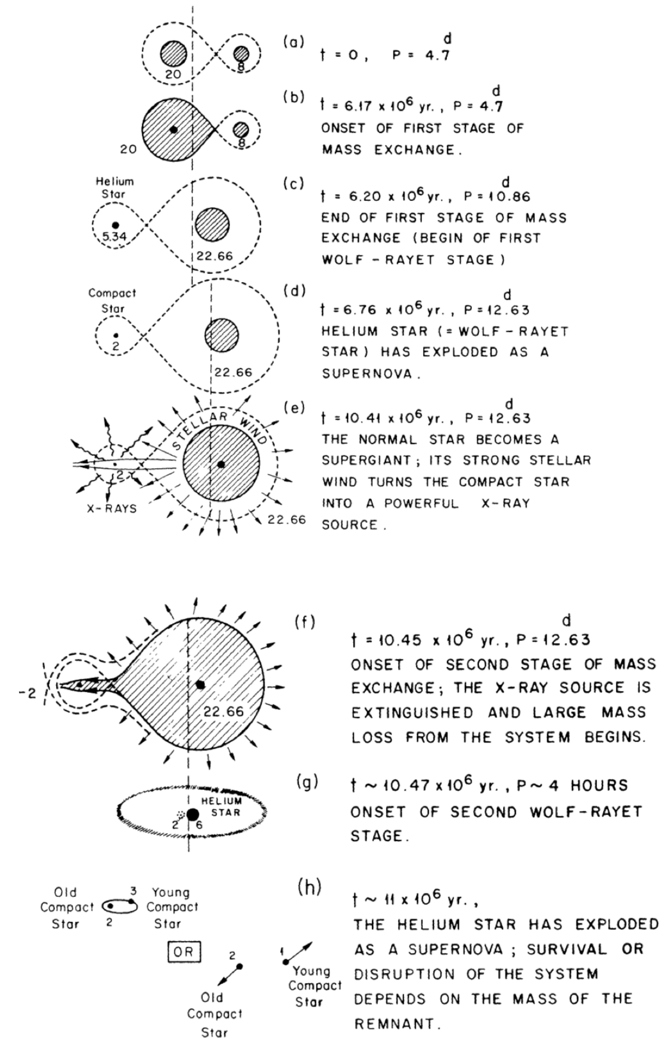

van den Heuvel 1976

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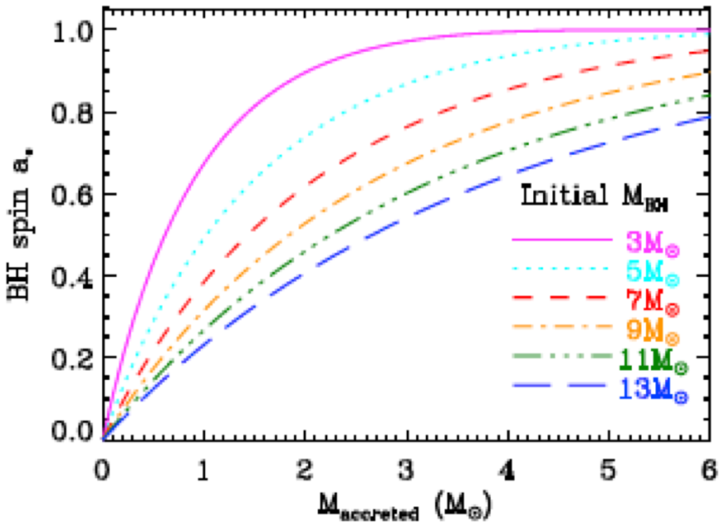
Fragos & McClintock (2015)



HMXBs accrete for $<10^{6\text{-}7}$ years

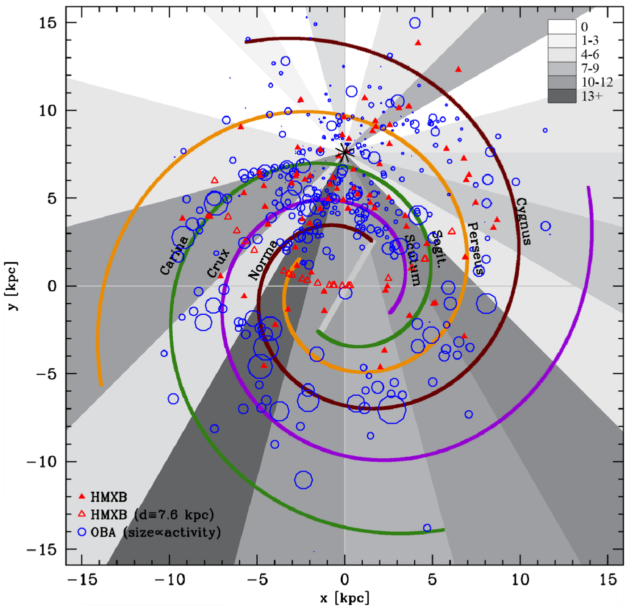
- Cyg X-1: $dM/dt \sim 5\times10^{-9}$ M_{sun}/year
- $L_{Edd} \sim 10^{-7}$ M_{sun}/year

Overview

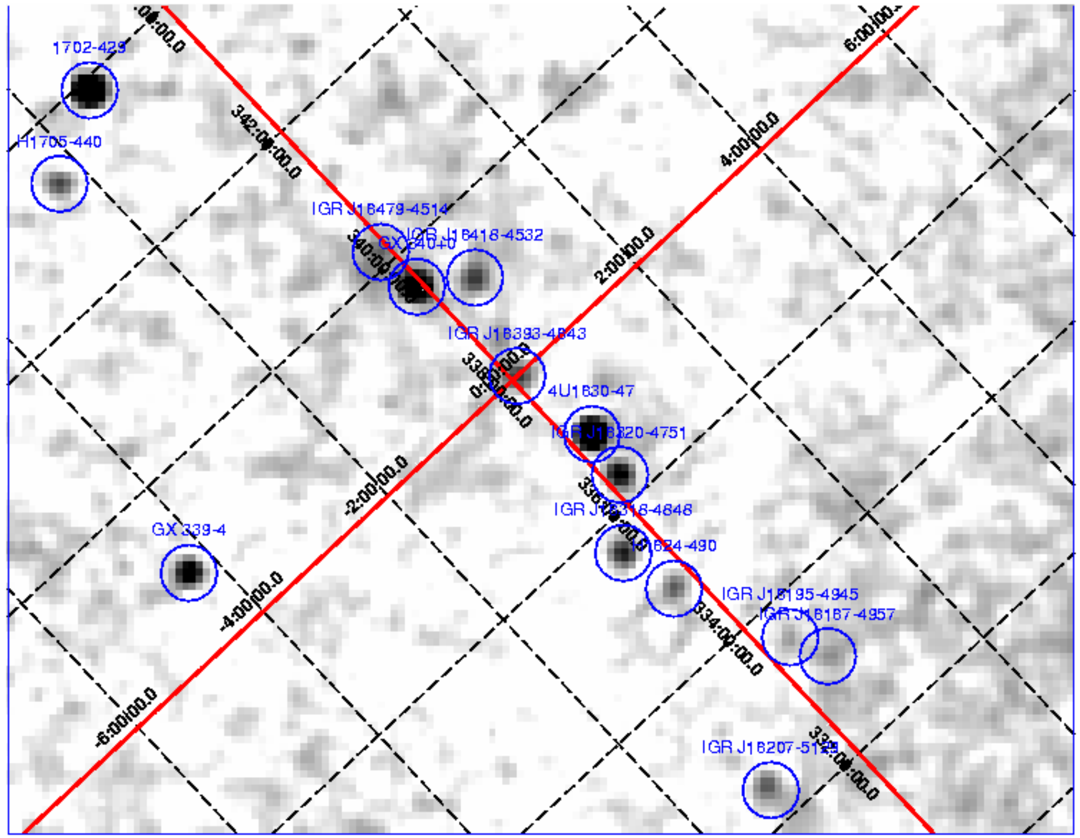
- Searches for HMXBs
  - Surveys with INTEGRAL and NuSTAR
  - Follow-up with NuSTAR, Chandra, and ground-based optical/NIR
- Black hole spin
  - Thermal and reflection methods
  - Improvements on reflection measurements with NuSTAR
  - Spins of BHs in HMXBs and in BBHs

HMXBs and INTEGRAL

- TOO observation of 4U 1630-47 in early 2003
- Turns out that Norma region is full of HMXBs



Bodaghee+12



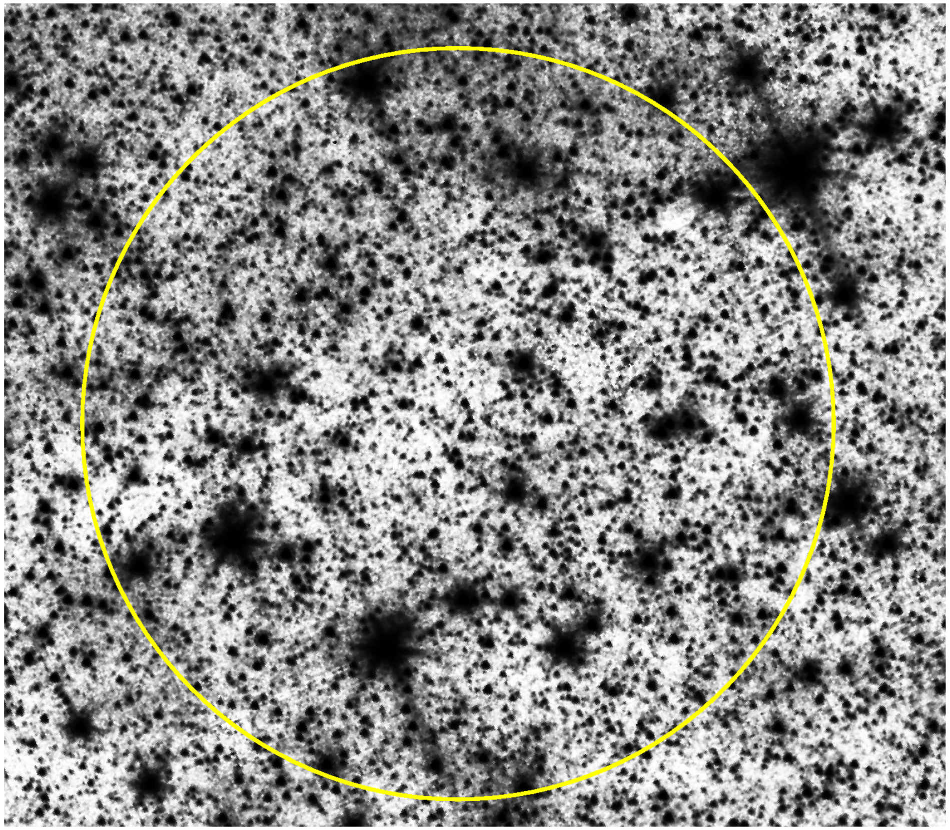
293 ks INTEGRAL/IBIS image
Tomsick+04 (proceedings of Munich workshop)

HMXB searches

- Chandra follow-up of IGR sources
- Norma Arm Region Chandra Survey (NARCS) and NuSTAR survey
  - Few HMXB candidates (Fornasini+14+17, Rahoui+14)
- Galactic Center NuSTAR survey
  - Few HMXB candidates (Hong+16)
- NuSTAR Legacy program to observe unidentified IGR sources
  - See talk by Maïca Clavel on Thursday
- NuSTAR serendipitous source survey

Chandra follow-up of IGR sources

- Going from few arcminute INTEGRAL positions to subarcsecond Chandra positions
- In total, we have obtained 68 Chandra counterparts



INTEGRAL 90% confidence error circle (3.3 arcminute radius) on a 3.6 micron Spitzer/GLIMPSE image

Chandra follow-up of IGR sources

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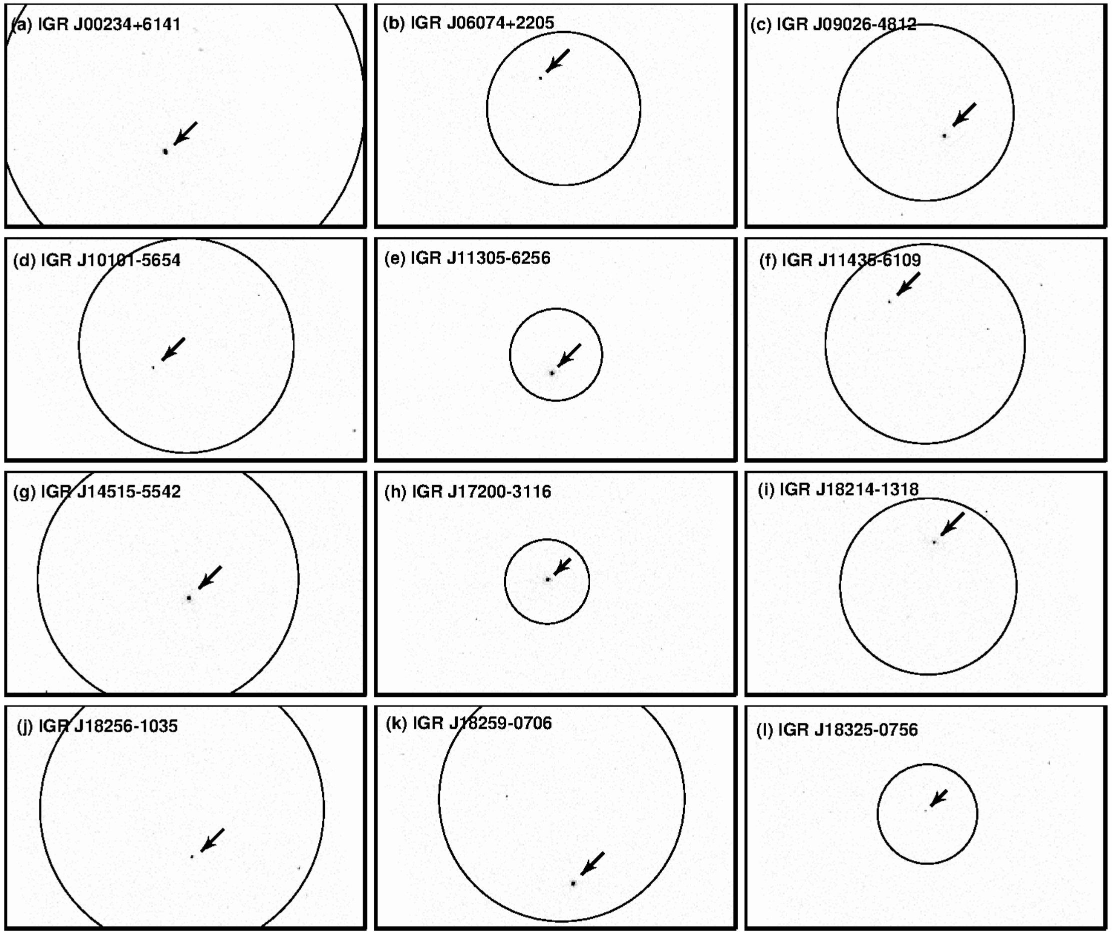
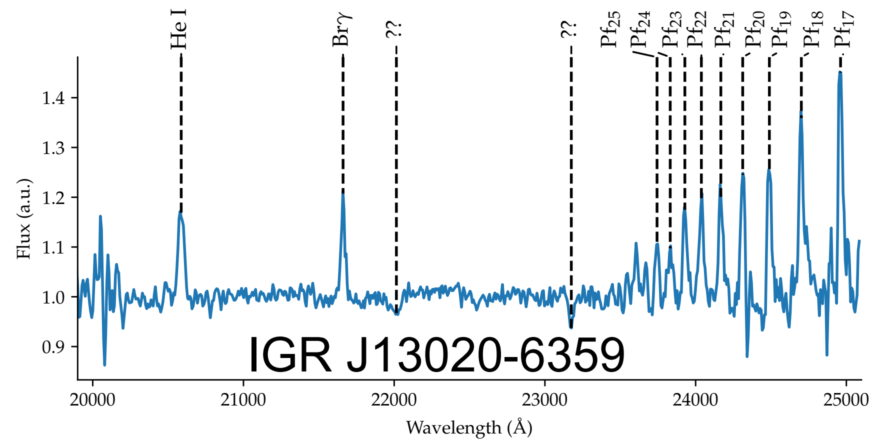
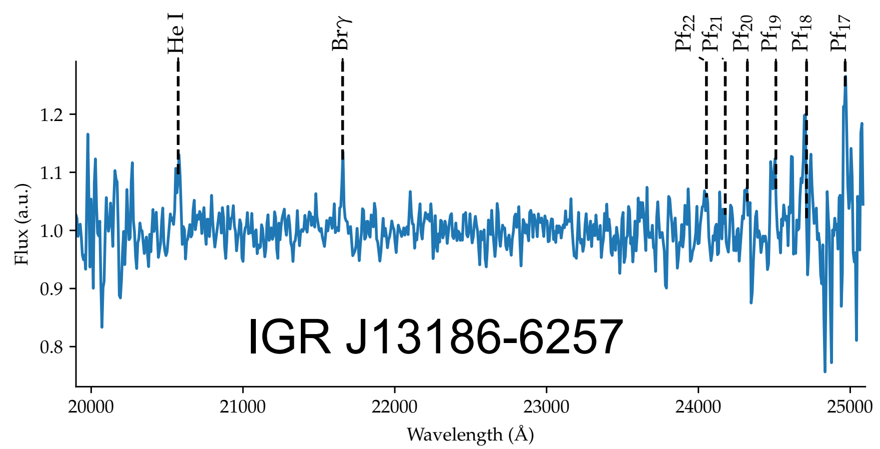


Tomsick+08

Optical/NIR spectroscopy

- Our effort
  - Chaty+08
  - Butler+09
  - Zurita Heras+09
  - Tomsick+11
  - Coleiro+13
  - Fortin+18
  - Hare+19, in prep.
- Many other groups such as Masetti et al.



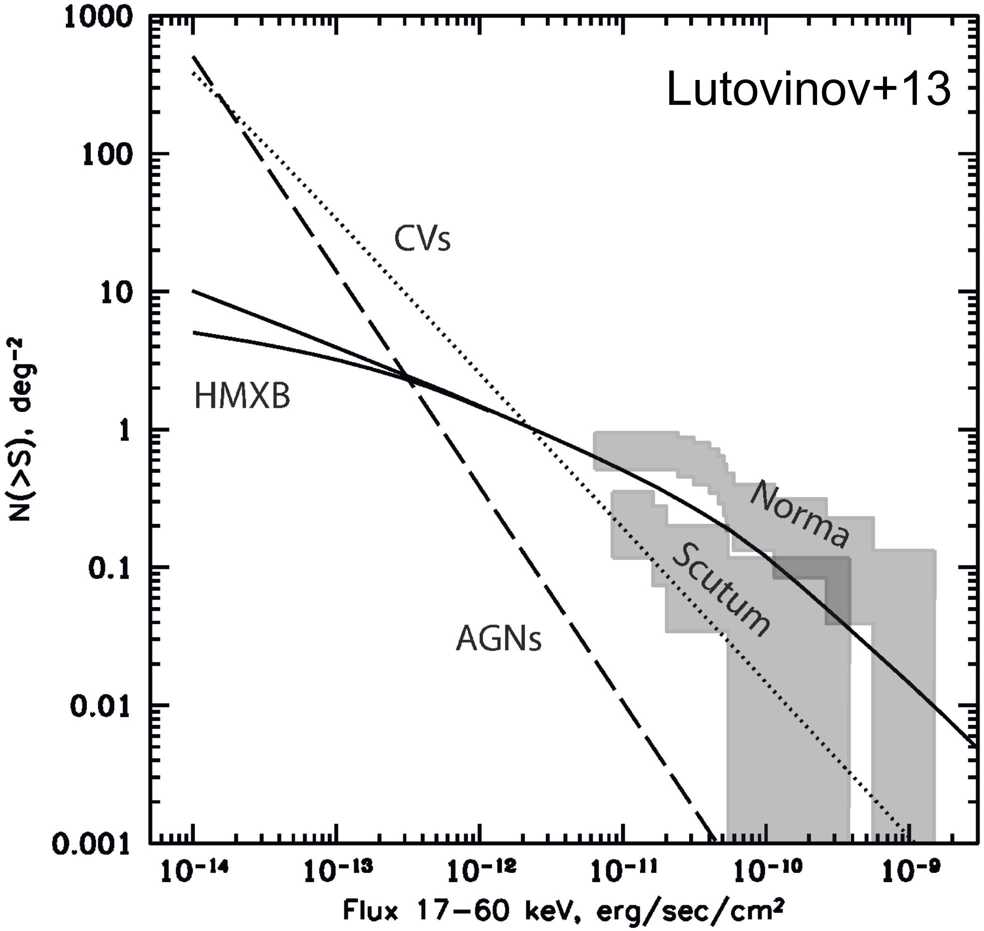


Bird+16 catalog listed 116 detected HMXBs (previously known and new).
Our effort has yielded 12 new IGR HMXBs and 4 candidates.

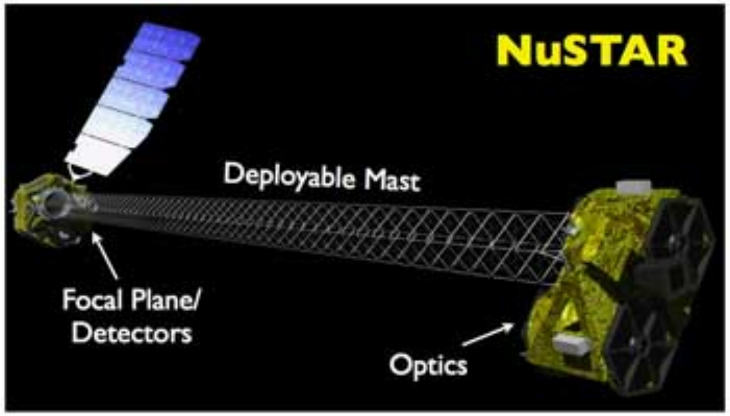
logN-logS

- View of the HMXB population from INTEGRAL observations
- INTEGRAL hugely successful in ~tripling the number of known supergiant HMXBs
- However, need better sensitivity to constrain the faint end

logN-logS for persistent HMXBs



The Nuclear Spectroscopic Telescope Array

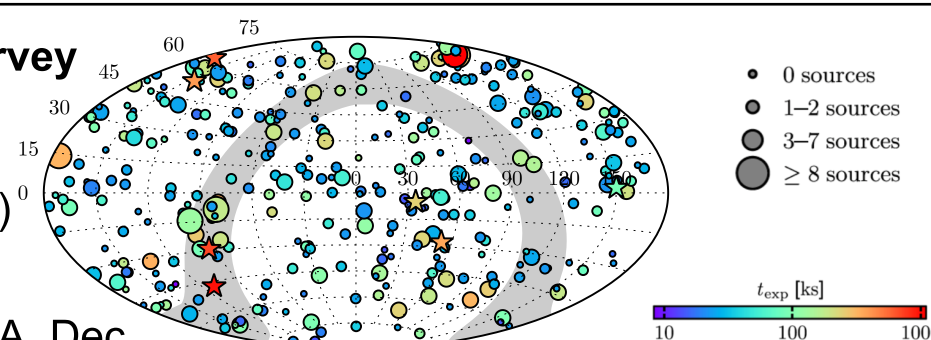


- Harrison+13
- Hard X-ray optics
- 10 meter deployable mast
- CdZnTe detectors

Energy Range:	3-79 keV
Angular Resolution:	58 arcsec (HPD) 18 arcsec (FWHM)
Sensitivity (3σ, 1 Ms):	2 x 10^{-15} erg/cm^2/s (6-10 keV) 1 x 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

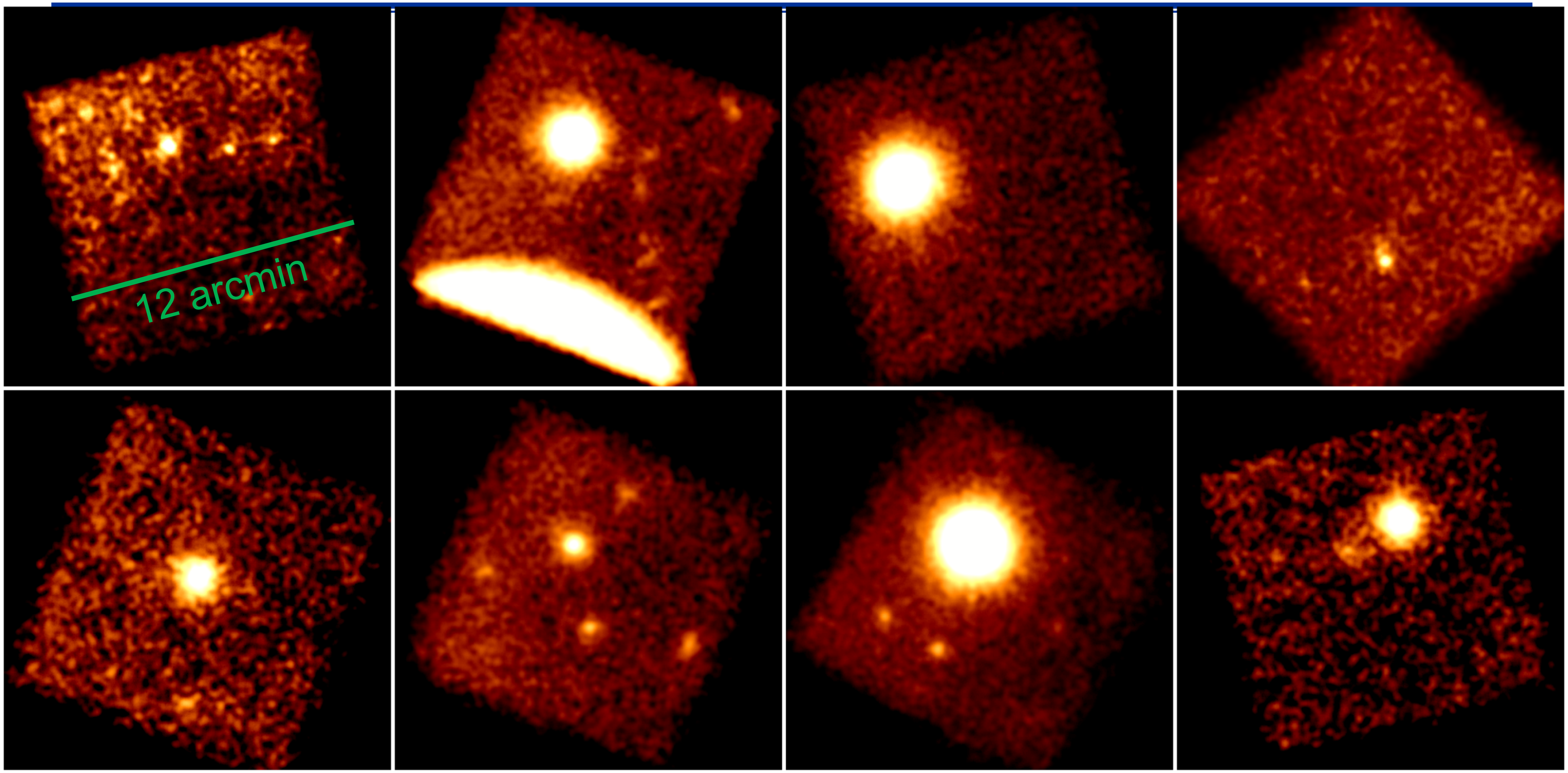
NuSTAR Serendipitous Survey

- Alexander+13
- Lansbury+17 (40 month)
- Tomsick+17+18 (Galactic)



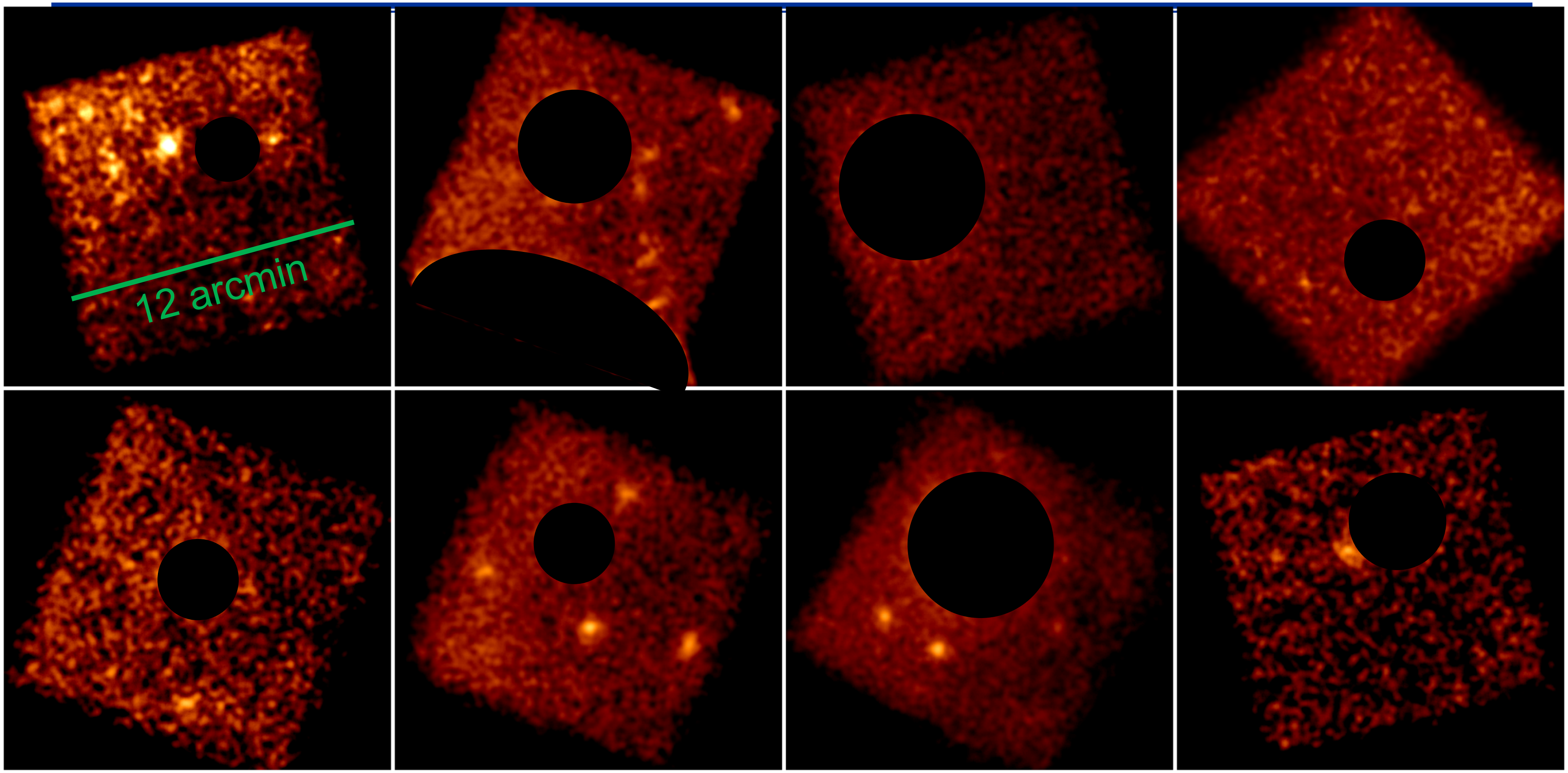
RA, Dec

NuSTAR fields (8 of 331)



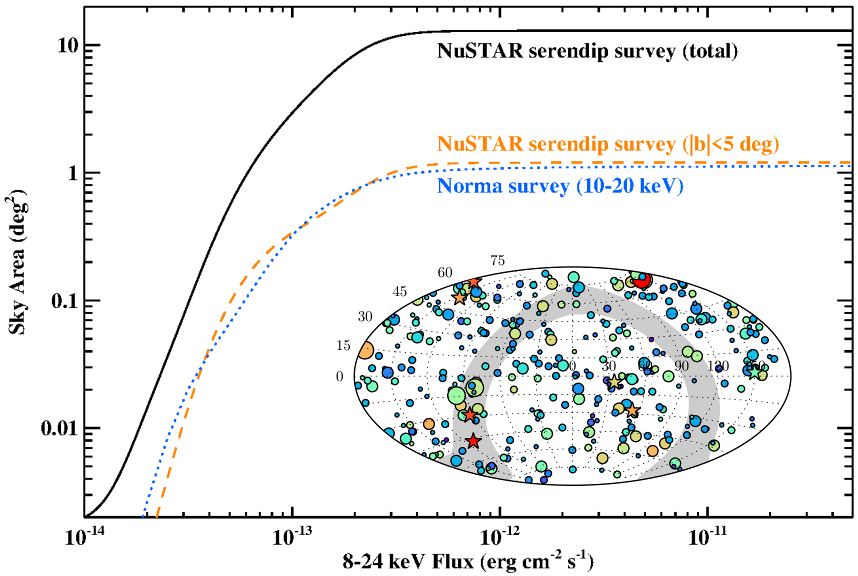
- The 40 month survey used 3-24 keV images from 331 observations

NuSTAR fields (8 of 331)



- Masking out the target sources and the stray light

Sky coverage and source classifications



Total coverage everywhere on the sky

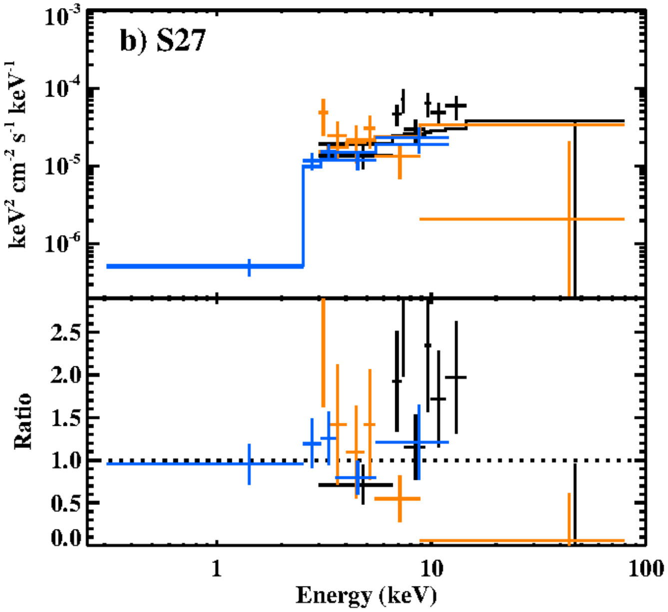
Coverage within 5º of the plane is relevant for the HMXB search

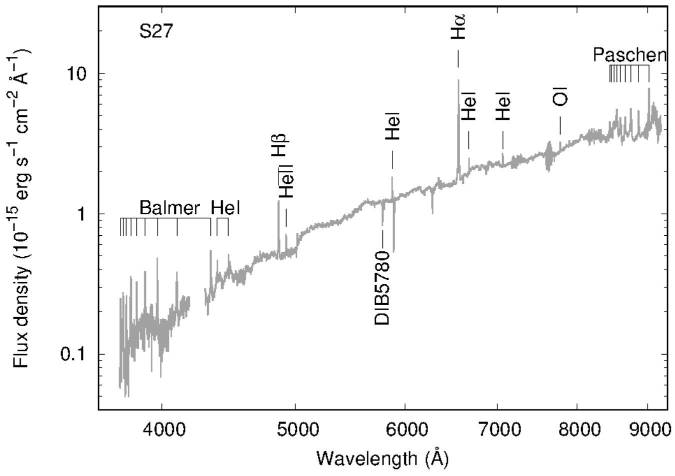
Results from 40 month catalog

- 276 of 497 sources classified (NuSTAR/X-ray/optical spectroscopy)
- 260 AGN (Lansbury+17)
- 16 Galactic
  - Active stars, CVs, X-ray binaries, and a magnetar (Tomsick+17)
  - HMXB and likely HMXB classified so far
    - IGR J13020-6359 (=S43): previously known accreting pulsar
    - NuSTAR J105008-5958.8 (=S27): new HMXB candidate

NuSTAR J105008-5958.8: new HMXB candidate

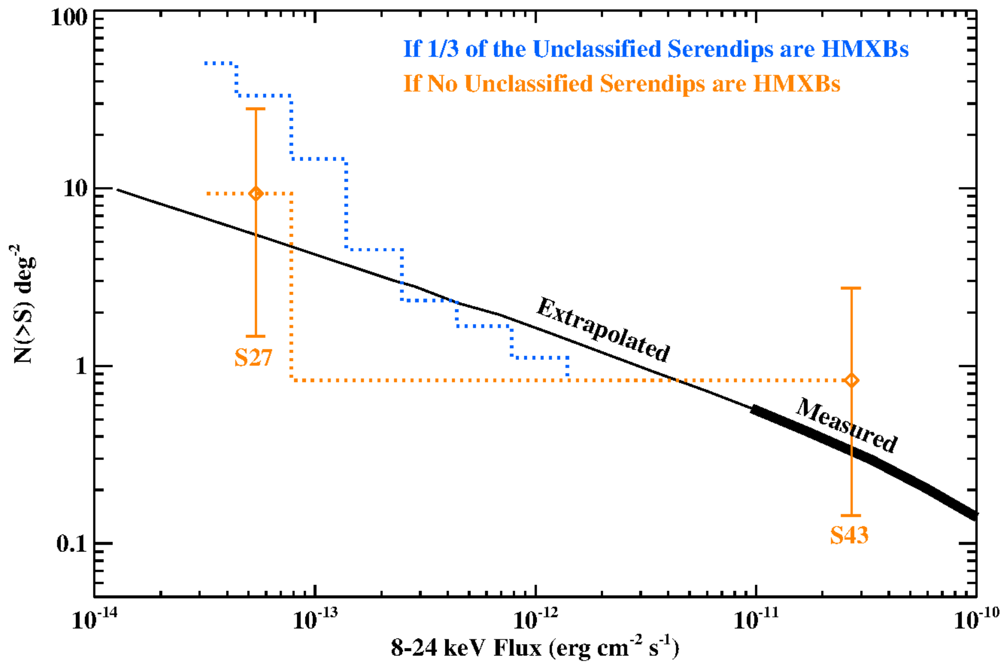
- XMM+NuSTAR
  - $\Gamma = 1.7^{+0.6}_{-0.5}$
  - $N_H = (3.1^{+2.3}_{-1.5})\times10^{22}$ cm^{-2}
- Optical counterpart
  - $A_V = 4.7\pm0.5$ (DIB line)
  - d = 7±1 kpc (l,b = 288.3º, -0.6º)
  - Gaia parallax = -0.007±0.039 mas
  - R = 15.1, V=16.5
- Absolute mag and L_x (d = 7 kpc)
  - $M_V = -2.4\pm0.6$ (B2Ve)
  - $L_x = (4\pm2)\times10^{32}$ erg/s
- Similarities to the first BH/Be system MWC 656 (Casares+14)
  - From radial velocity curve: P_{orb}~60d, M_{BH}~5 M_{sun}, M_2~13 M_{sun}
  - ***Please do a similar study for J1050***





Extending the logN-logS

- HMXB logN-logS only well-measured down to 10^{-11} erg/cm^2/s
- Two serendips are likely or definite HMXBs (S27 and S43)
- The survey is highly incomplete near the Galactic plane
- Data still allow for an unknown low flux HMXB population
- Still more work to do to fully characterize the Galactic HMXB population

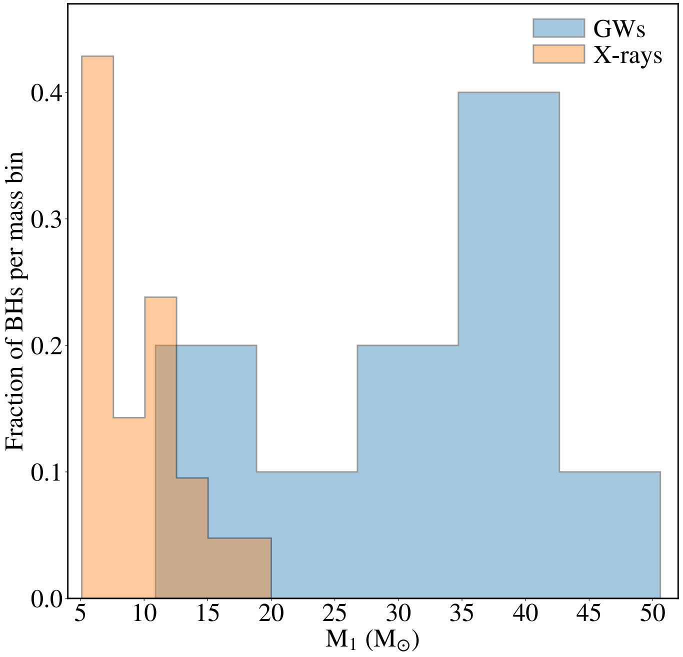


- Surface density (logN-logS) for HMXBs at -5º<b<5º (adapted from Tomsick+17)
- Black curve from Lutovinov+13 based on the INTEGRAL survey

What HMXB properties provide information about whether they are BBH progenitors?

- Orbital parameters: P_{orb}, e
  - Important for understanding binary evolution (merging times, kicks)
- BH mass
  - Distributions show higher values for BBHs (Perna+19)
- BH spin
  - If HMXBs are the progenitors of BBHs, then their distributions of spin magnitudes should match
  - Spin orientation

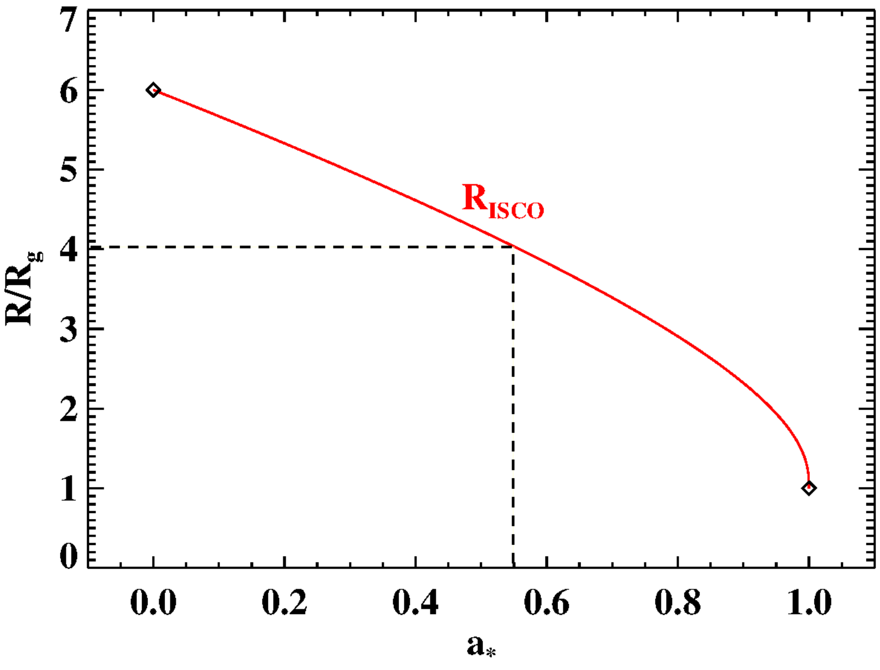
Perna+19



Mass distributions for 24 BHs in X-ray binaries ("X-rays") and 20 BHs in mergers ("GWs"). Maybe not a selection effect after all?

Measuring BH spin for X-ray binaries

- Methods for measuring a_* rely on constraining the inner radius of the accretion disk (R_{in})
- If $R_{in}=R_{ISCO}$, then determining R_{in} gives a measurement of a_*
- As long as $R_{in}<6R_g$, we have a lower limit on a_*

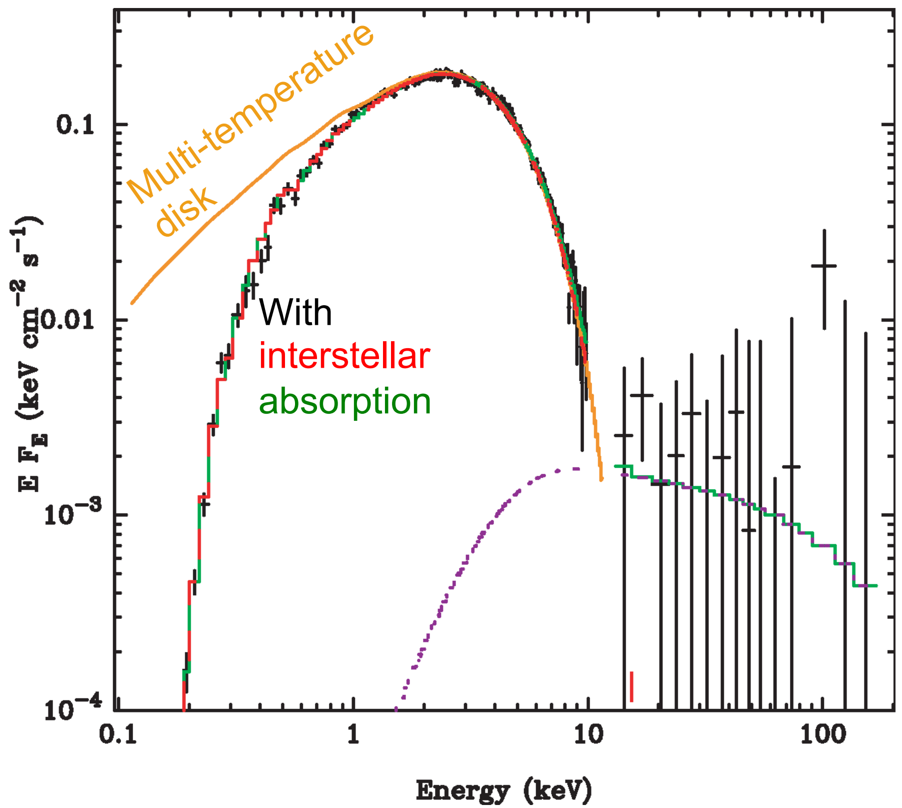


For example:

- A measurement of R_{in} = $4R_g$ means that $R_{ISCO} \leq 4R_g$ and $a_* \geq 0.55$

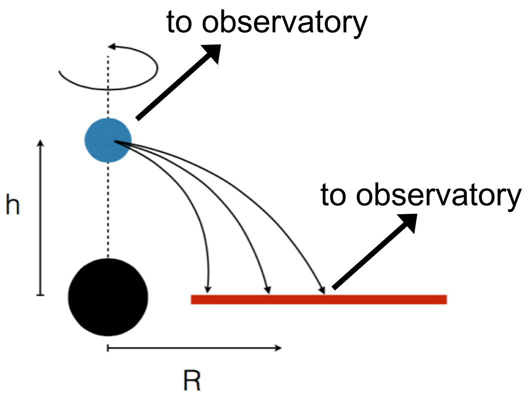
Modeling spectra to constrain BH spin: Thermal

- Measuring a_* by modeling the thermal disk 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

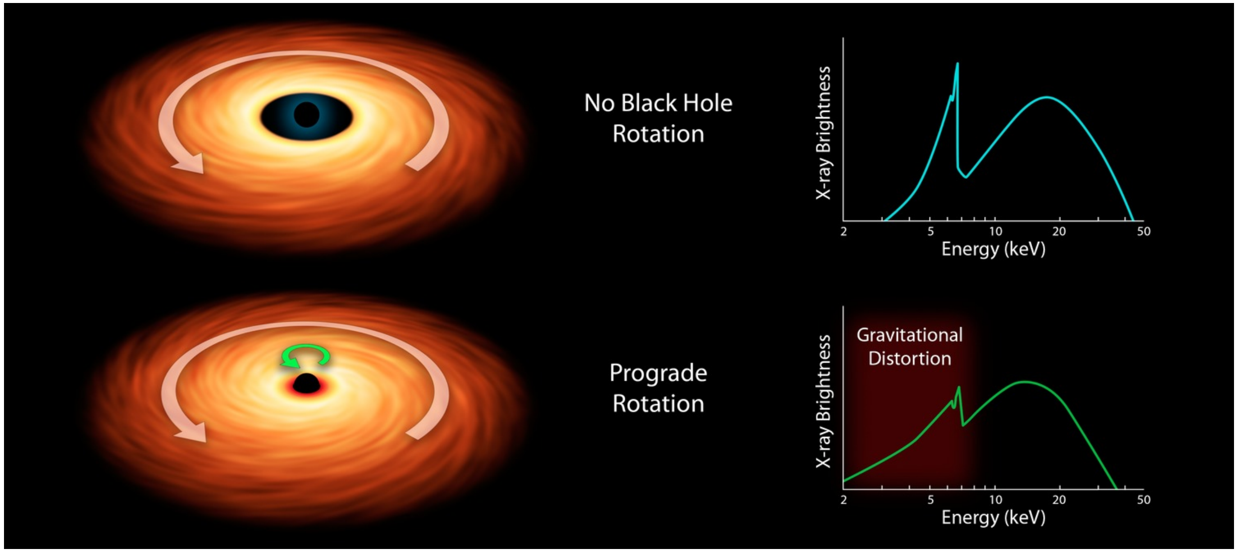


Modeling the LMC X-3 thermal component (Davis+06; Steiner+10; Steiner +14 McClintock+14)

Using reflection to measure BH spin



adapted from
Middleton 2015



- Critical region of the spectrum a few to ~50 keV
- The NuSTAR capabilities (bandpass, throughput, energy resolution) are very well-suited for reflection studies

Reflection measurements with NuSTAR

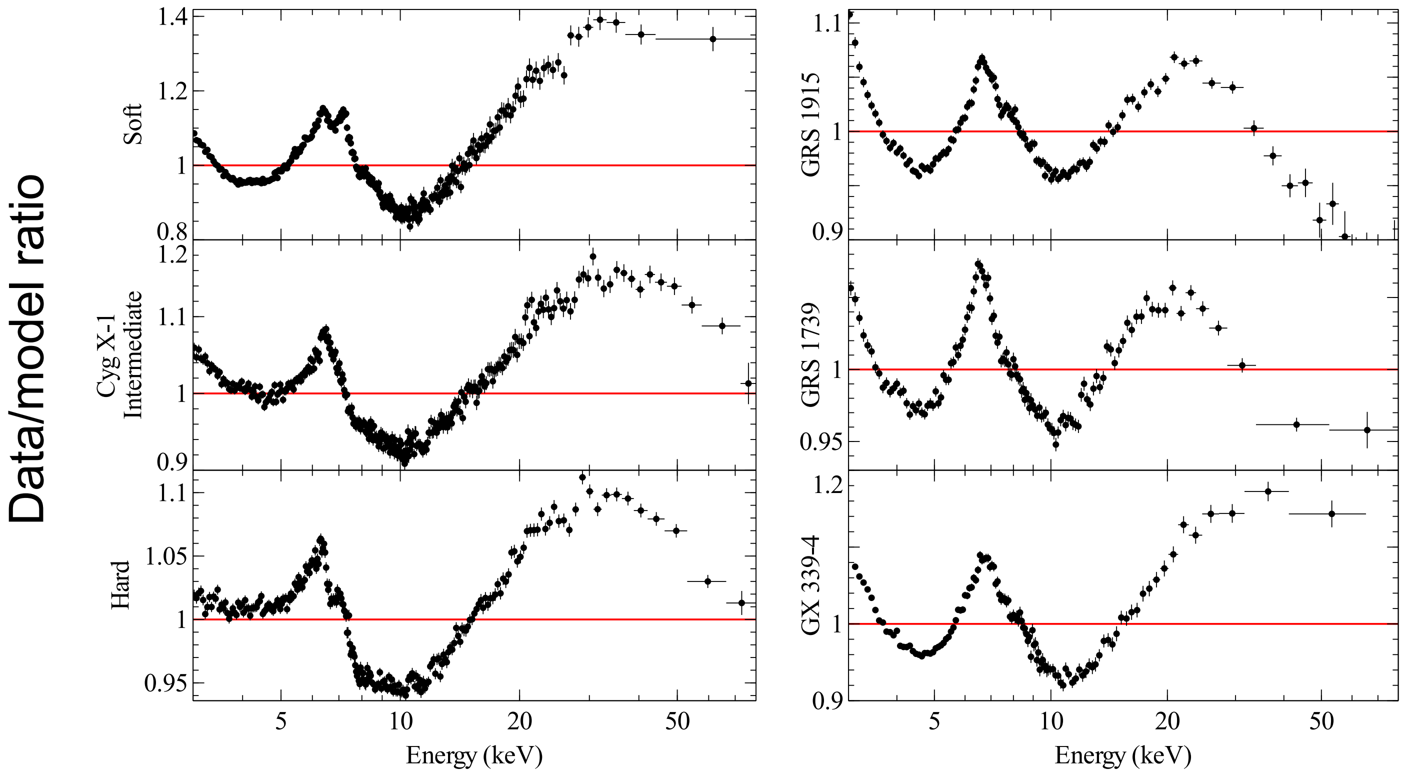
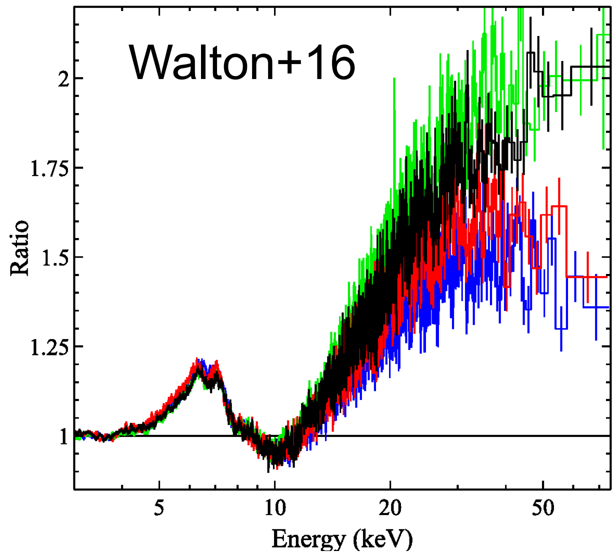


Figure credit: Michael Parker

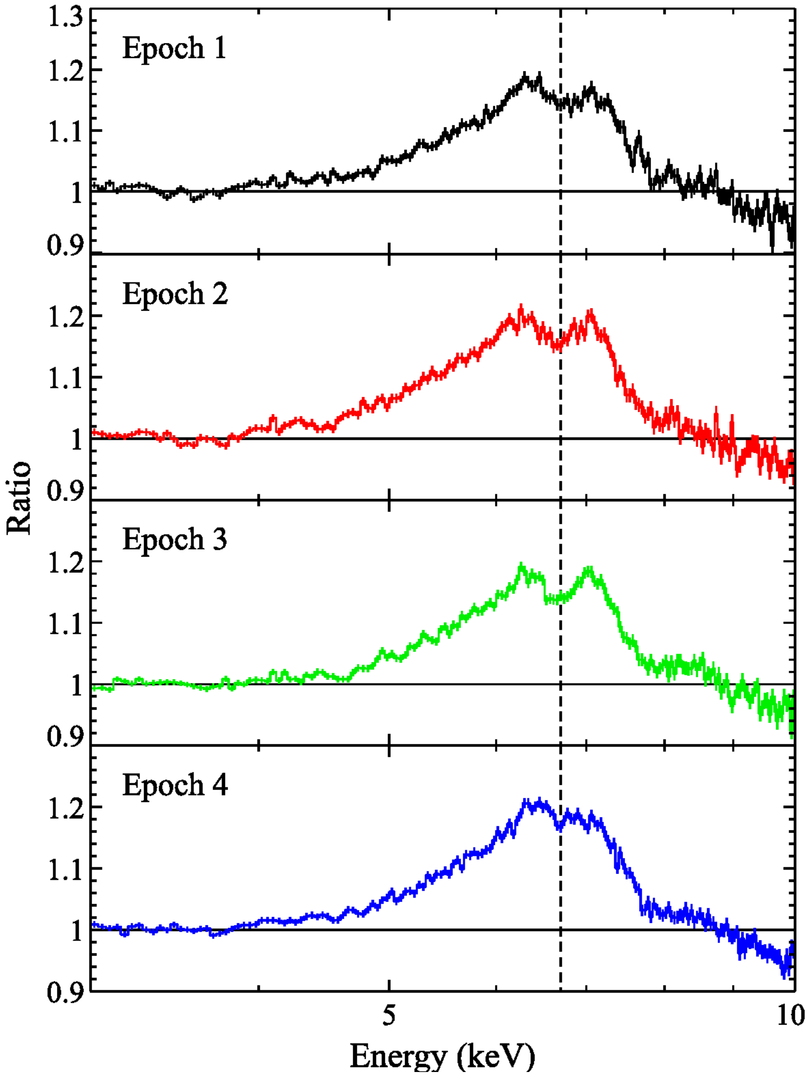
Results published in:
- Miller+13
- Tomsick+14
- Miller+15
- Parker+15
- Walton+16
- Parker+16
- Tomsick+18

- Residuals to a power-law continuum model

Cyg X-1 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

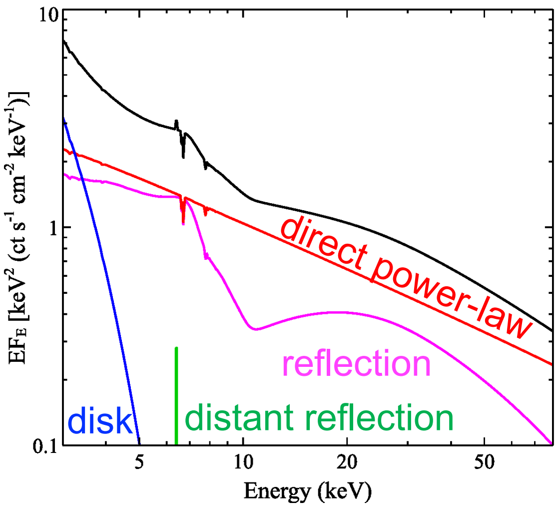
0.26-0.37

0.97-0.09

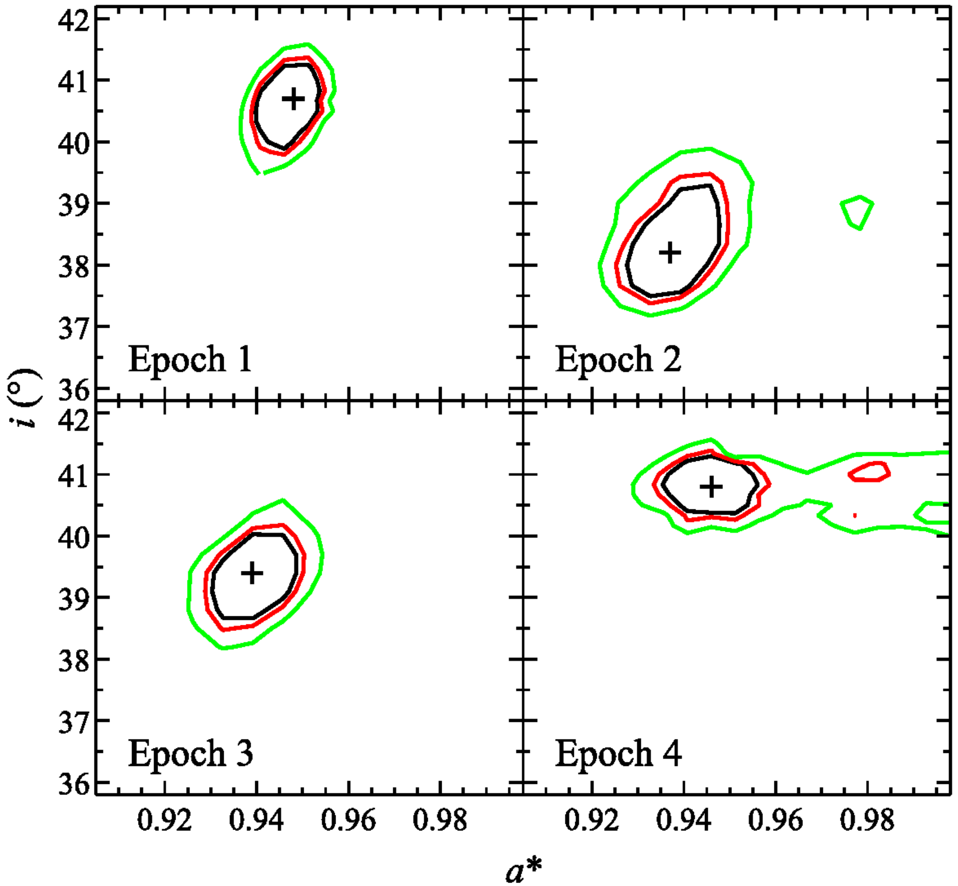
0.85-0.99

0.49-0.59

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



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



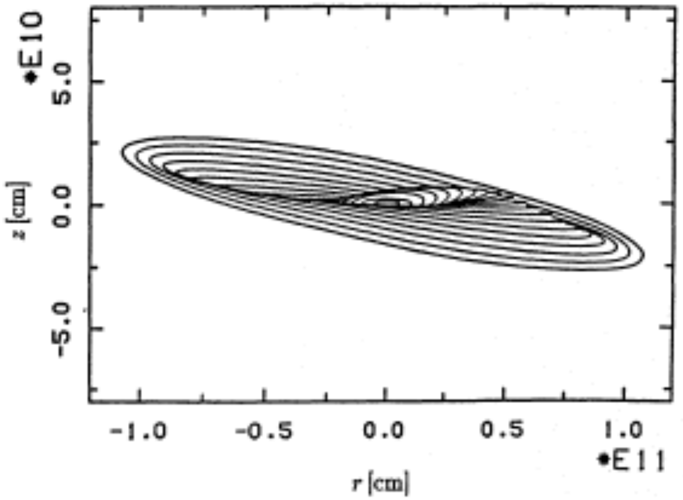
Walton+16

Warped disk?

- From *NuSTAR* studies
  - $i > 40^{\circ}$ (Tomsick+14)
  - $37^{\circ} < i < 42^{\circ}$ (Walton+16)

- These are significantly higher than the measured binary inclination
  - $i_{binary} = 27.1^{\circ} \pm 0.8^{\circ}$ (Orosz+11)

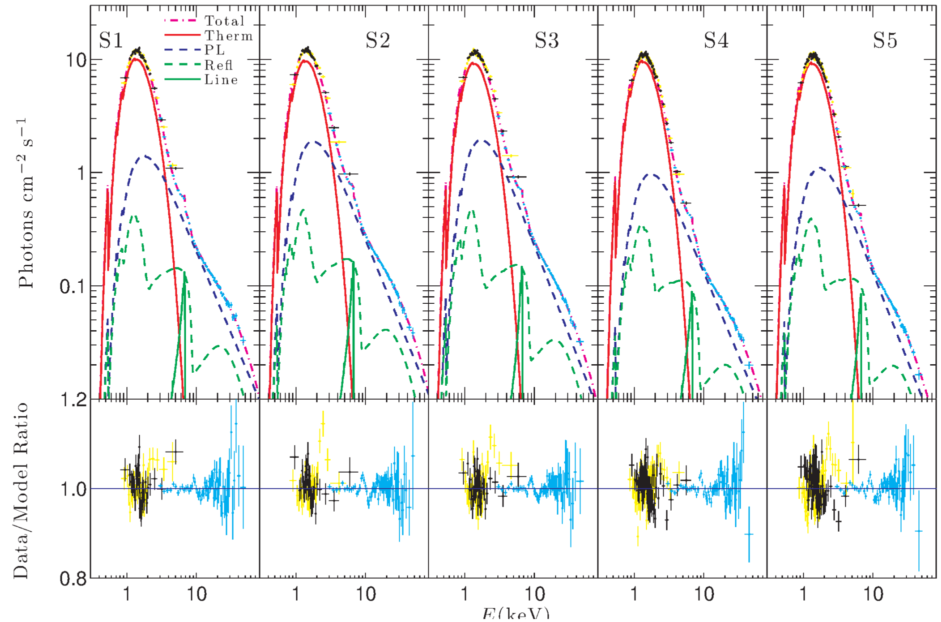
- Possible misalignment between the BH spin axis and the orbital angular momentum vector

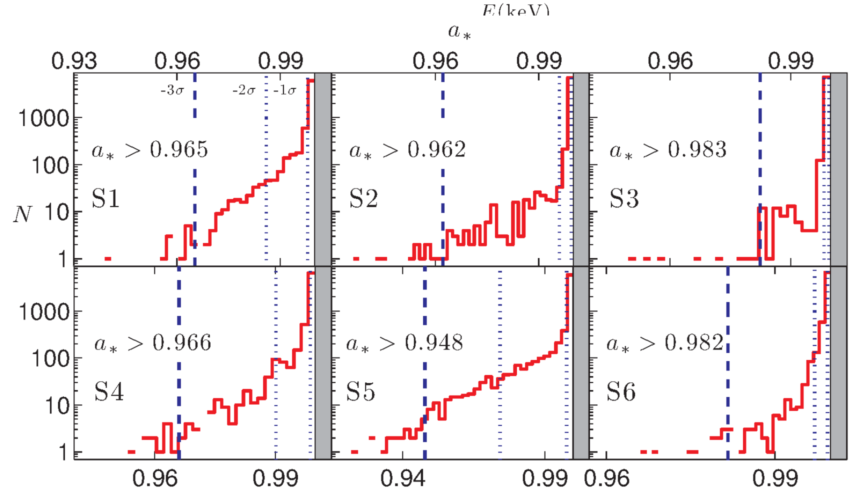


- Warped disk calculation by Schandl & Meyer (1994)
- See also King & Nixon (2016)

Cyg X-1 thermal method

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





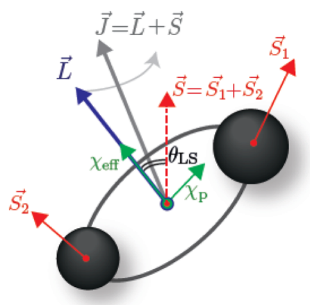
Summary of HMXB BH spin measurements

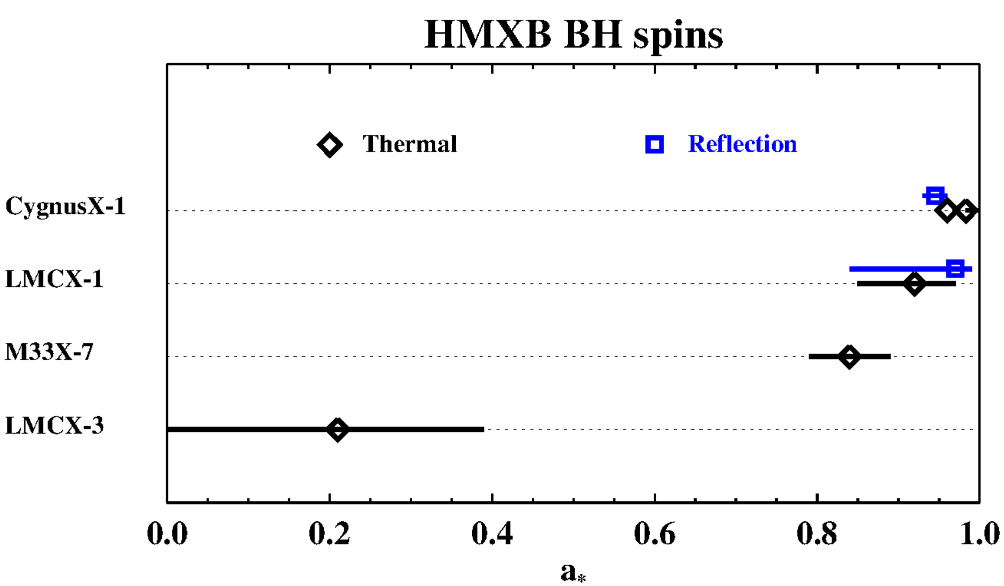
Source	a_* reflection	a_* thermal, i_{binary}	a_* thermal, $i_{inner\ disk}$	References
Cyg X-1	0.945 ± 0.015	>0.983	~0.96	Walton+16, Gou+14
LMC X-1	$0.97^{+0.02}_{-0.13}$	$0.92^{+0.05}_{-0.07}$	?	Steiner+12, Gou+09
M33 X-7	-	0.84 ± 0.05	?	Liu+08+10
LMC X-3	-	$0.25^{+0.20}_{-0.29}$	?	Steiner+14

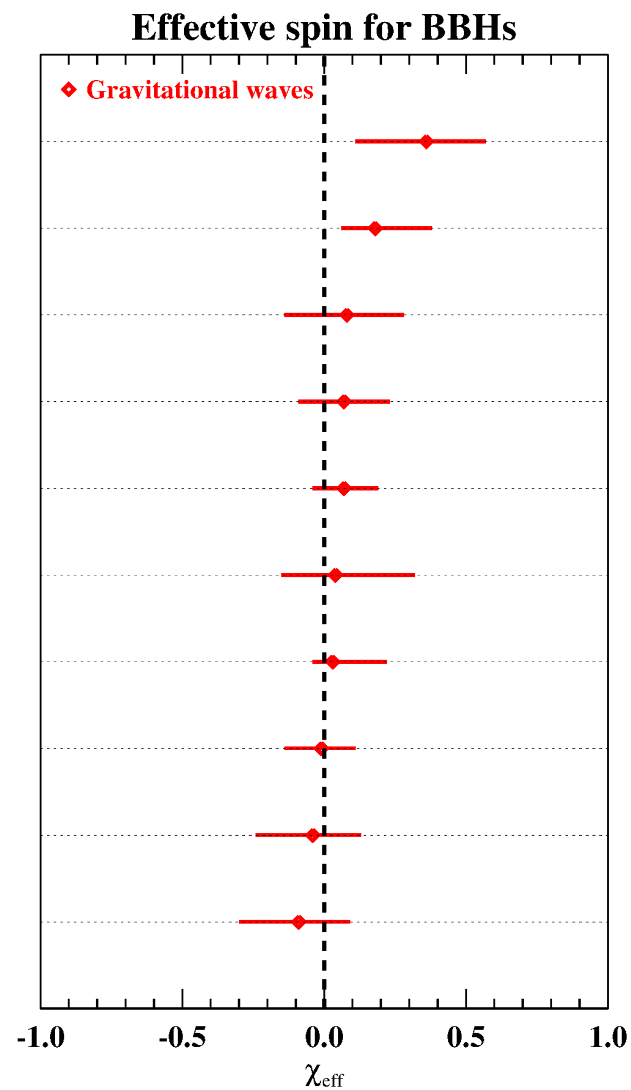
- Lots more LMXB BH spin measurements
  - Very useful for checking consistency between methods
    - Excellent agreement for GX 339-4 and GRS 1915+105
    - Not as good for GRO J1655-40 and 4U 1543-47

HMXB spins vs. BBH effective spins

- $\chi_{eff} = (M_1\, a_1 \cos\theta_1 + M_2\, a_2 \cos\theta_2) / (M_1+M_2)$
- Spins for BBHs are either low or strongly misaligned
- Neither possibility seems to match with expectations from HMXBs

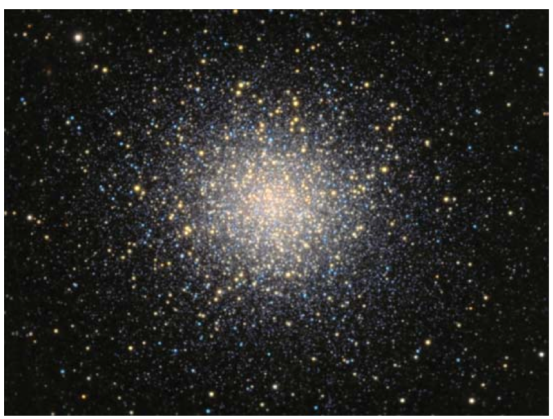




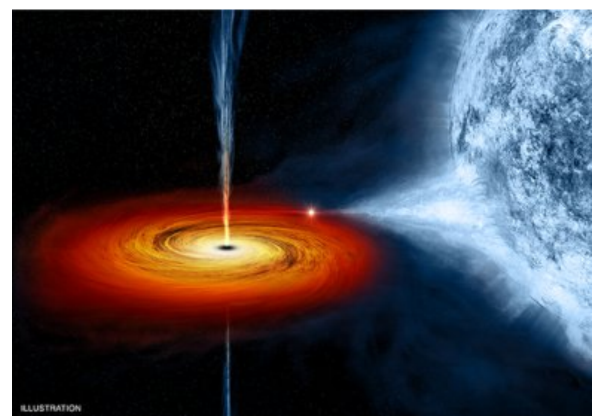


Possible interpretation for spin mismatch

- If the low χ_{eff} BBH values continue to be seen, perhaps BBHs are formed in capture events in dense star clusters rather than HMXBs
  - Estimate of capture rates has a large uncertainty, but could be high enough (Rodriguez+16)
  - BHs still may have at least moderate values of a_* but with random θ_1 and θ_2



instead of



?

Summary and Conclusions

- HMXB population
  - Better sensitivity (NuSTAR and Chandra) has not yet produced INTEGRAL's rate of discovery
  - Framework for constraining the faint population (Lutovinov+13, Tomsick+17, Clavel+19)
  - Currently working on classifications of sources detected in the surveys

- BH spin
  - Reflection and thermal method measurements show that BHs in HMXBs tend to have high spin
  - BBH tend to have low χ_{eff}
    - Do they form as captures in clusters or HMXBs?