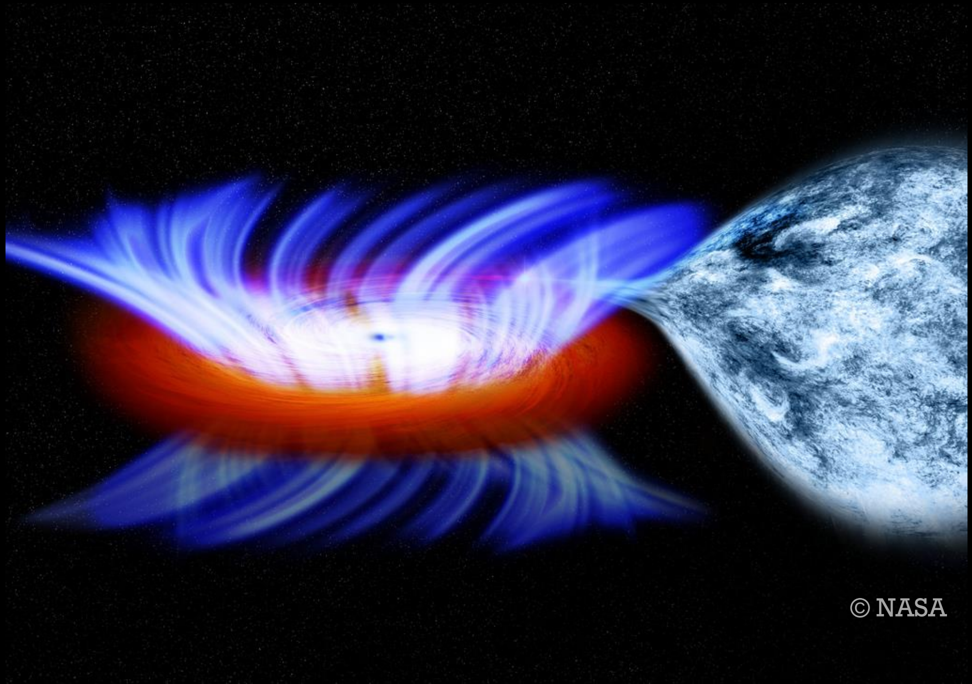
Probing the Connection between X-Ray Binaries and Ultraluminous X-Ray Sources



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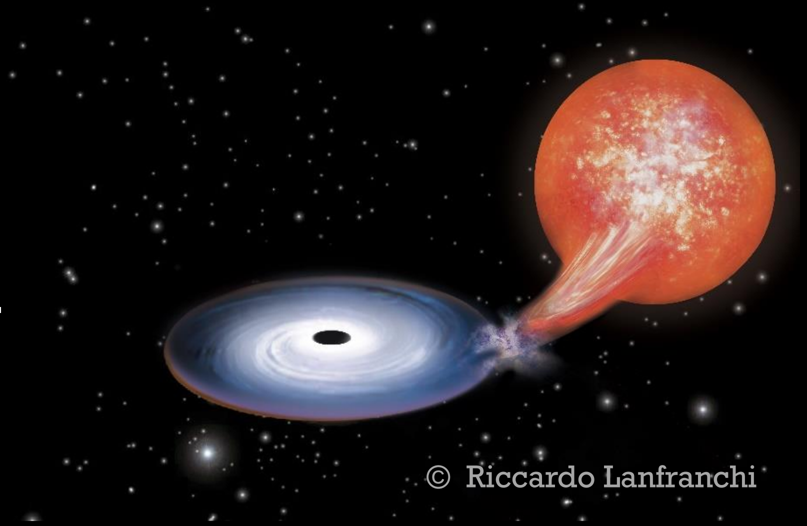
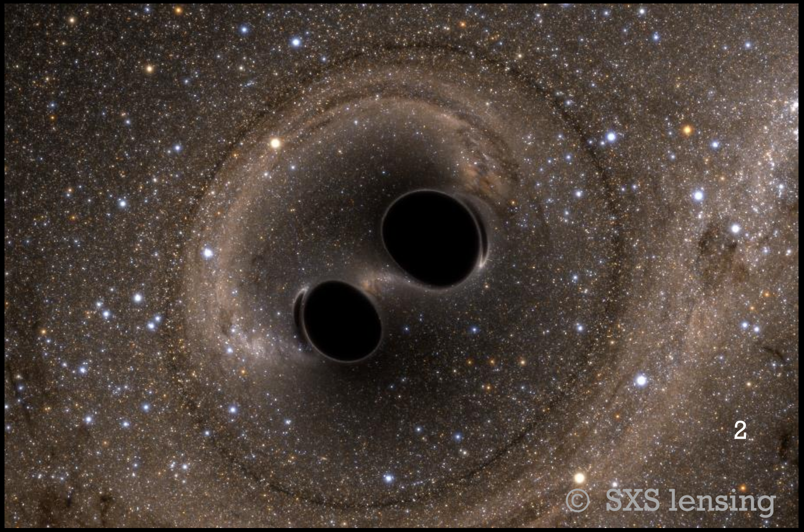
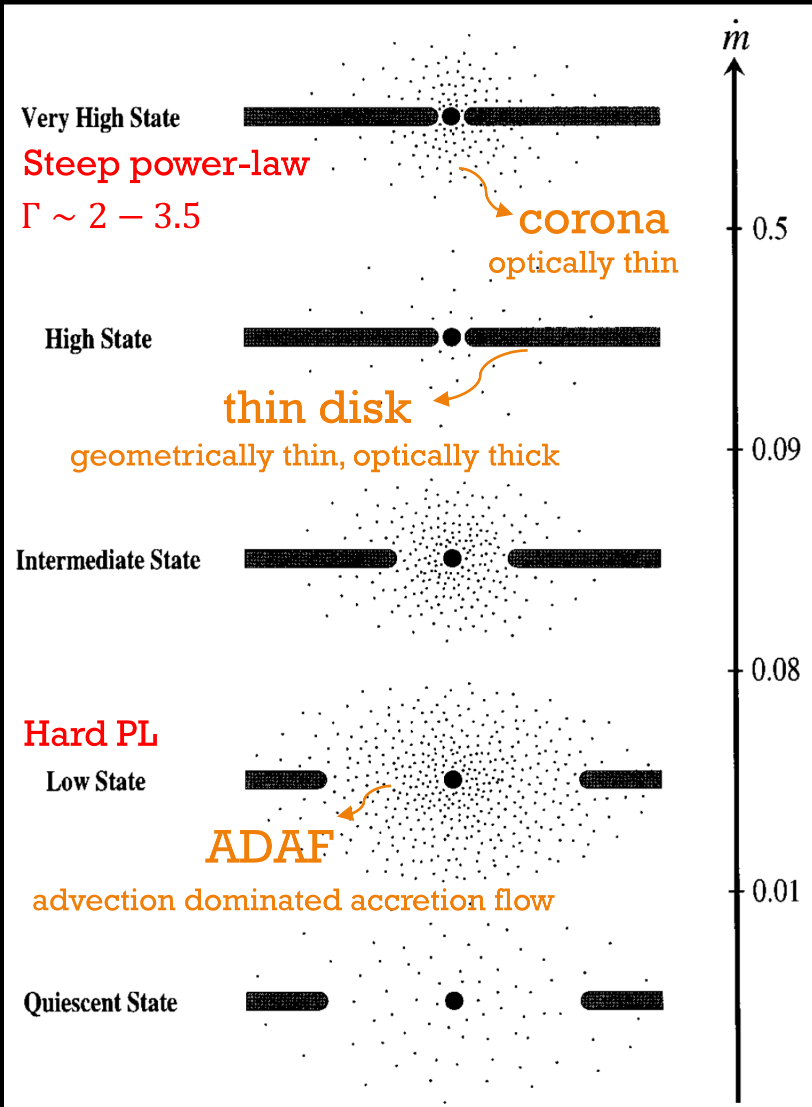
How to Observe BHs?

- Electromagnetic wave: accretion
  - Gravitational potential energy
  - Very efficient: $\dot{E} = \eta \dot{m} c^2$, where $\eta \gtrsim 0.1$ and $\dot{m}$ is the mass accretion rate.
  - UV to X-rays
- Gravitational wave: merge
  - First detected in 2015 by the Laser Interferometer Gravitational-Wave Observatory (LIGO)
  - New window to explore the universe: multi-messenger astronomy

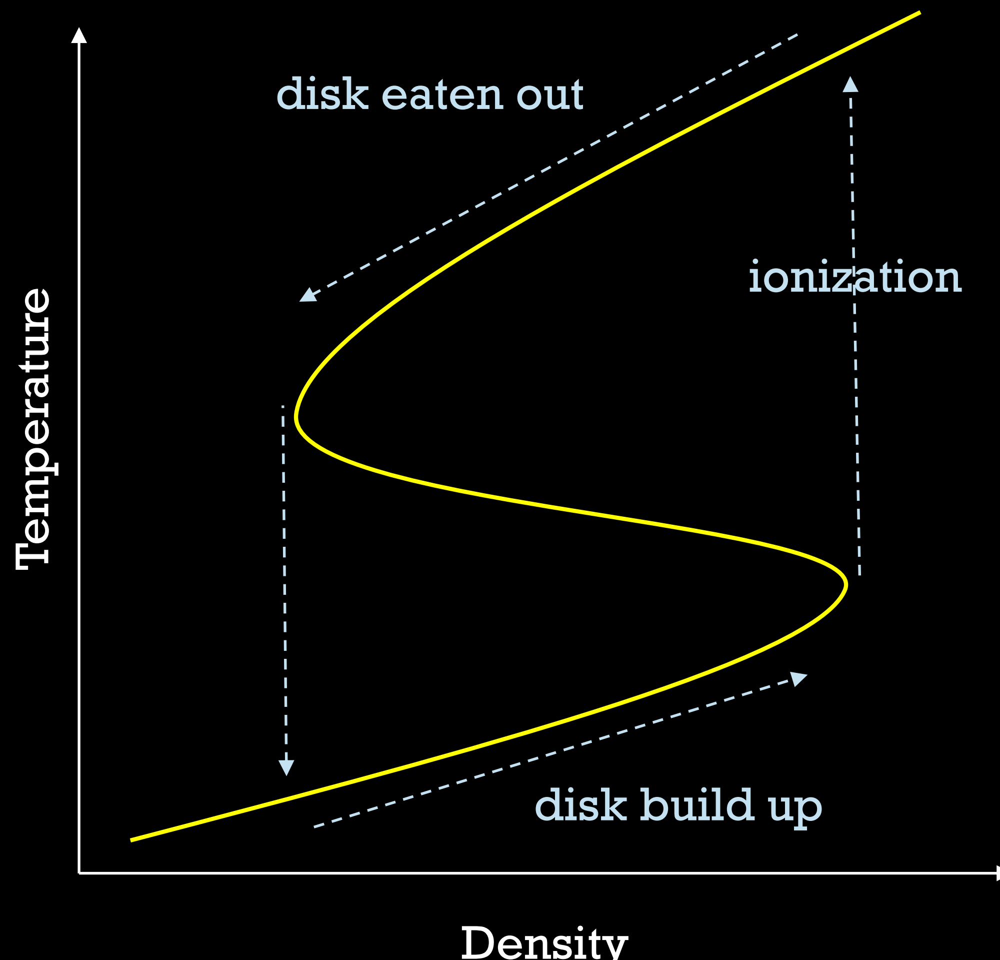




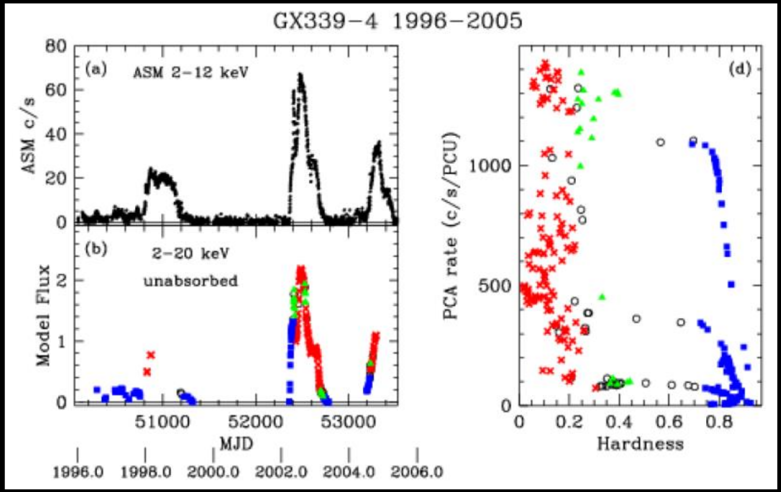
Stellar-Mass BHs



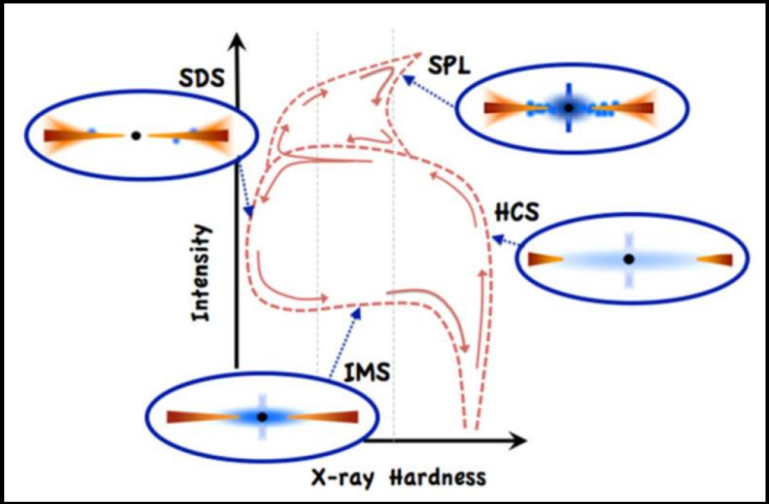
Esin et al. (1997)



Spectral Evolution



Remillard (2004)

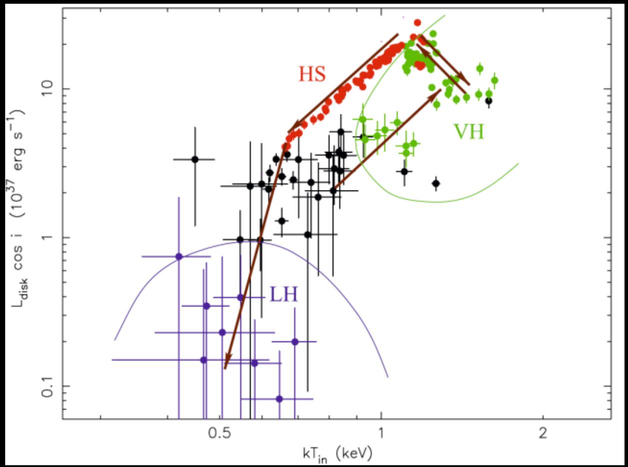


Tetarenko et al. (2016)

For thermal state: $L_{disk} \sim R_{in}^2 T_{in}^4 \propto T_{in}^4$

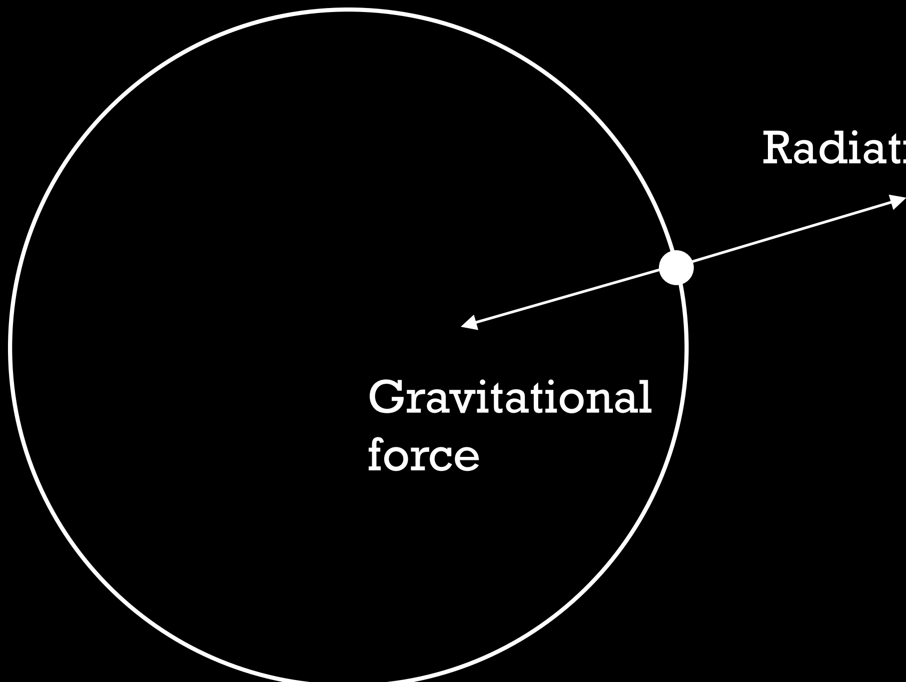
Can be used to estimate the BH mass

Valid for $R_{in} \sim R_{ISCO}$



Soria (2007)

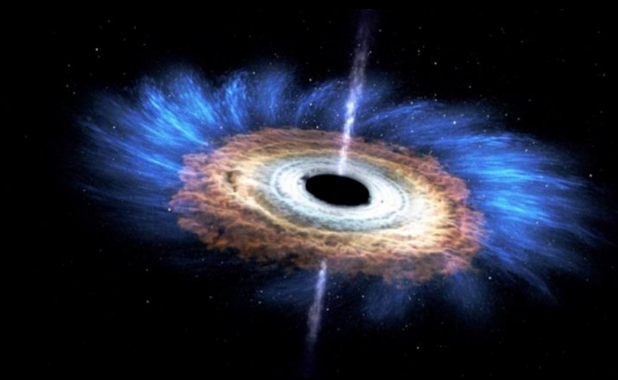
Eddington Limit



- Luminosities of Galactic BHXBs are strongly Eddington limited
- $L_{Edd} = \frac{4\pi c G M m_p}{\sigma_T} \sim 1.3 \times 10^{38} \left(\frac{M}{M_\odot}\right)$ erg s^{-1}, where m_p is the proton mass, σ_T is the Thomson cross section, and M is the BH mass.

Ultraluminous X-ray Sources

- Extra galactic, off-nucleus X-ray point sources with $L_{0.3-10keV} > 1.3 \times 10^{39}$ erg s^{-1} (or 3×10^{39} erg s^{-1}).
  - Intermediate-mass BH with sub-Eddington accretion?
  - Stellar-mass BH with strong beaming (microquasar)?
  - Stellar-mass BH with super-Eddington accretion and mild beaming?



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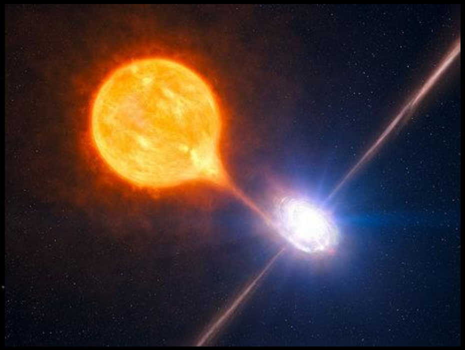

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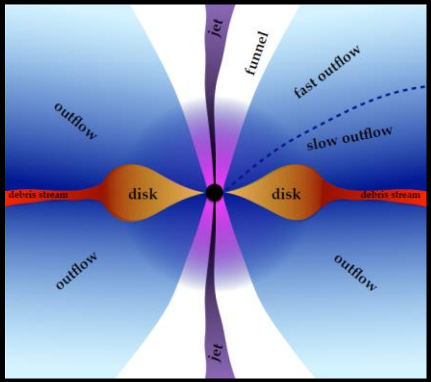
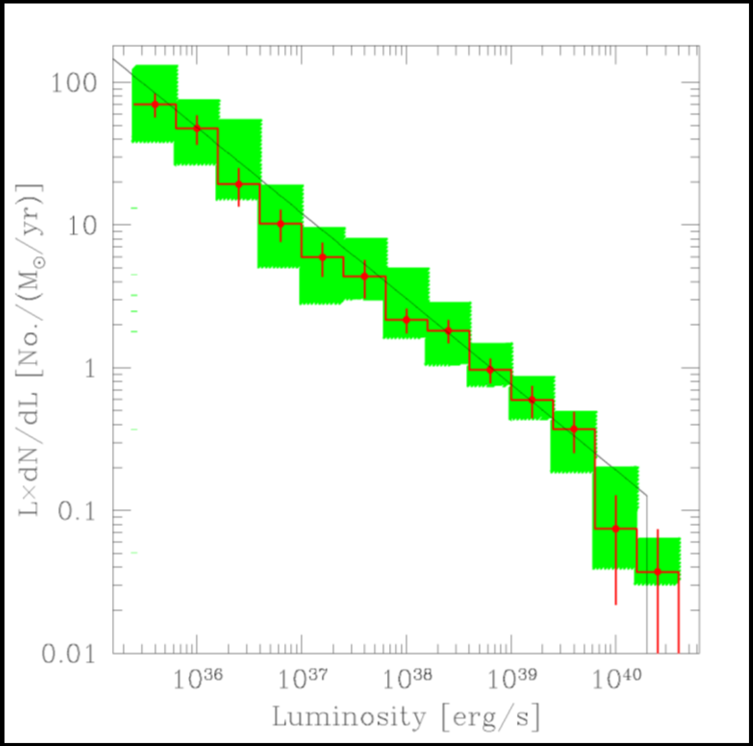


Dai et al. (2017)

X-ray Luminosity Function

- The X-ray luminosity function of ULXs is consistent with the high luminosity tail of BHXBs.
  - Most ULXs are high luminosity BHXBs.
- The luminosity function in star-forming galaxies has a break at $(1-2)\times 10^{40}$ erg s^{-1}.
  - Extreme ULXs with luminosities above the break are IMBH candidates.



Grimm et al. (2004)

ULX Spectra

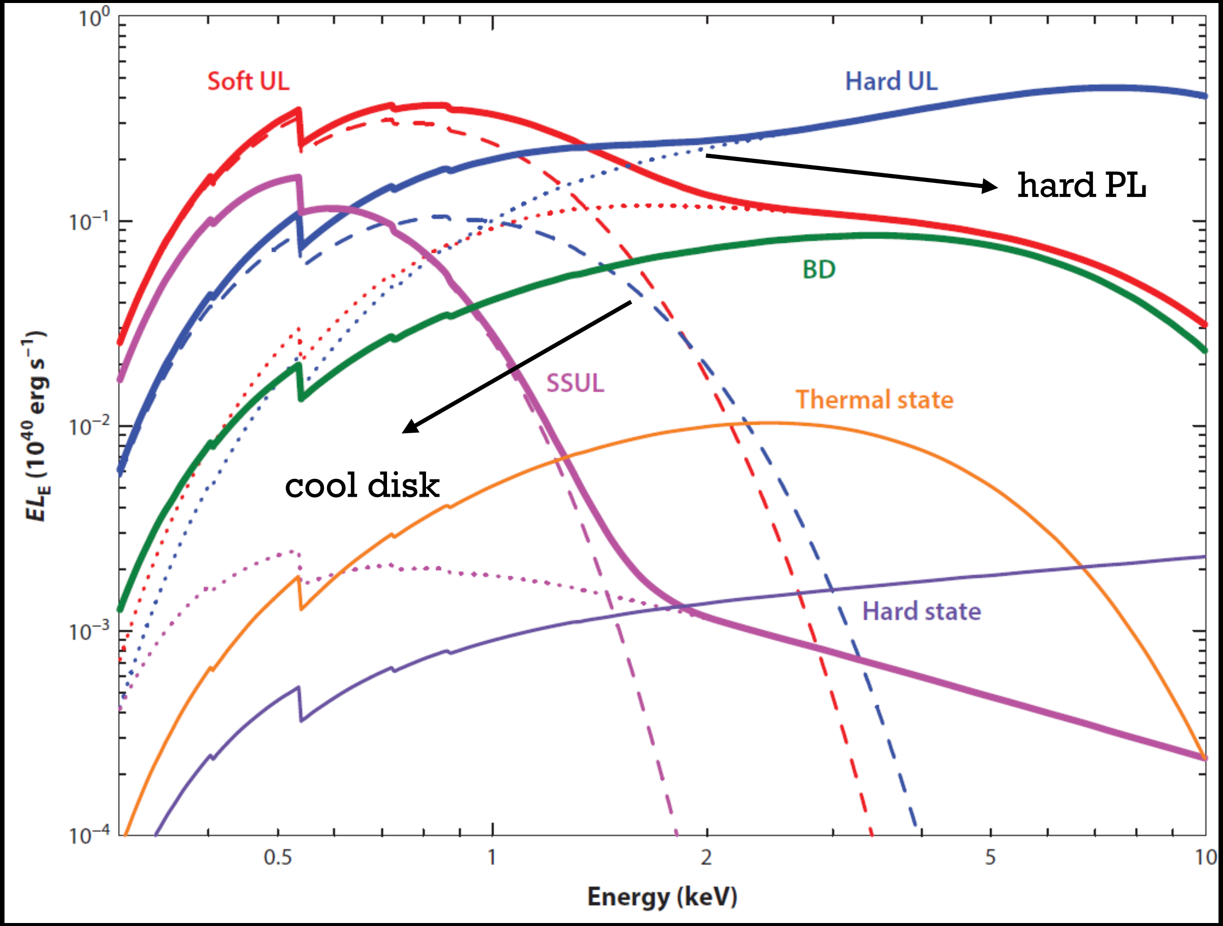
- Late 1990 ASCA observations: A hotter ($kT_{in} > 1$ keV) and more luminous disk compared to BHXBs.
  - Fast spinning, more massive BHs ($\sim 100 M_{\odot}$).

Galaxy Name	Model[a]	Γ or kT (keV)[b]	Normalization[c]	N_H[d] (10^{21} cm^{-2})	Abundance[e]	χ^2/d.o.f.[f]
			Spiral Galaxies			
M33 (1)	PL	$\Gamma = 2.33$	6.95×10^{-3}	3.20		659/595
		2.28–2.37		2.94–3.47		
	RS	$kT = 3.33$	1.88×10^{-2}	1.45	0	555/594
		3.17–3.48		1.28–1.64	<0.05	
M33 (2)	PL	$\Gamma = 2.31$	7.42×10^{-3}	2.99		838/676
		2.27–2.35		2.77–3.21		
	RS	$kT = 3.43$	2.00×10^{-2}	1.27	0	652/675
		3.31–3.56		1.14–1.41	<0.04	
NGC 1313 (1)......	PL	$\Gamma = 1.74$	4.74×10^{-4}	0.151		244/259
		1.67–1.82		<0.57		
	RS	$kT = 6.68$	1.77×10^{-3}	0	0.10	253/258
		5.92–7.47		<0.09	<0.27	
NGC 1313 (2)......	PL	$\Gamma = 2.77$	1.27×10^{-3}	2.95		185/198
		2.65–2.88		2.50–3.43		
	RS	$kT = 2.05$	3.16×10^{-3}	0.910	0.06	196/197
		1.87–2.24		0.596–1.23	<0.14	
NGC 5408	PL	$\Gamma = 2.39$	4.20×10^{-4}	0		261/269
		2.33–2.48		<0.29		
	RS	$kT = 2.02$	1.64×10^{-3}	0	0.03	343/268
		1.86–2.19		<0.04	<0.12	

Colbert & Mushotzky (1999)

ULX Spectra

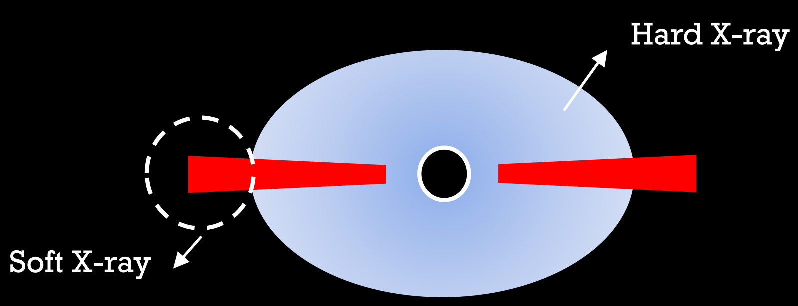
Chandra & XMM-Newton era

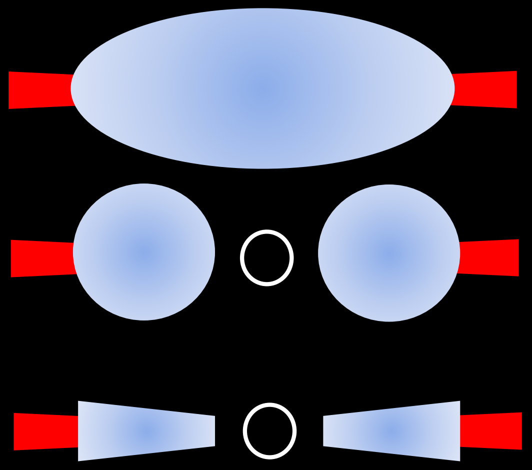


Kaaret et al. (2017)

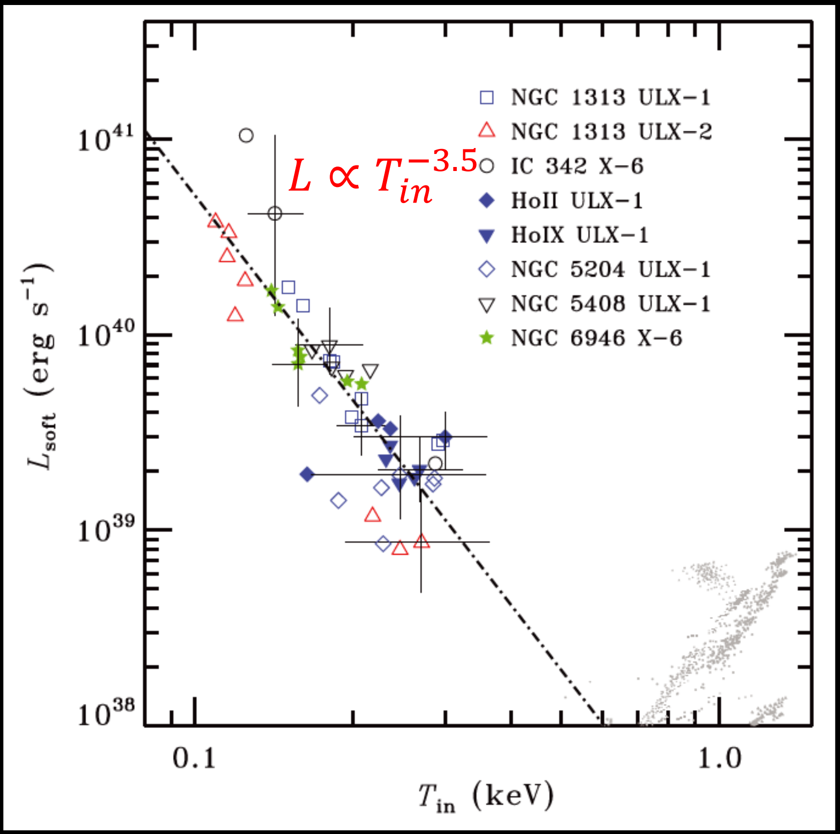
ULX Spectra

- Chandra & XMM-Newton era: two component model
  - Cool disk ($kT_{in} = 0.1 - 0.3$ keV) + hard ($\Gamma = 1.5 - 2.5$) power law.
  - Disk+ Comptonized corona.
    - GBXB: hot ($kT_{in} \approx 1$ keV) disk and optically thin ($\tau \lesssim 1$) corona
    - ULXs: cool disk and optically thick ($\tau > 6$) corona
  - Disk extended to ISCO (SPL): IMBH with $> 10^3 M_\odot$?
    - $L_{disk} \propto T_{in}^4$?

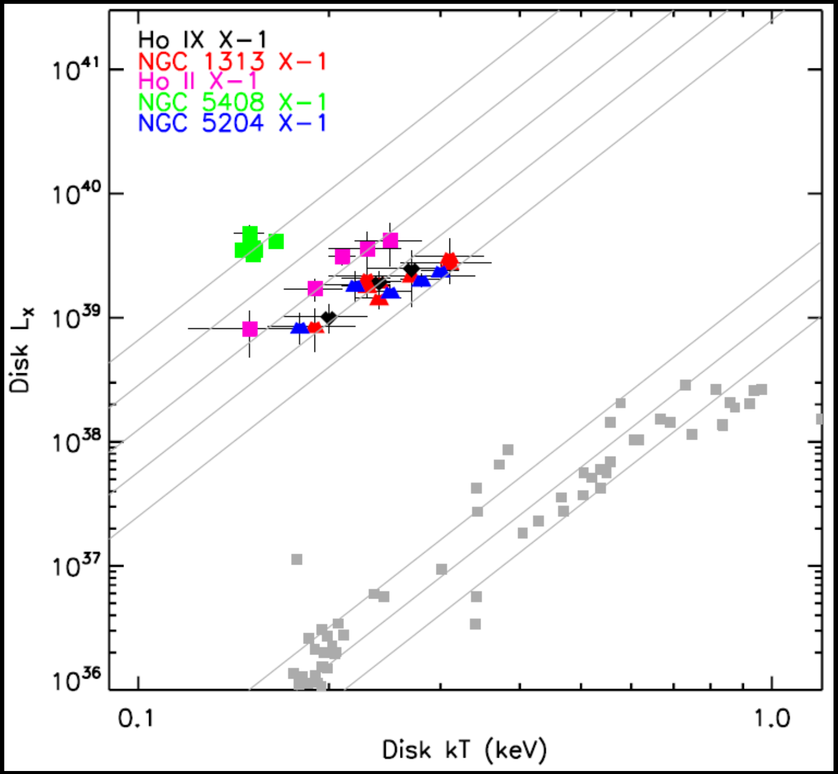




Luminosity - Temperature



Kajava & Poutanen (2009)

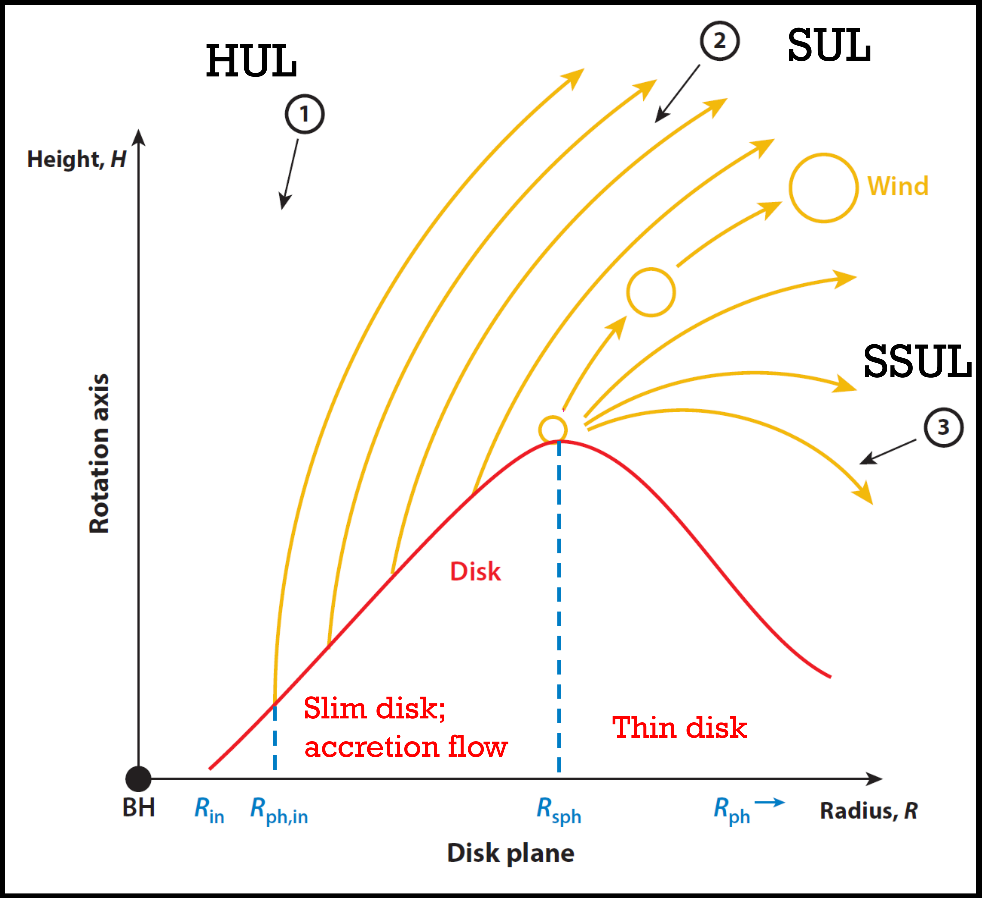


Miller et al. (2013)

Outer disk?

Non-thermal?

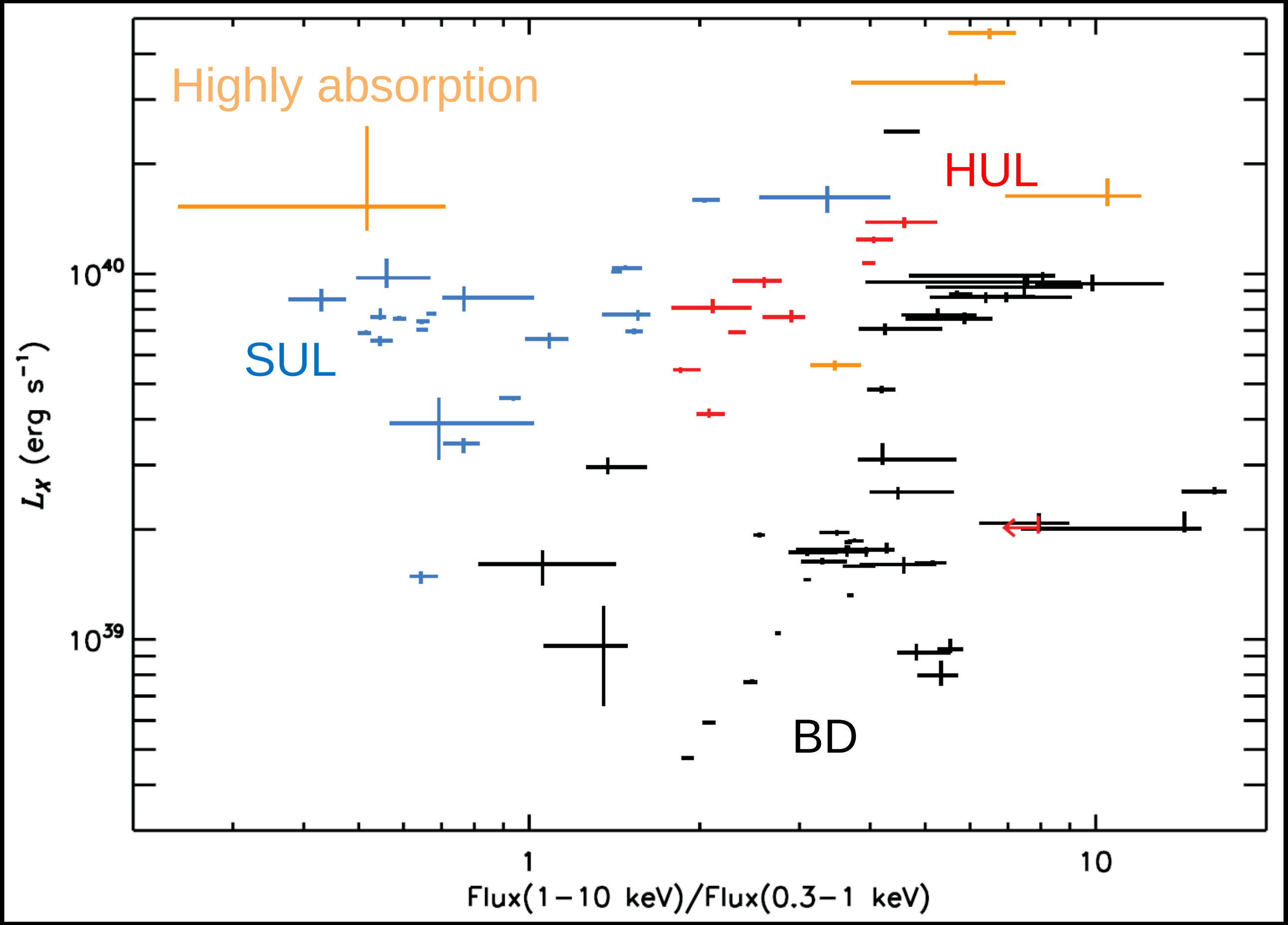
Super-Critical Accretion



Middleton et al. (2015)

- Thin disk: $T \propto r^{-0.75}$
  - Multi-color disk blackbody
- Hard component
  - Slim disk: analytically approximated by $T \propto r^{-0.6}$
  - Thick accretion flow
  - Detailed spectrum is under developing
- Soft component: wind
- $\frac{1}{b} \propto \dot{m}^2$

ULX Spectra



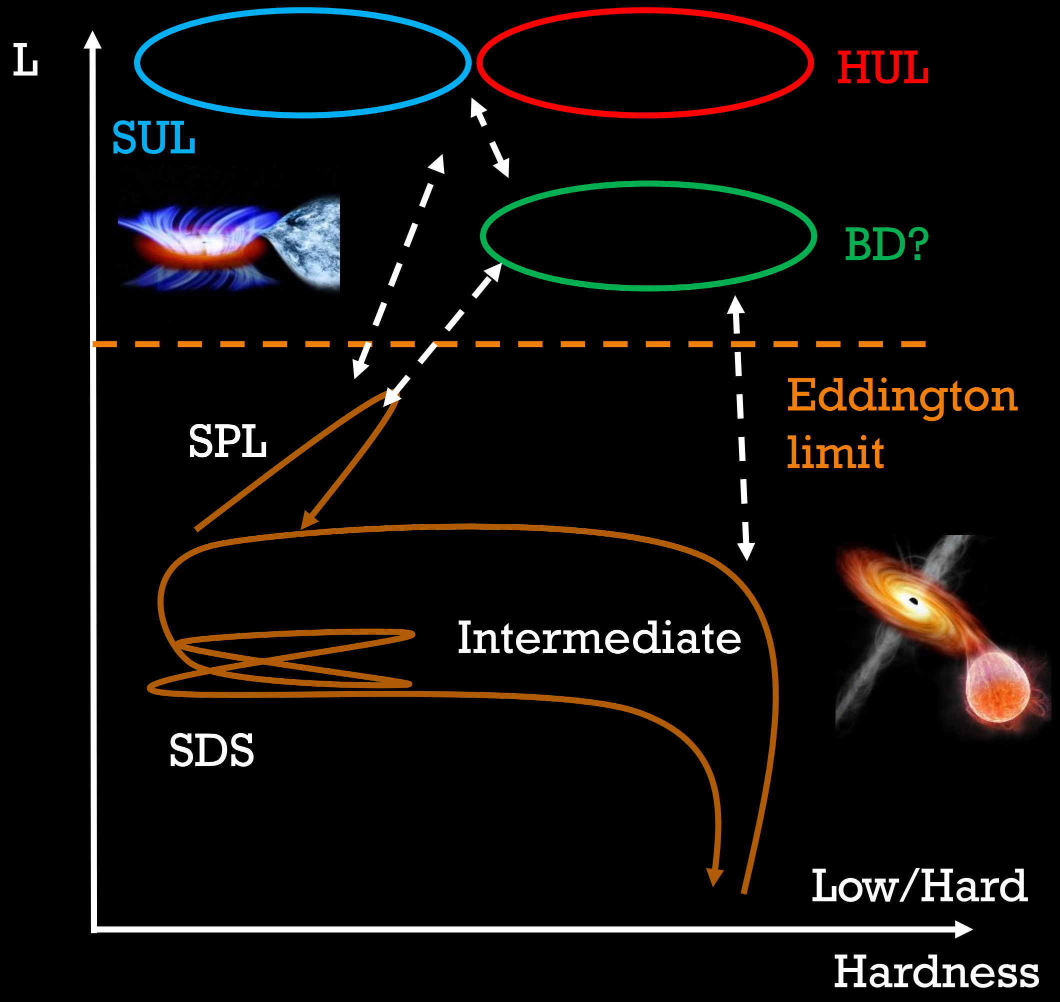
Sutton et al. (2013)

From ~20 persistent ULXs

HMXB vs LMXB

- Most well-investigated ULXs are persistent X-ray sources with low-level variabilities.
  - HMXB with long timescale super-Eddington accretion rate?
    - It is possible when the companion evolved to the Hertzsprung Gap with forming a common envelope (supergiant HMXB).
    - Timescale ~ $10^4 – 10^5$ years.
    - Many persistent ULXs have high-mass companion
  - LMXB with long-lasting super-Eddington outbursts?
    - Transient ULXs
    - Can a transient LMXB with canonical outbursts evolved to a ULX?
    - Spectral evolution?

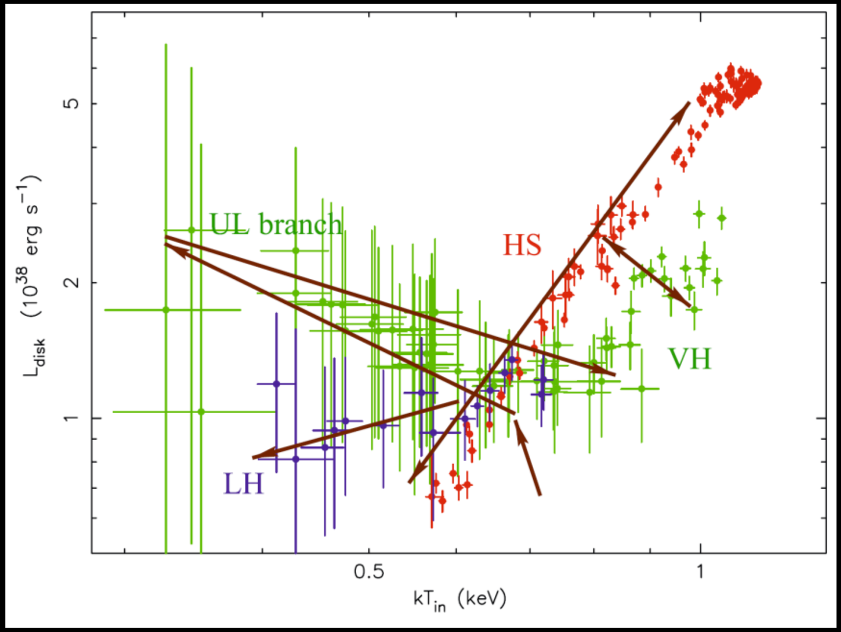
BHXB-ULX Connection?



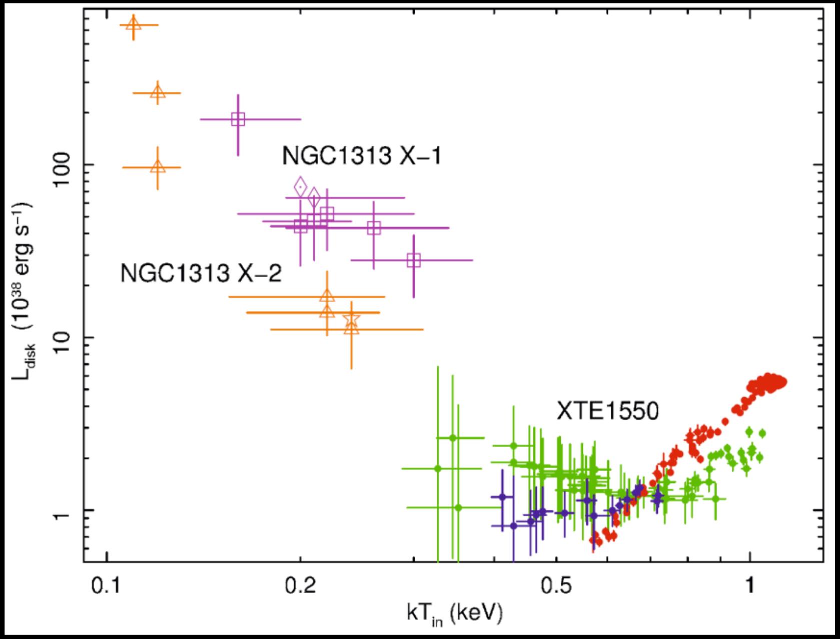
Persistent sources

Transient sources

BHXB-ULX Connection?

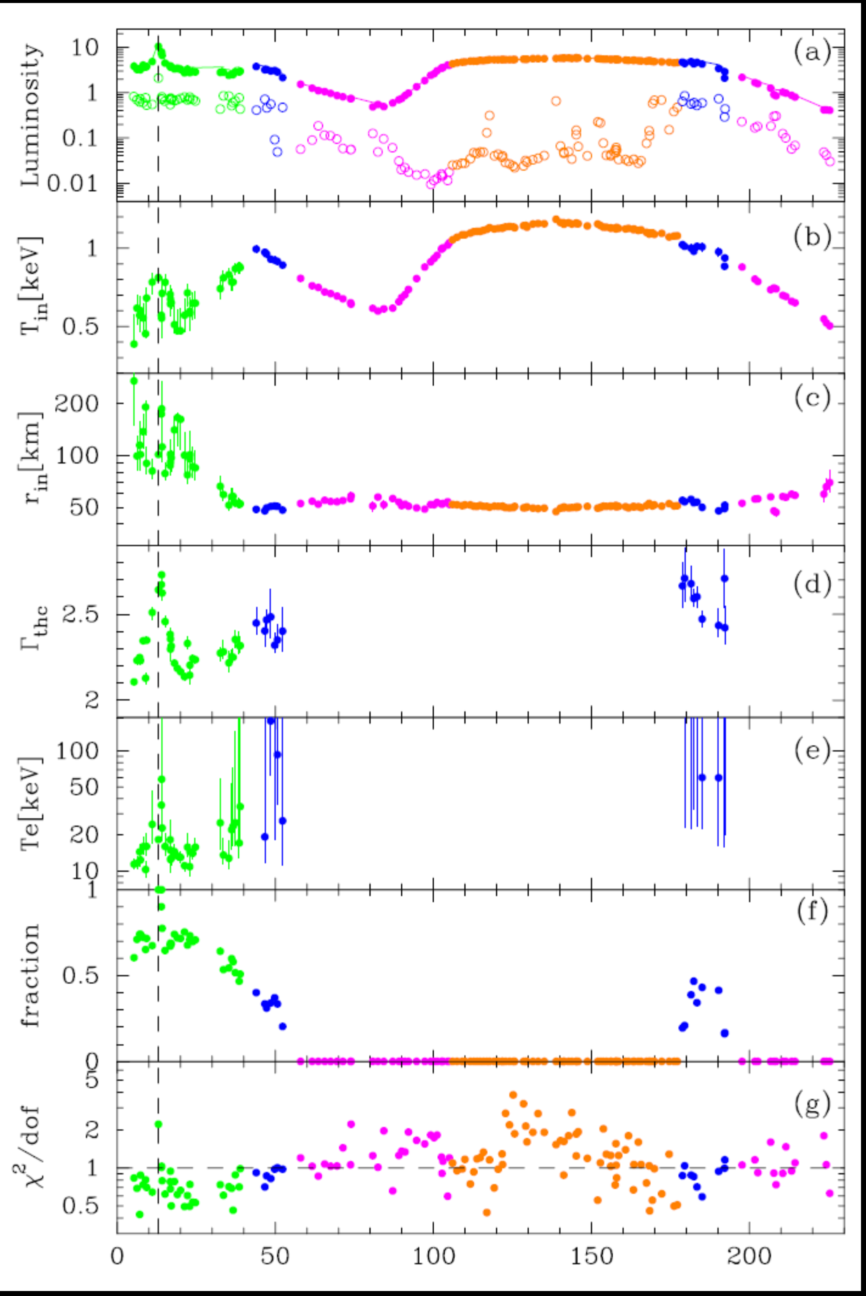


Soria (2007)



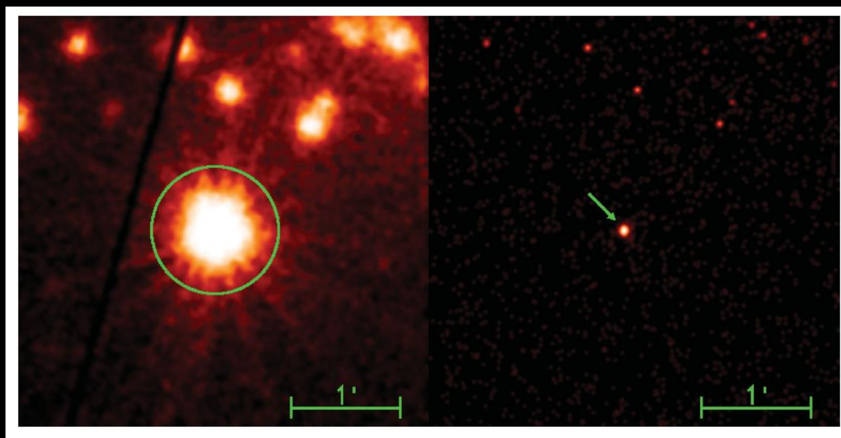
Soria (2007)

- XTE J1550-564 is likely a link bridging the BHXBs and ULXs.
  - The ultraluminous branch (strong very high state) is a key signature similar to the HUL spectrum.
  - However, the luminosity of XTE J1550-564 is still in the BHXB regime.



Kubota & Done (2004)

M31 ULX-1



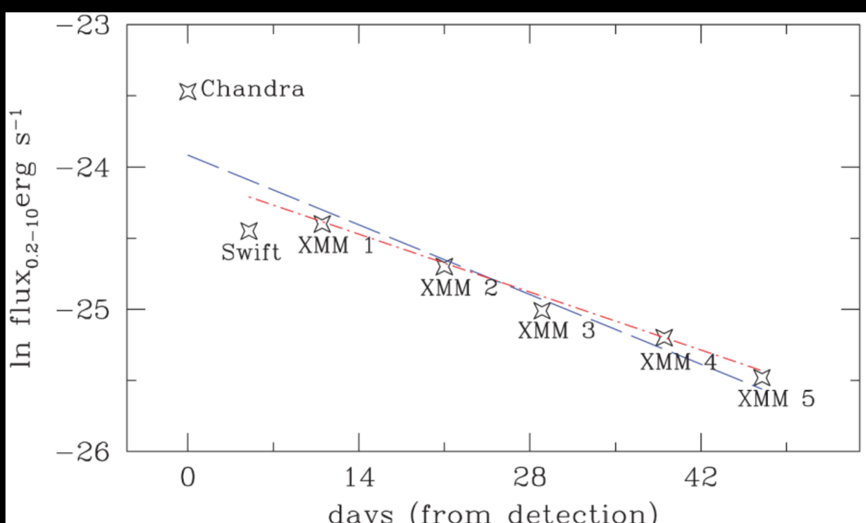
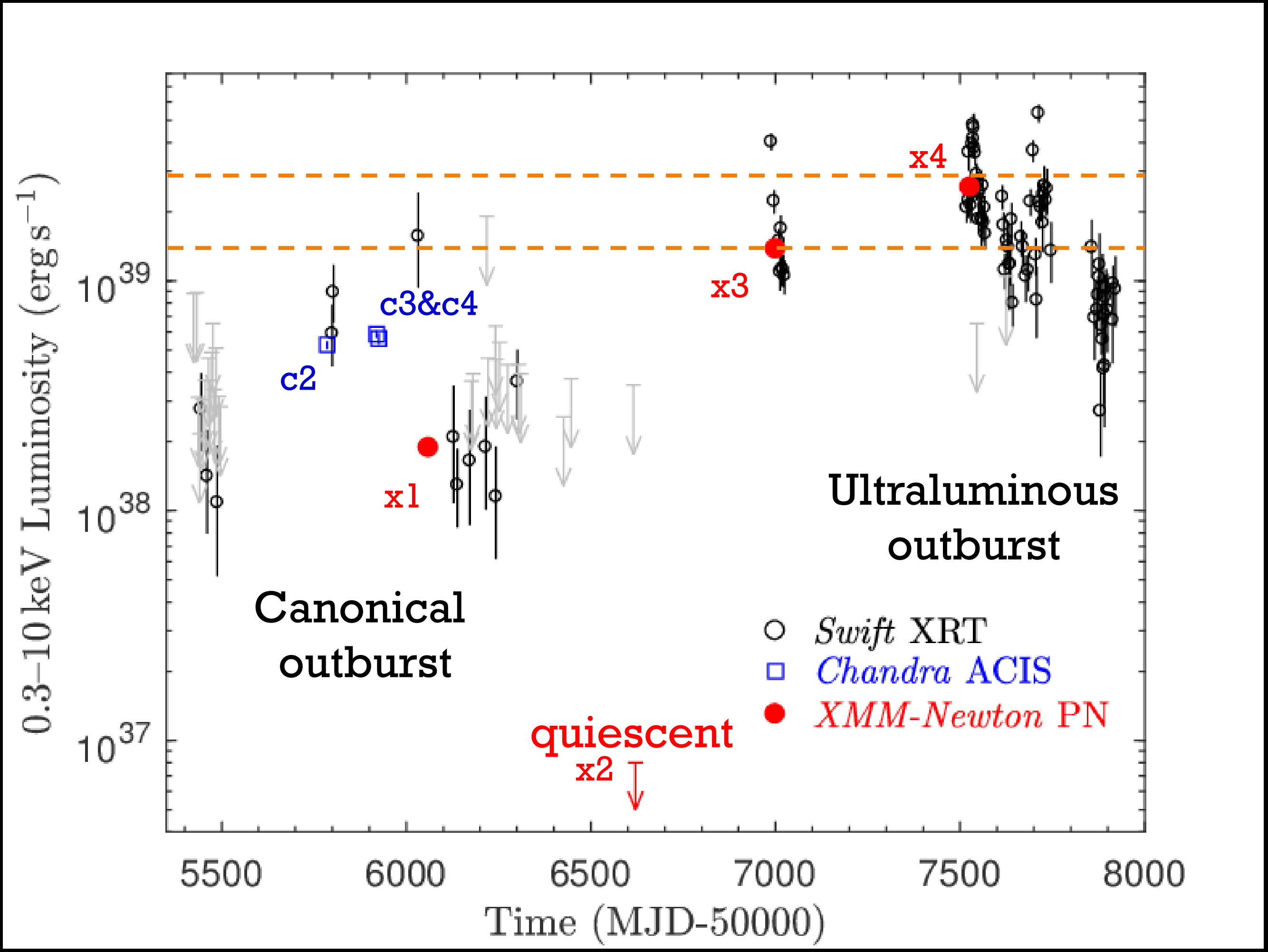


Table 2. Best-fitting spectral parameters.

Observation	1	2	3	4	5
TBABS*BHSPEC					
$n_H = 0.067 \times 10^{22}$ cm^{-2}					
$\cos(i^\circ) = 0.87^{+0.04}_{-0.02}$					
$a_* = 0.36^{+0.10}_{-0.11}$					
BH mass ($M_\odot$) = 10*					
log L/L_{Edd}	$-0.133^{+0.016}_{-0.026}$	$-0.283^{+0.015}_{-0.011}$	$-0.418^{+0.016}_{-0.013}$	$-0.521^{+0.005}_{-0.005}$	$-0.612^{+0.005}_{-0.005}$
χ^2 (d.o.f.) 3169.4 (2801)					
Null P 1×10^{-6}					
$n_H < 0.068 \times 10^{22}$ cm^{-2}					
$\cos(i^\circ) = 0.86$*					
$a_* > 0.76$					
BH mass ($M_\odot$) = $14.9^{+0.2}_{-0.8}$					
log L/L_{Edd}	$-0.257^{+0.015}_{-0.005}$	$-0.403^{+0.016}_{-0.005}$	$-0.537^{+0.016}_{-0.006}$	$-0.640^{+0.016}_{-0.005}$	$-0.731^{+0.016}_{-0.006}$
χ^2 (d.o.f.) 3078.5 (2801)					
Null P 2×10^{-4}					
$n_H = 0.067 \times 10^{22}$ cm^{-2}					
$\cos(i^\circ) = 0.5$*					
$a_* = 0.76^{+0.01}_{-0.01}$					
BH mass ($M_\odot$) > 29.6					
log L/L_{Edd}	$-0.381^{+0.007}_{-0.003}$	$-0.530^{+0.006}_{-0.003}$	$-0.664^{+0.008}_{-0.005}$	$-0.766^{+0.007}_{-0.005}$	$-0.857^{+0.008}_{-0.005}$
χ^2 (d.o.f.) 3009.5(2801)					
Null P 0.003					
TBABS*(DISKPBB+COMPTT)					
n_H $0.104^{+0.001}_{-0.001} \times 10^{22}$ cm^{-2}					
kT_{in} (keV)	$0.44^{+0.08}_{-0.08}$	$0.51^{+0.01}_{-0.01}$	$0.67^{+0.03}_{-0.03}$	$0.80^{+0.03}_{-0.03}$	$0.92^{+0.03}_{-0.03}$
p	$0.60^{+0.03}_{-0.01}$	$0.60^{+0.03}_{-0.02}$	$0.60^{+0.02}_{-0.01}$	$0.56^{+0.01}_{-0.01}$	$0.55^{+0.01}_{-0.01}$
Norm	7.59	3.69	1.14	0.37	0.18
$kT_{comp,seed}$ (keV)	$0.55^{+0.10}_{-0.13}$	$0.96^{+0.04}_{-0.04}$	$0.61^{+0.27}_{-0.16}$	<1.26	–
kT_{comp} (keV)	$0.98^{+0.30}_{-0.10}$	$0.49^{+0.03}_{-0.02}$	$0.81^{+0.06}_{-0.04}$	<11.73	–
τ	$11.33^{+6.60}_{-5.22}$	$16.39^{+4.09}_{-3.95}$	>19.00	(25.50)	–
χ^2 (d.o.f.) 2752.2 (2777)					
Null P 0.73					

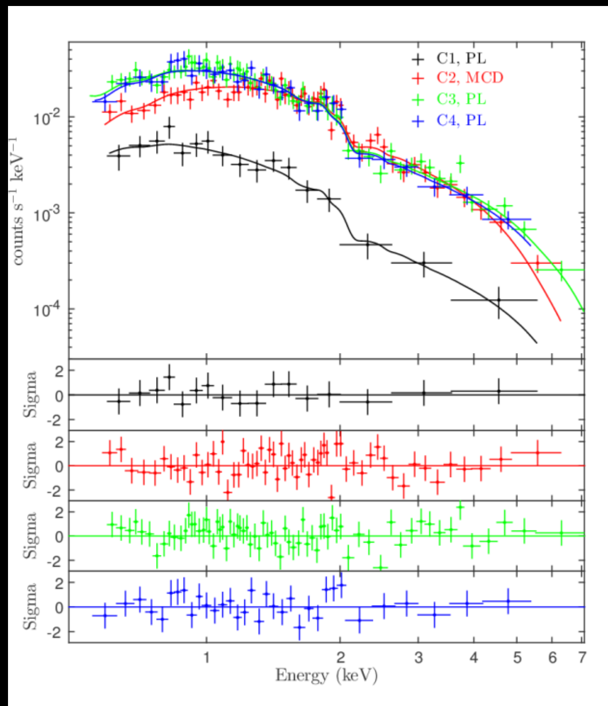
Kubota & Done (2004)

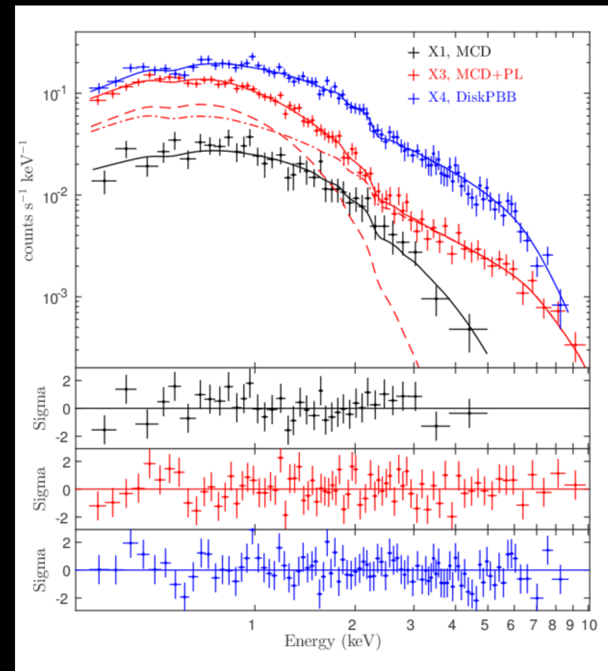
P9



Hu et al. sbumitted

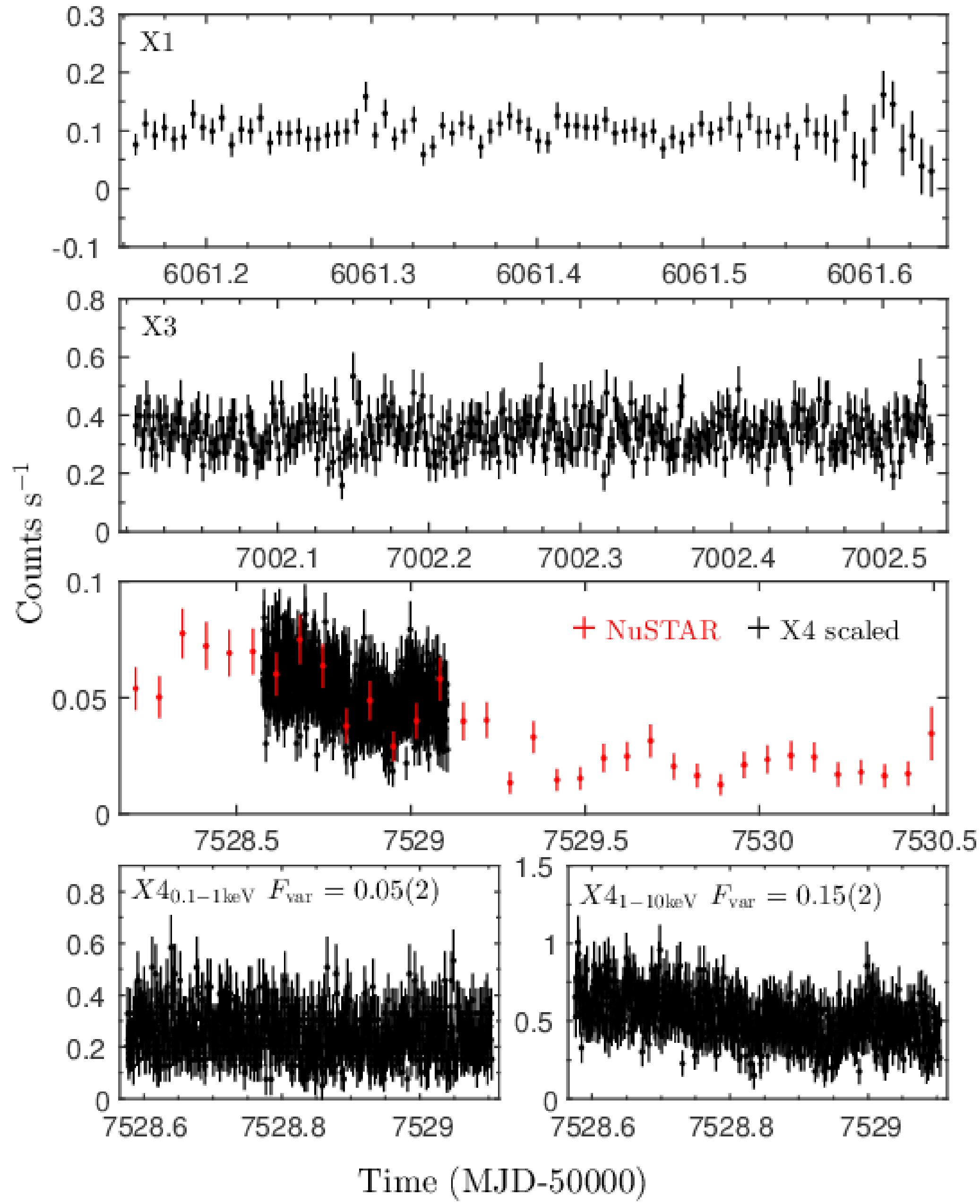
P9 Spectroscopy





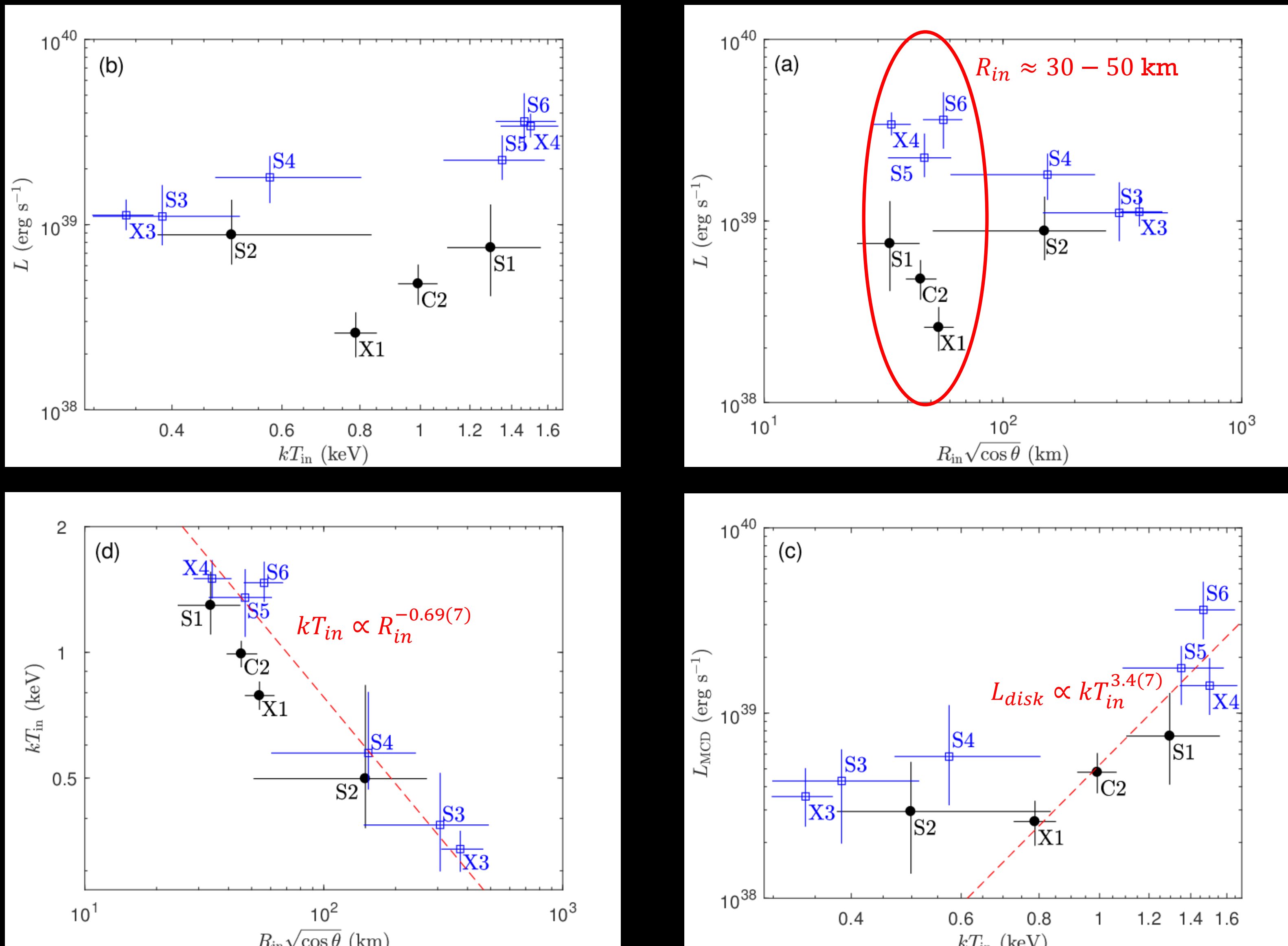
Obs.	Model	$L_{0.3-10\ \mathrm{keV}}$ (10^{39} erg s^{-1})	L_{MCD} (10^{39} erg s^{-1})	N_{H} (10^{22} cm^{-2})	$R_{\mathrm{in}}\sqrt{\cos\theta}$ (km)	kT_{in} (keV)	Γ or p	χ^2/dof	State
C1	PL	$0.10^{+0.03}_{-0.02}$	⋯	$0.13^{+0.17}_{-0.13}$	⋯	⋯	$2.4^{+0.5}_{-0.4}$	12.4/16	SPL
C2	MCD	0.5 ± 0.1	0.5 ± 0.1	0.07 ± 0.04	49^{+7}_{-6}	$0.96^{+0.07}_{-0.06}$	⋯	62.7/57	Thermal
C3	PL	0.79 ± 0.06	⋯	0.09 ± 0.04	⋯	⋯	2.2 ± 0.1	62.2/67	SPL
C4	PL	$0.83^{+0.10}_{-0.08}$	⋯	$0.14^{+0.08}_{-0.07}$	⋯	⋯	2.3 ± 0.02	27.1/31	SPL
X1	MCD	$0.26^{+0.08}_{-0.07}$	$0.26^{+0.08}_{-0.07}$	$0.024^{+0.018}_{-0.014}$	53^{+8}_{-7}	0.78 ± 0.02	⋯	77.8/93	Thermal
X3	MCD+PL	1.1 ± 0.2	$0.36^{+0.07}_{-0.08}$	0.07(2)	370^{+90}_{-60}	0.34 ± 0.04	1.8 ± 0.2	171.9/189	UL (HUL)
X4[a]	DiskPBB	3.3 ± 0.3	⋯	0.09 ± 0.02	16 ± 3	2.2 ± 0.2	0.57 ± 0.01[b]	308.3/312	UL (BD)
	MCD+PL	$3.4^{+0.6}_{-0.4}$	$1.4^{+0.5}_{-0.4}$	$0.11^{+0.03}_{-0.02}$	34^{+7}_{-6}	1.5 ± 0.2	$2.0^{+0.2}_{-0.1}$	308.3/311	

Hu et al. submitted



X1
X3
NuSTAR
X4 scaled
$X4_{0.1-1\mathrm{keV}}$ $F_{\mathrm{var}} = 0.05(2)$
$X4_{1-10\mathrm{keV}}$ $F_{\mathrm{var}} = 0.15(2)$
Counts s^{-1}
Time (MJD-50000)

P9 Spectroscopy



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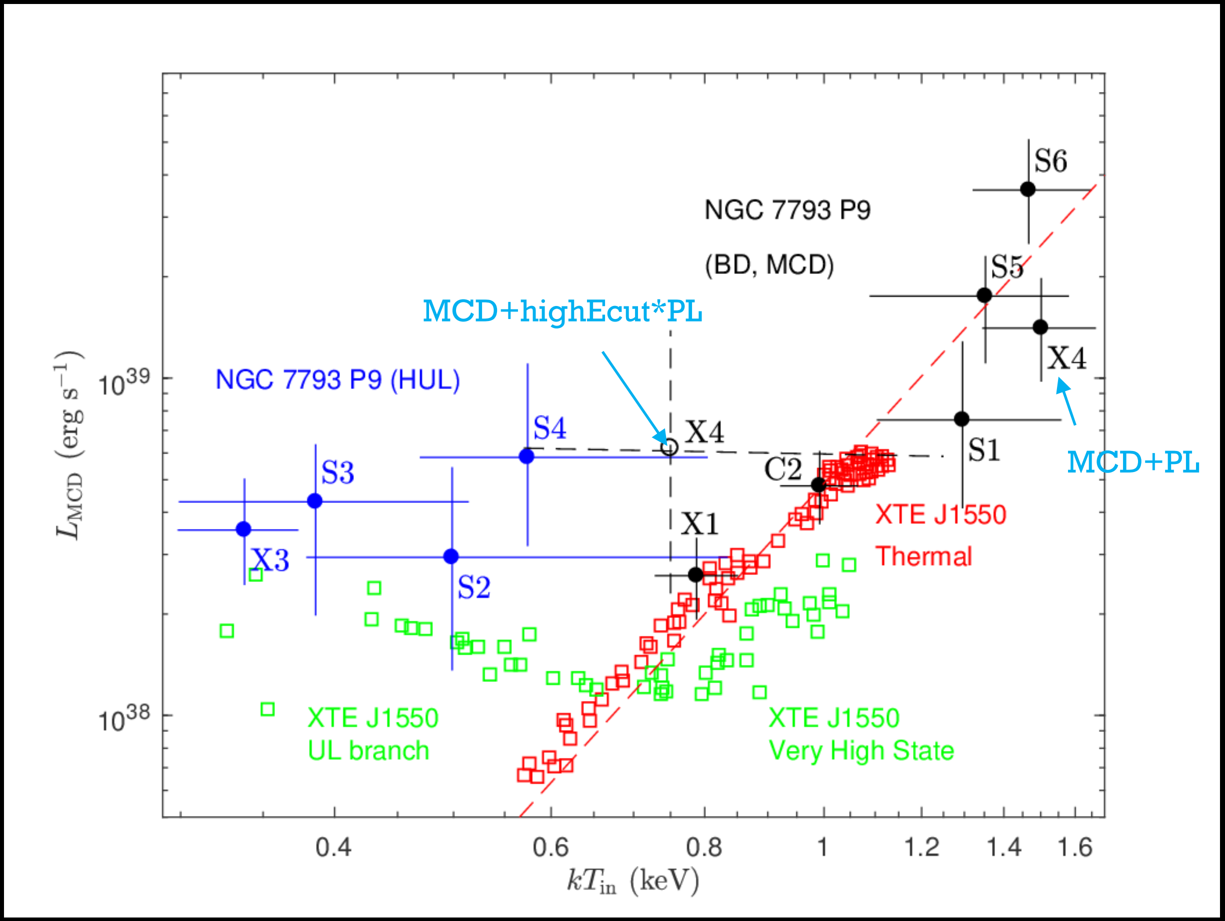
P9 Spectroscopy



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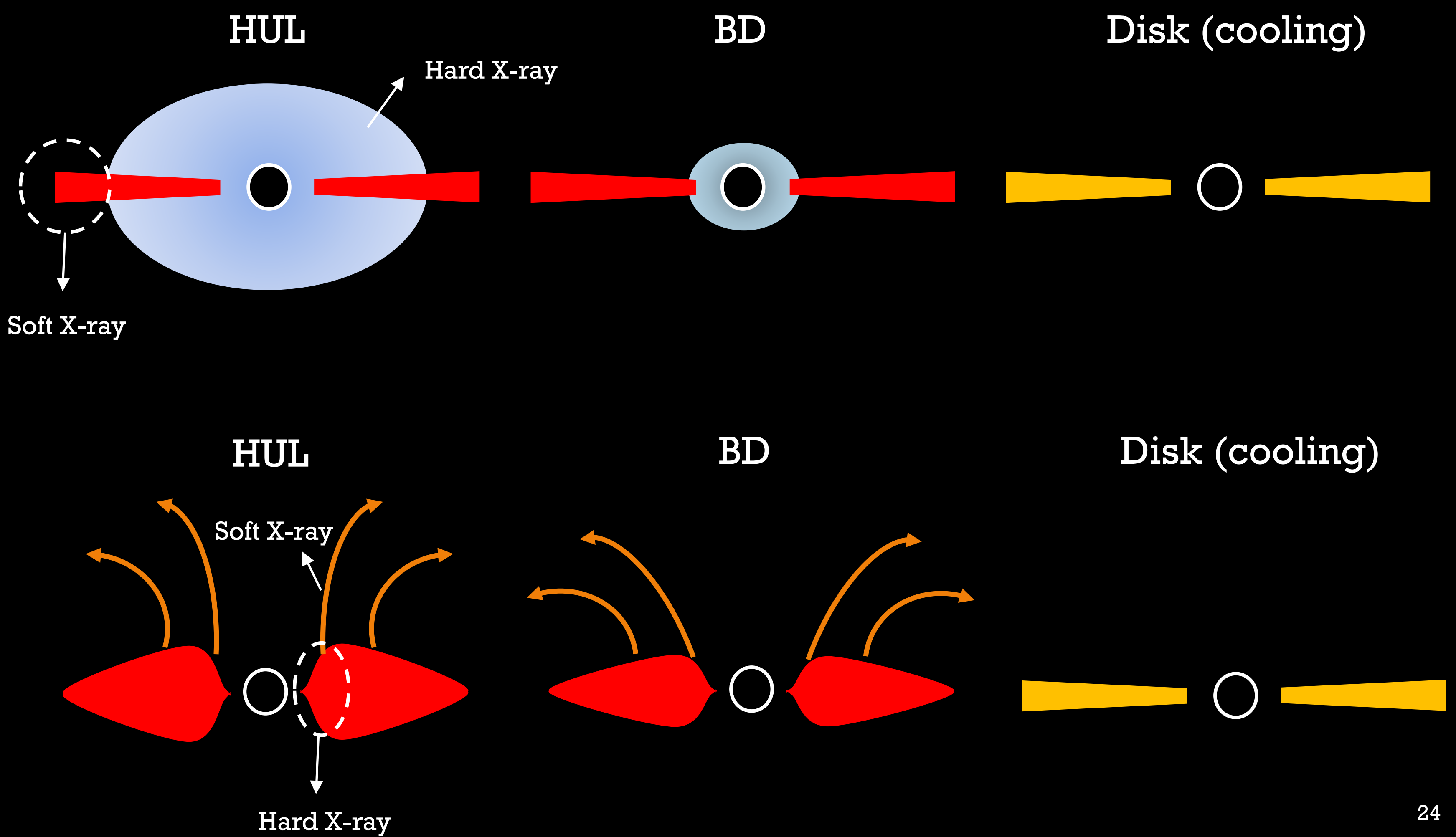
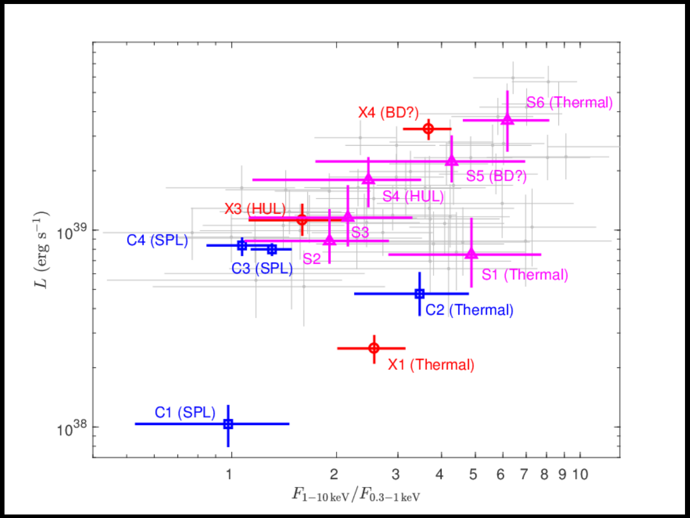
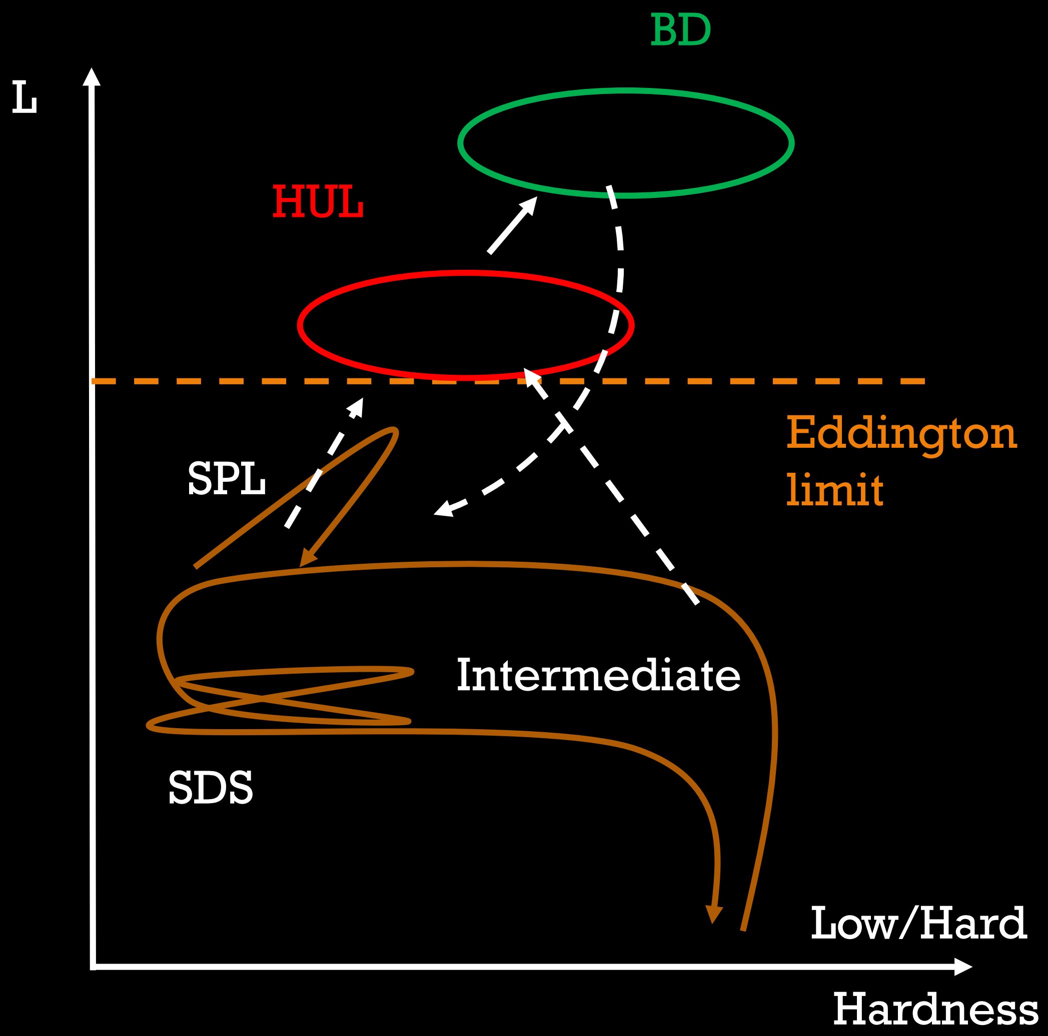
Model Comparison



BHXB-ULX Connection?





Discussion & Future Work

- P9 likely exhibits a hot thin disk and an optically thick corona, but the super-critical accretion model cannot be excluded.
  - The hard component of the HUL spectrum can be described by neither an MCD nor a Slim disk.
  - The disk component of the BD state (if we fit it with MCD+PL) fit the $L_{disk} \propto T_{in}^4$ well.
- Comprehensively tracking the spectral evolution of transient ULXs is helpful for understanding the connection between ULXs and BHXBs.
  - Capture the beginning of the outburst
    - BD? SUL? SPL?
  - Track the variability of the disk and test the model

Soria (2007)

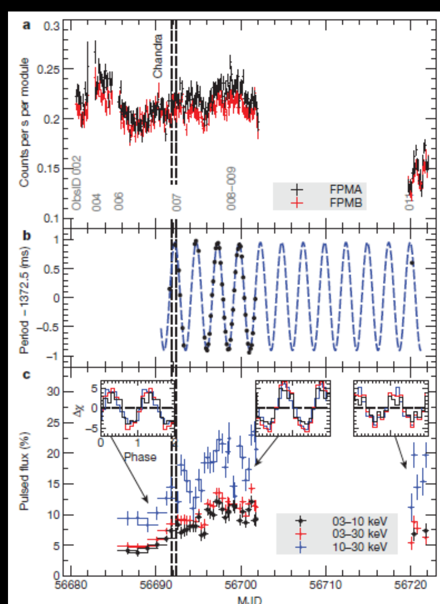
Ultraluminous Pulsar

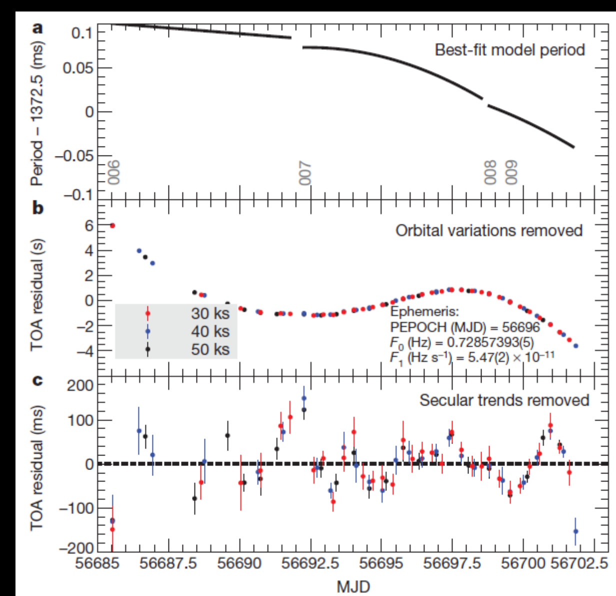
LETTER

doi:10.1038/nature13791

An ultraluminous X-ray source powered by an accreting neutron star

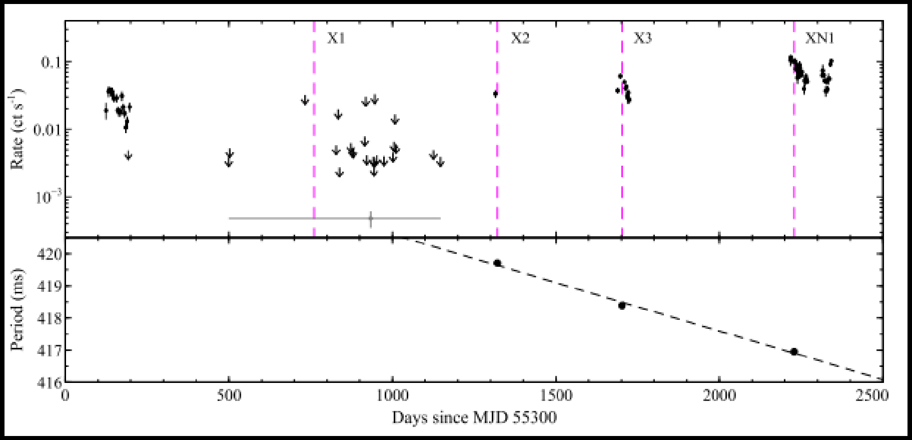
M. Bachetti[1,2], F. A. Harrison[3], D. J. Walton[3], B. W. Grefenstette[3], D. Chakrabarty[4], F. Fürst[3], D. Barret[1,2], A. Beloborodov[5], S. E. Boggs[6], F. E. Christensen[7], W. W. Craig[8], A. C. Fabian[9], C. J. Hailey[10], A. Hornschemeier[11], V. Kaspi[12], S. R. Kulkarni[3], T. Maccarone[13], J. M. Miller[14], V. Rana[3], D. Stern[15], S. P. Tendulkar[3], J. Tomsick[6], N. A. Webb[1,2] & W. W. Zhang[11]

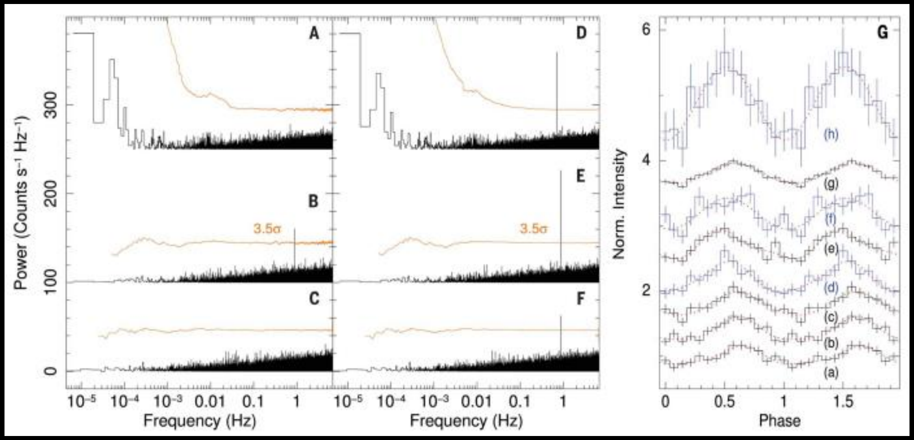


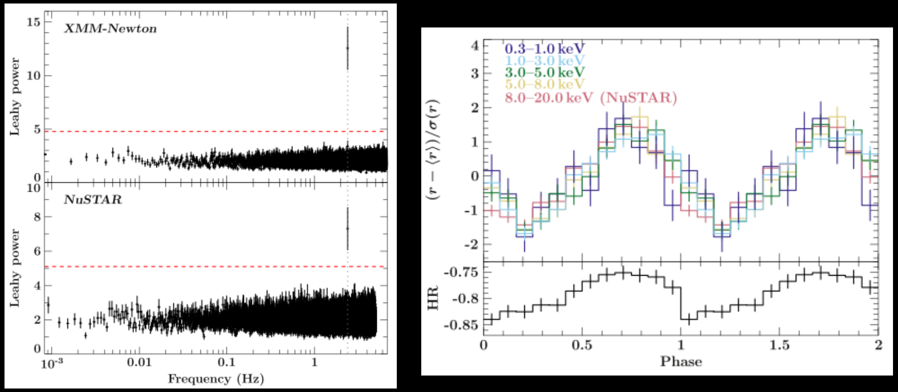


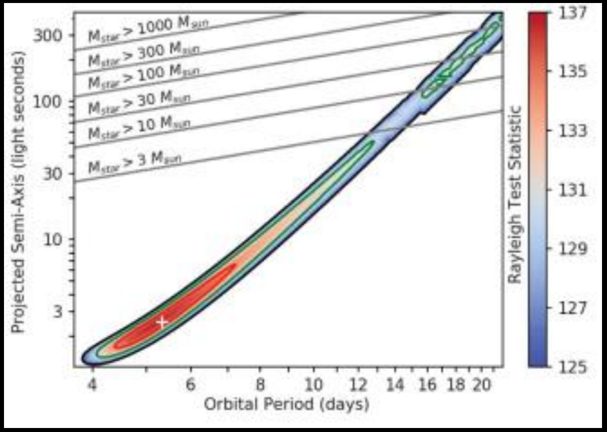
Bachetti et al. (2014)

NGC 7793 P13 & NGC 5907 ULX-1





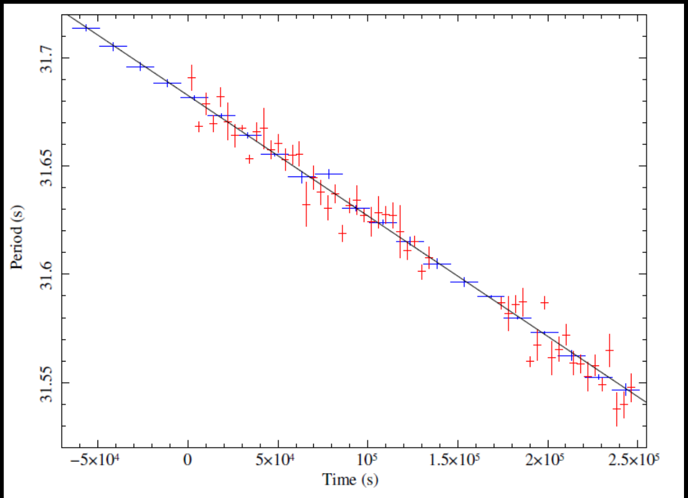


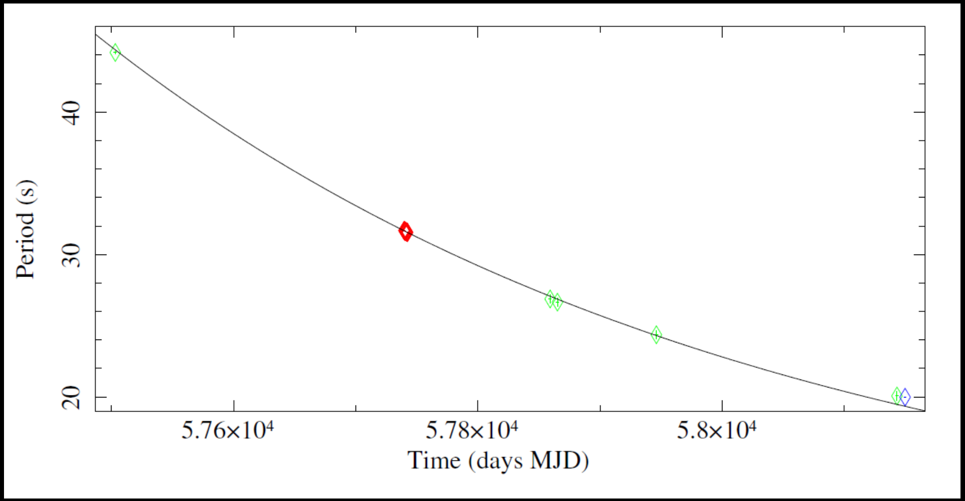


Furst et al. (2016)

Israel et al. (2017)

NGC 300 ULX-1





Carpano et al. (2018)

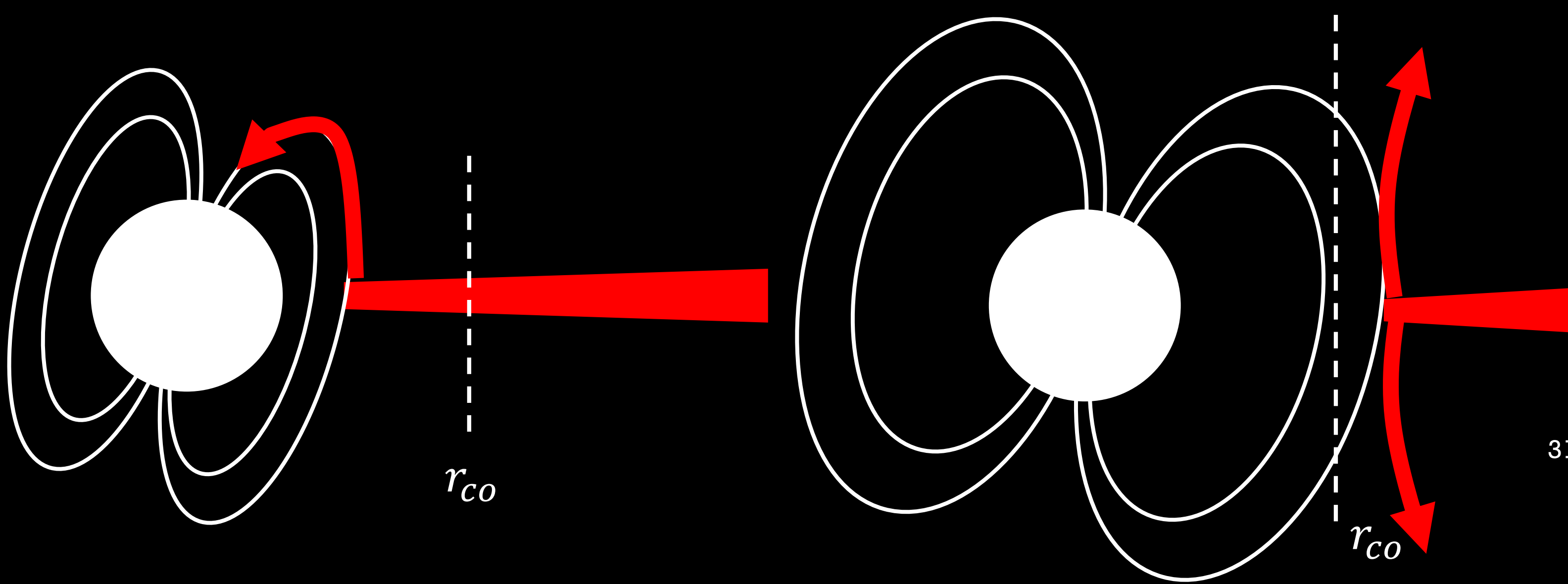
Magnetic Field & Luminosity

- The luminosity of an NS can have $L > L_{Edd}$ if the surface magnetic field is very high
  - The electron scattering cross sections is much lower than the Thomson cross section ($L_{Edd} = \frac{4\pi c G M m_p}{\sigma_T}$).
  - $B > 10^{15}$ G can have $L \sim 10^{41}$ erg/s
  - P_{spin} inferred B field is much lower

Name	M82 X-2	NGC 7793	NGC 5907	NGC 300
Peak L (erg/s)	1.8×10^{40}	5×10^{39}	10^{41}	5×10^{39}
$P_s(s)$	1.37	0.42	1.13	40 – 20
$\dot{\nu}\ (s^{-2})$	10^{-10}	4×10^{-11}	4×10^{-9}	$10^{-9} - 10^{-10}$
$P_{orb}(day)$	2.51	65(?)	~5.3	?
$P_{sup}(day)$	~55(?)	~3200(?)	78	?

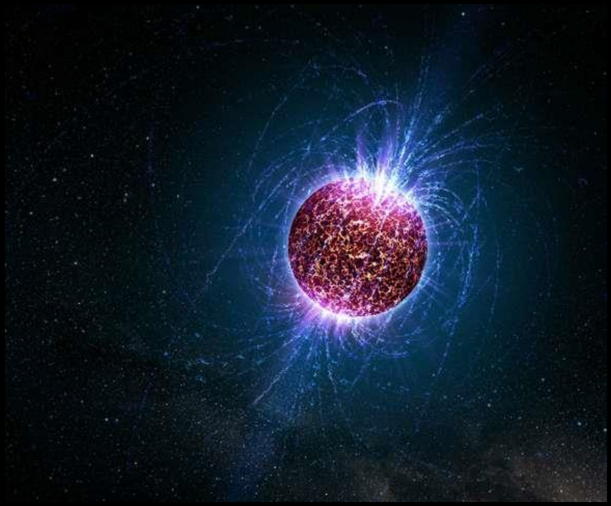
Propeller Effect

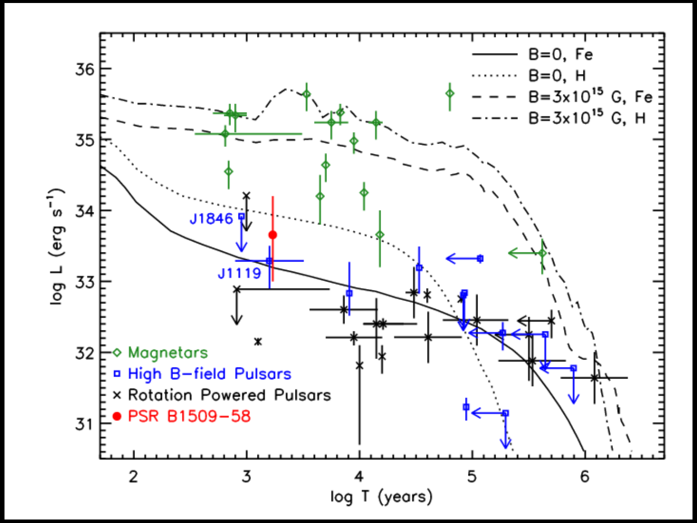
- Corotation radius: $r_{co} = \left(\frac{GMP_{spin}^2}{4\pi^2}\right)^{1/3}$
- Magnetospheric Radius: $r_m = \xi r_A = \xi \left(\frac{\mu^4}{2GM\dot{M}^2}\right)^{1/7}$
- $r_{co} > r_m$: accretion is possible and NS spin-up
- $r_{co} < r_m$: accretion is prohibited due to centrifugal barrier.



Magnetic Field & Luminosity

- Are non-dipolar magnetic fields common in NSs?
  - M82 X-2: $B_p \sim 10^{12}G, B_{tot} \sim 2 \times 10^{13}G$
  - NGC 7793 P13: $B_p \sim 3 \times 10^{12}G, \mathrm{B_{tot}} \gtrsim 5 \times 10^{13}G$
  - NGC 5907 ULX-1: $B_p \sim 3 \times 10^{13}G, B_{tot} \sim 3 \times 10^{14}G$

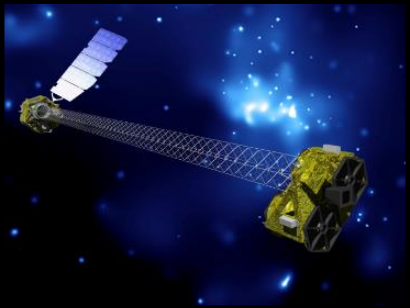




Hu et al. (2017a)

Super-Critical Accretion

- Super-critical accretion?
  - Eddington limited accreting NS with magnetar-level B field have $P \gtrsim 0.1$s.
  - Time resolution of XMM-Newton (~0.1s) and Chandra (3s)
  - Low B-field ultraluminous pulsar with super-critical accretion can have much shorter period.
    - Ultraluminous millisecond pulsar?
    - NuSTAR, NICER, and future eXTP, Lobster X-ray telescopes.



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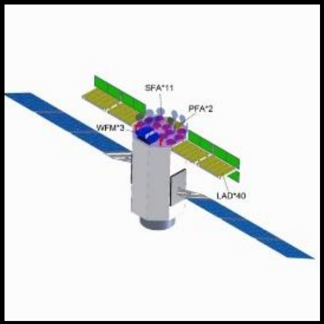

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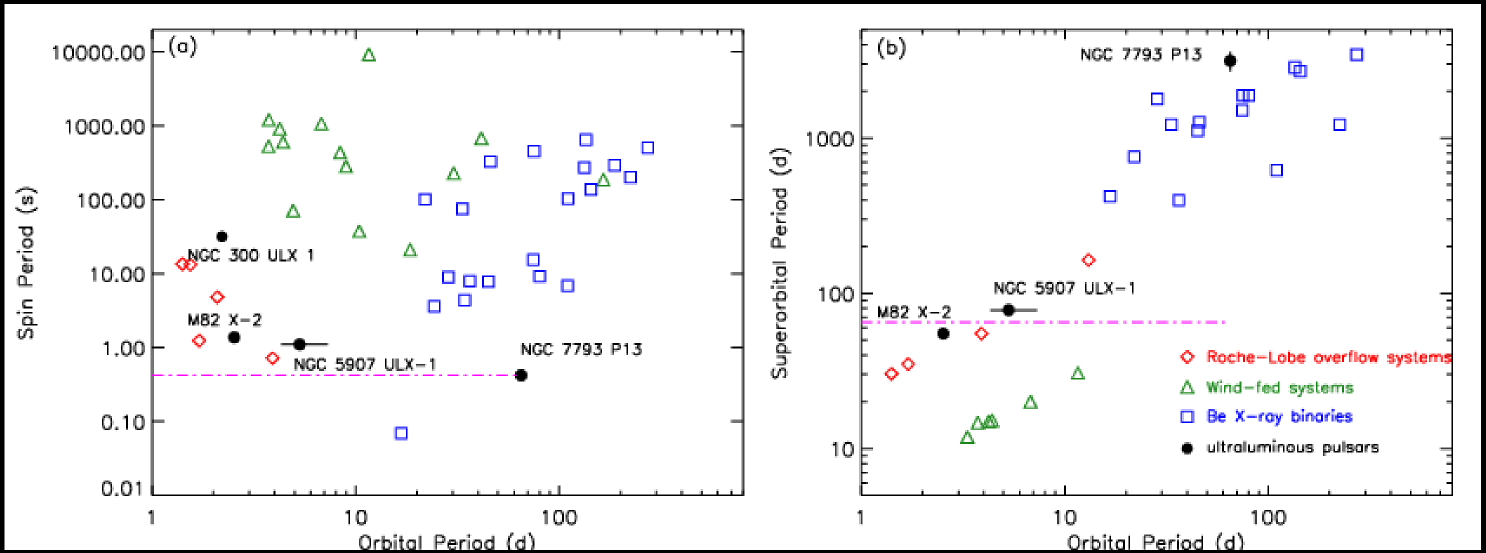
Spin-Orbital-Superorbital Relation

- If the 65-d modulation is orbital and the 3000 d modulation is superorbital, NGC 7793 P13 could be a Be X-ray binary.
  - Roche-lobe size is larger than the Companion star radius
  - Search for the feature of Be star?
  - The magnetar argument may not be valid because the accretion mechanism may not be disk-fed.



Hu et al. (2017b)

Accretion Mechanisms

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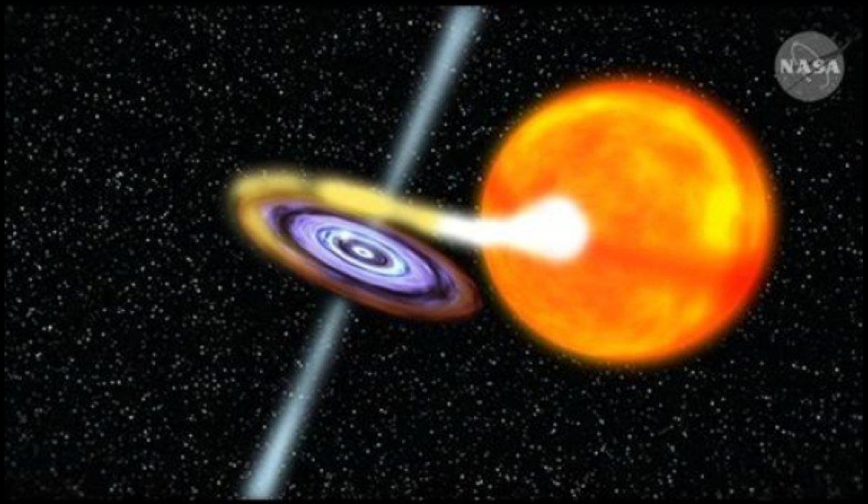

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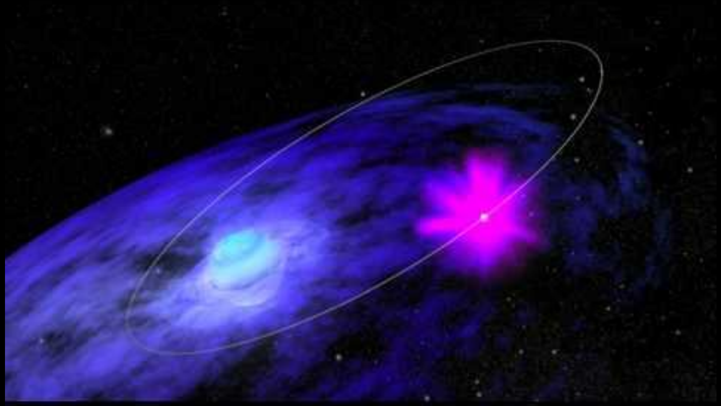

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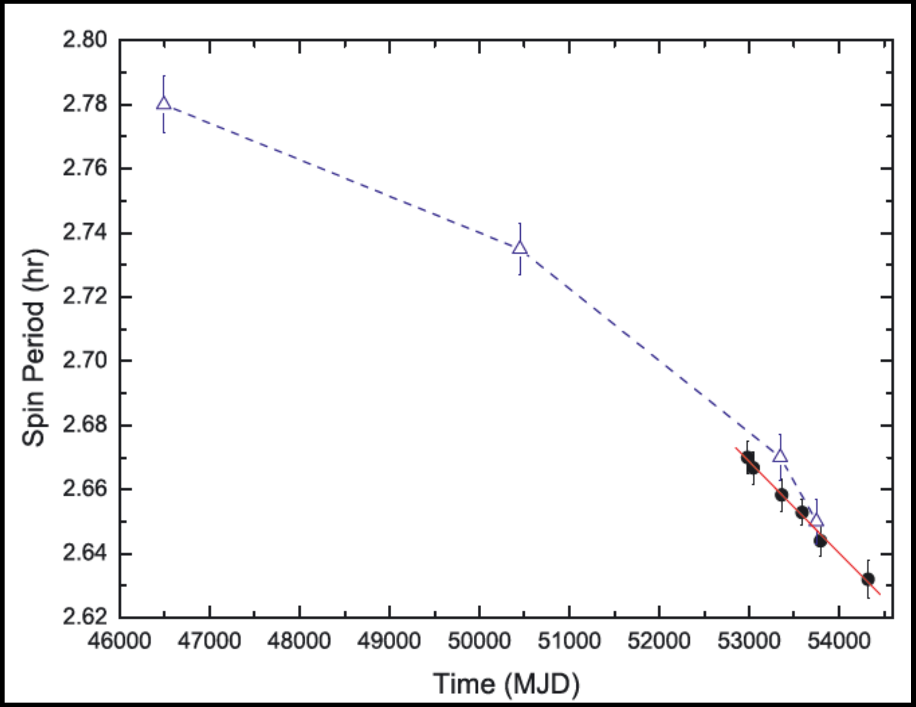
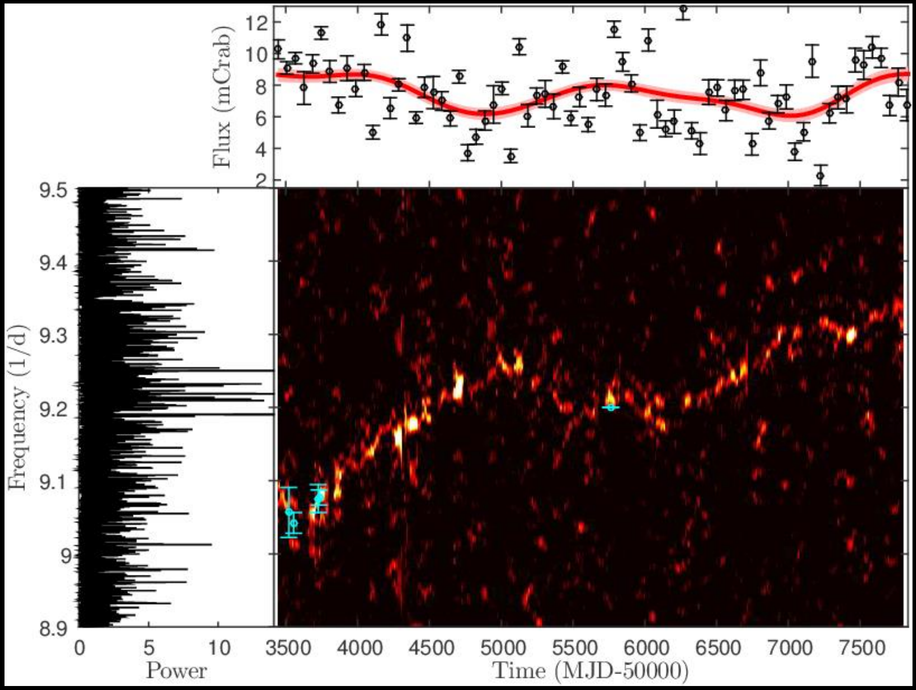
Example: 4U 0114+650



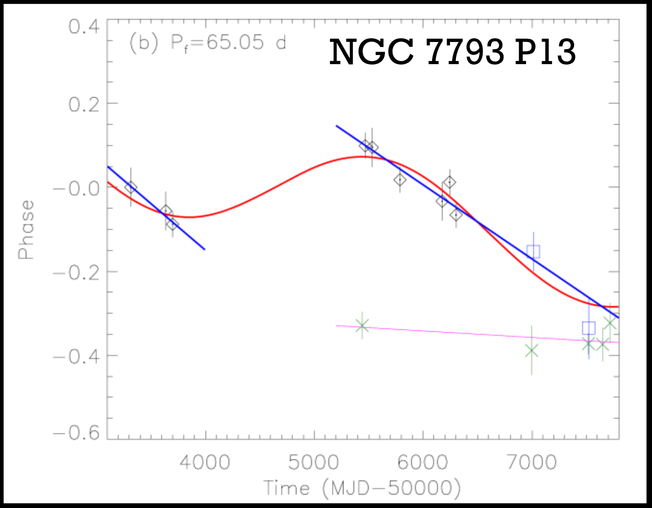
Wang (2011)



Hu et al. (2017c)

Monitoring of the spin period evolution helps to reveal the accretion mechanism

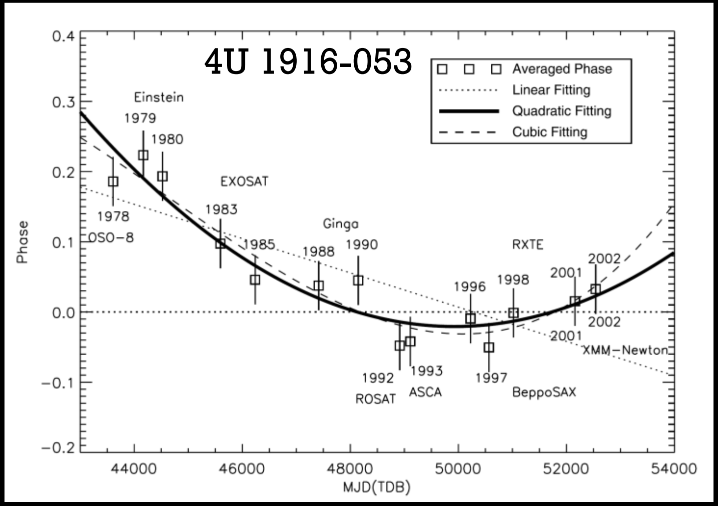
Orbital? Superorbital?



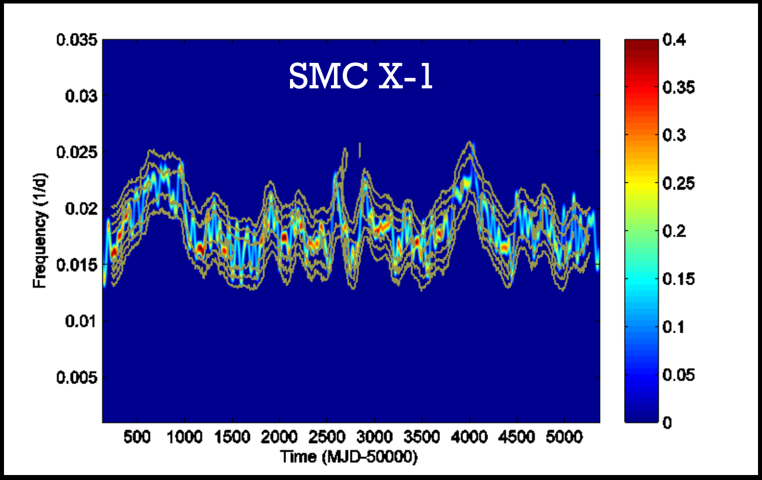
Hu et al. (2017b)

The superorbital modulation period is less stable than the orbital period.

Keep monitoring



Hu et al. (2008)



Hu et al. (2011)

Summary

- ULXs are nature laboratories to test the physics in extreme conditions
- NGC 7793 P9 is an important sample to fill in the link between BHXBs and ULXs
    - The detailed spectral evolution is still unclear
    - More samples will be necessary to comprehensively investigate the link between BHXBs and ULXs
- Ultraluminous pulsars are accreting magnetar candidates
    - Super-critical accretion is also possible
    - The accretion mechanism is controversial
    - Further stability tests will be necessary

THANK YOU