Summary after 8th and 9th lecture:

8th lecture:

Solar system:

- **Sun – the main X-ray source**
- **fluorescence of X-rays**
- **solar wind**
- **charge transfer (CT) process.**

Planets, Moon, Comets:

- **Earth and geocorona**
- **aurora in X-rays**
- **Moon and it's X-ray emission**
- **spectrum of CT process**
- **Comets and their emission contours**
- **Jupiter, Mars, Venus, Saturn, Titan**

Nuclear burning stars:

- **solar magnetic dynamo**
- **connection of X-rays with stellar parameters**
- **coronal age-activity relation**
- **binaries with rapidly rotating companions**
- **very low-mass stars and brown dwarfs**

9th lecture:

X-ray emission processes:

-heating via accretion
-radiative cooling

Premain sequence stars:

- **classical TTauri stars**
- **weak TTauri stars**
- **Herbig Ae/Be stars**

White Dwarfs:

- **emission from WD atmosphere**
- **Chandra images of Planetary Nebule**

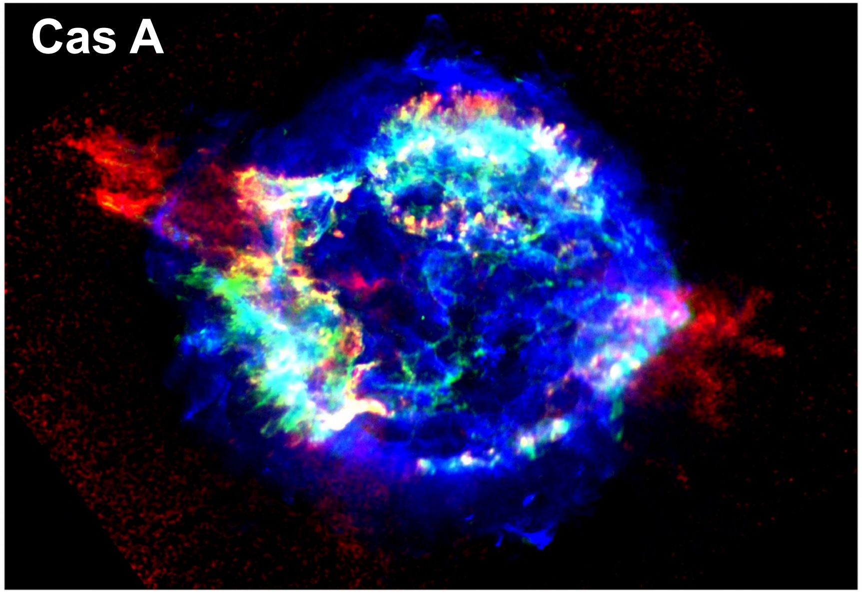
Accreting WD, CV:

- **Dwarf Novae**
- **Polars**
- **Intermediate Polars**
- **Classical Novae**

Pulsars and isolated Neutron Stars:

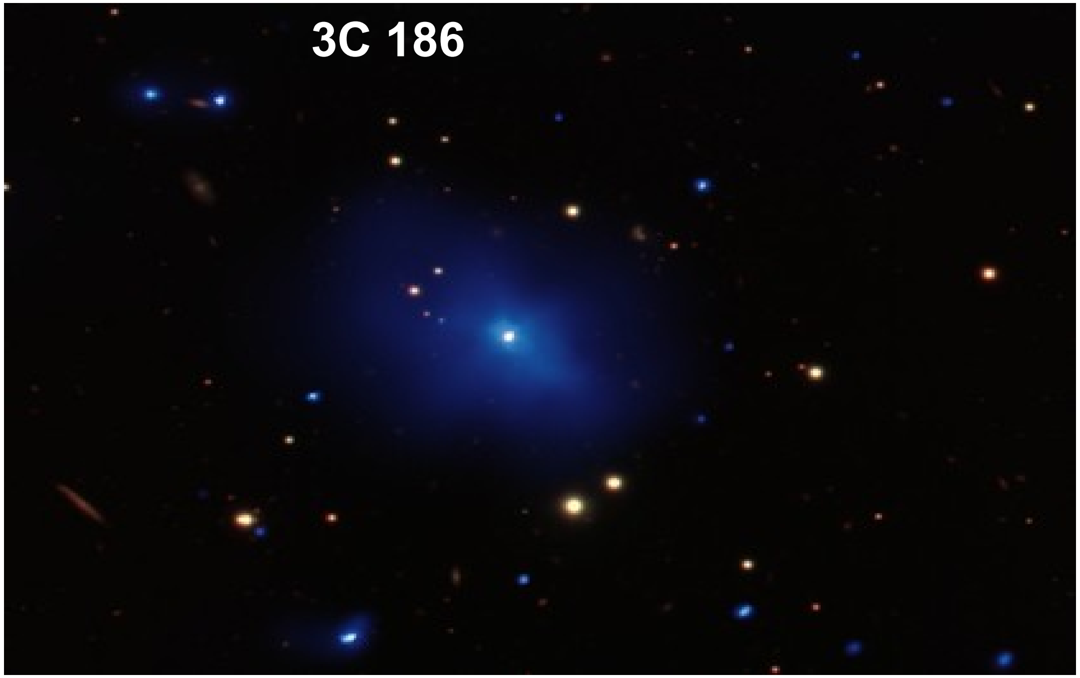
- **period – period dot relation**
- **Crab Nebula**
- **cooling of NS**
- **lines as a diagnostic of gravitational redshift**

The theory of different emission processes across astrophysical objects:



- Solar system objects
- Nuclear Burning Stars
- White Dwarfs
- Cataclysmic Variables
- Classical Novae
- Pulsars and Isolated Neutron Stars
- Accreting Neutrons Stars and Black Hole binaries
- Supernova Remnants
- Interstellar Medium
- Galactic Center

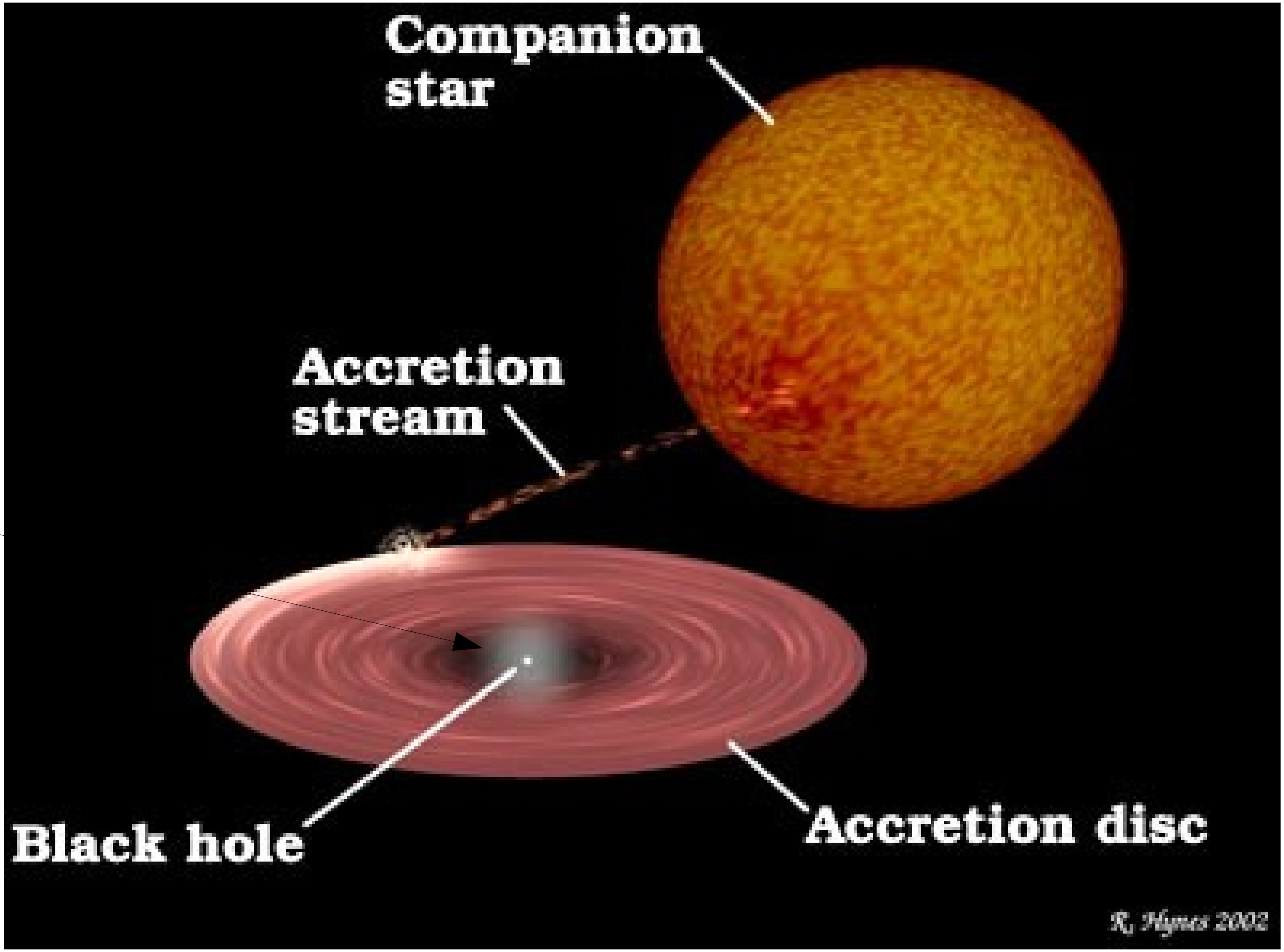
- Nearby Galaxies
- Active Galactic Nuclei
- Clusters of Galaxies
- Gamma- Ray Bursts
- Cosmic X-ray Background



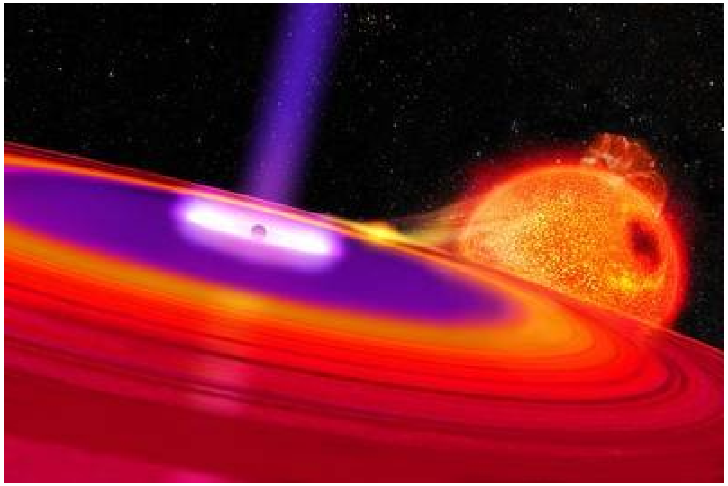
Lecture 10th : Accretion disks around NSs and BHs

Shakura & Sunayev 1973

Neutron Star



Accretion physics:



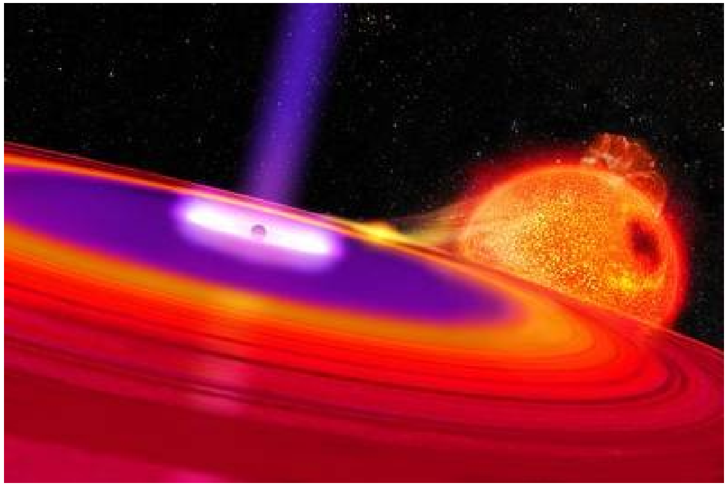
Shakura Sunayev (1973) assuming viscous heating – αP_tot.

From equations of:

- continuity
- motion in radial direction
- energy conservation

they derived total flux generated via accretion:

$$F(r) = \frac{3}{8\pi} \frac{GM\dot{M}}{r^3} \left[1 - \left(\frac{r_0}{r} \right)^{1/2} \right] \quad ; \qquad r_0 = 3 R_{Schw} = 6\mathrm{GM}/c^2$$



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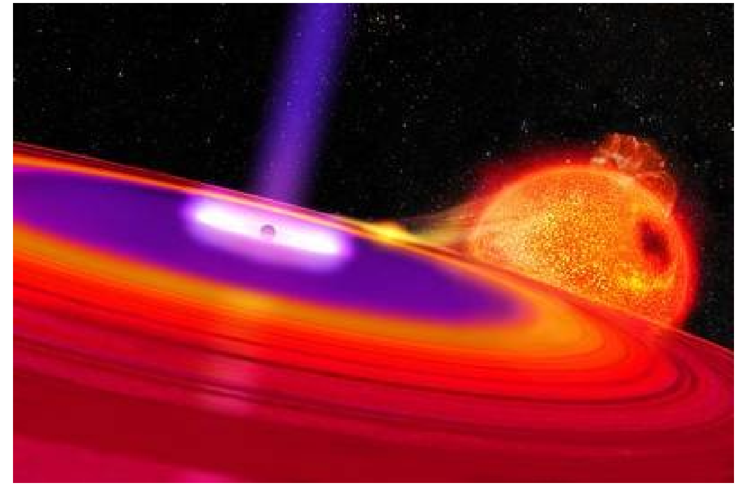
Multi – black body emission from an accretion disk:

$$T_{eff}(r) = \left\{\frac{3}{8\pi\sigma}\frac{GM\dot{M}}{r^3}\left[1-\left(\frac{r_0}{r}\right)^{1/2}\right]\right\}^{1/4} \quad \Rightarrow T_{eff}(r) \propto r^{-3/4}$$

Accretion physics:

Total luminosity is equal the flux integrated over disk surface:



$$L_{bol} = \int_{r_0}^{\infty} \frac{3GM\dot{M}}{2r^2}\left[1-\left(\frac{r_0}{r}\right)^{1/2}\right]dr = \frac{GM\dot{M}}{2r_0}$$

For Schwarszchild metric:

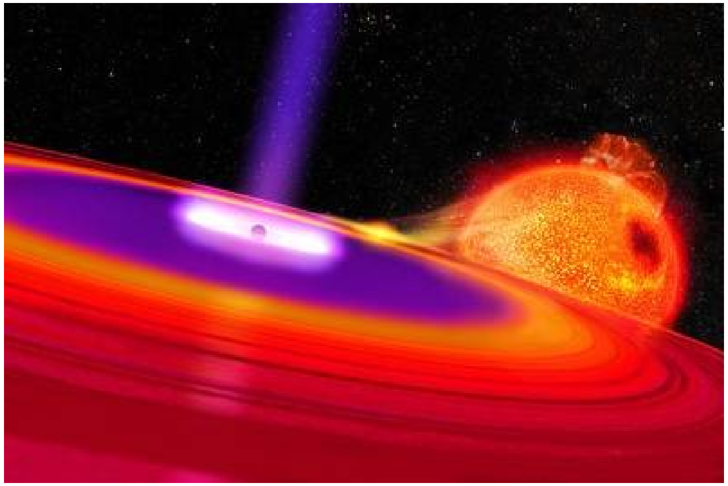
$$L_{bol} = \int_0^{2\pi}\int_{r_0}^{\infty} 2\mathrm{F}\, r\, dr\, d\phi = 4\pi\int_{r_0}^{\infty} F\, r\, dr$$

$$r_0 = 3R_{Schw} = 6GM/c^2 \quad ;$$

$$L_{bol} = \frac{1}{12}\dot{M}c^2 = \eta\dot{M}c^2$$

accretion efficiency

Accretion physics:



Eddington Luminosity:

$$\frac{\sigma_T}{c}\frac{L}{4\pi r^2}=\frac{G M m_H}{r^2};$$

$$L<L_{Edd}=\frac{4\pi c G M m_H}{\sigma_T}=10^{38}\frac{M}{M_{Sun}}$$

We can define Eddington accretion rate:

$$\dot{M}_{Edd}=\frac{L_{Edd}}{\eta c^2}; \qquad \dot{m}=\frac{\dot{M}}{\dot{M}_{Edd}}$$

X-ray binaries:

A class of objects where X-ray emission from an accretions disk is prominent.

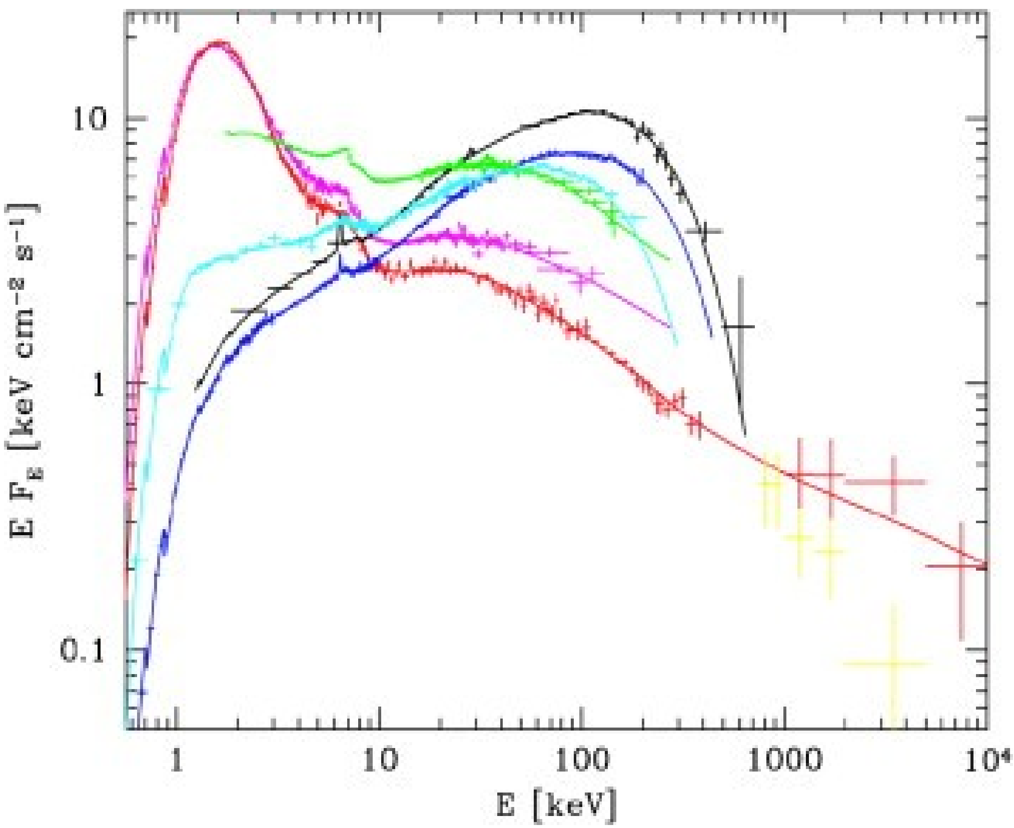
$$L_{bol} = \eta * \dot{M} * c^2$$

$$T_{disk} \propto 4 \times 10^6 \left(\frac{M_{BH,NS}}{10\, M_{Sun}} \right)^{-1/4}$$

For $M = 1.4\, M_{Sun}$:

$$T_{disk} \approx 10^7 K$$

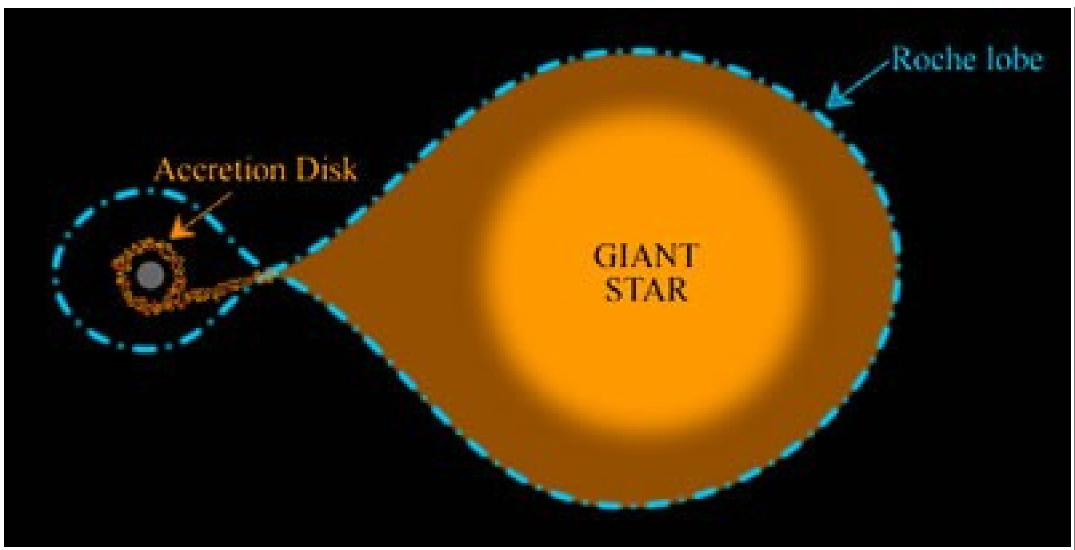
Cyg X-1 Zdziarski + 2002

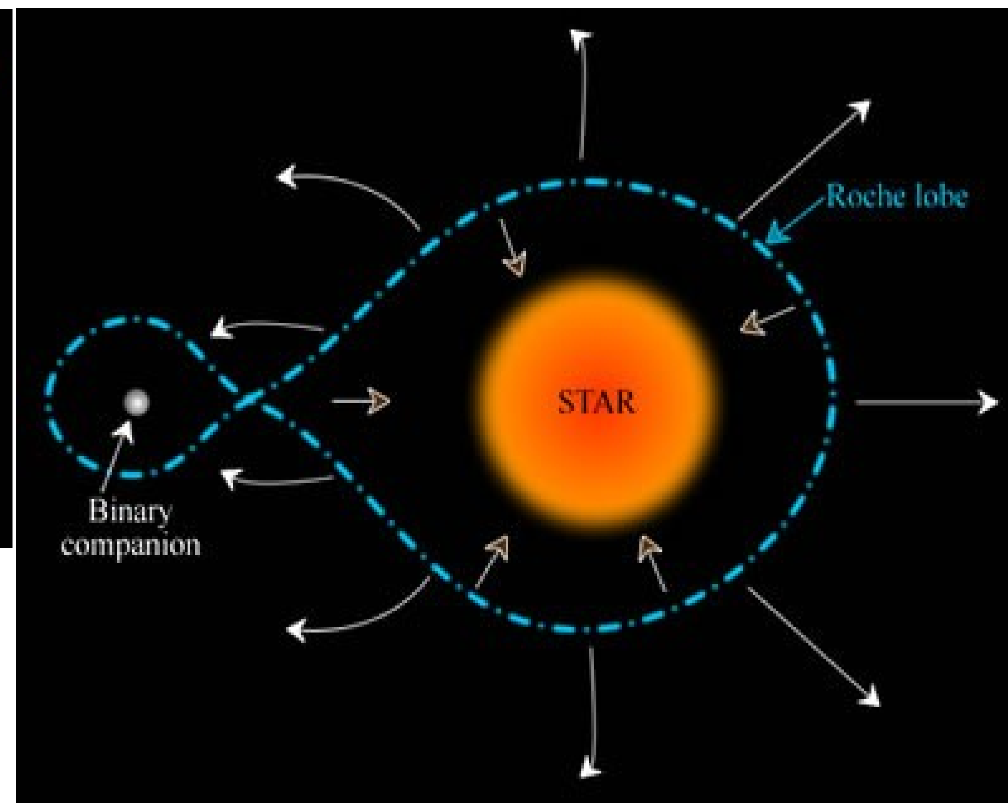


Accreting Neutron Stars:

Donors: “normal star” or a White Dwarf. A few hundred sources of this kind are known in our galaxy and the nearest galaxies:

- high X-ray luminosity 10^{34-38} erg/s
- hard spectra
- high degree of variability of different nature





Roche lobe overflow

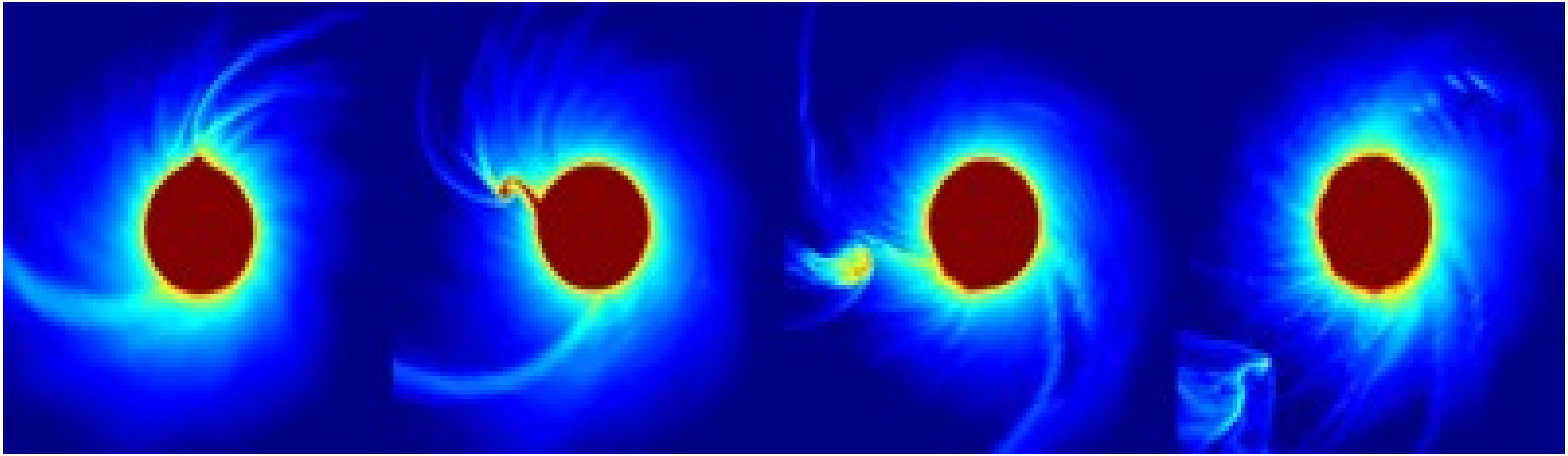
Stellar wind

Accreting Neutron Stars:

The first fundamental property is the mass of the companion:

HMXB – High Mass X-ray Binaries

secondary is a Be star or OB supergiant, orbital period of the order of days to tens of days,
mass transfer due to a stellar wind.
Stellar disk of OB or Be star.

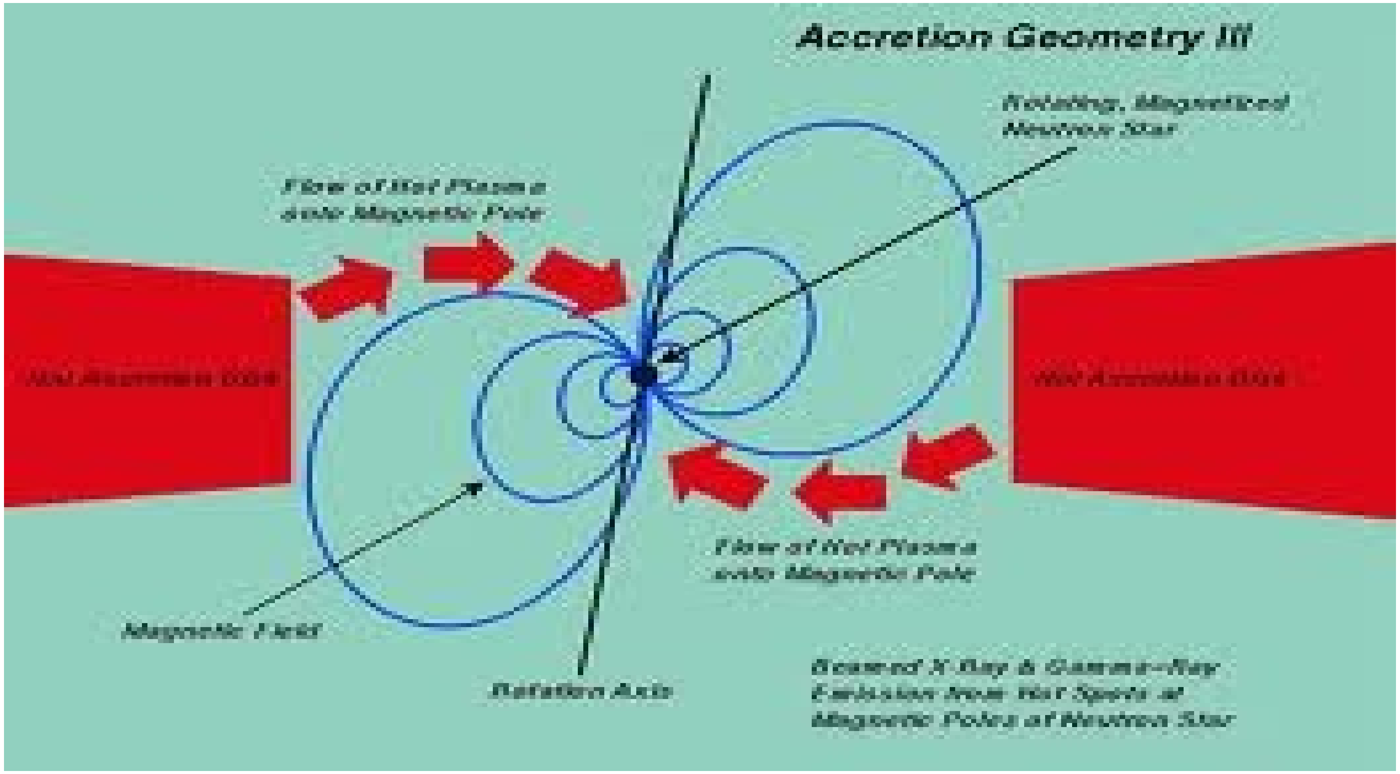


Accreting Neutron Stars:

LMXB – Low Mass X-ray Binaries

secondary is a star of type A or later, the orbital period of the order of hours to days and the mass transfer is by Roche Lobe overflow.

Strong magnetic field up to 10^{12} G



Accreting Neutron Stars:

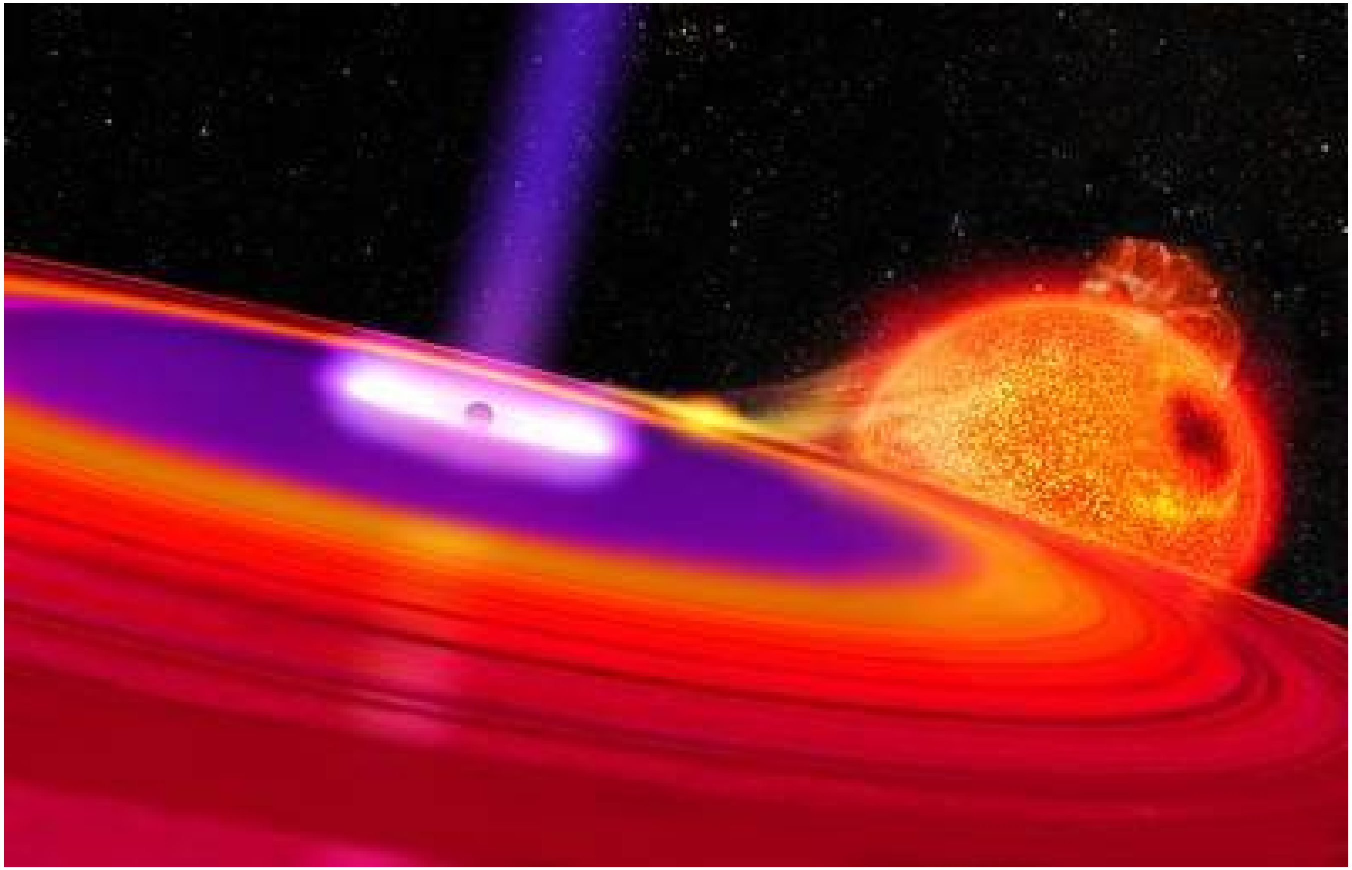
Timing behavior, including spectral variability is the tool with the highest diagnostic power. Time resolution up to ms, RXTE:

- Transients – show up in episodes (days to weeks) of X-ray emission, sometimes recurrent.
- Eclipsing X-ray binaries – allow a straight determination of the binary period, usually HMXB
- X-ray binary pulsars – regular (coherent) modulation of the X-ray flux because of the spin of the NS. Doppler shift of the pulse frequency is observed, allowing an estimate of the mass of the NS.
- X-ray Bursters – LMXB that show repeated short duration (minutes) bursts of X-ray flux.
  Type 1 – thermonuclear flush
  Type 2 – intermittent accretion due to disk inst.
- QPO sources – quasi periodic oscillations – two peaks in PDS of all LMXB, origin still unknown.

Accreting Neutron Stars:

The distinction between NS and BH is not always easy:

1) NS – if regular pulsations or Type 1 X-ray burst are observed
2) BH – if a soft spectrum has fast irregular variability
3) BH – if a mass of the compact object is above 3 M_{Sun}
4) NS – if a mass of the compact object is above 1 M_{sun}

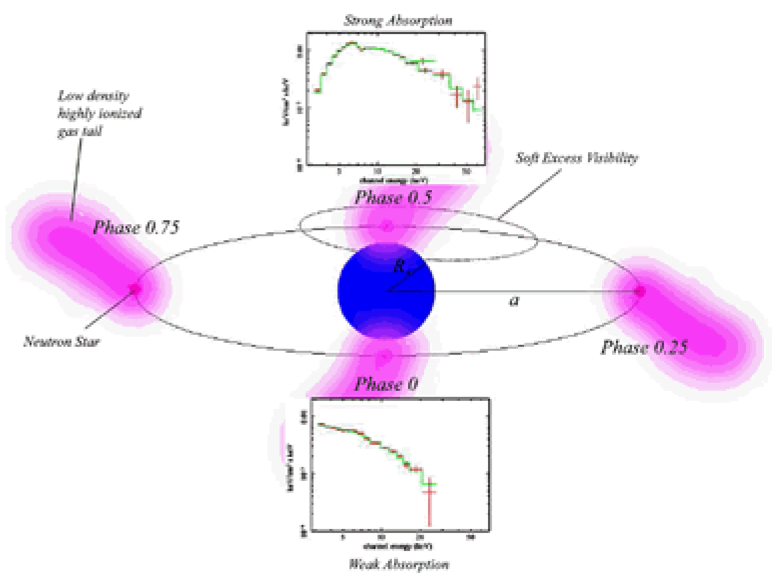


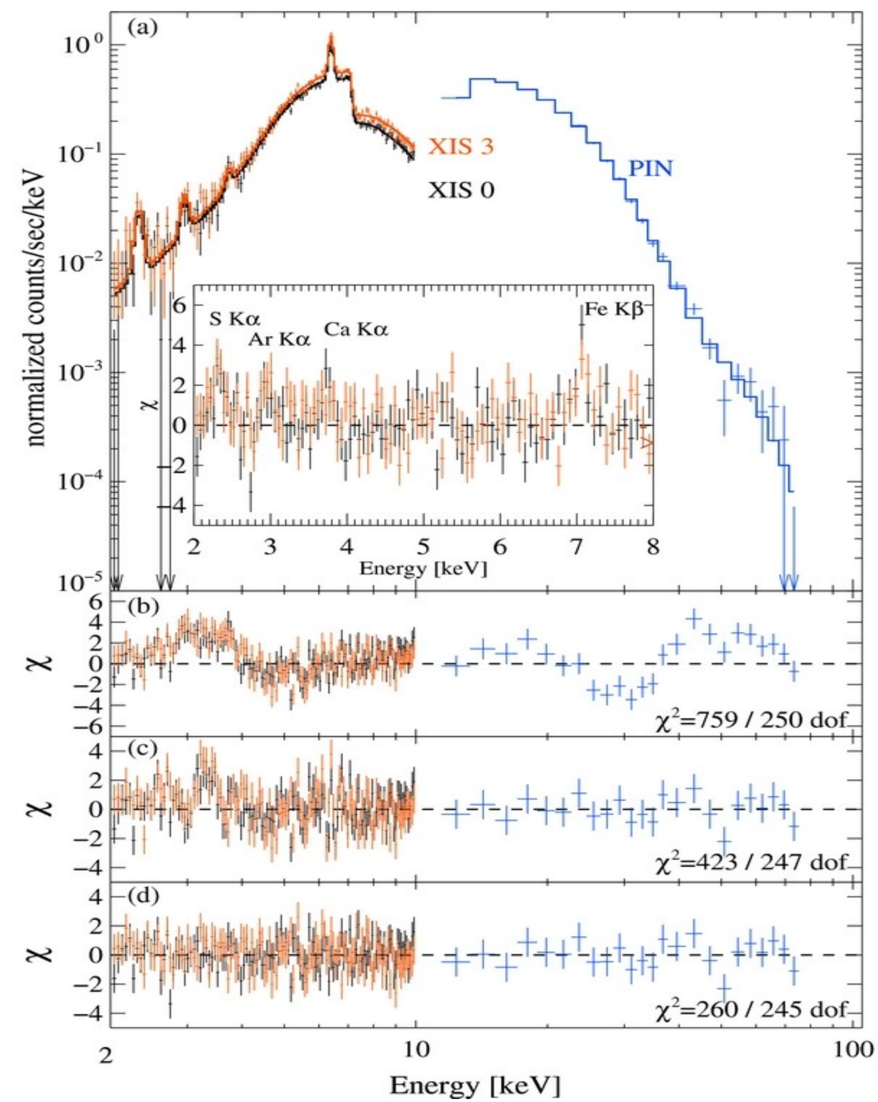
HMXB – 130 objects:

GX 301- 2 Suchy + 2012

- Be stars $M \geq 5\ M_{Sun}$, or
  OB supergiant $M \geq 15\ M_{sun}$

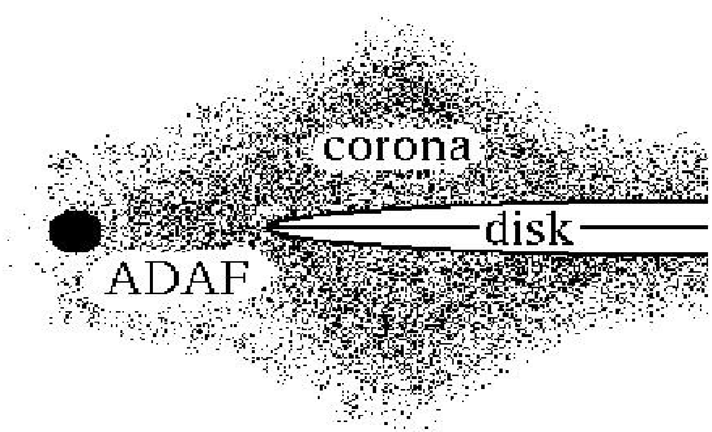
- Accretion rate: $10^{-5}\ M_{Sun}$/yr,
- L_X/L_{opt} close to 1,
- Hard spectra highly absorbed
- Orbital periods from 4.8 h up to 187 days.

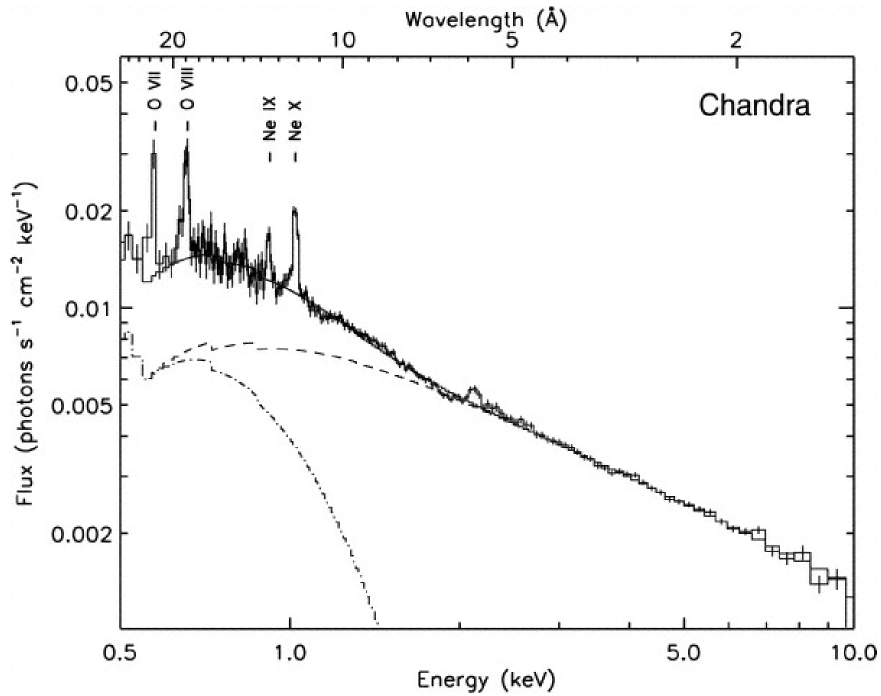


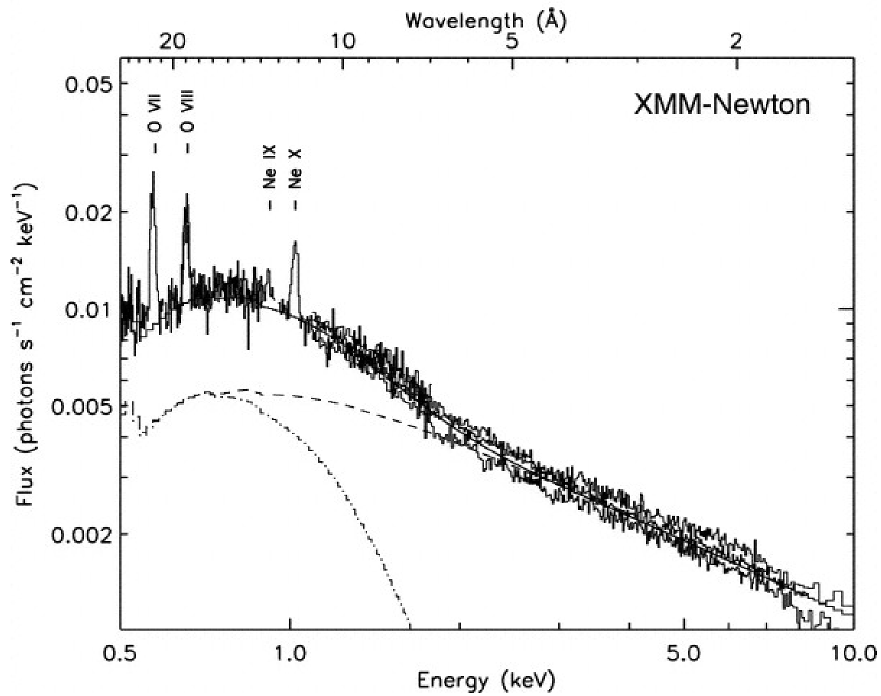


LMXB – 150 objects:

- A-M type stars, $M \leq 2\,M_{Sun}$,
- Accretion rate: spans 4 orders of magnitude,
- L_X/L_{opt} close to 20 – 1000,
- Hard spectra present different spectral states,
- Orbital periods from 0.19 h up to 17 days.

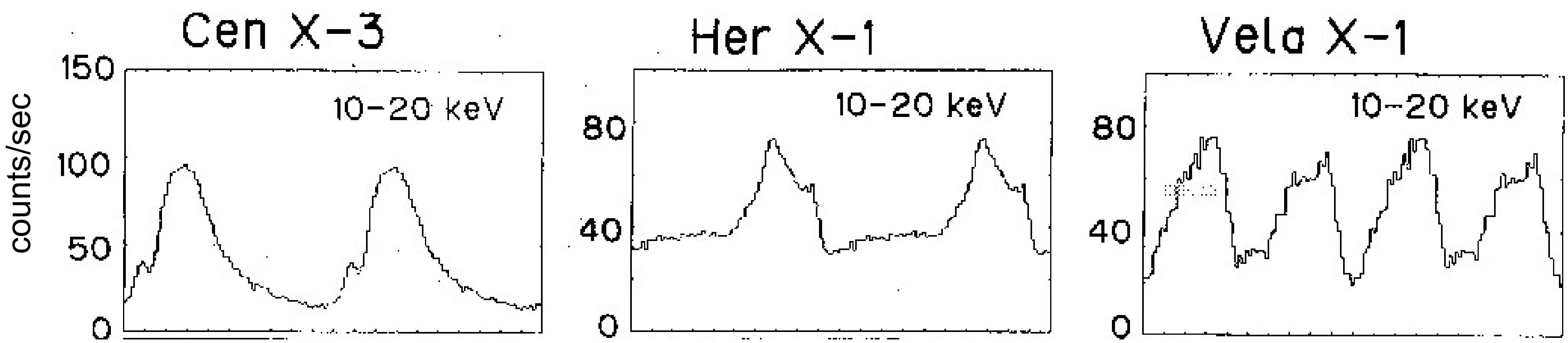






Classical X-ray pulsars – 160 objects:

Cen X-3 4.8 s
Her X-1 1.24 s

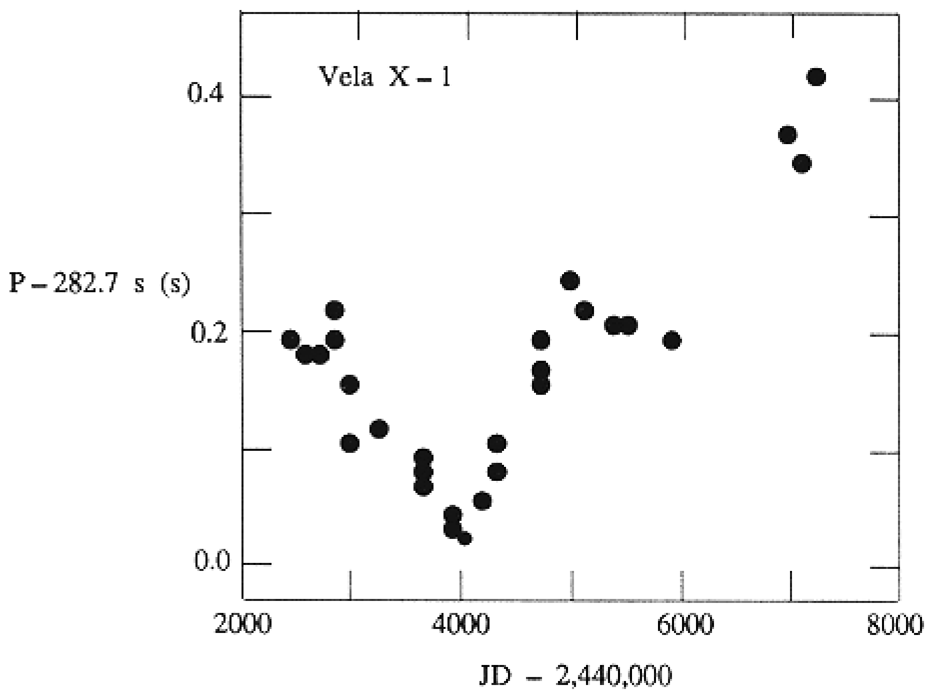


Regular modulation of the pulse arrival time (Doppler shift of the pulse frequency) with the same binary period.

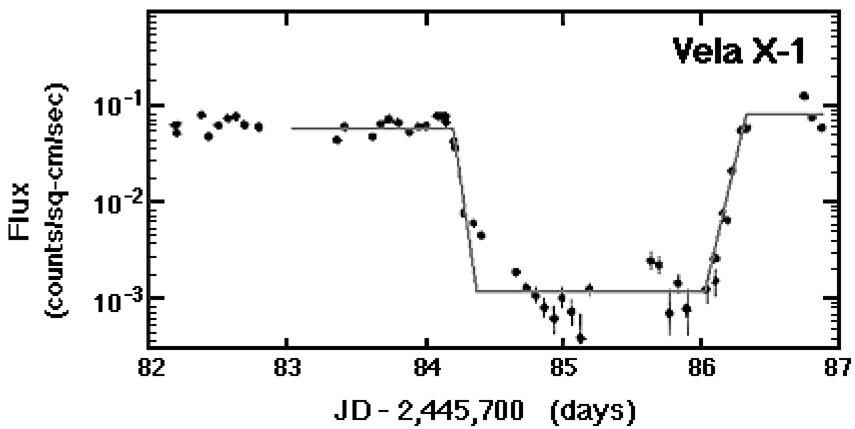
90 in our Galaxy, 50 in SMC, 10 in CMC and 10 in M31 and other galaxies in the Local Group. Most of them are HMXB.

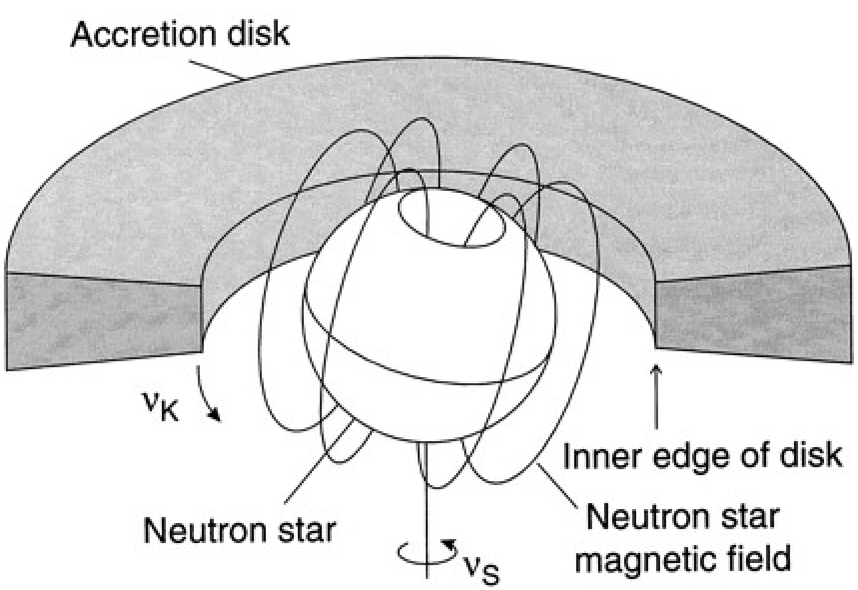
Classical X-ray pulsars – 160 objects:

Spin-Up/Spin-Down effect:



RXTE:



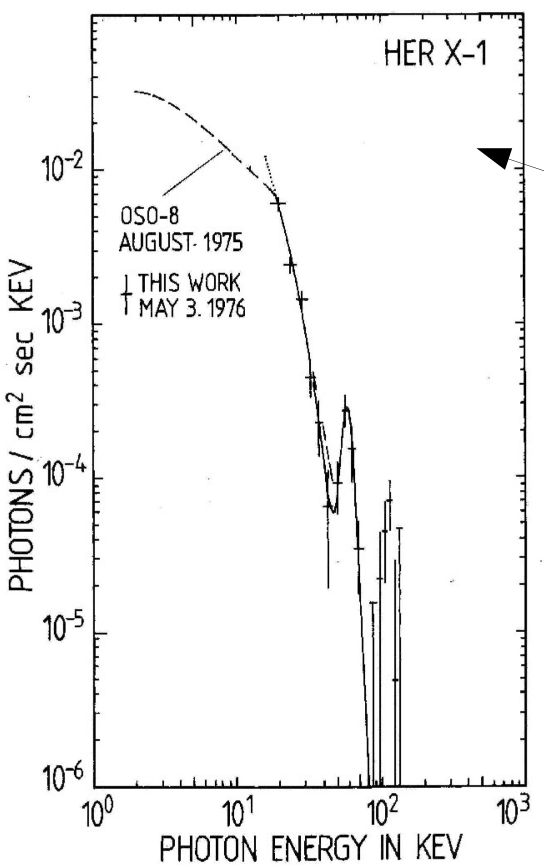


Accretion barrier or propeller effect.

Classical X-ray pulsars – 160 objects:

Spectroscopic observations show hard power-law component with cyclotron lines.

$$E_c = \tilde{h} e B / m_e c \sim 11.6 B_{12} (1+z)^{-1} keV$$



$$B = 4 \times 10^{12} G$$

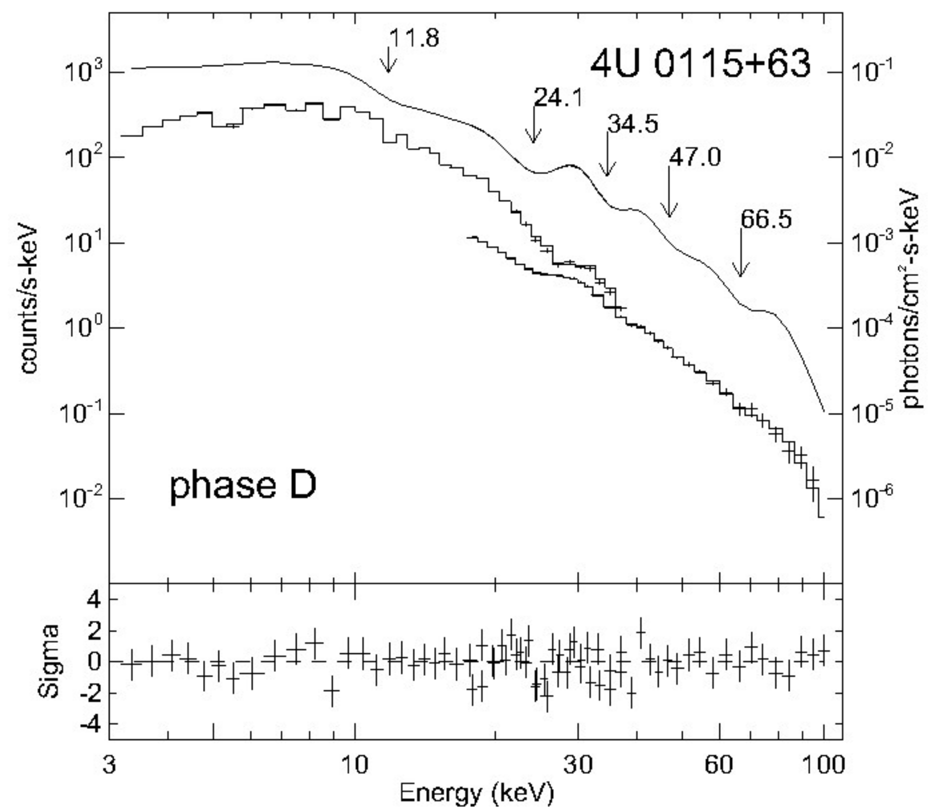
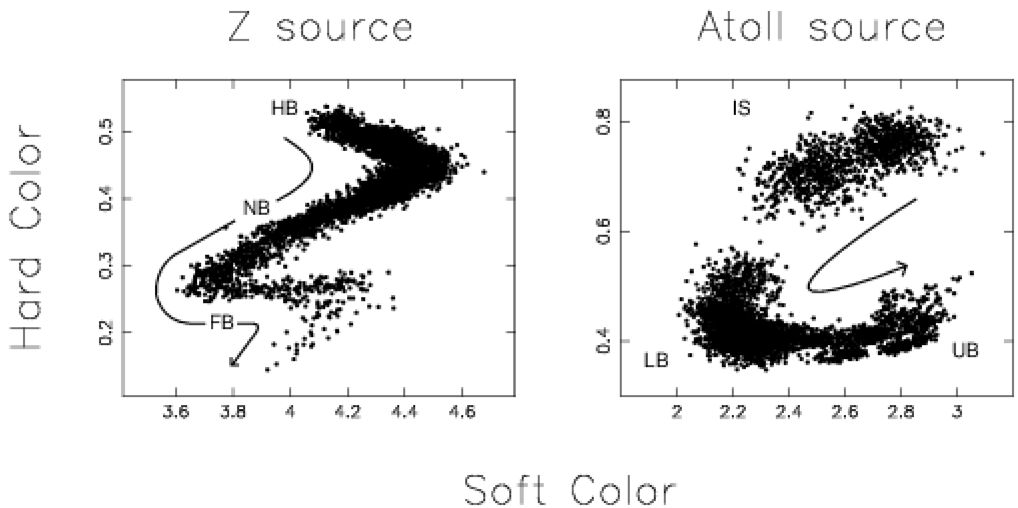


Fig. 6 Spectrum of 4U 0115+63 of phase bin

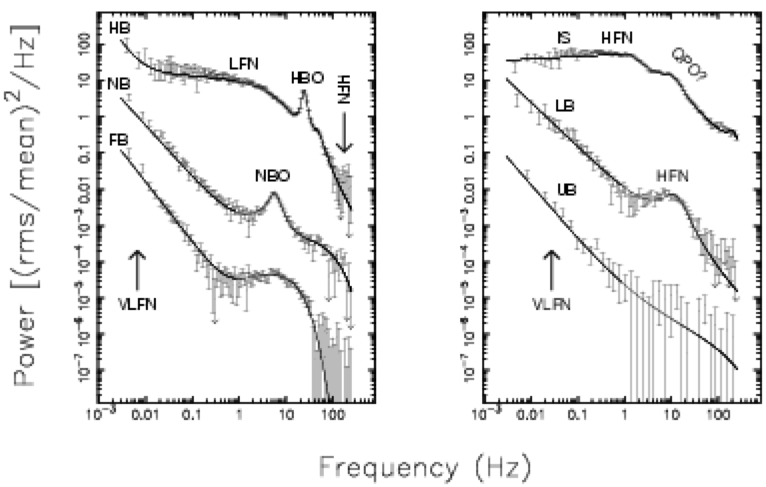
LMXB – weakly magnetized NS: $B \sim 10^{8-10} G$

Old systems with lifetimes that have allowed strong field of the NS to decay.

HB – horizontal branch
NB – normal branch
FB – flaring branch



IS – island state
LB – lower banana
UB – upper banana



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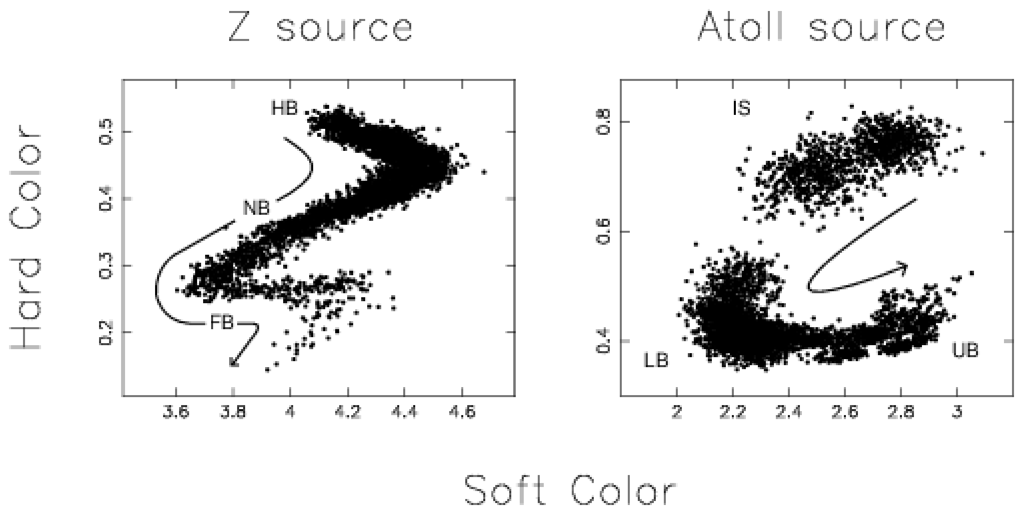

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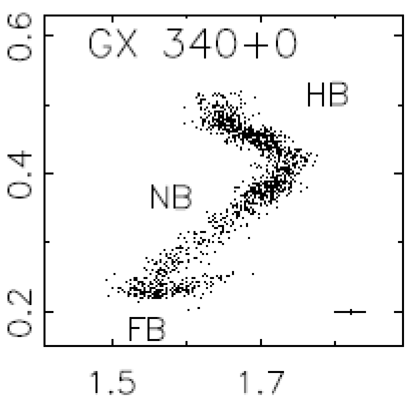
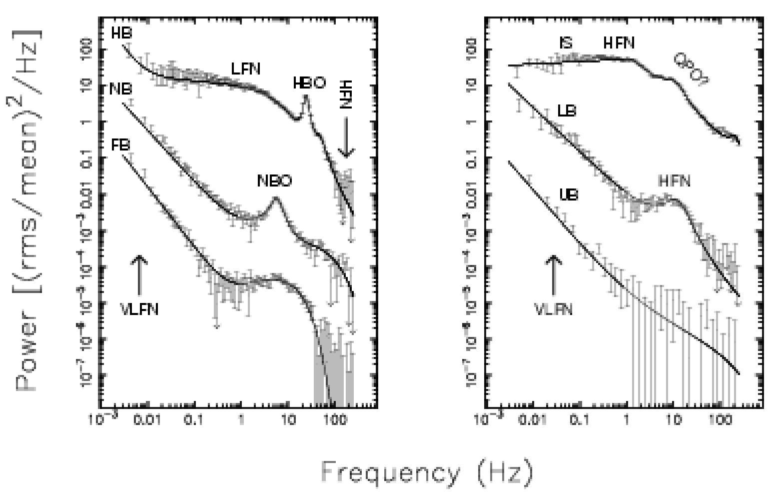
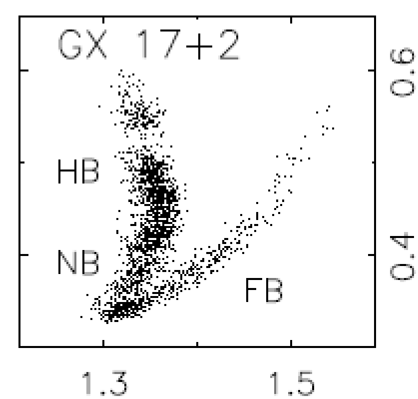






LMXB – weakly magnetized NS:

Z-sources – (6 objects) high L > 10^{37} erg/s, QPOs
Atoll-sources – (18 objects) low L < 10^{37} erg/s, X-ray bursts.

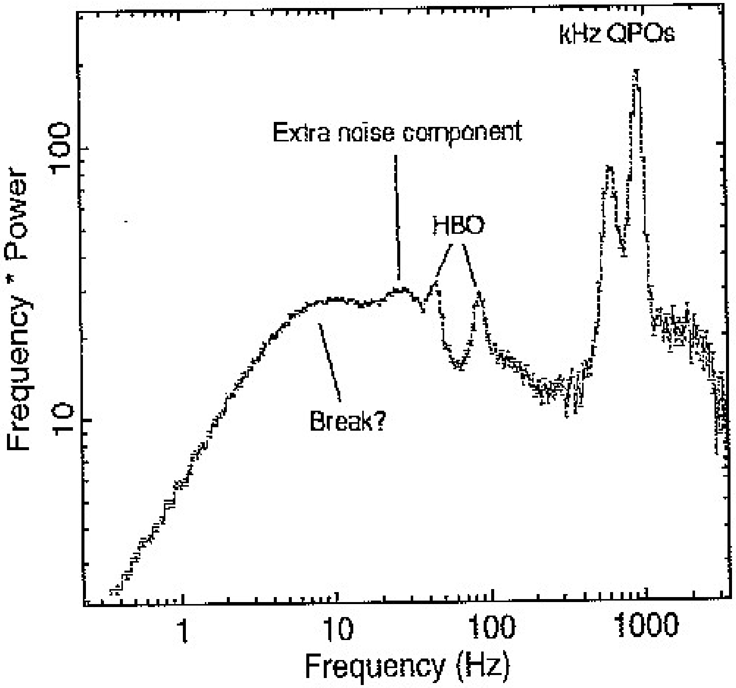
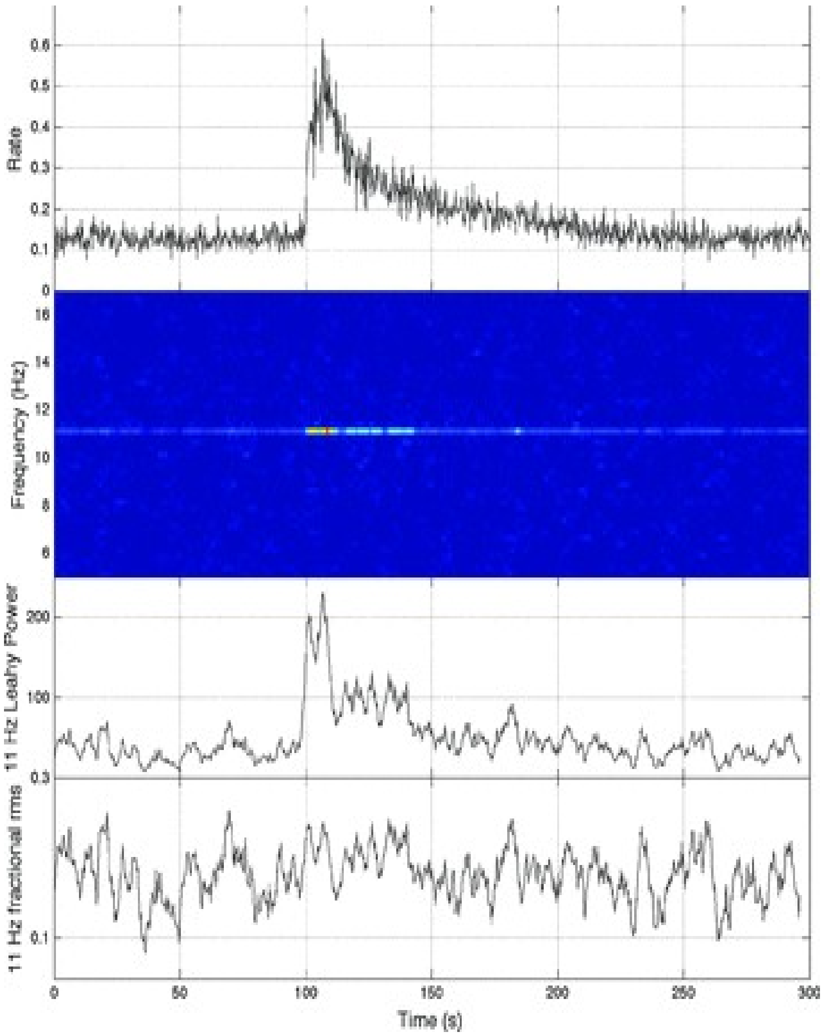


Fig. 15.8 Power Density Spectrum of Sco X-1 (after [1])

X-ray bursters:

J17480-2446 Motta+ 2011



Thermonuclear flush on the neutron star surface.
Fast rise (<1-10s)
exponential decay with duration between 10 s and a few minutes.
The time between bursts is typically from 1 h to a few hours.

Black Hole Binaries:

The presently known stellar-mass black holes where all discovered from X-ray observations.

BH – if we observe any general relativity effects.

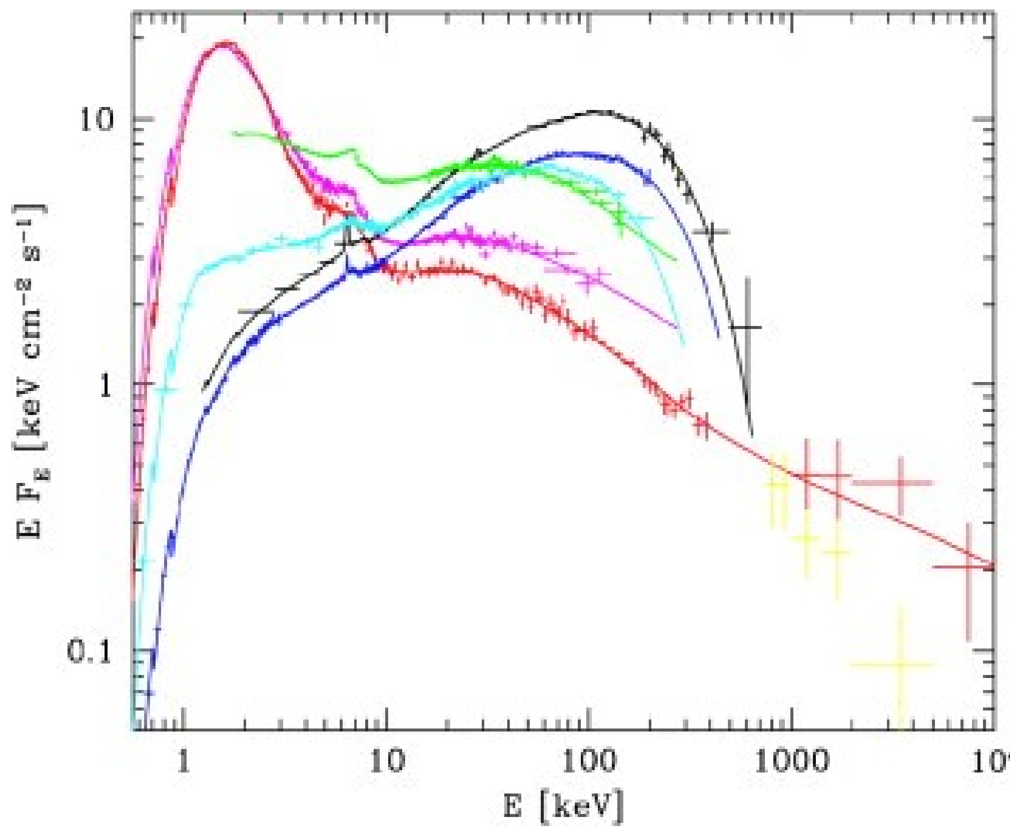
Cyg X-1 is a HMXB with O-type star companion.

From the mass function:

$$f(M) = M_x^3 \sin^3 i / (M_x + M_c)^2 = PK^3 / 2\pi G$$

P, K are optically measurable quantities.

Cyg X-1 Zdziarski + 2002



Black Hole Binaries:

For HMXB the optical light from the companion dominates for LMXB the companions are very faint.

Table 16.1 Black-hole binaries confirmed with the mass function

Source name		Year[a]	Type[b]	$f(M)$ ($M_\odot$)	M_x ($M_\odot$)	X-ray[c] spectrum
Cyg X-1			H, P	0.244±0.005	6.9–13.2	S+PL
LMC X-3			H, P	2.3 ±0.3	5.9–9.2	S+PL
LMC X-1			H, P	0.14±0.05	4.0–10.0	S+PL
J0422+32	V518 Per	'92	L, T	1.19±0.02	3.2–13.2	PL
0620–003	V616 Mon	'17, '75	L, T	2.72±0.06	3.3–12.9	S+PL
1009–45	MM Vel	'93	L, T	3.17±0.12	6.3–8.0	S+PL
J1118+480	KV Uma	2000	L, T	6.1 ±0.3	6.5–7.2	PL
1124–684	GU Mus	'91	L, T	3.01±0.15	6.5–8.2	S+PL
1354–645	BW Cir	'71,'87,'97	L, T	5.75±0.3	>7.8	S+PL
1543–475	IL Lup	'71,'83,'92	L, T	0.25±0.01	7.4–11.4	S+PL
J1550–564	V381 Nor	'98	L, T	6.86±0.71	8.4–10.8	S+PL
J1650–500		2001	L, T	2.73±0.56	4–7.3	PL
J1655–40	V1033 Sco	'94	L, T	2.73±0.09	6.0–6.6	S+PL
1659–487	GX 339–4	(P~460d)	L, T	5.8±0.5	>5.8	S+PL
1705–250	V2107 Oph	'77	L, T	4.86±0.13	5.6–8.3	S+PL
J1819.3–2525	V4641 Sgr	'99	L, T	3.13±0.13	6.8–7.4	S+PL
J1859+226	V406 Vul	'99	L, T	7.4±1.1	7.6–12	S+PL
1915+105	V1487 Aql	'92—	L, T	9.5±3.0	10–18	S+PL
2000+251	QZ Vul	'88	L, T	5.01±0.12	7.1–7.8	S+PL
2023+338	V404 Cyg	'38,'56,'89	L, T	6.08±0.06	10.1–13.4	PL

[a] The year of outburst, including earlier records as optical novae.
[b] H: high-mass binary. L: low-mass binary: P: persistent. T: transient.
[c] X-ray spectral type near the maximum luminosity. S: soft thermal. PL: power-law.
References: see [39], except for 1354–645 [8] and J1650-500 [60].

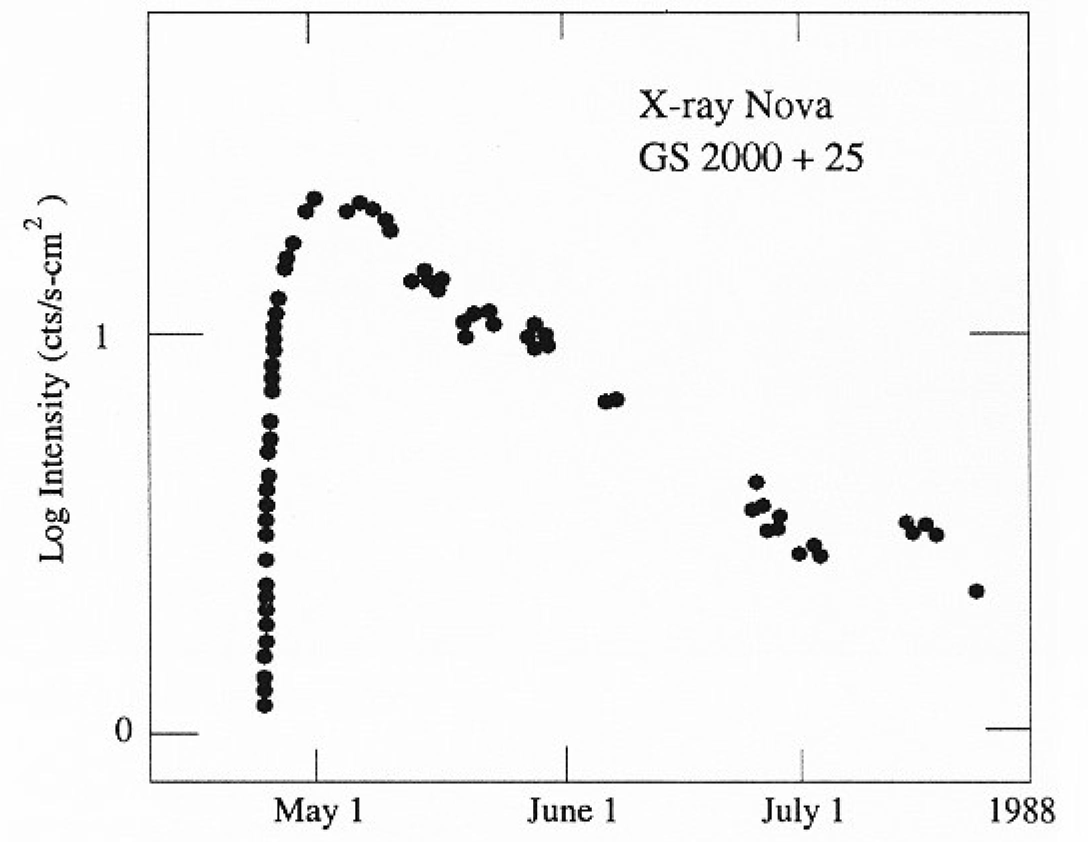
Based on the criterion:

$$M_x > 3\, M_{Sun}$$

Black Hole Binaries – Soft X-ray transients:

300 X-ray binaries, half of them are transients. They are seen only during episodic X-ray outburst without a fixed periodicity.

$$L_x = 10^{38-39} ergs/s$$

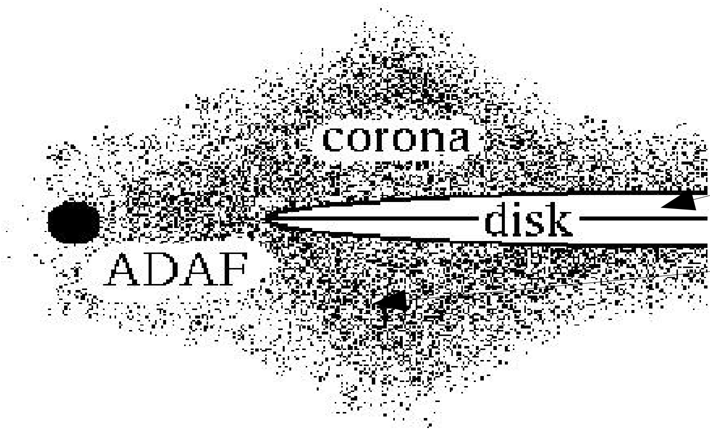


The source returns to quiescence after a few months.

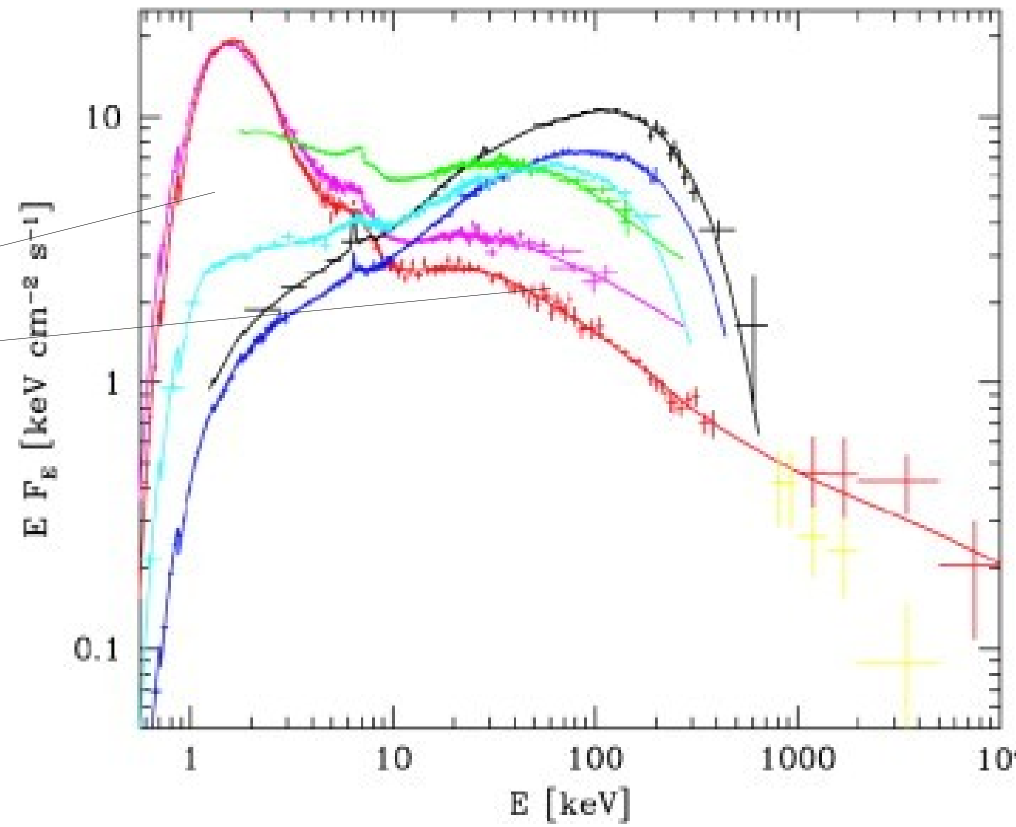
Sudden onset of the accretion flow onto the compact object.

There is a minimum accretion rate corresponding to: $L_x \ll 10^{36} ergs/s$ below which X-ray emission is turned off.

X-ray spectra of X-ray binaries: spectral state transitions:



Cyg X-1 **Zdziarski + 2002**



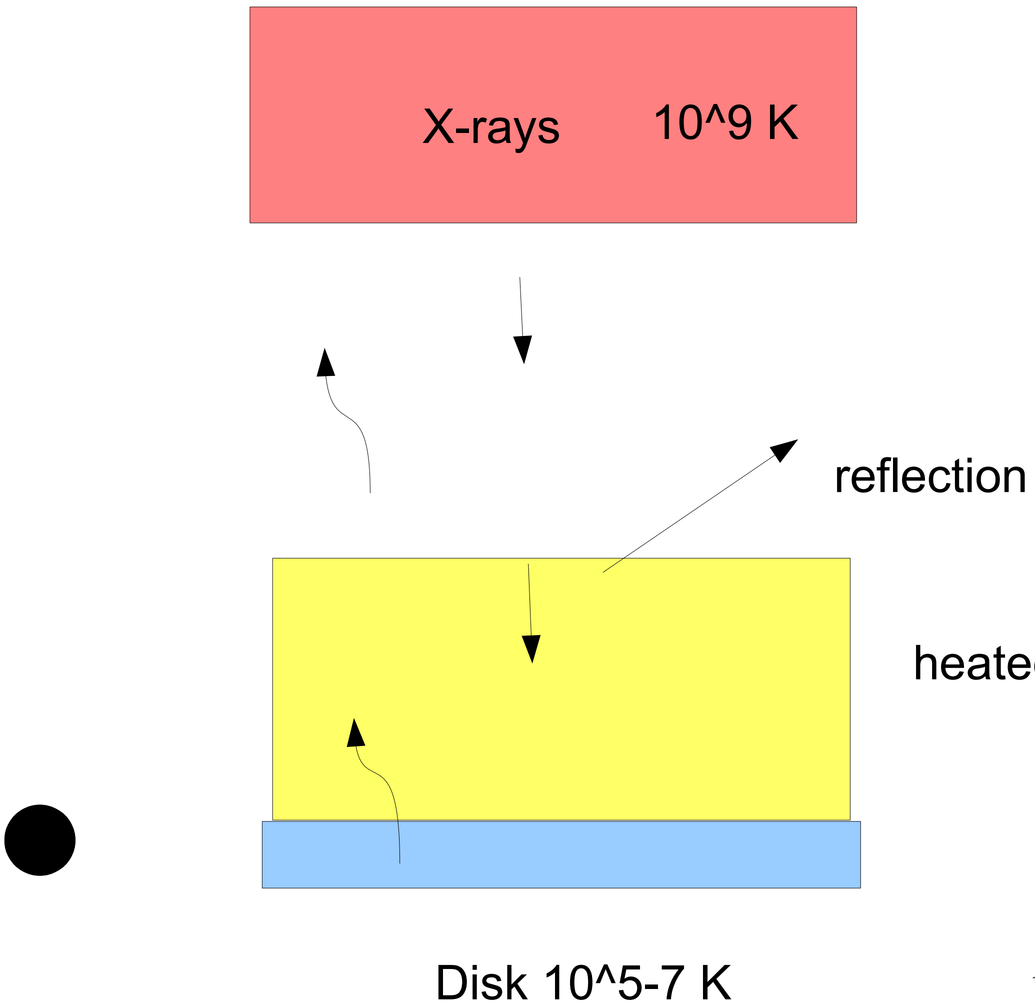
$$T_{disk} \approx 10^7 K \quad ; \quad 1 \quad keV$$

Disk is too cold to produce spectra up to a few hundred keV.
Hot corona above an accretion disk.

X-ray spectra of X-ray binaries: spectral state transitions:

Radiative interaction of hard X-rays with colder disk matter:

$$F_X = f_{cor} * \frac{3\,G\,M\,\dot{M}}{8\,\pi\,r^3} * b(r)$$

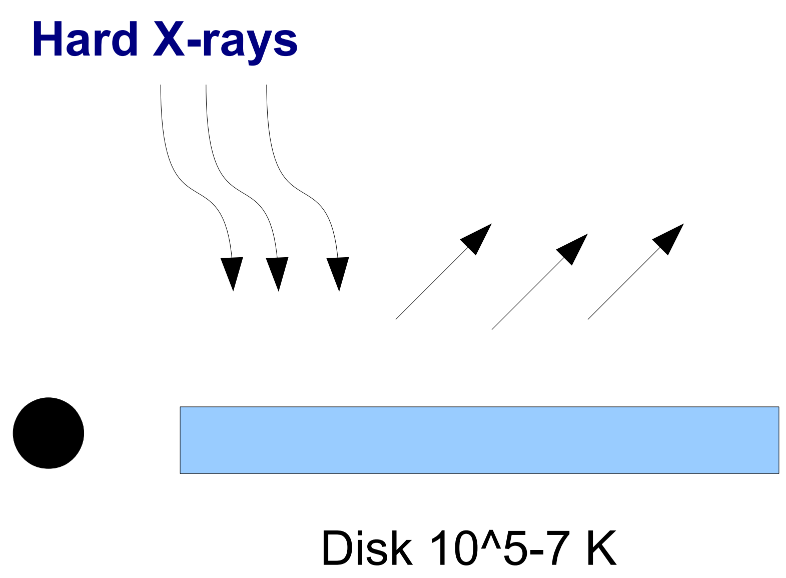


heated atmosphere up to few * 10^7 K.

$$F_{disk} = (1 - f_{cor}) * \frac{3\,G\,M\,\dot{M}}{8\,\pi\,r^3} * b(r)$$

First observation of X-ray reflection:

Compton scattering
hard energetic photons
from colder matter.
An atmosphere is heated
by highly energetic photons
up to inverse Compton
temperature.



Pounds+ 1990 Nature

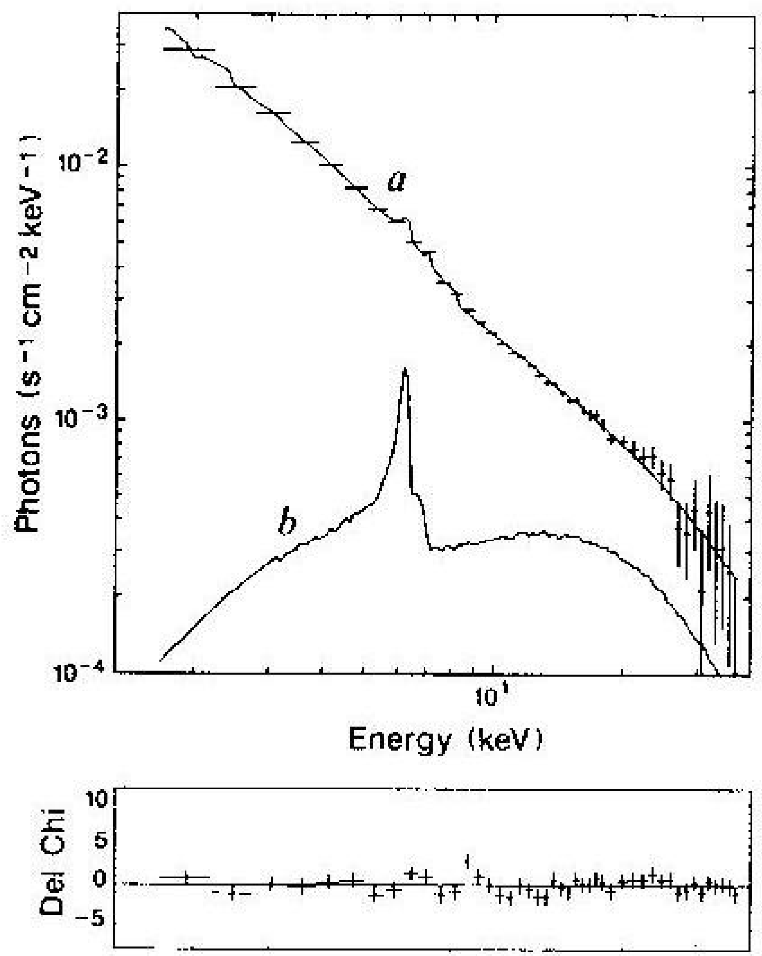
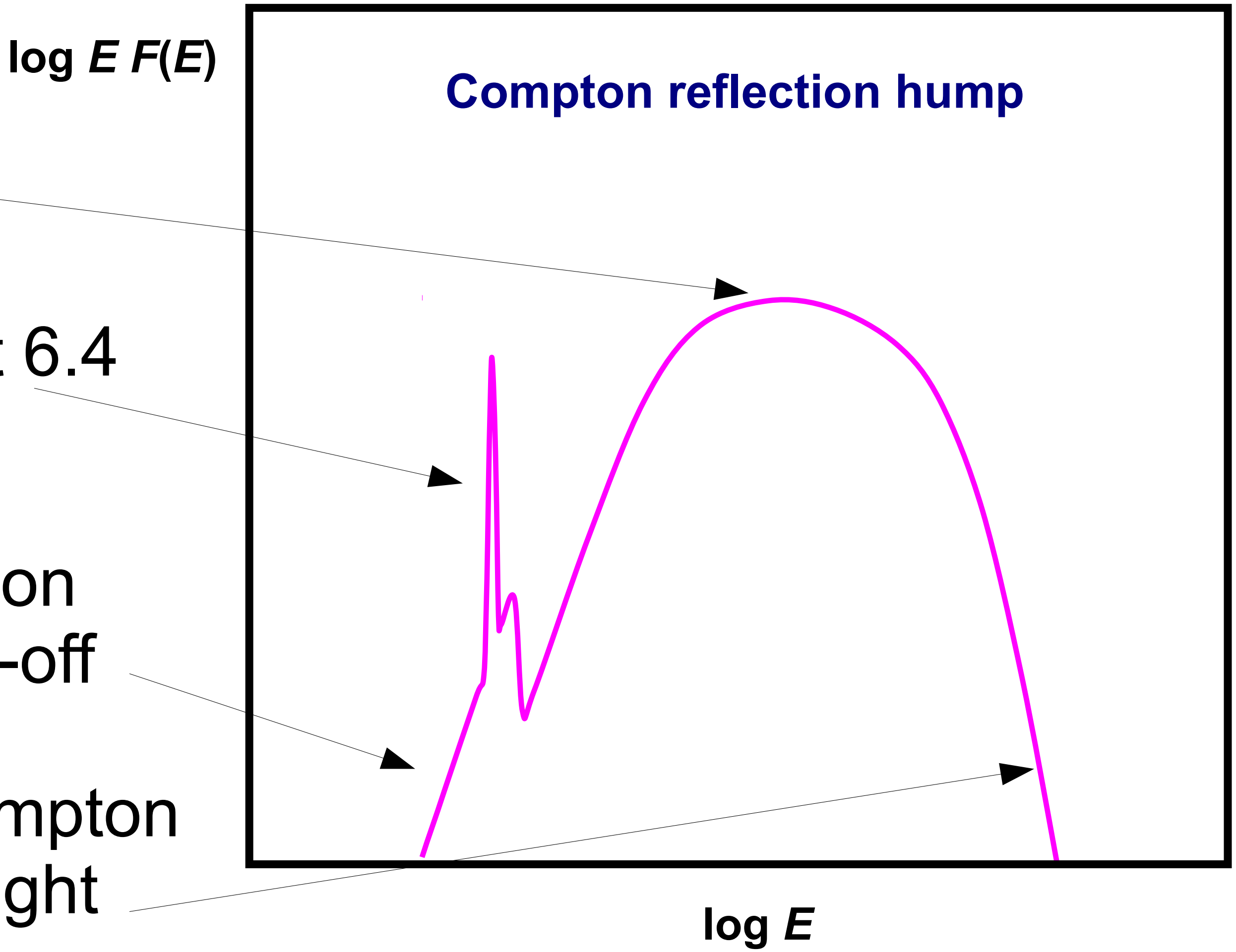


FIG. 2 a, Power law plus reflection and warm absorber model (as detailed in the text), together with residuals. b, Reflection component only.

NATURE · VOL 344 · 8 MARCH 1990

Modeling of Compton reflection:

- Peak about 20 keV
- Fluorescent Fe line at 6.4 or 6.7 keV
- Bound – free absorption on the low energy cut-off
- Klein-Nishina and Compton down-scattering at hight energy cut-off.



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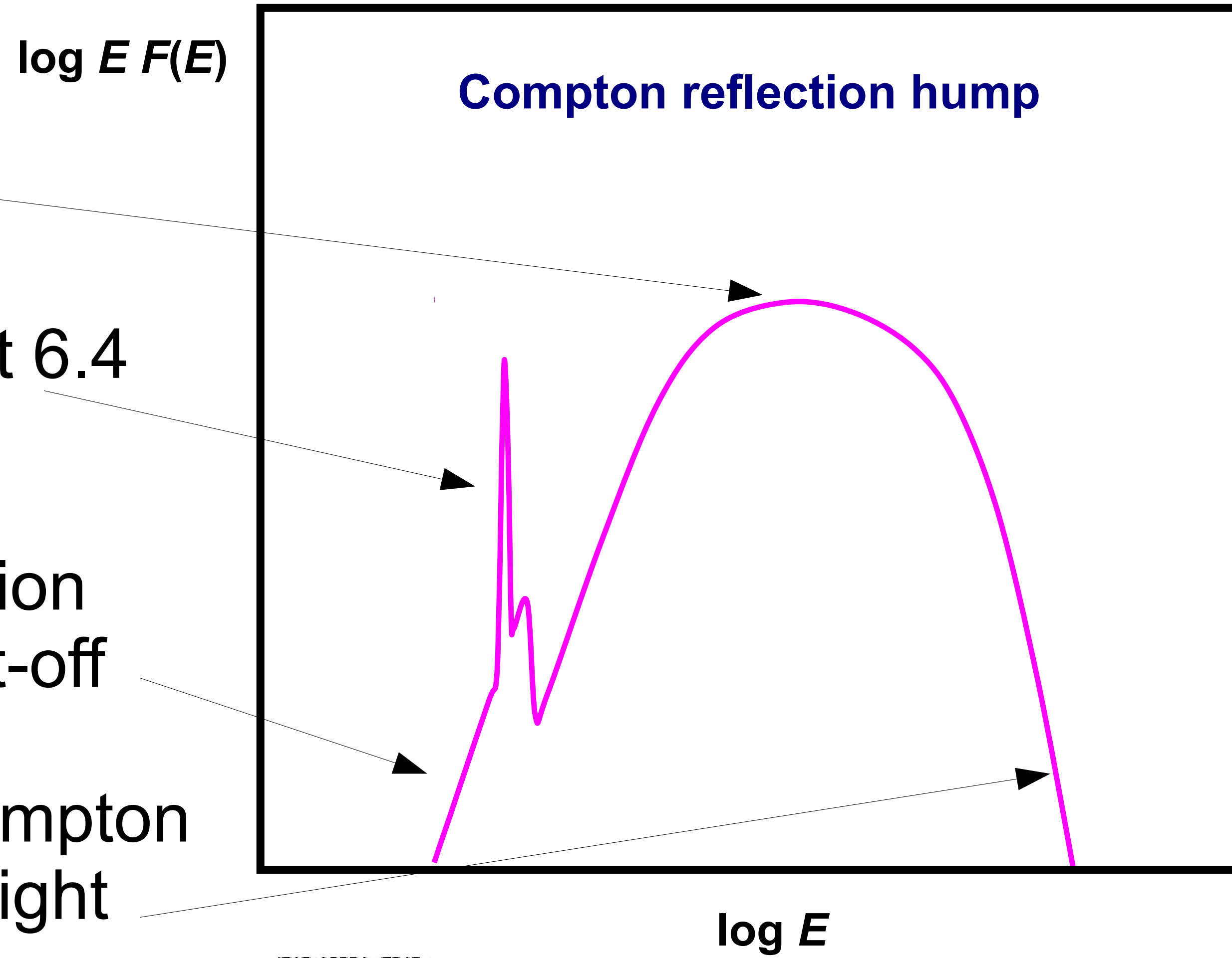
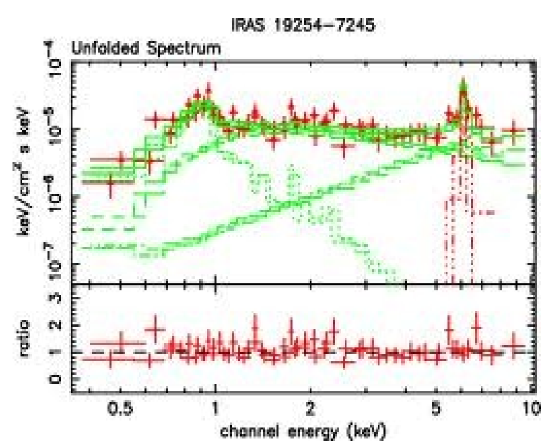
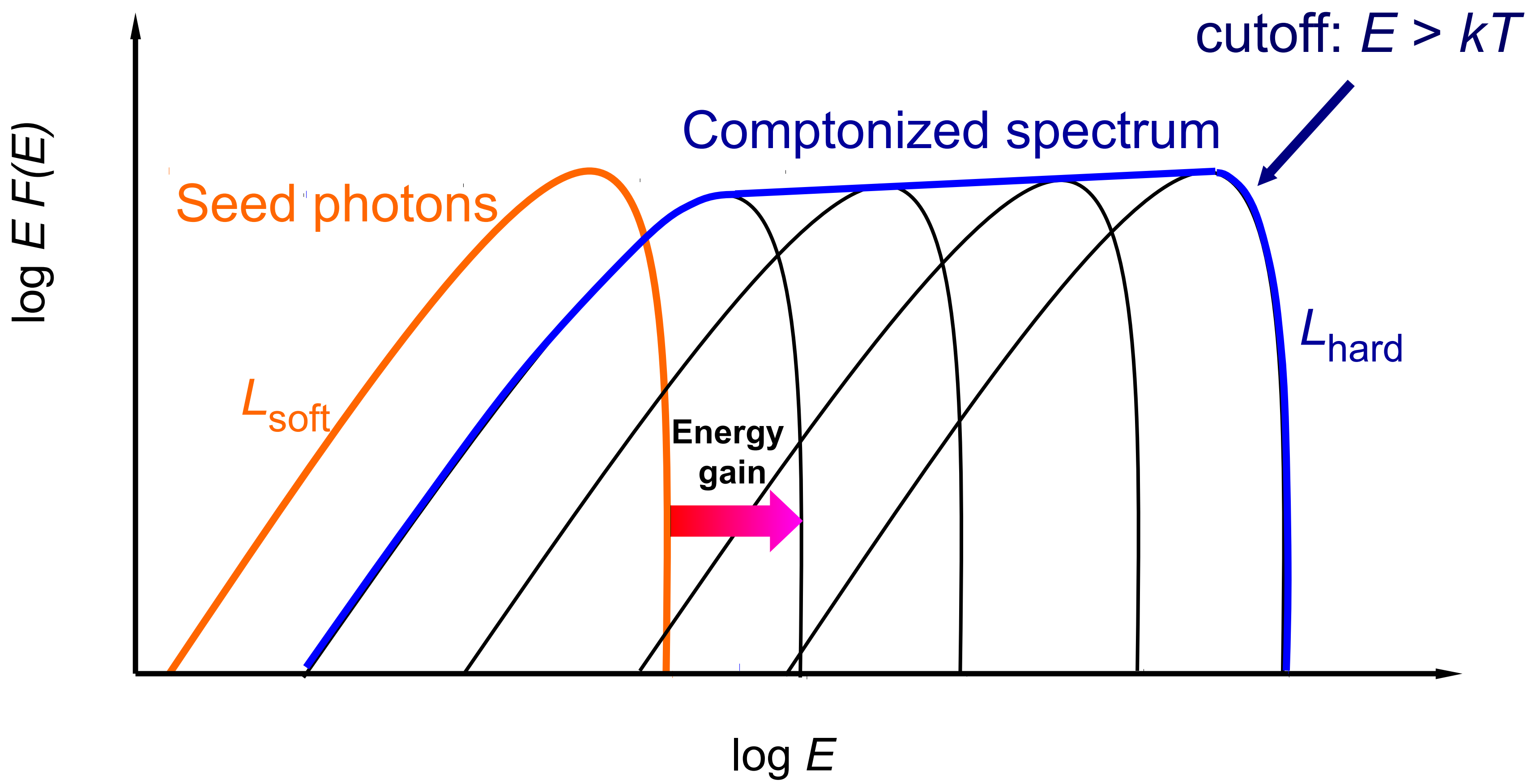




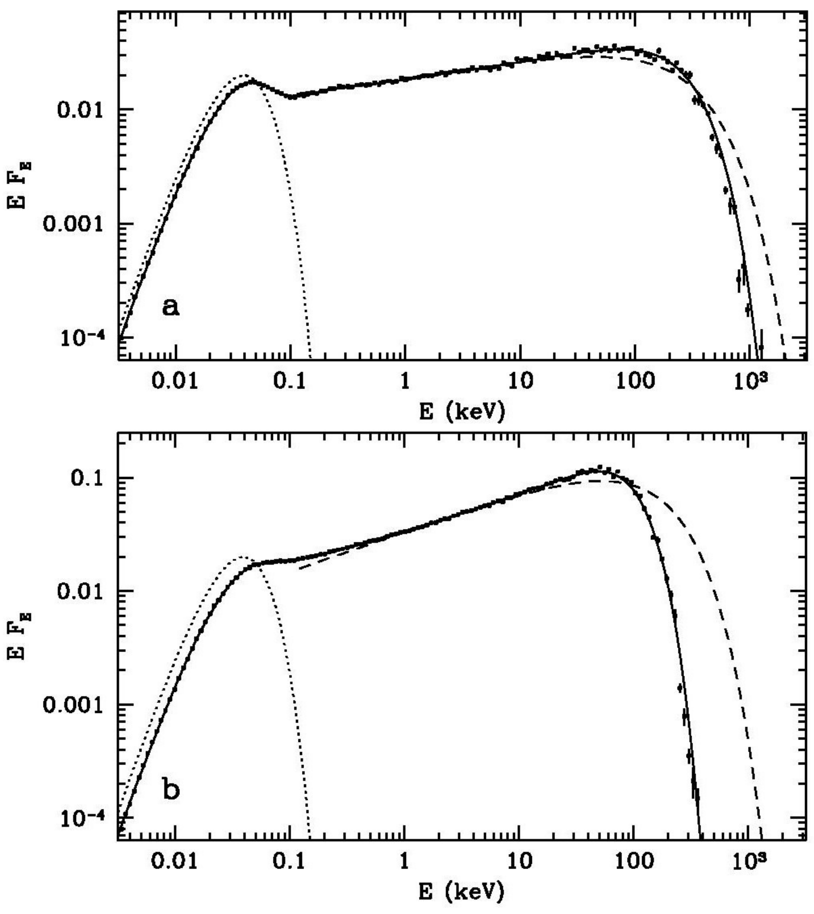
Compton up-scattering:



Soft disk photons are taking energy from hot electrons passing the corona – radiative cooling of the corona, power law forms.

Compton up-scattering:

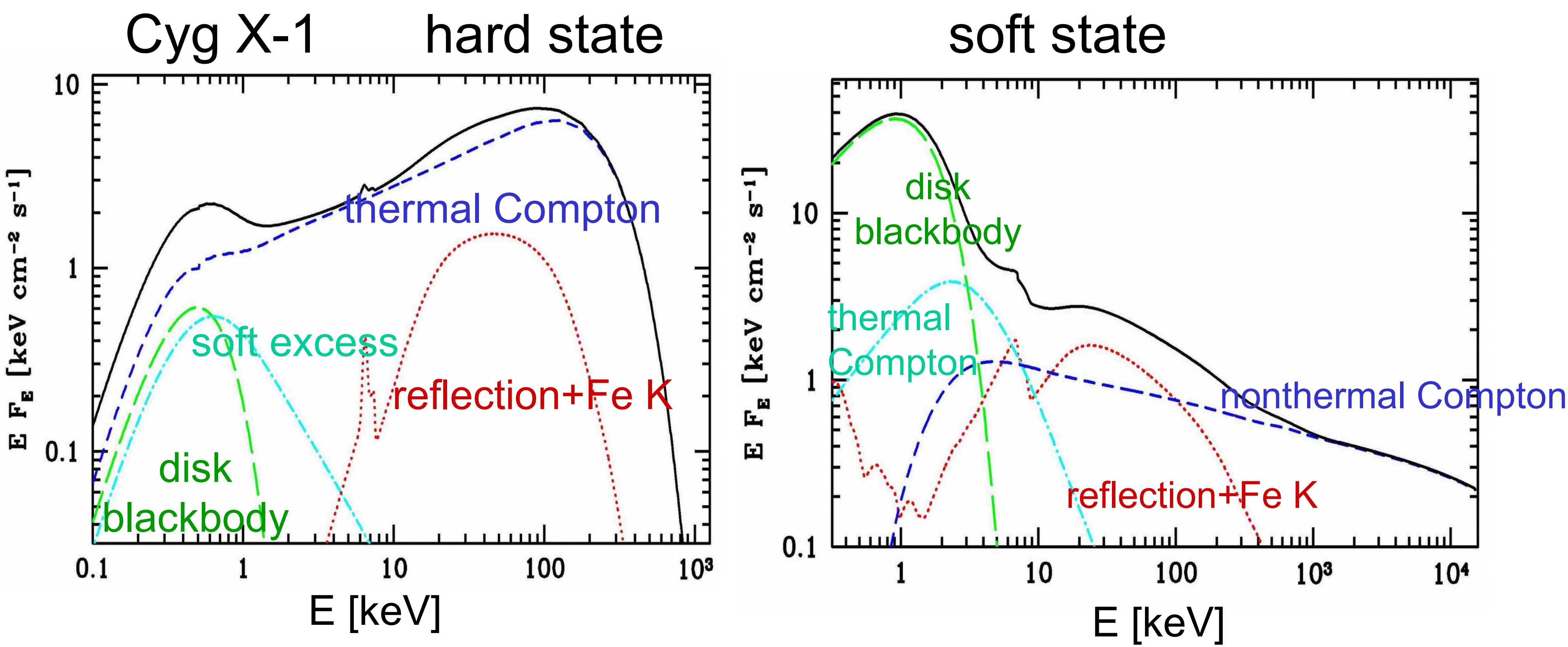
Final power law spectrum depends on the disk temperature, and temperature and optical depth of the corona:



$\tau_T = 1$

$\tau_T = 4$

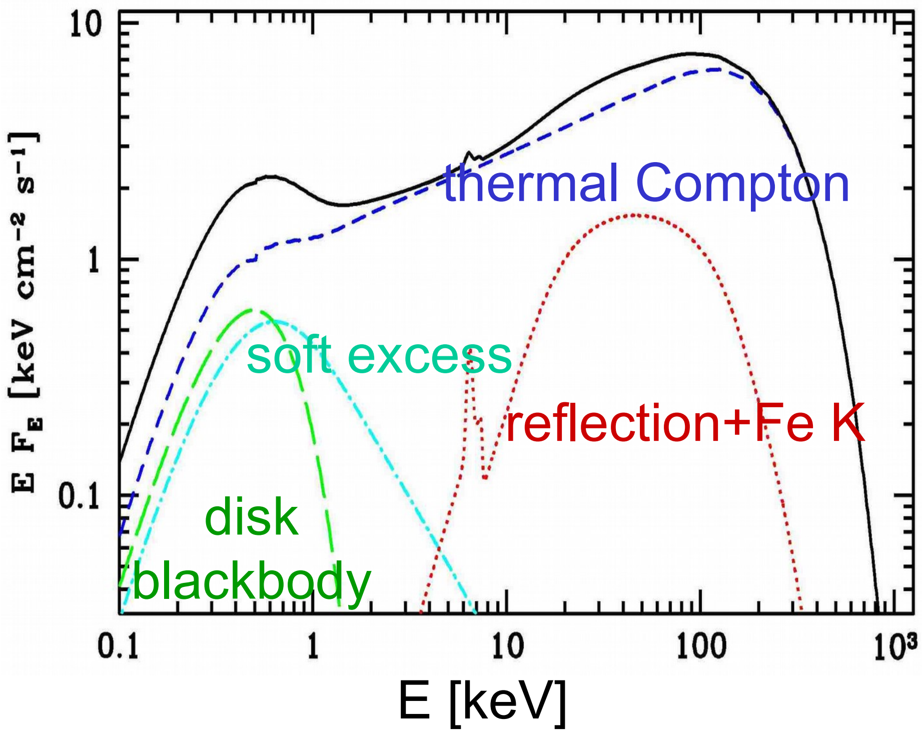
Final spectra of X-ray binary:



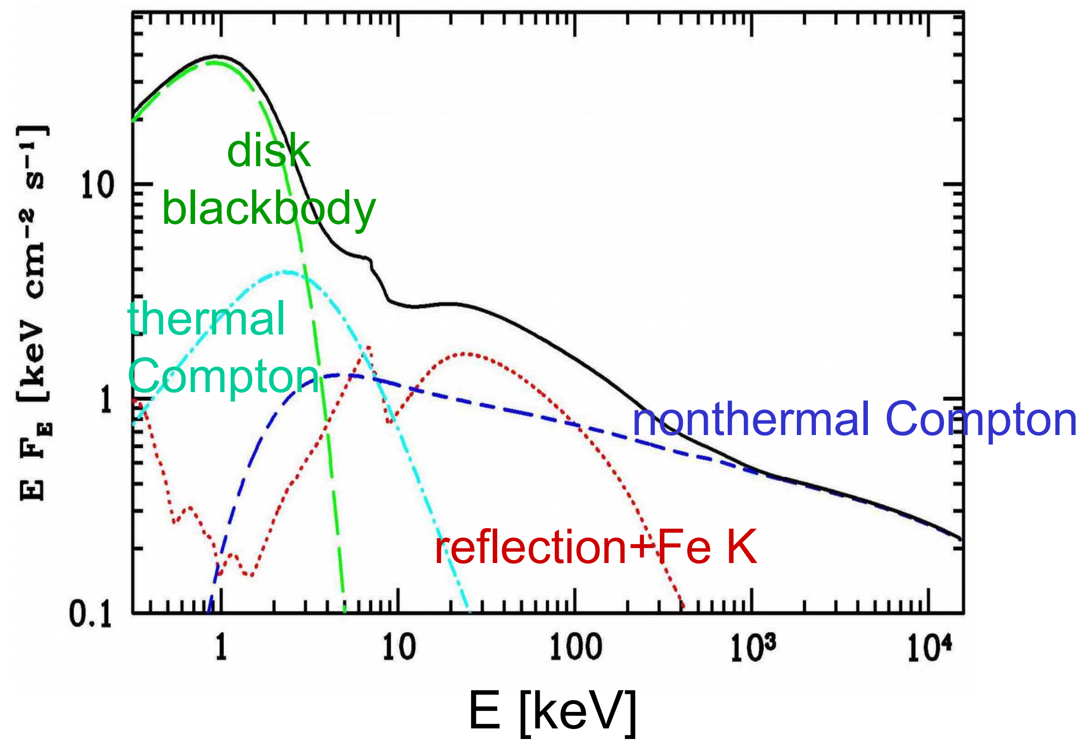
Each component is separately as XSPEC and SHERPA models.

Final spectra of X-ray binary:

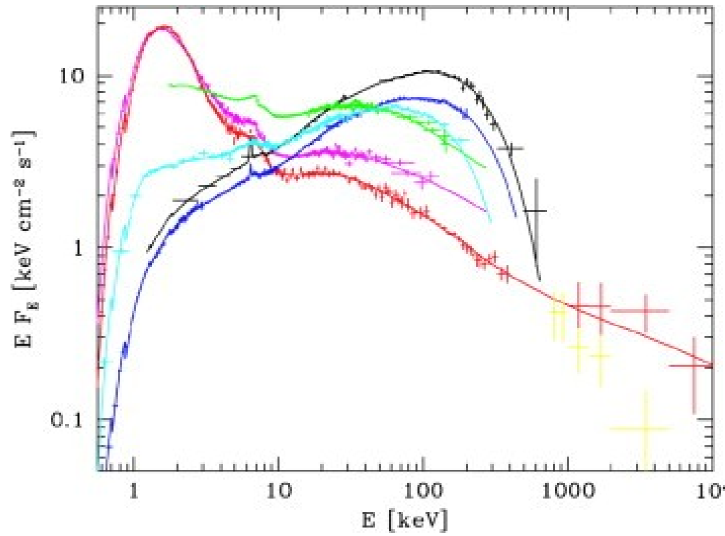
Cyg X-1 hard state



soft state

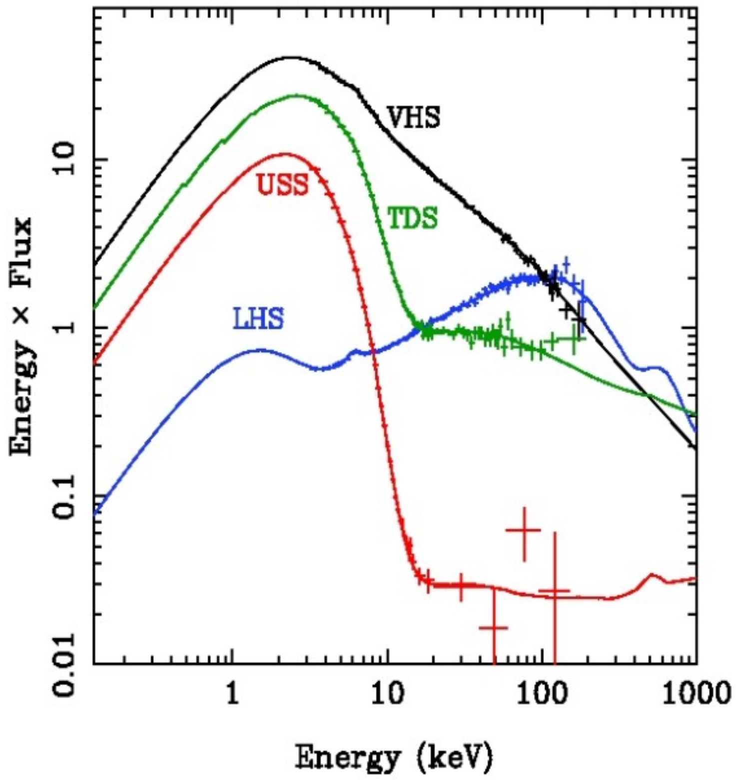


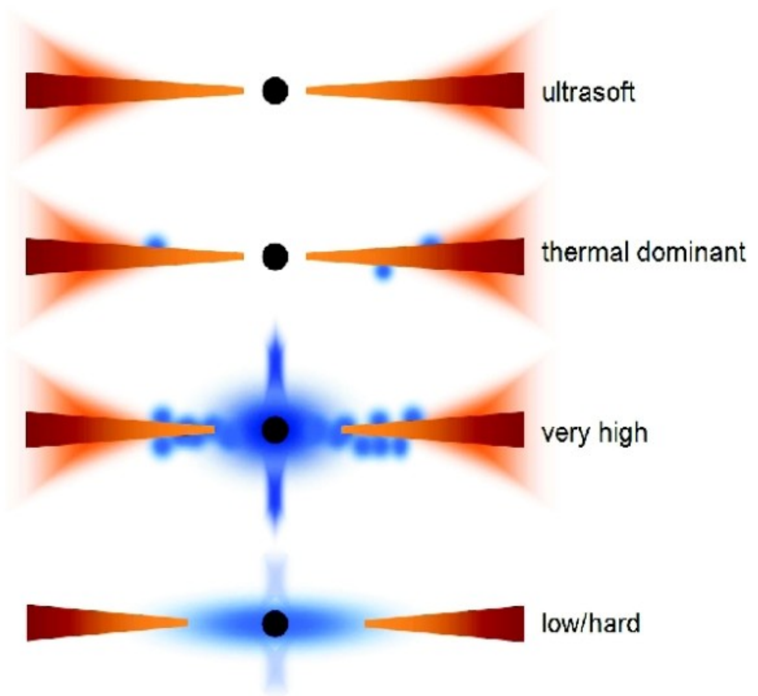
Zdziarski+ 2002



Spectral state transition:

GRO J1655-40, Done + 2007

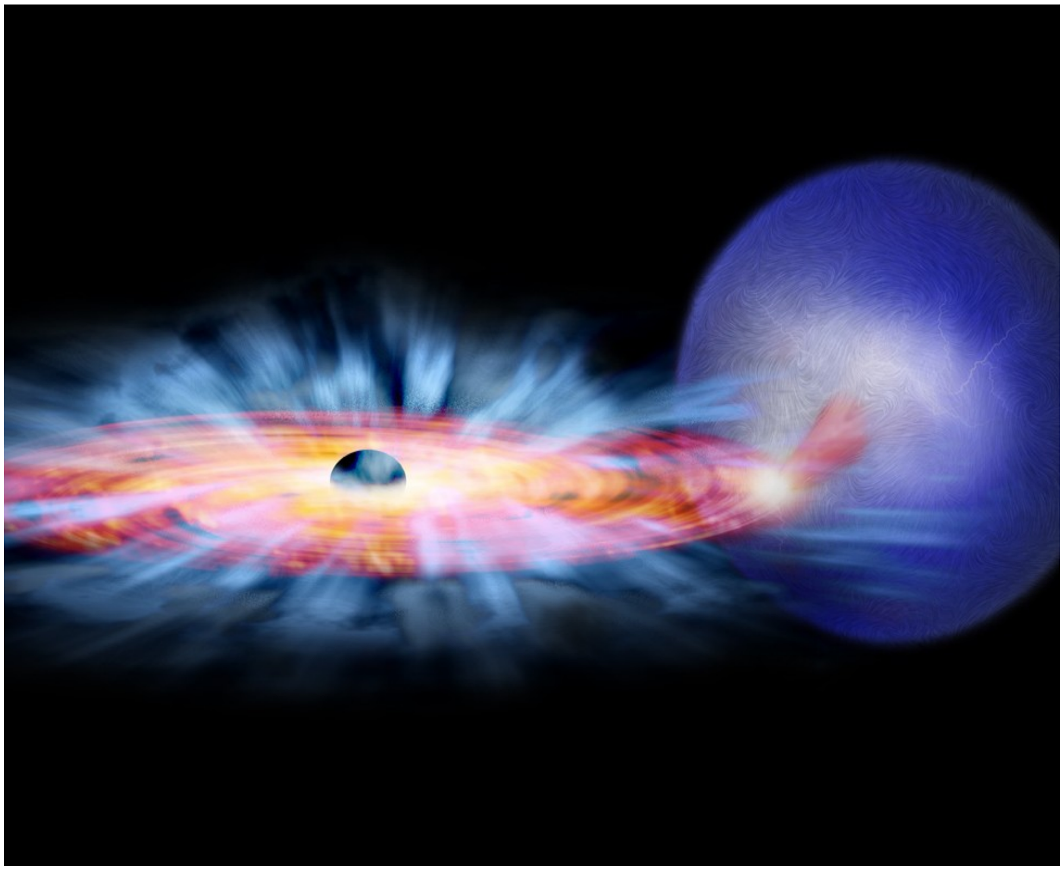


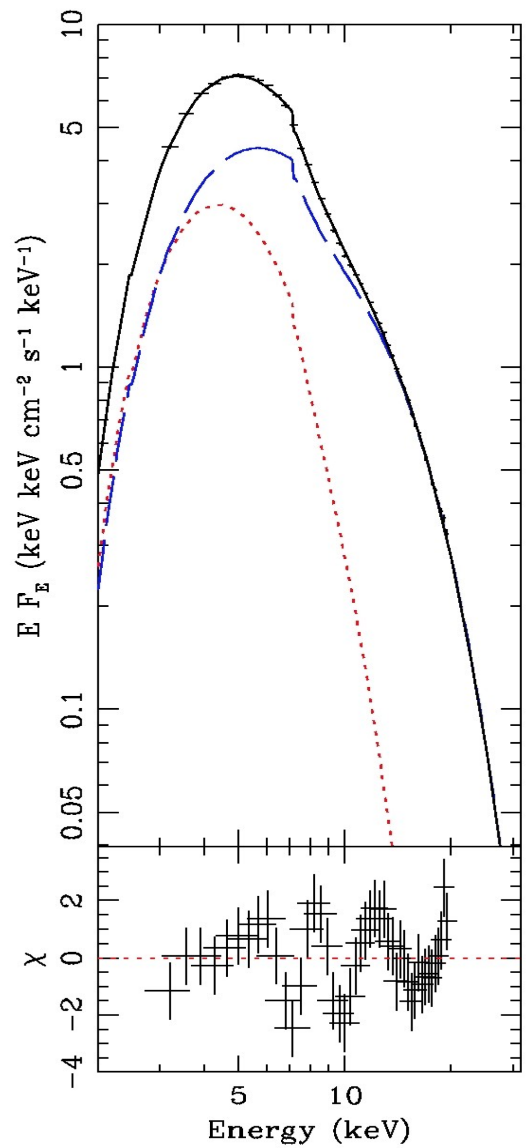


Broad – band emission from X-ray BH binary.
Multi-temperature disk emission + X-ray hard power-law.

Accretion disk atmospheres in binaries:

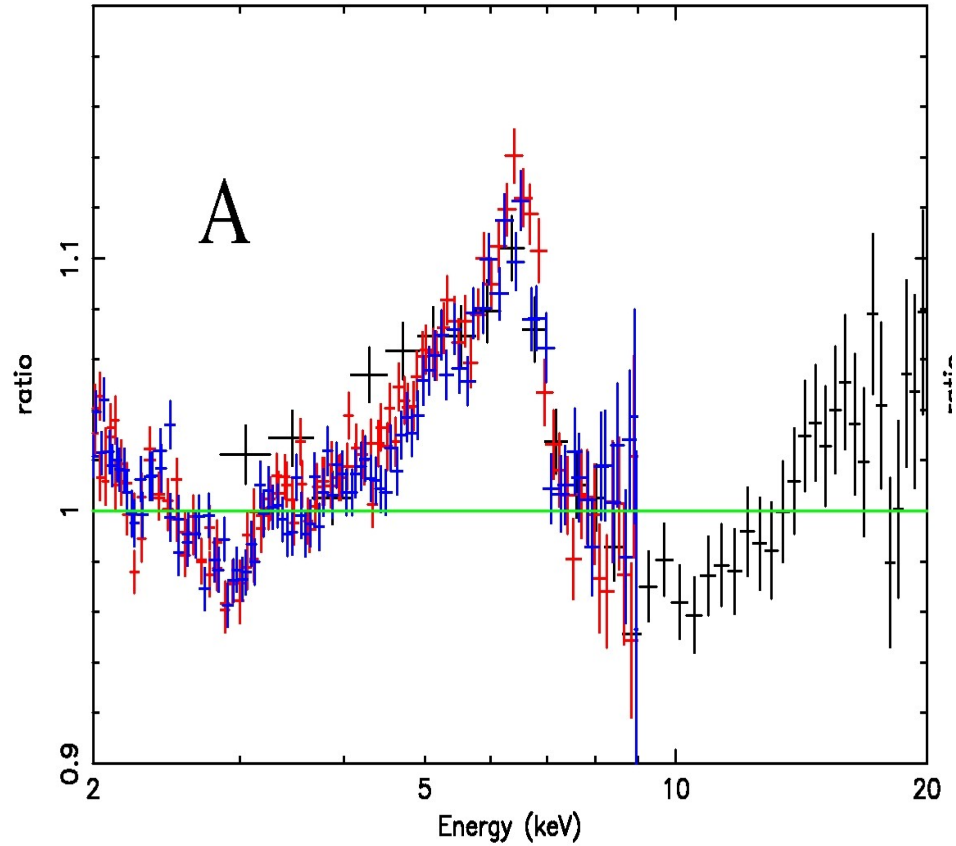
GRS 1915+105, **Middleton + 2006**





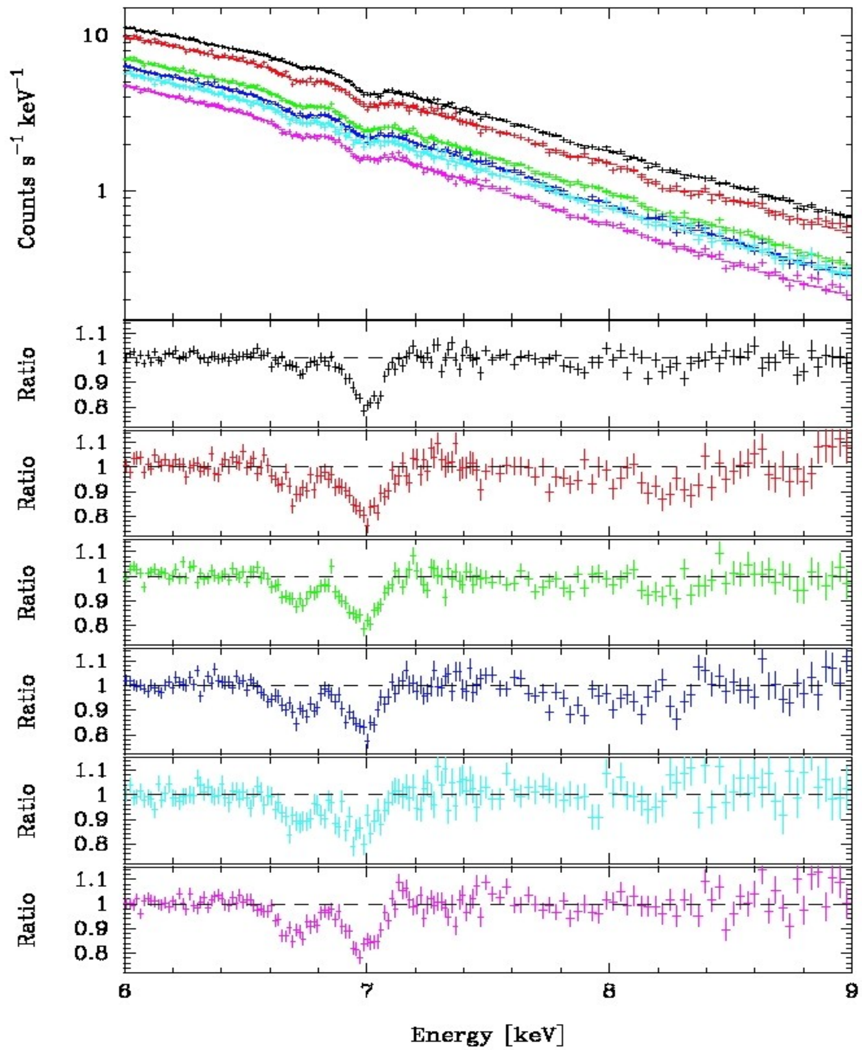
Accretion disk atmospheres in binaries:

GX 339-4 **XMM**
Miller + 2006



Broad Iron line complex.

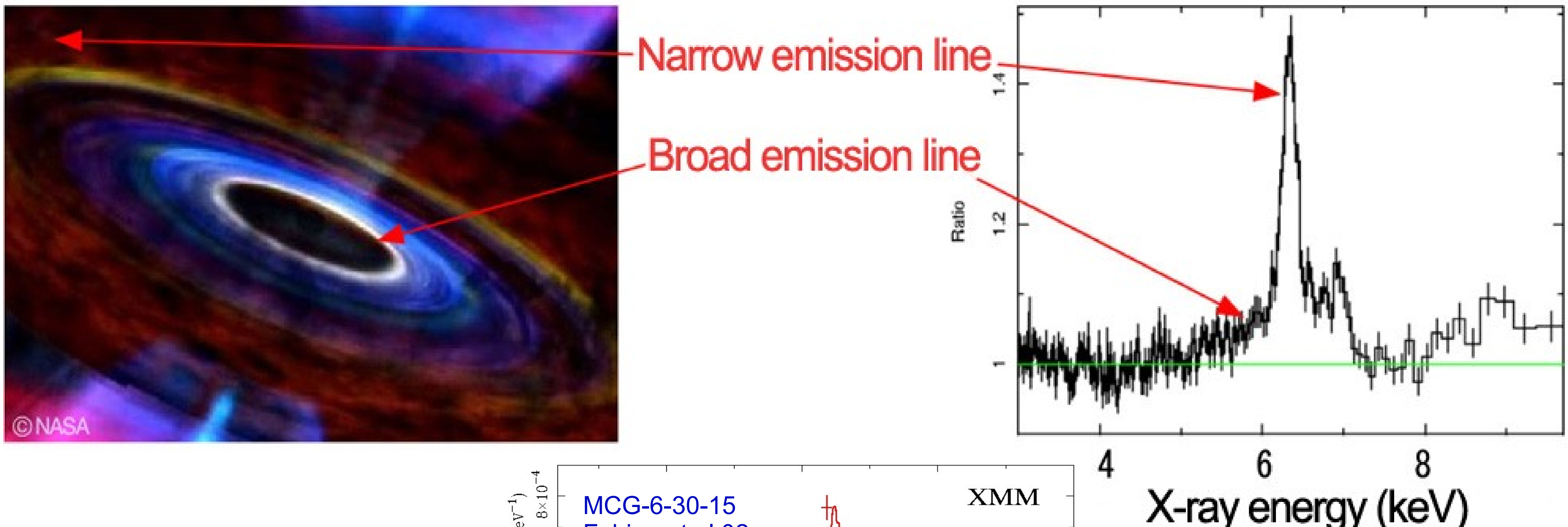
4U 1630-472 **Suzaku**
Kubota + 2007

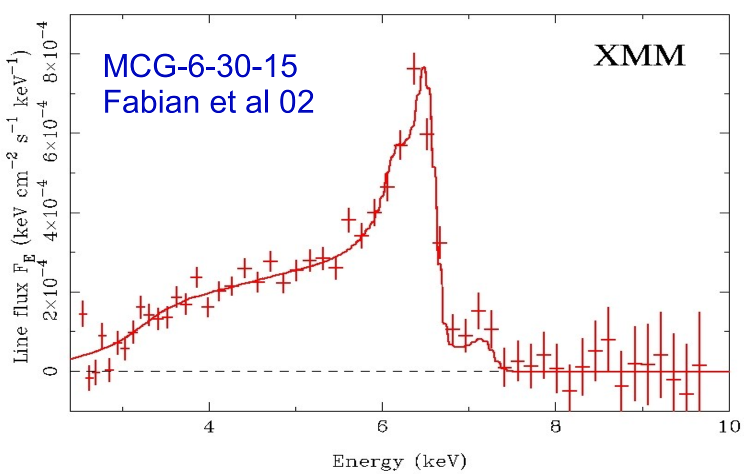


Narrow Iron line complex.

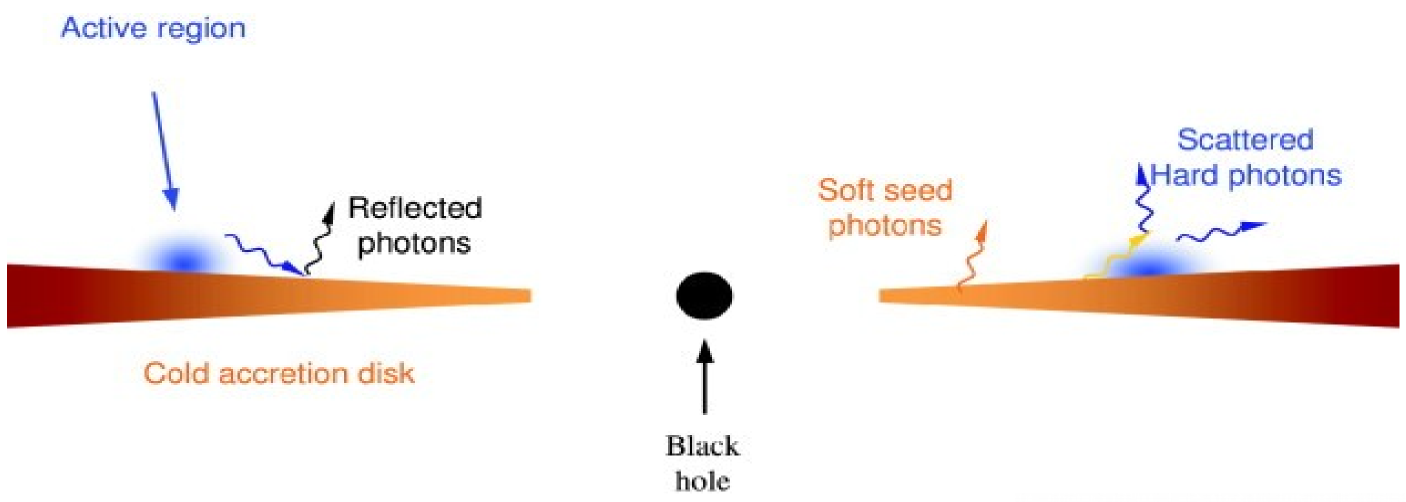
Broad iron line:

Observed only in a few objects. If broad gives strong constrains on the black hole.

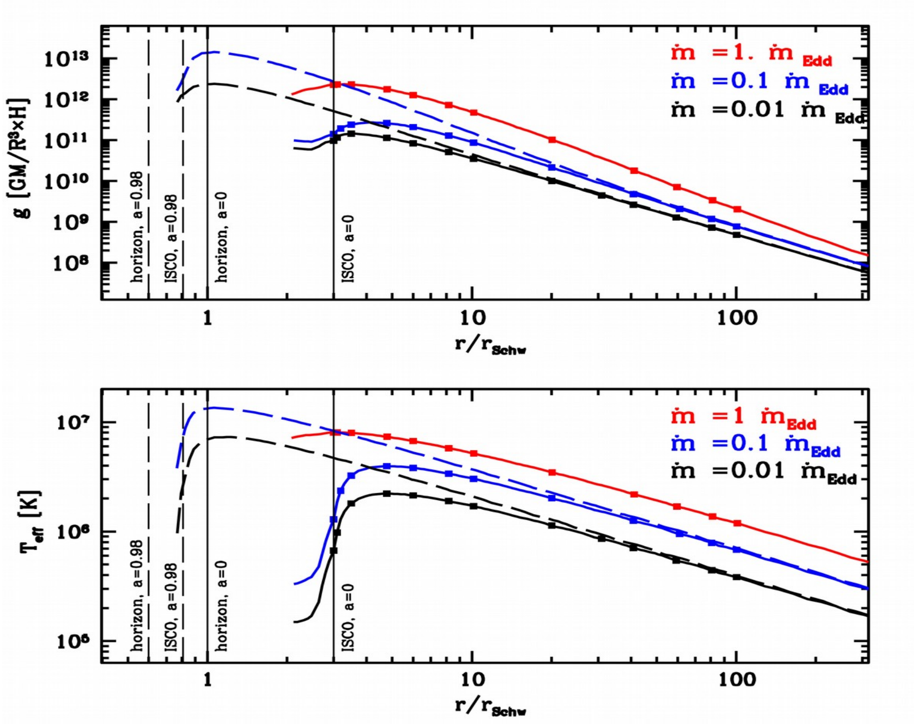




Accretion disk atmospheres in binaries:

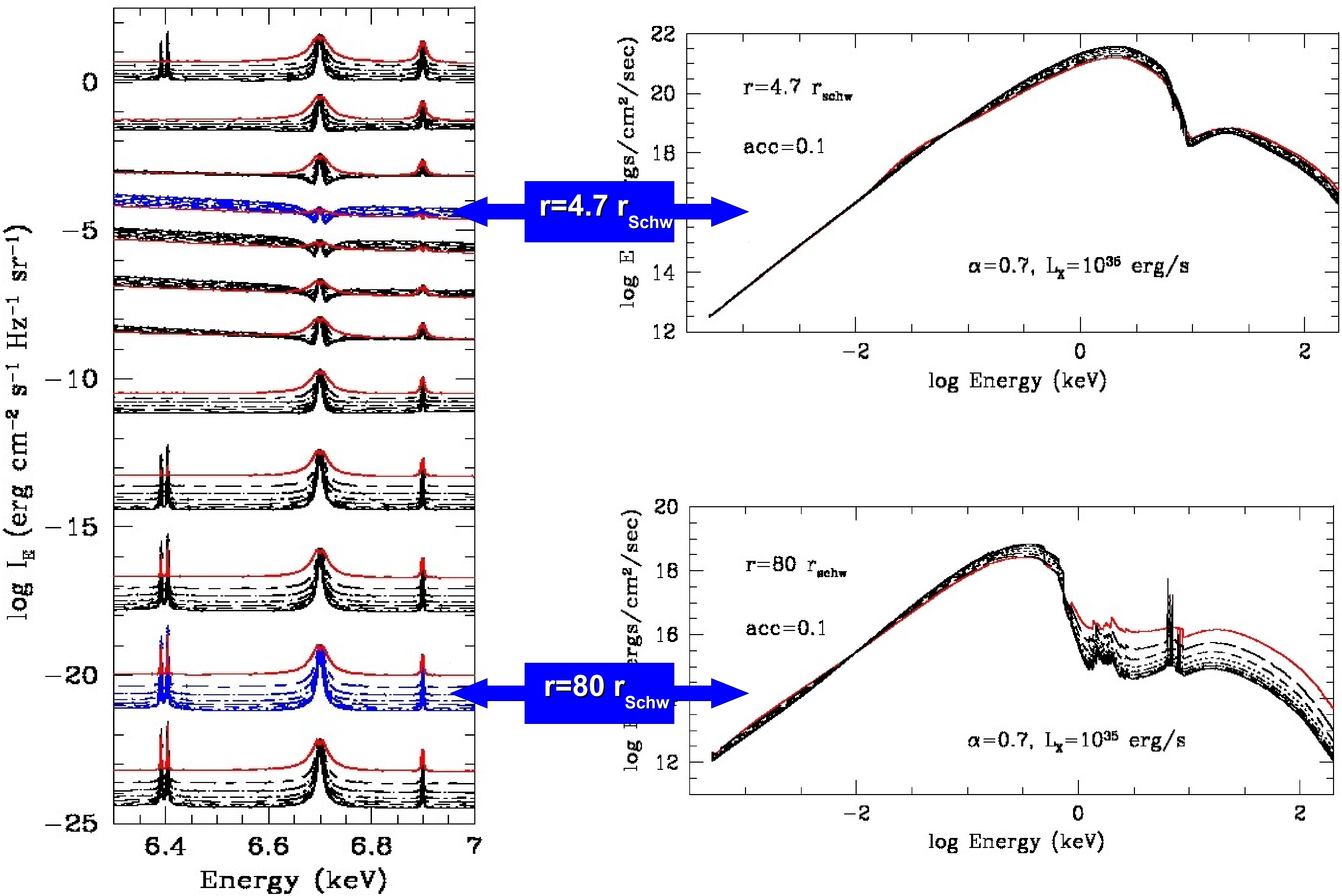


Radiative transfer is computed at each ring, with ionization, hydrostatic and thermal equilibrium, taking into account illumination by external X-ray source.

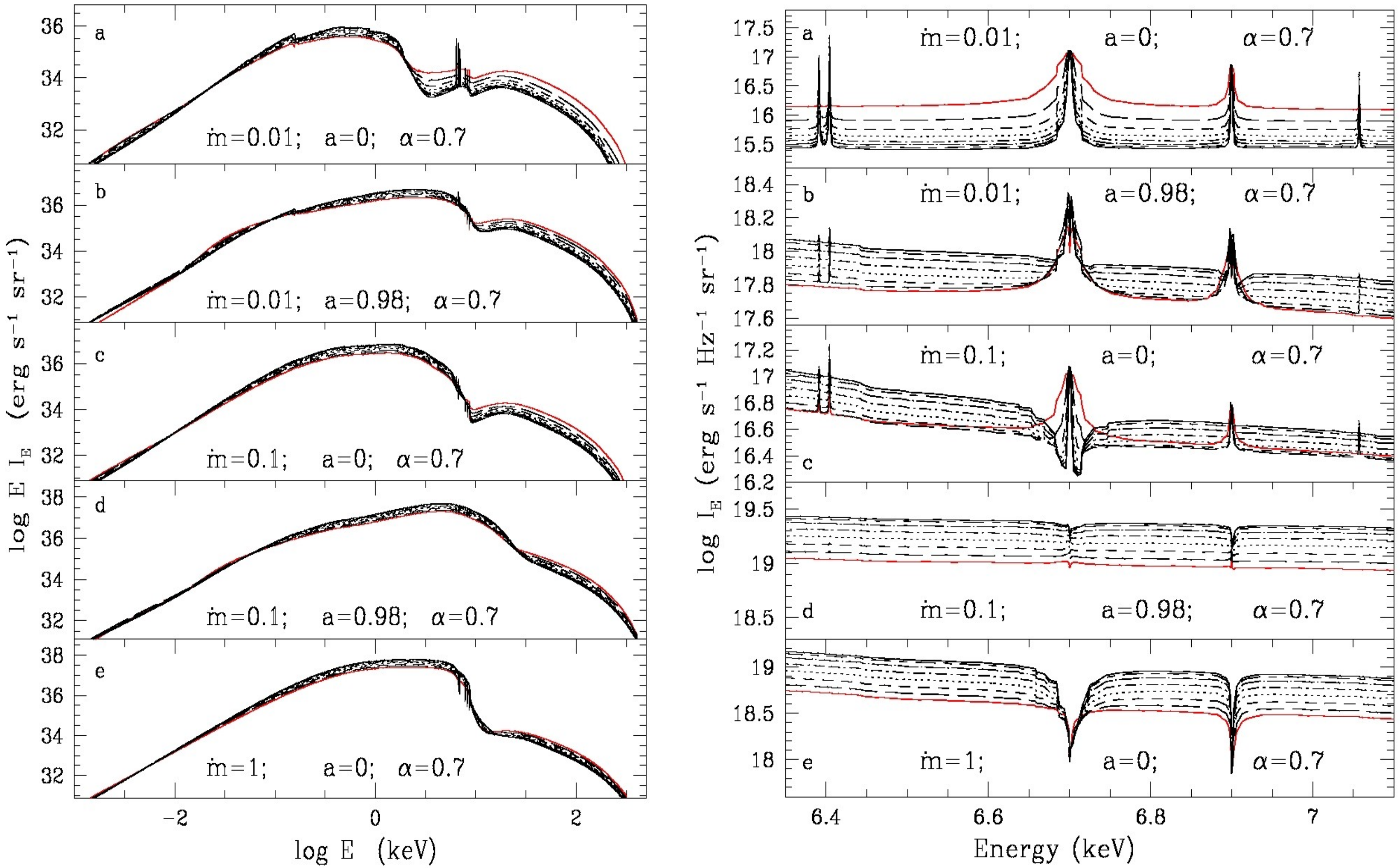


Irradiation of hot accretion disk atmospheres in GBHc;

$\dot{m} = 0.1\ \dot{m}_{Edd}$, a=0



Iron line complex integrated over disk surface:



Ultraluminous X-ray sources

- ULXs were first discovered by Einstein X-ray observatory in the '80s (Long et al. 1981, Fabbiano 1987).
- Bright off-nuclear point sources with X-ray luminosity > 10^{39} erg/s.

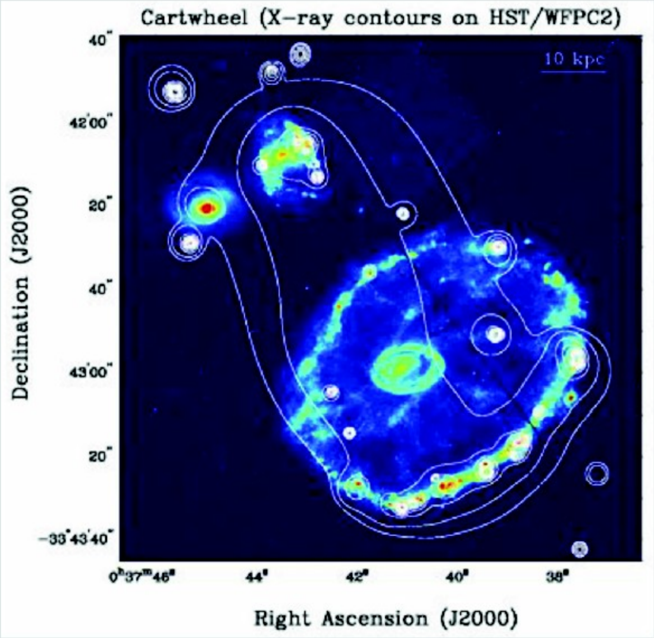
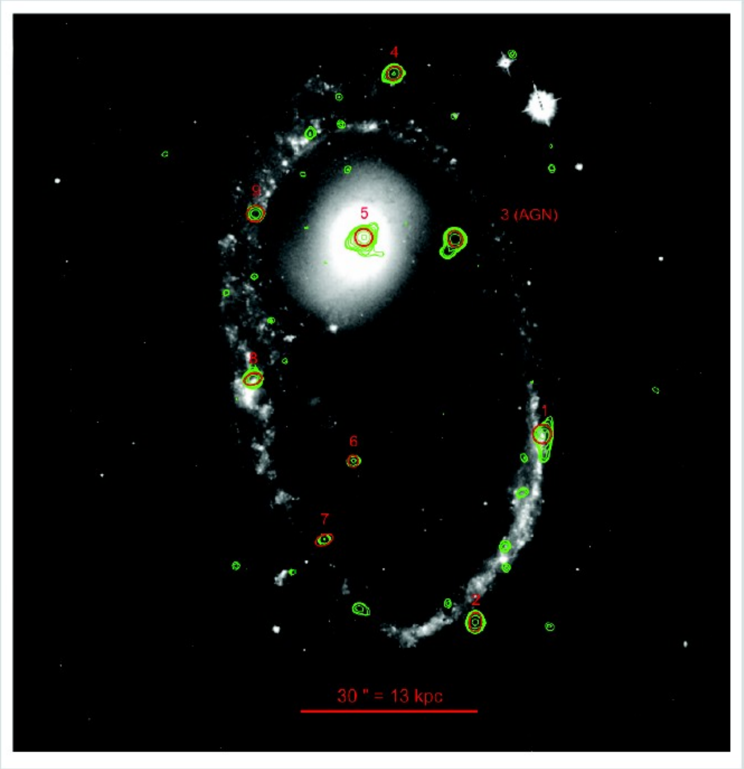


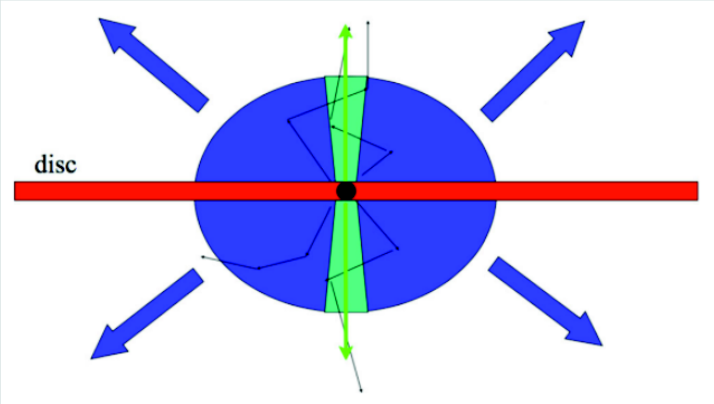
Image credit: CXC, Cartwheel galaxy



Wolter et al. 2018, AM 0644-741

Why care about ULXs?

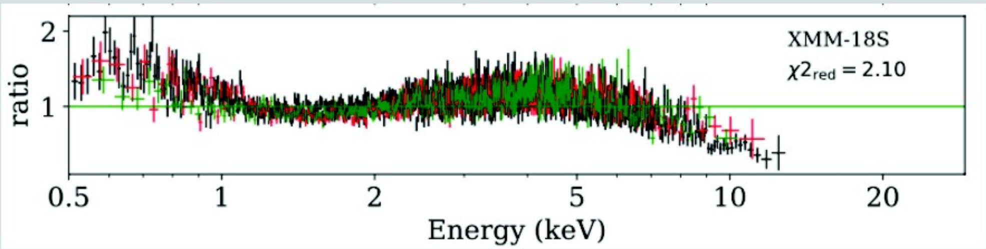
- 1.38x10^{39} erg/s Eddington limit for a $10\ \mathrm{M}_\odot$ BH.
- Possibility of higher mass BH (IMBH: $10^2 - 10^4\ \mathrm{M}_\odot$). Hyperluminous X-ray sources ($L_\mathrm{x} > 10^{41}$ erg/s) are the prime candidates for IMBHs. Which may bridge the gap between the stellar mass BH and super massive BH.
- Stellar mass BH and/or NS with super-Eddington accretion.
- Geometrical beaming is required for a BH/NS to explain the luminosity: $L = L_\mathrm{Edd}[1 + ln(\frac{\dot{M}}{\dot{M}_{Edd}})]/b$ (King et al. 2001, 2009).



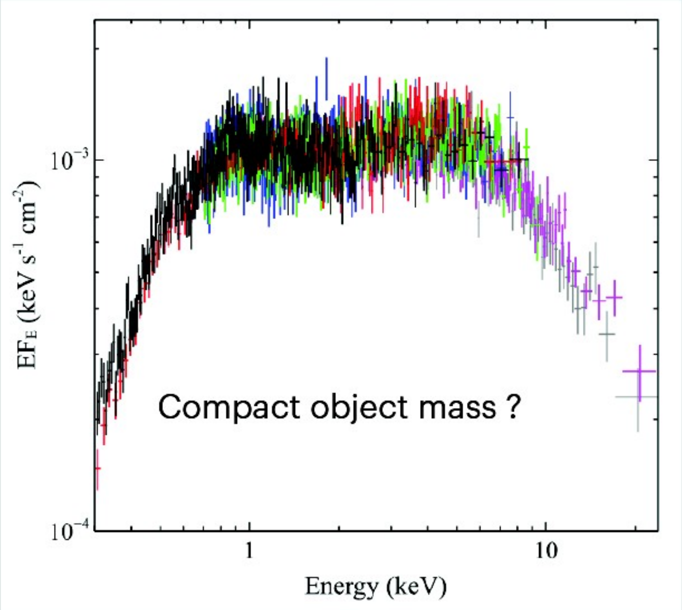
King et al. 2016

Spectral Comparison

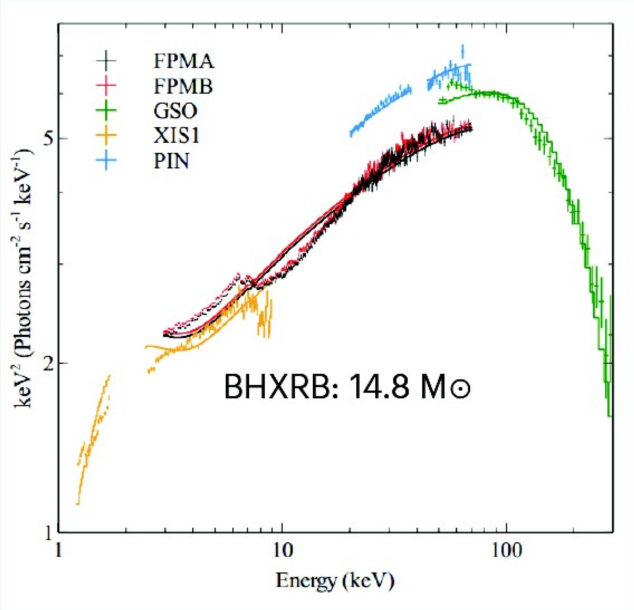
- Spectral curvature in 5-10 keV.
- Spectral cut-off at very low energy 5-10 keV.



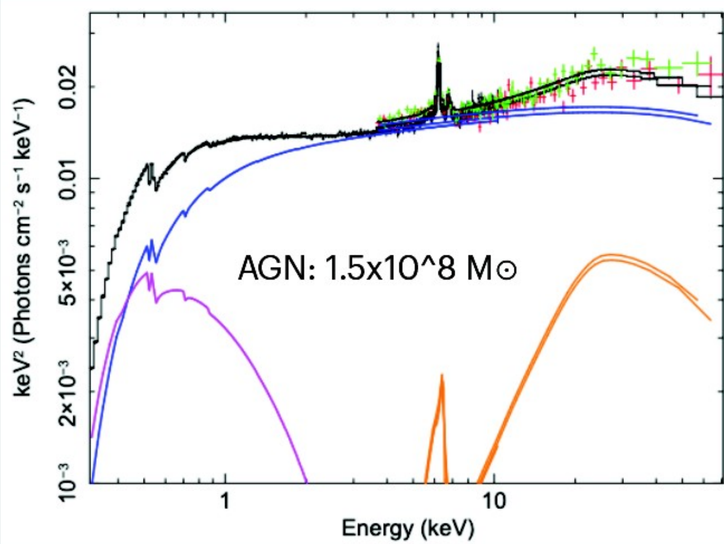
Mondal et al. 2021, Circinus ULX5



Walton et al. 2015, Ho II X-1



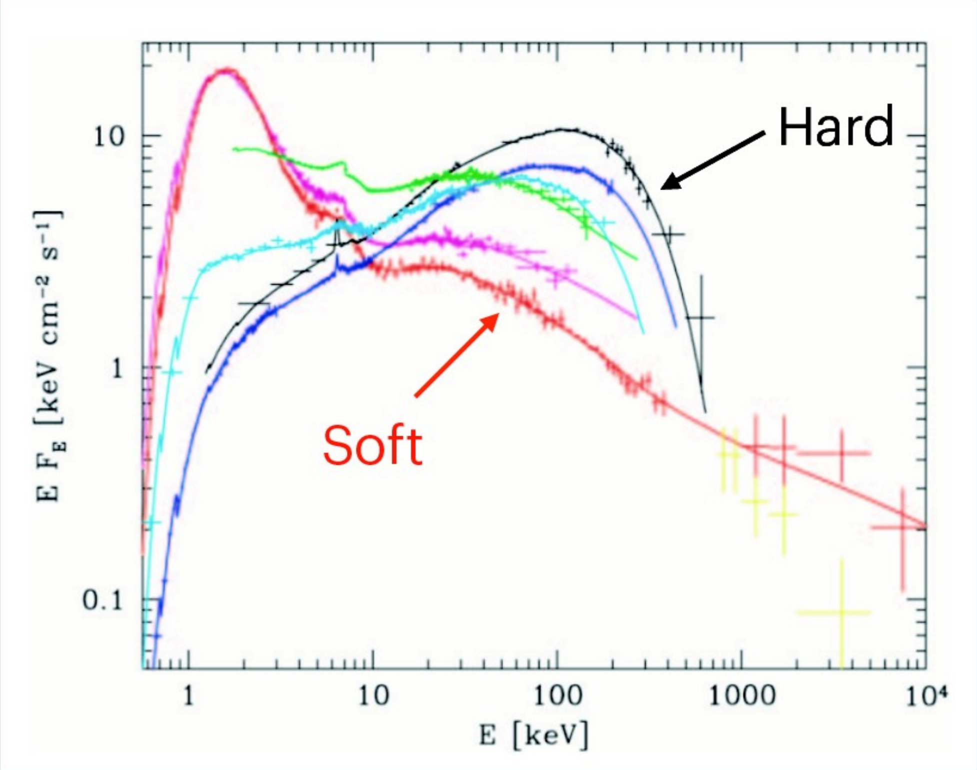
Parker et al. 2016, Cyg X-1



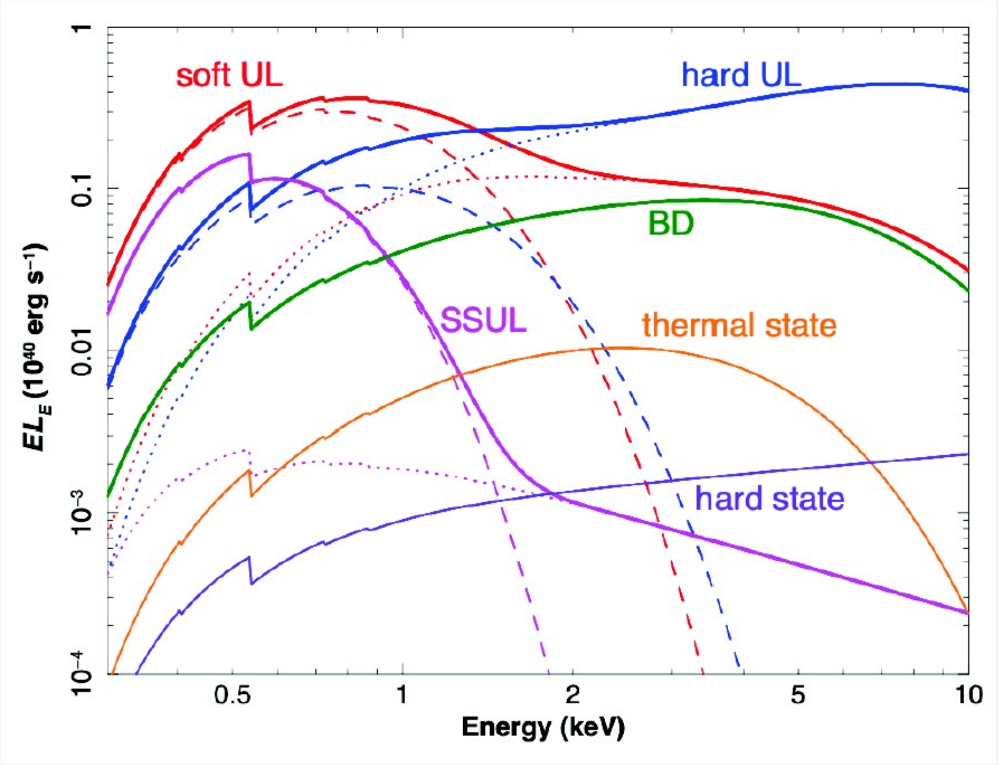
Porquet et al. 2018, Ark 120

Spectral states of ULXs

- Mainly three types of spectral states: hard UL, soft UL and BD.



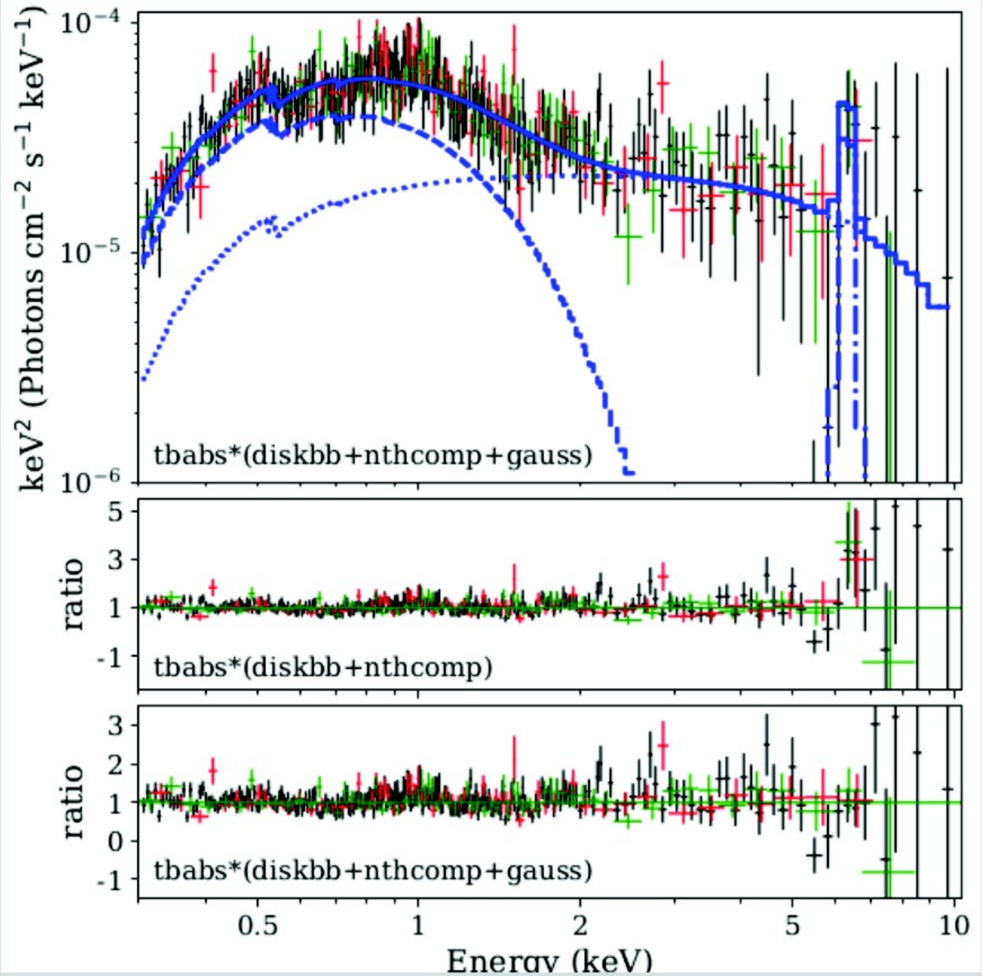
Zdziarski et al 2002, Cyg X-1



Kaaret et al. 2017

NGC 7456 ULX-1

- Soft ULX & detection of Fe Kα.
- Monte Carlo simulation yields detection at 99% confidence limit.
- Due to limited signal to noise quality upper limit on line width σ<300 eV.
- Considering Keplerian motion the line must be originated >85rg.
- Highest EW ~ 2000 eV measured so far in ULX.
- Only one another ULX type source(M82 X-1; Strohmayer & Mushotzky 2003).



Mondal et al. 2021, MNRAS Letter

No Lecture on Feb. 7th – visit for the title

NEXT NEW LECTURE on Feb. 9nd 2023

- You can still upload your HW#6 and hands-on results
  Up to the Feb. 19th (Copernicus birthday).

- theory, but we still practice

wi-fi password: a w sercu maj
We have eduroam as well