Hard X-ray Emission in Soft States Low Mass X-ray Binaries

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Five Years of INTEGRAL
Chia, 18 Oct 2007

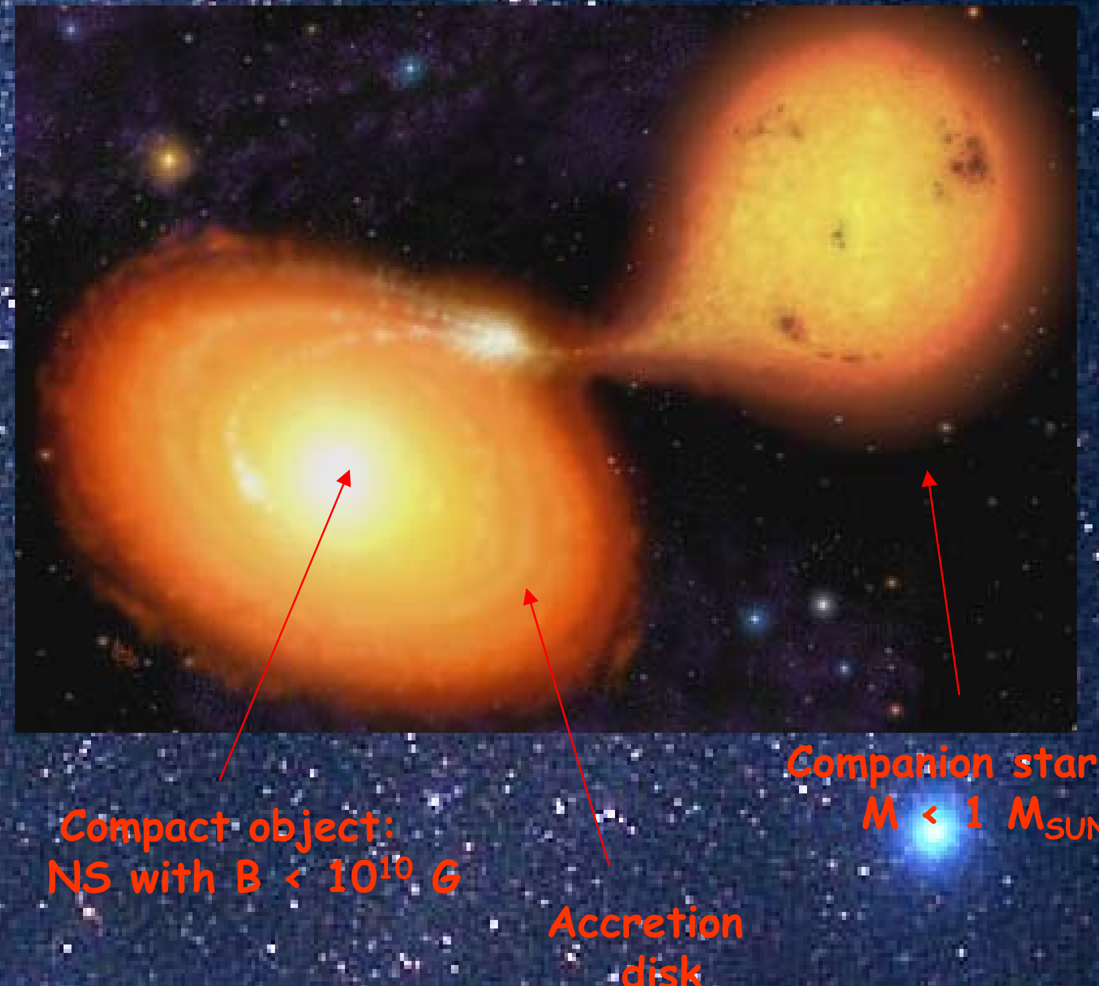
Low Mass X-ray Binaries

Close X-ray binaries:

• Rich time variability, such as twin QPOs at kHz frequencies (from 400 to 1300 Hz, increasing with increasing mass accretion rate); **kHz QPOs are thought to reflect Keplerian frequencies at the inner accretion disk.**

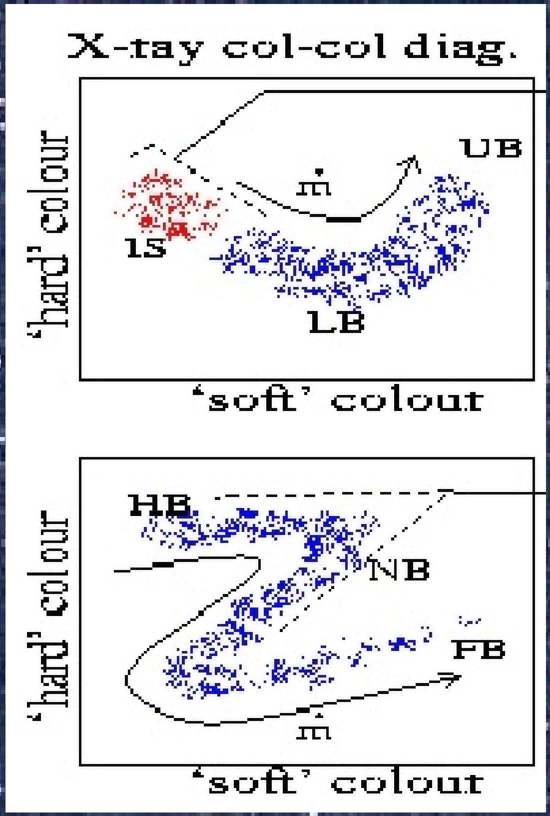
• Type-I X-ray bursts, with nearly coherent oscillations in the range **300-600 Hz** (probably the **NS spin** frequency).

• Most are **transient**, with quiescent luminosities of 10^{32}-10^{33} erg/s and outburst luminosities of 10^{36}-10^{38} erg/s.



Neutron star low mass x-ray binaries classification

<u>Atoll sources</u>:
- Lx ~ 0.01-0.1 L(Edd)
- type I X-ray bursts
- most are transients



<u>Z-sources</u>:
- Lx ~ 0.1-1.0 L(Edd)
- a few X-ray bursts
- all persistent

Atoll sources: energy spectra

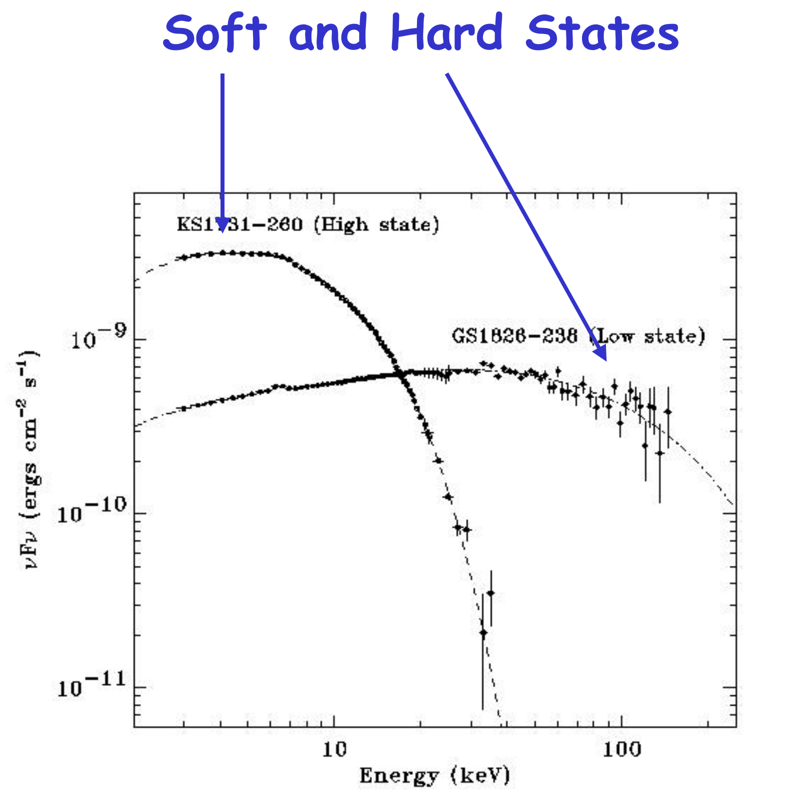
- Soft component (few keV)
  (blackbody or disk-blackbody model)

- Power law with exponential
  cutoff (5-20 keV): Thermal
  Comptonization.

- Soft and hard states:
  in the hard state the cutoff shifts
  to higher energies (up to > 200 keV)

- Iron emission (fluorescence) line
  at ~6.4 keV

- Evidence for a reflection component



X-ray energy spectra of Z sources up to ~20 keV

Very soft (thermal) spectra. Two components needed (at least).
Most popular proposed interpretations:

- Eastern model (Mitsuda et al. 1984):
  multitemperature-blackbody + blackbody/Comptonized spectra
  (disk emission with $kT = a\,R^{-3/4}$, and NS surface comptonized emission)

- Western model (White et al. 1986):
  blackbody + Comptonized blackbody spectra
  (NS or disk emission, and disk emission modified by Comptonization in a hotter region).

- Birmingham model (Church et al. 1997, 2006):
  blackbody + Comptonized spectra
  (NS emission, and Comptonized emission from an extended ADC).

Strong Analogies with the Spectra of Black Holes Candidates in X-ray Binaries

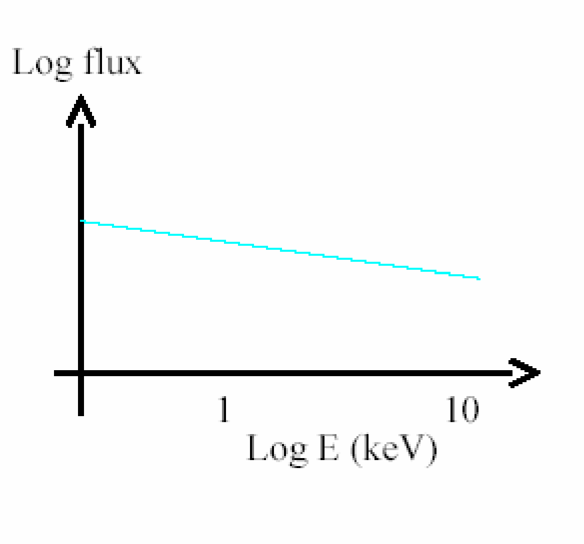
Hard/low States

Fitted by

- Low energy blackbody (temperature about 0.1 keV)
- Power law:

  Γ = 1.4 - 1.9

  Plus a high energy cutoff at about 100 KeV.
- Luminosity < 0.1 L_{EDD}.



Spectra of BHXBs

Soft/high States

Fitted by:

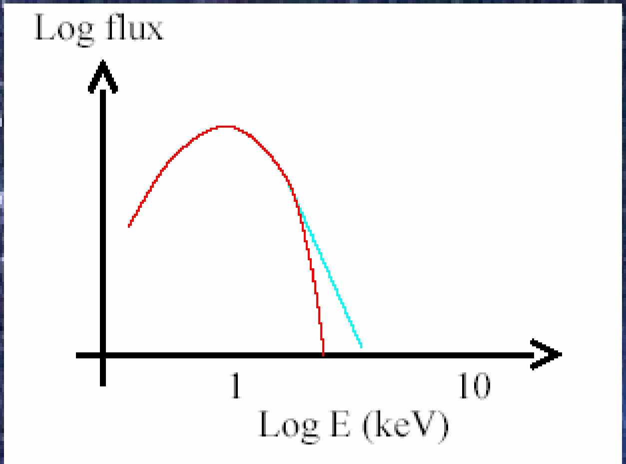
- A low energy blackbody (temp. kT about 0.5-1KeV) dominating the X-ray spectrum (and the power-law emission).

- Power law:

$\Gamma = 2 - 3$

Without any evidence of a high energy cutoff up to energies of about 0.5 - 1 MeV

- Luminosity > 0.2-0.3 L_{EDD}.

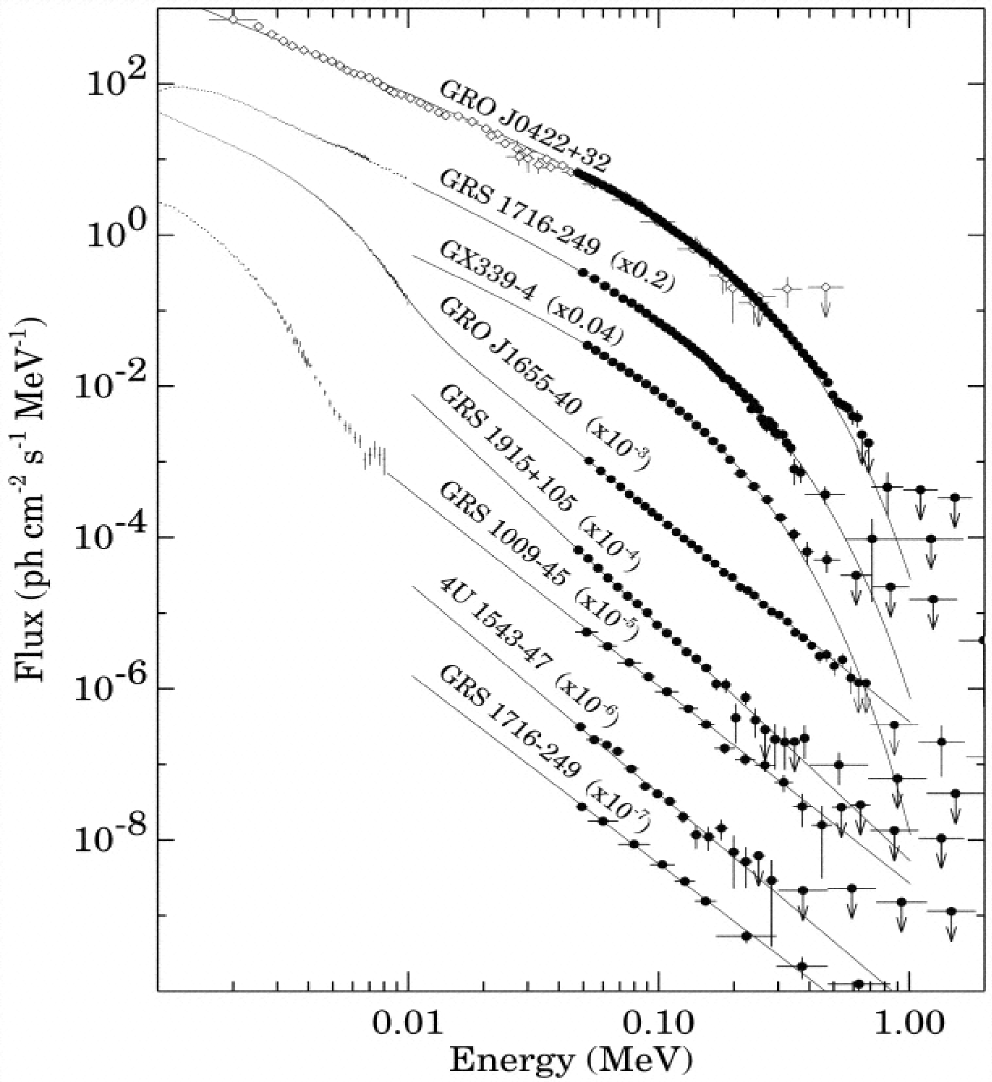


Broad Band Spectra of BHXBs

No high energy cutoff is present up to 1 MeV.

Titarchuk & Zannias 1998, Luarent & Titarchuk 1999 proposed that the hard emission might be caused by a converging relativistic flow towards the event horizon of the BH.
However, in bright NS the converging flow should be stopped by the pressure of the radiation emitted from the NS surface.

(Grove et al. 1998)



Spectra of LMXBs containing NS

- Strong analogies with spectra of BHXBs: presence of hard/low and soft/high states.

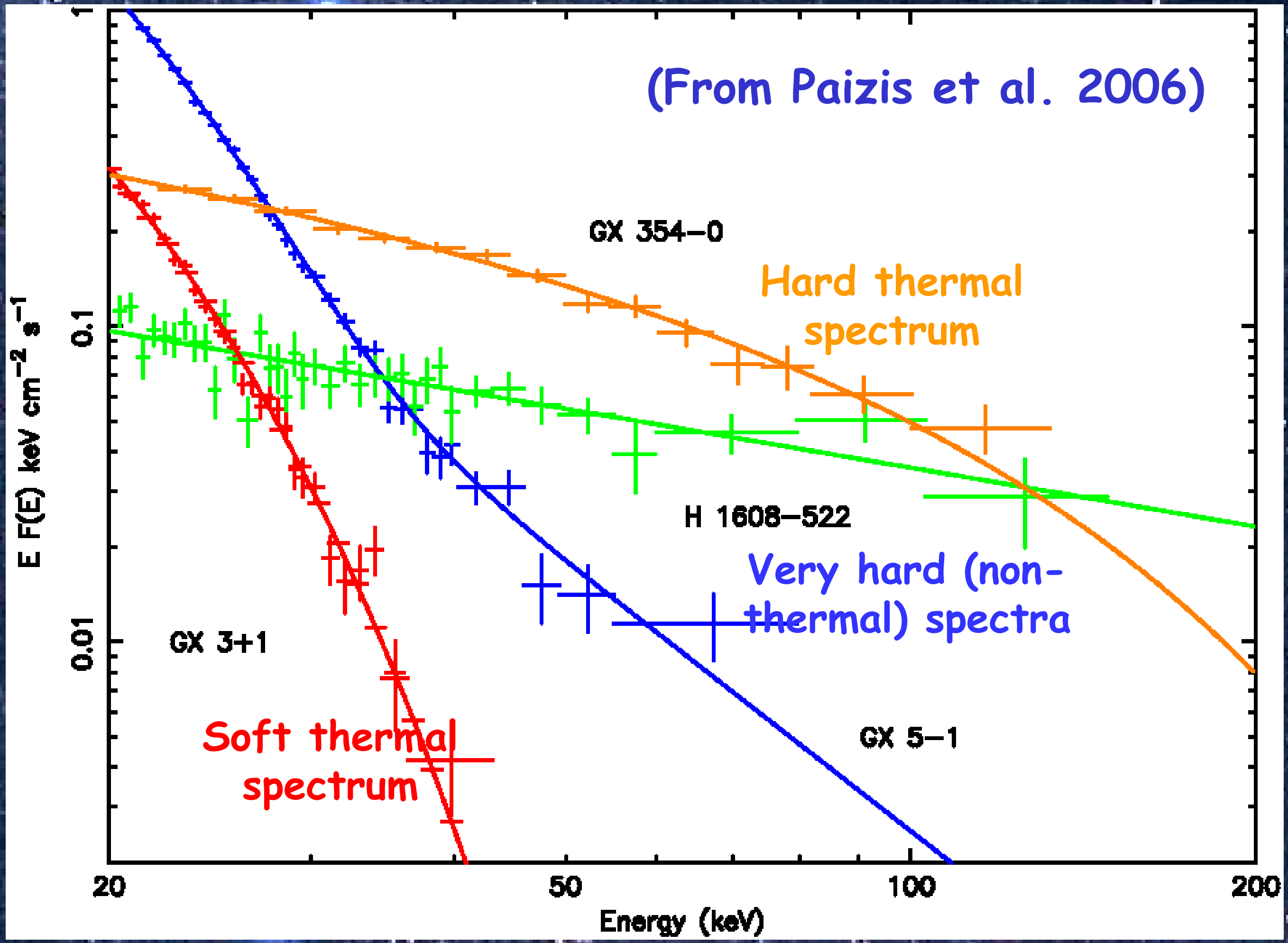
- Possible difference in the temperatures of the Comptonizing region.

⇓

Extra cooling due to the soft emission from the NS surface?

Hard X-ray emission from NS LMXBs with INTEGRAL

With increasing the Mdot the source state changes from hard thermal (GX 354-0), or very hard (H 1608, cutoff moves to higher energies), to intermediate (GX 5-1), and to soft thermal (GX 3+1).



Hard X-ray emission discovered in bright LMXBs (hystorical detections)

- Sco X-1: thermal-like spectrum with kT ~ 3-4 keV
  BUT: evidence for a variable hard component dominating the spectrum above 40 keV (Peterson & Jacobson 1966; Riegler et al. 1970; Agrawal et al. 1971; Haymes et al. 1971)

- Evidence for a hard component was found also in Cyg X-2 (Peterson 1973), and GX 349+2 (Greenhill et al. 1979)

- Limited attention given to these findings for the lack of good spatial resolution and broad band spectra.

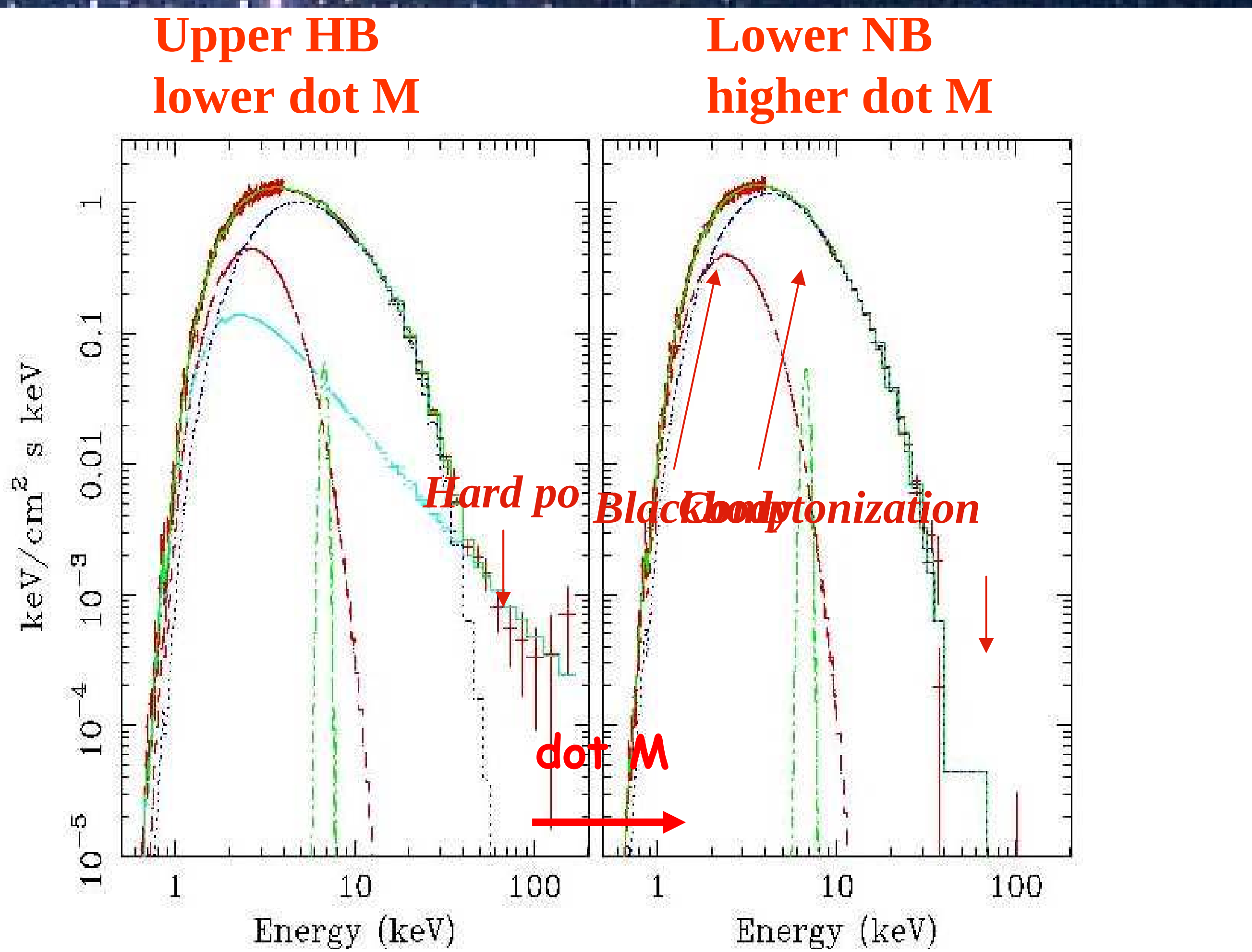
- Renewed interest since the early 2000 thanks to the broad band studies performed with BeppoSAX (0.1 – 200 keV) and RXTE (2 – 200 keV) and, more recently, INTEGRAL (3 – 200 keV).

BeppoSAX spectra of GX 17+2

Hard tail in the HB
8 % of source Lx
(1-200 keV range)

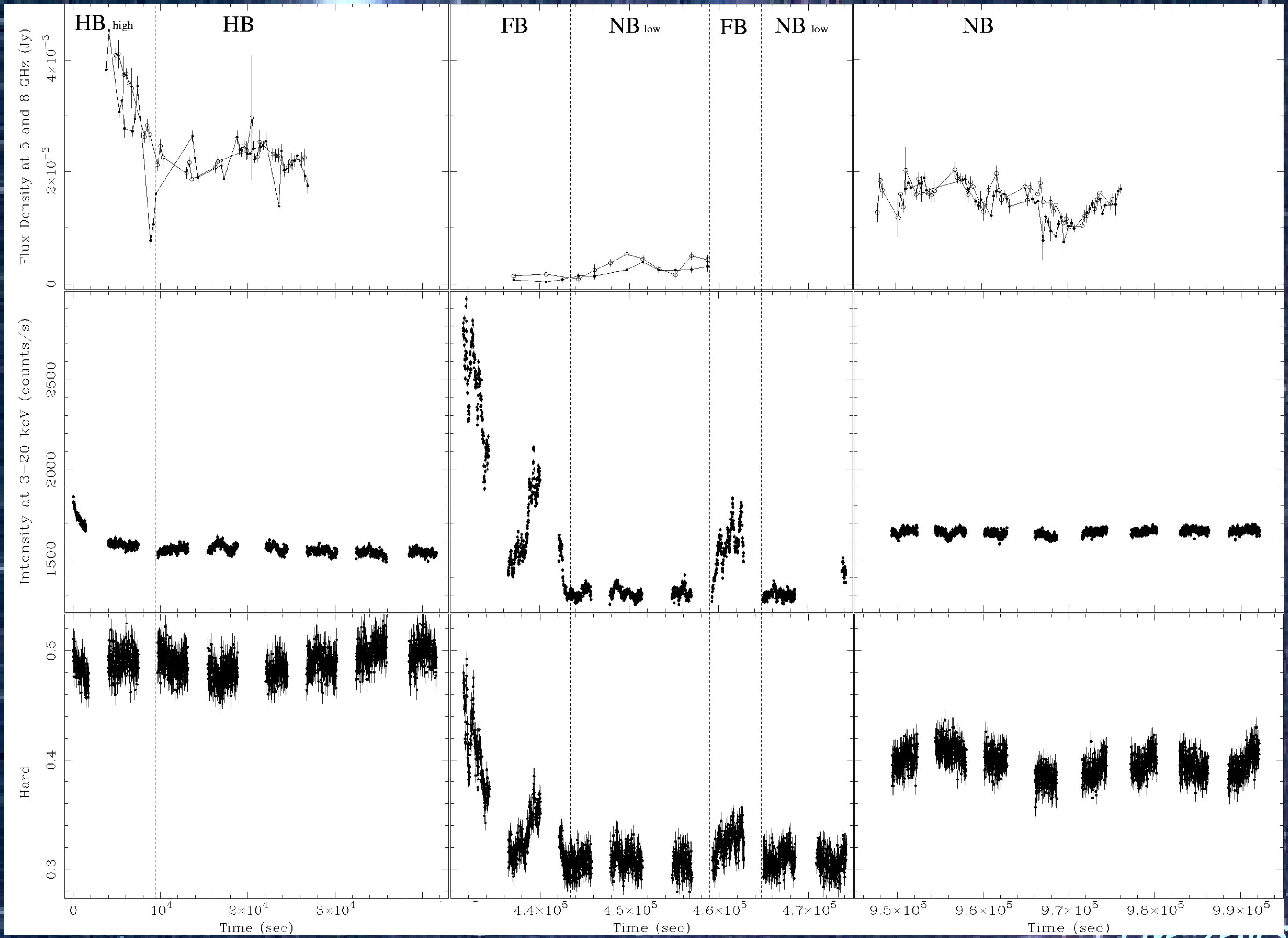
Power law slope 2.7

Hard tail intensity
decreases by a
factor of > 20
in the NB
(i.e. higher mass
accretion rates)



(Di Salvo et al. 2000)

RXTE/VLA Observation of GX 17+2



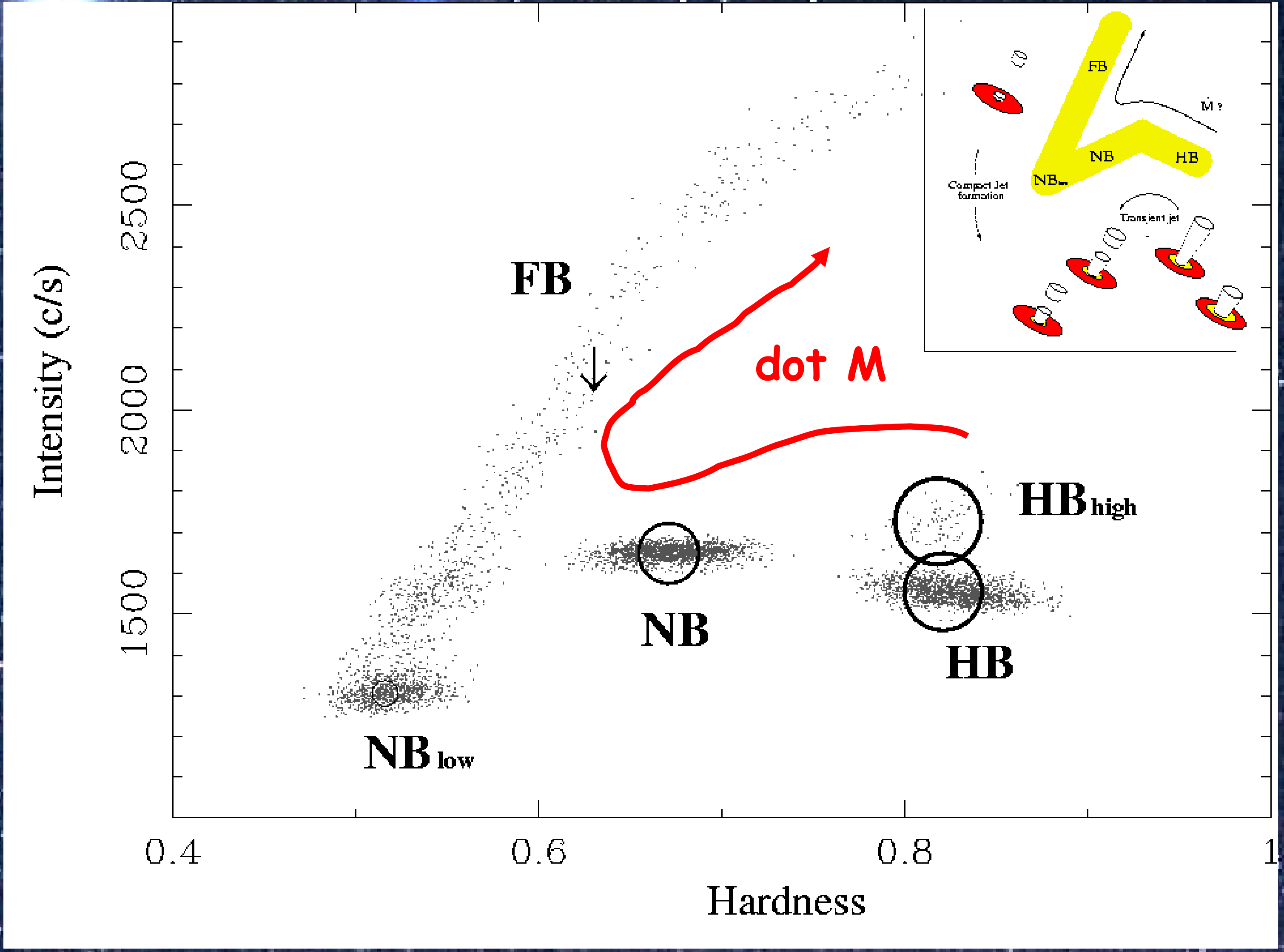
Radio Flux

3-20 keV Count rate

[10-20 keV]/[7-10 keV] Hardness ratio

Migliari et al. 2007, ApJ, in press

From the radio counterpart the jet seems to become more intense going to lower accretion rates

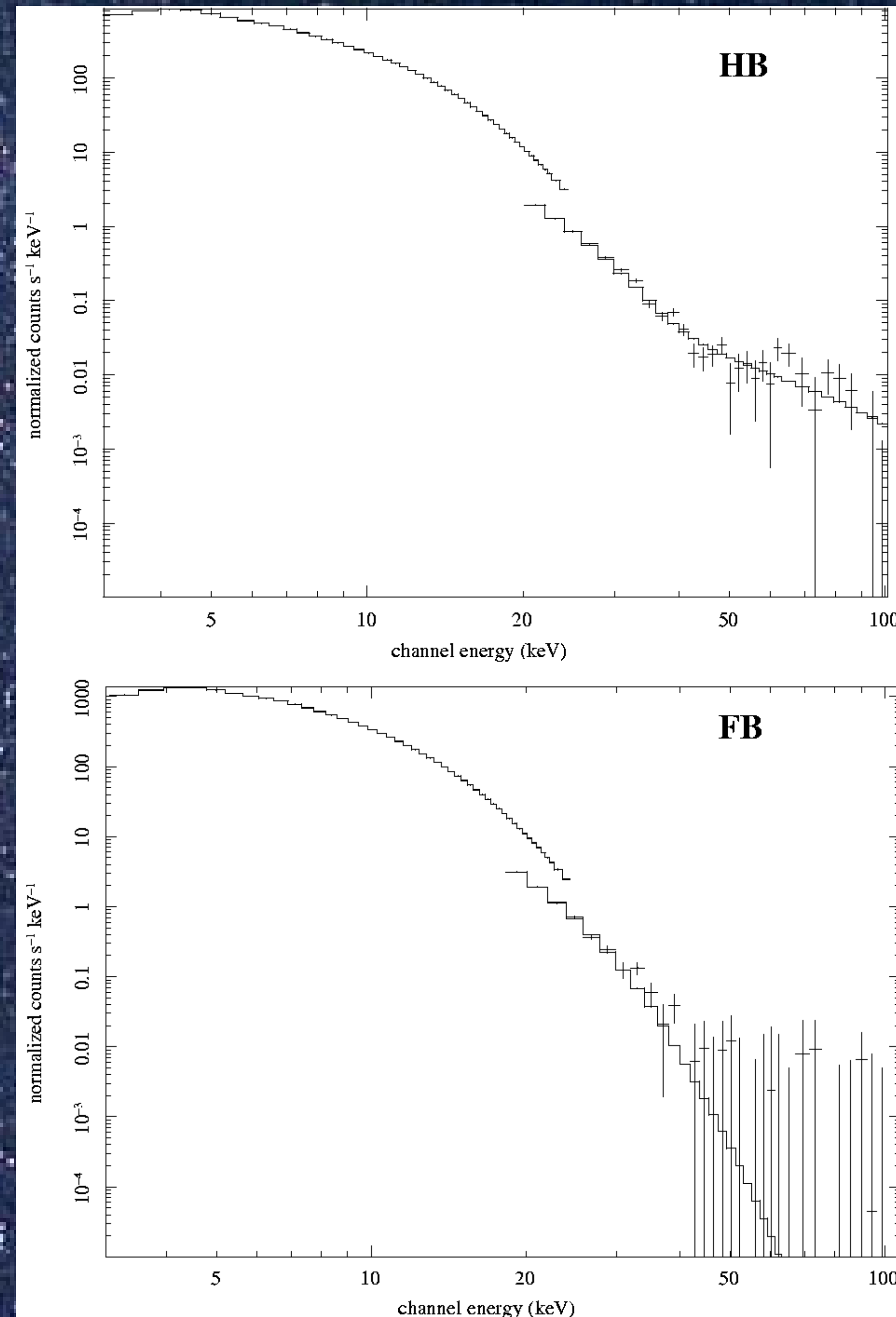


Bigger circles indicate more intense radio emission.

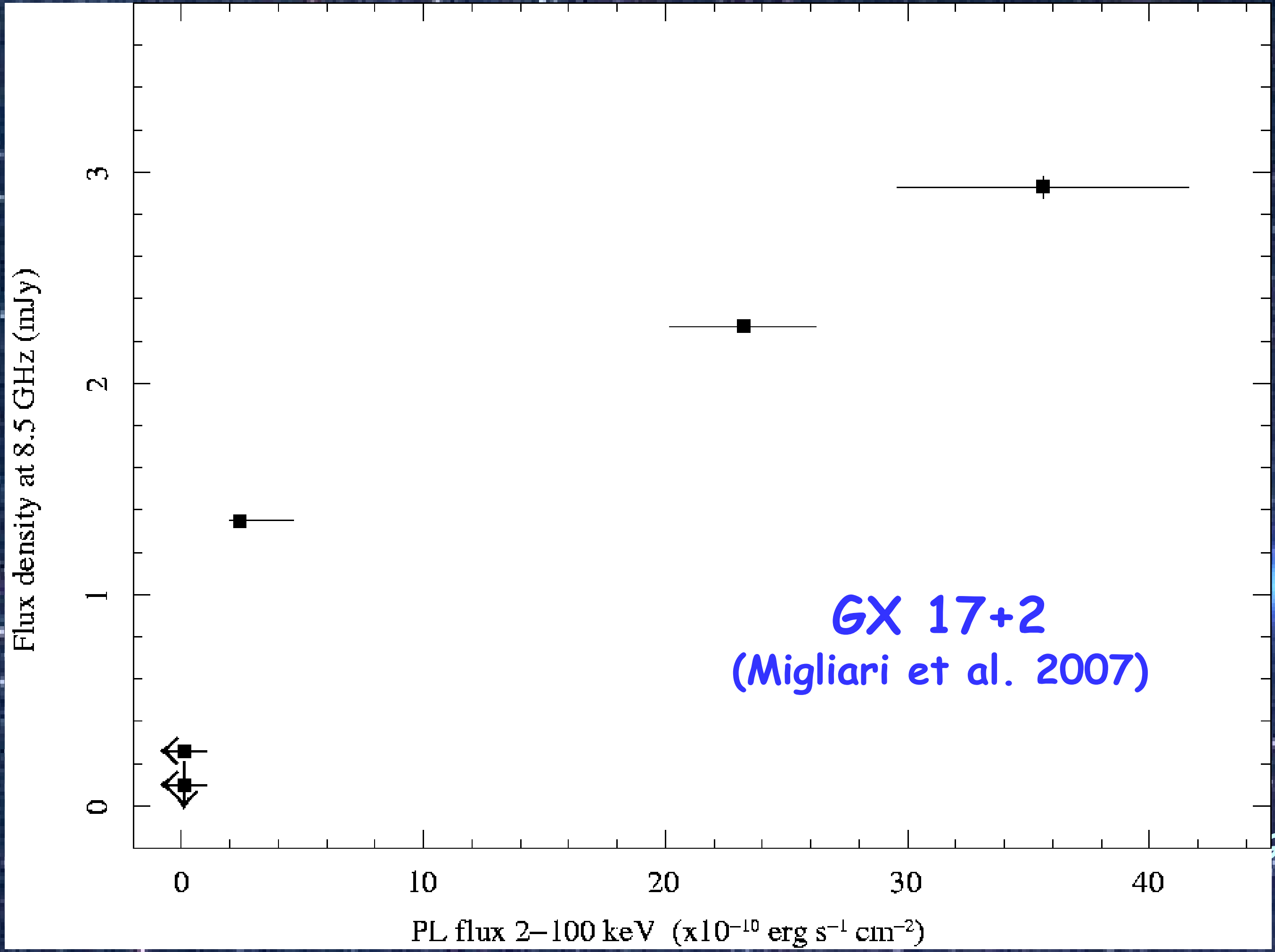
RXTE/PCA spectra of GX 17+2

At the same time the hard power-law component becomes more intense going to lower mass accretion rates

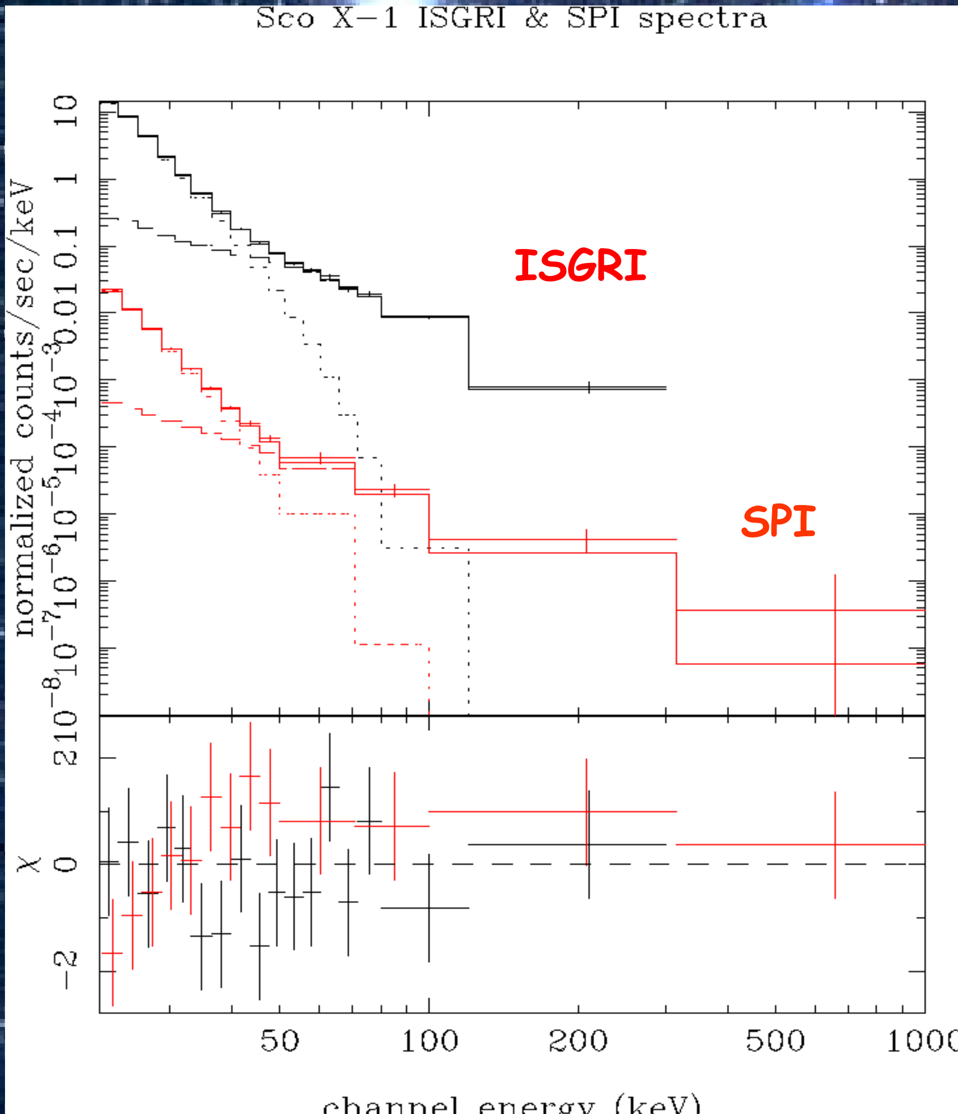
dot M



Strong correlation between the X-ray flux in the hard power-law component and the 8.5 GHz radio flux density



Hard X-ray Emission in LMXBs: INTEGRAL/RXTE Observations of Sco X-1



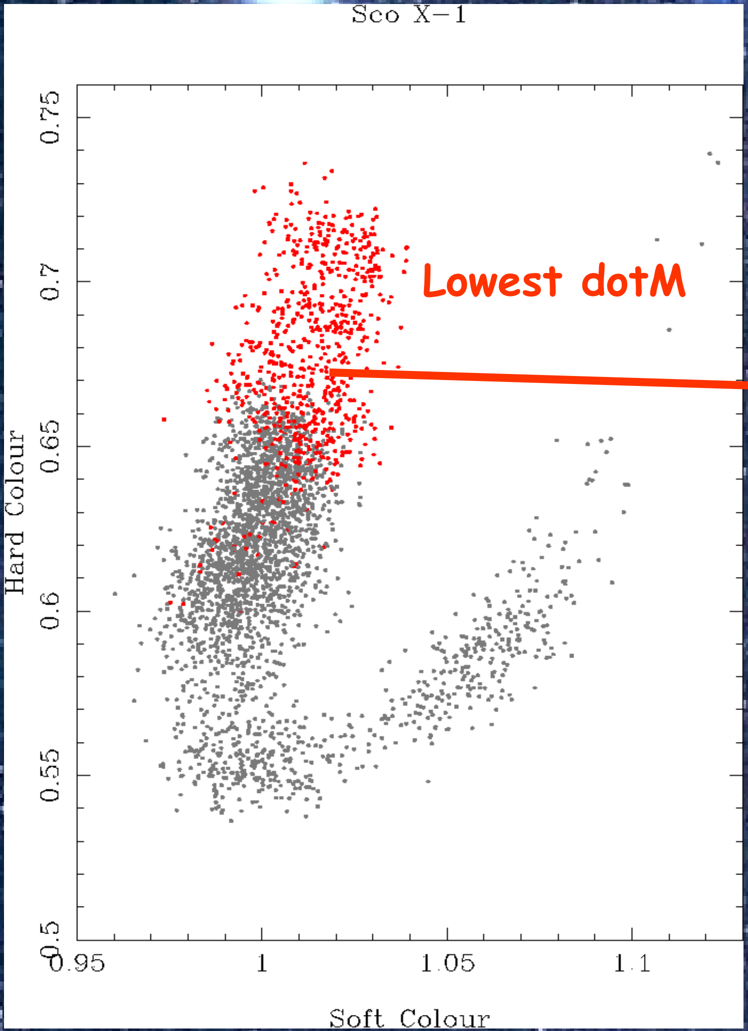
Soft Comptonization:
kT (seed) = 1.3 keV (fixed)
kTe = 4.7 keV
τ = 2.4

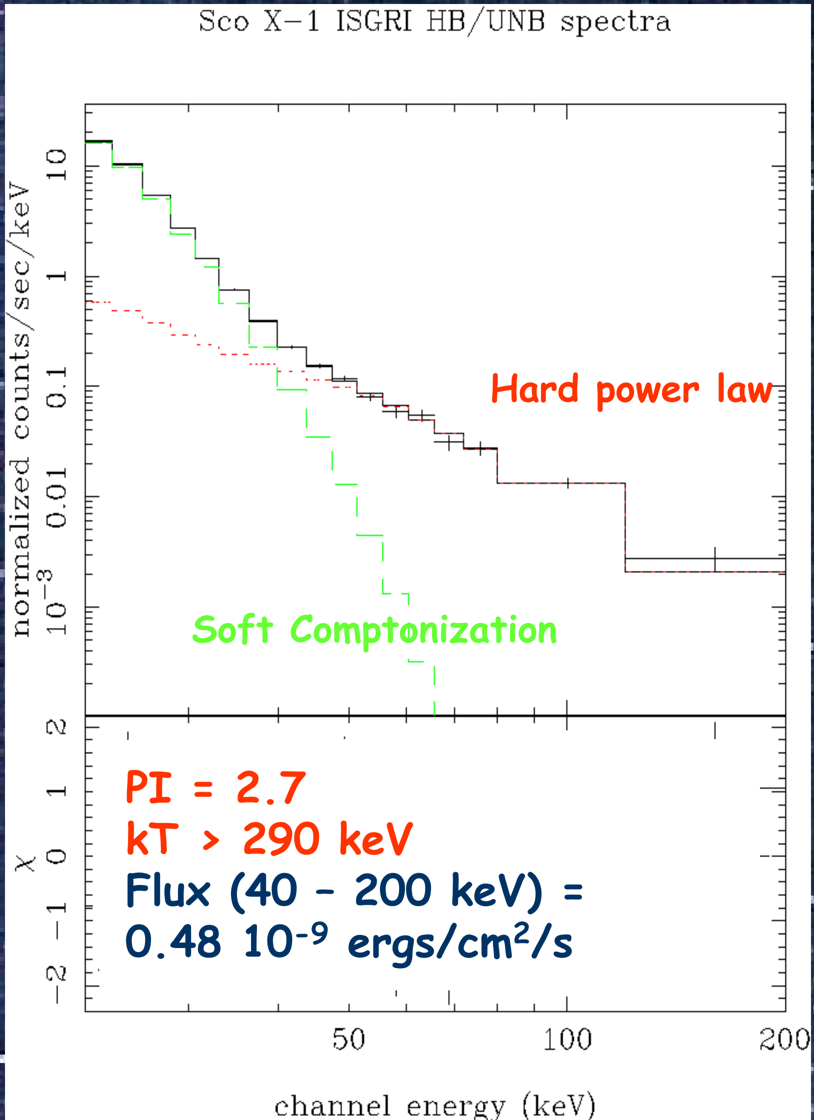
Hard Power law:
PI = 2.3
kT > 200 keV

Flux (20 – 40 keV) = 5.9 10^{-9} ergs/cm^2/s
Flux (40 – 200 keV) = 0.33 10^{-9} ergs/cm^2/s

Di Salvo et al. (2005, ApJL)

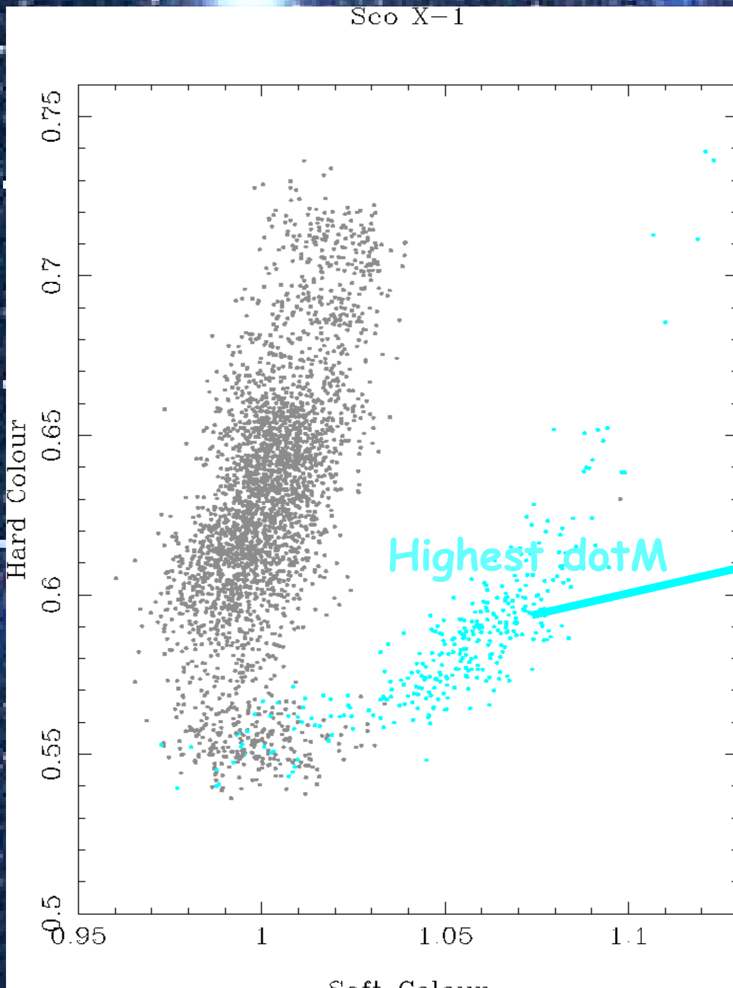
INTEGRAL/RXTE Observations of Sco X-1

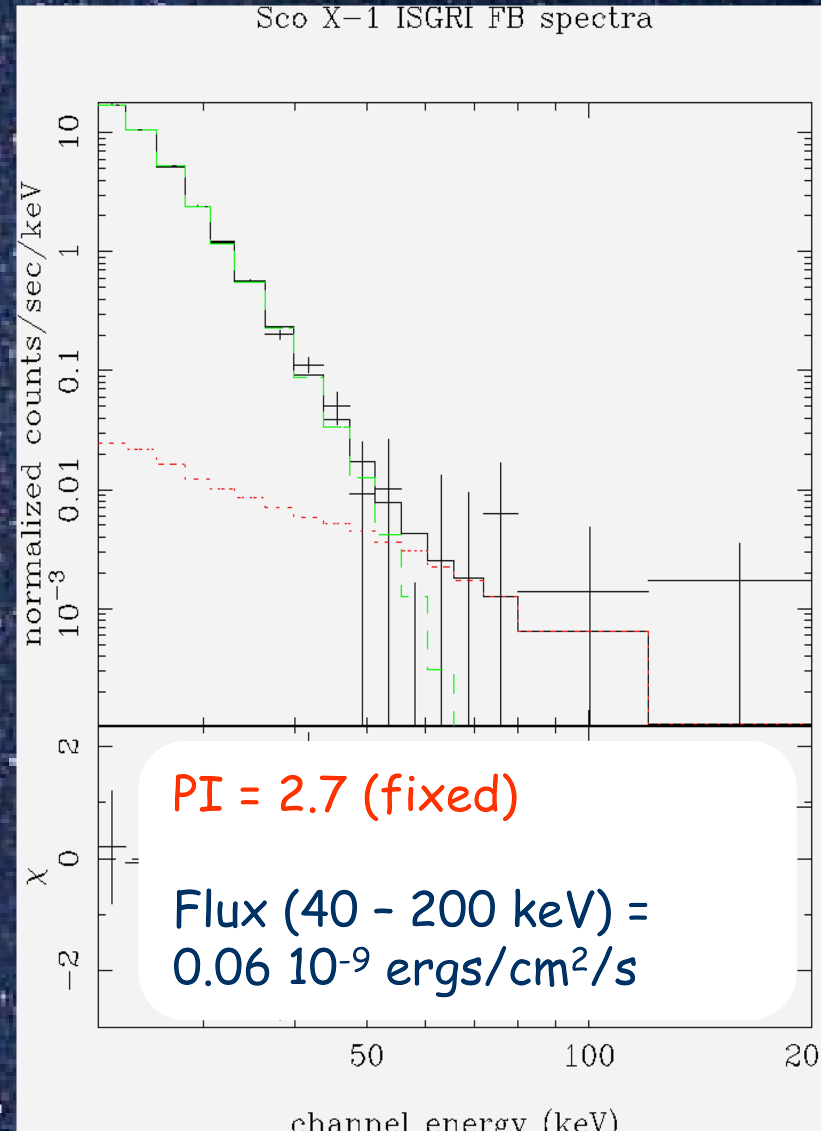




Di Salvo et al. (2005, ApJL)

INTEGRAL/RXTE Observations of Sco X-1

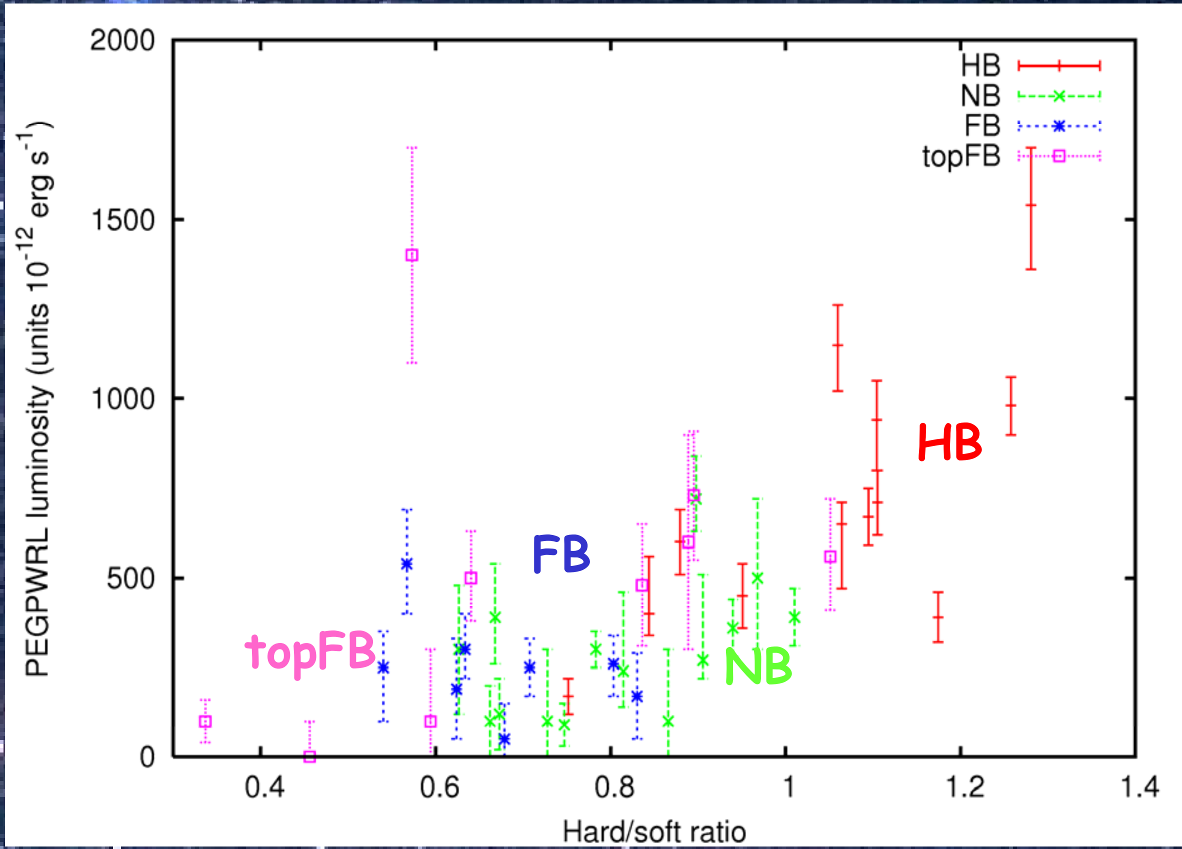




Di Salvo et al. (2005, ApJL)

Spectral Evolution of Sco X-1 with RXTE

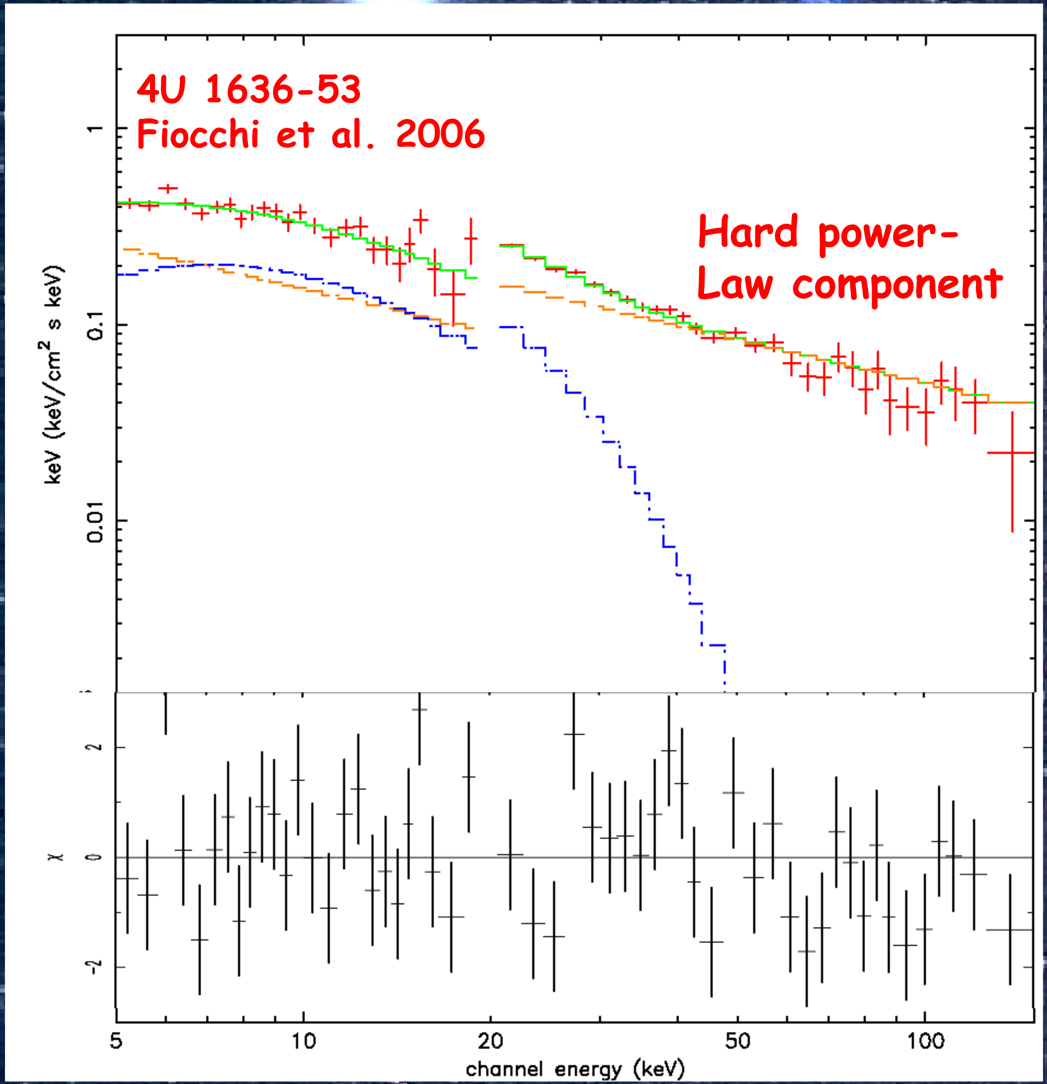
- Extensive analysis of RXTE data in the 3-200 keV energy range, over a period of 6 years.
- High-energy excess fitted with a power law or hybrid Comptonization model (EQPAIR).
- The presence and the intensity of the hard tail is correlated to the ratio of hard (Comptonized)/ soft (Disk) components, which is strongly correlated to the position on the CD.
- Hybrid Comptonization model gives good fit results. Non-thermal fraction up to 45 % of total heating fraction.



→ D'Aì, Di Salvo, Zycki et al., 2007, ApJ, 667, 411

Five Years of INTEGRAL
Chia, 18 Oct 2007

Hard tail detections in atoll sources



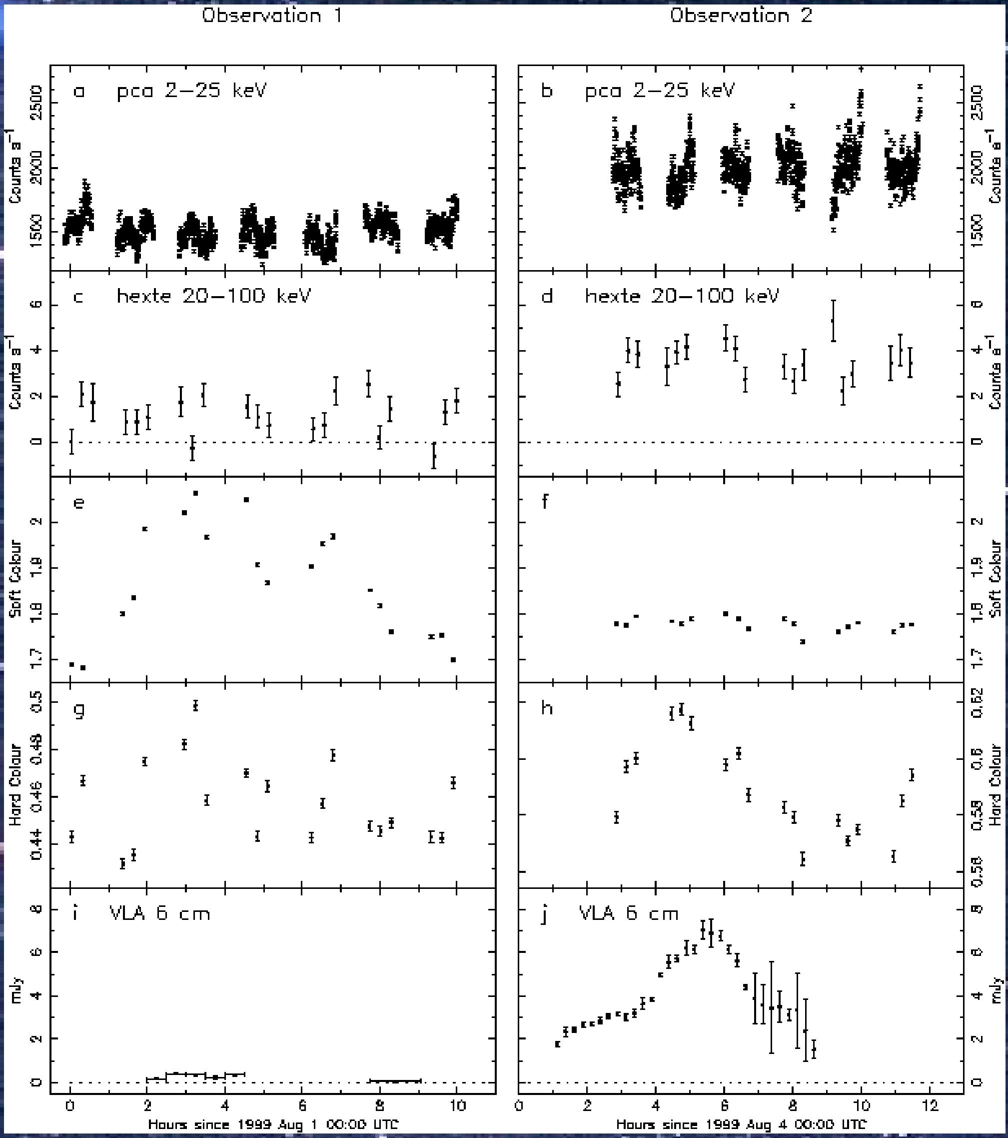
INTEGRAL spectrum of the bright atoll source 4U 1636-53 (Fiocchi et al. 2006).

See also Paizis et al. (2006) for the hard tail in the INTEGRAL spectrum of the bright atoll GX 13+1 and Tarana et al. (2007) for the hard tail in the INTEGRAL spectrum of the atoll source 4U 1820-30.

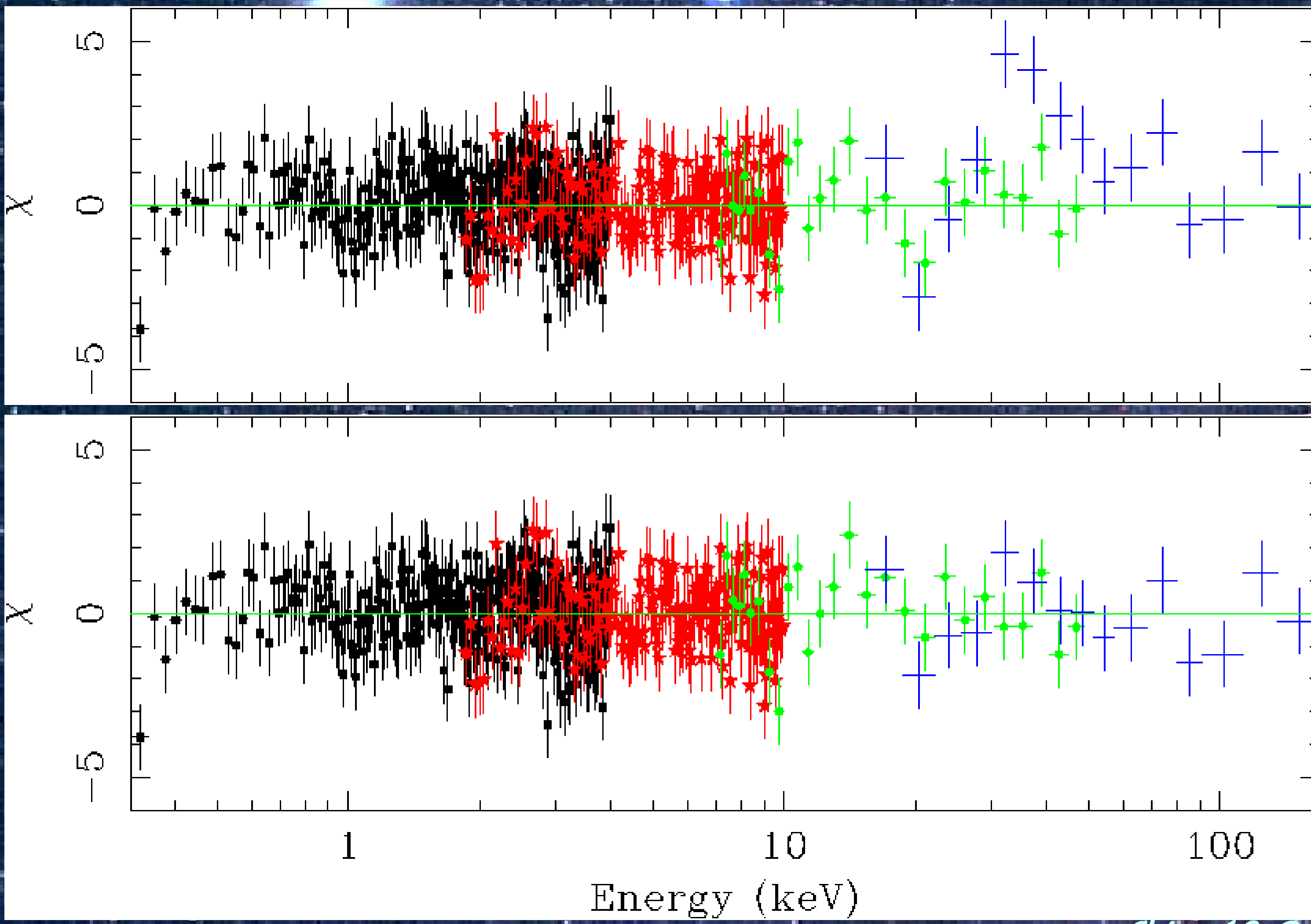
Simultaneous X-ray and radio observations of GX 13+1

RXTE/VLA observations of the bright atoll GX13+1. When the count rate is the highest in the hard (20-100 keV) range the radio flux is the highest, suggesting a strong correlation between the hard X-ray component and the radio flux.

(From Homan et al. 2004)



Hard X-ray emission in the soft state of the atoll source 4U 1705-44

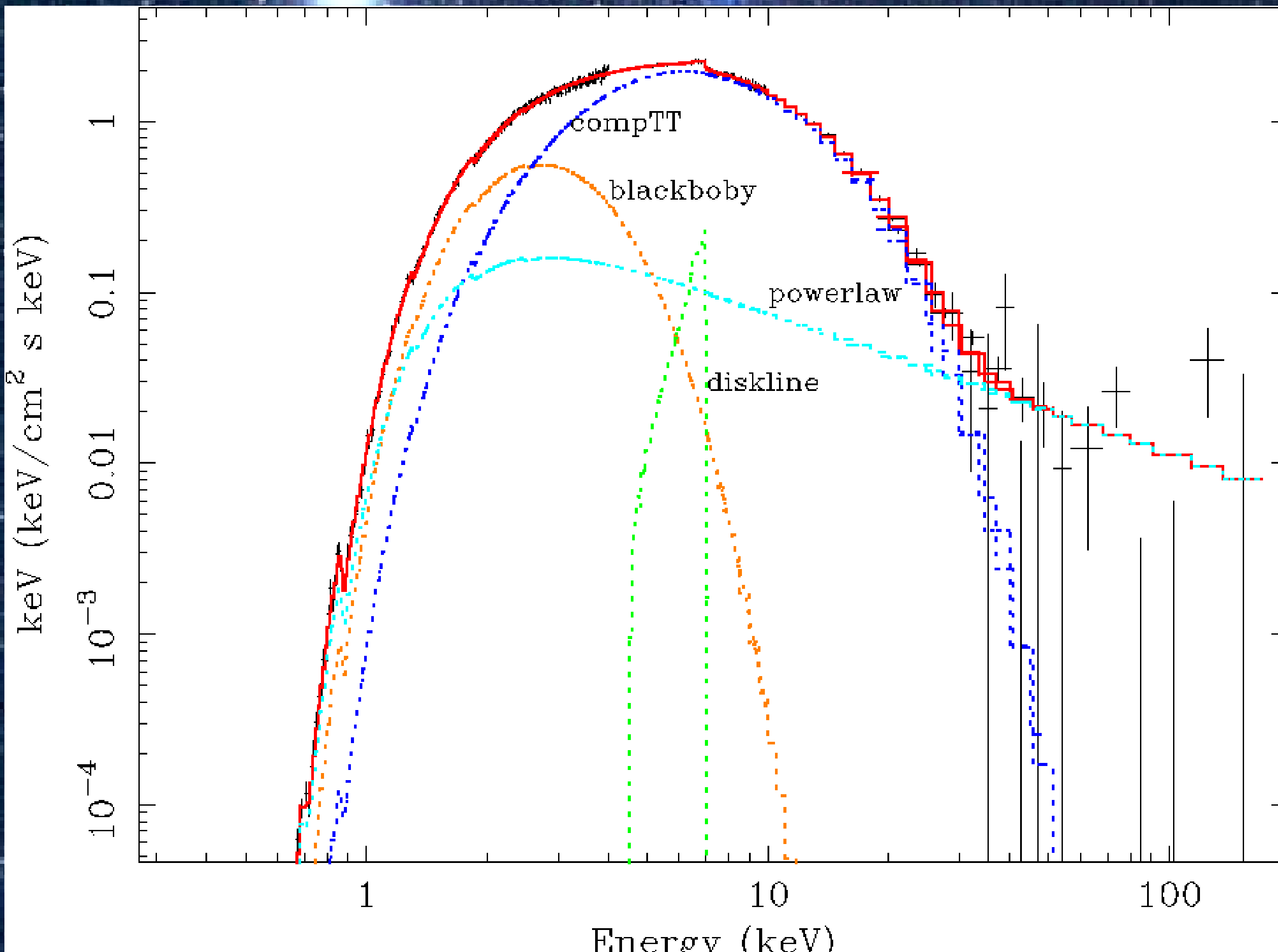


Broad band residuals without the hard power-law component

Broad band residuals with the hard power-law component (P.I. = 2.9)

(From Piraino et al. 2007)

BeppoSAX Observation of 4U1705-44 during a soft state



A BeppoSAX observation confirms the results from Chandra and discovers a hard (power-law) X-ray emission during a soft state

(From Piraino et al. 2007, A&A)

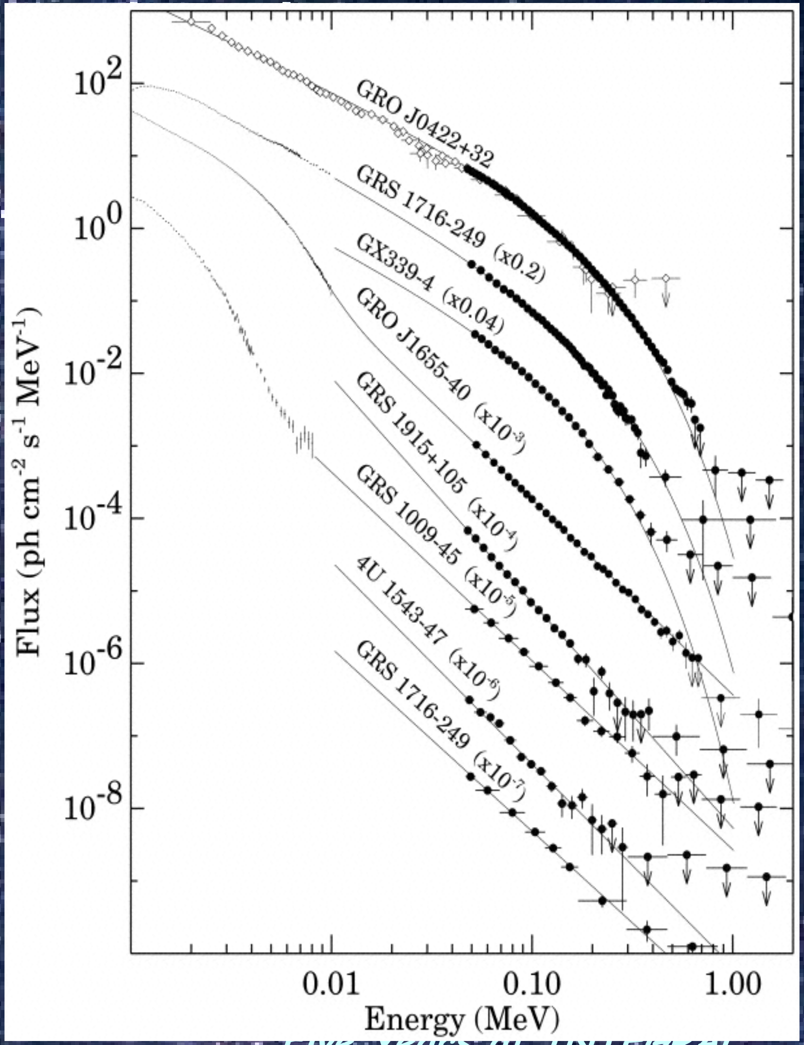
NS hard tails: analogy with BHCs

(Grove et al. 1998)

- BHCs in low state: extended power law with high energy cutoff (plus faint very soft and reflection components seen occasionally)
  Similar to hard state Atolls

- BHCs in IS/VHS: very soft thermal component plus power law without high energy cutoff up to 1 MeV
  Similar to Z-sources in HB-NB, and some soft states of atolls

- BHCs in HS: very soft thermal component.
  Similar to Z-sources in NB-FB, and some soft states of atolls?



Hard X-ray NS/BHC indicators are uncertain at least !

Geometry and Models for hard tails in NS binaries

If we assume the simplest hypothesis of a common origin of the hard X-ray component in soft states of BHC and NS LMXBs:

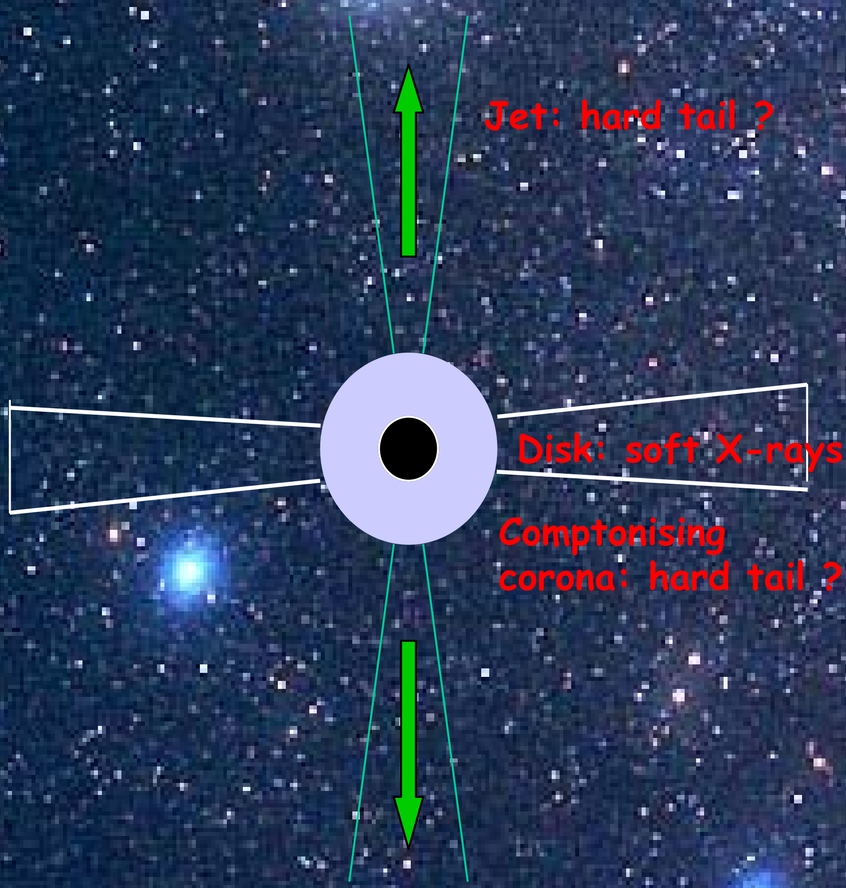
~~Thermal Comptonization~~ → Predicts high energy cutoffs or very high inferred temperatures, not compatible with expected Compton cooling

Non-thermal Comptonization from a radial converging → It does not explain the presence of the hard X-ray component in bright NS LMXBs

Comptonization on (relativistic) electrons with a non-thermal distribution of velocities →

- Power-law resulting spectra with no necessity of a high-energy cutoff;
- Possible for both BHC and NS;
- May explain the observed correlation with radio

Geometry and Models for hard tails in NS binaries



- Bulk motion Comptonisation converging radial or disk inflow
  (Titarchuk et al. 1996, 1997; Psaltis 2001; Farinelli et al. 2007)
  Inflow in Z-sources is strongly affected by radiation from the NS

- Comptonisation by non-thermal e- in a (non-confined) corona or injected in the corona by relativistic jets
  (Poutanen & Coppi 1998; Zdziarski 2000; Vadawale et al. 2001; Di Salvo et al. 2000)
  Power law spectra can extend up to very high energies, and natural correlation with radio emission

The radio connection: other NS binaries

- Radio jets: likely a common phenomenon also in X-ray binaries

Class	Fraction as radio sources
Persistent BHCs	4/4
Transient BHCs	~15/35
NS Z-sources	6/6
NS Atoll sources	~5/100

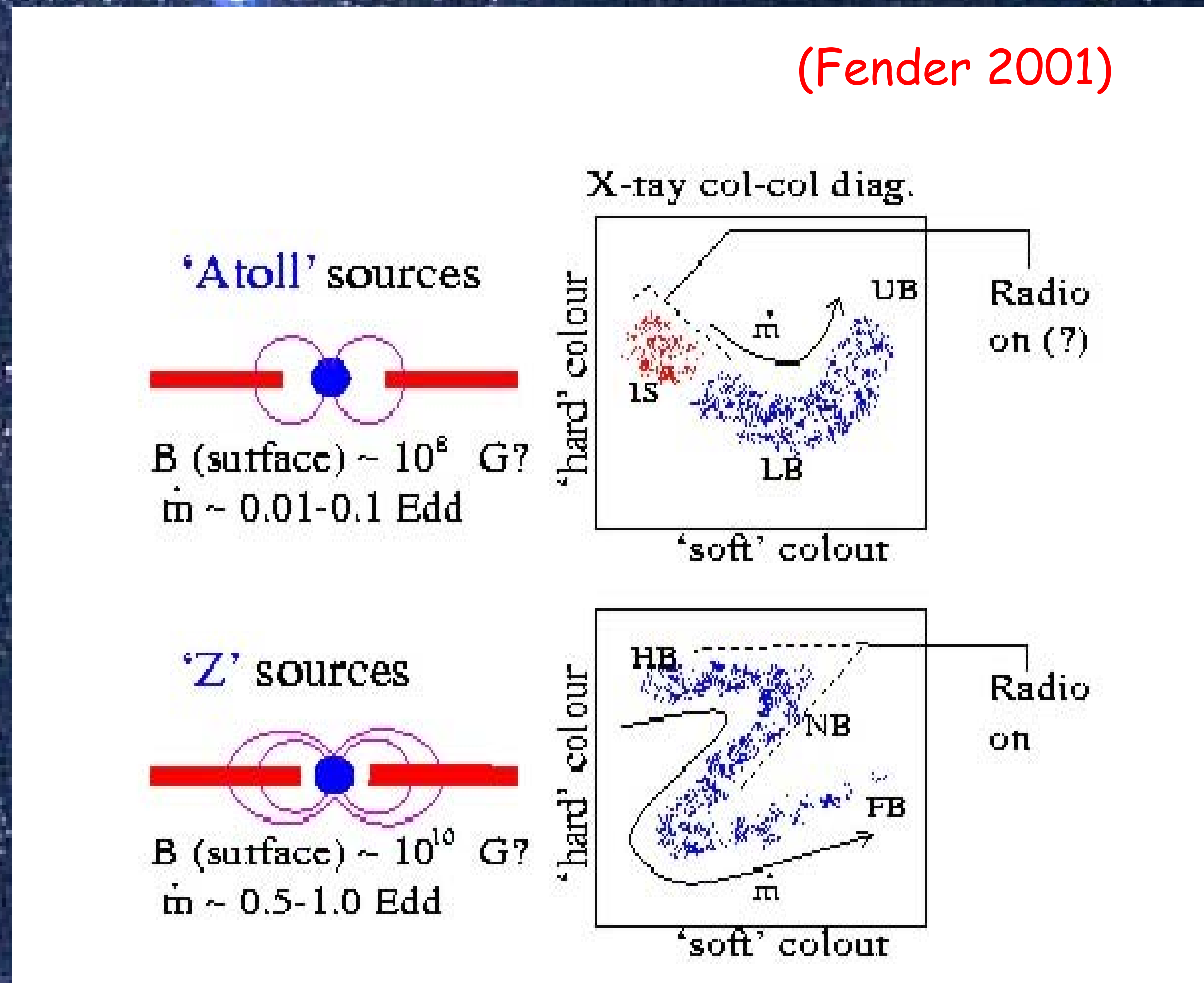
(Fender 2001)

In NS LMXBs:
- At lower accretion rates (e.g. HB, NB), optically thick, compact (often unresolved on arcsec scales), continuously replenished jet (similar to the ones usually observed in BHCs and AGNs)
- At high accretion rates (or state transitions), transient optically thin (arcsec-scale) plasmons moving away from the binary core at ultra-relativistic velocities.

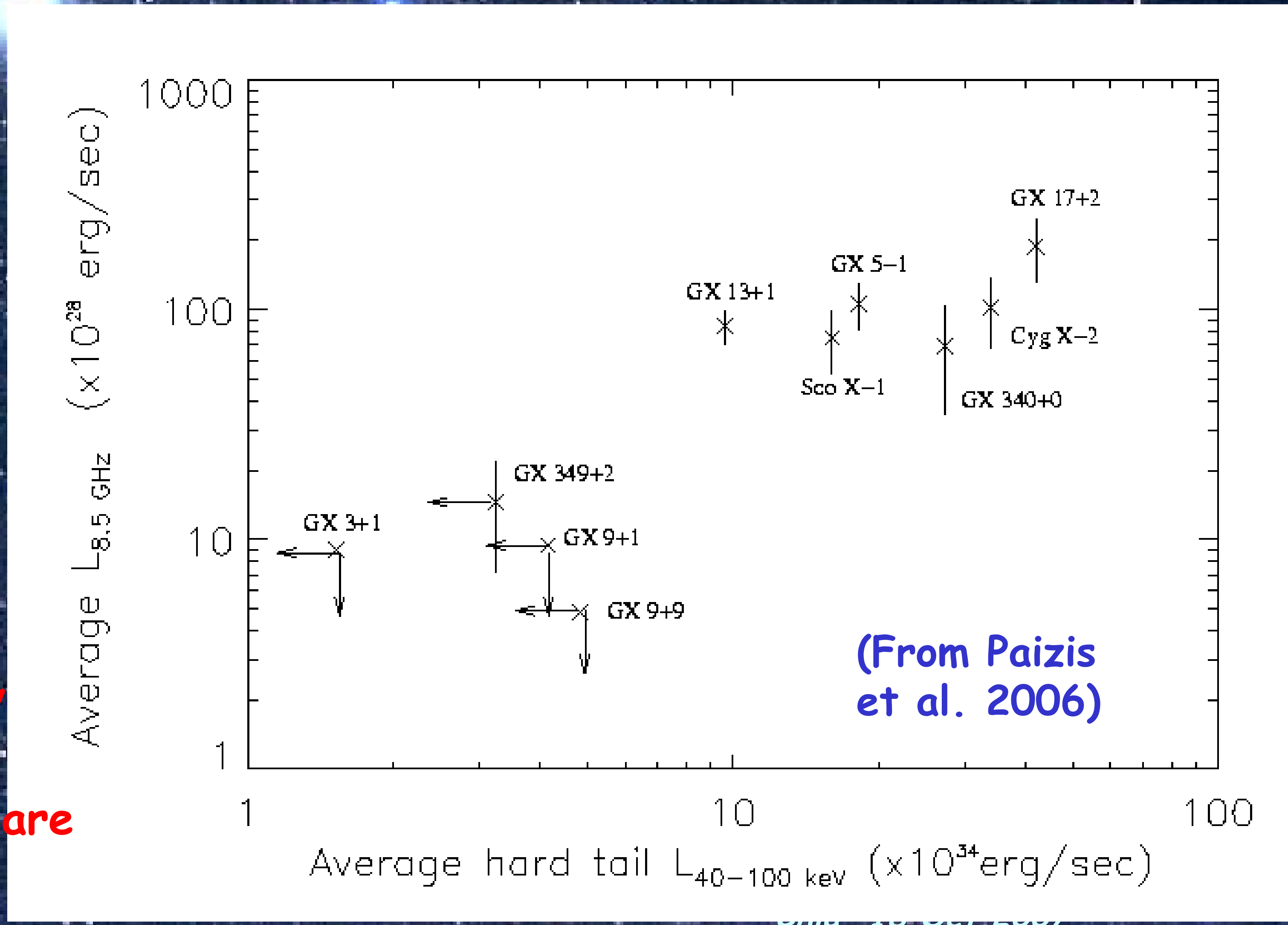
The radio jets and states of NS X-ray binaries

- Radio emission (probably due to jets) is anti-correlated with the mass accretion rate

-Similarity with the hard X-ray tails!

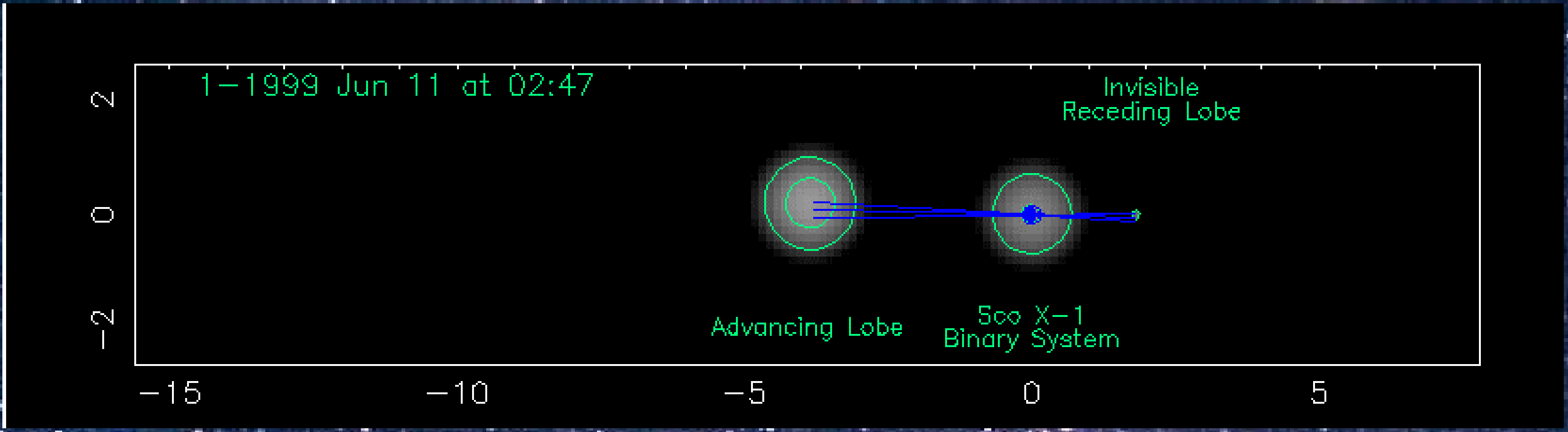


Again a strong correlation between the radio and the hard X-ray flux



More simultaneous hard X-ray / radio observations are needed

Radio-Image Movie of Sco X-1

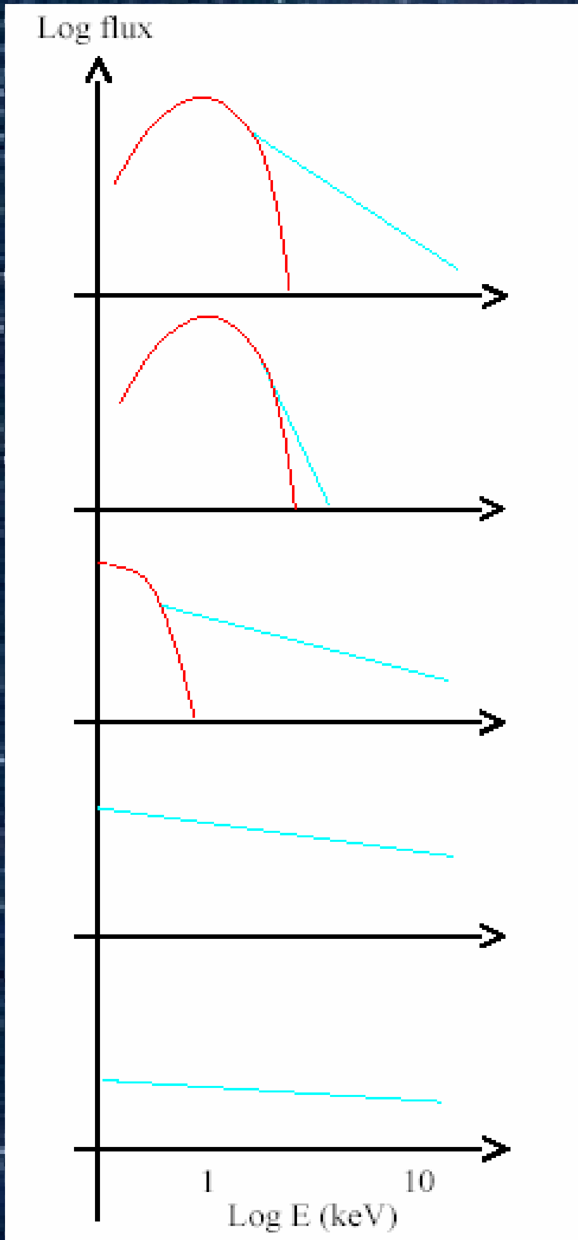


This movie (made using data from several radio telescopes) covers a period of 56 hours during June of 1999. Numbers in the axes are distances in bilions of miles. The zero point is the location of the binary system.
(From www.nrao.edu. Credits to E.B. Fomalont & C.F. Bradshaw, NRAO/AUI/NSF).

The end

Thank you very much!

Spectra of transient BHXBs



Very high States

Soft/high States

Intermediate States

Low/hard States

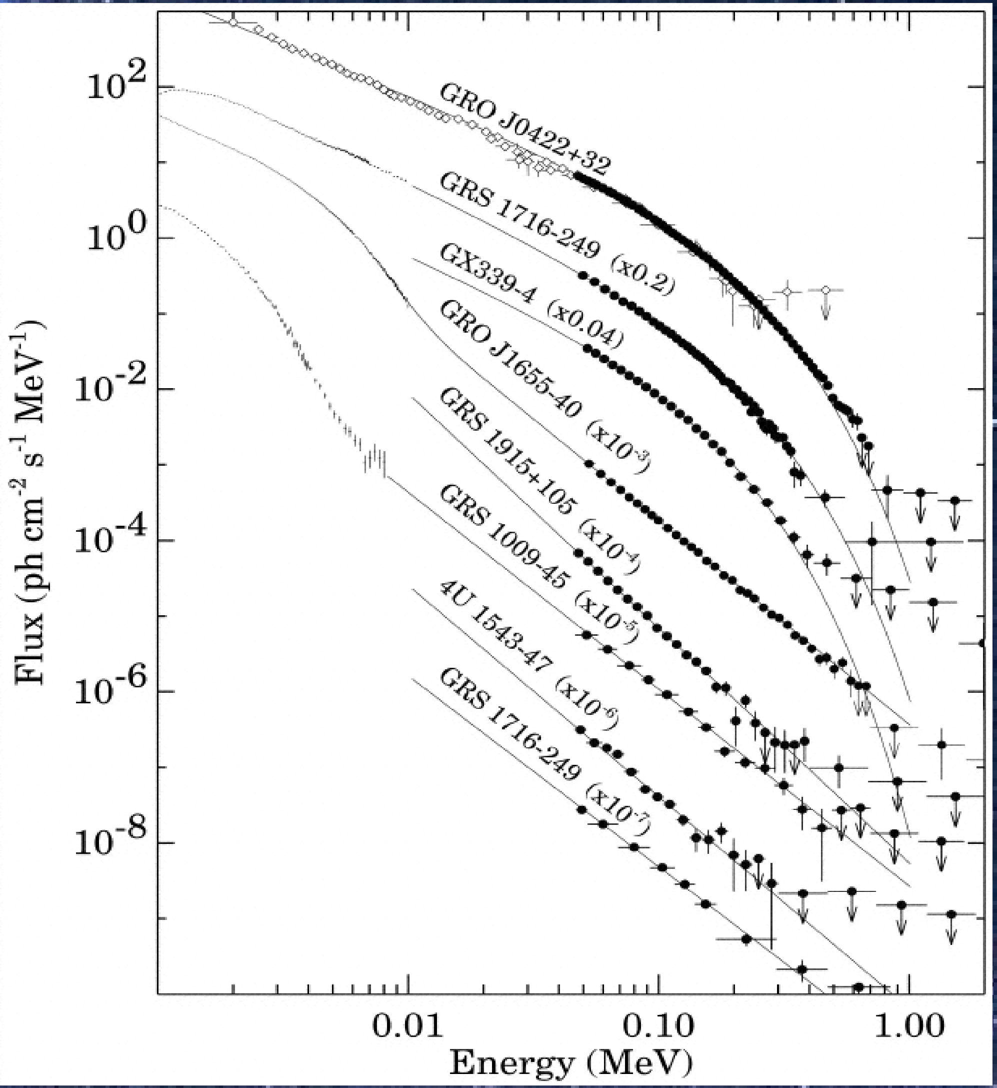
Quiescent States

Broad Band Spectra of BHXBs

No high energy cutoff is present up to 1 MeV.

Titarchuk & Zannias 1998, Luarent & Titarchuk 1999 proposed that the hard emission might be caused by a converging relativistic flow towards the event horizon of the BH.
Since in bright NS the converging flow should be stopped by the pressure of the radiation emitted from the NS surface this component was proposed to be a **signature of the presence of an event horizon in the system.**

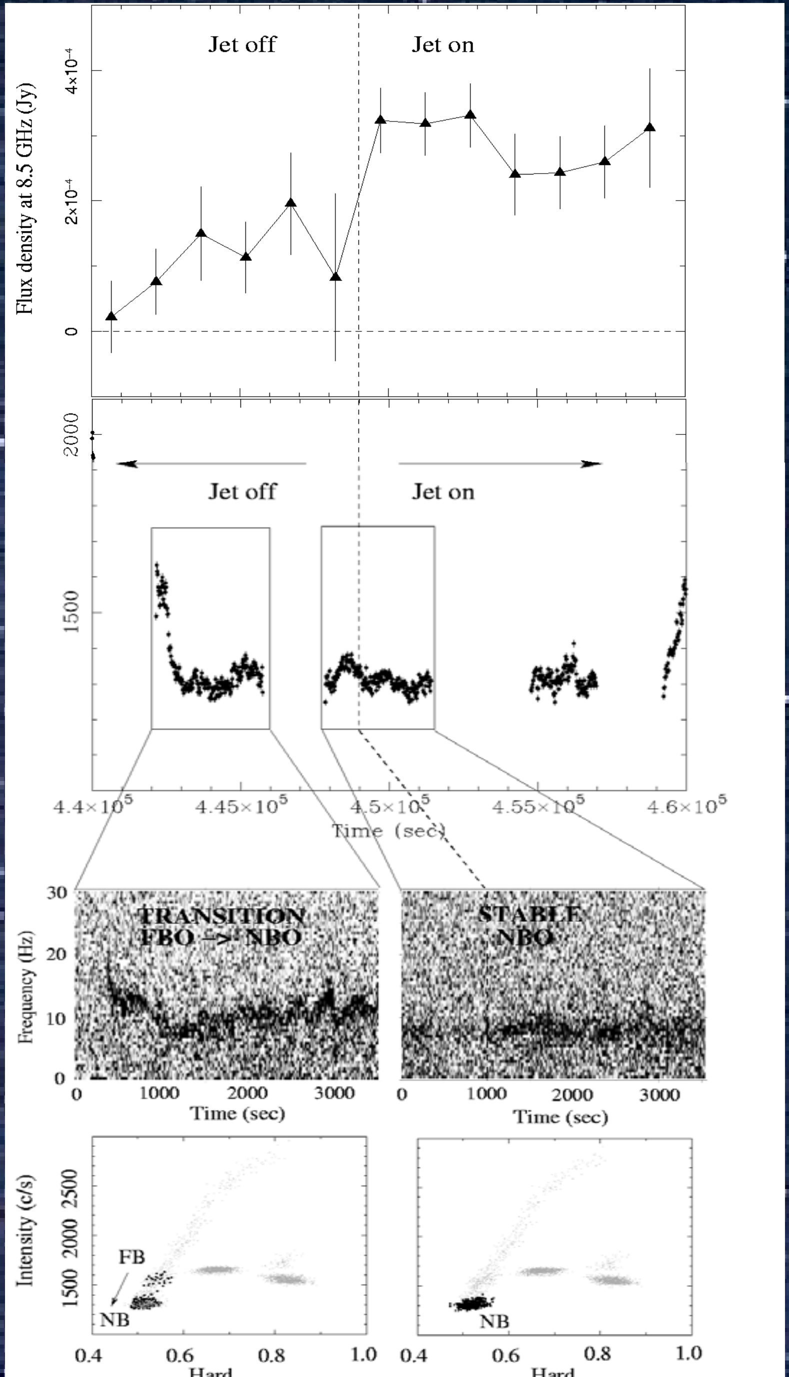
(Grove et al. 1998)



Simultaneous radio-hard X-ray observations of GX 17+2 with RXTE and VLA

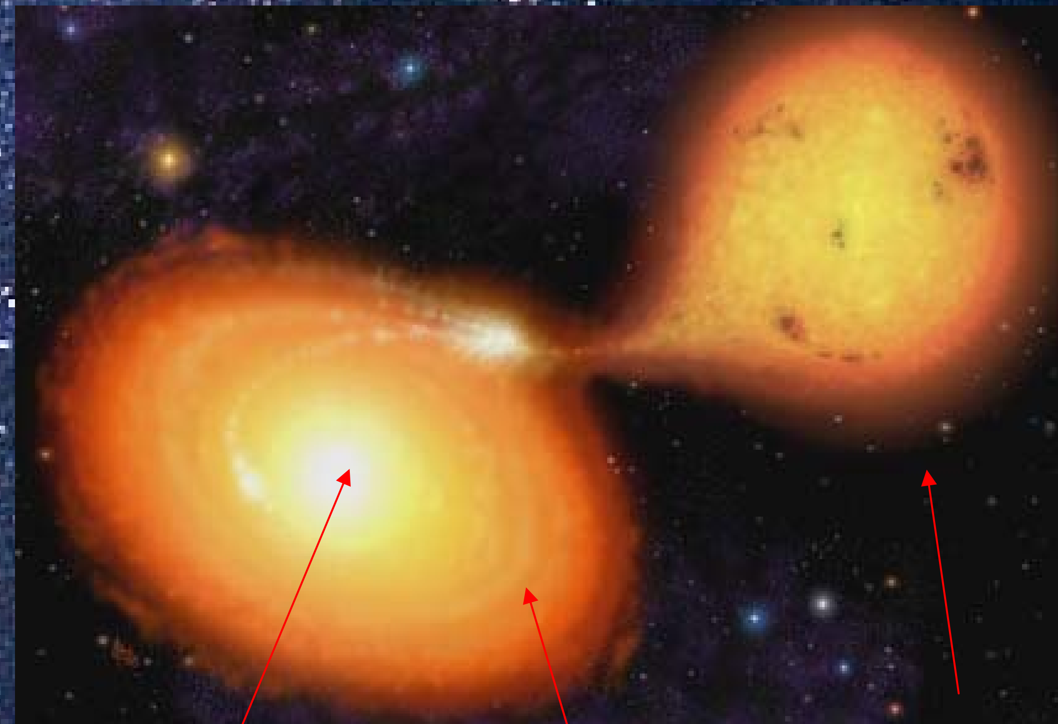
Two RXTE orbits showing a FB to NB X-ray transition (see lower panel) contemporaneous to the formation of a compact jet (see the upper panel)

(Migliari et al. 2007)



Low Mass X-ray Binaries

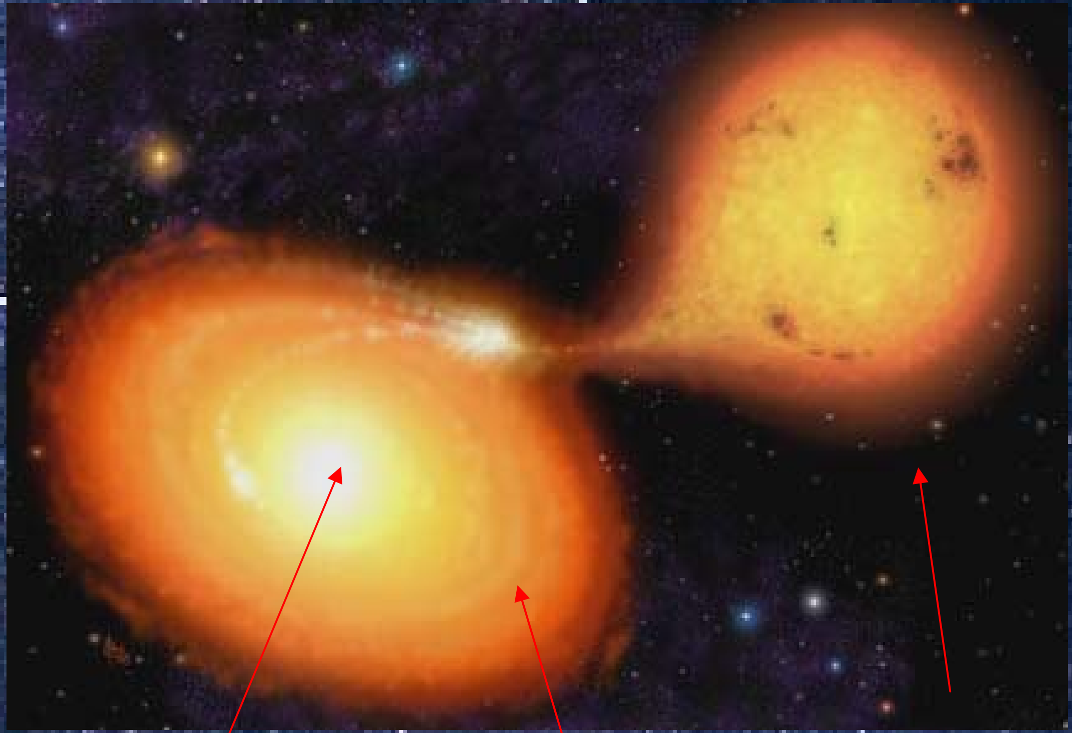
Close X-ray binaries:



Low Mass X-ray Binaries

Close X-ray binaries:

- Rich time variability, such as twin QPOs at kHz frequencies (from 400 to 1300 Hz, increasing with increasing mass accretion rate); kHz QPOs are thought to reflect Keplerian frequencies at the inner accretion disk.

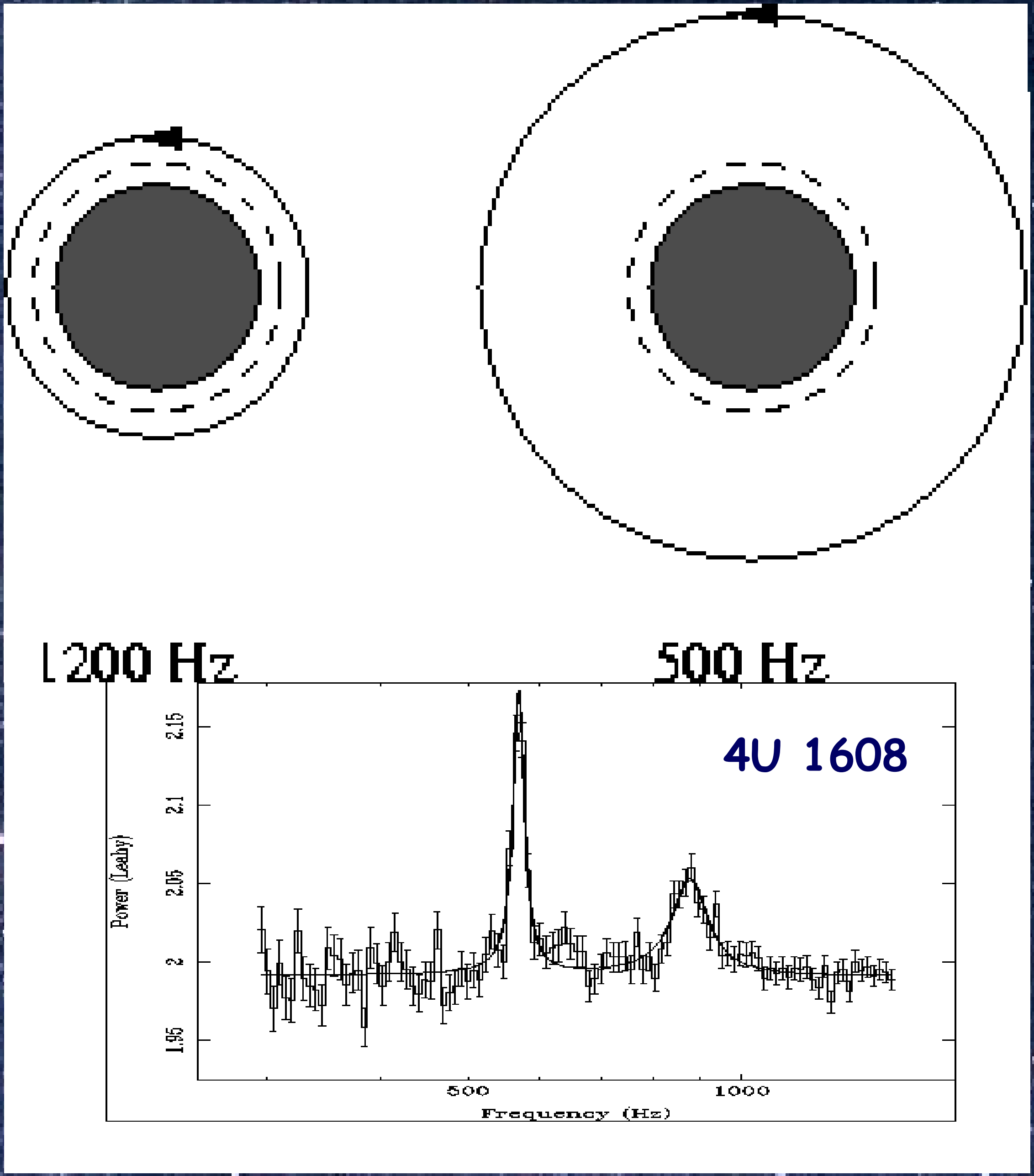


kHz QPOs

Two peaks are usually present, whose frequency increses when the mass accretion rate increases, with almost constant separation.

Possibly related to Keplerian frequencies at the inner edge of the disk.

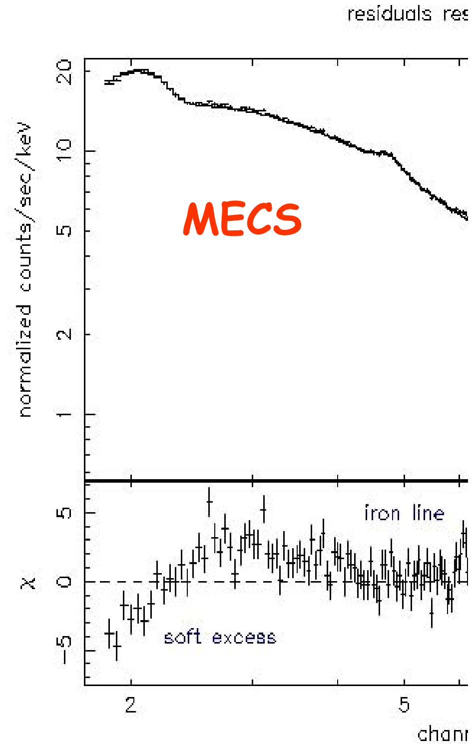
The peak separation is usually close to the NS spin frequency (if known from pulsations or burst oscillations) or half this value.



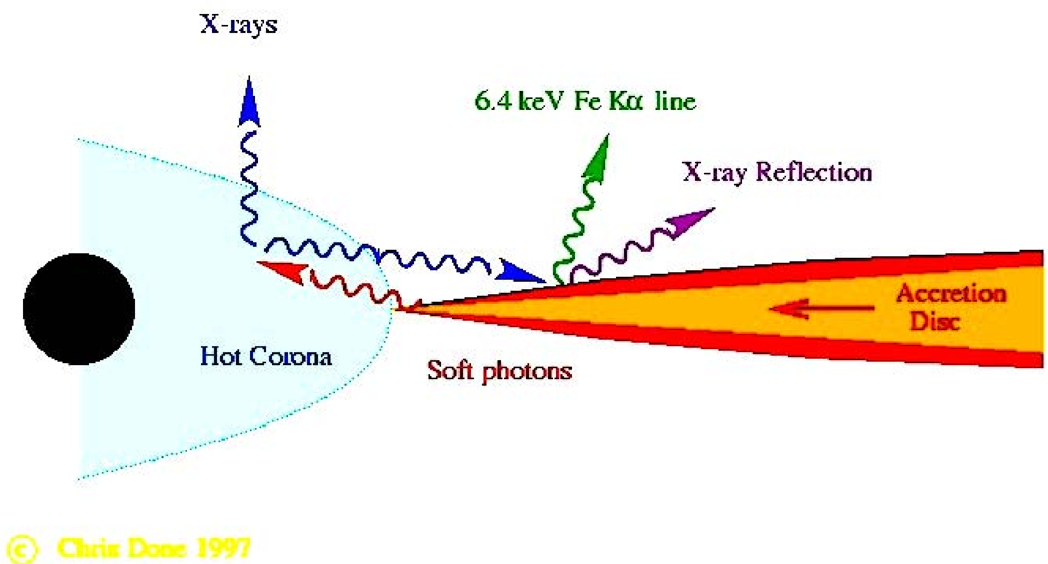
Fe K-shell Line and Reflection

Cygnus X-1: BeppoSAX Broad Band (0.1 - 200 keV) Spectrum during a hard/low state

Di Salvo et al. (2001)



Schetch of the Emission Region

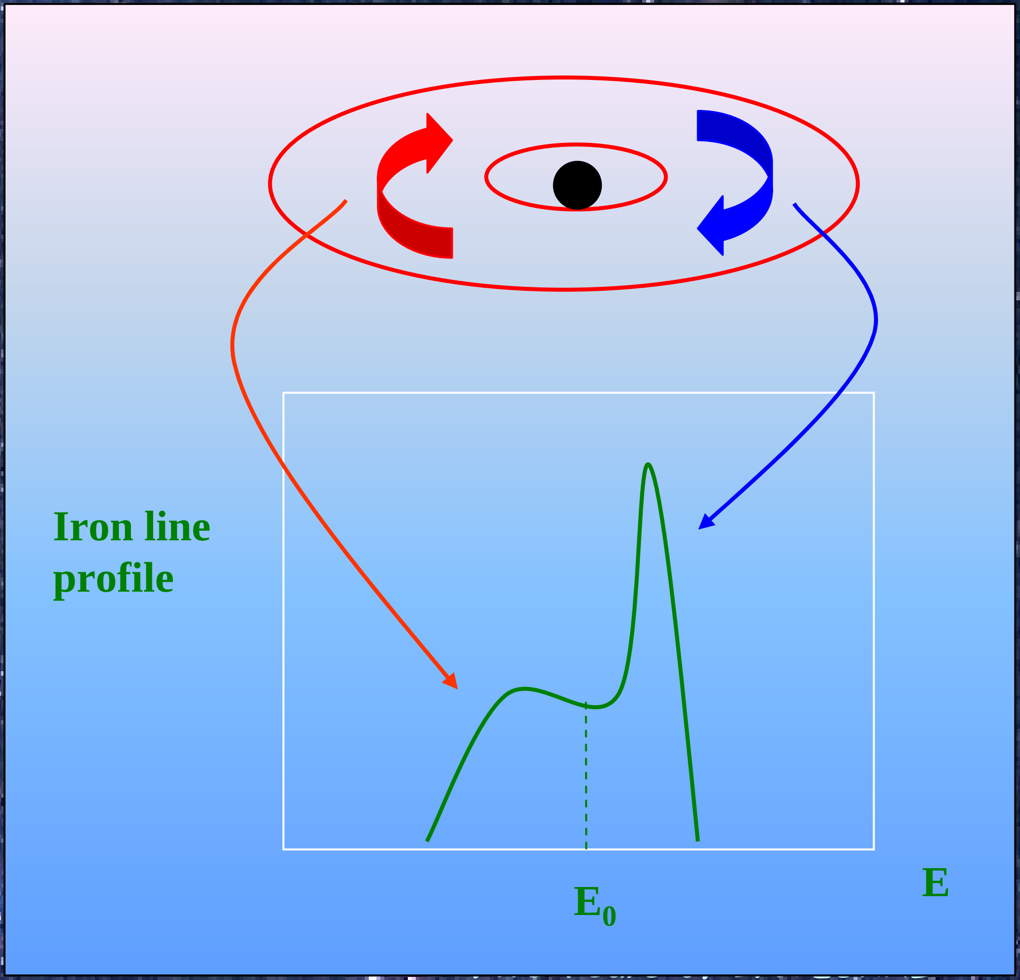


Fe K-shell Line and Reflection

Important information can be obtained from the iron line profile.

Doppler and relativistic effects due to the keplerian motion in the disk modify the profile (light bending, Doppler shifts, Doppler boosting, Gravitational redshift).

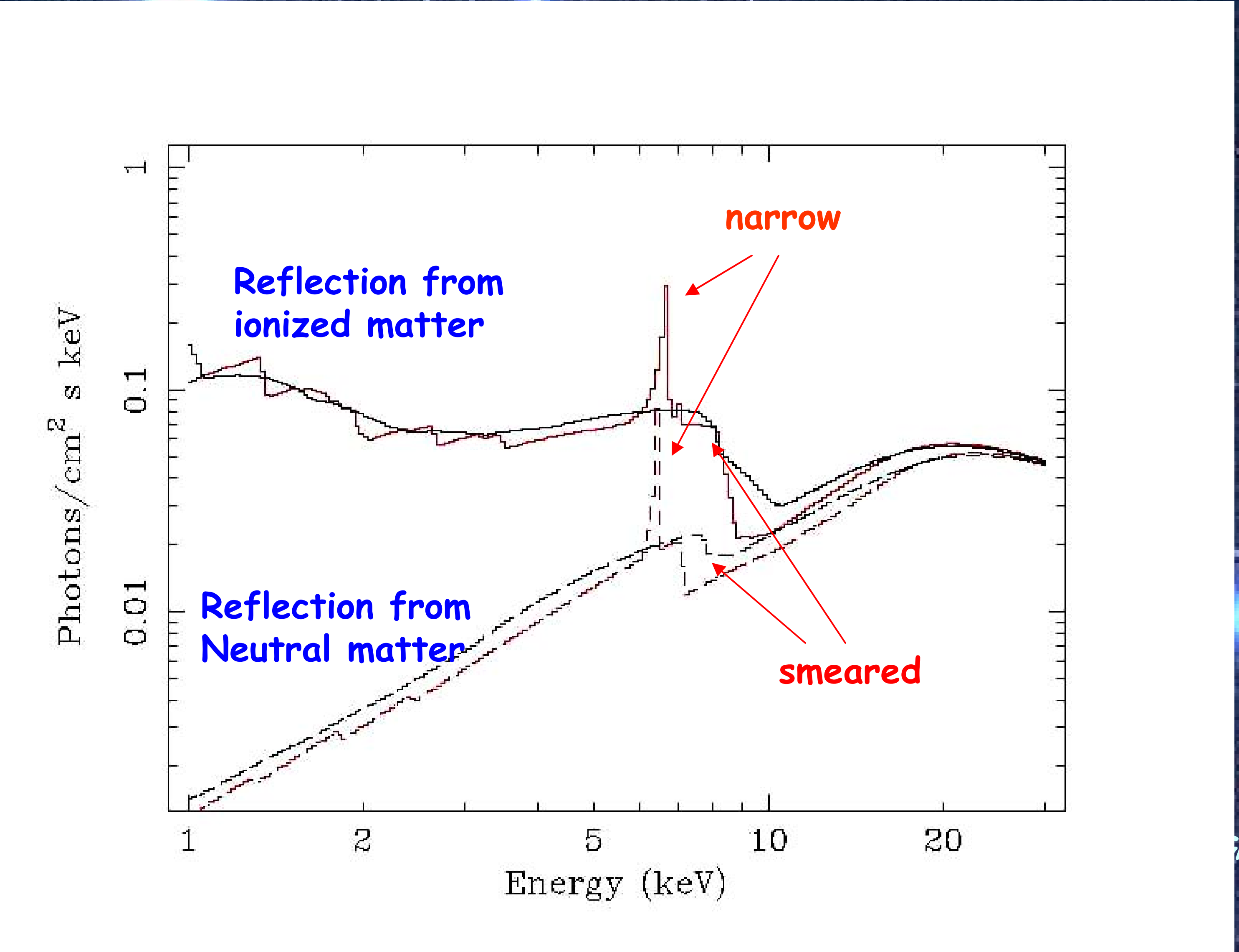
From high resolution spectra we can obtain info on the inner disk radius and inclination of the disk.



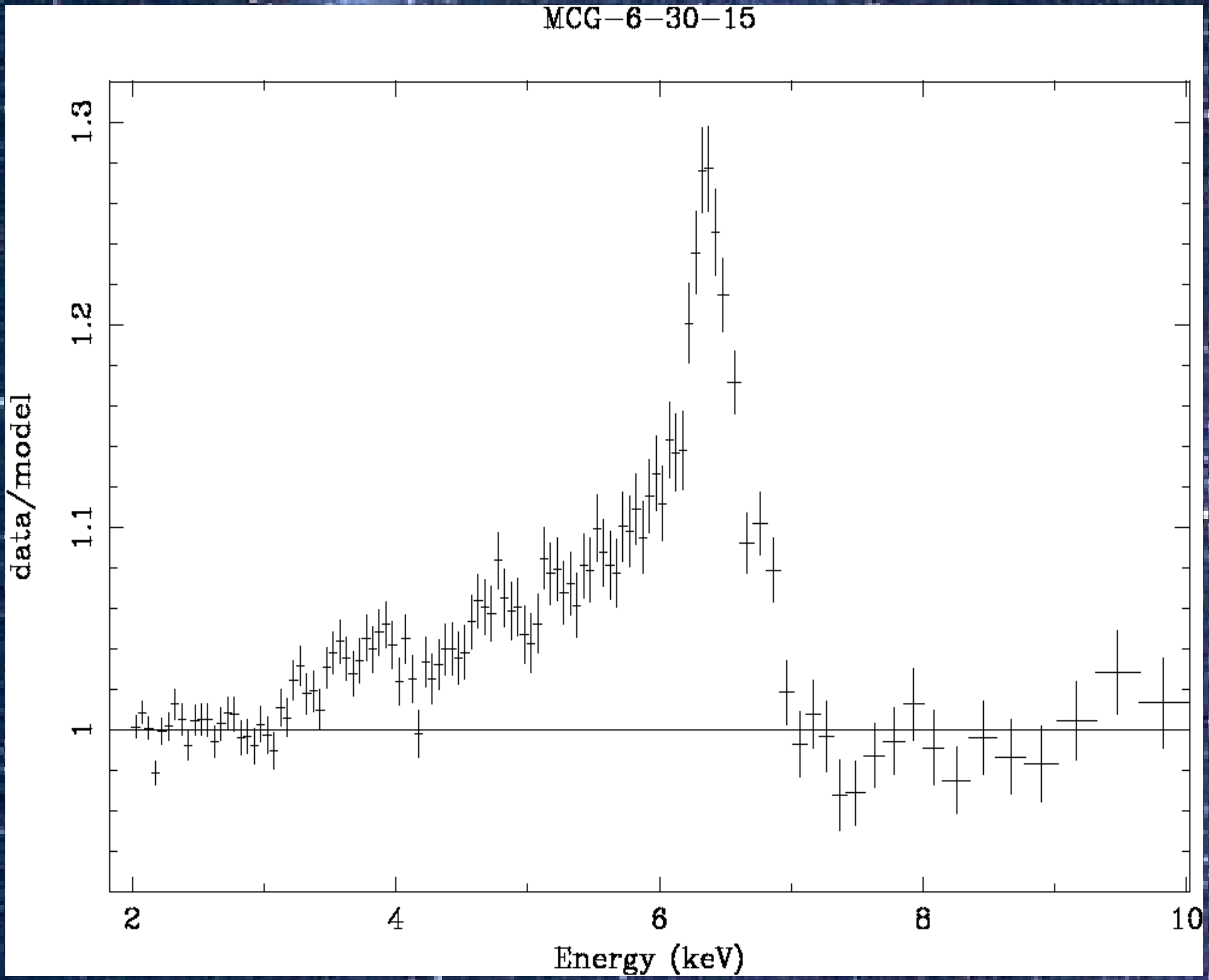
Spectra of BHXBs: Compton Reflection Component

- The reflection component is given by the hard Comptonized component that is (direct) Compton scattered by the accretion disk.
  - For energies of the incident photons less than 10 keV: photoabsorption is dominant → emission lines and absorption edges (the strongest in the Fe 6.4 – 7 keV energy range).
  - For energies of the incident photons higher than 10 keV: Compton “reflection” is dominating → large “bump” between 10 e 50 KeV.

Self consistent models of Compton reflection and associated iron line



High resolution spectroscopy of massive BHs: MCG-6-30-15



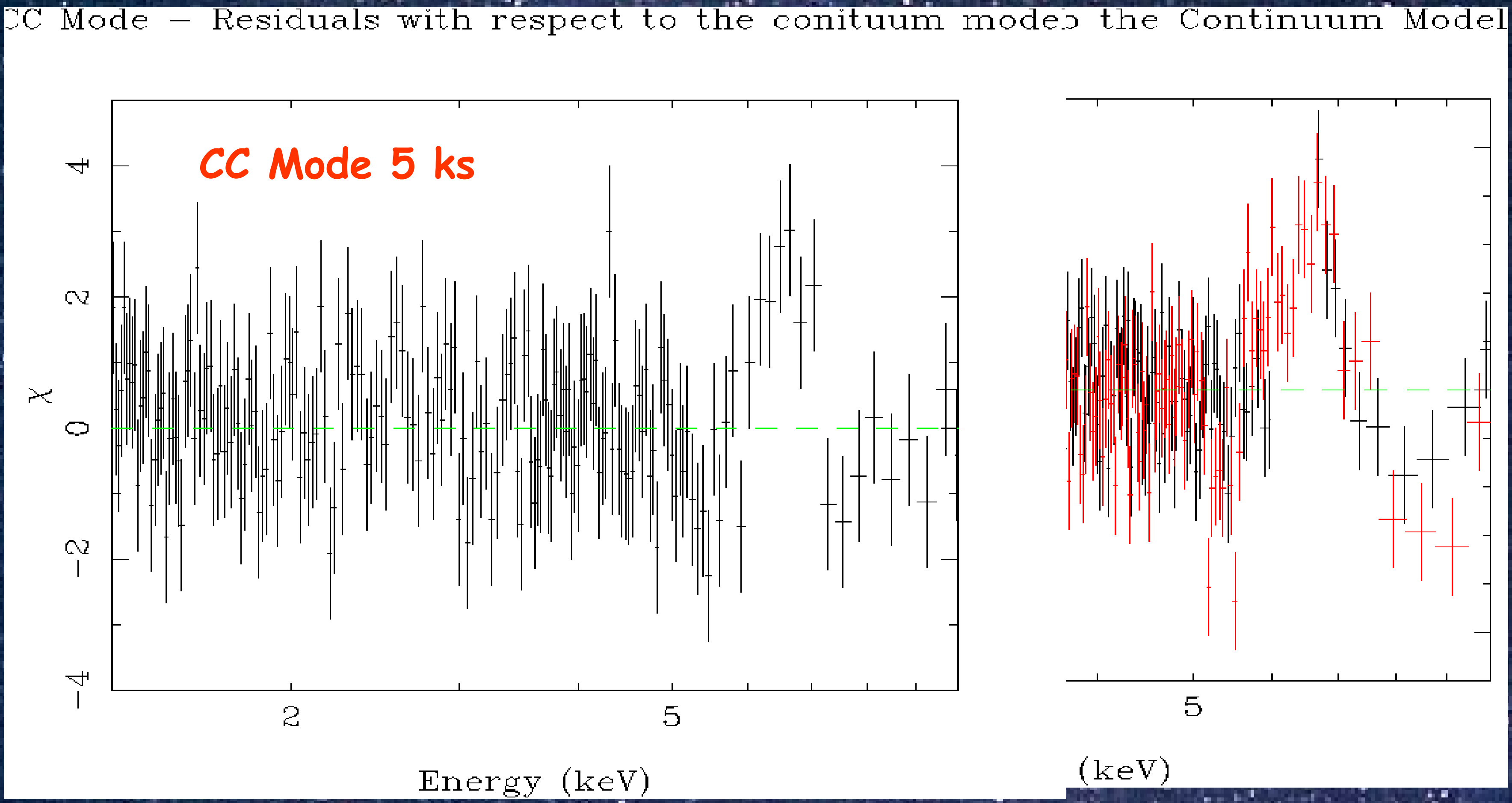
XMM observation of the iron line region in MCG-6-30-15 taken in 2001. The red wing extends to less than 4 keV, indicating an inner radius of less than 6 G M / C^2.

Spinning black hole? (a > 0.93)

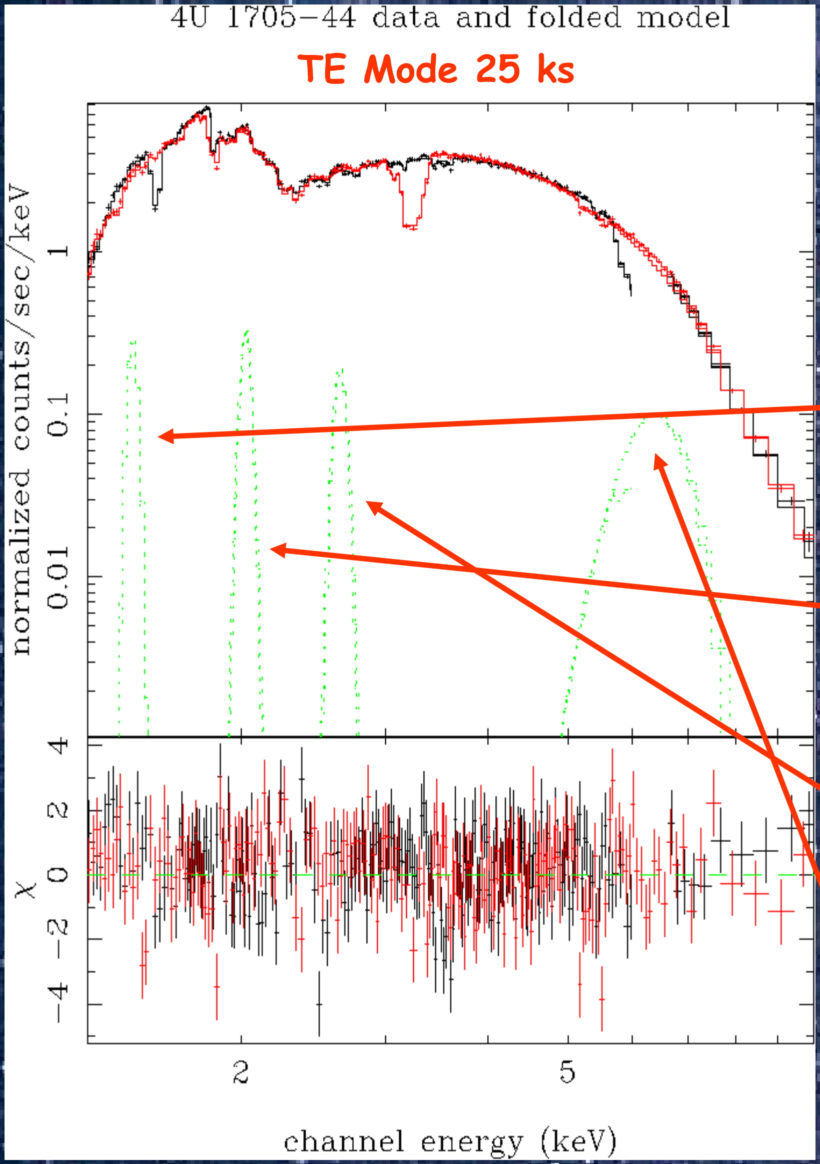
Fabian et al. 2002)

Fe K-shell Line in Neutron Star Low Mass X-ray binaries

Chandra observation of the LMXB/atoll source 4U 1705-44 during a high/soft state (Di Salvo et al. 2005, ApJ Letters)



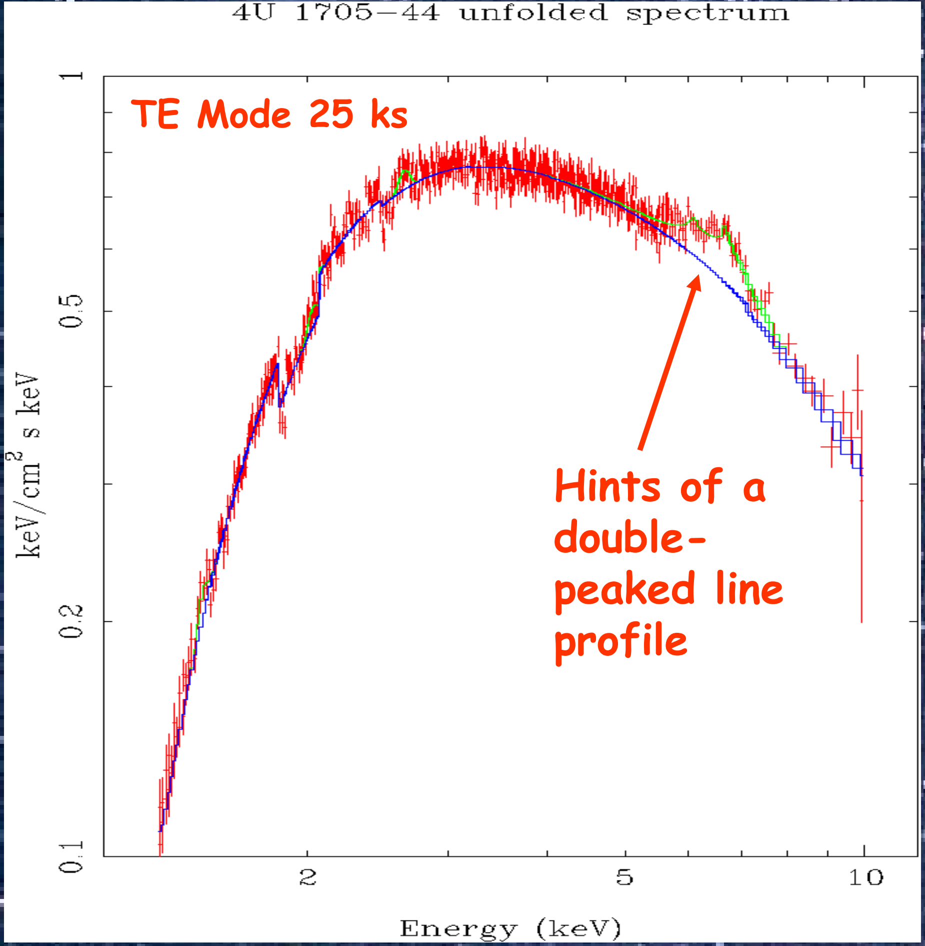
Fe K-shell Line in NS LMXBs



Soft Comptonization model for the X-ray continuum plus 3 narrow lines and a broad Fe line:

- E1 = 1.476 keV, σ1 = 17 eV (ID: Mg XII Ly-α, 1.473 keV)
- E2 = 2.03 keV, σ2 = 28 eV (ID: Si XIV Ly-α, 2.006 keV)
- E3 = 2.64 keV, σ3 = 40 eV (ID: S XVI Ly-α, 2.6223 keV)
- E_Fe = 6.54 keV, σFe = 0.51 keV EW = 170 eV

Fe K-shell Line in Neutron Star Low Mass X-ray binaries



Fitting the iron line profile with a disk (relativistic) line we find:

- E_{Fe} = 6.40 keV
- Rin = 7-11 Rg (15-23 km)
- Inclination = 55 – 84 deg

Alternatively, Compton broadening in the external parts of the Comptonizing corona (σ = 0.5 implies τ = 1.4 for kT = 2 keV)

Diskline Parameters in 4U 1705-44

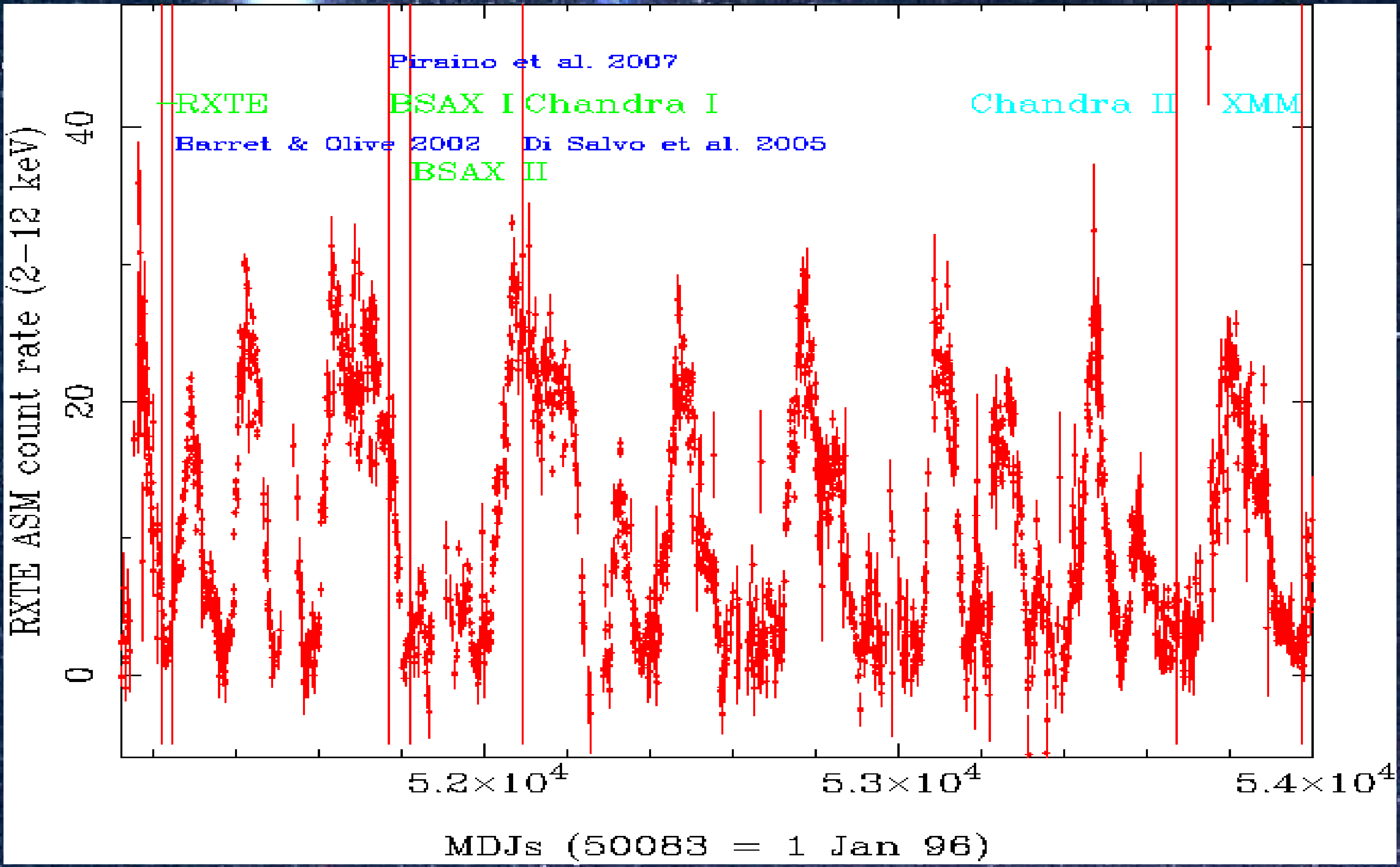
CHANDRA (Di Salvo et al. 2005)

- E_Fe = 6.40 +/- 0.04 keV
- Rin = 7-11 Rg (15-23 km)
- Inclination = 55 – 84 deg
- Fe Eq.W = 170 eV

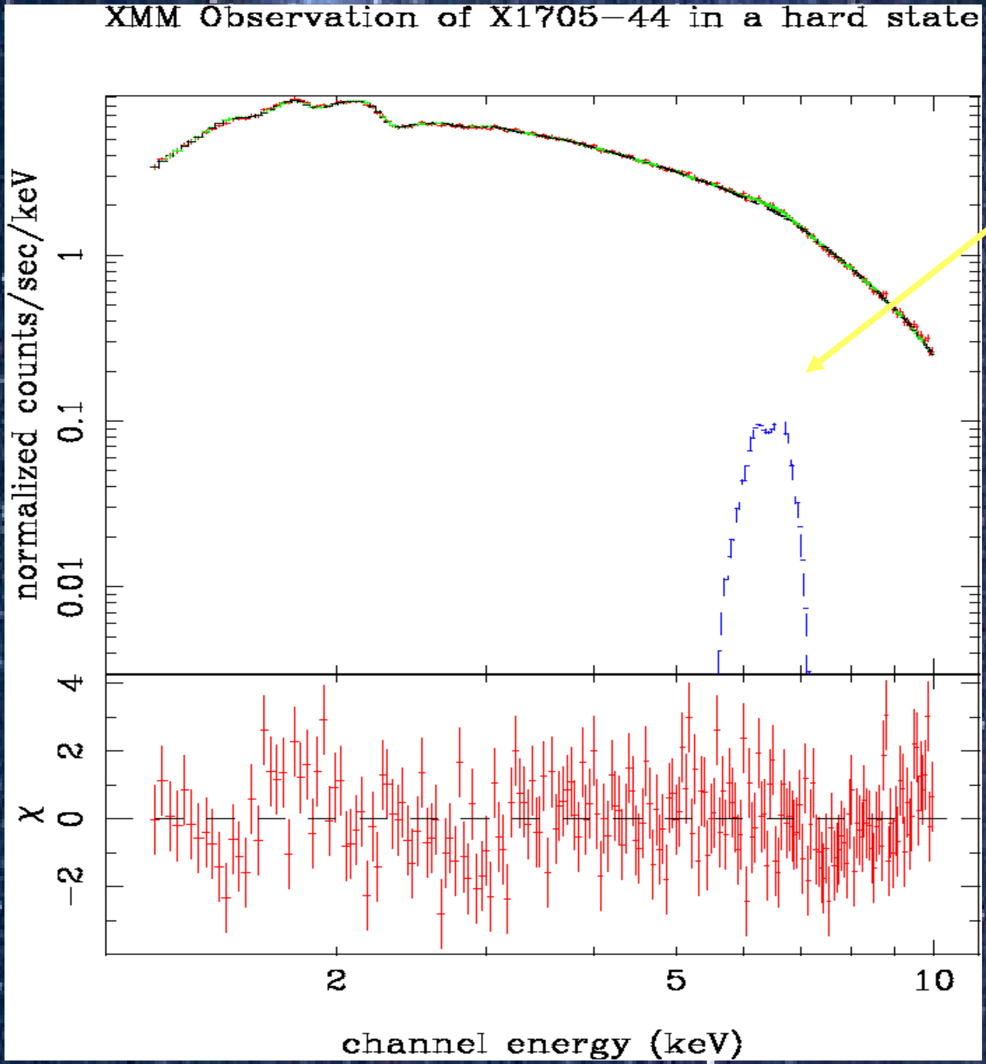
BeppoSAX (Piraino et al. 2007)

- E_Fe = $6.7^{+0.2}_{-0.5}$ keV
- Rin = 6-12 Rg (13-25 km)
- Inclination = 20 – 48 deg
- Fe Eq.W = 109 eV

High energy resolution observations of 4U 1705-44



Fe K-shell line in 4U 1705-44 during a hard state observed by XMM-Newton



The iron line observed by XMM during a hard/low state appears less intense and narrower than during the soft state observed by Chandra and BeppoSAX.

This is also confirmed by the second Chandra observation performed during a soft state.

4U1705-44 during a hard state

XMM-Newton (Di Salvo et al. 2007, in prep.)

- E_Fe = 6.40 keV
- Rin = 20 Rg (about 45 km)
- Inclination = 60 deg
- Fe Eq.W = 40 eV

The iron line observed by XMM during a hard/low state appears less intense and narrower than during the soft state observed by Chandra and BeppoSAX.
The observation is in agreement with a larger inner disk radius.

Interestingly, the frequency of the upper kHz QPO varies from 500 Hz to 1100 Hz when the sources goes from the hard to the soft state, indicating that the inner disk radius varies from 16 to 30 km from the soft to the high state.