Hard X-ray emission from Neutron Star Binaries

Based on Luigi's work (and talk!)……

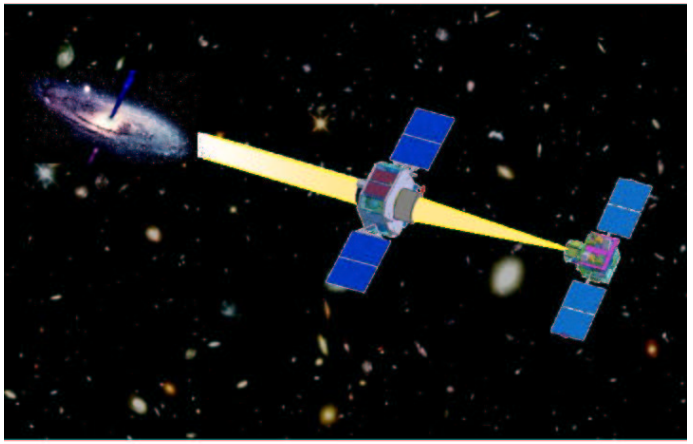
Sergio Campana (Astronomical Observatory of Brera)

Luigi Stella (Astronomical Observatory of Rome)
Tiziana Di Salvo (University of Amsterdam)

And a few notes on transient systems

Talk outline:

- History
- Hard tails in Atoll and Z- sources
- Relationship with source properties
- Analogy with BHCs
- Models
- Transients
- Perspectives with Simbol-X



Paris, March 2004

A bit of history ...

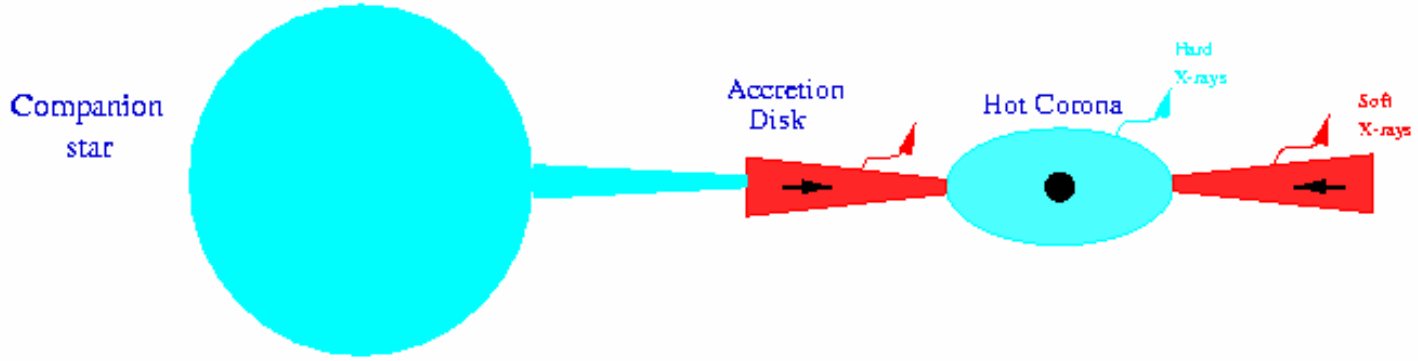
- Sco X-1: thermal-like spectrum with kT ~ 3-4 keV
  BUT: evidence for a **variable** hard component dominating the spectrum above 40 keV (Peterson & Jacobson 1966; Riegler et al. 1970; Agrawal et al. 1971; Haymes et al. 1971)

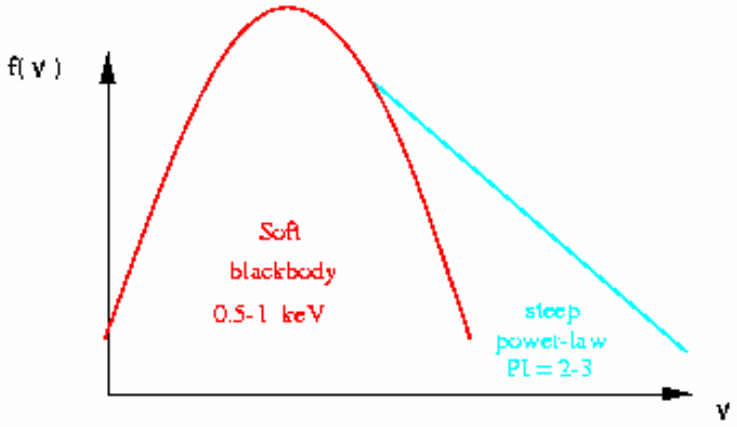
- Yet, extended spectrum of Cyg X-1 was considered the prototype ``hard spectrum'' and the base for model development

Black Hole Candidates: high/soft vs. low hard states

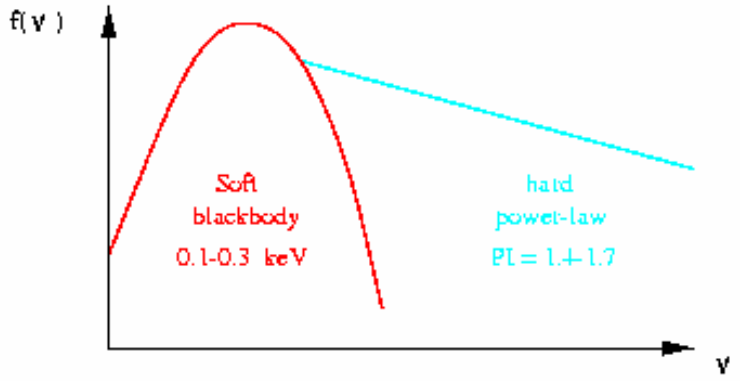
Standard accretion disk plus hot inner Comptonising corona model

(Lightman & Eardley 1975; Lightman, Eardley & Shapiro, 1976; Galeev Rosner & Vaiana 1979)





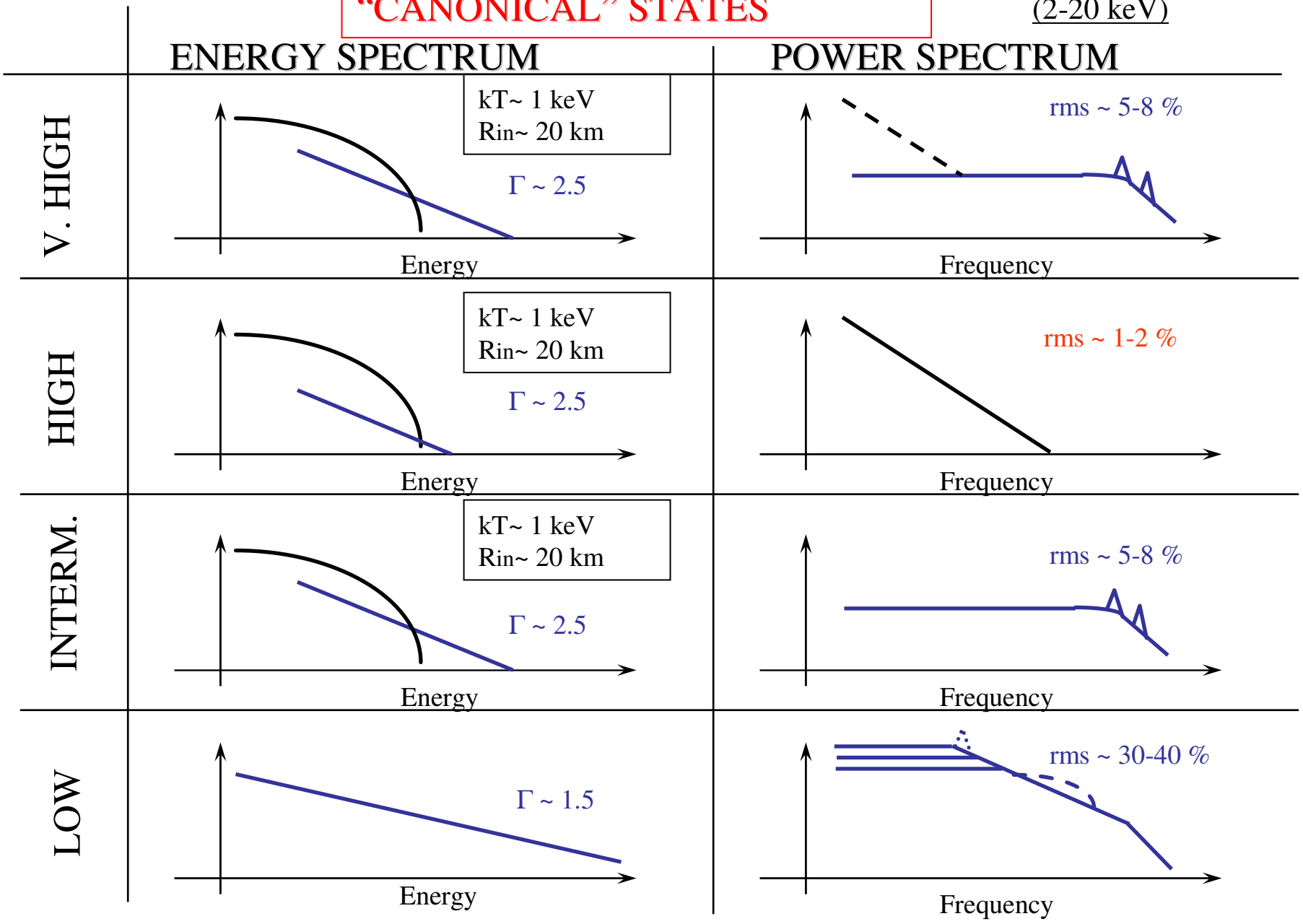
HIGH / SOFT STATE



LOW / HARD STATE

"CANONICAL" STATES

(2-20 keV)



e.g. Belloni et al. 2001

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- Yet, extended spectrum of Cyg X-1 was considered the prototype "hard spectrum" and the base for model development

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

- Limited attention given to these findings, partly because the nature of bright low mass X-ray binaries remained unclear until the early '80s

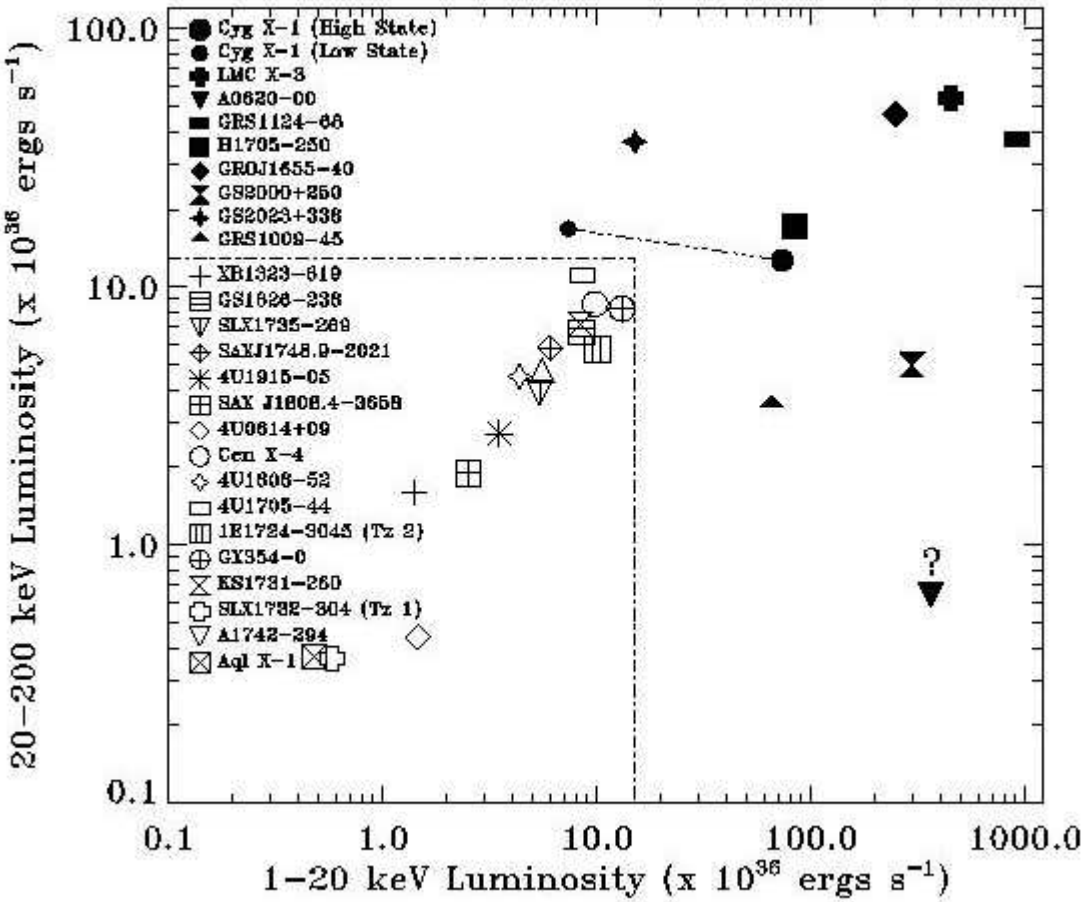
- Renewed interest in the early '90 thanks to the SIGMA discovery of hard components, extending up to 100-200 keV in Terzan 2 (Barret et al 1991), KS 1731-260 (Barret et al. 1992), SLX 1735-269 (Goldwurm et al. 1996), Terzan 1 (Borrell et al. 1996).

- Not as hard as BHC

Can one tell NSs from BHCs by their hard X-rays ?

- Are there only BHCs outside the burster box ?

(Barret et al. 2001)

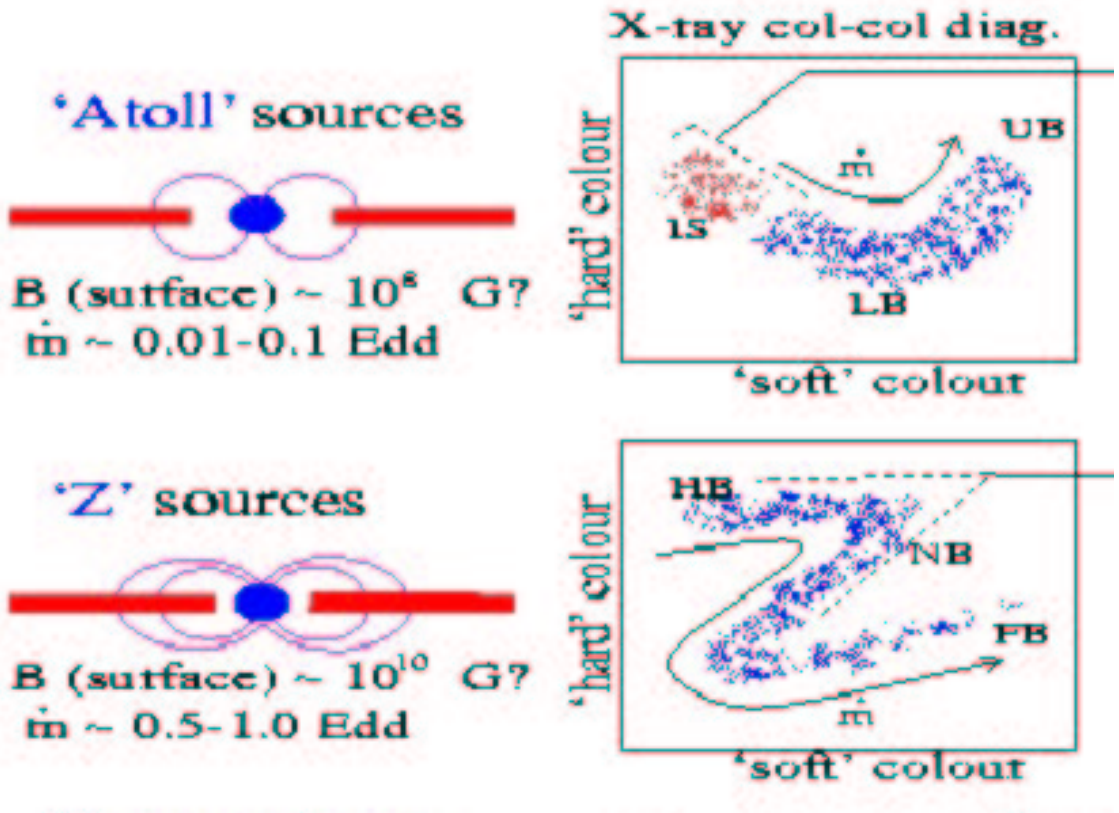


Neutron star low mass X-ray binaries: basics

- Late type mass donor (usually K-M star) or white dwarf
- Accreting NS primary: fast spinning (2-5 ms), weakly magnetic
- Characteristic phenomena: type I X-ray bursts, fast (>>1 Hz) quasi periodic oscillations in the X-ray flux
- Modern classification: Z-sources, Atoll sources

Atoll sources:
Lx ~ 0.01-0.1 L(Edd)
type I X-ray bursts
some transients

Z-sources:
Lx ~ 0.1-1.0 L(Edd)
all persistent



X-ray energy spectra up to ~20 keV

Two components needed (at least):

- Eastern model (Mitsuda et al. 1984):
  disk-blackbody + blackbody spectra
  (disk emission with kT = a $R^{-3/4}$, and NS surface)
  OK for Z-sources
  Additional power law required for many Atolls

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

Atoll sources: energy spectra

Atoll sources

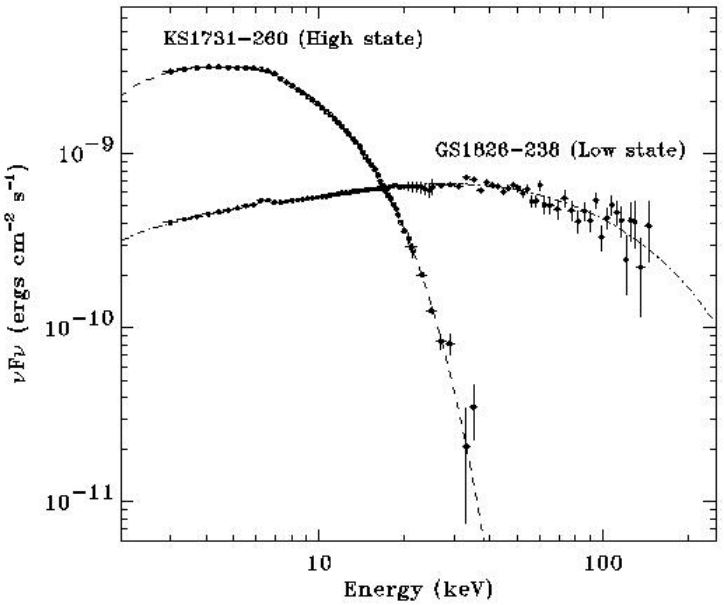
- Soft component (few keV)
  (blackbody or disk-blackbody model)

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

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

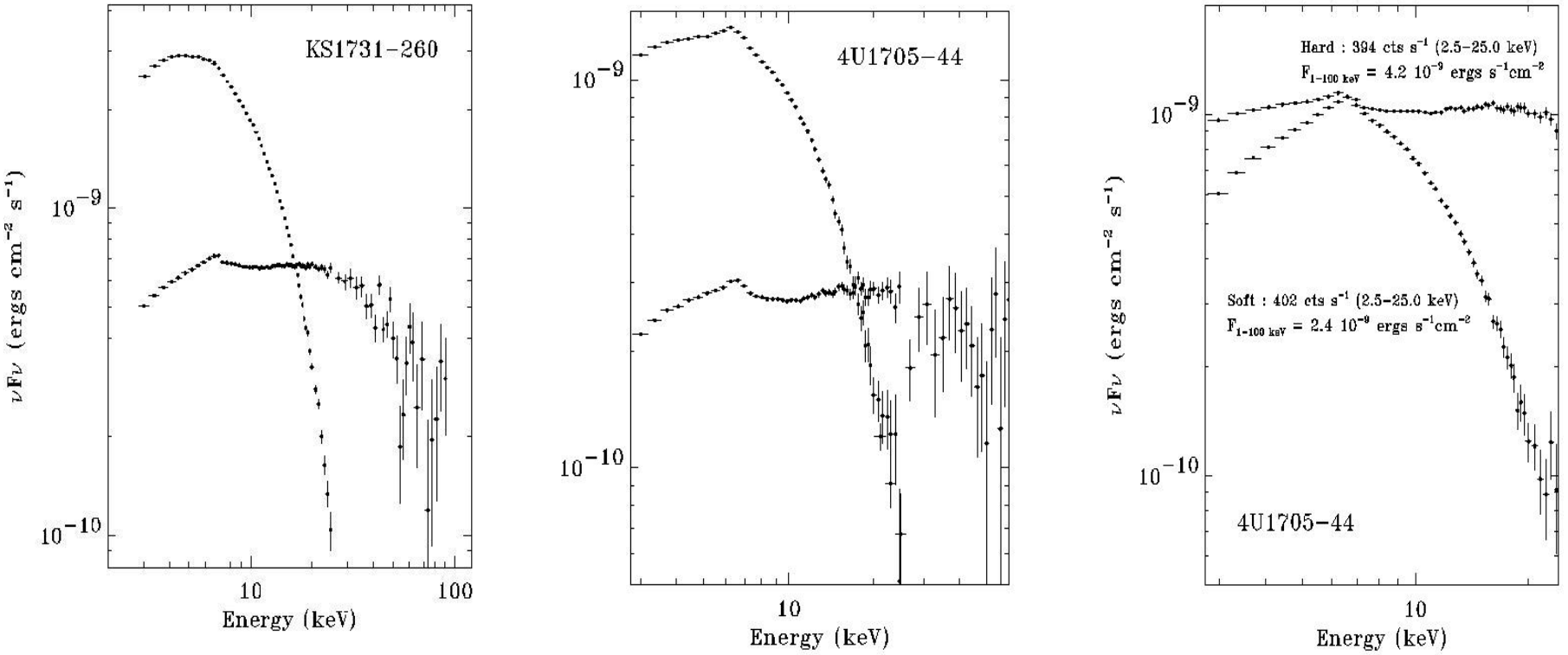
- Iron emission (fluorescence) line
  at ~6.4 keV

- Evidence for a reflection component



Atoll Sources: hard/soft state transitions

Barret et al. (2001)



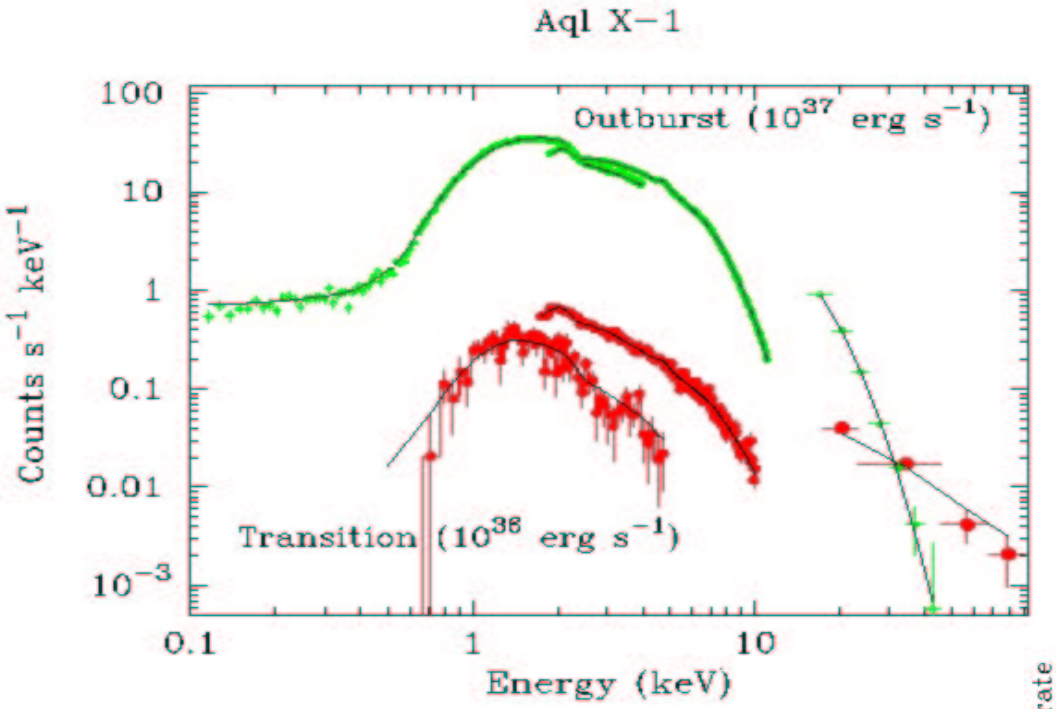
- Usually: hard state <= > lower flux (but see 4U1705-44)

- Analogy of Atolls in their hard state with low state BHCs (more later)

Maccarone (2003)

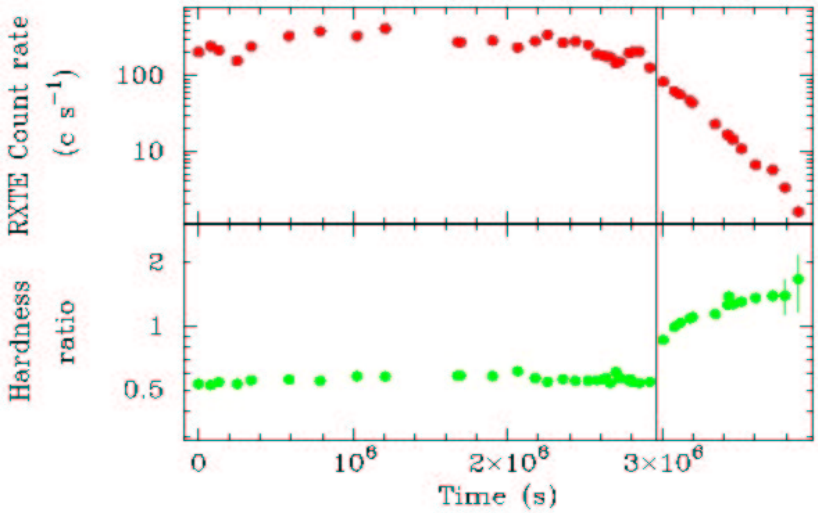
Limiting luminosity for all LMXRBs (NS+BH) at 4×10^{36} erg/s

NS Transient sources (atoll)

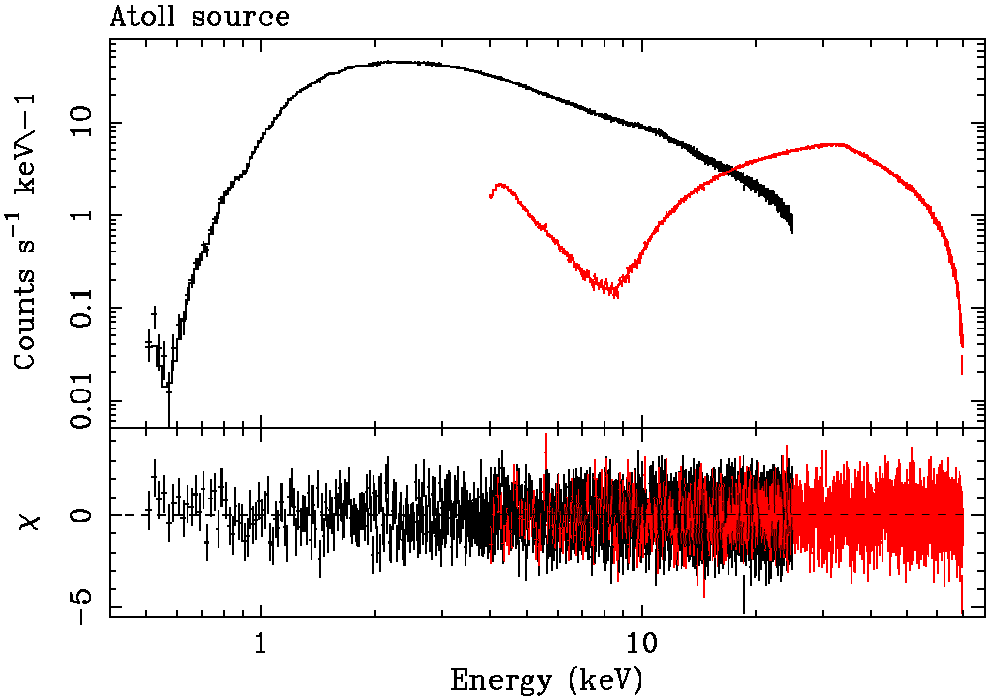


Campana et al. 1998

Zhang et al. 1998

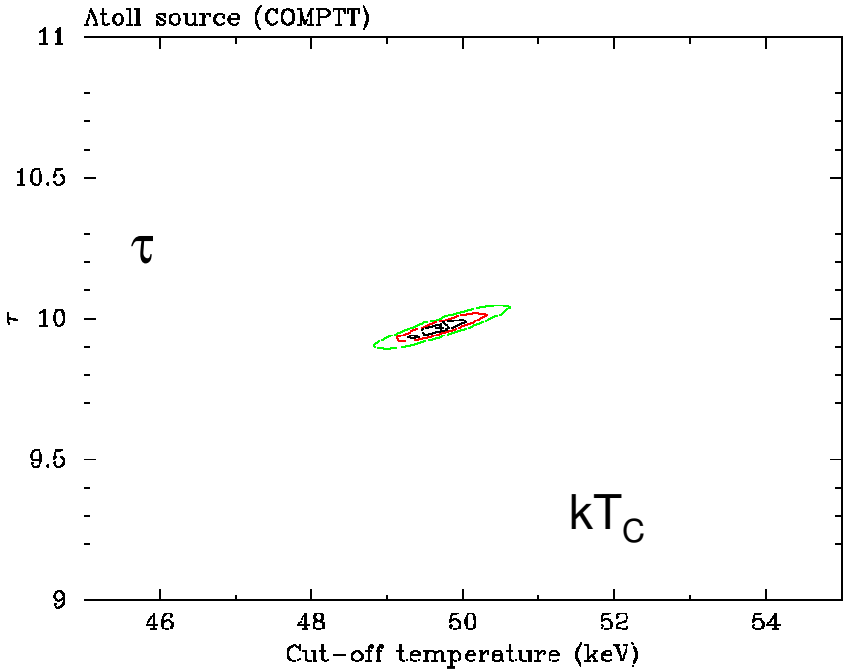


Simbol-X: simulated atoll spectrum (hard)



$F_x=10^{-9}$ erg/s/cm^2

$L_x=4\times10^{36}$ erg/s @ 5 kpc



SDD 265 c s^{-1}

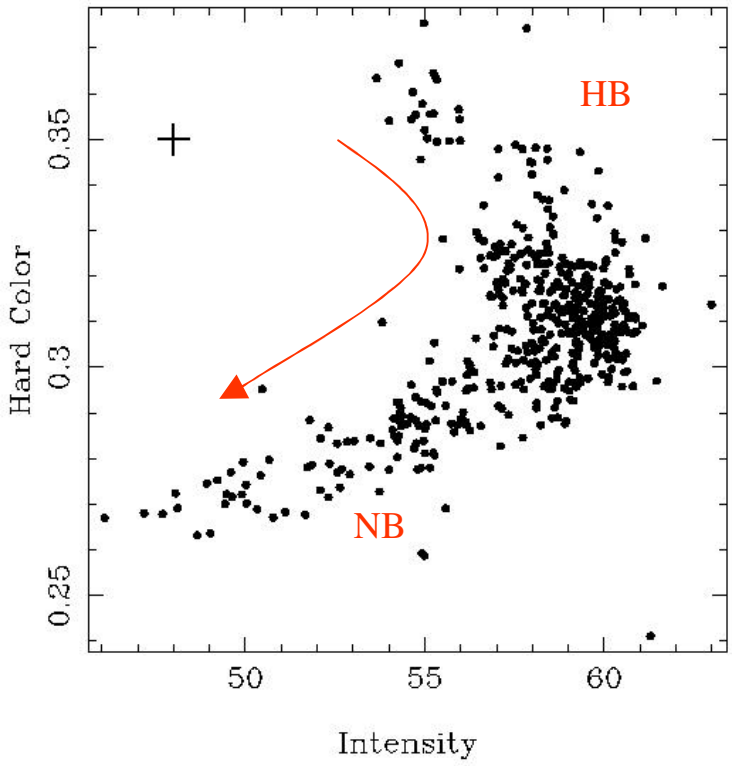
CZT 175 c s^{-1}

10 ks

Z-sources: BeppoSAX observation of GX 17+2

- Only Horizontal Branch (HB) and Normal Branch (NB) observed

- HC = (7-10.5 keV)/(4.5-7 keV)



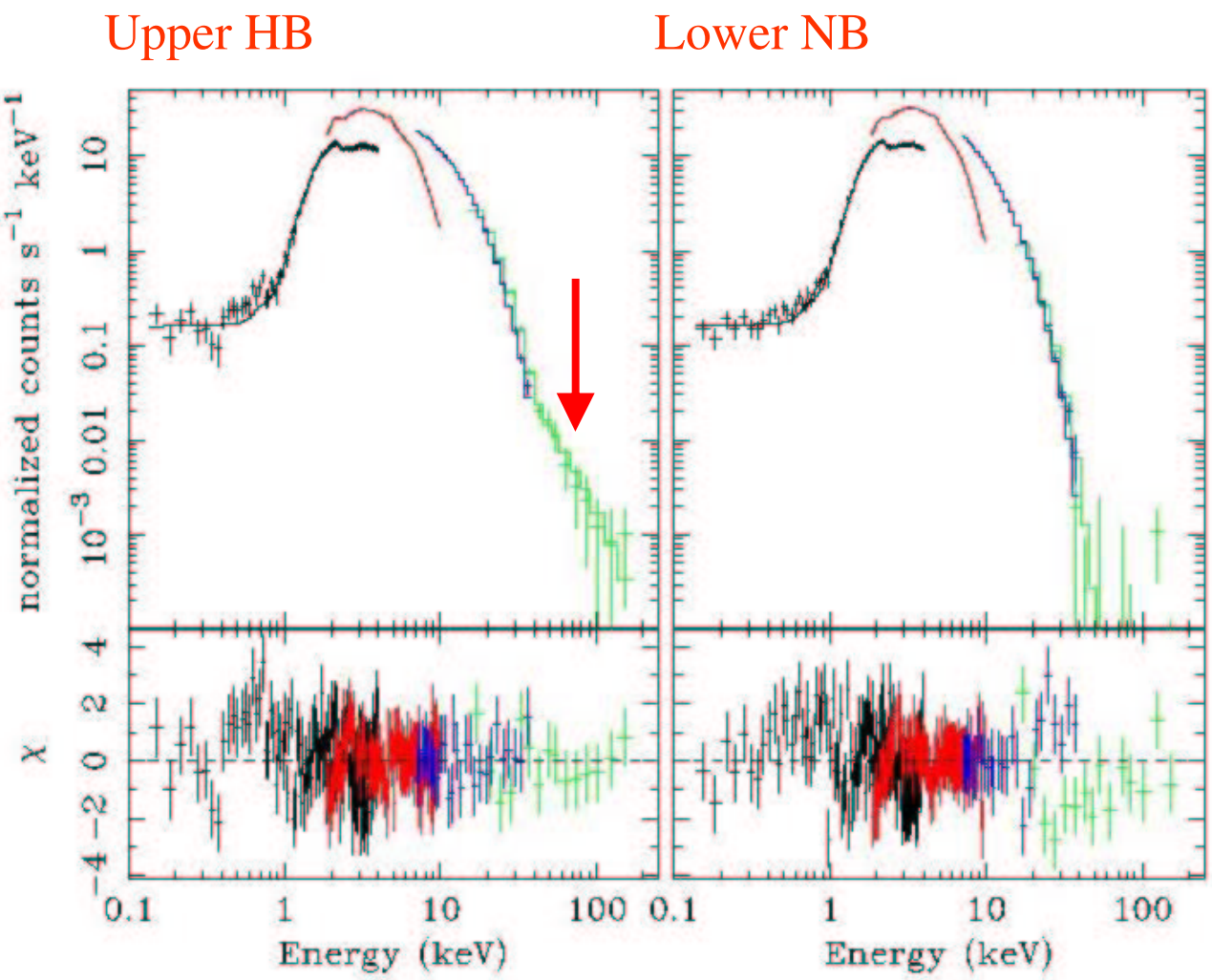
GX 17+2: BeppoSAX spectra

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

- power law slope 2.7

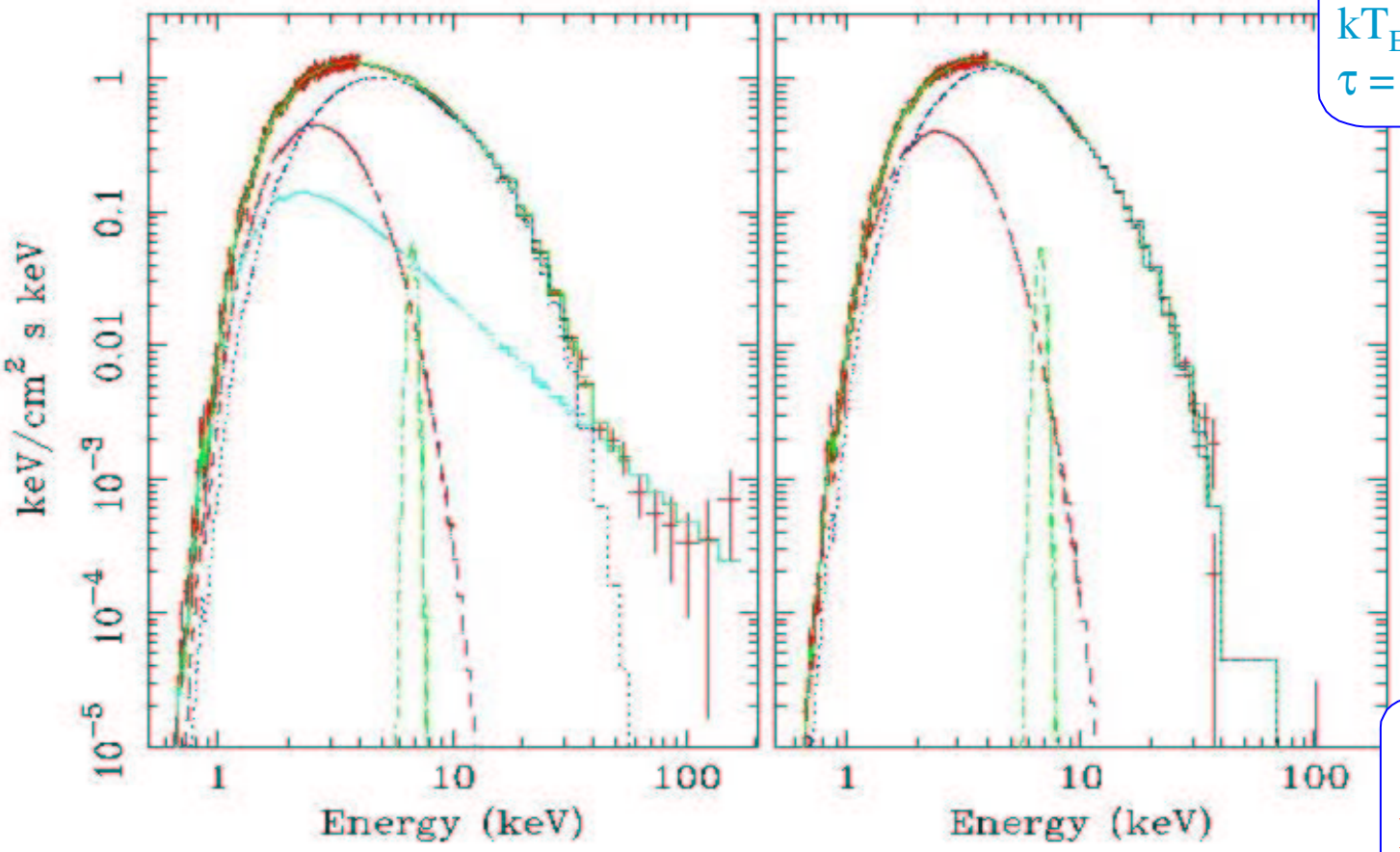
- No evidence for cutoff

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



(Di Salvo et al. 2000)

GX 17+2: BeppoSAX unfolded spectra



Comp
kT_W = 1.0 keV,
R_W = 15 km,
kT_E = 3.0-3.3 keV,
τ = 9.5-11.6

Blackbody
kT_{BB} = 0.6 keV,
R_{BB} = 37 km,
Flux = 10% F_{tot}

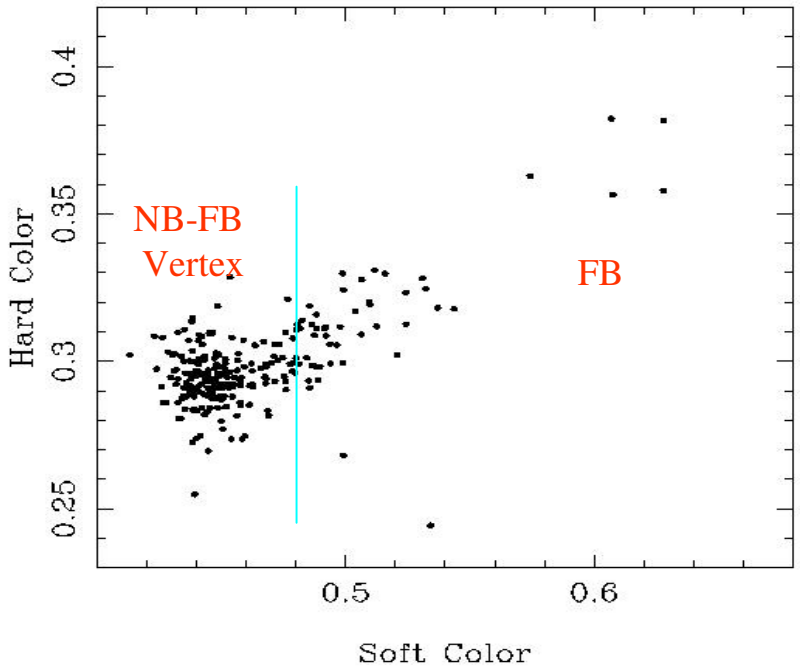
Z-sources: BeppoSAX observation of GX 349+2

- Only NB-FB Vertex and
  FB observed

- Color-Color Diagram

HC= (7-10.5 keV)/(4.5-7 keV)

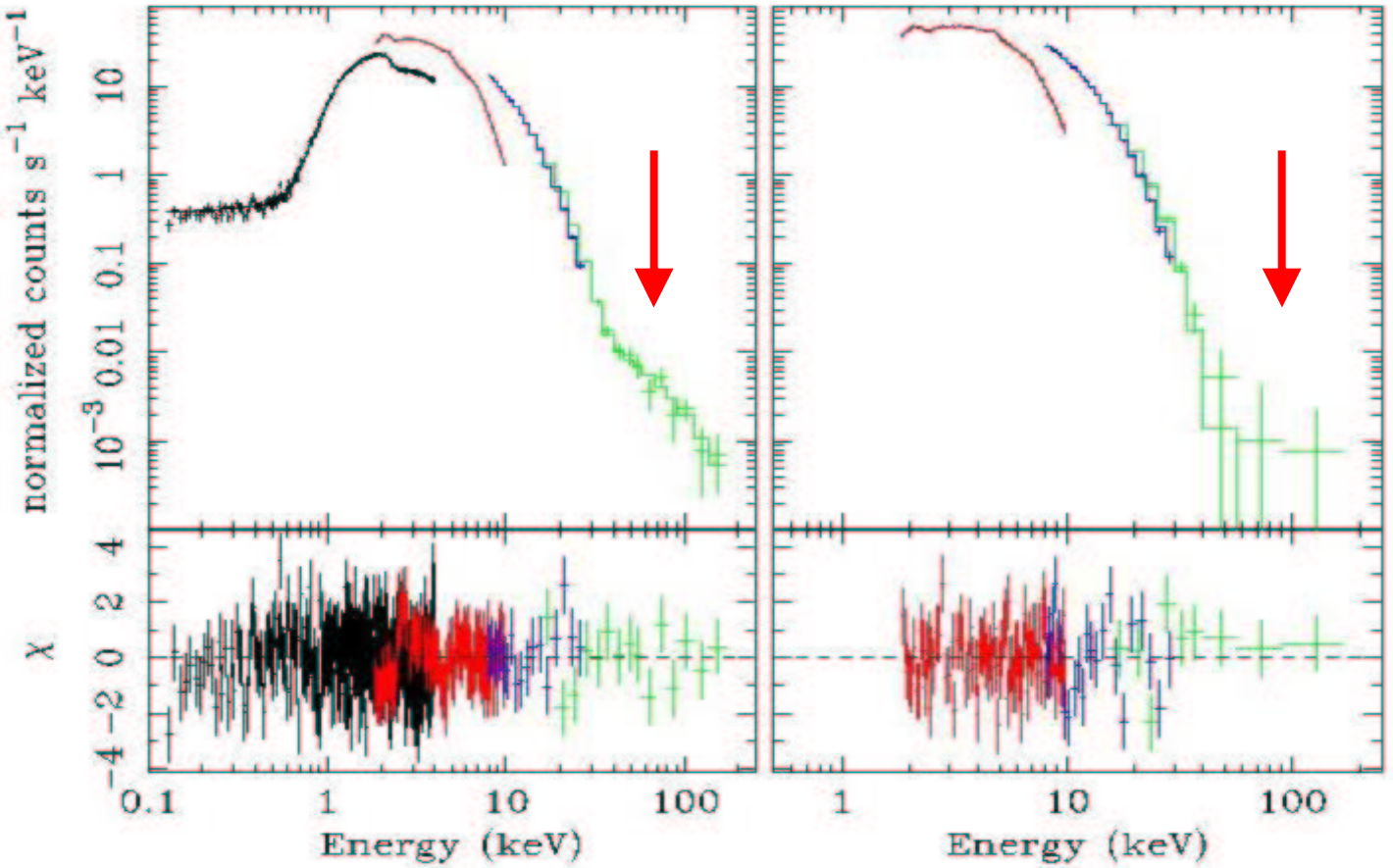
SC= (4.5-7 keV)/(1.8-4.5 keV)



(Di Salvo et al. 2001)

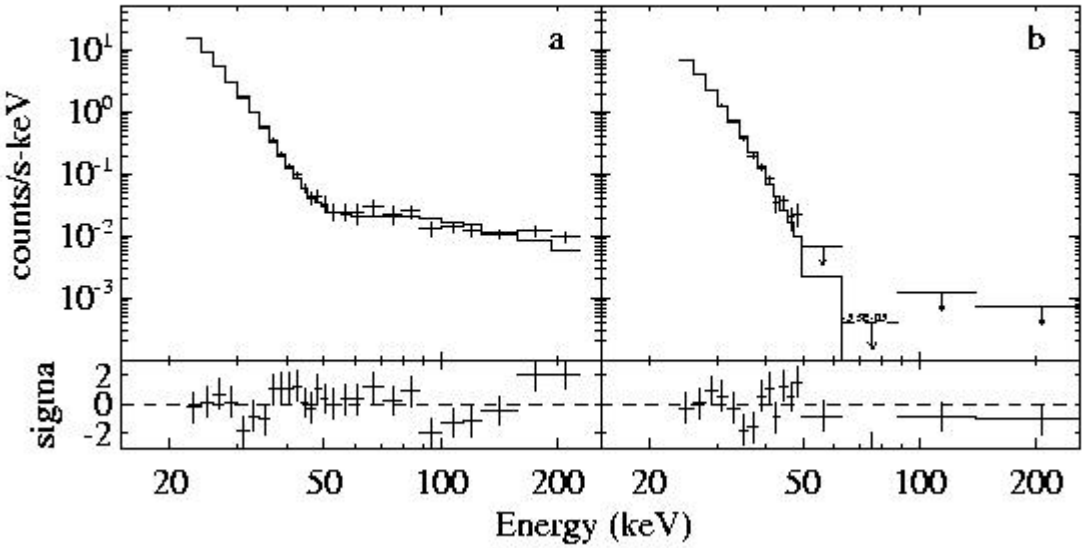
GX 349+2: BeppoSAX energy spectra

NB-FB Vertex FB



Z-sources: RXTE observations of Sco X -1

- Variable hard power-law component
- Uncorrelated with the position in the X-ray colour-colour diagram
- Likely correlated with periods of radio flares (more later)



(D'Amico et al. 2001)

Hard tails in Z (and other bright) sources

GX 17+2 (Di Salvo et al. 2000) (hard component in HB)

GX 349+2 (Di Salvo et al. 2001) (hard component in NB/FB vertex)

Sco X-1 (D'amico et al. 2001, Strickman & Barret 2000)
(variable hard power-law component, not correlated with the position in the CD, but probably with periods of radio flares)

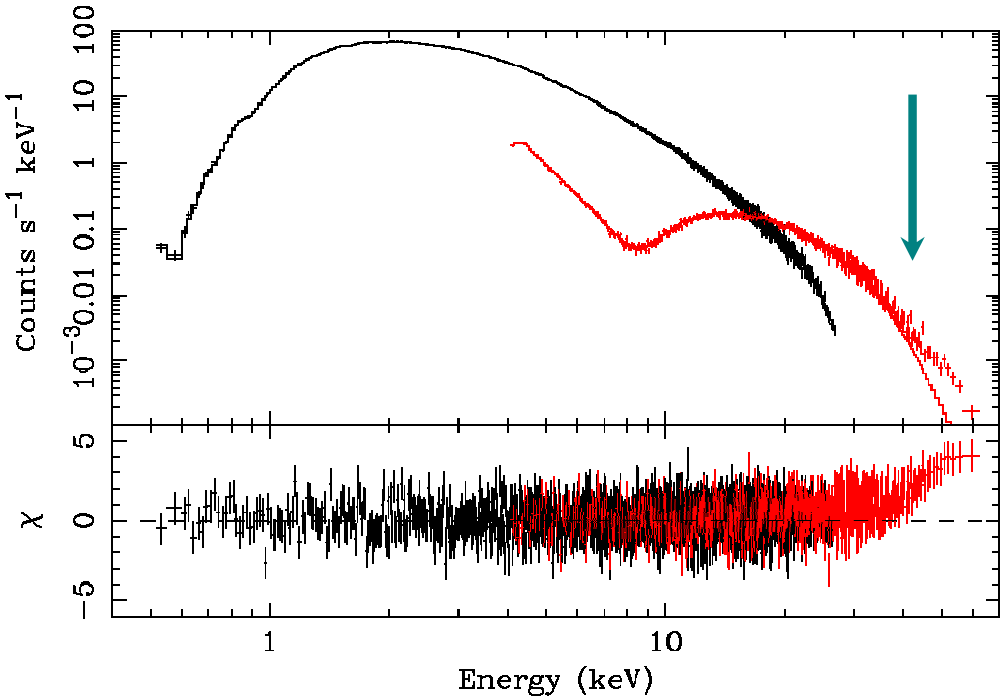
GX 5-1 (Asai et al. 1994)
(hard component decreased from the NB to the FB, but possible confusion with a nearby source)

Cyg X-2 (Frontera et al. 1998; Di Salvo et al. 2002)

Cir X-1 (Iaria et al. 2001)
(steep hard component observed at periastron in the non-flaring spectrum)

Rapid Burster (X1730-33) (Masetti et al. 2001)
(hard component clearly detected in type II bursts)

Simbol-X: looking at hard tails



CONT:
F_x=2x10^{-9} erg/s/cm^2

TAIL:
F_x=6x10^{-12} erg/s/cm^2

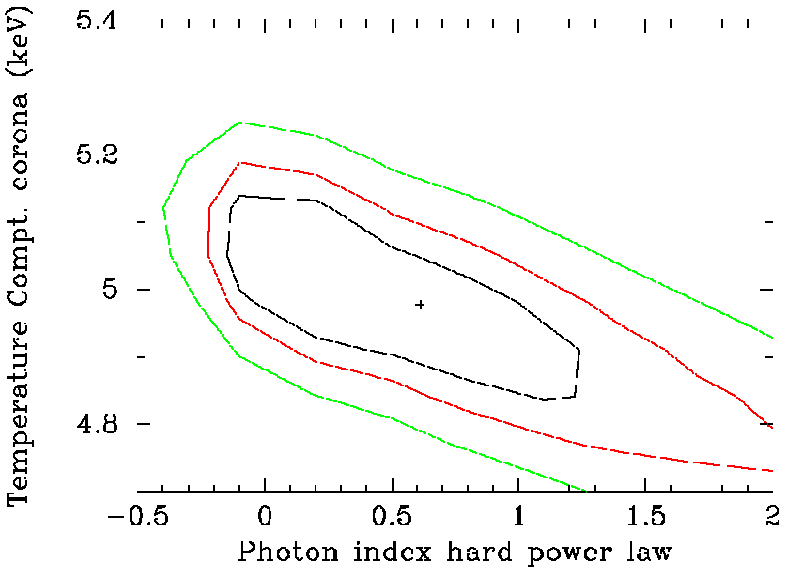
Tail/Cont$_{(0.5-20)}$= 0.1%

kTc=5 keV 20 ks

Tau=3

SDD=220 c/s

CZT=5 c/s

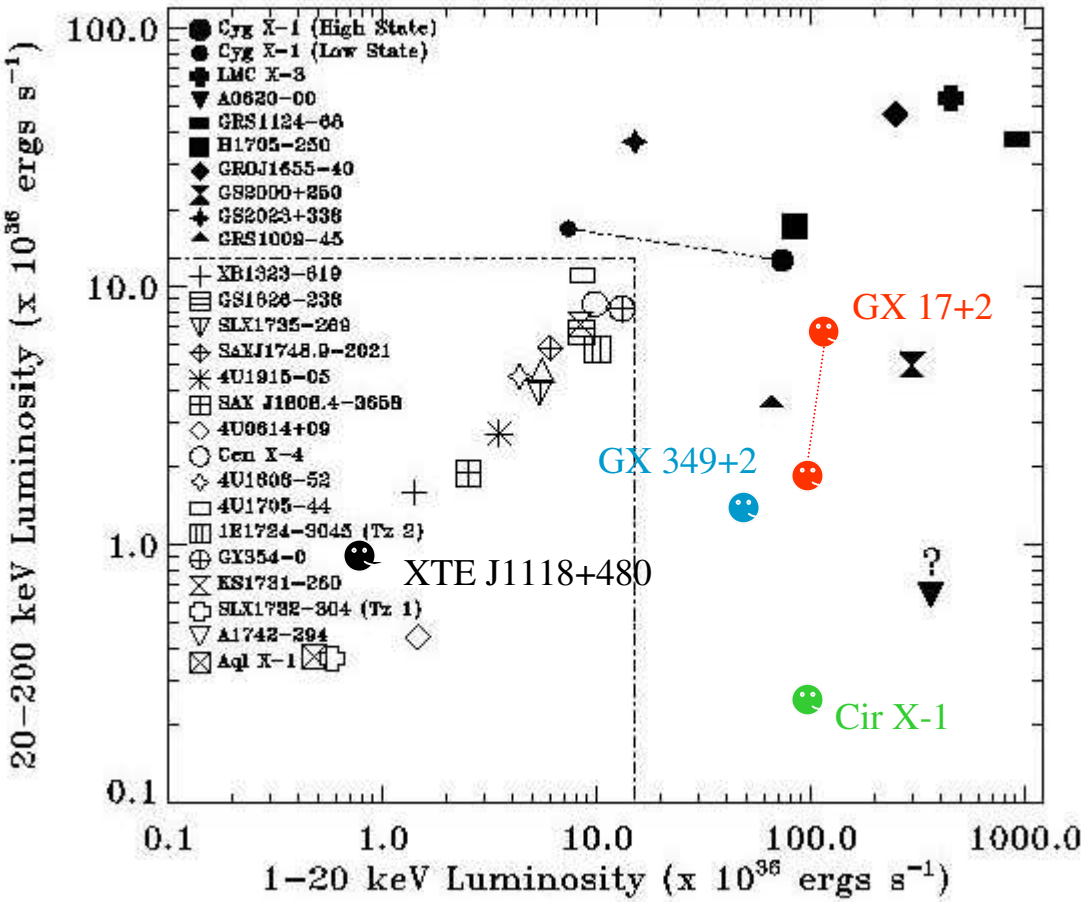


Can one tell NSs from BHCs by their hard X-rays ?

- Are there only BHCs outside the burster box ?
  (Barret et al. 2001)

- Z-sources lie outside !
  (Di Salvo et al. 2001)

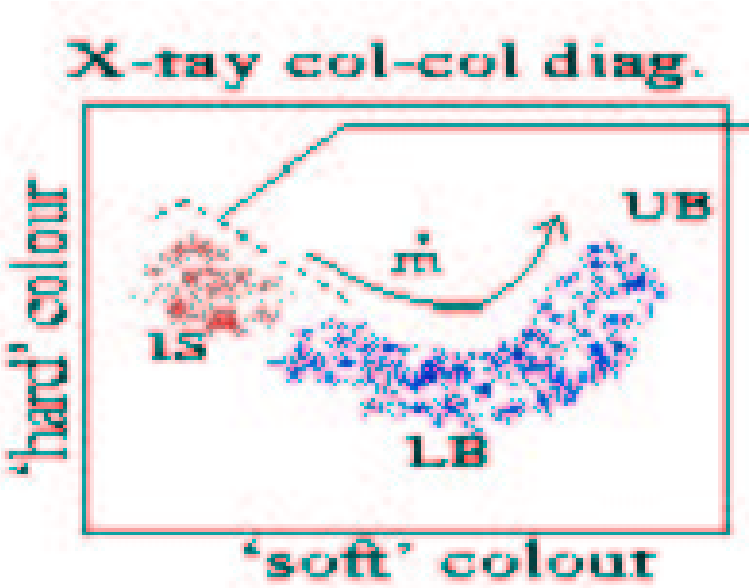
- A BHC (XTE J1118+480) lies inside !



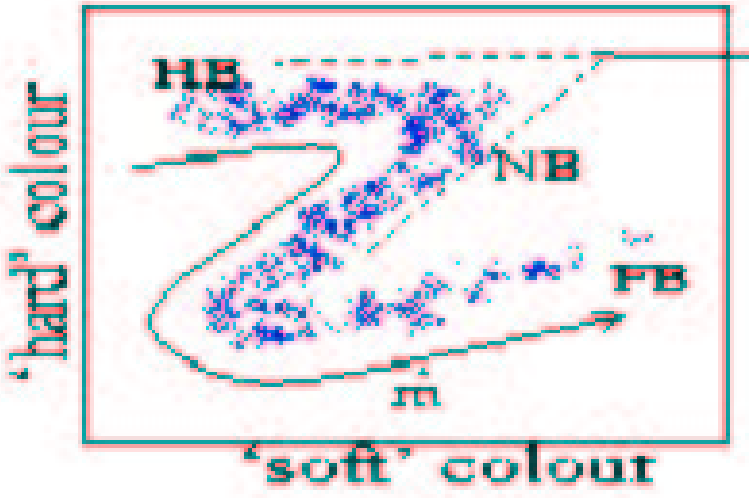
Hard X-ray NS/BHC indicators are uncertain at least

NS hard tails in relation to other properties

- Usually seen at low Lx and/or accretion rate: 1st parameter
  (see also van Paradijs & van der Klis 1992)
  - At low Lx (island state ?) of Atoll sources
  - In HB and NB of Z-sources
  - QPO frequencies increase for increasing accretion rate (uniquely determined by Sz coordinate)
  - QPO rms amplitude increases with energy: is there a relationship with hard tails ?



- Exceptions might be important !
  - In Sco X-1, no clear relation to position on Z-pattern
  - Could the hard tail be responsible for the fact that some sources wander in the color-color diagram over times of week to months ?
  - 2nd parameter needed ?



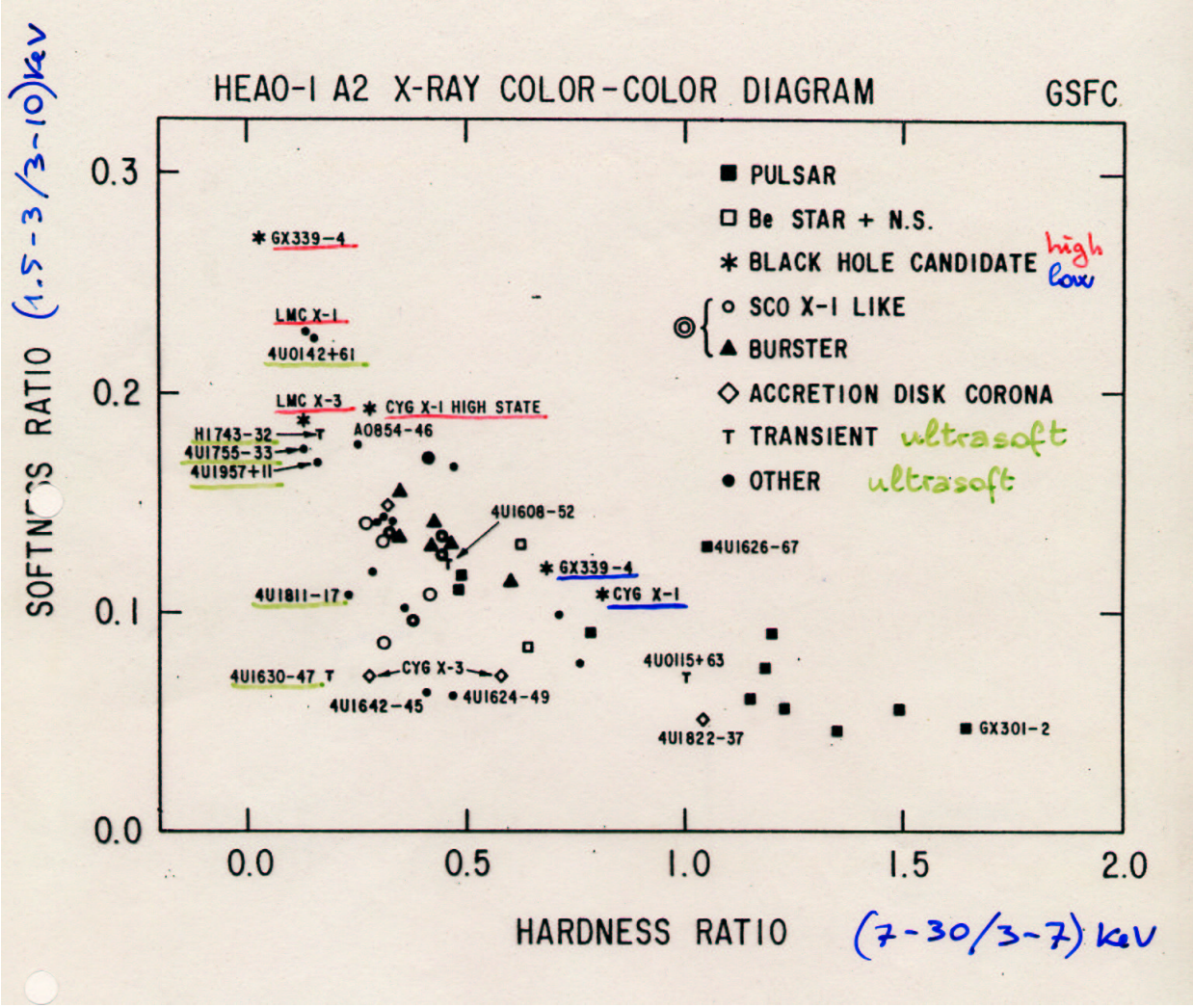
The classical X-ray color-color diagram

(White & Marshall 1984)

- Soft component is softer in BHCs than in NSs

- Agrees with basic theory of optically thick accretion

$$T(bb) \sim M^{1/4}$$



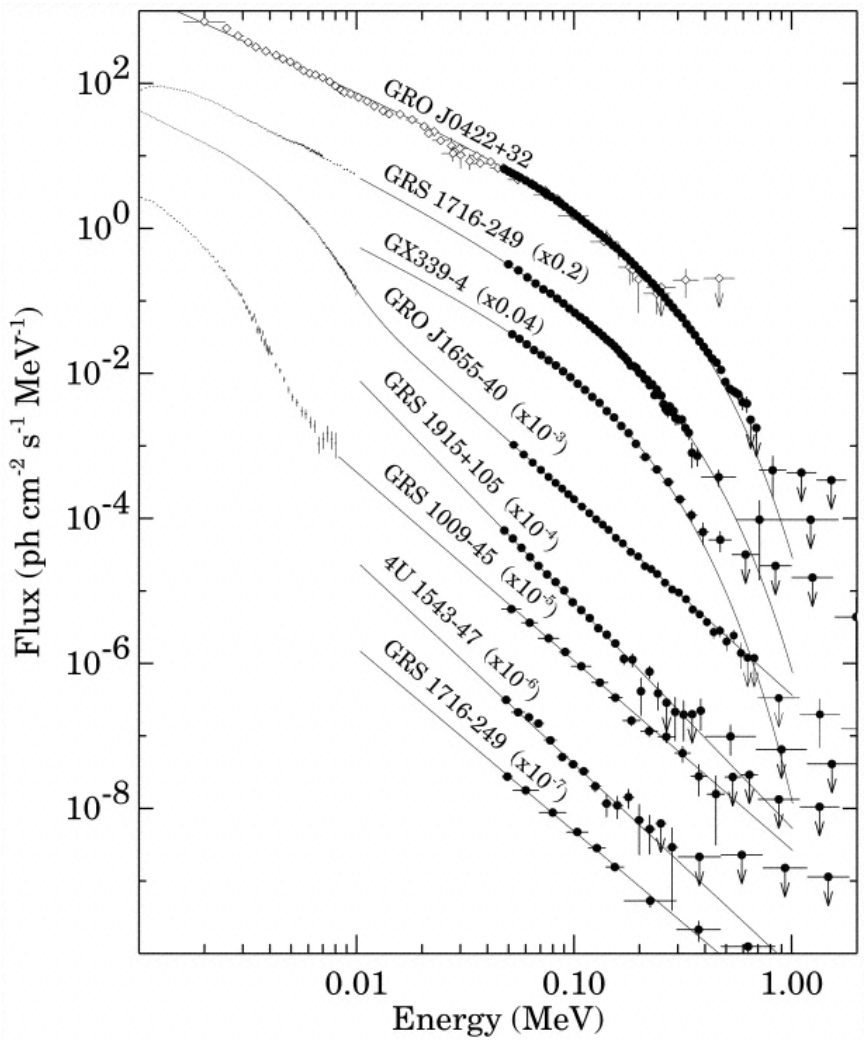
Desiderata: a hard X-ray equivalent

NS hard tails: analogy with BHCs I.

- 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
However spectral evolution for increasing accretion rates differs: BHCs evolve to IS/HS, Atolls to soft state (cutoff moves to lower energies)

- BHCs in IS: very soft thermal component plus power law (often) without high energy cutoff
Similar to Z-sources in HB-NB
However a high energy cutoff in hard tail of Z-sources might have remained undetected
BHCs in HS: very soft thermal component.
Similar to Z-sources in NB-FB.

(Grove et al. 1998)



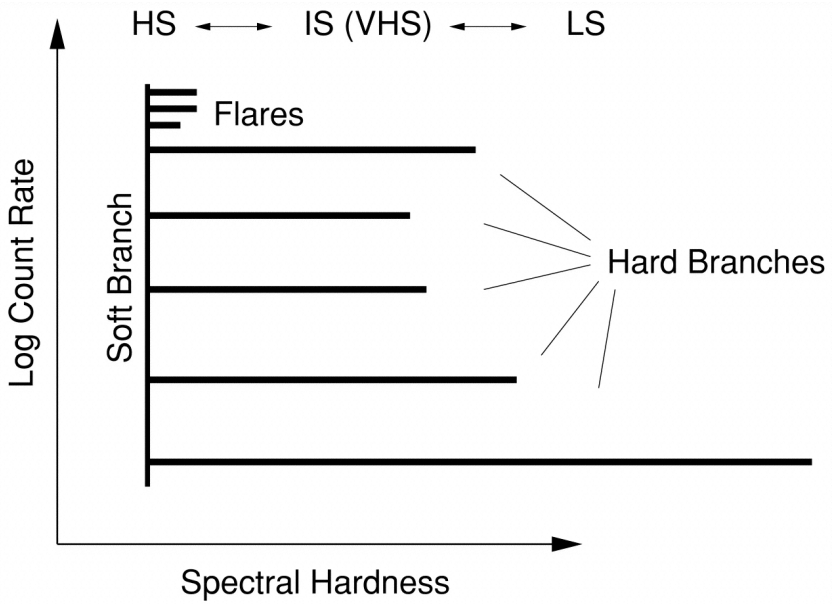
NS hard tails: analogy with BHCs II.

- BHC state transitions driven by:
1st parameter: mass accretion rate

- Evidence for a:
2nd parameter

- The behaviour of Sco X-1 suggests that there might be a similar "2nd parameter" in NS systems

(Homan et al. 2001)



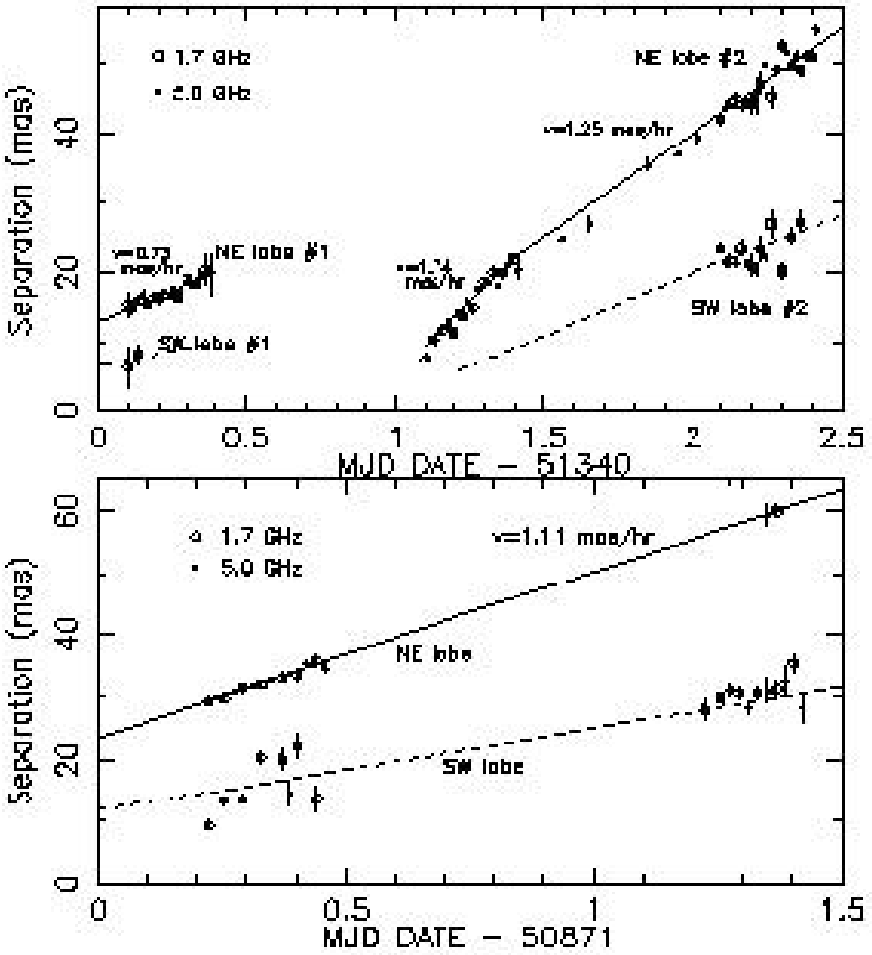
Schematic behaviour of XTE J1550-564

The radio connection: the case of Sco X-1

- Sco X-1 radio emission resolved into core+jets with VLBA.

- Core is stationary and variable.

- Lobes are variable and expand at relativistic speeds (0.3-0.4 c)



(Fomalont et al. 2001; Bradshow et al. 2001, Strickman & Barret 2000)

The radio connection: other NS binaries

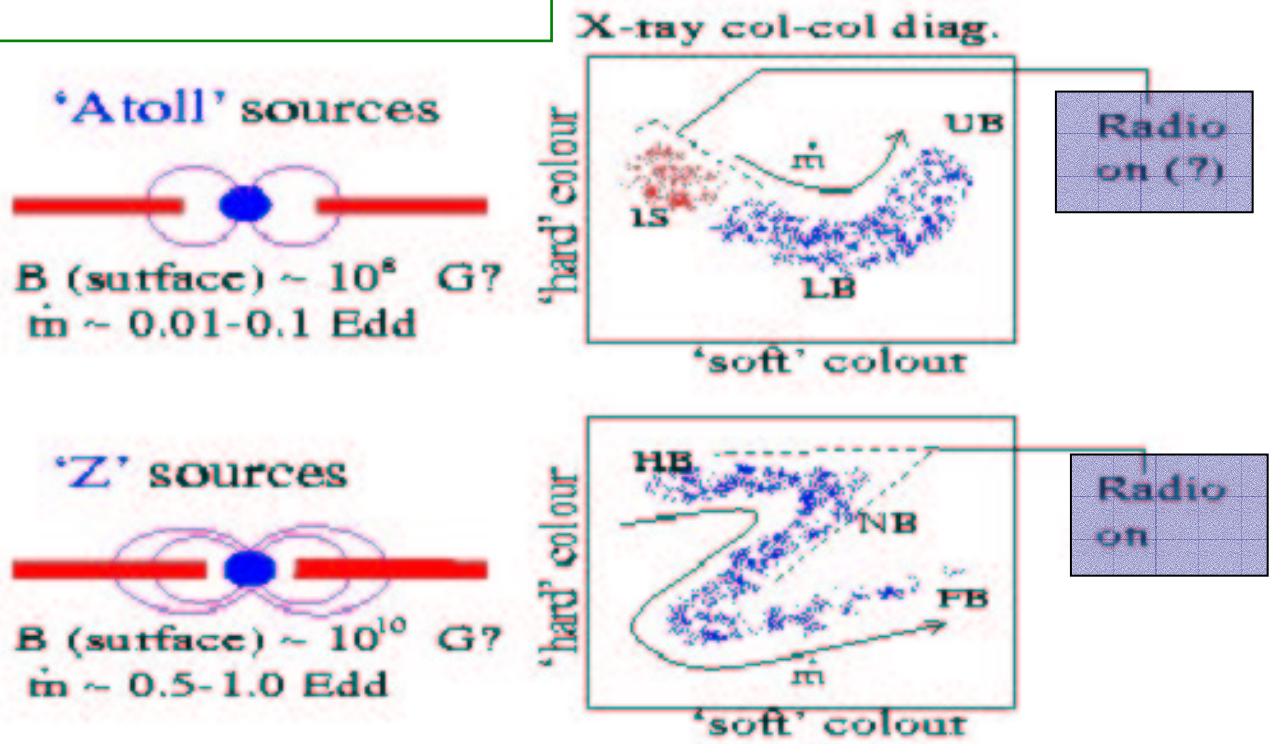
- Radio jets: likely a common phenomenon also in NS binaries

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)

- Radio emission (probably due to jets) is anticorrelated with the accretion rate.

- Similarity with the hard X-ray tail!



Perspectives for SIMBOL-X

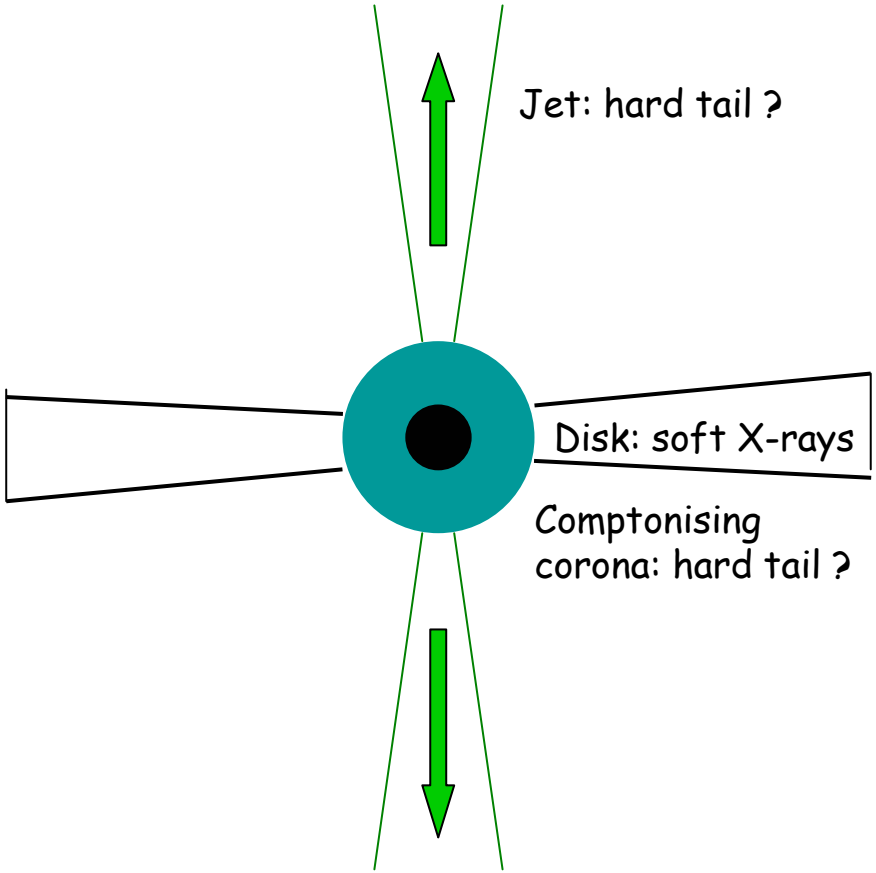
- Greatly expand the knowledge of hard tails in NS&BH LMXRBs through extensive high sensitivity hard X-ray observations

- Contemporaneous exploitation of other diagnostics as Fe-line and reflection components and QPOs

- As with microquasars, a great deal should be learned about the jets through multi-wavelength simultaneous campaigns (radio)

- Sources in external galaxies (M31, LMC and SMC in particular)

Generic geometry and additional diagnostics



Inner disk regions diagnostics

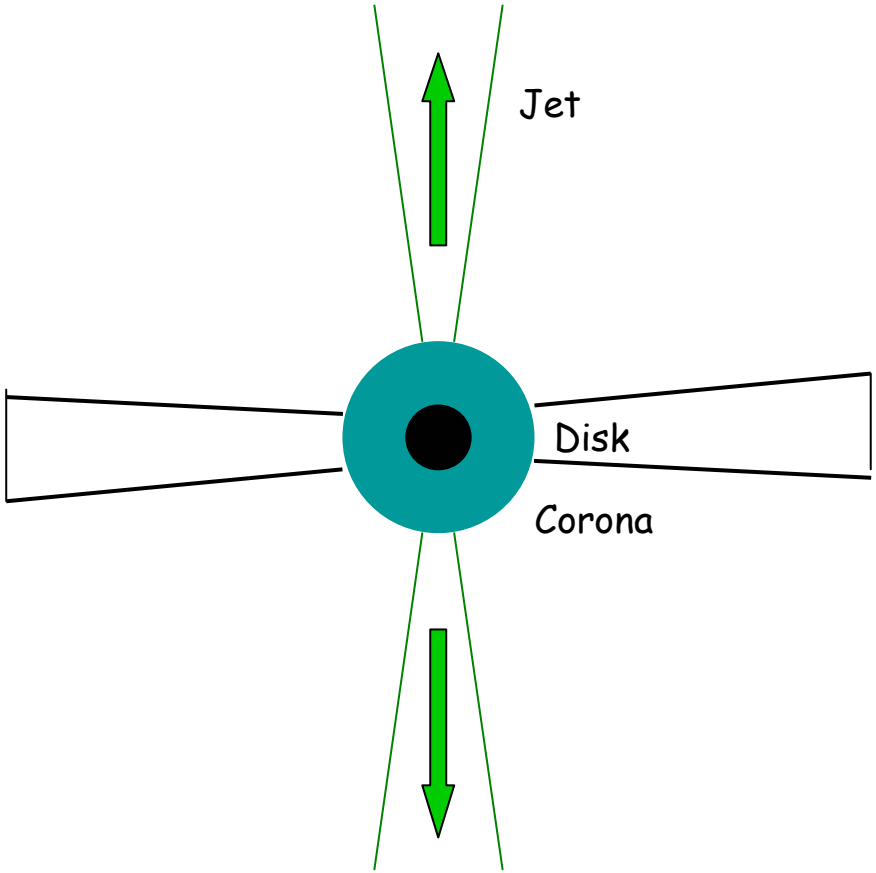
a. Highest QPO frequency

b. Reflection component

c. Fe-line line profile

- a and b increase as accretion rate increases: inner disk radius shrinks: hard tail decreases
- Fe-line diagnostic non fully exploited yet

Models for hard tails in NS binaries



- Comptonisation by thermal e- in a corona
  predicts high energy cutoff

- Comptonisation (or synchrotron radiation) by non-thermal e- in a (non-confined) corona or relativistic jets
  (Zdziarski 2000; Vadawale et al. 2001)
  power law spectra can extend up to very high energies

- Bulk motion Comptonisation converging radial or disk inflow (Titarchuk & Zannias 1998; Luarent & Titarchuk 1999, Psaltis 2001)
  Inflow in Z-sources is strongly affected by radiation from the NS

- Boundary layer emission (Kluzniak & Wagoner 1985; Kluzniak & Wilson 1991; Inogamow & Sunyaev 1999; Popham & Sunyaev 2001; Sibigatullin & Sunyaev 2000)
  works only for NSs

Conclusions

- Quite a lot has been learned over the last ~10 years on the hard X-ray/soft gamma ray emission of old accreting NS in LMXRBs

- Important analogies are emerging with the hard emission from BHCs: which require extensive studies at hard X-ray energies

-Ultimately, a great deal should be learned about high energy phenomena in the closest vicinity of these NS