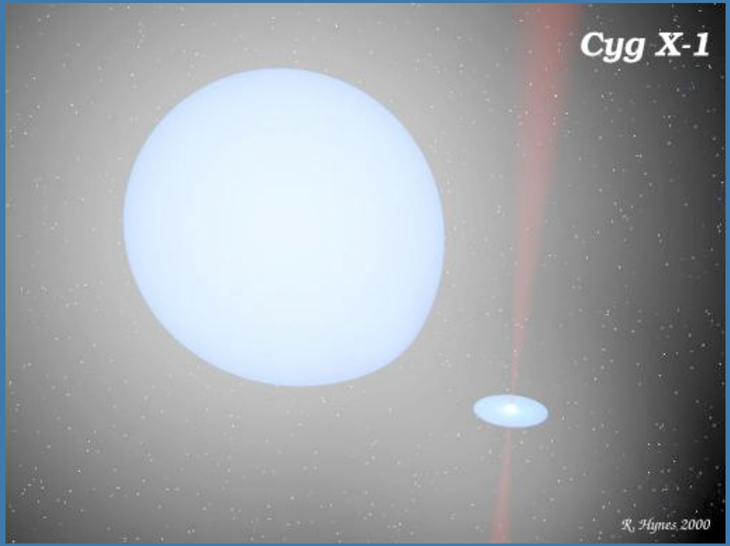
Jet-disc coupling in black hole X-ray binaries

Julien Malzac (CESR/CNRS, Toulouse, France)

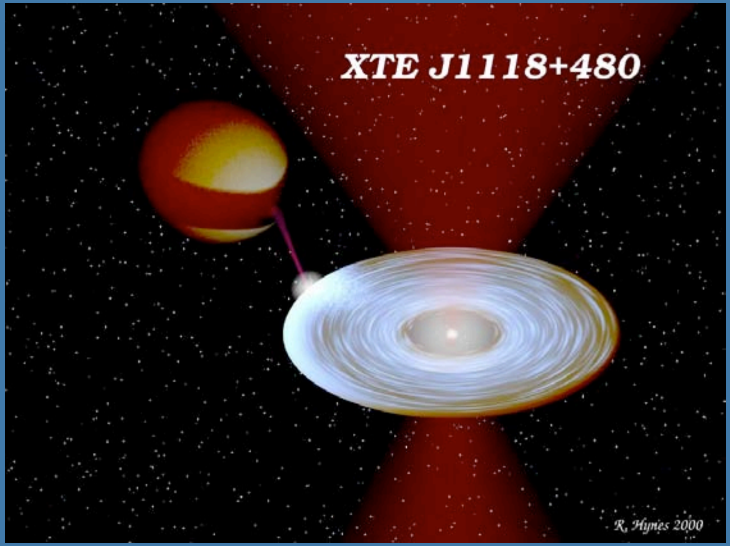
Outline

1. Properties of stellar mass accreting black holes

2. Cygnus X-1: jet disc coupling during a state transition

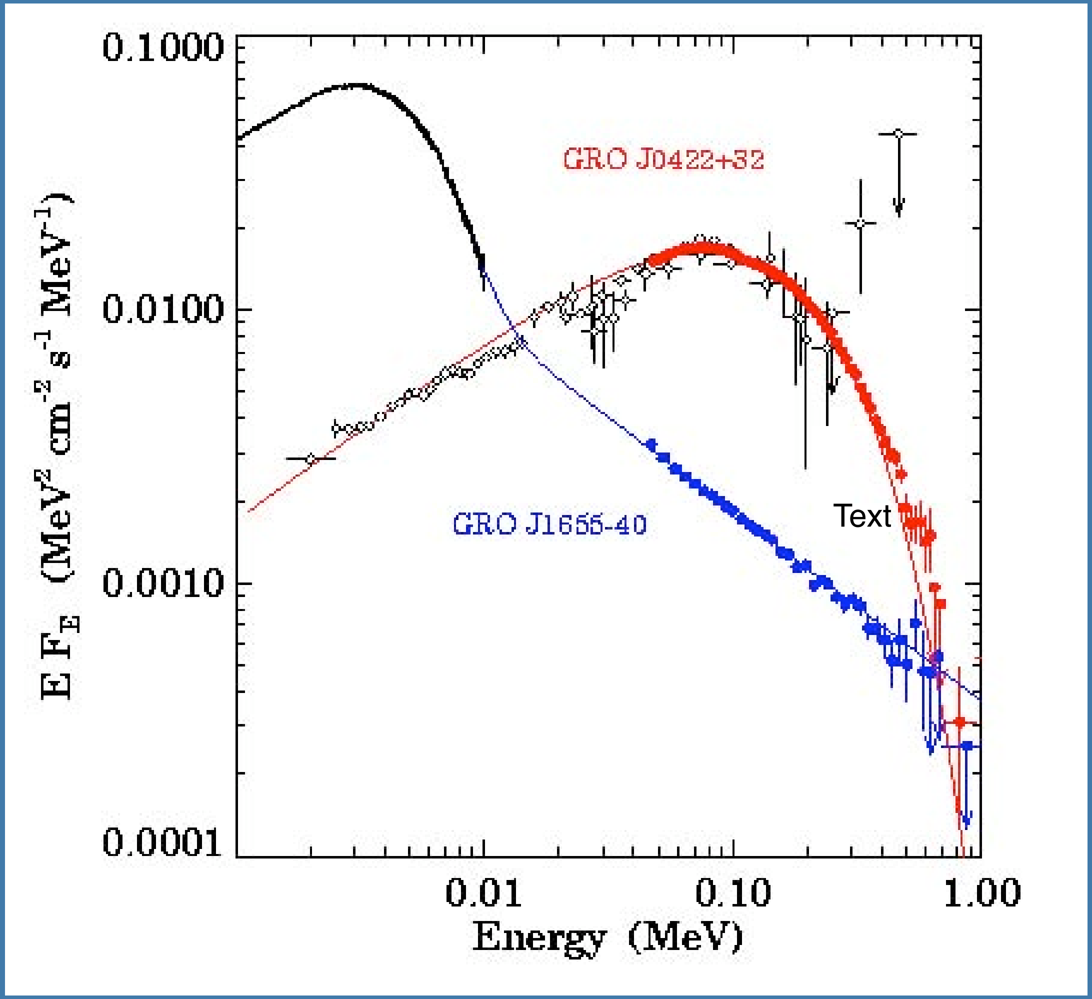


3. XTE J1118+480 : jet disc coupling on short time scales (<1s)



With help from: Andrea Merloni, Andy Fabian, Tomaso Belloni, Sylvain Chaty, Gottfried Kanbach, Hendrik Spruit, Pierre-Olivier Petrucci, Elisabeth Jourdain, Patrick Sizun, Marion Cadolle Bel, Guy Pooley, Clément Cabanac, Jérome Rodriguez, Jean Pierre Roques, Philippe Durouchoux, Andrea Goldwurm, Philippe Laurent

X-ray spectral states of galactic black holes



(from Grove et al. 1997)

- When $L_X > 0.01\, L_{Edd}$:
  - spectrum peaks in the X-rays
  - thermal disc spectrum
  + steep power law

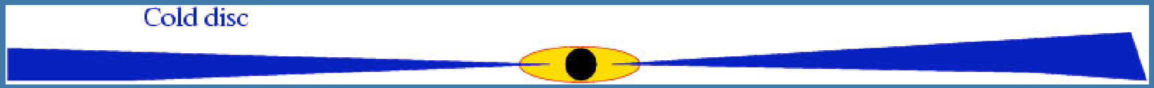
$\Rightarrow$ HIGH SOFT STATE

- When $L_X < 0.01\, L_{Edd}$:
  - spectrum peaks in the hard X-rays
  - hard power law
  + cut-off

$\Rightarrow$ LOW HARD STATE

Geometry of the accretion flow

High soft state:

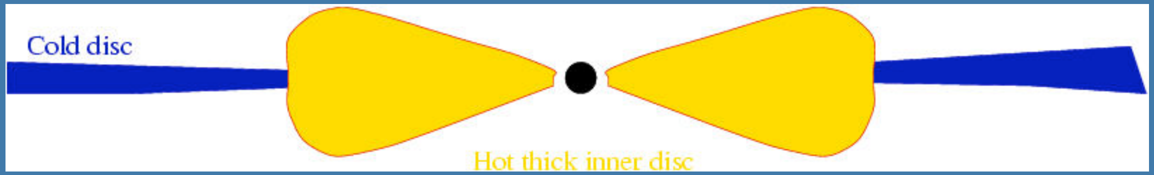


cold geometrically thin disc
down to the last stable orbit
+ weak corona

(Shakura & Sunyaev 1973)

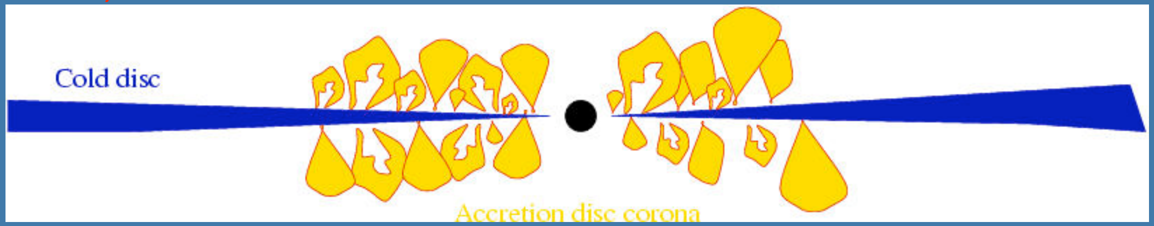
⇒ Thermal emission (mainly)

Low hard state:



cold disc truncated at ~
100-1000 Rg
+ hot inner disc

(Shapiro, Ligthman & Eardley 1976; Narayan & Yi 1994)

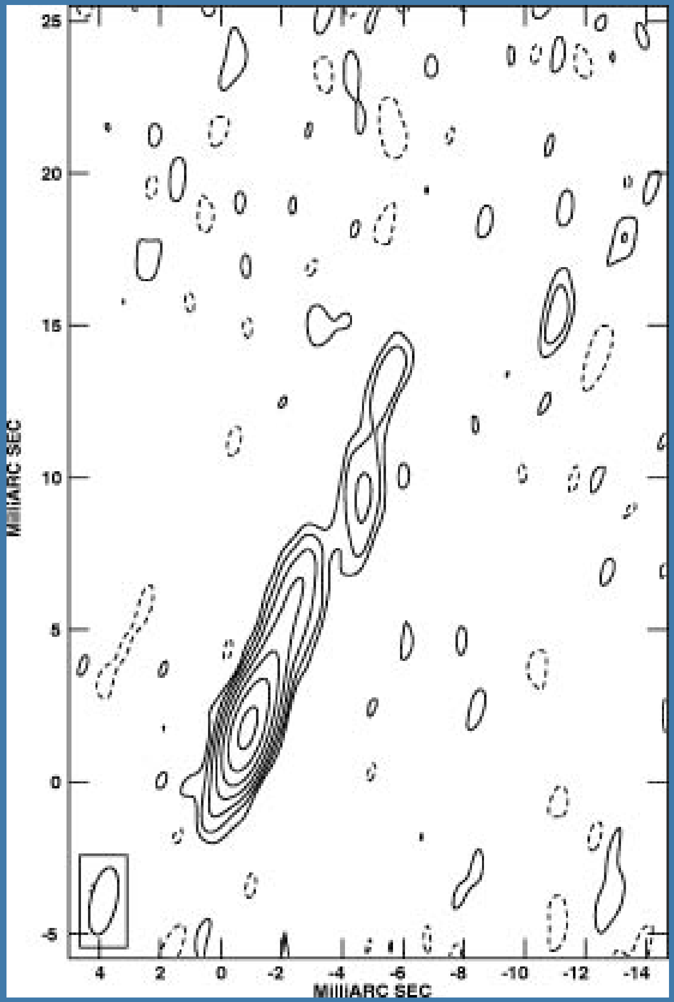


Accretion disc corona
atop a standard thin disc

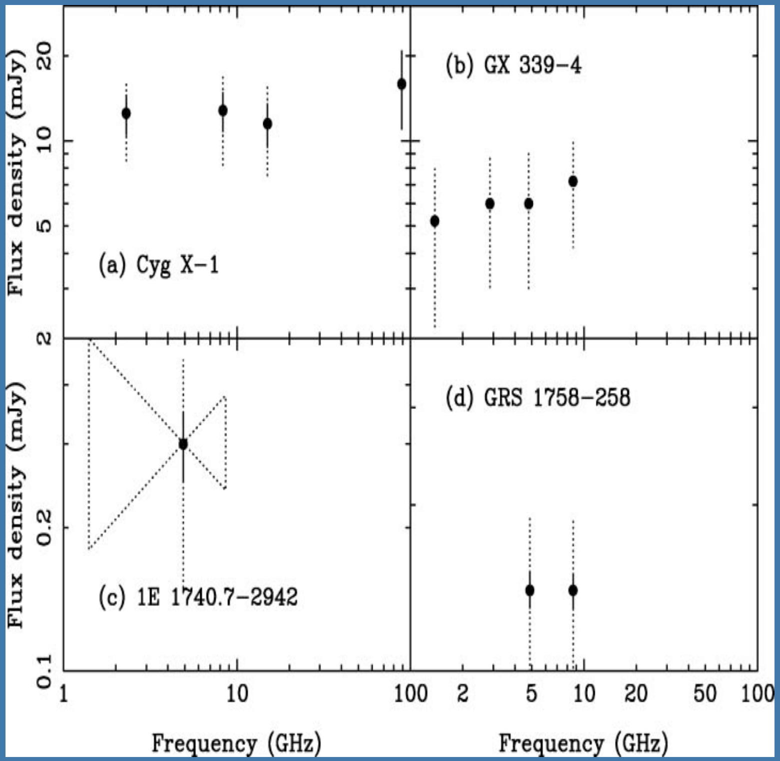
(Bisnovatyi-Kogan & Blinikov 1976; Haardt & Maraschi 1993; Beloborodov 1999)

⇒ componisation in the hot (10^9 K) plasma

Evidence for compact radio jets in the hard state



Cygnus X-1
(Stirling et al. 2001)

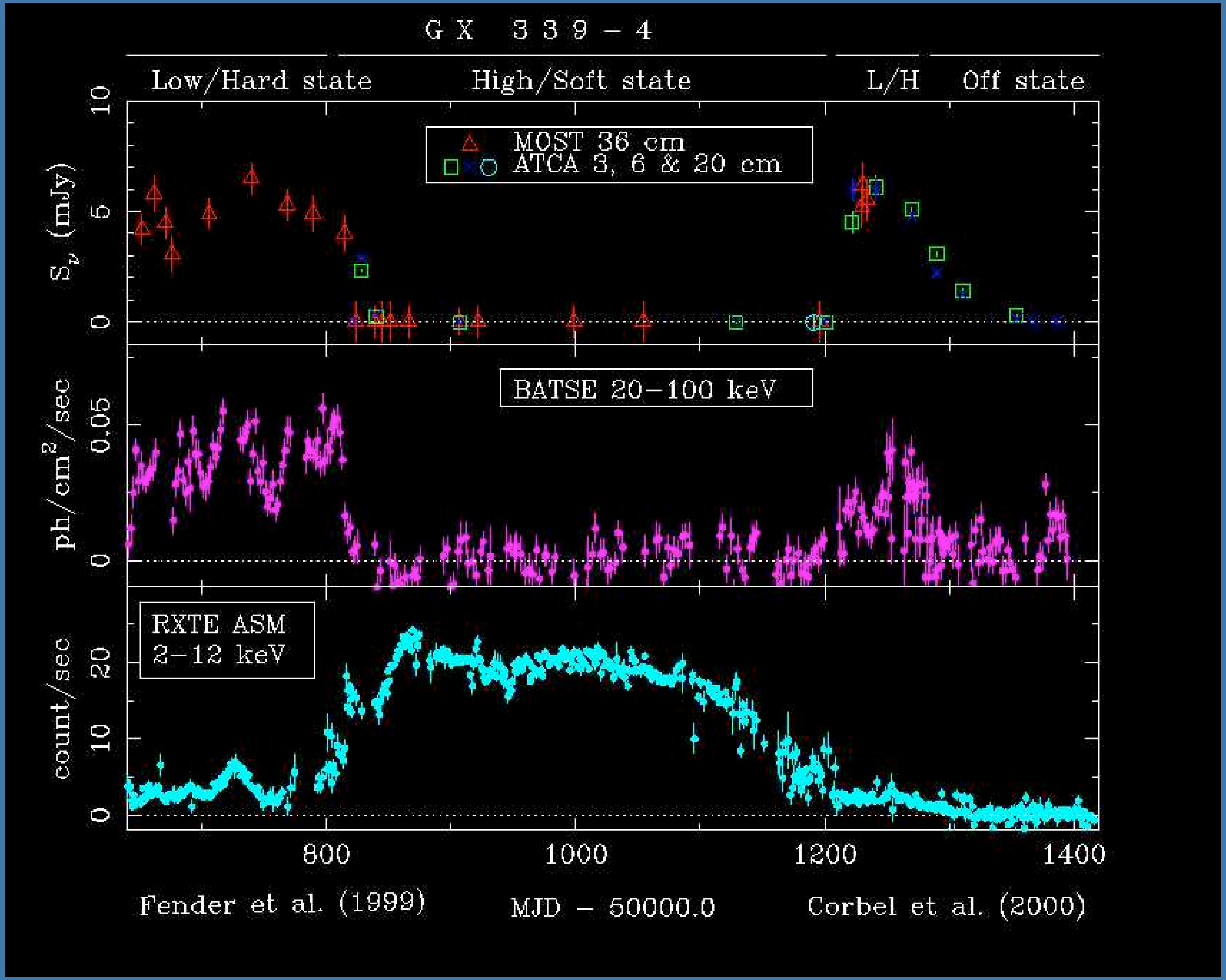


Flat/inverted radio spectra

(Fender 2001)

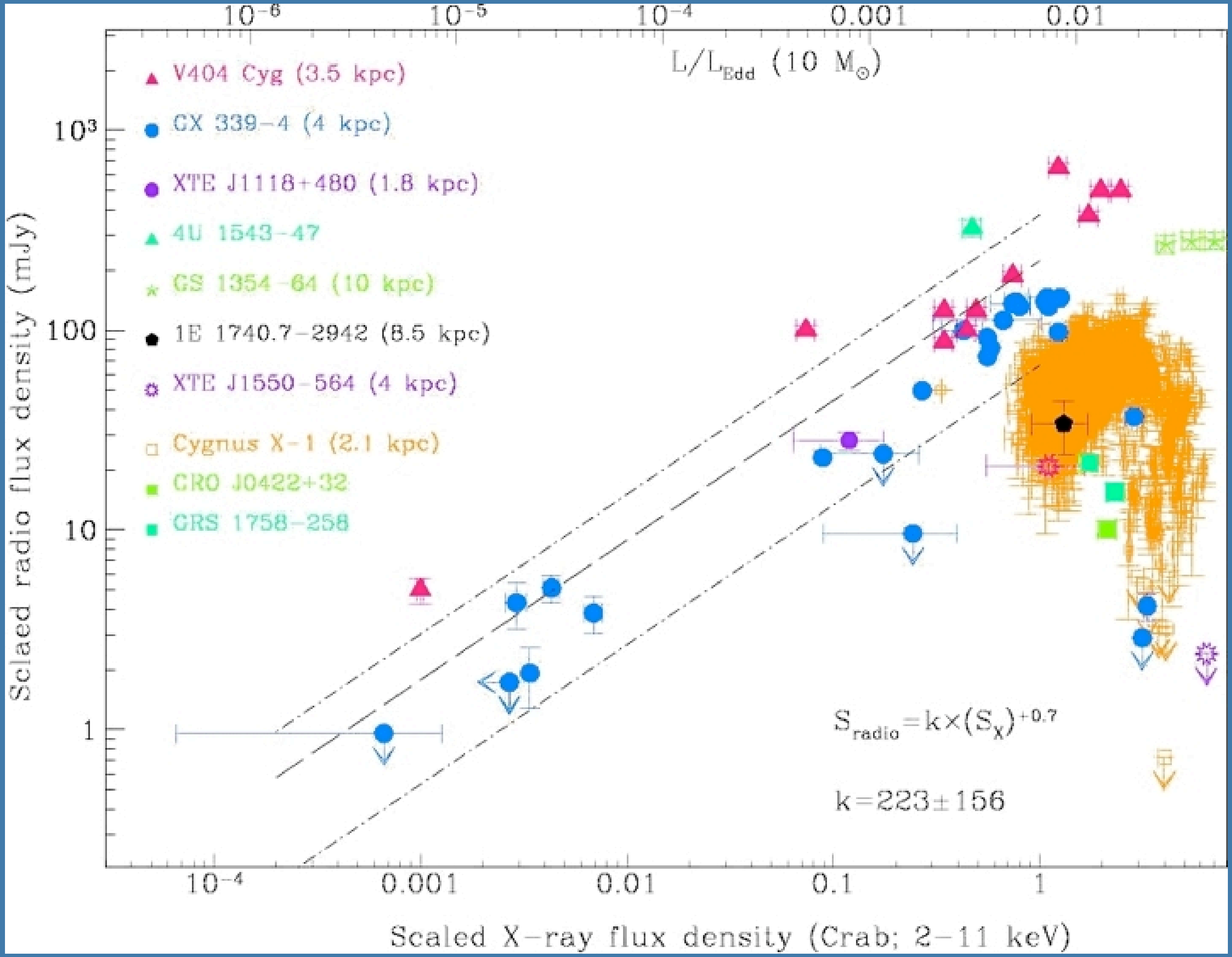
⇒ Self-absorbed synchrotron from compact jets

X-ray/Radio correlations



⇒ Jet quenched in the high soft state

Radio/X-ray correlation in X-ray binaries

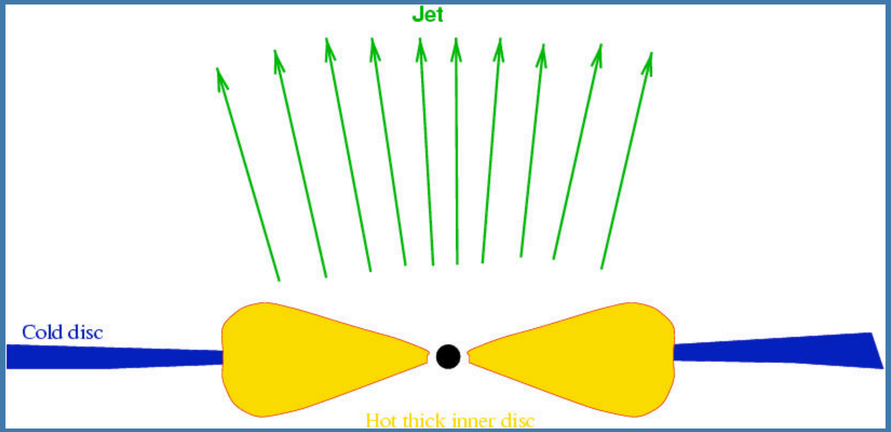


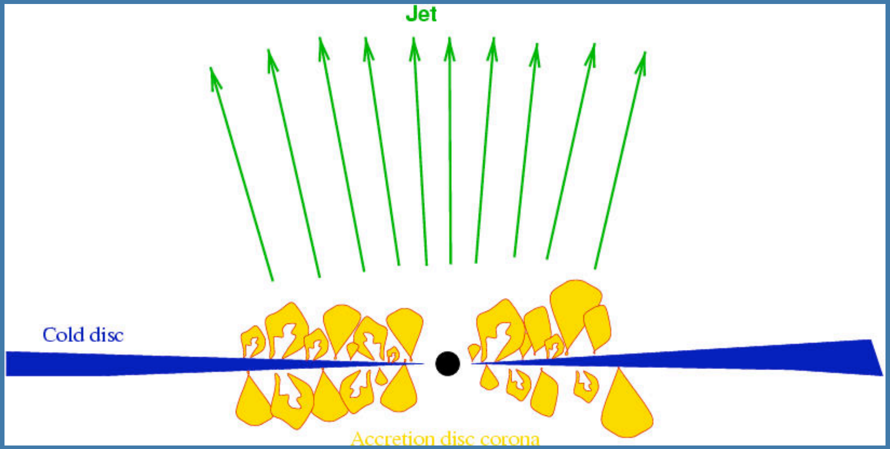
(Galllo, Fender & Pooley, MNRAS, 2003)

Origin of the radio/X-ray correlations ?

- Standard hard state models are wrong: X-ray emission from the jet
  (Falcke et al. 2001; Markoff et al. 2003; Georganopoulos et al. 2002)

- Jet/corona association (Meier 2001; Merloni & Fabian 2001;Livio et al. 2003)





A possible explanation:

- MHD jets are driven by the poloidal component of the magnetic field Bp

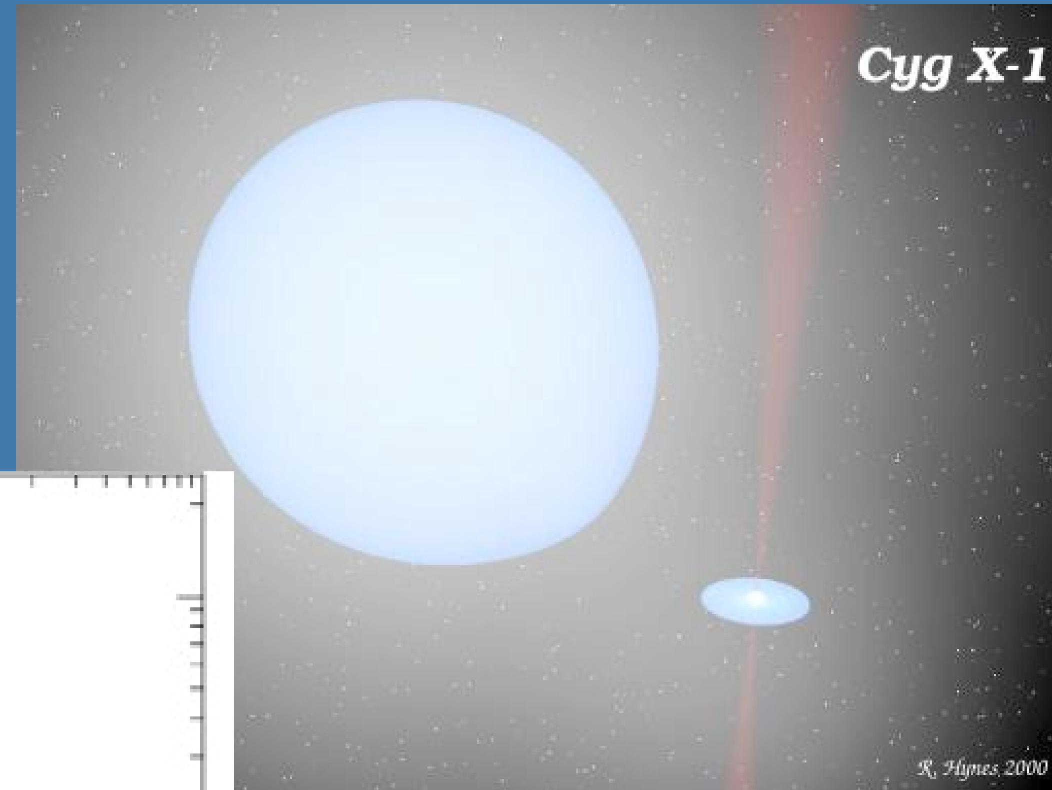
(Blandford & Znajek 1977, Blandford & Payne 1982)

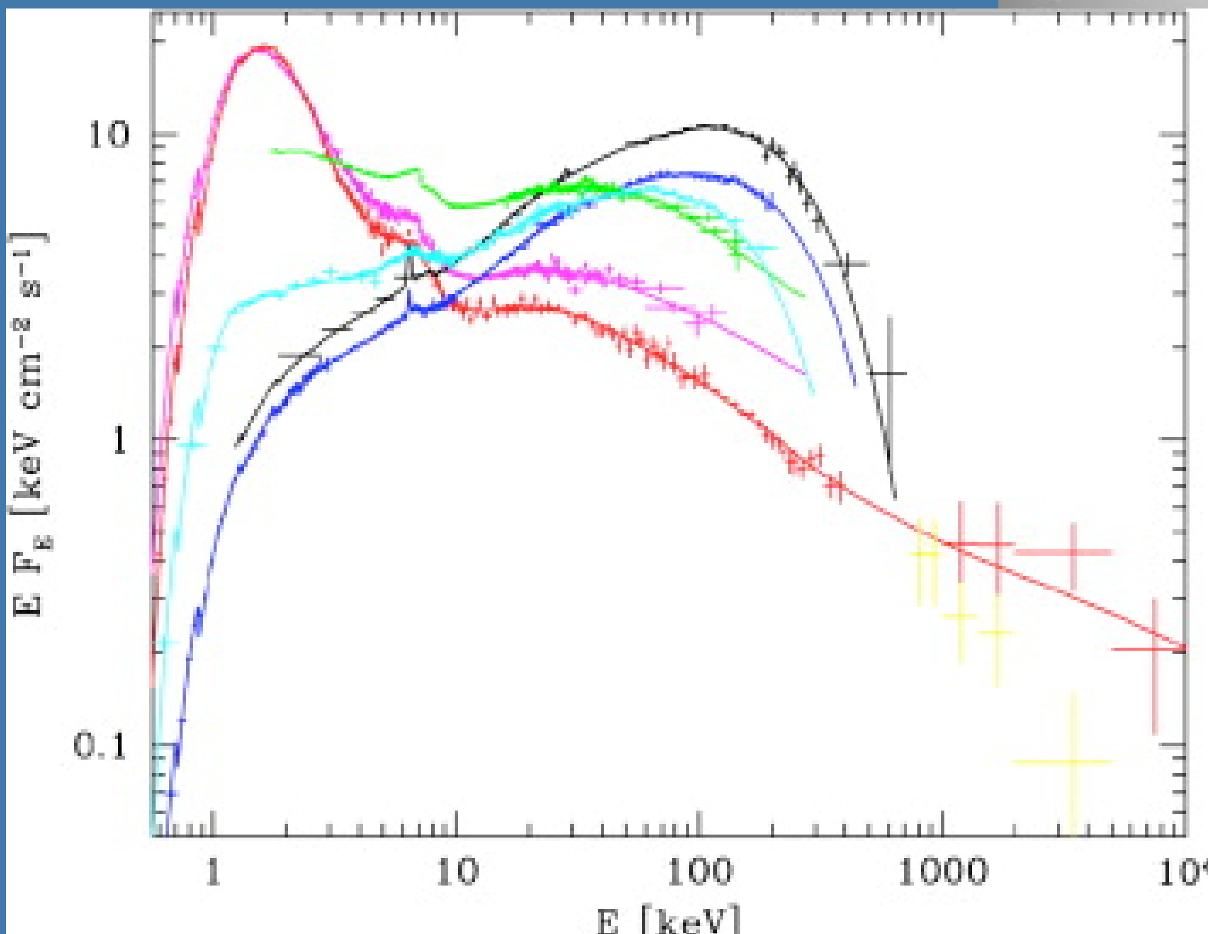
- If the field is generated by dynamo processes in the disc/corona: Bp/B~H/R

(Livio, Ogilvie & Pringle 1999; Meier 2001; Merloni & Fabian 2001)

⇒ geometrically thick accretion flows are more efficient at launching jets

Spectral states of Cygnus X-1

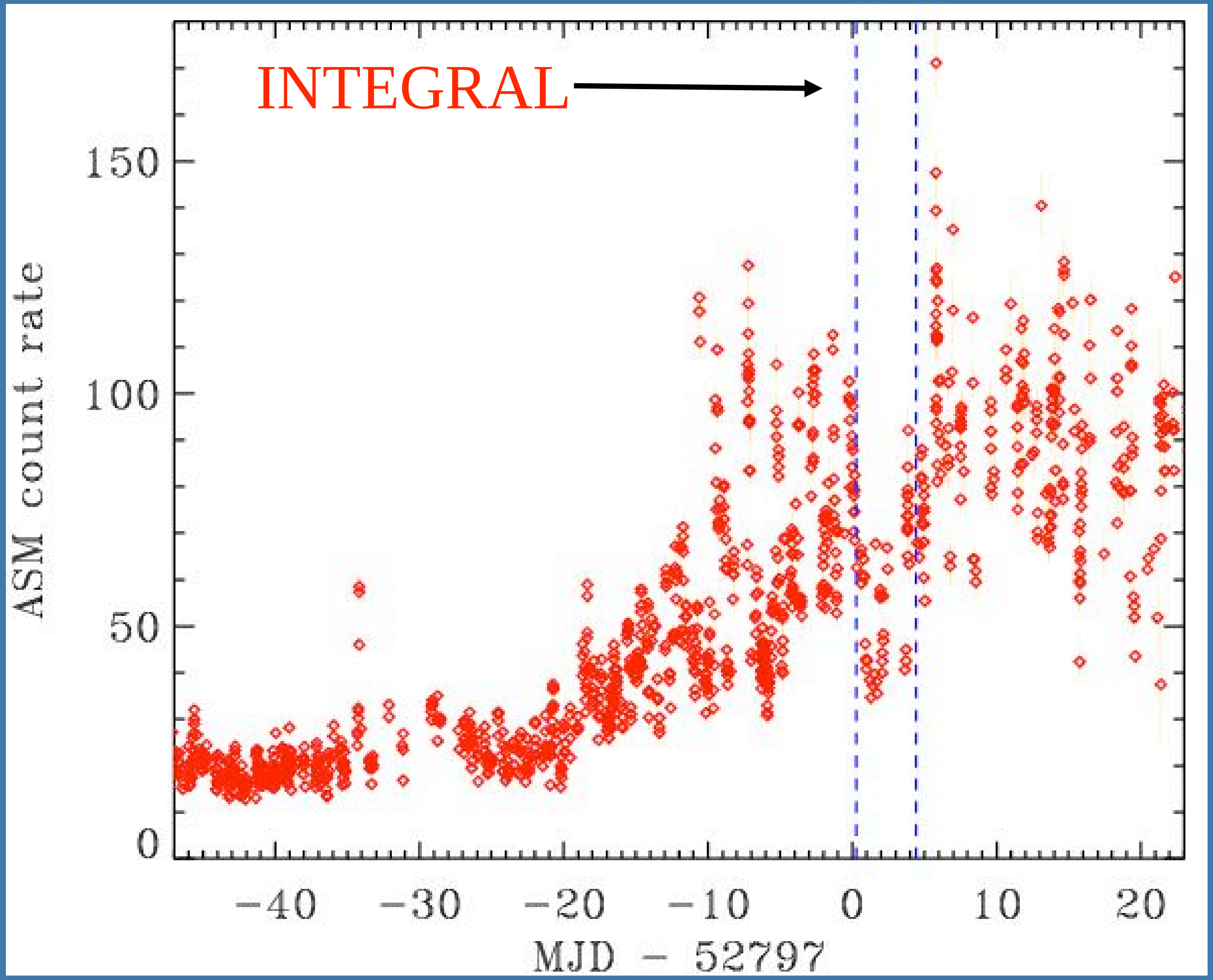


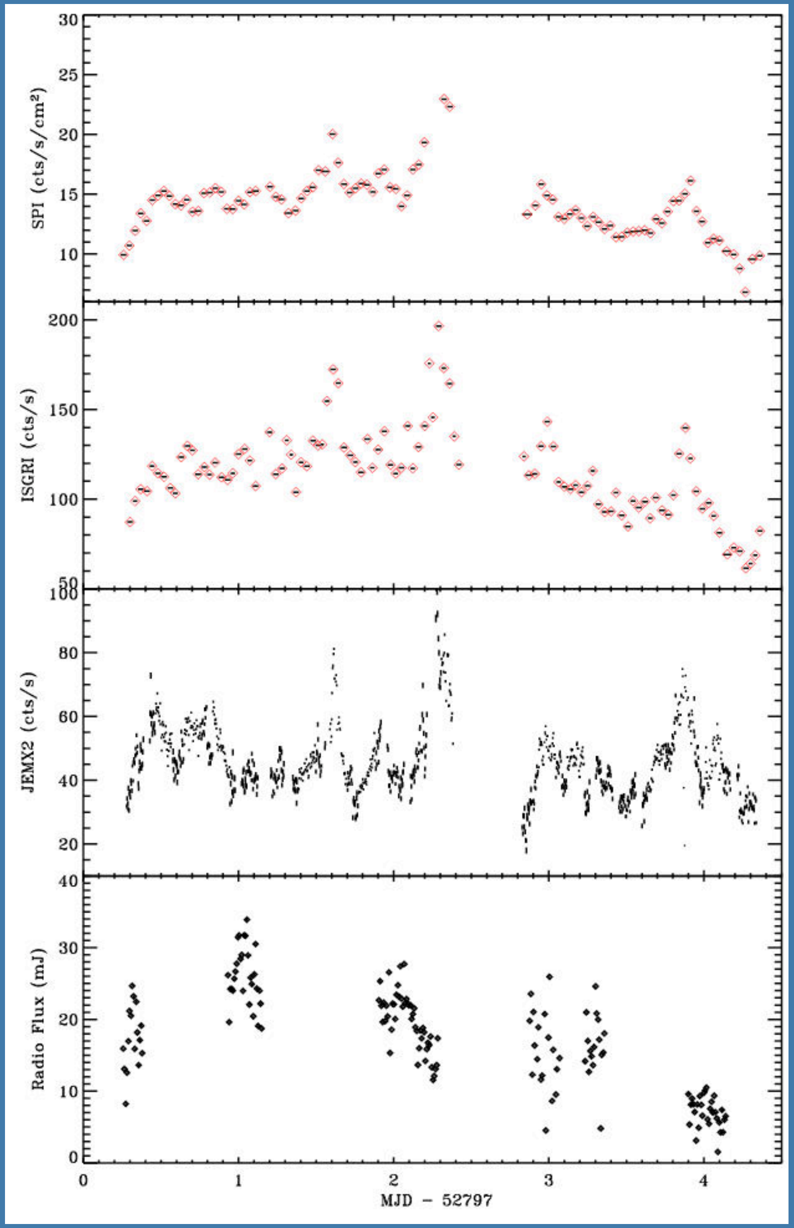


(from Zdziarski et al. 2002)

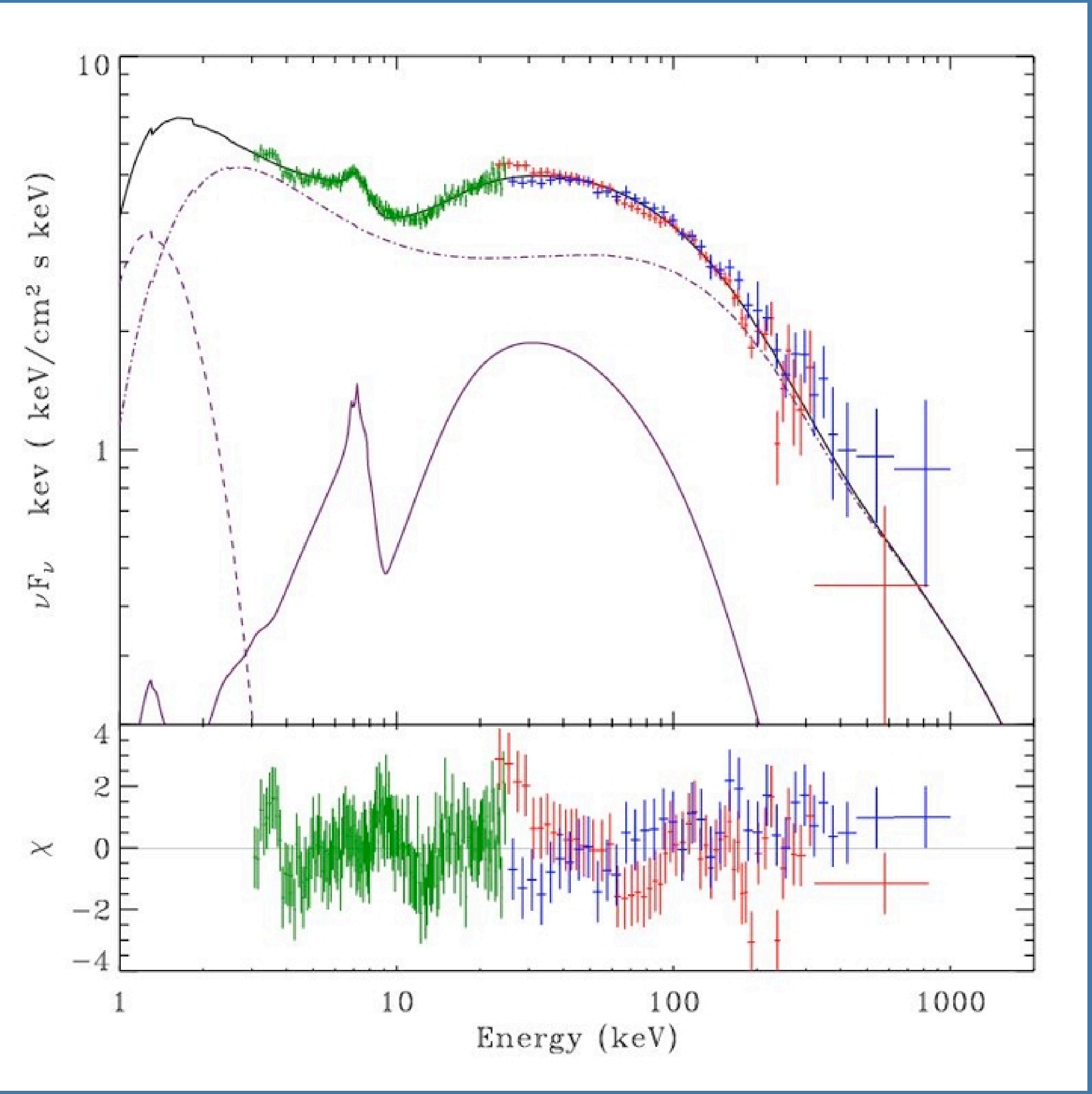
300 ks observation performed on June 7-11 2003 (rev 79/80)

At this epoch the RXTE ASM light curve of Cyg X-1
shows a strong X-ray activity characteristic of state transitions:





Fit of the broad band spectrum with EQPAIR



$$l_{\rm h}/l_{\rm s} = 0.85^{+0.02}_{-0.03}$$
$$l_{\rm nt}/l_{\rm h} = 0.51^{+0.04}_{-0.04}$$
$$\tau_{\rm i} = 0.55^{+0.01}_{-0.06}$$
$$\gamma_{\rm inj} = 8.41^{+0.62}_{-0.92}$$
$$\Omega/2\pi = 0.71^{+0.09}_{-0.03}$$
$$\xi = 525^{+143}_{-84}\ {\rm erg\,cm\,s^{-1}}$$
$$E_{\rm line} = 7.02^{+0.3}_{-0.2}\ {\rm keV}$$
$$EW = 90.2\ {\rm eV}$$
$$kT_{\rm e} = 50\ {\rm keV}$$
$$\tau_{\rm T} = 0.55$$
$$\chi^2/\nu = 244/245$$

Spectral variability

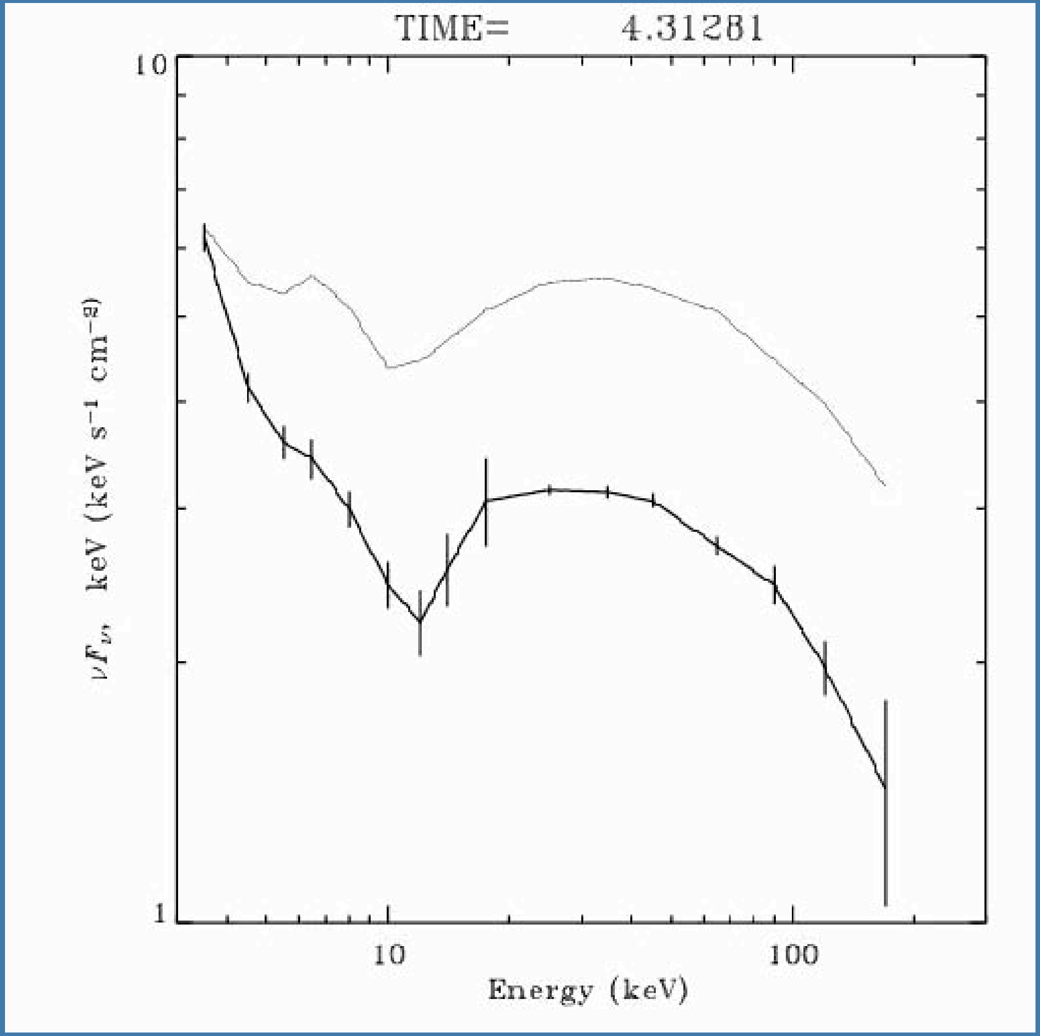
- Extract light curves in 18 energy bands

(resolution: 1 scw ~30 min)

- Light curves normalized to flux given by the best fit model of the time averaged spectrum (rev 79 80)

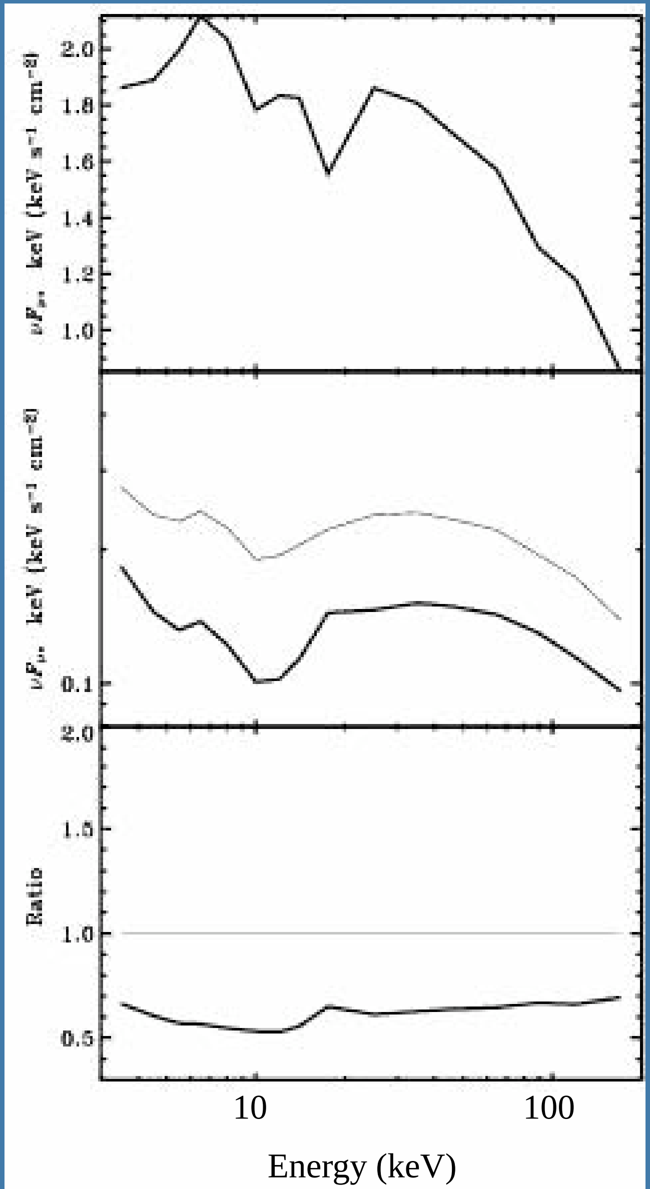
⇨ estimate of the spectrum for each science window

⇨ important spectral variability within the observation



Principal Component Analysis (PCA) shows 2 independent spectral variability modes...

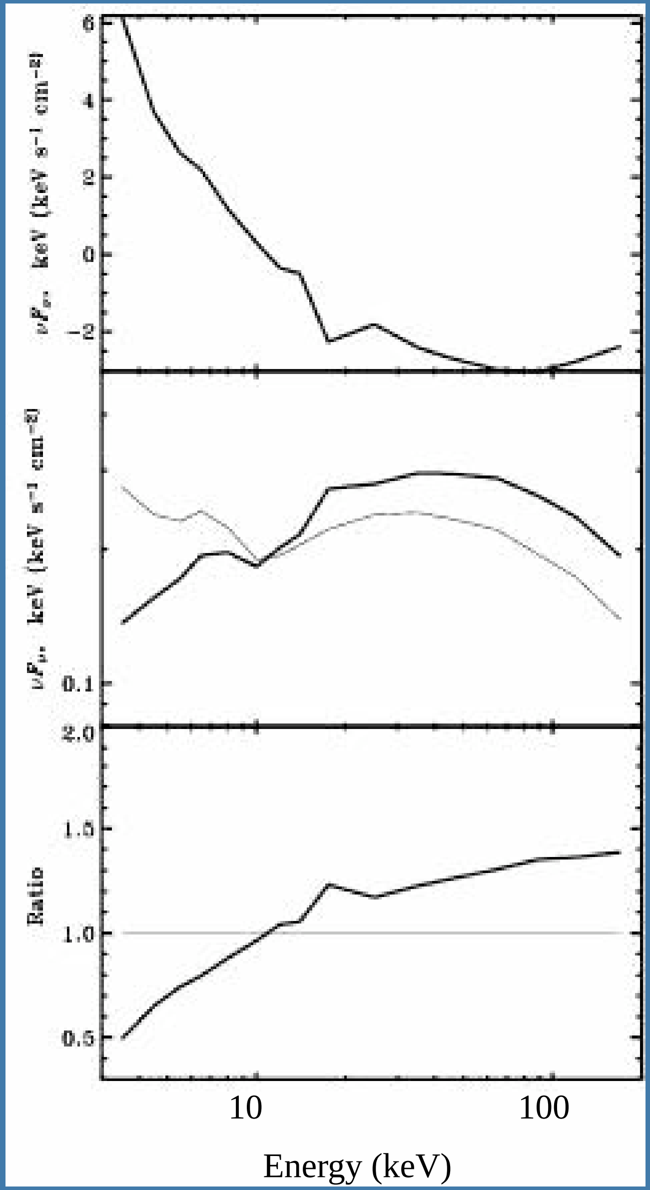
PCA 1: The flaring mode



67 % of the sample variance

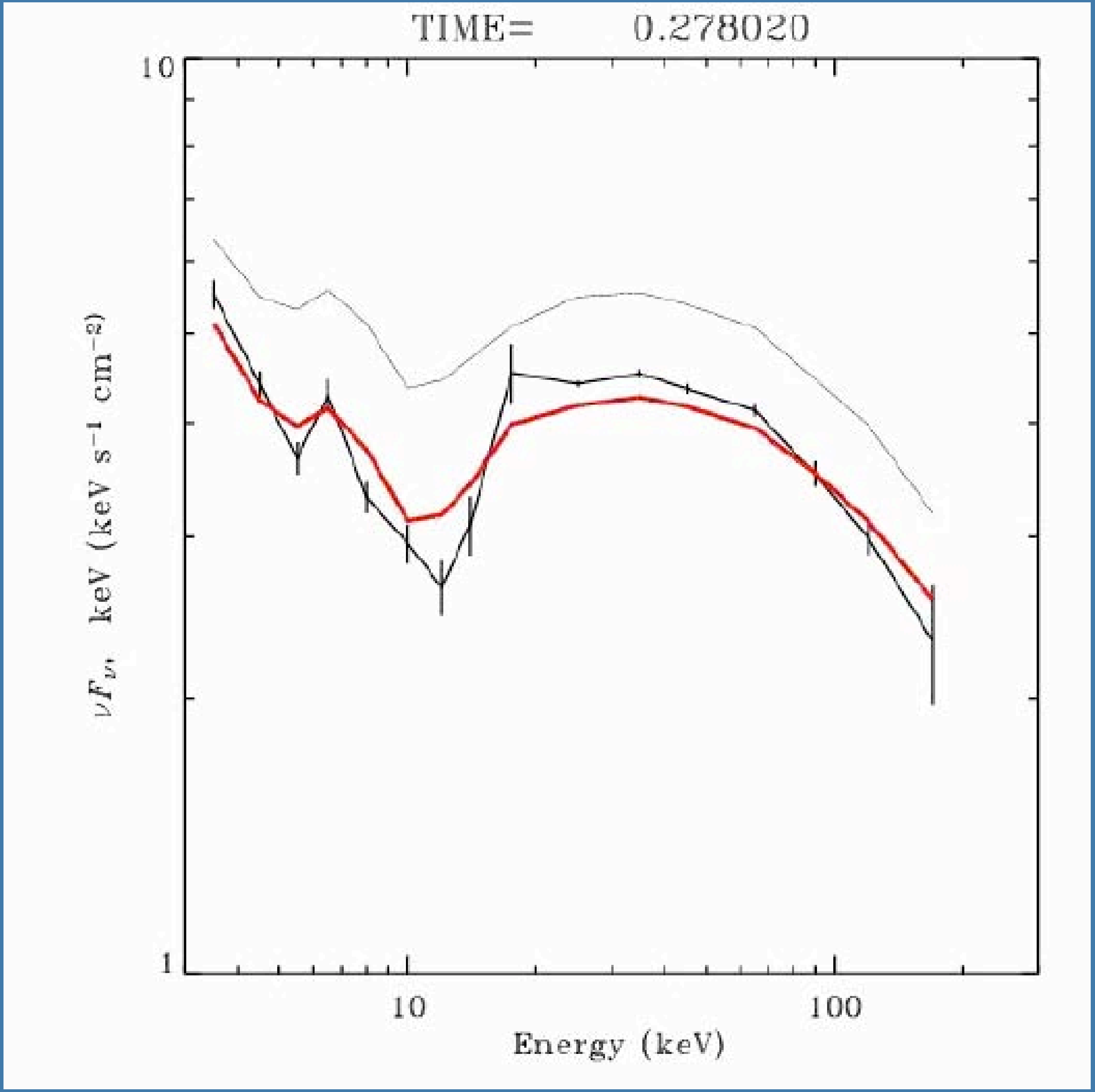
change in overall luminosity
with only little spectral changes

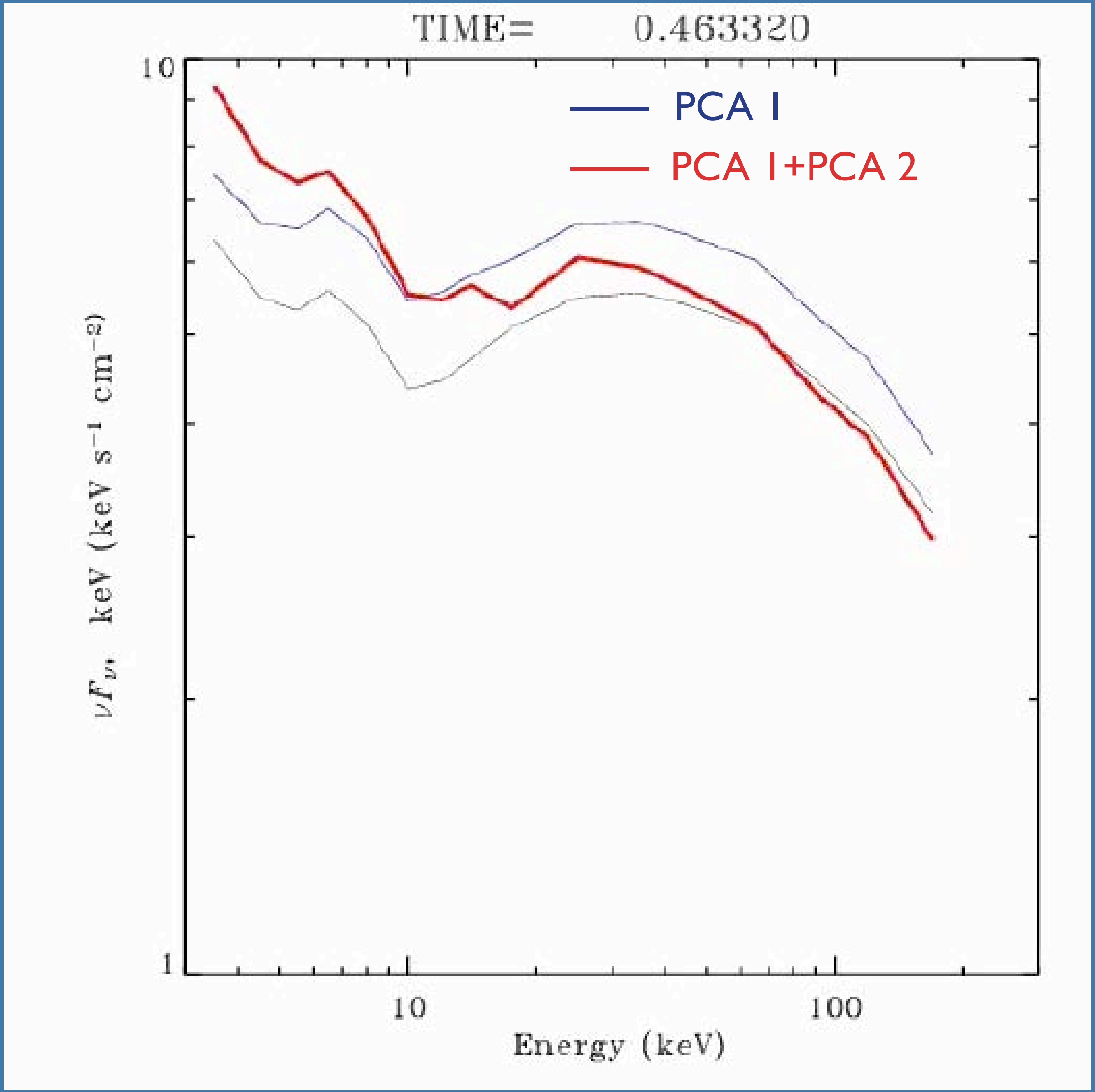
PCA 2: pivoting mode



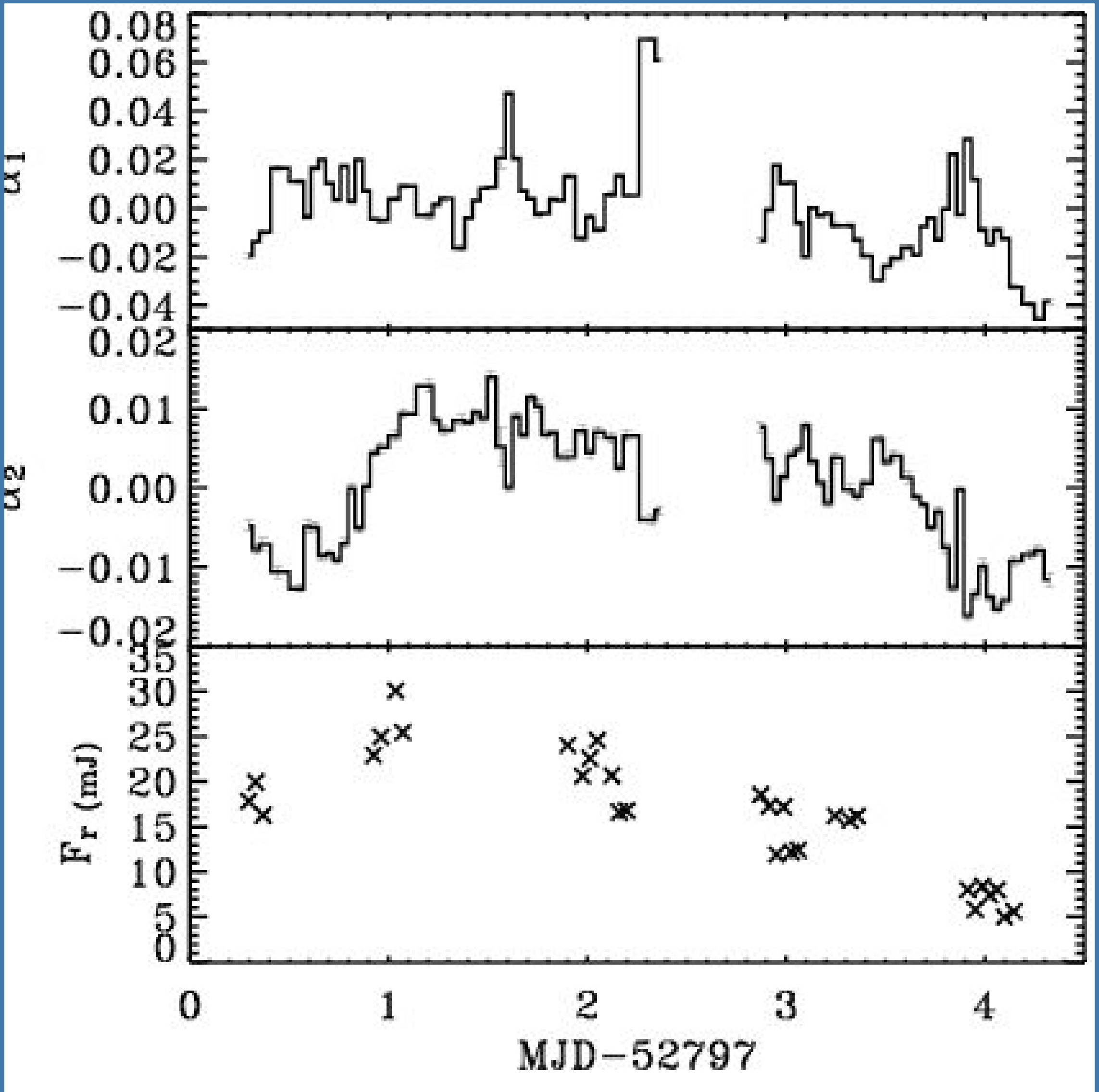
27 % of the sample variance

spectral pivot around ~ 10 keV


TIME= 0.278020
10
1
10
100
Energy (keV)
νF_ν keV (keV s^{-1} cm^{-2})



TIME= 0.463320
PCA 1
PCA 1+PCA 2
10
1
10
100
Energy (keV)
νF_ν keV (keV s^{-1} cm^{-2})



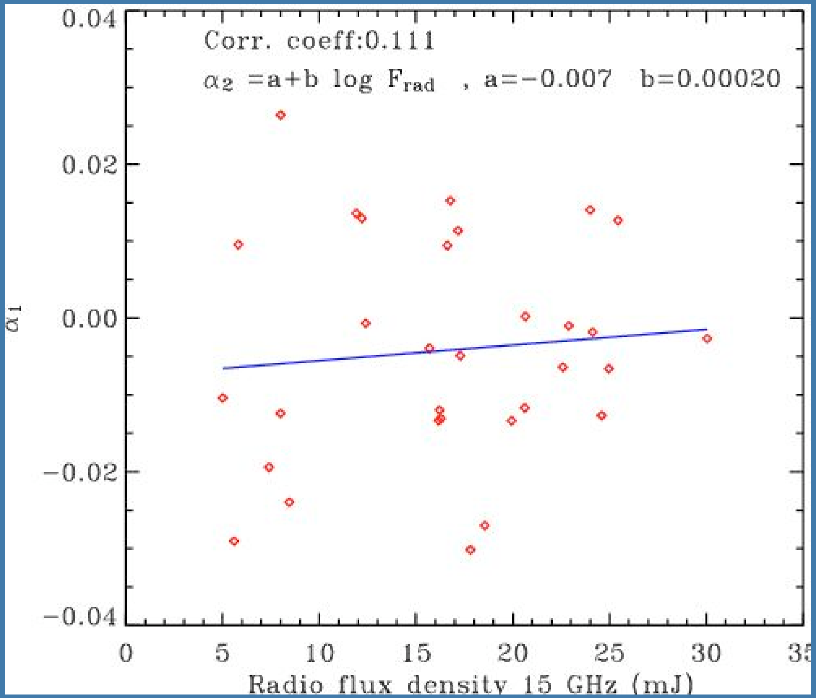
Flaring mode (PCA 1)
~ hard X-ray luminosity

Pivoting mode (PCA 2)
~ hardness

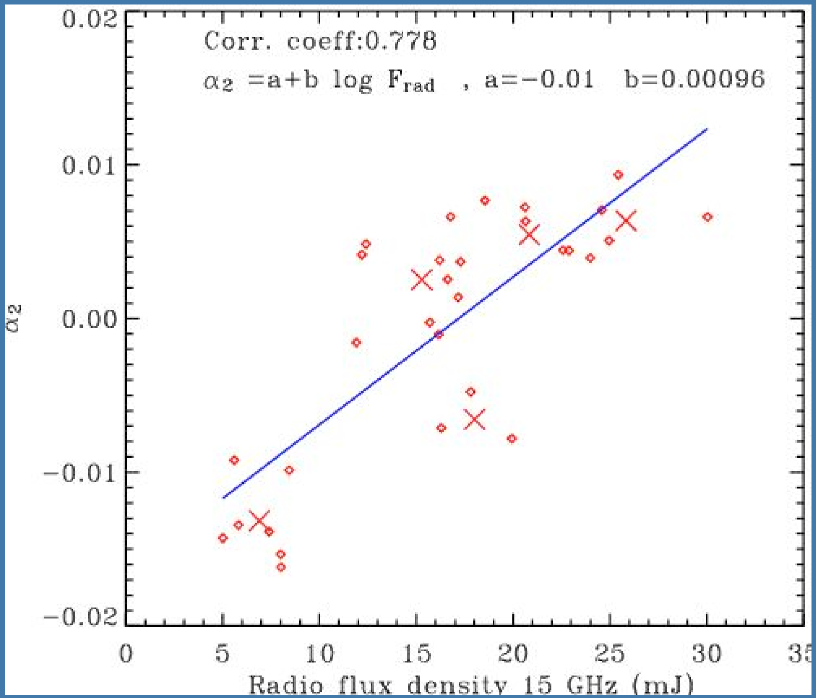
Radio flux

Radio vs high energies correlations

PCA 1 (flares) vs Radio



PCA 2 (pivot) vs Radio

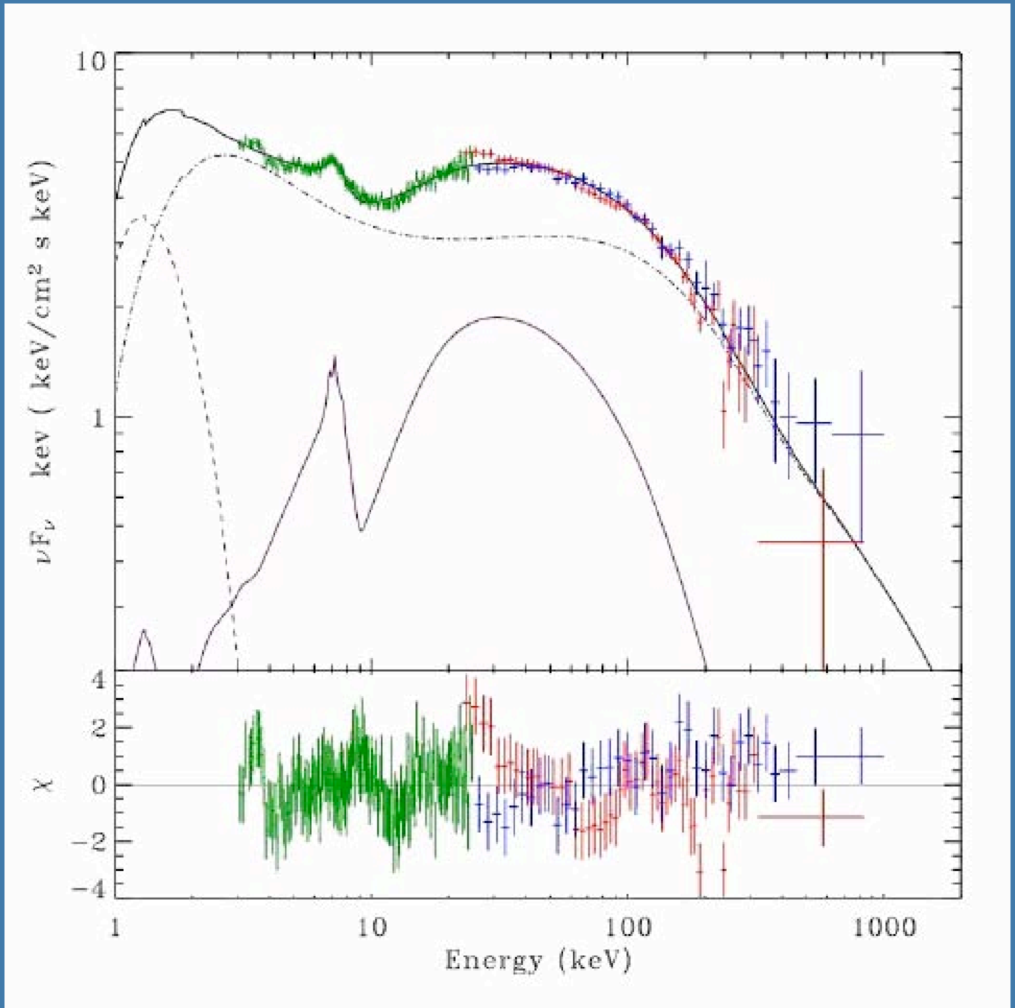


Radio flux uncorrelated with the flaring mode

but strongly correlated with the pivoting mode

harder spectra => stronger radio flux

PCA 1: changes in the heating rate of the hot plasma ?

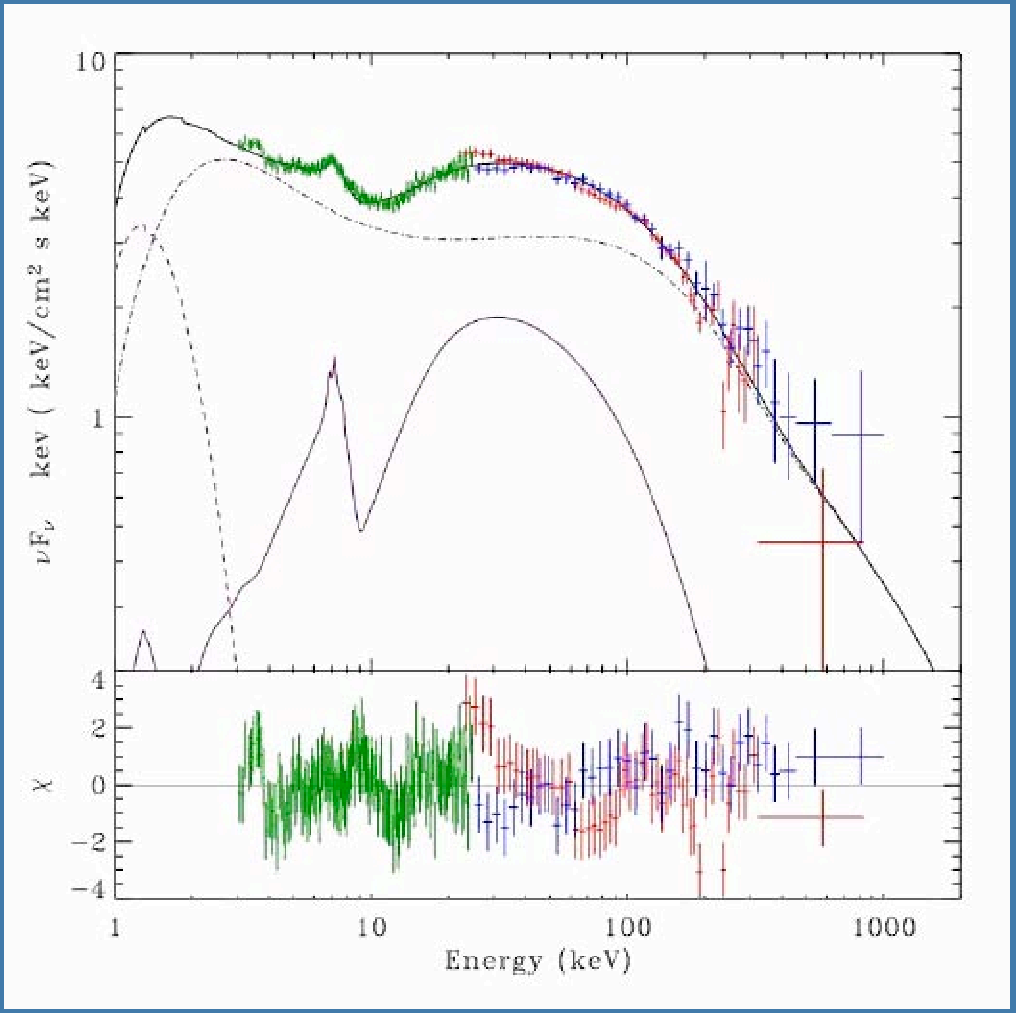


$$4 < l_h < 17$$

rapid changes in luminosity whith small spectral variability

rapid (hours) variations uncorrelated with extended radio jet emission

PCA 2: changes in the inner disc temperature ?



$T_{\rm in} \nearrow \Rightarrow L_{\rm disc} \propto T_{\rm in}^4 \nearrow$

$\Rightarrow$ cooling of the hot plasma $\nearrow$

$\Rightarrow$ softer spectrum

PCA 2 is a mini state transition:

soft $\longrightarrow$ hard$\longrightarrow$ soft

Radio flux correlated to hardness (pivoting mode)

$\Rightarrow$ jet power anti-correlates with the cold disc luminosity/ temperature

$$200\,{\rm eV} < kT_{\rm in} < 350\,{\rm eV}$$

This interpretation of PCA 2 requires a jump of bolometric luminosity by a factor of ~2 during the transition

$\Rightarrow$ inefficient accretion flow in the hard state ?

Jet disc coupling in Cygnus X-1 in an intermediate state

- PCA demonstrates 2 independent variability modes:
  1. Flares: changes in X-ray luminosity at constant spectrum

     fluctuations of the heating rate in the corona
  2. Pivoting around 10 keV correlated with the radio emission:

     fluctuations of the accretion disc luminosity

due to changes in the disc inner radius and size of the region

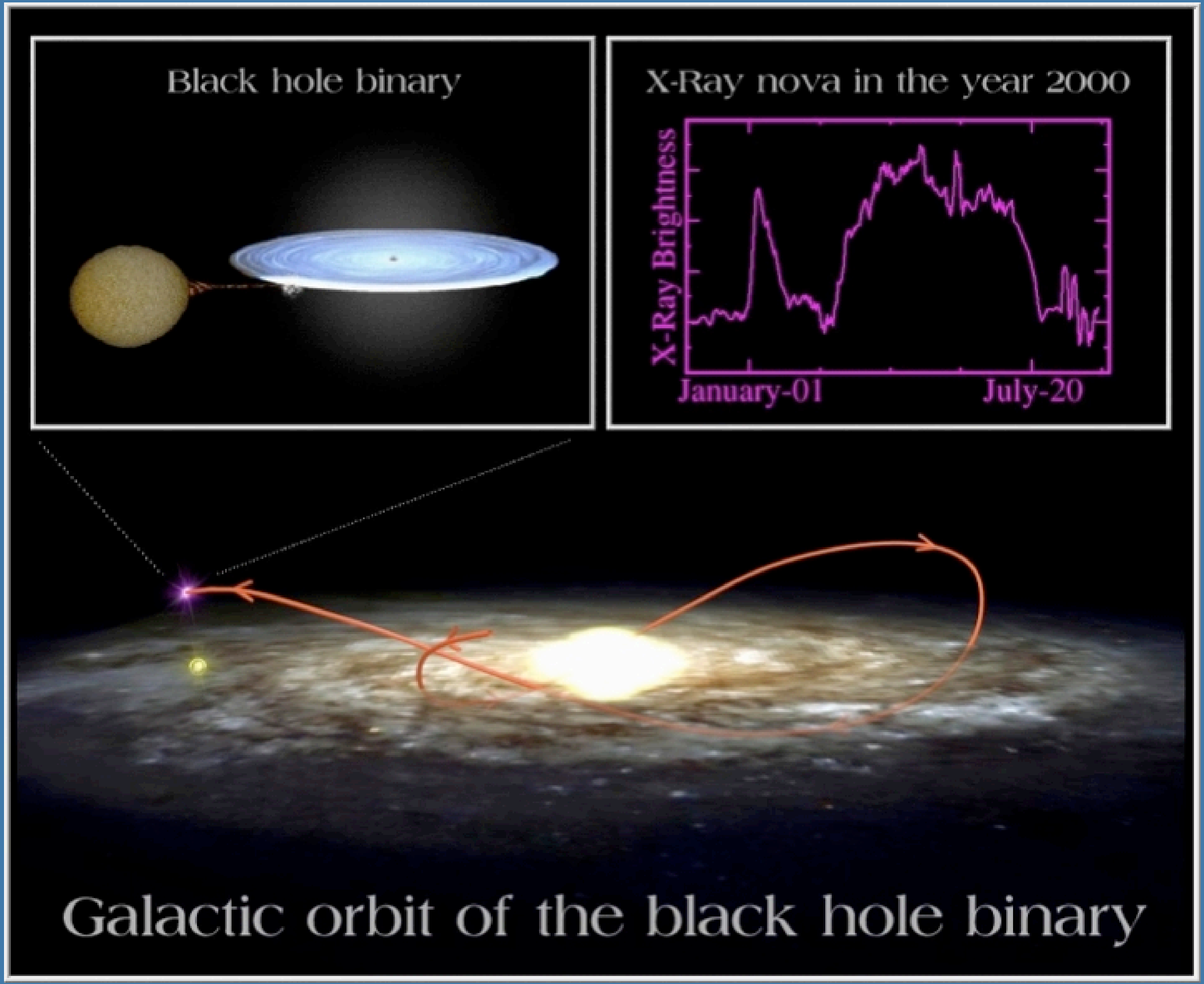
where the jet is launched (jet shrinks as the inner disc radius decreases) and/or redistribution of the accretion power between the jet and cold disc.

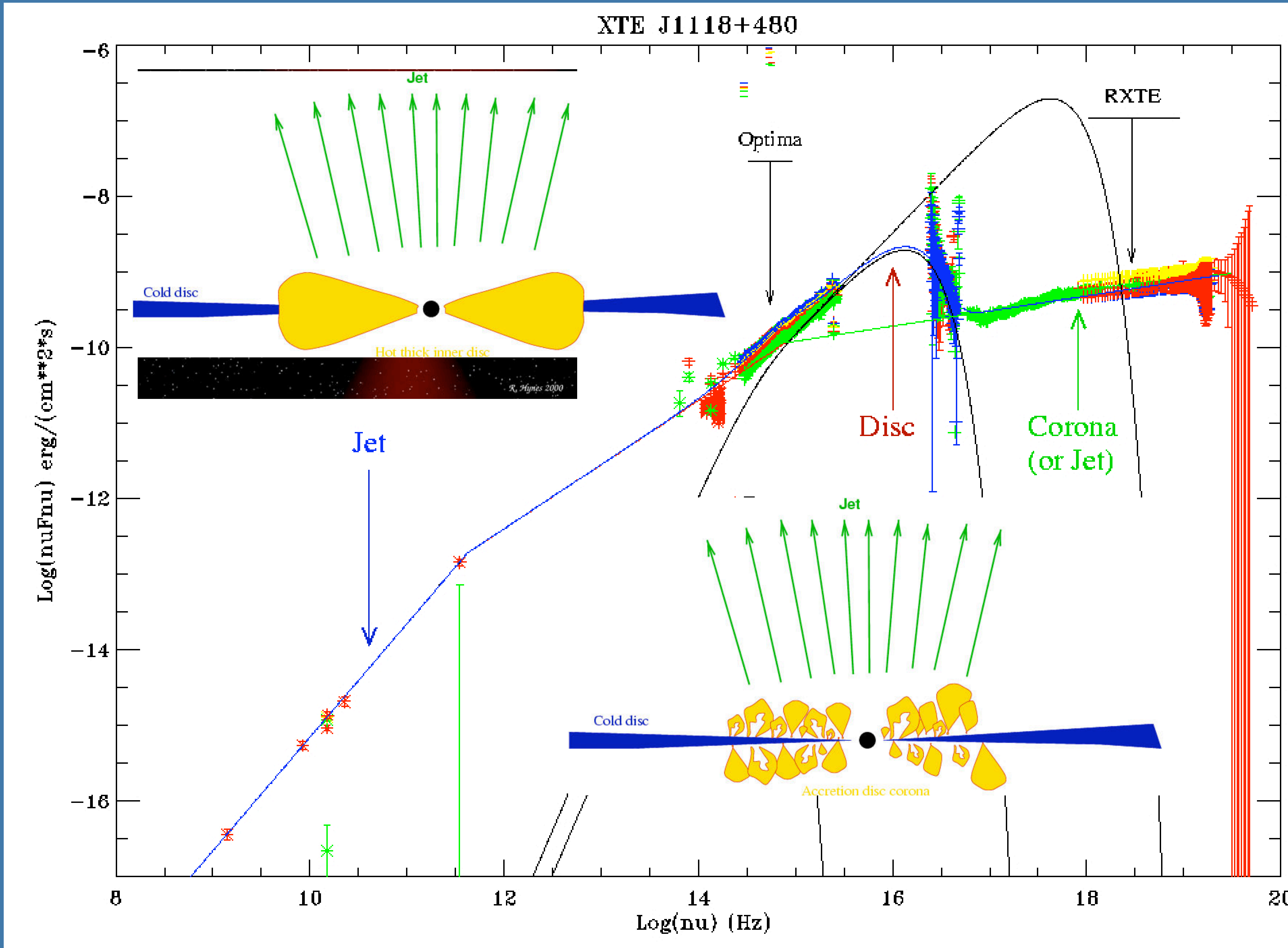
- Unanswered questions:

What causes the flaring mode ?

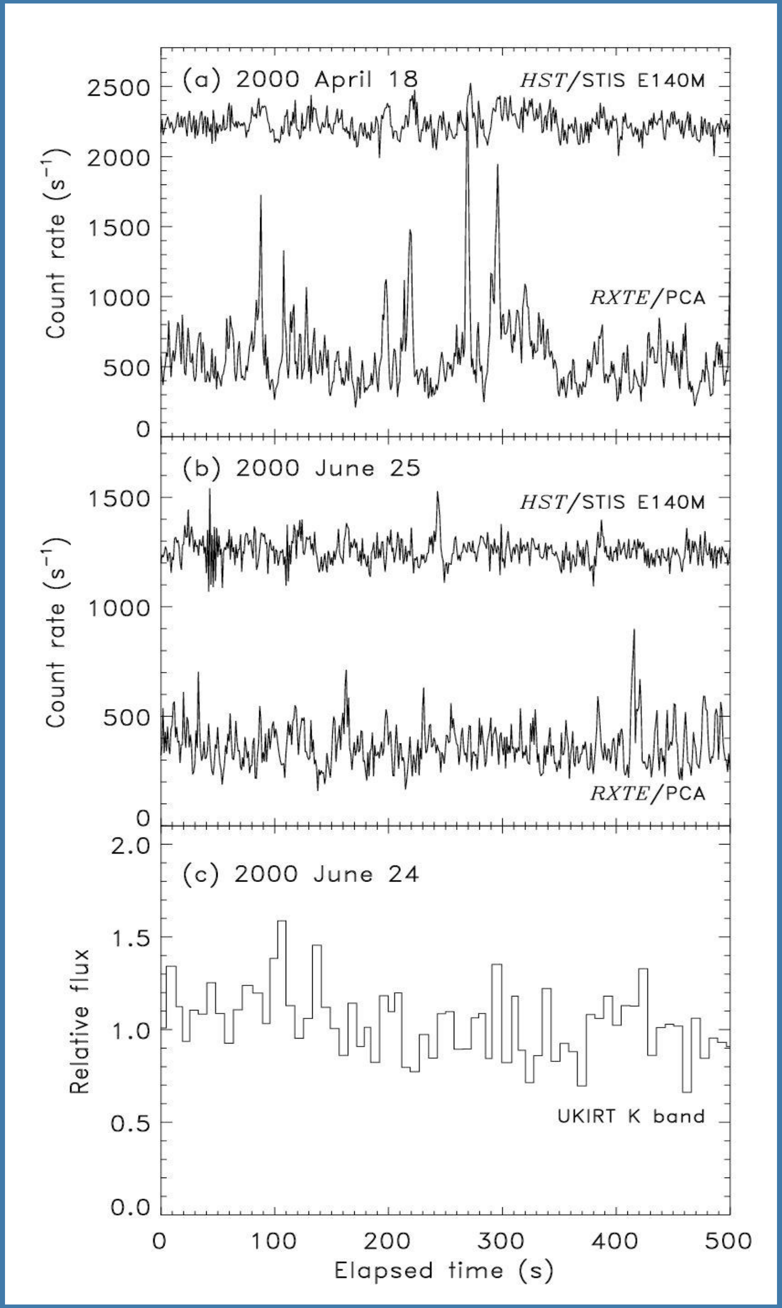
Why is the corona/hot flow luminosity unaffected by the dramatic changes in jet and disc power ?

The X-ray nova KV UMa (aka XTE J1118+480)





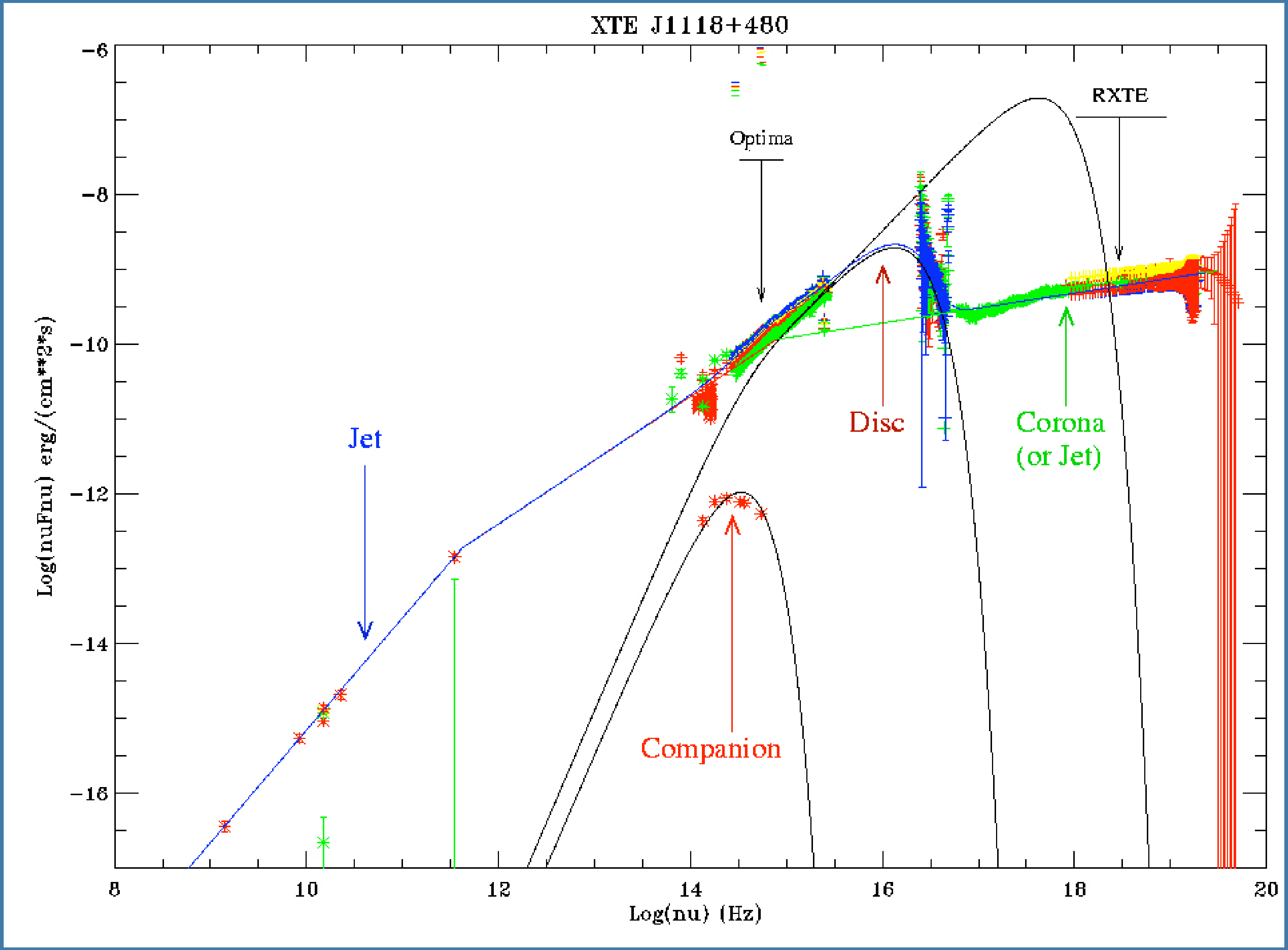
Chaty et al., MNRAS 2003



X-ray, UV, optical and IR flickering

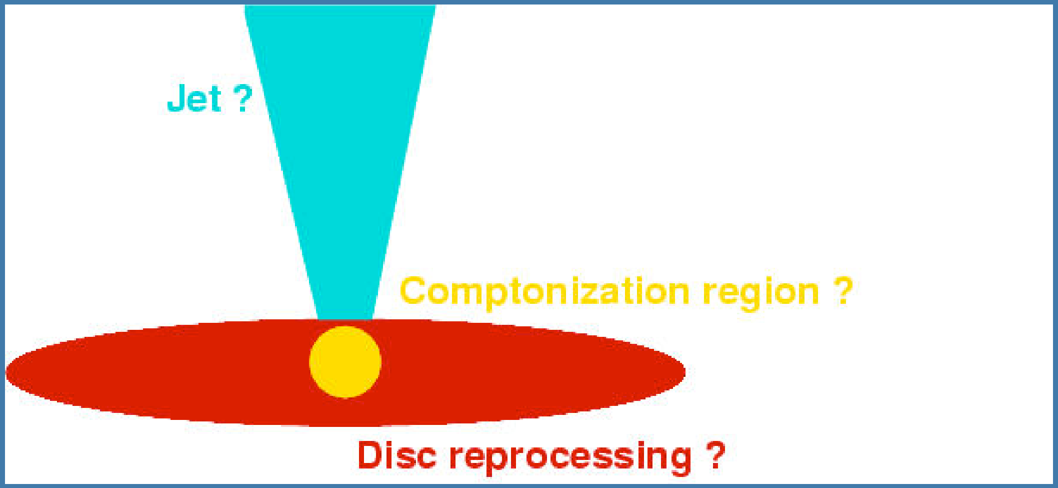
(From Hynes et al. 2003)

Origin of the optical flickering ?

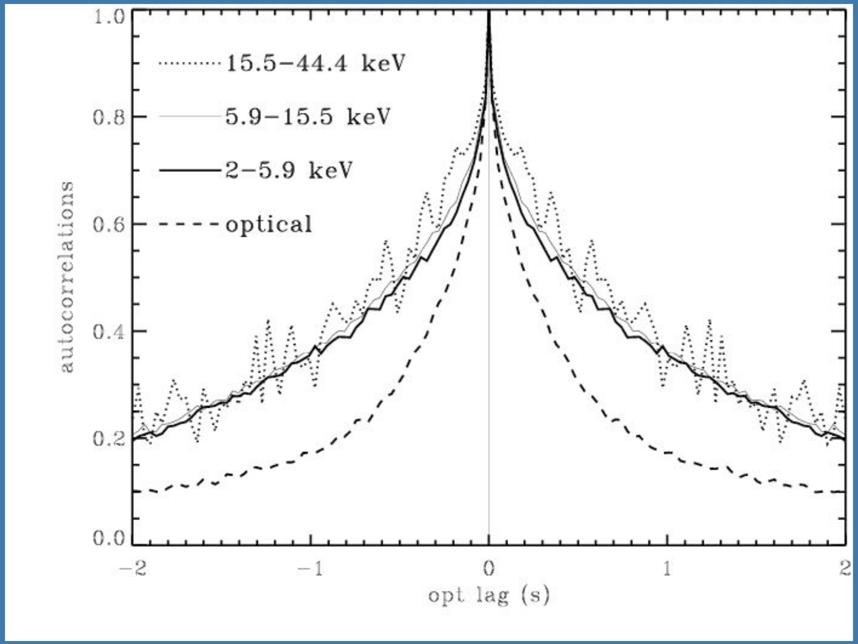


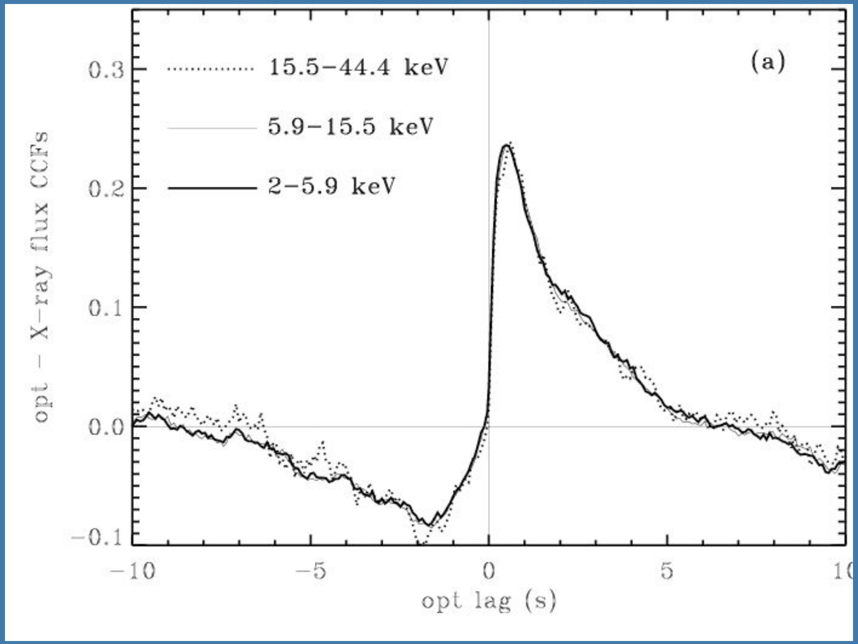
Origin of the optical flickering ?

- Reprocessing of the X-rays in the outer disc ?
  - optical varies on shorter time-scales than the X-rays
  - reprocessing models fail to reproduce the Opt/X CCF



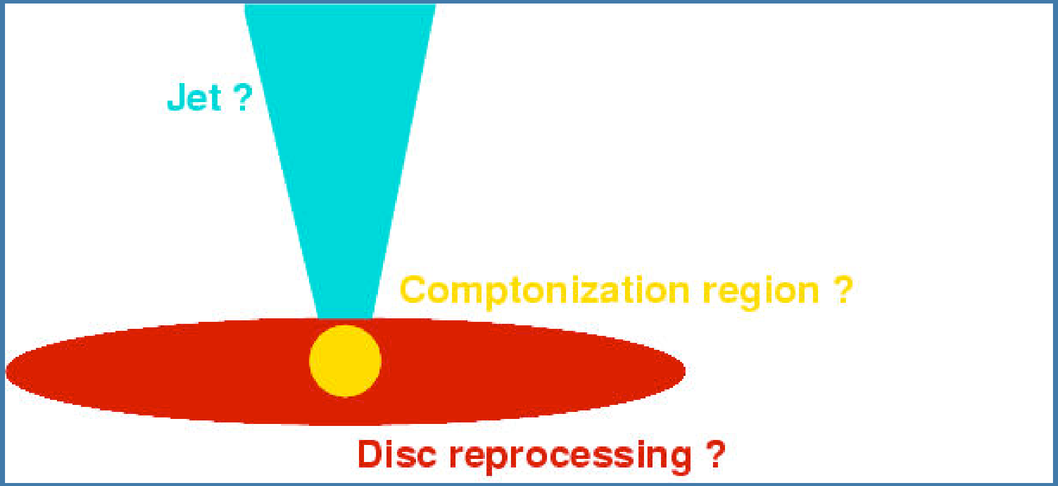
Auto-correlation and X/opt. cross-correlation functions





(Kanbach et al, Nature 2001,
Malzac et al., A&A 2003)

Origin of the optical flickering ?



- Reprocessing of the X-rays
  in the outer disc:

  - optical varies on shorter time-scales than the X-rays

  - reprocessing models fail to reproduce the Opt/X CCF

$\Rightarrow$ ruled out

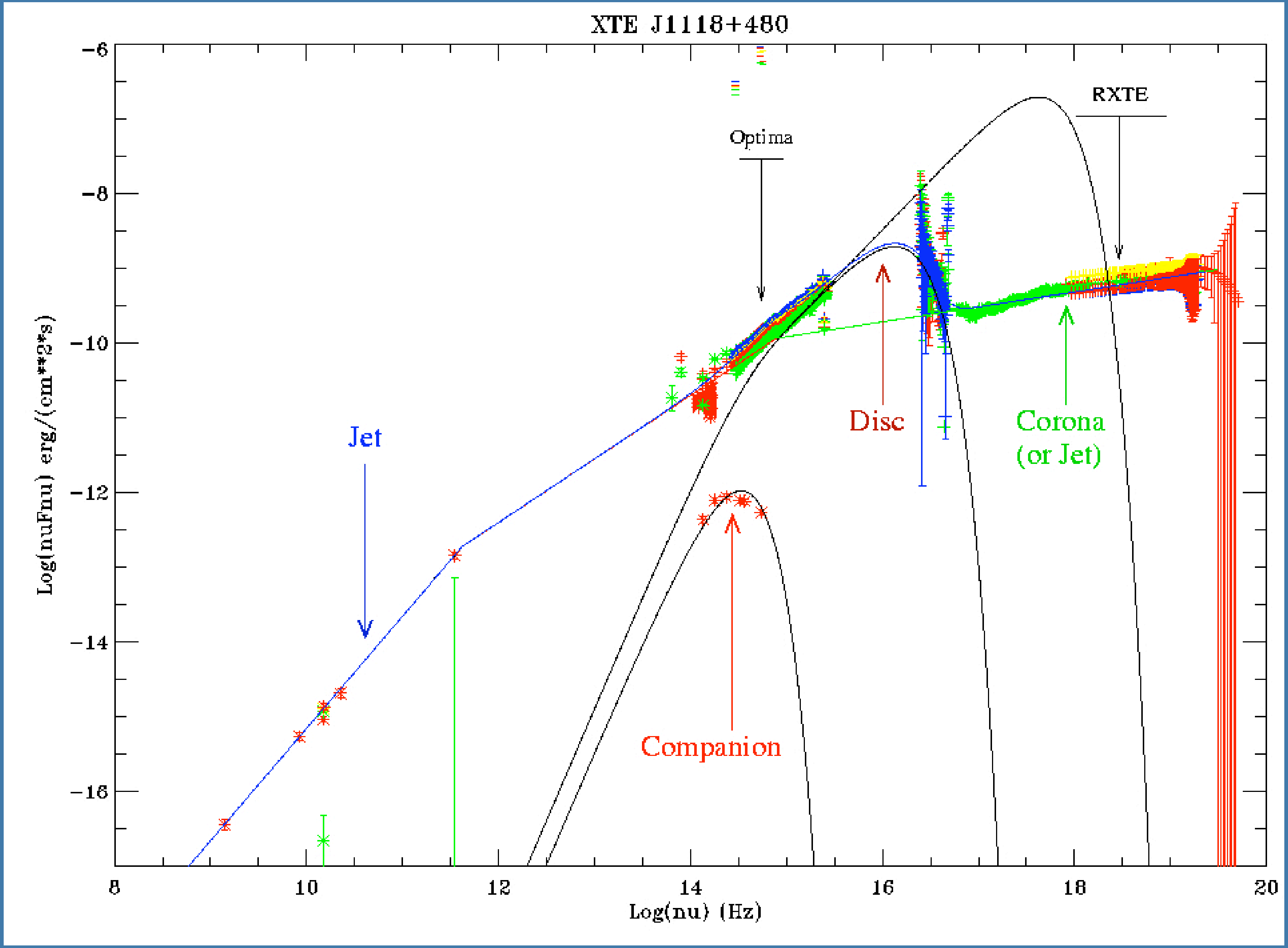
- Synchrotron emission
  in the Comptonising plasma:

- requires $R \sim 1000\ R_S$

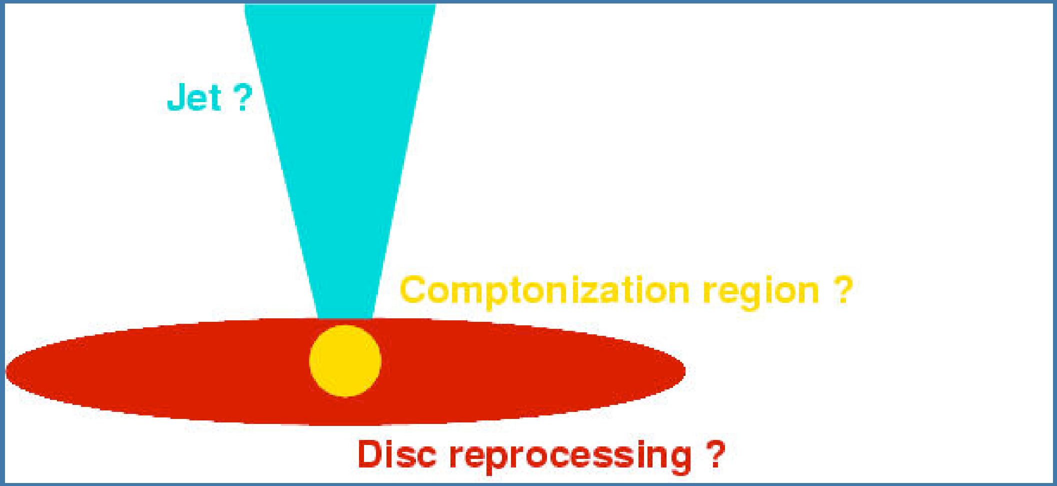
- problem to reproduce the IR/opt/UV variability

- power-law spectrum ?

Origin of the optical flickering ?



Origin of the optical flickering ?



- Reprocessing of the X-rays
  in the outer disc:

  - optical varies on shorter time-scales than the X-rays

  - reprocessing models fail to reproduce the Opt/X CCF

$\Rightarrow$ ruled out

- Synchrotron emission
  in the Comptonising plasma:

- requires $R \sim 1000\ R_S$

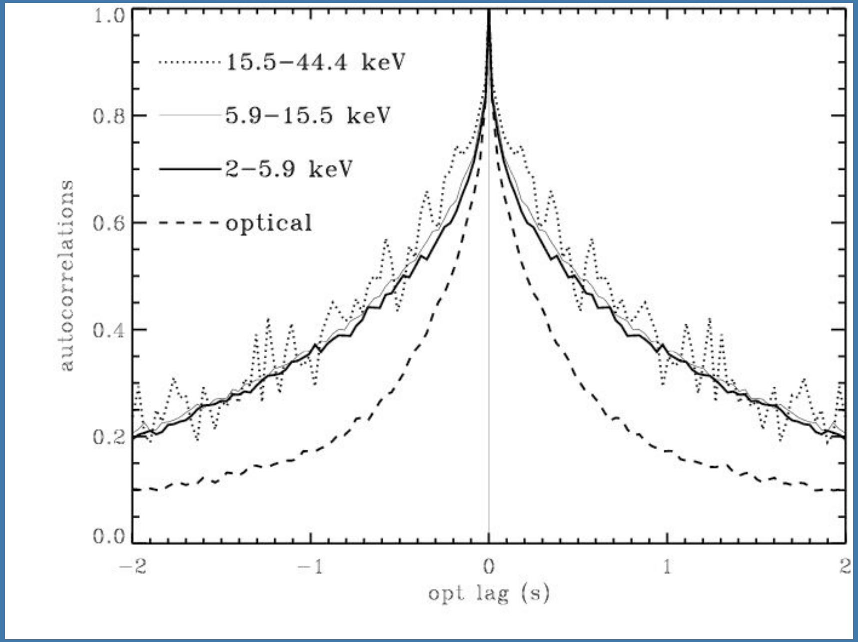
- problem to reproduce the IR/opt/UV variability

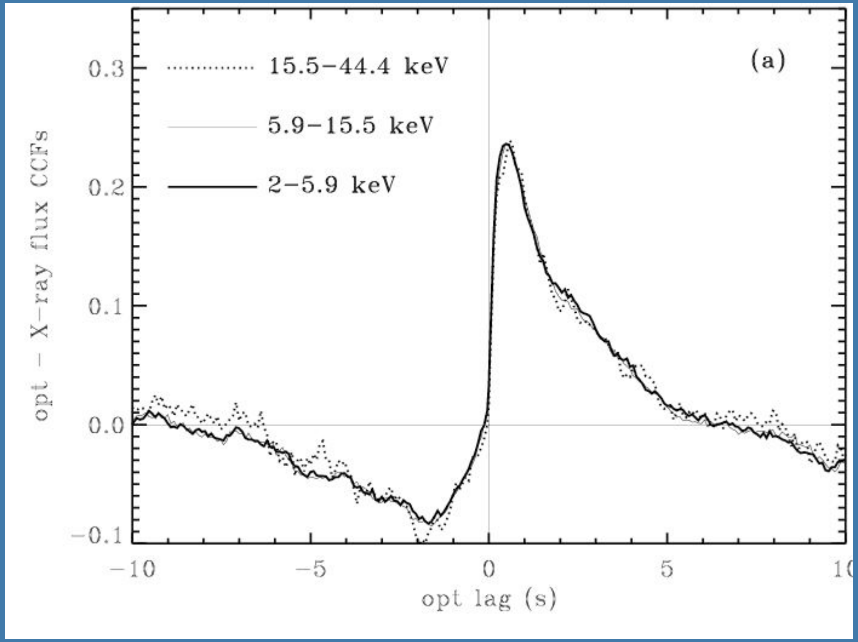
- power-law spectrum ?

$\Rightarrow$ unlikely

- Synchrotron emission in the jet ?

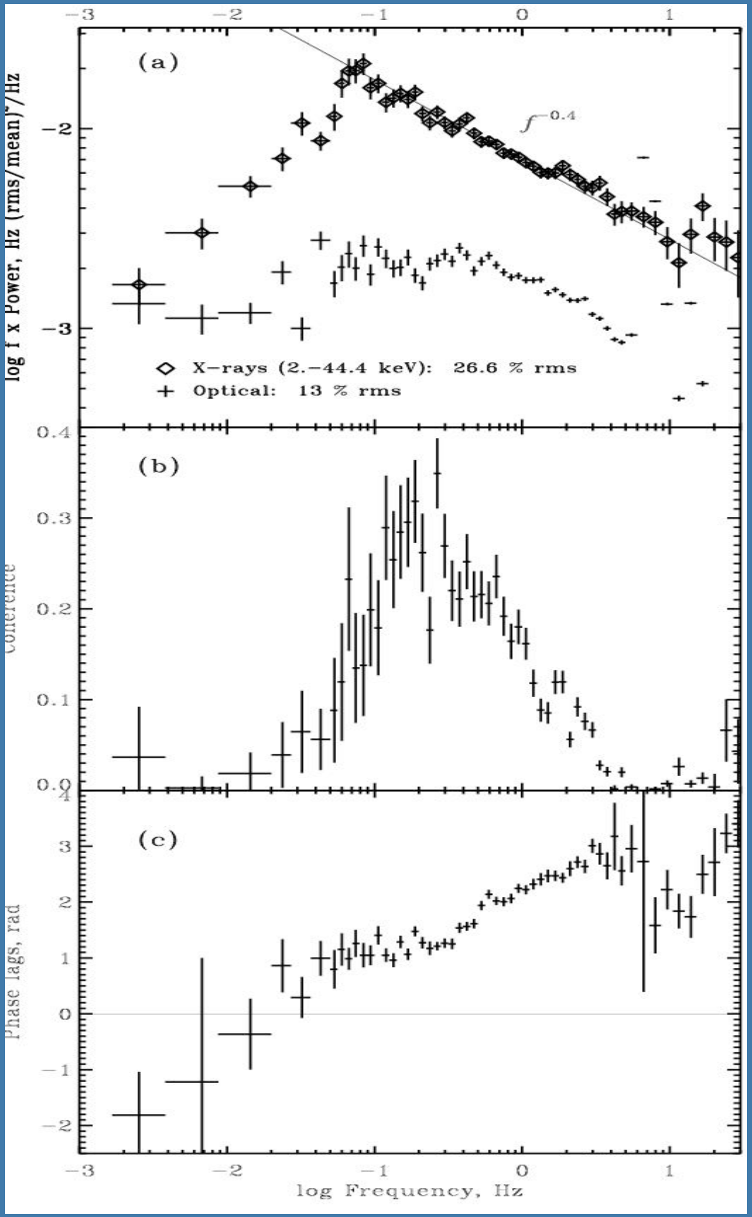
Auto-correlation and X/opt. cross-correlation functions





(Kanbach et al, Nature 2001,
Malzac et al., A&A 2003)

Fourier Analysis



X-ray power spectrum typical of low/ hard state sources

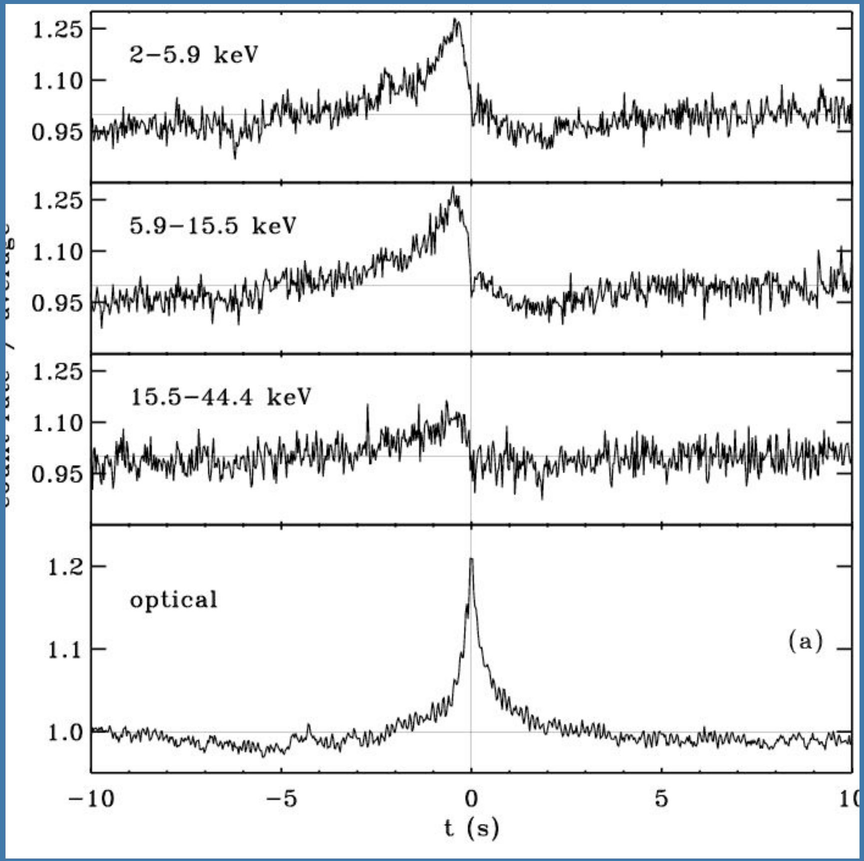
Coherence spectrum:
Opt and X-rays mostly
correlated for 1 to 10 s fluctuations

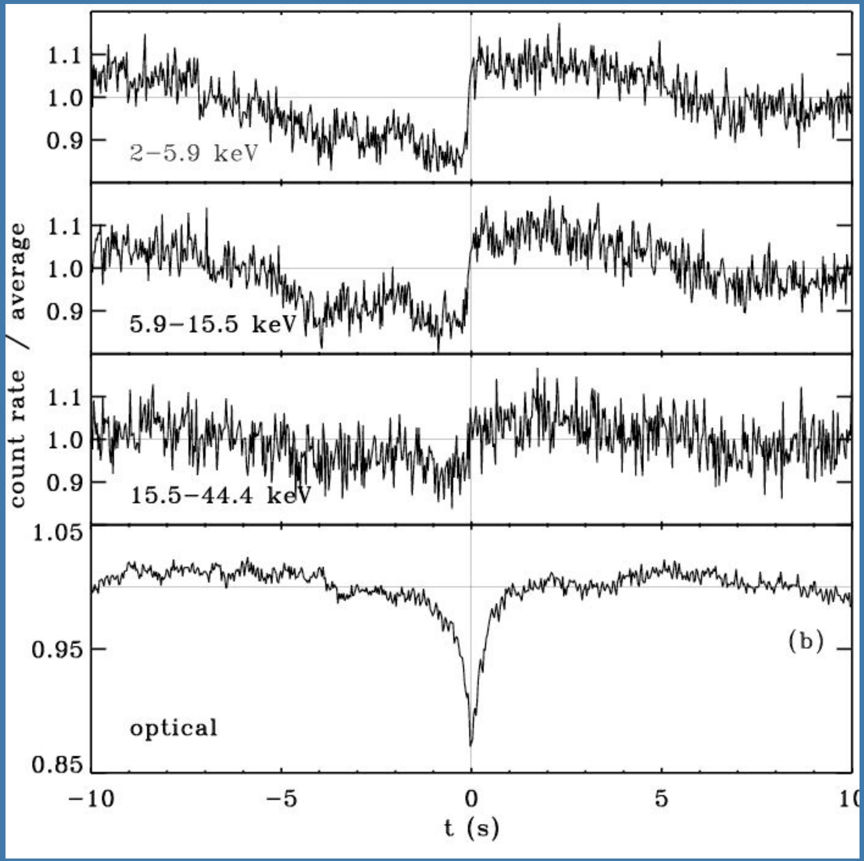
Opt. Phase lag $\varphi = 2\pi f \ \Delta t \sim \pi / 2$

$$\Rightarrow Opt \propto -\frac{\partial X}{\partial t}$$

(Malzac et al. A&A 2003)

Event superposition analysis

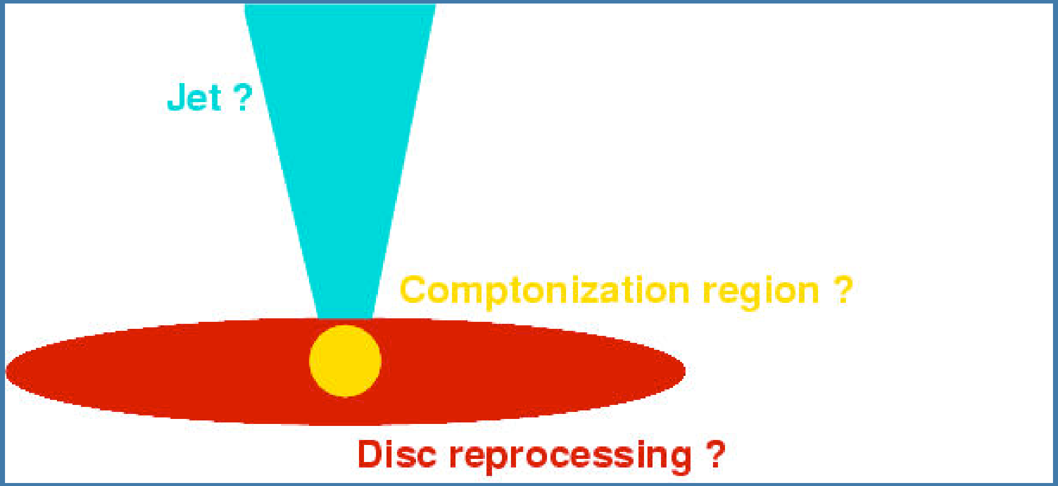




$$Opt \propto -\frac{dX}{dt}$$

(Malzac et al. 2003)

Origin of the optical flickering ?



- Reprocessing of the X-rays in the outer disc:

  - optical varies on shorter time-scales than the X-rays

  - reprocessing models fail to reproduce the Opt/X CCF

$\Rightarrow$ ruled out

- Synchrotron emission in the Comptonising plasma:

- requires $R \sim 1000\ R_S$
- problem to reproduce the IR/opt/UV variability
- power-law spectrum ?

$\Rightarrow$ unlikely

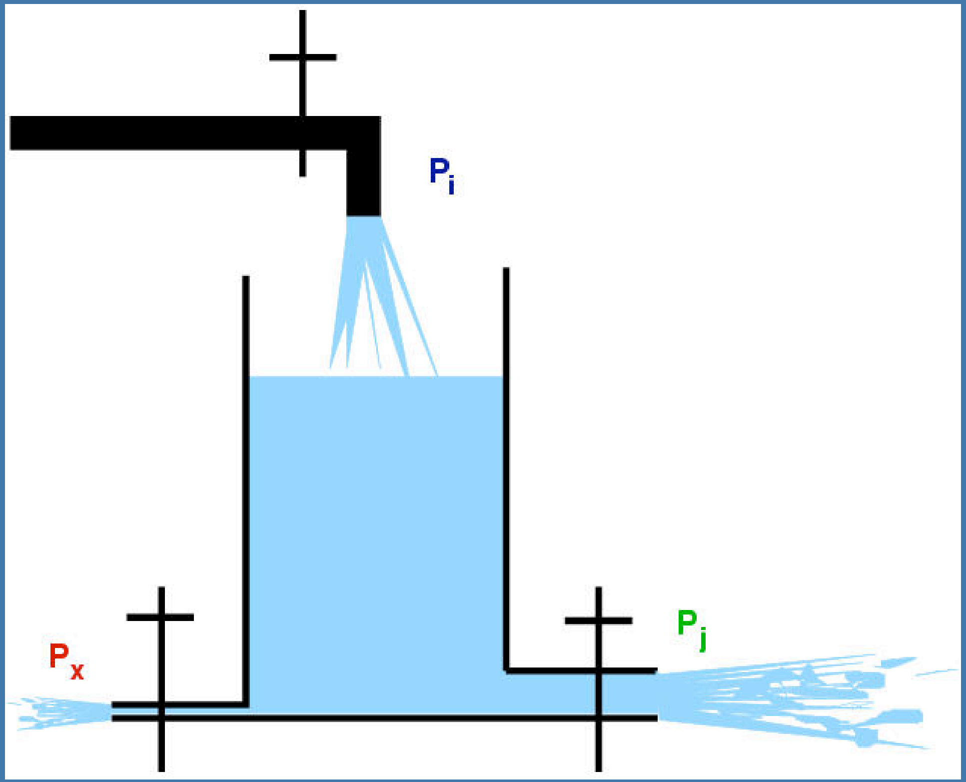
- Synchrotron emission in the jet:

  - simple propagation models do not work

$\Rightarrow$ more complex jet/disc coupling ?

Jet corona coupling through common energy reservoir

A simple analogue:



- Steady state: $P_i = P_j + P_X$
- P_j tap opened more:
  $P_j \nearrow$, water level drops, $P_X \searrow$
- P_j tap partly closed:
  $P_j \searrow$, water level rises, $P_X \nearrow$

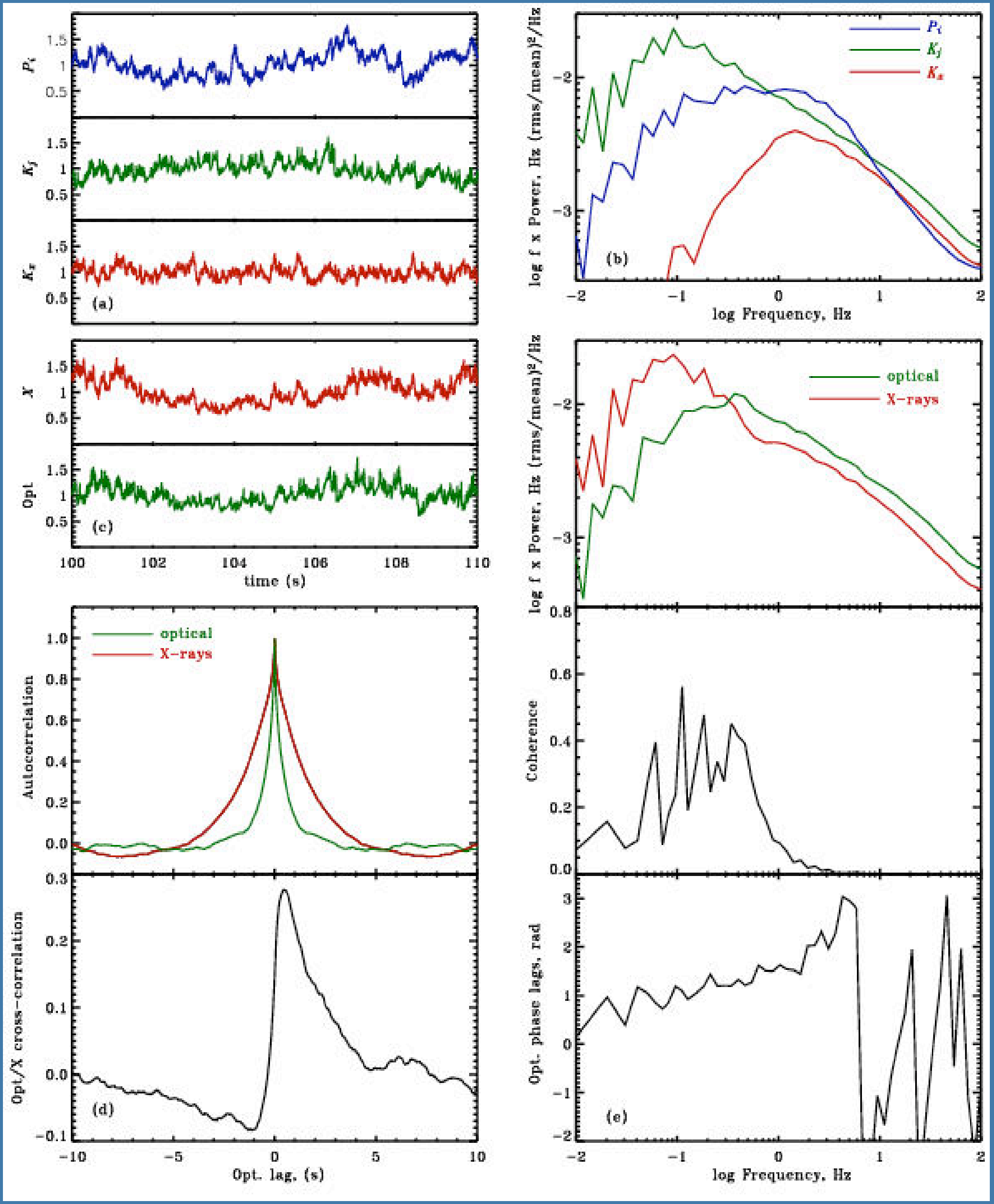
taps controlled by a stochastic process $\Rightarrow$ behaviour of XTE J1118+480

Malzac, Merloni & Fabian, MNRAS, 2004

Time dependent model

$$f_X = 0.1$$

$$T_{dis} = 0.5\,\mathrm{s}$$



Malzac, Merloni & Fabian MNRAS 2004

Fast jet-disc coupling in XTE J1118+480

- Fast optical/X-ray photometry provides a unique opportunity to study accretion/ejection processes on short time-scales
-
- Jet/disc coupling on short time-scales could explain the complex behaviour of XTE J1118+480.
  The coupling mechanism must involve $P_{\rm J} \propto -\frac{dP_{\rm X}}{dt}$
-
- This needs to be confirmed:
  XTE J1118+480 is unique! Further observations and
  comparisons with other sources (including neutron stars) are required !
-
- Detailed numerical models needed !