Interaction between disks and jets in black hole binaries:
The case of KV UMa

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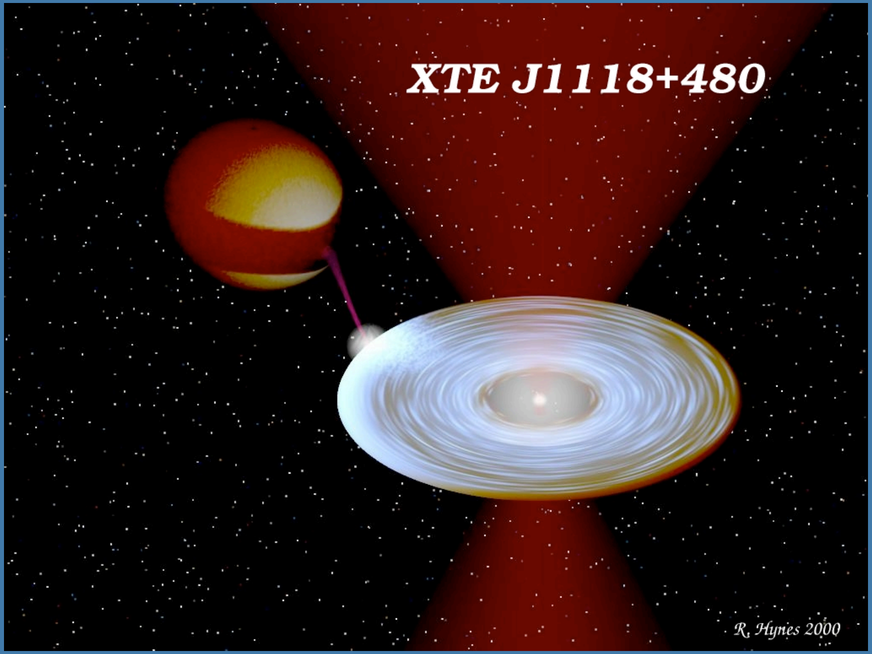
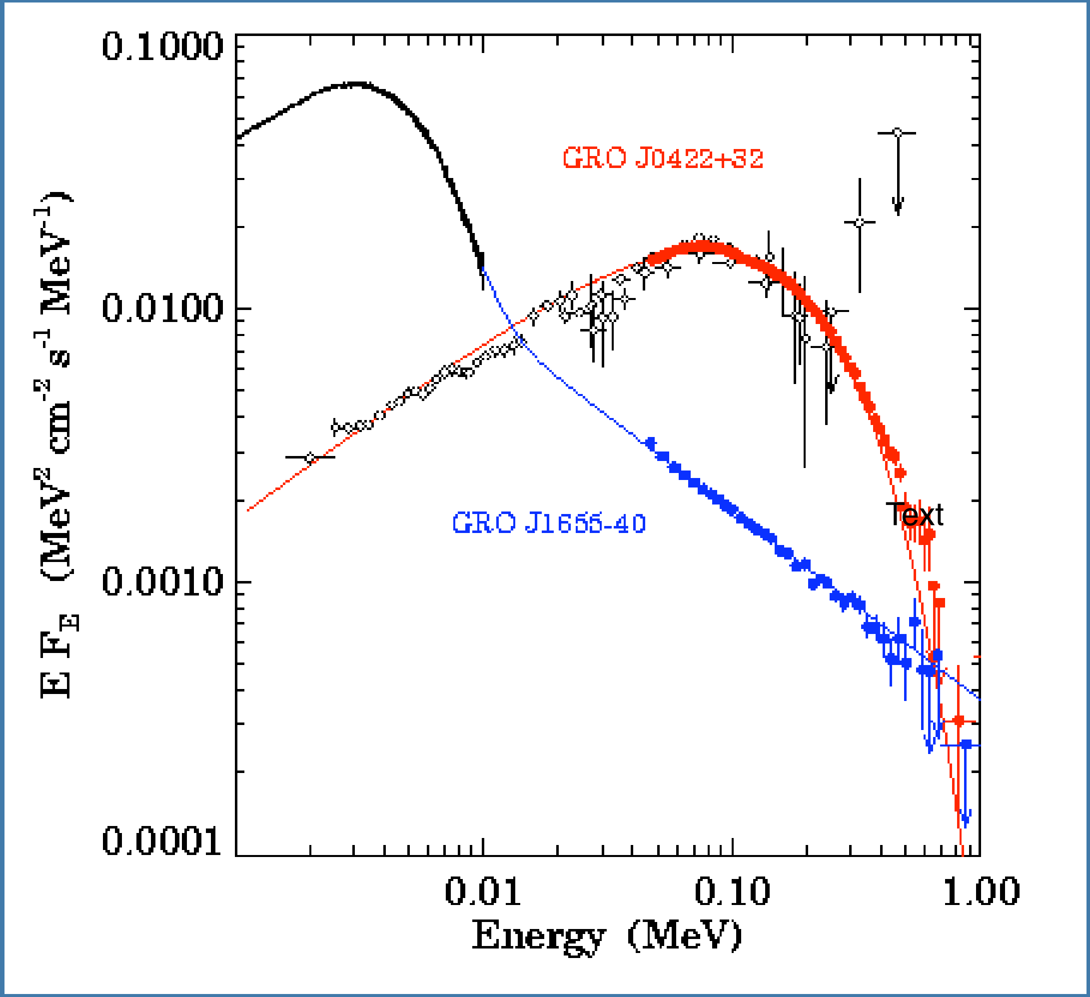


In collaboration with: Andrea Merloni, Andy Fabian, Tomaso Belloni,
Hendrik Spruit, Sylvain Chaty, Gottfried Kanbach

Outline

- Properties of stellar mass accreting black holes
- KV UMa (rapid X-ray and optical variability)
- An energy reservoir model for disc/jet coupling
- Consequences for KV UMa and other sources

X-ray spectral states of galactic black holes



(from Grove et al. 1997)

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

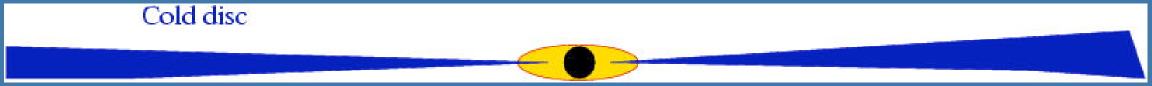
⇒ HIGH SOFT STATE

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

⇒ LOW HARD STATE

Geometry of the accretion flow

High soft state:

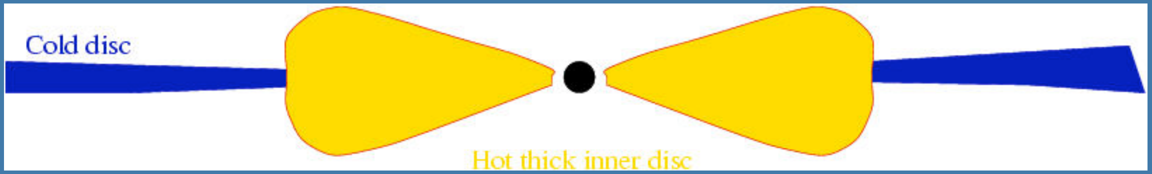


cold geometrically thin disc
down to the last stable orbit
+ weak corona

(Shakura & Sunyaev 1973)

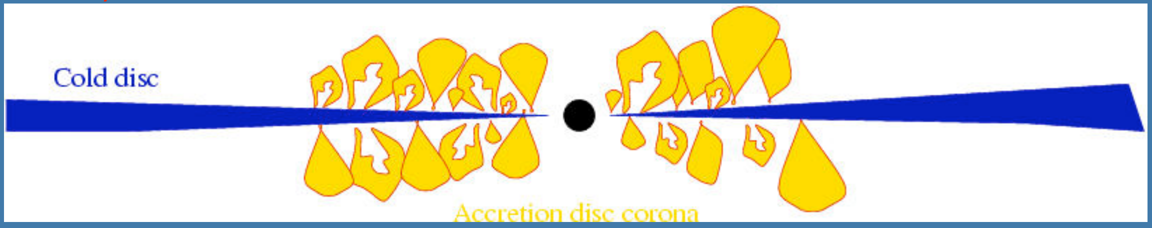
⇒ Thermal emission (mainly)

Low hard state:



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

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

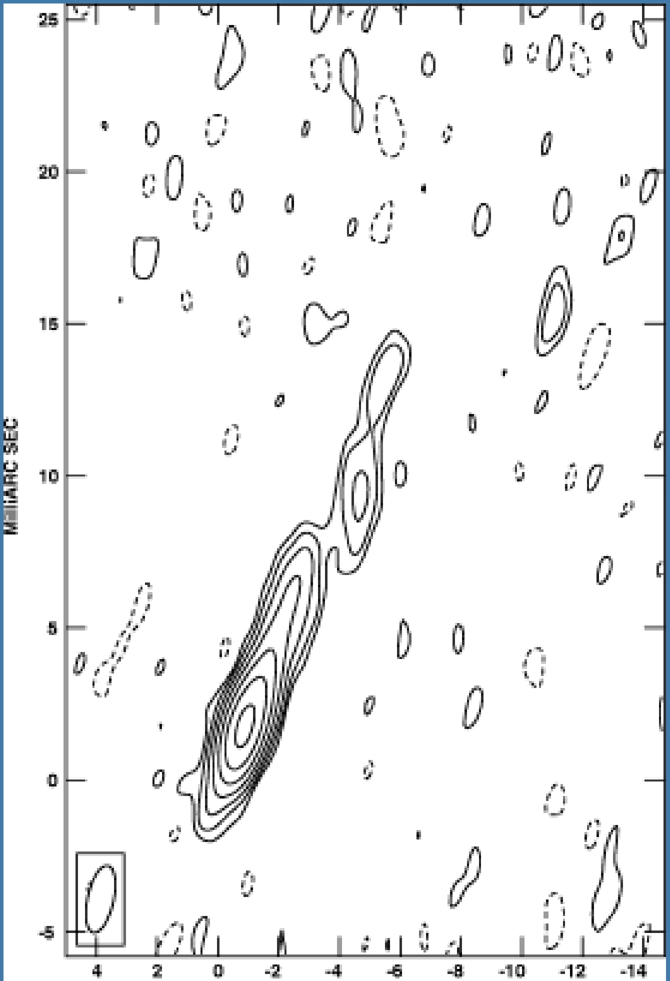


Accretion disc corona
atop a standard thin disc

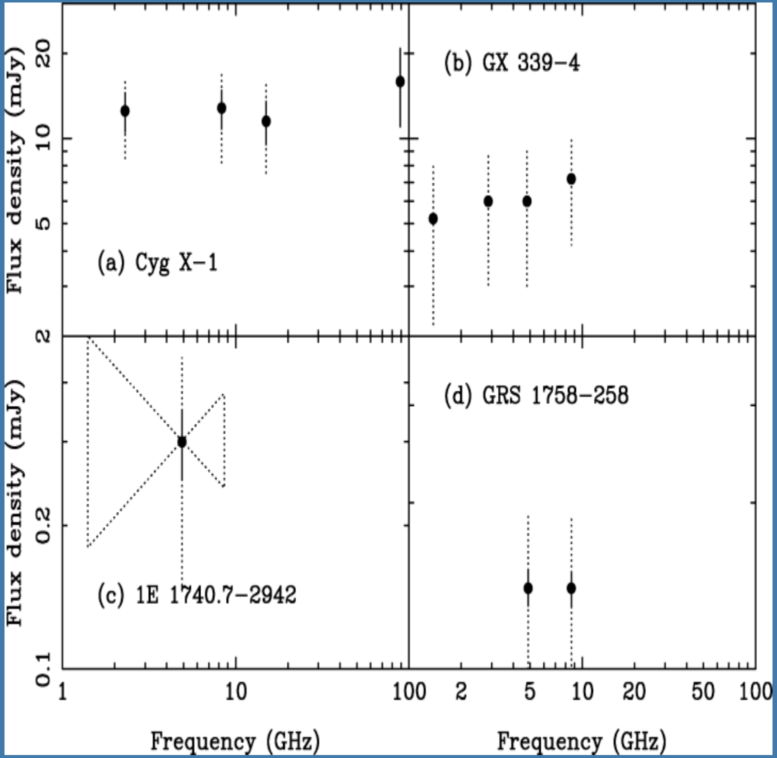
(Bisnovatyi-Kogan & Blinikov 1976; Haardt & Maraschi 1993; Beloborodov 1999)

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

Evidence for compact radio jets in the hard state



Cygnus X-1
(Stirling et al. 2001)

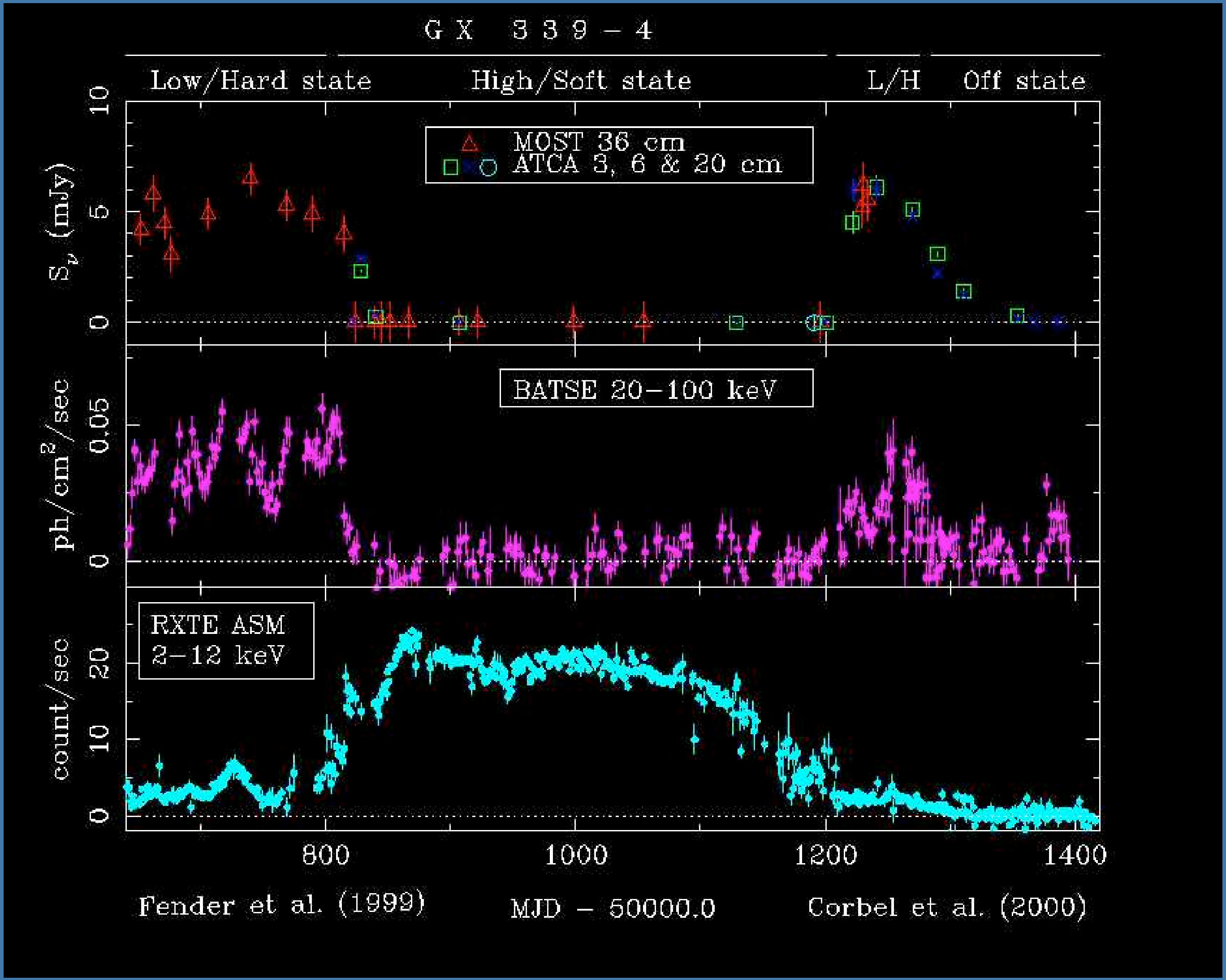


Flat/inverted radio spectra

(Fender 2001)

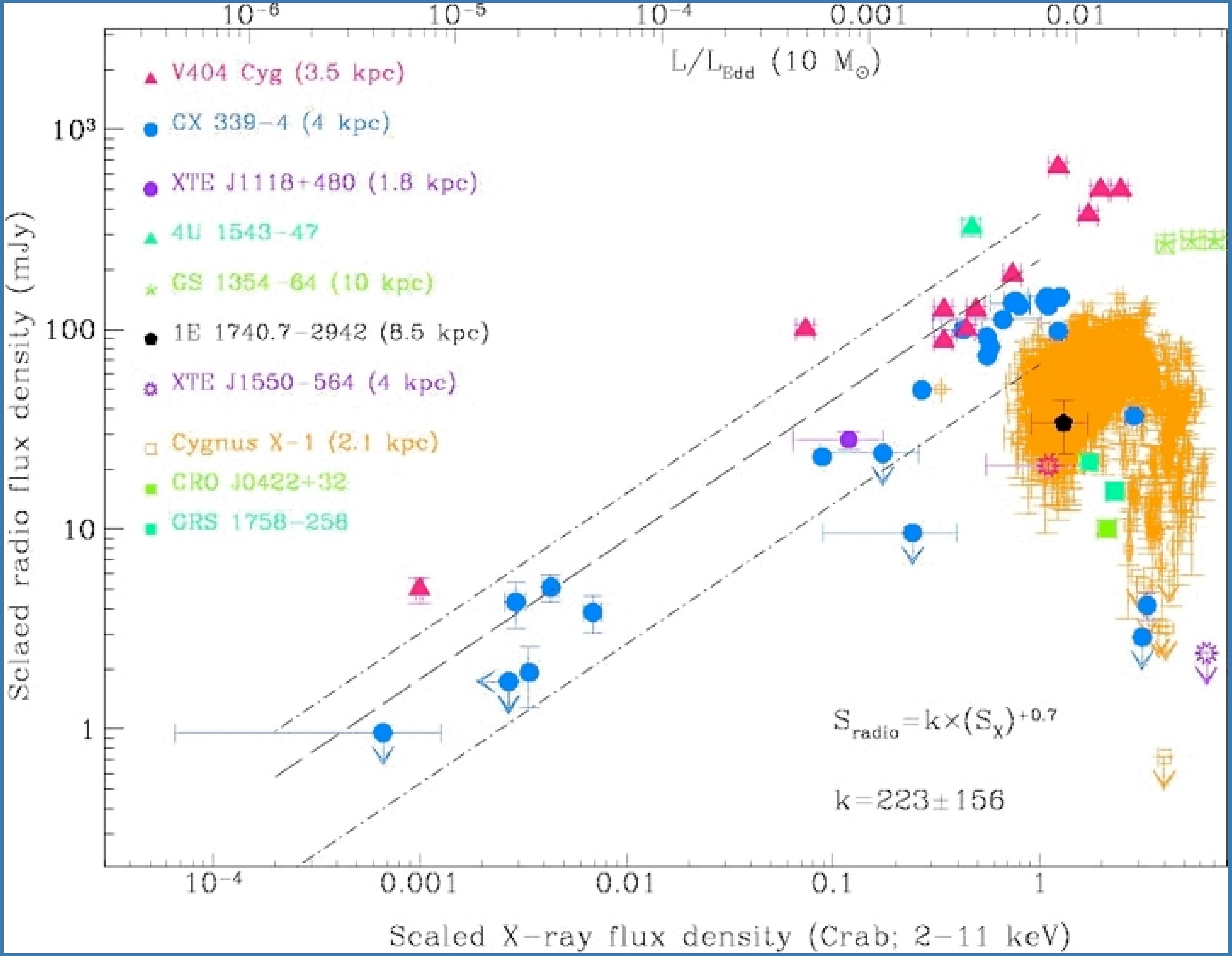
⇒ Self-absorbed synchrotron from compact jets

X-ray/Radio correlations



⇒ Jet quenched in the high soft state

Radio/X-ray correlation in X-ray binaries



(Galllo, Fender & Pooley, MNRAS, 2003)

Existence of a jet dominated regime at low $\dot{m}$

Scaling laws for jet and X-ray luminosities with mass accretion rate:
(Fender, Gallo & Jonker 2003)

$$L_{\rm radio} \propto P_{\rm X}^{0.7}$$

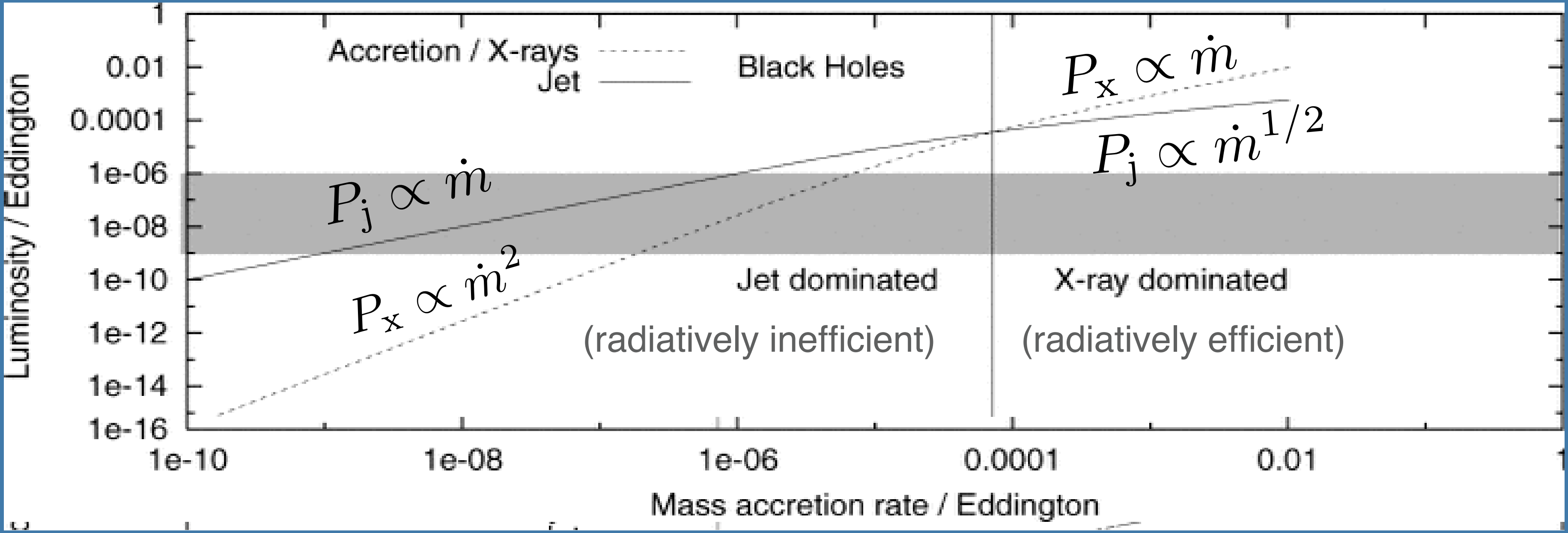
$$L_{\rm radio} \propto P_{\rm J}^{1.4}$$

$$\Rightarrow \quad P_{\rm J} \propto P_{\rm X}^{0.5}$$

$$\dot{m} = P_{\rm X} + P_{\rm J}$$

$$\dot{m} = A^{-2} P_{\rm J}^2 + P_{\rm J}$$

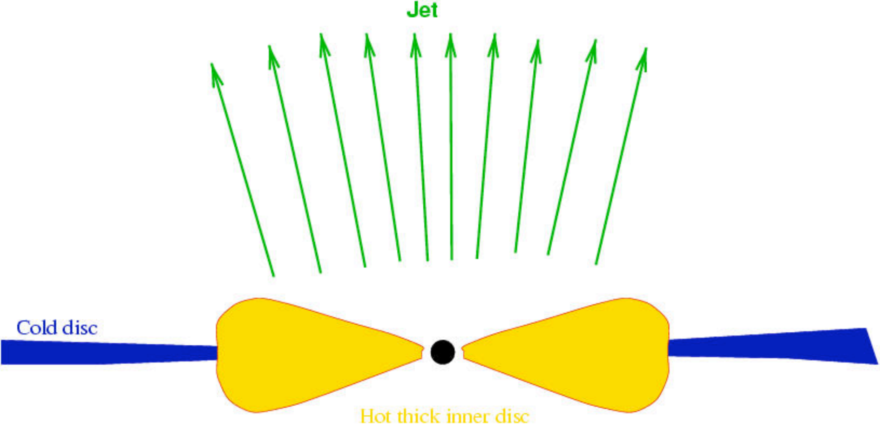
$$\dot{m} = P_{\rm X} + A P_{\rm X}^{0.5}$$

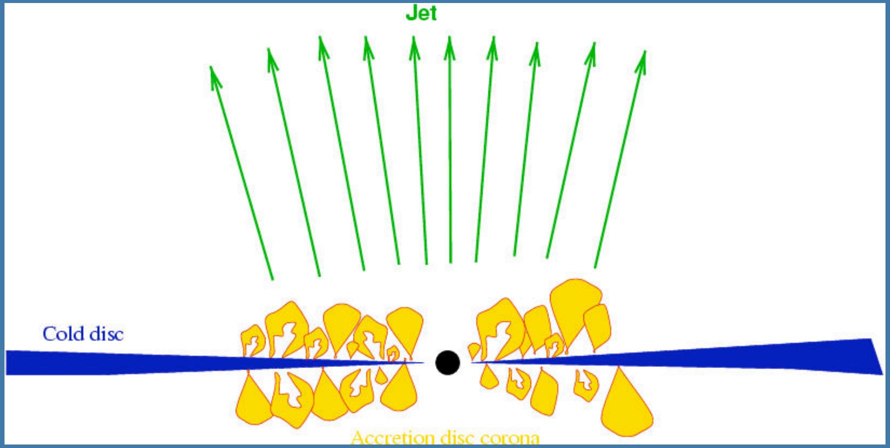


Origin of the radio/X-ray correlations ?

- 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

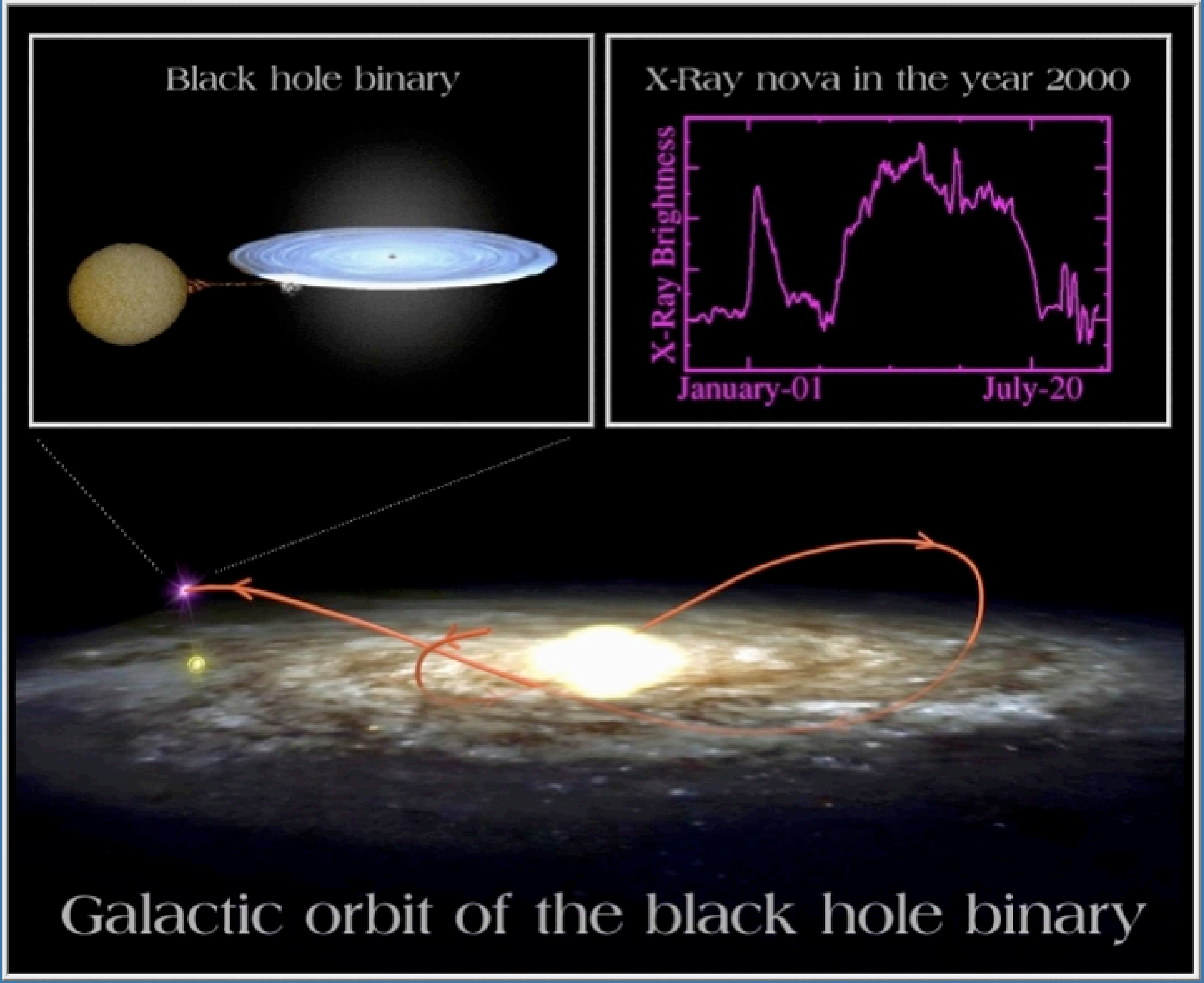
(Blandford & Znajek 1977, Blandford & Payne 1982)

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

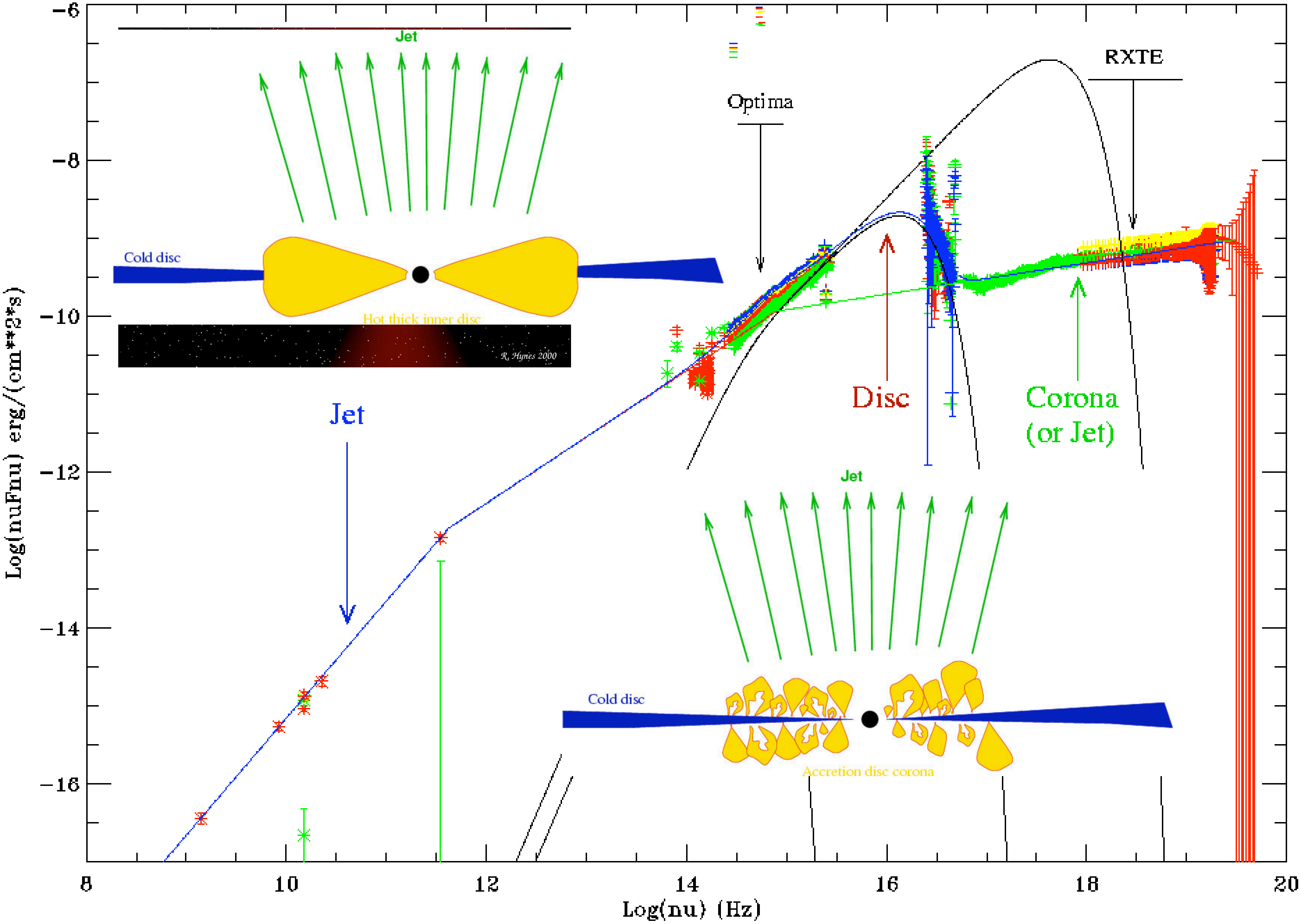
(Livio, Ogilvie & Pringle 1999; Meier 2001; Merloni & Fabian 2001)

⇒ geometrically thick accretion flows are more efficient at launching jets

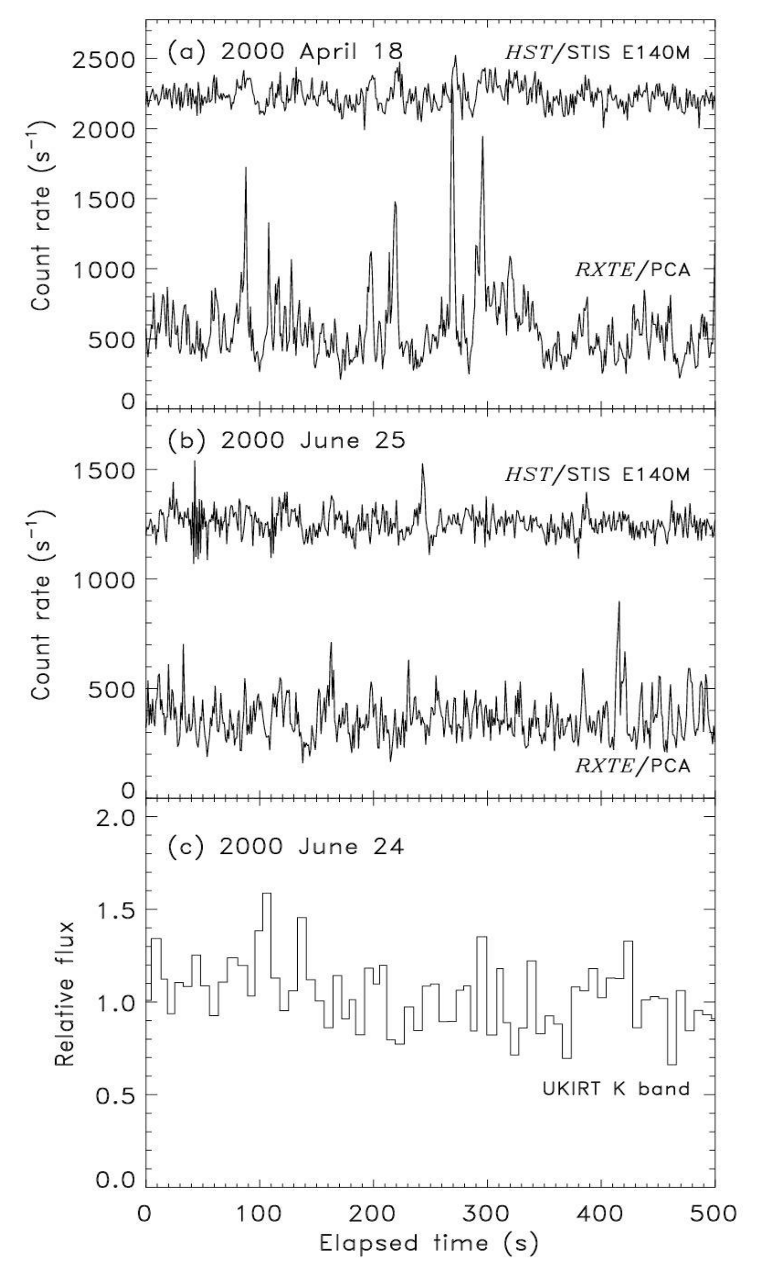
The X-ray nova KV UMa (aka XTE J1118+480)



XTE J1118+480

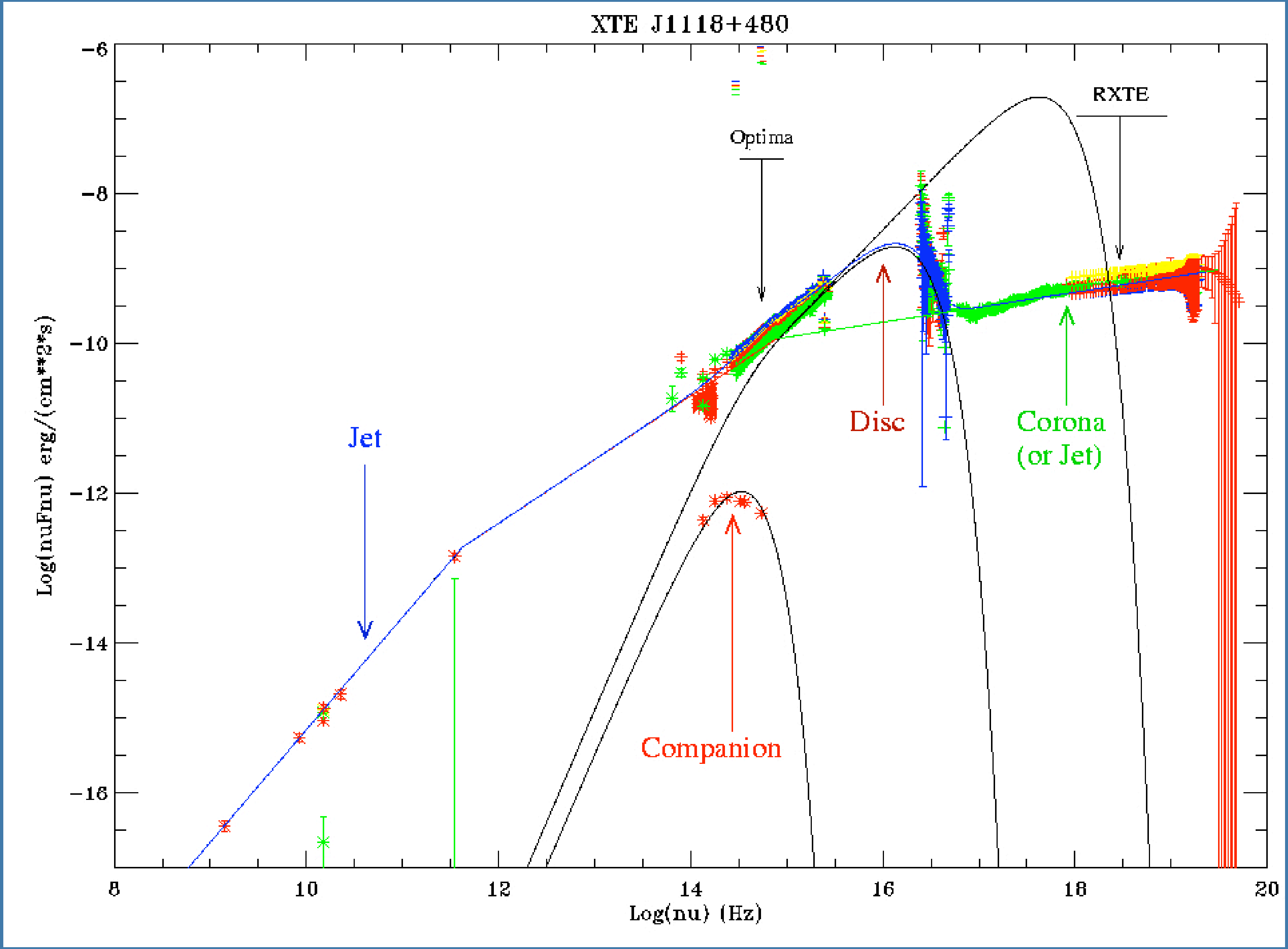


X-ray, UV, optical and IR flickering



(From Hynes et al. 2003)

Origin of the optical flickering ?

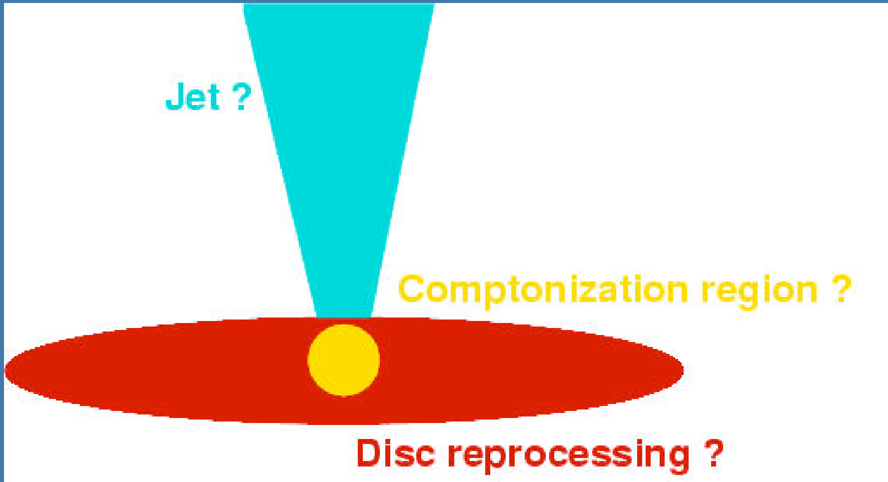


Origin of the optical flickering ?

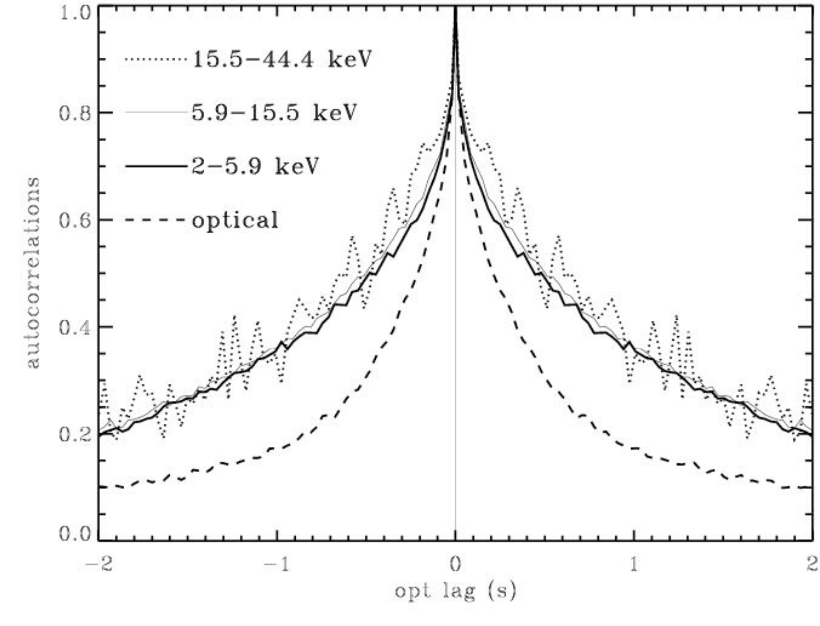
- Reprocessing of the X-rays
  in the outer disc ?

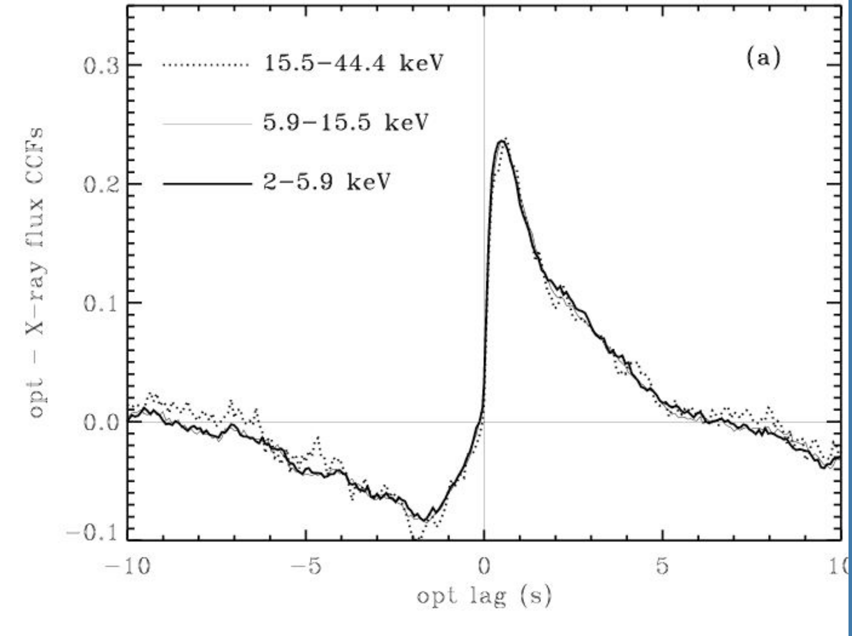
  - optical varies on shorter time-scales than the X-rays

  - 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)

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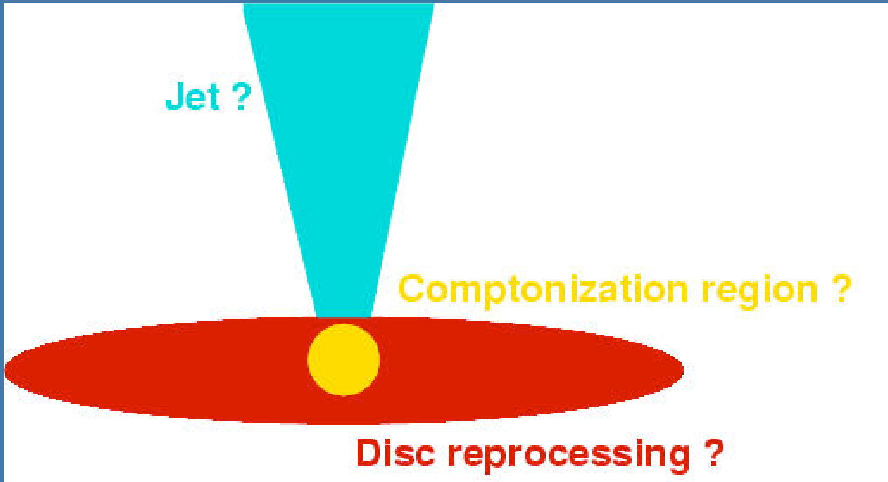
$\Rightarrow$ ruled out



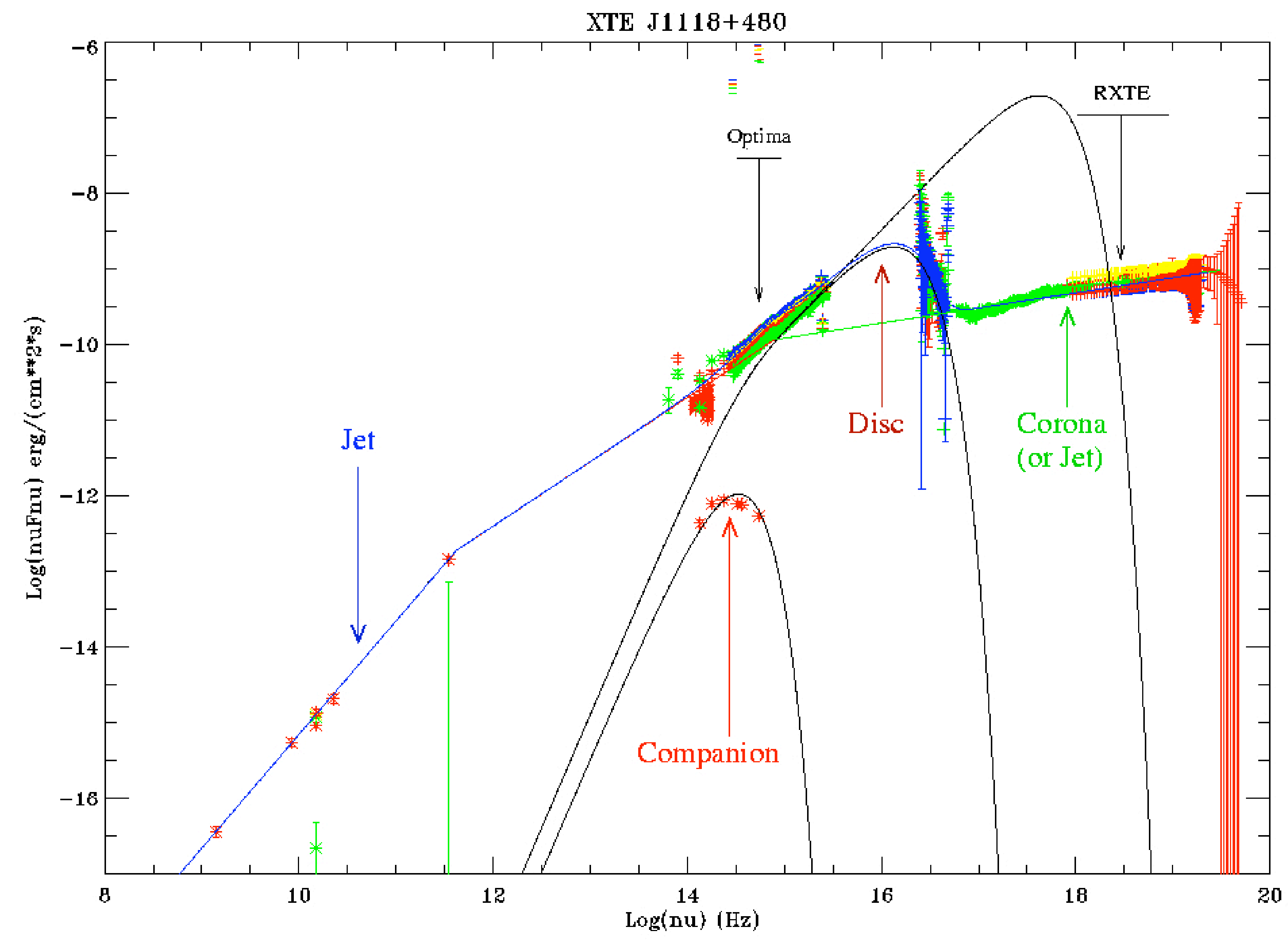
- Synchrotron emission
  in the Comptonising plasma:

- requires $R \sim 1000\ R_S$

- problem to reproduce the IR/opt/UV variability

- power-law spectrum ?

Origin of the optical flickering ?



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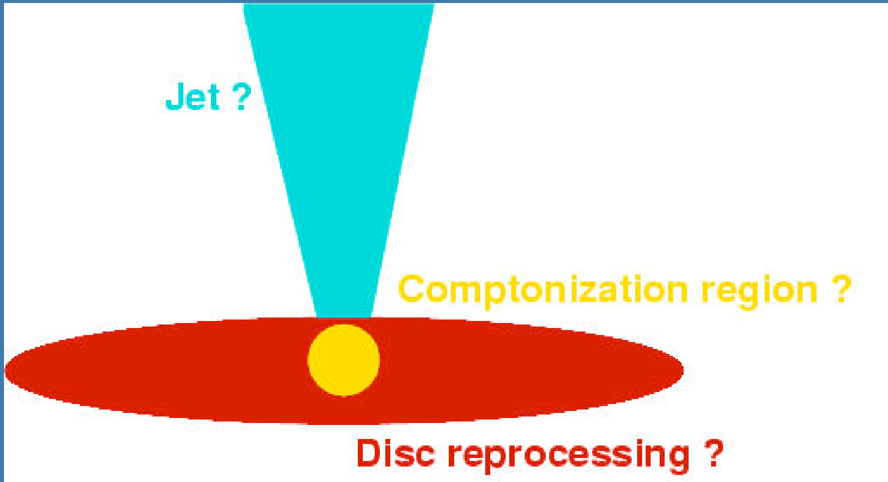
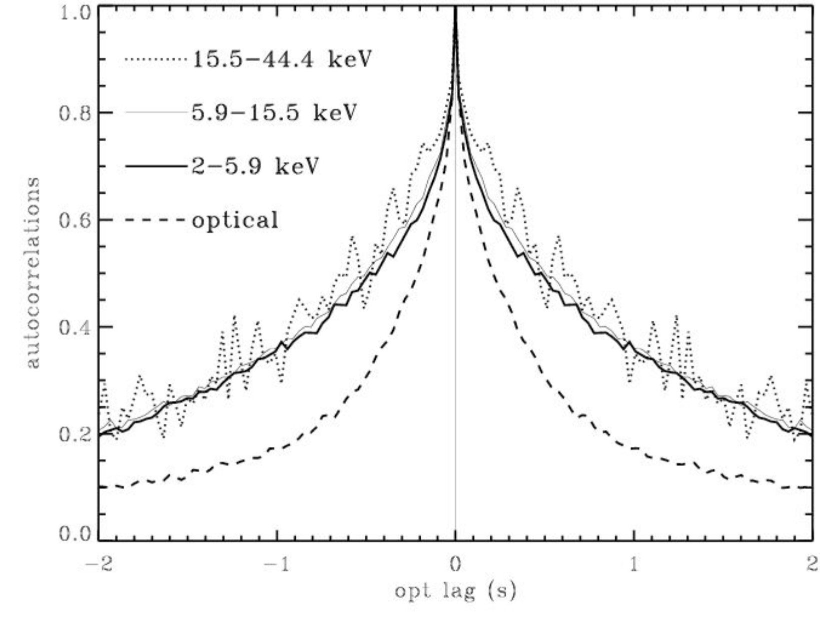
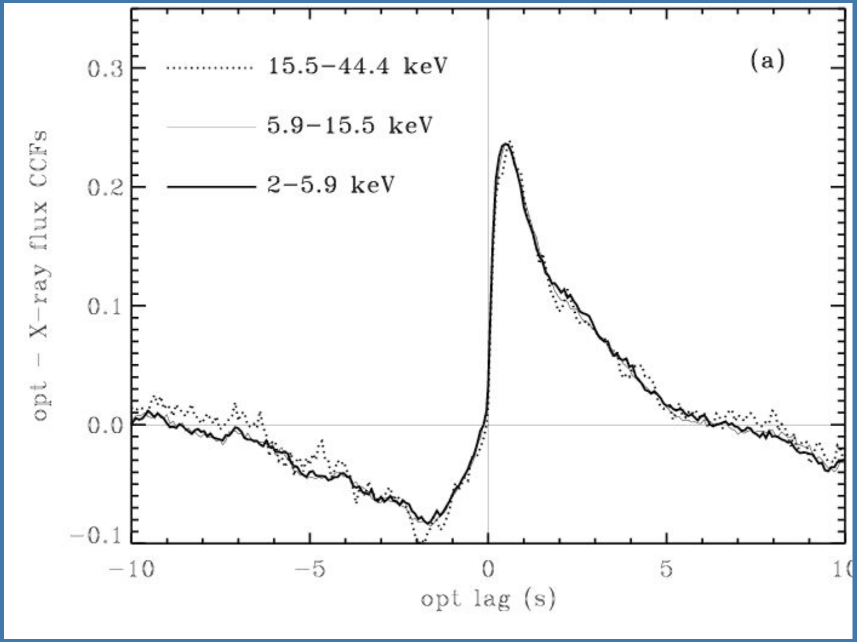
⇒ unlikely



- Synchrotron emission in the jet ?

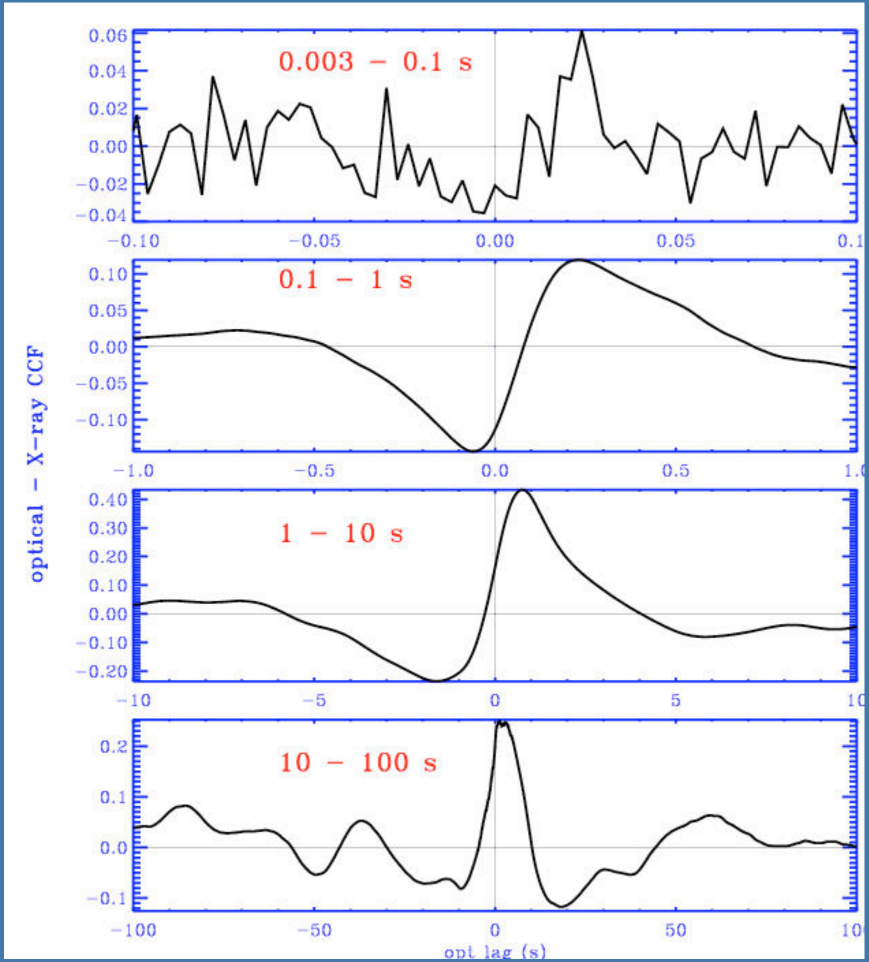
Auto-correlation and X/opt. cross-correlation functions





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

Dependence of the CCF
on the time-scale of the fluctuations

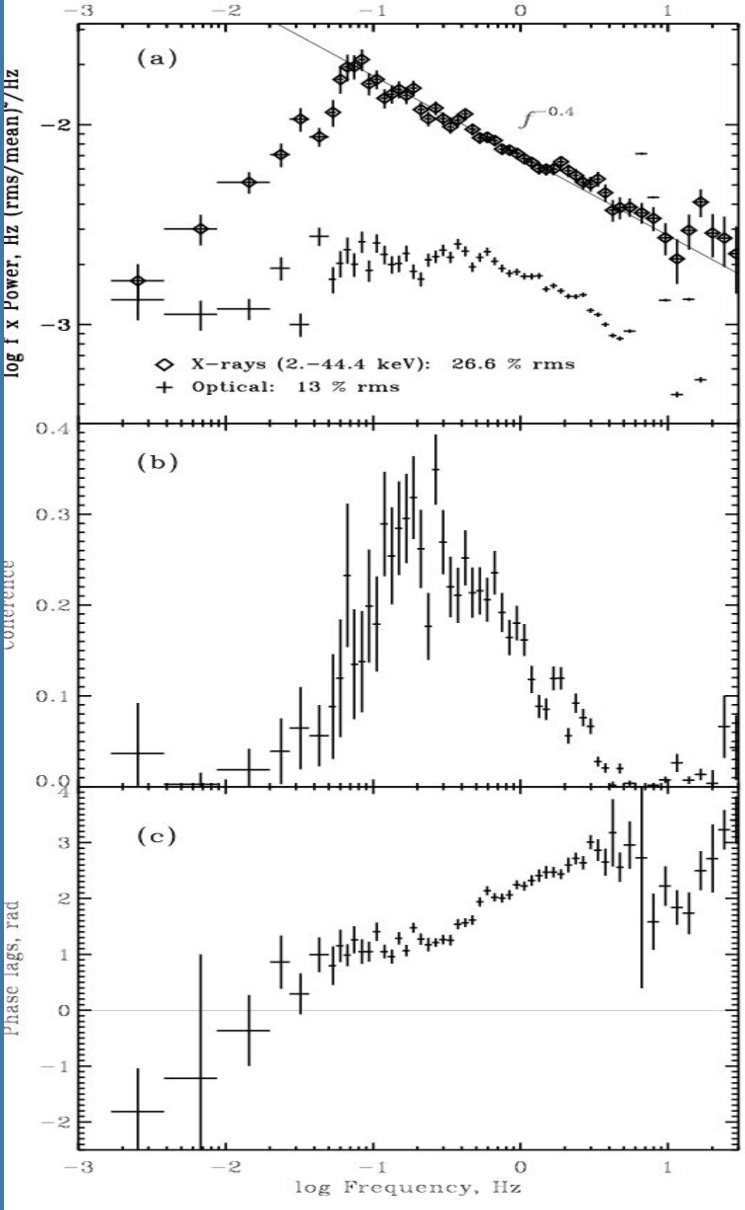


Light curves filtered to keep only fluctuations of specified time-scales

⇒ Nearly scale-invariant CCF

⇒ The optical lag does depend on time-scale

Fourier Analysis



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

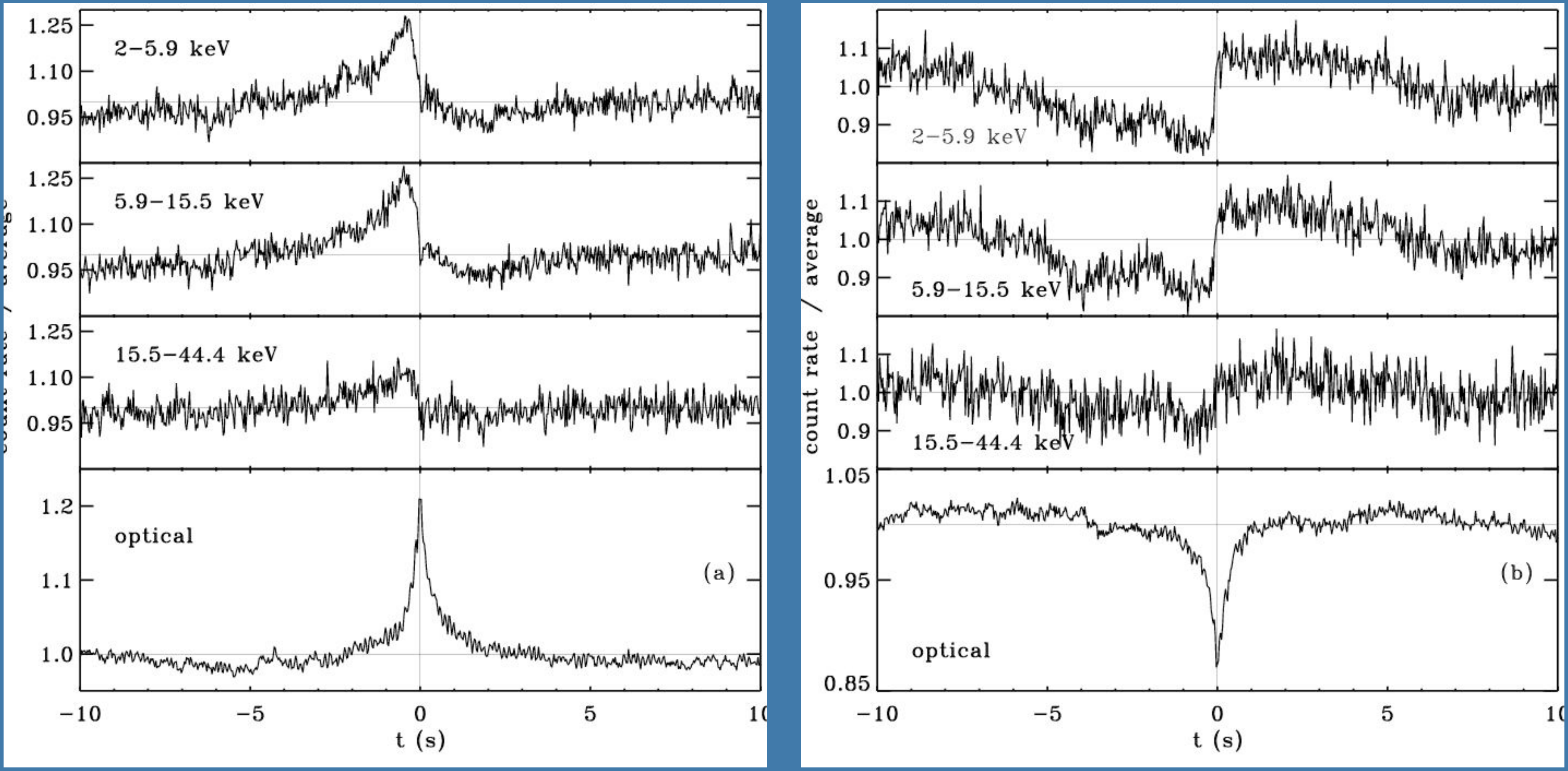
Coherence spectrum:
Opt and X-rays mostly
correlated for 1 to 10 s fluctuations

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

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

(Malzac et al. 2003)

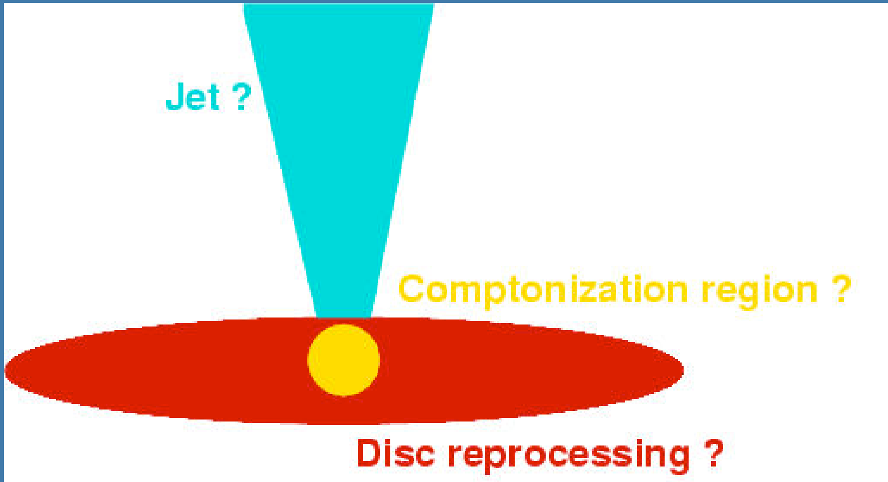
Event superposition analysis



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

(Malzac et al. 2003)

Origin of the optical flickering ?



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- Synchrotron emission
  in the Comptonising plasma:

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

⇒ unlikely

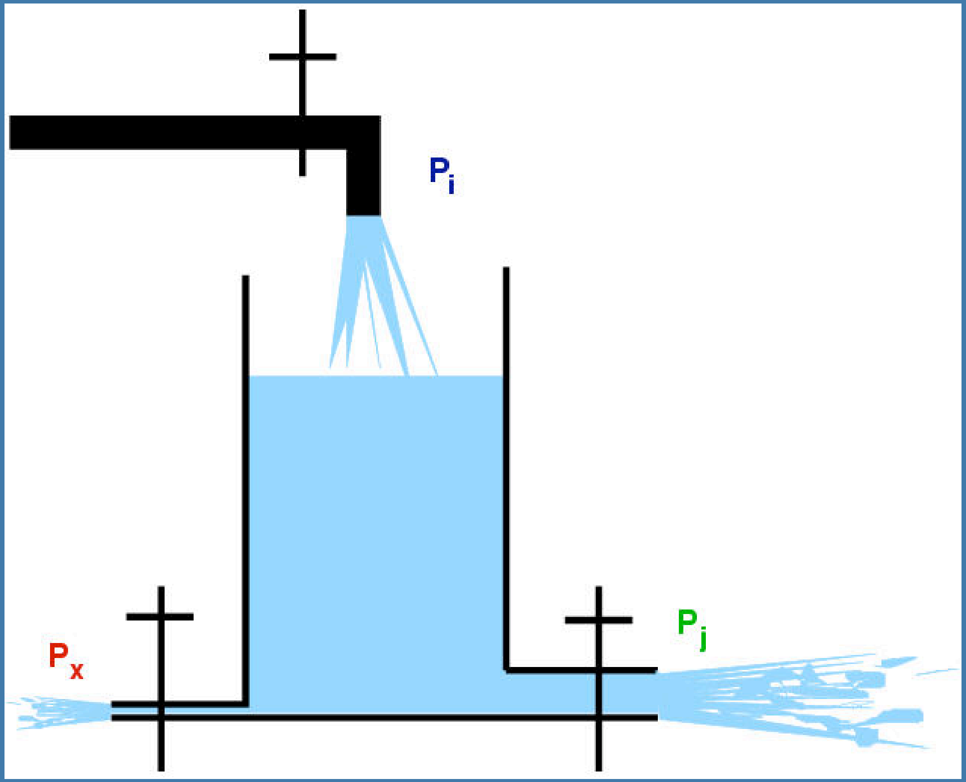
- Synchrotron emission in the jet:

  - simple propagation models do not work

⇒ 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 KV UMa

Time dependent model

- On short time-scales the system is out of equilibrium:

$$\dot{E} = P_{\rm i}(t) - K_{\rm j}(t)E(t) - K_{\rm x}(t)E(t)$$

→ we impose independent random fluctuations of $P_{\rm i}$, $K_{\rm x}$ and $K_{\rm j}$ and then solve the equation for E(t)

- We then generate synthetic light curves assuming:

$$X(t) \propto P_{\rm x} = K_{\rm x}(t)E(t)$$

$$Opt(t) \propto P_{\rm j}(t-\Delta) = K_{\rm j}(t-\Delta)E(t-\Delta)$$

Travel time from the disc to the jet optical photo-sphere

⇒Time delay $\Delta \sim 0.05 \quad {\rm s}$

- Main parameters:

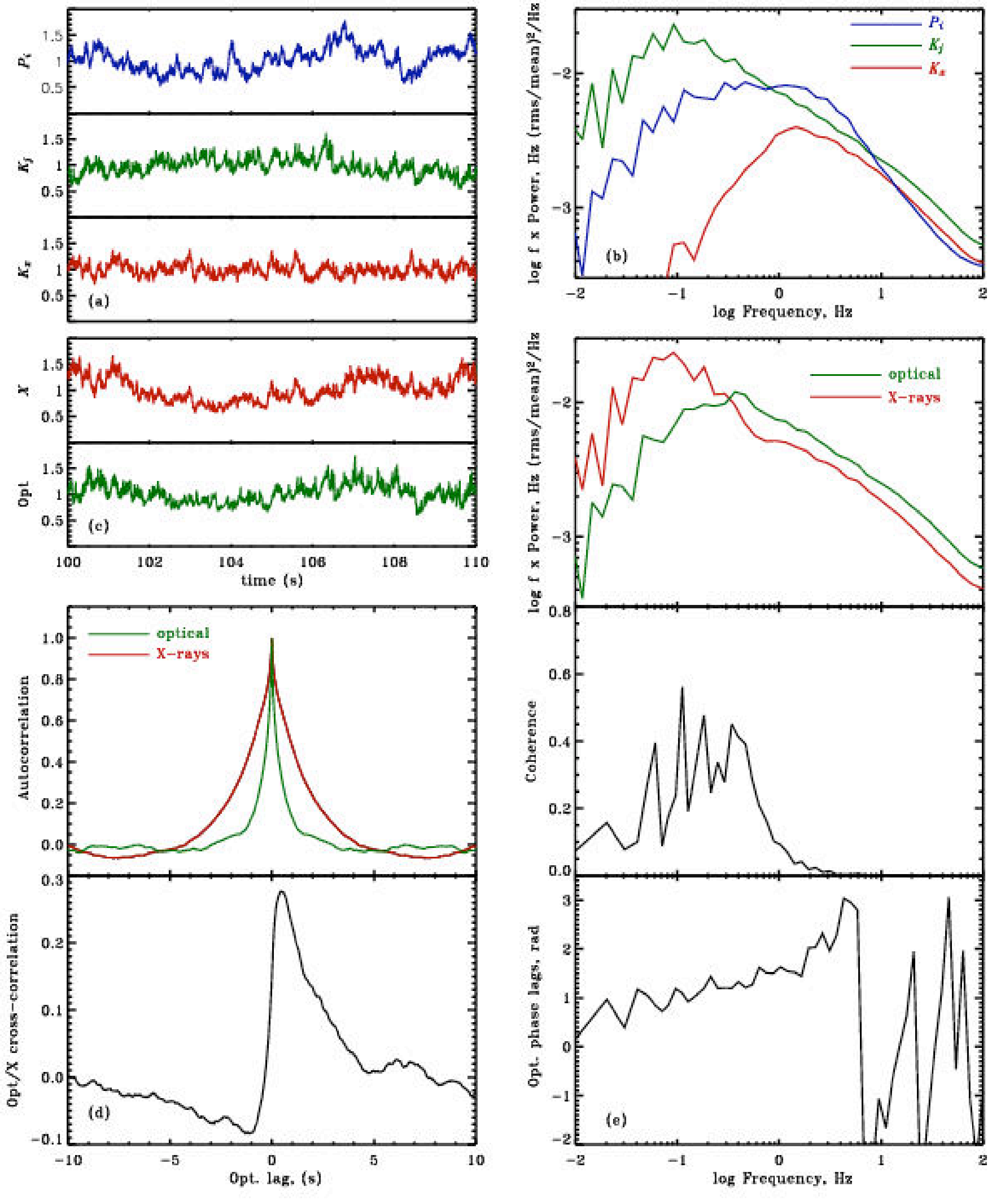
Dissipation time of the energy reservoir: $\boxed{T_{dis} = \left[K_X + K_j\right]^{-1}}$

Fraction of the power dissipated into the X-rays: $\boxed{f_X = K_X T_{dis}}$

Time dependent model

$$f_X = 0.1$$

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



Jet/corona coupling through a magnetic reservoir

- The energy content of the comptonising electrons is far too low to account for the observed luminosities

  The electrons have to be connected to an energy reservoir.

  A natural candidate is the magnetic field: $E = VB^2/(8\pi)$

  Field amplification = storage of magnetic energy.

  → Dissipation through reconnection:

$$P_\mathrm{x} = \frac{v_\mathrm{d}}{R_\mathrm{x}} E = K_\mathrm{x} E$$

- The jet is driven by the poloïdal component of the magnetic field:

$$P_\mathrm{j} = \frac{B_\mathrm{p}^2}{8\pi} A R_c \Omega$$

If the field is amplified by the MRI, $B_\mathrm{p} \simeq \frac{H}{R_\mathrm{c}} B = hB$

$$P_\mathrm{j} = \frac{A}{V} h^2 R_c \Omega E = K_\mathrm{j} E$$

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

Constraints on the accretion flow

Assuming a magnetic reservoir: $$\frac{v_{\rm d}}{R_{\rm x}} = \frac{f_{\rm x}}{T_{\rm dis}}, \qquad \frac{A}{V} h^2 v_{\rm k}(R_c) = \frac{1-f_{\rm x}}{T_{\rm dis}}$$

For $f_{\rm x} = 0.1,\ T_{\rm dis} = 0.5\ :\ v_{\rm d}/c \simeq 2\times 10^5 r_{\rm x},\ h \simeq 0.17(r_{\rm c}/100)^{3/2}$

$$(r_{\rm x} = R_{\rm x}/R_{\rm s}, r_{\rm c} = R_{\rm c}/R_{\rm s})$$

Inner hot disc: $$B \simeq 3\times 10^6 (r_{\rm c}/100)^{-9/4}\ {\rm G}$$

Accretion disc corona: $$B \simeq 2\times 10^7 (r_{\rm c}/100)^{-5/4} \left[\frac{N \ln(r_{\rm c}/3)}{10\ln(100/3)}\right]^{-1/2} \quad {\rm G}$$

$$\frac{h}{a} \simeq 1.6(r_{\rm c}/100)^{5/2} \frac{3}{r_{\rm x}} \frac{\ln(r_{\rm c}/3)}{\ln(100/3)}$$

$\Longrightarrow$ The parameters of the time-dependent model are consistent with both geometries

Constraint on the parameters

$$P_{\rm j} = P_{\rm i} - \left(1 - \frac{\dot{K}_{\rm x}}{K_{\rm x}^2}\right) P_{\rm x} - \frac{\dot{P}_{\rm x}}{K_{\rm x}}$$

The observed relation $Opt \propto -\frac{dX}{dt}$ i.e. $P_{\rm j} \propto -\dot{P}_{\rm x}$ fulfilled if:

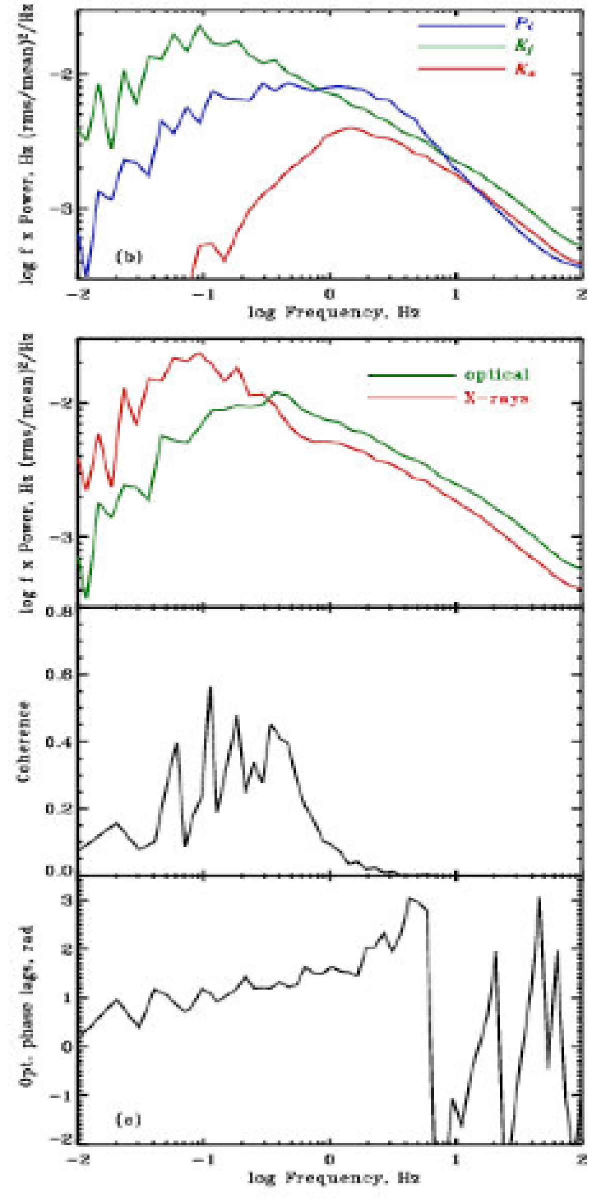
- $P_{\rm i} \simeq {\rm const},\ K_{\rm x} \simeq {\rm const},\ \dot{K}_{\rm x} << 1 \Rightarrow$ 1-10 s variability driven by $K_{\rm j}$

  ⇒ jet activity responsible for most of the X-ray variability

- $P_{\rm x} << P_{\rm i} \Rightarrow$ jet power dominates over the X-ray emission $(f_{\rm x} << 1)$

  ⇒ jet dominates the energetic output of the system

Time-scales



- Fluctuations of K_{x} ranging from 0.01 to 1 s corresponding to 10-100 Rs

  $\Longrightarrow$ consistent with X-ray production

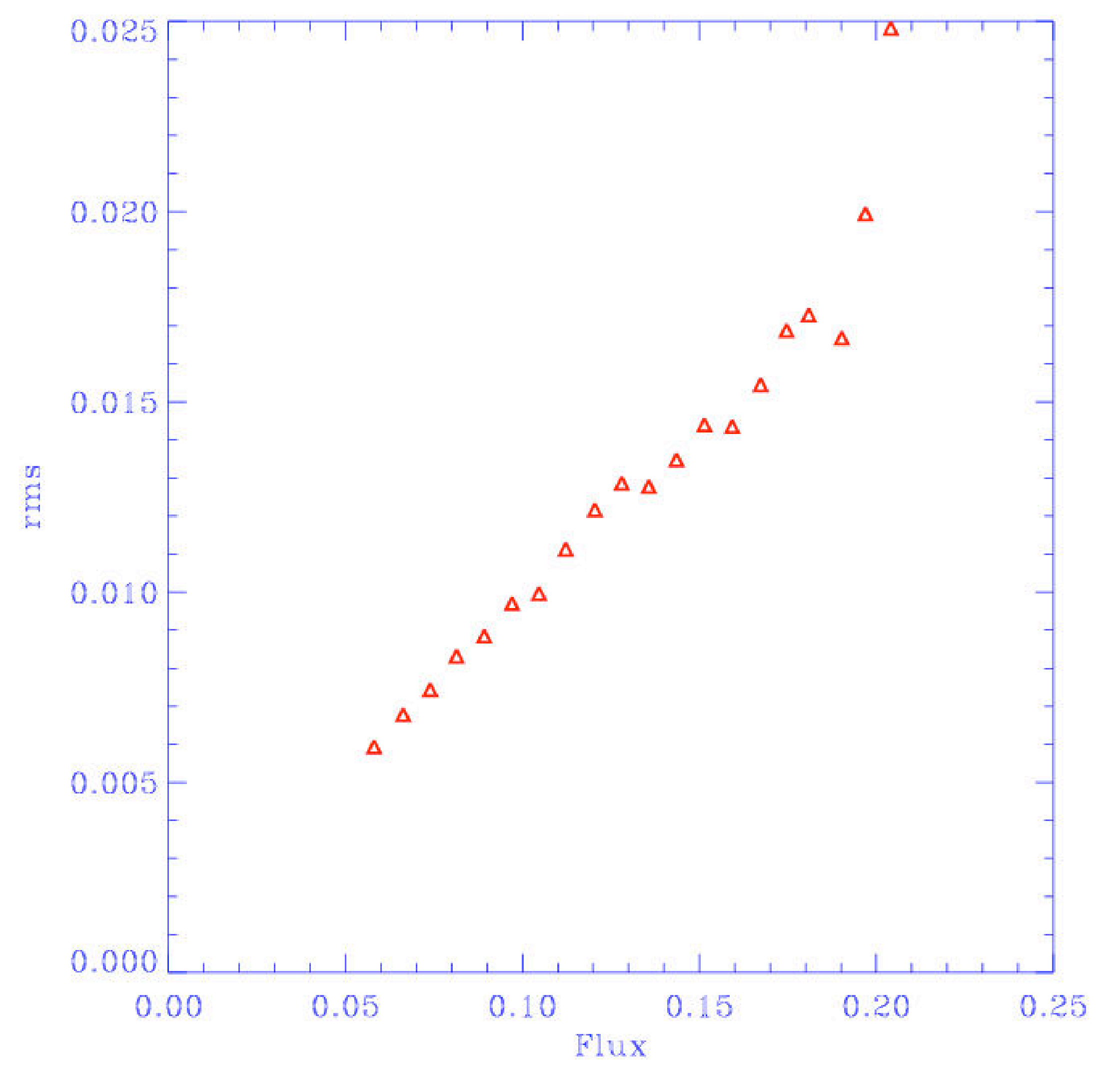
  in the hot phase (local process)

- Fluctuations of K_{j} ranging from 0.01 and 10 s

  $\Longrightarrow$ large scale coherent structures

  $\Longrightarrow$ jet activity modulates the X-ray emission

rms-flux correlation



Jet dominance in KV UMa

Is it consistent with the spectral data ?

- For the observed jet and X-ray luminosities: $P_{\rm j}/P_{\rm x} \sim 10 \Rightarrow \eta_{\rm jet} \sim 0.01$

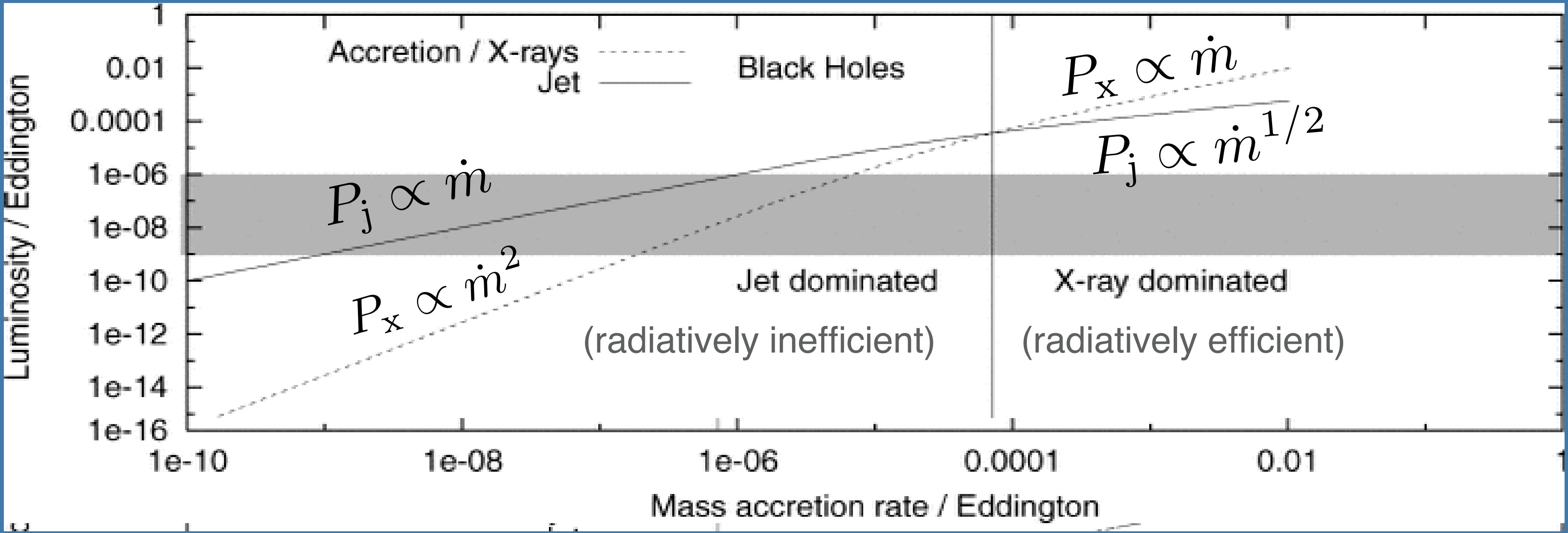
- In KV UMa the observed thermal disc component enables one to estimate the mass accretion rate:

Hot inner disc: $\dot{m} = 4\epsilon(R_{\rm in}/R_{\rm s})L_{\rm disc} \sim 200L_{\rm x}$
Accretion disc corona: $\dot{m} = 4\epsilon(R_{\rm in}/R_{\rm s})L_{\rm disc}/(1-f_h) \sim 10L_{\rm x}$

$\Rightarrow$ Radiatively inefficient
$\Rightarrow$ The total energy budget would allow for jet dominance

Jet dominance in the low hard state ?

Scaling laws for jet and X-ray luminosities with mass accretion rate:
(Fender, Gallo & Jonker 2003)



Transition at the critical luminosity $P_{x,cr} = \dot{m}/2 = P_j^2/P_x$

If, in KV UMa, $P_j/P_x \simeq 10 \Rightarrow P_{x,cr} \simeq 0.1 L_{Edd}$

$\Rightarrow$ All black holes in the low hard state
are jet dominated and radiatively inefficient

Conclusions

- Fast optical/X-ray photometry provides a unique opportunity to study accretion/ejection processes on short time-scales

- Jet/disc coupling through a common energy reservoir can explain the complex behaviour of KV UMa

- Such models require $P_{\rm j} >> P_{\rm x}$ (possibly true for all hard state sources)