"It's black, and it looks like a hole. I'd say it's a black hole."

What are BHC?, II

Stars end their life as one of three kinds of different compact objects:

White Dwarf: $\rho \sim 10^5 \ldots 10^6\,\mathrm{g\,cm^{-3}}$, $R \sim R_\oplus$, Equilibrium between gravitation and pressure from degenerate electrons, $M < 1.44\,M_\odot$ (Chandrasekhar-limit).

Neutron Star: $\rho \sim 10^{13} \ldots 10^{16}\,\mathrm{g\,cm^{-3}}$, $R \sim 10\,\mathrm{km}$, this density causes inv. β-decay ($\mathrm{p} + \mathrm{e}^- \rightarrow \mathrm{n}$), i.e., star consists (mainly) of neutrons. $1.44\,M_\odot < M \lesssim 3\,M_\odot$ (Oppenheimer-Volkoff limit).

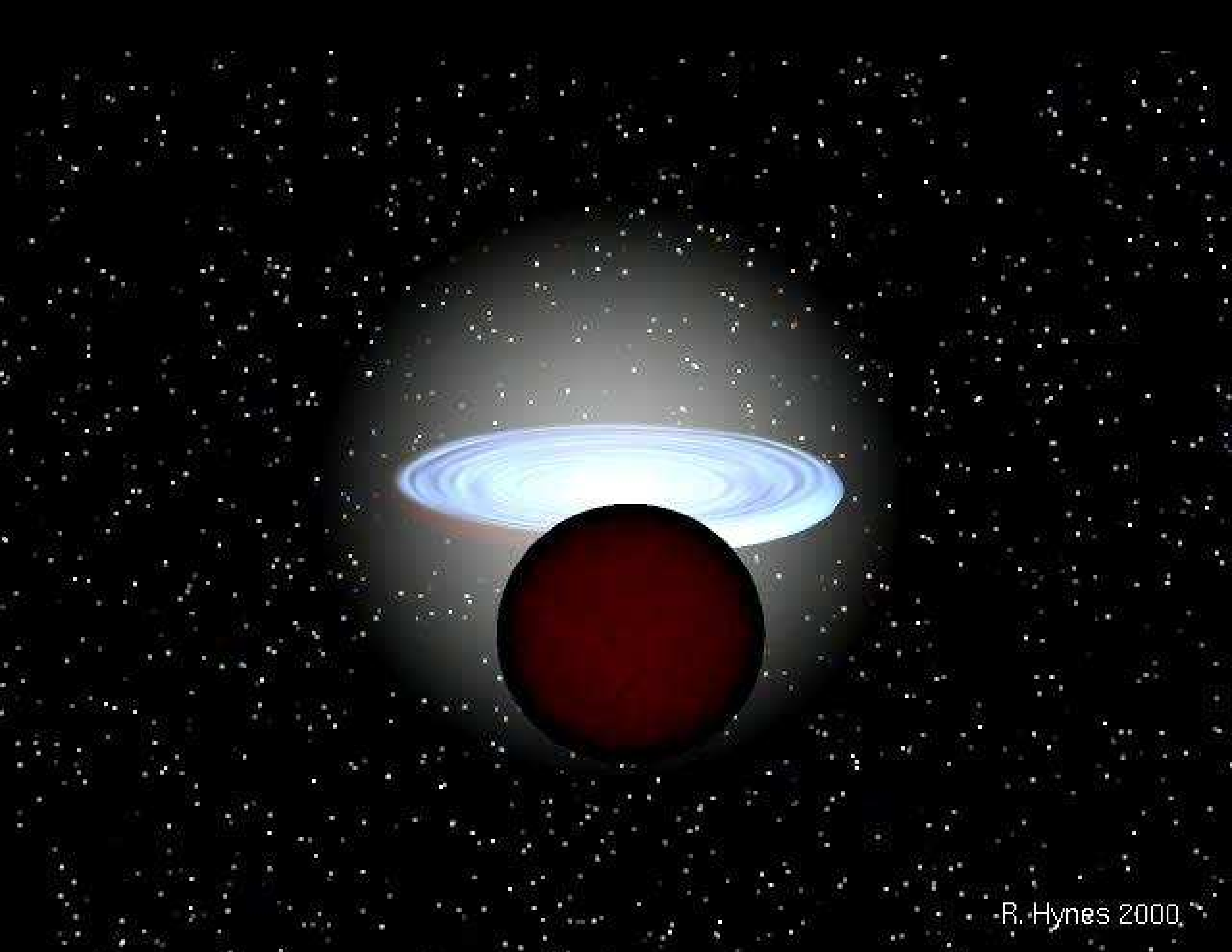
Black Hole: For $M \gtrsim 3\,M_\odot$ no stable configuration known

$\Longrightarrow$ Star collapses completely

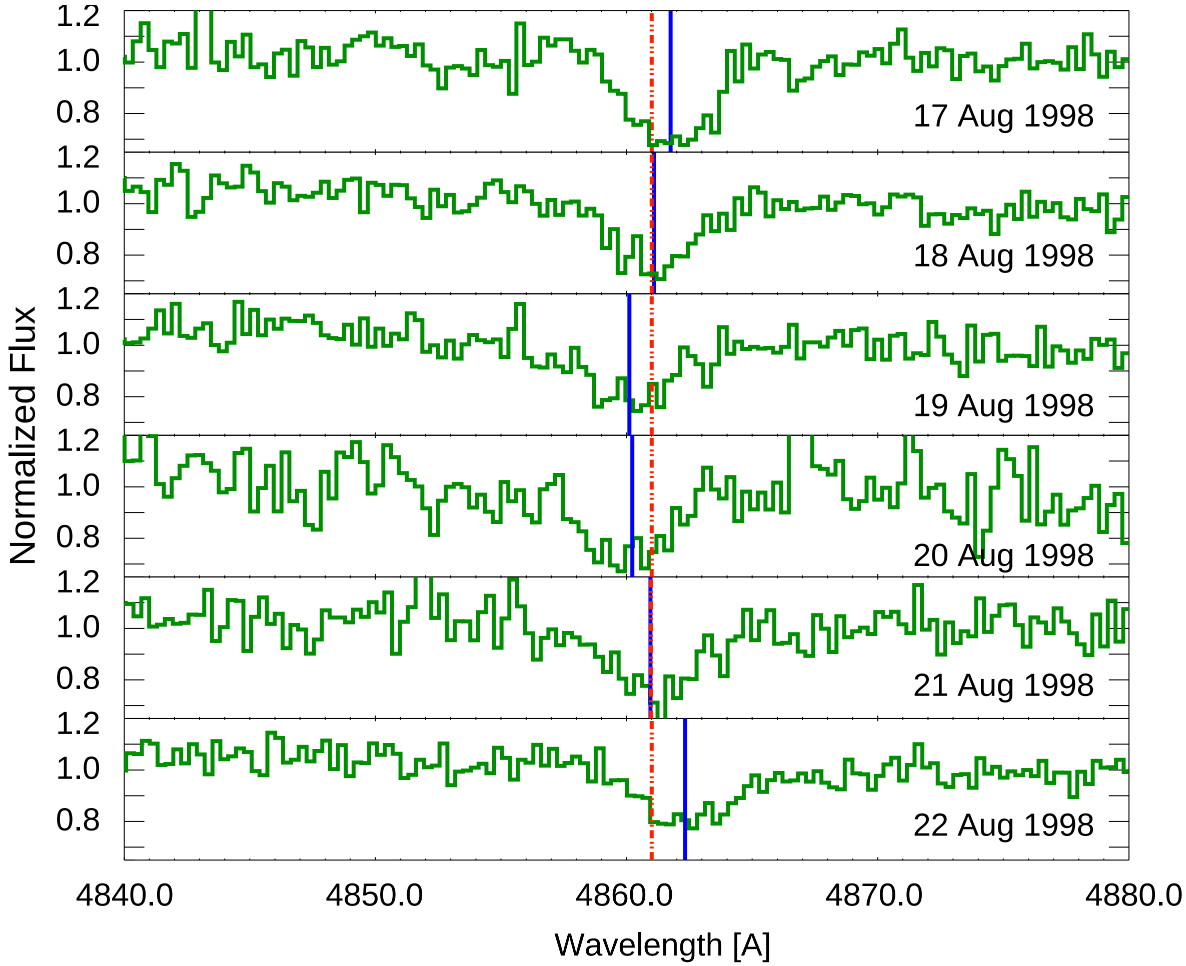
$\Longrightarrow$ Black Hole

Size scale: $R_\mathrm{S} = 2GM/c^2 = 3(M/M_\odot)\,\mathrm{km}$

If mass of compact object $M > 3\,M_\odot$: Black Hole Candidate


R. Hynes 2000

What are BHC?, IV



Motion of the Hβ line in HDE 226868/Cyg X-1
(Pottschmidt, Wilms)

In binary system: Determine mass of compact object using Kepler's 3rd Law

$$\frac{a^3}{P^2} = \frac{G(M_1 + M_2)}{4\pi^2}$$

(a: semi-major axis, P: period, $M_{1,2}$: Masses).

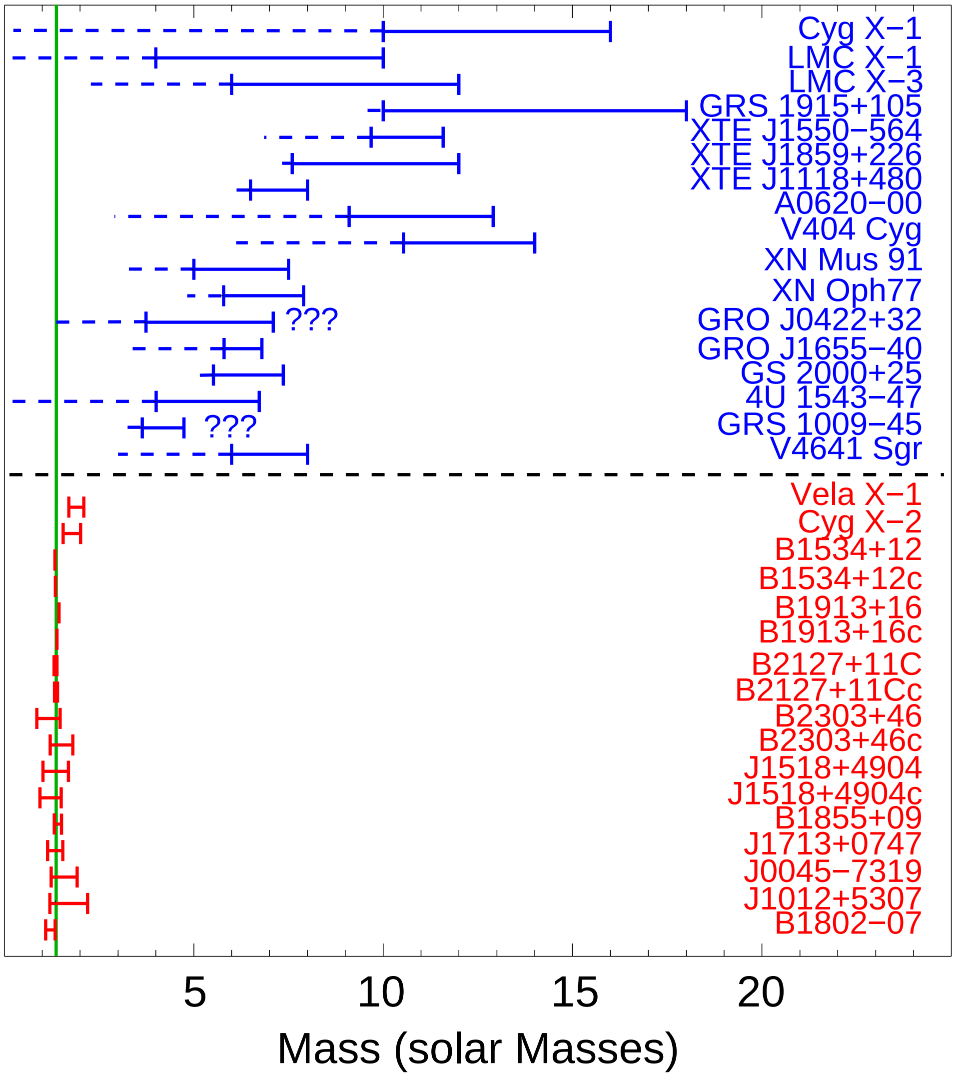
Derive from this the mass function

$$\mathrm{MF} = \frac{M_2^3 \sin^3 i}{(1 + (M_1/M_2))^2} = \frac{K_1^2 P}{2\pi G}$$

MF is lower mass for M_2.

(K_2 : velocity amplitude)

What are BHC?, V



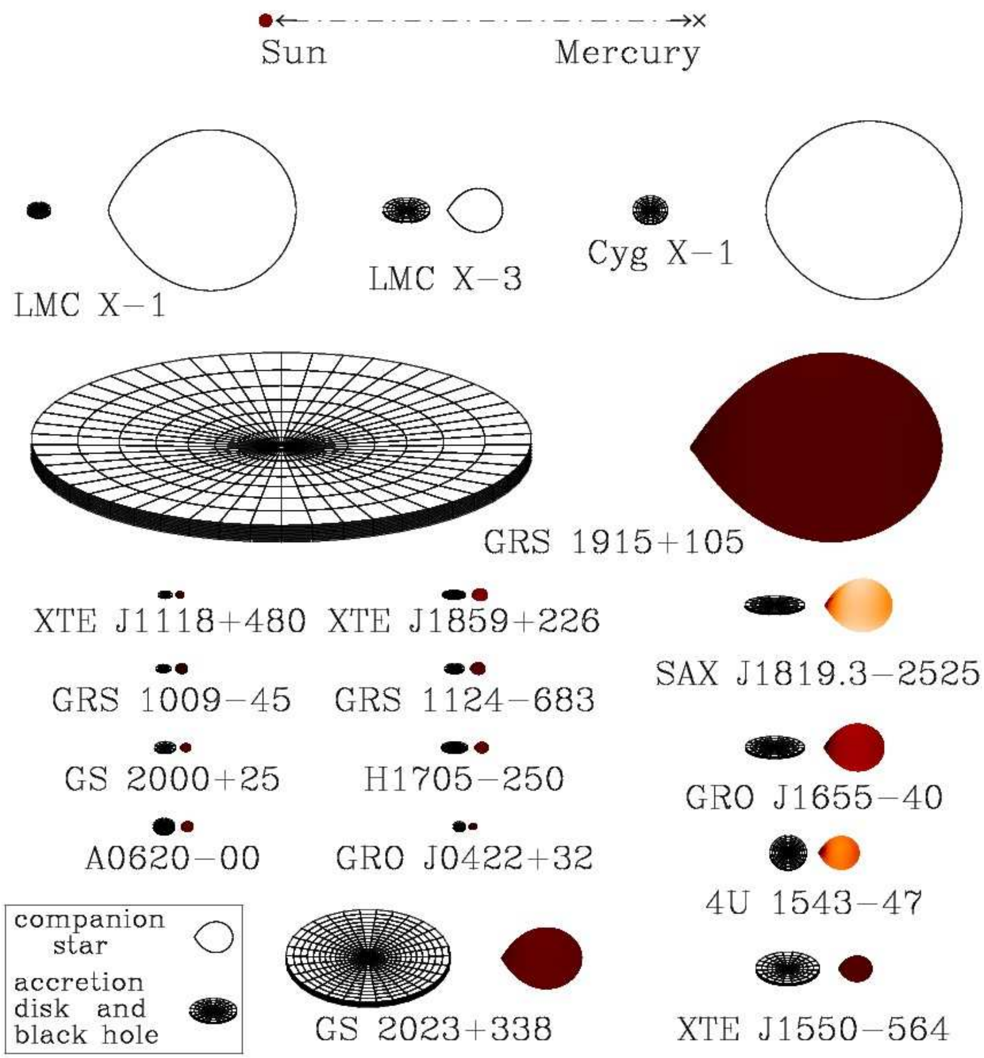
after Orosz (2004, priv. comm.)

- 1971: First BHC (Cyg X-1)
- 1983: LMC X-3
- Currently 20 dynamically confirmed Galactic Black Holes

Statistics:

- 3 High Mass X-ray Binaries
- Low Mass X-ray Binary BHC: mainly transient sources
- Masses $< 20\,M_\odot$

What are BHC?, VI



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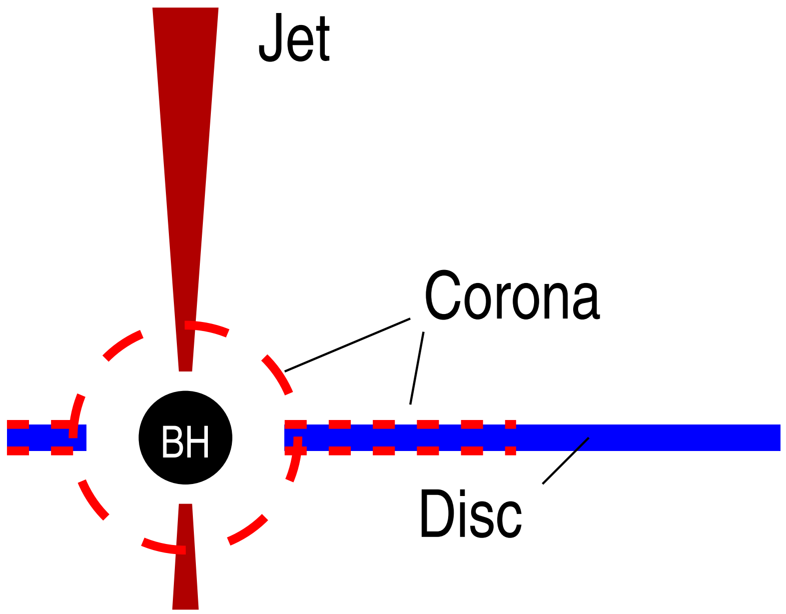
Current Questions



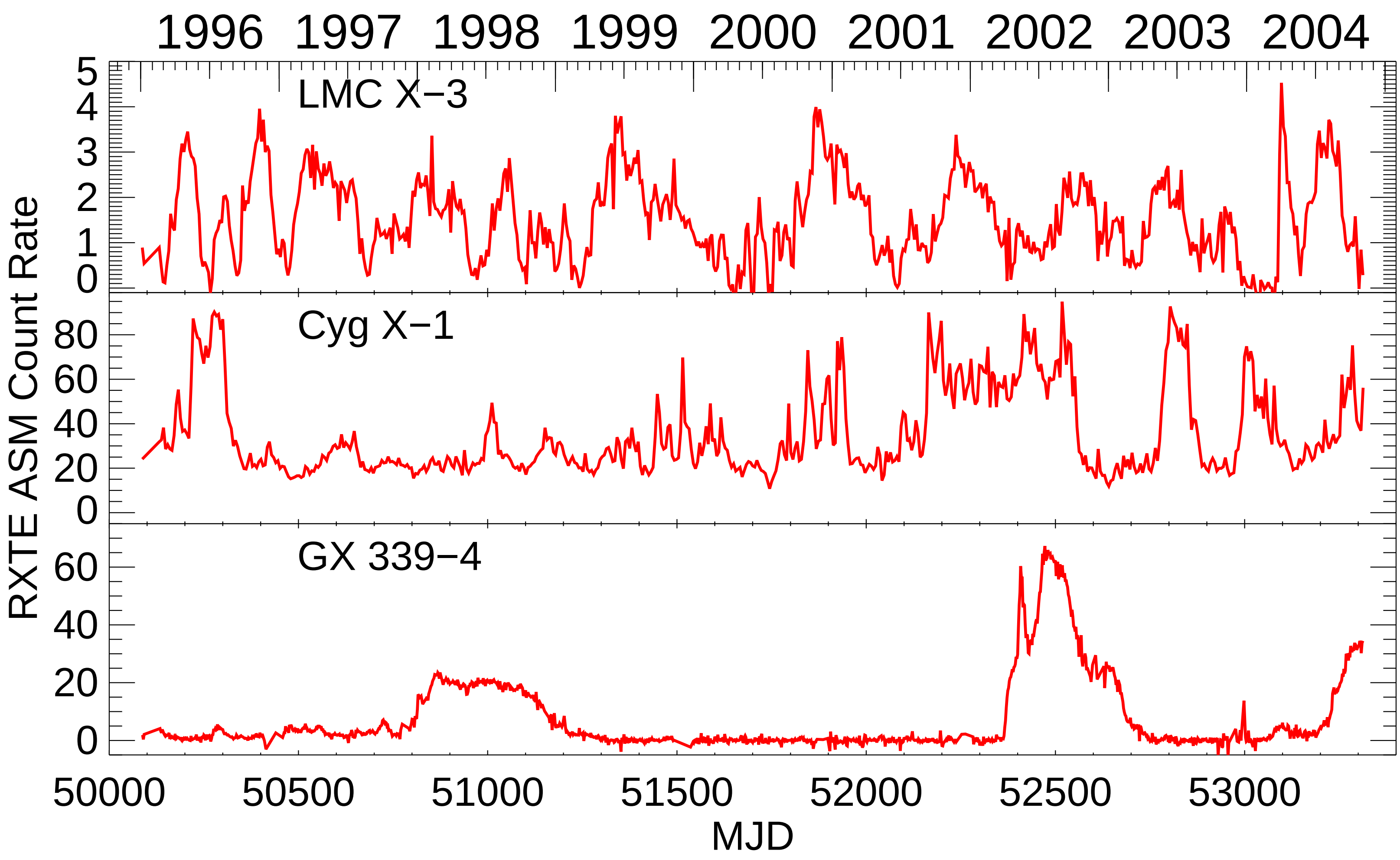
What we want to learn:

1. What does the accretion region look like: “accretion geometry”
2. What are the physical processes responsible for the broad-band emission?
3. Is there evidence for GR effects?

Active Galactic Nuclei and BHC have similar geometry $\Longrightarrow$ study similar physical processes!

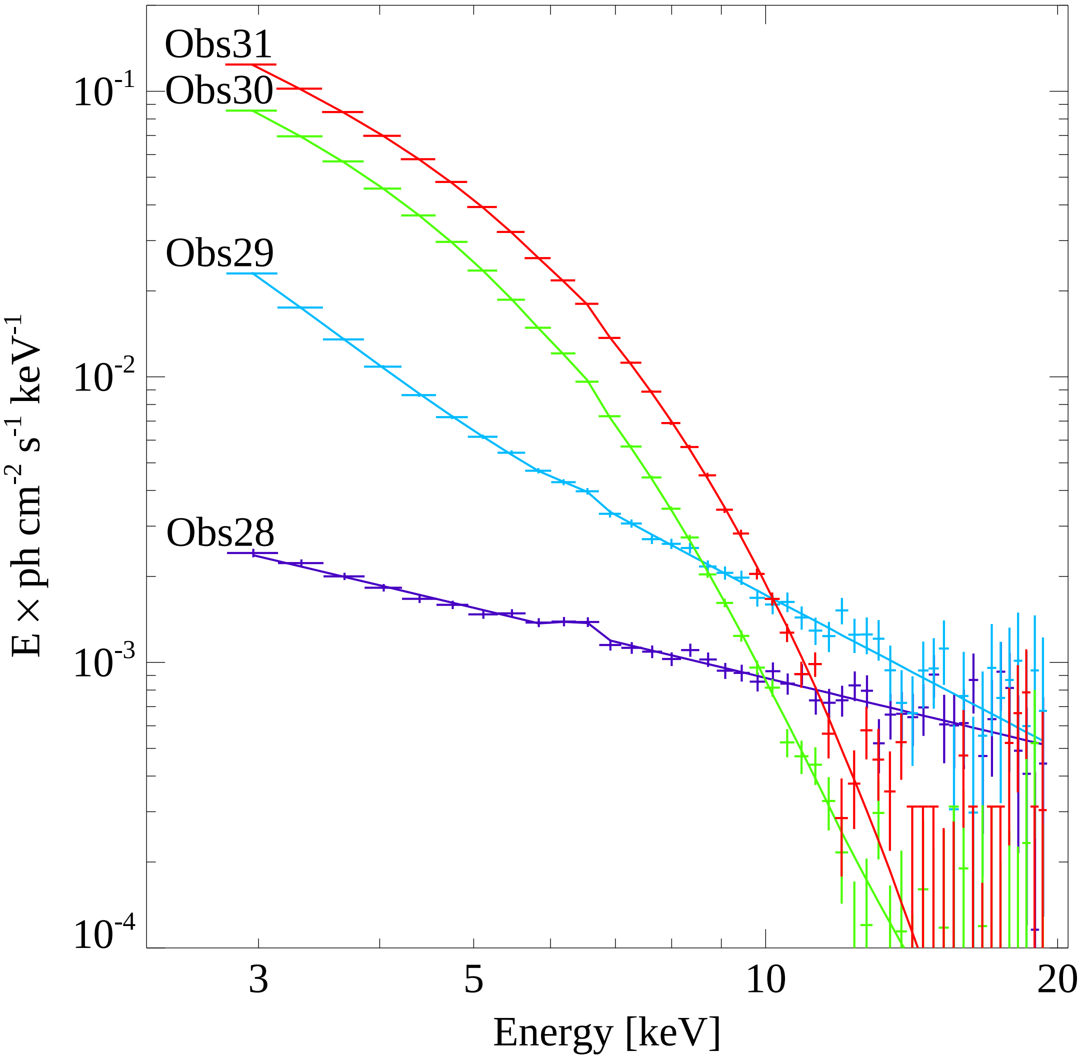
X-rays produced close to event horizon, observations give *one of the few constraints* to study physics in the strong gravitational field limit.

Long-Term Evolution



Black Holes: Variability on all time scales

Spectral States

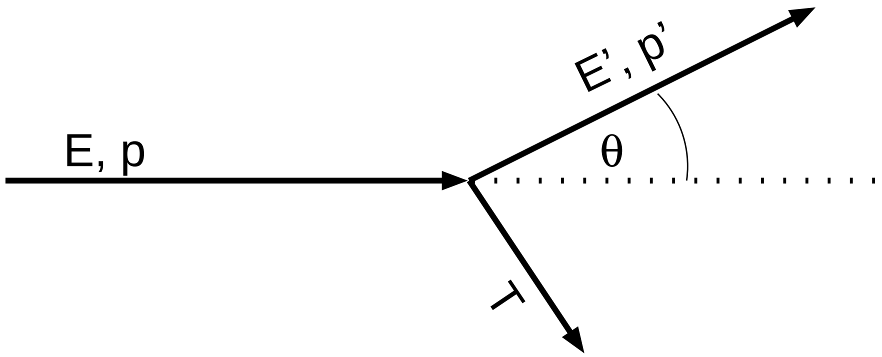


(LMC X-3; Wilms et al., 2001)

X-ray States:

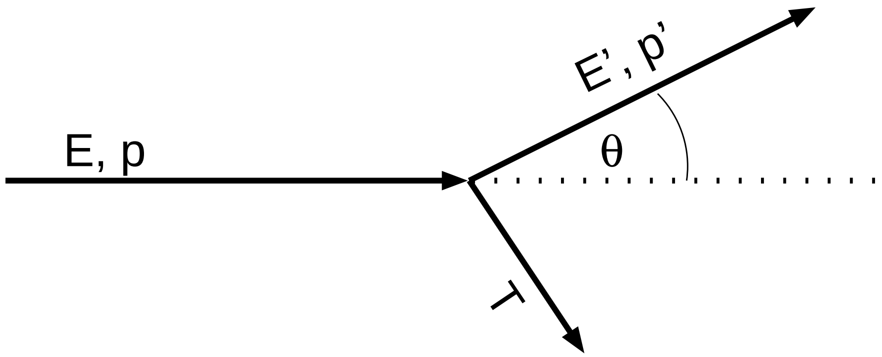
- $L_X \gtrsim 0.05\,L_{Edd}$:
  soft state/high state:
  - thermally dominated
  - low variability (few percent rms)
- $L_X \lesssim 0.05\,L_{Edd}$:
  hard state/low state:
  - power law spectrum,
  - high variability (few 10 percent rms)

Hard State: Comptonization



Sunyaev & Trümper (1979): power law continuum caused by Comptonization

Hard State: Comptonization

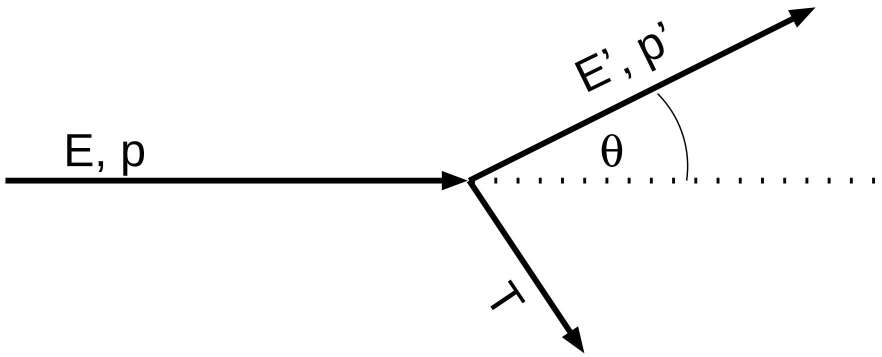


Sunyaev & Trümper (1979): power law continuum caused by Comptonization

Frame of rest of electron: Photon's energy change due to Compton scattering:

$$E' = \frac{E}{1 + \frac{E}{m_e c^2}(1 - \cos\theta)} \quad \text{, for } E \ll m_e c^2\text{:} \quad \frac{\Delta E}{E} \sim -\frac{E}{m_e c^2}$$

Hard State: Comptonization



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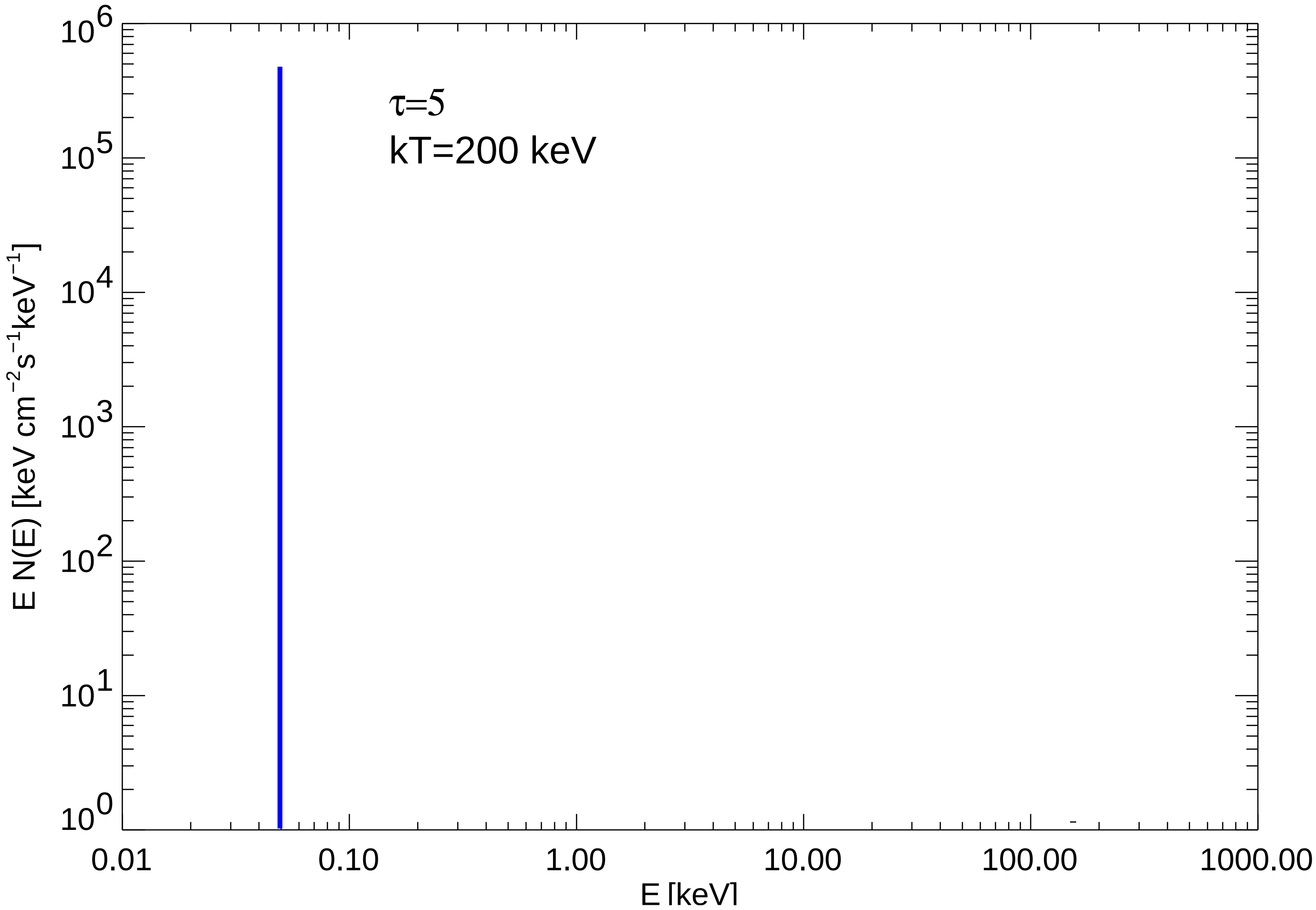
If electron not at rest: energy transfer onto photon possible.

For thermal electrons:

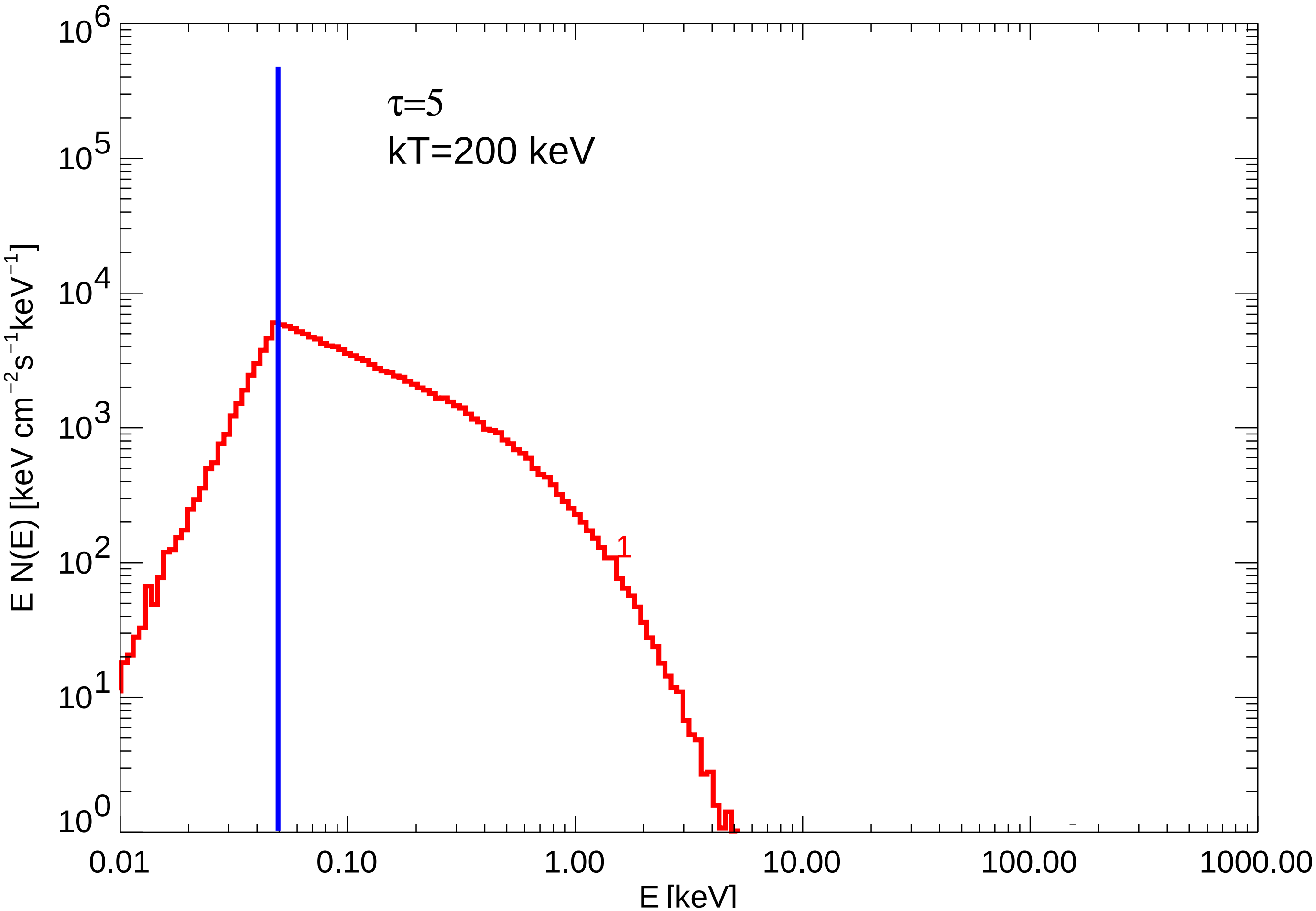
$$\frac{\Delta E}{E} \sim \frac{4kT_e - E}{m_e c^2}$$

Hard State: Comptonization



Computation of spectrum either through solution of Kompaneets equation or directly through Monte Carlo simulation

Hard State: Comptonization



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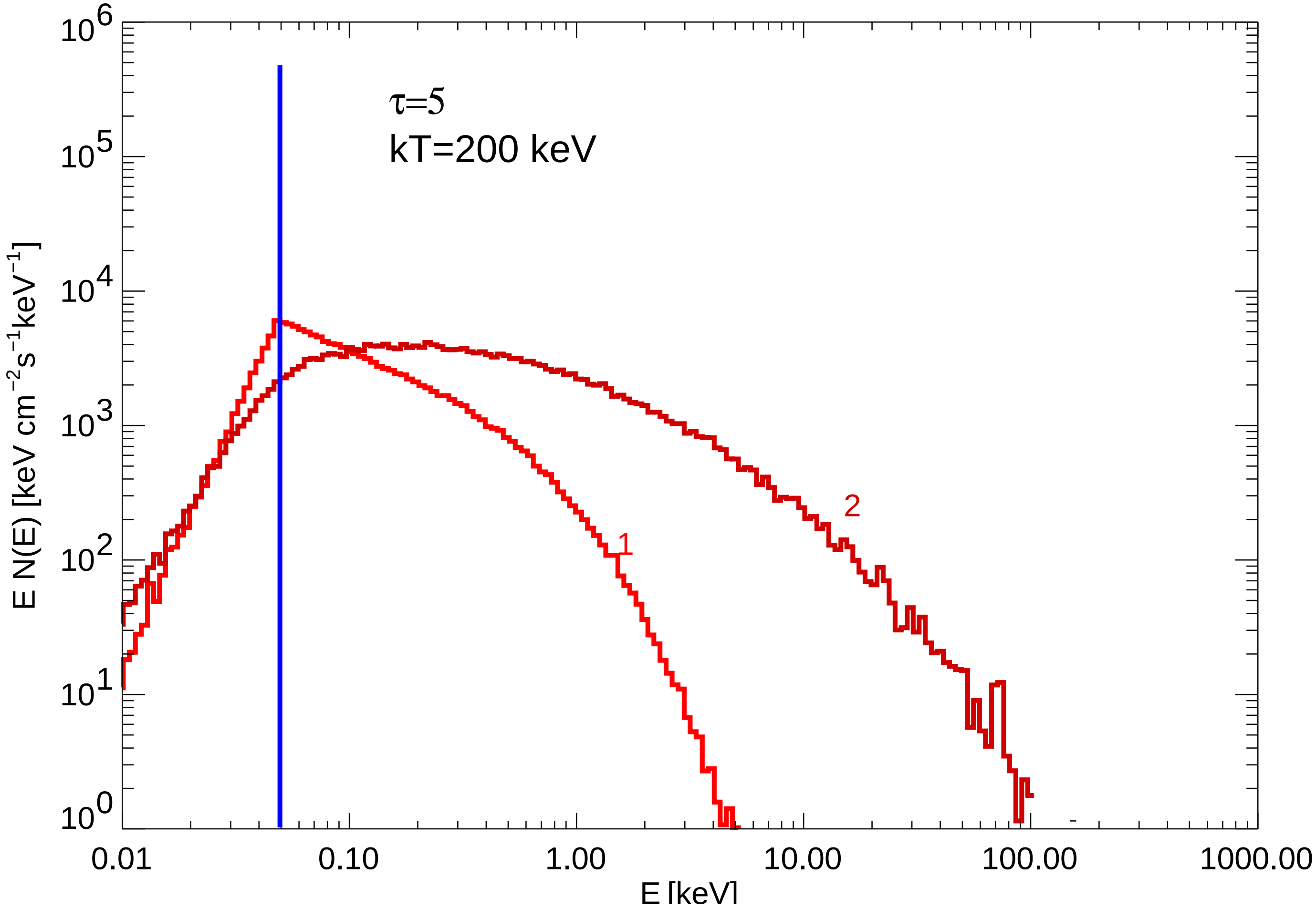

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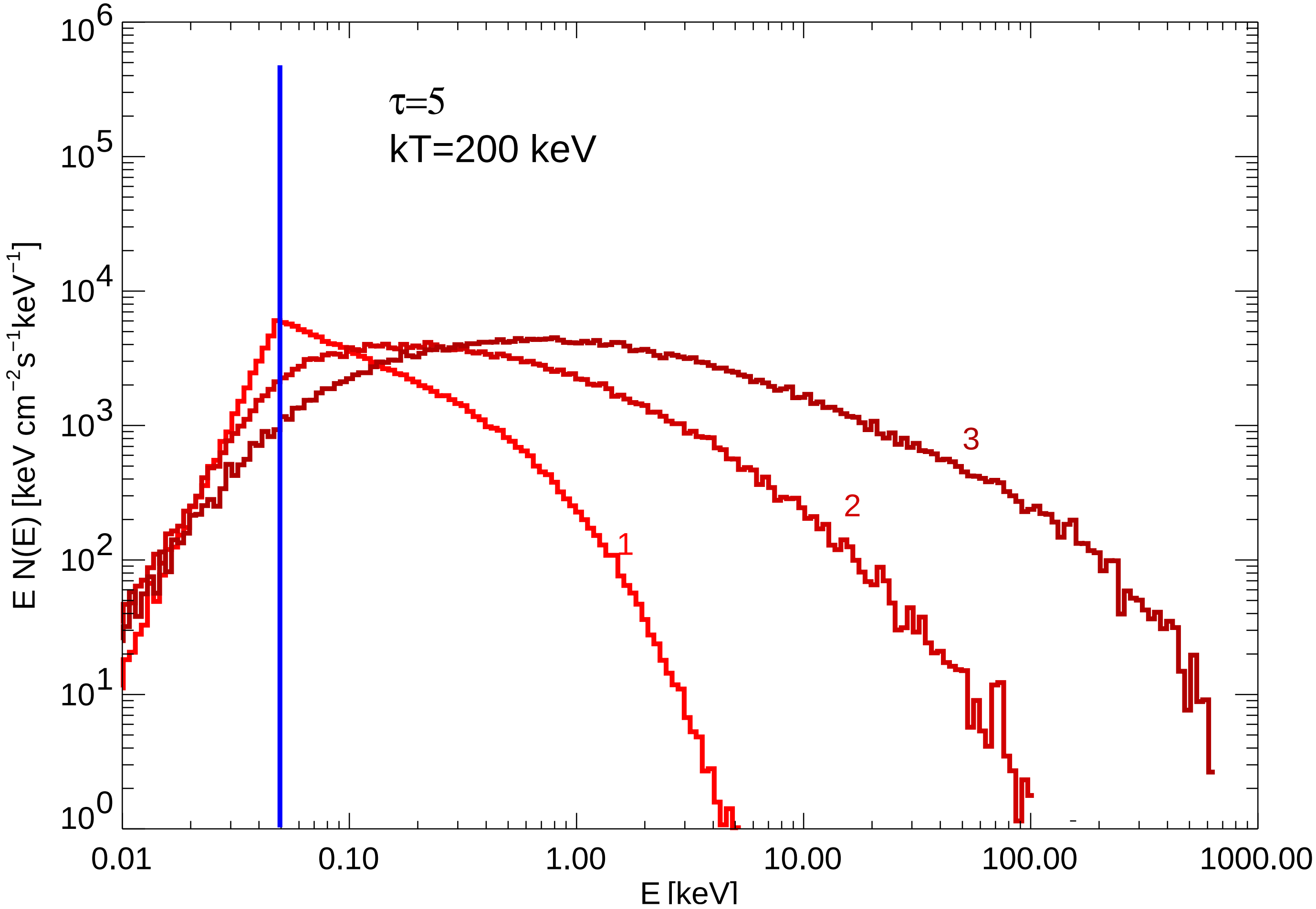

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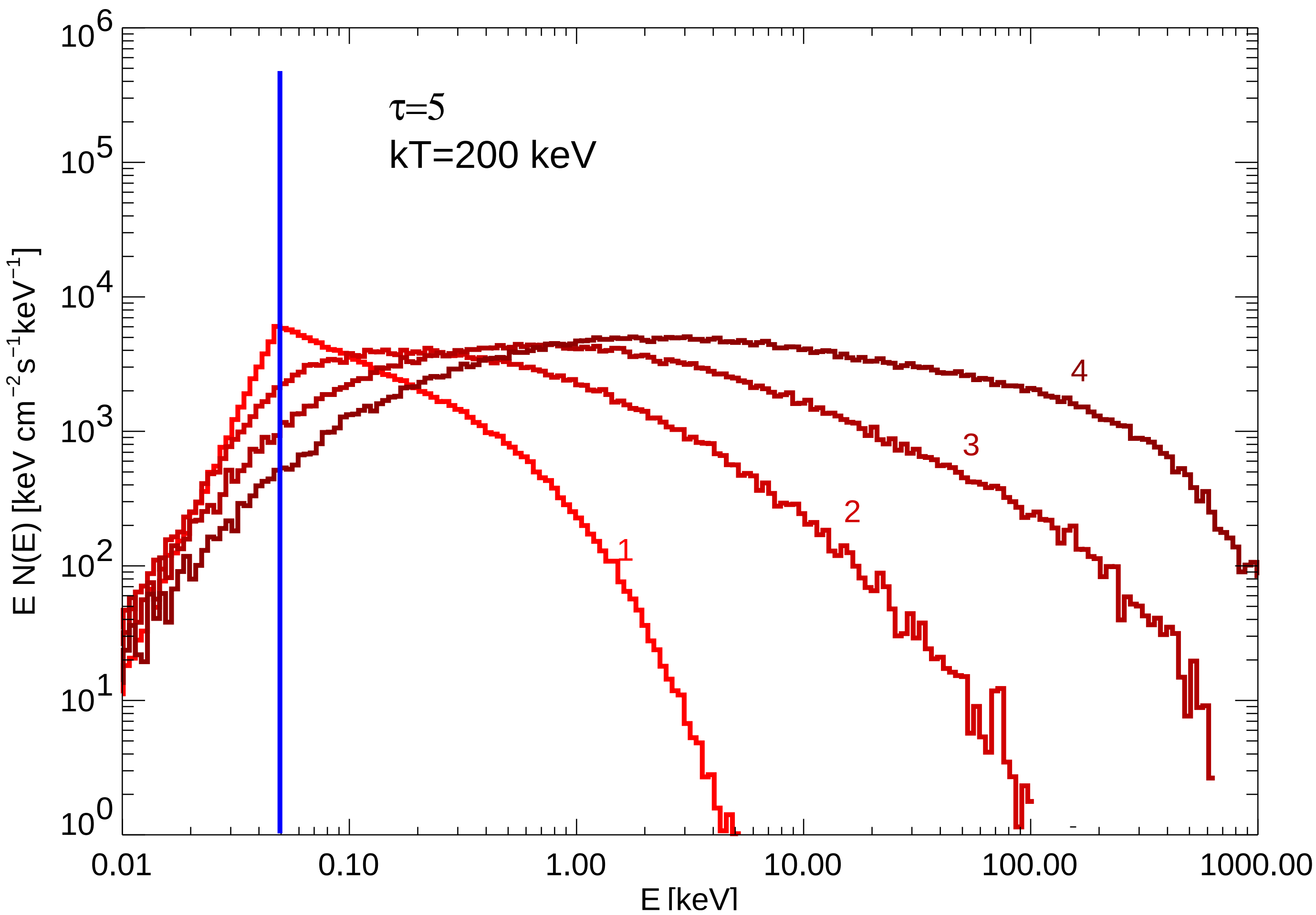

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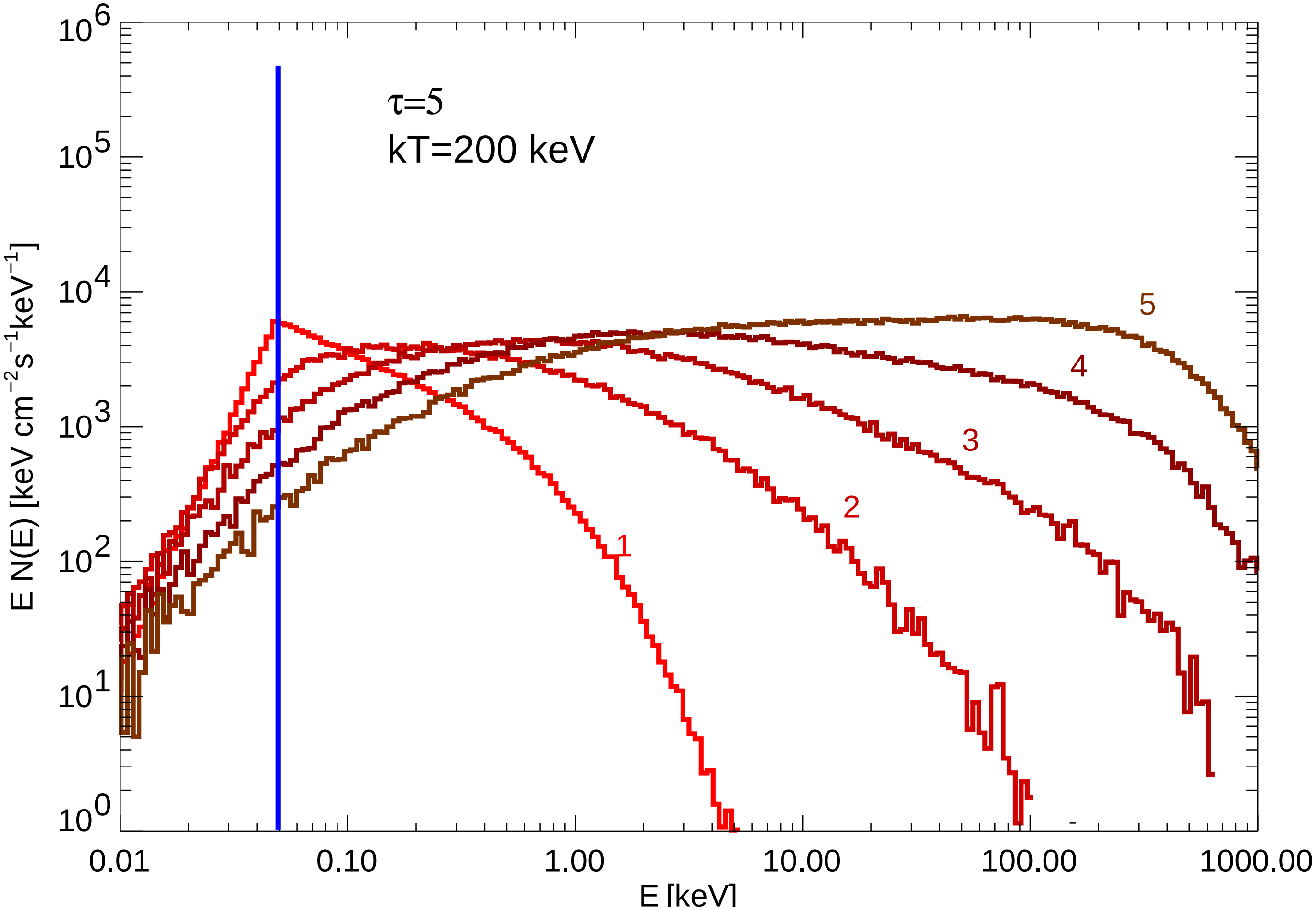
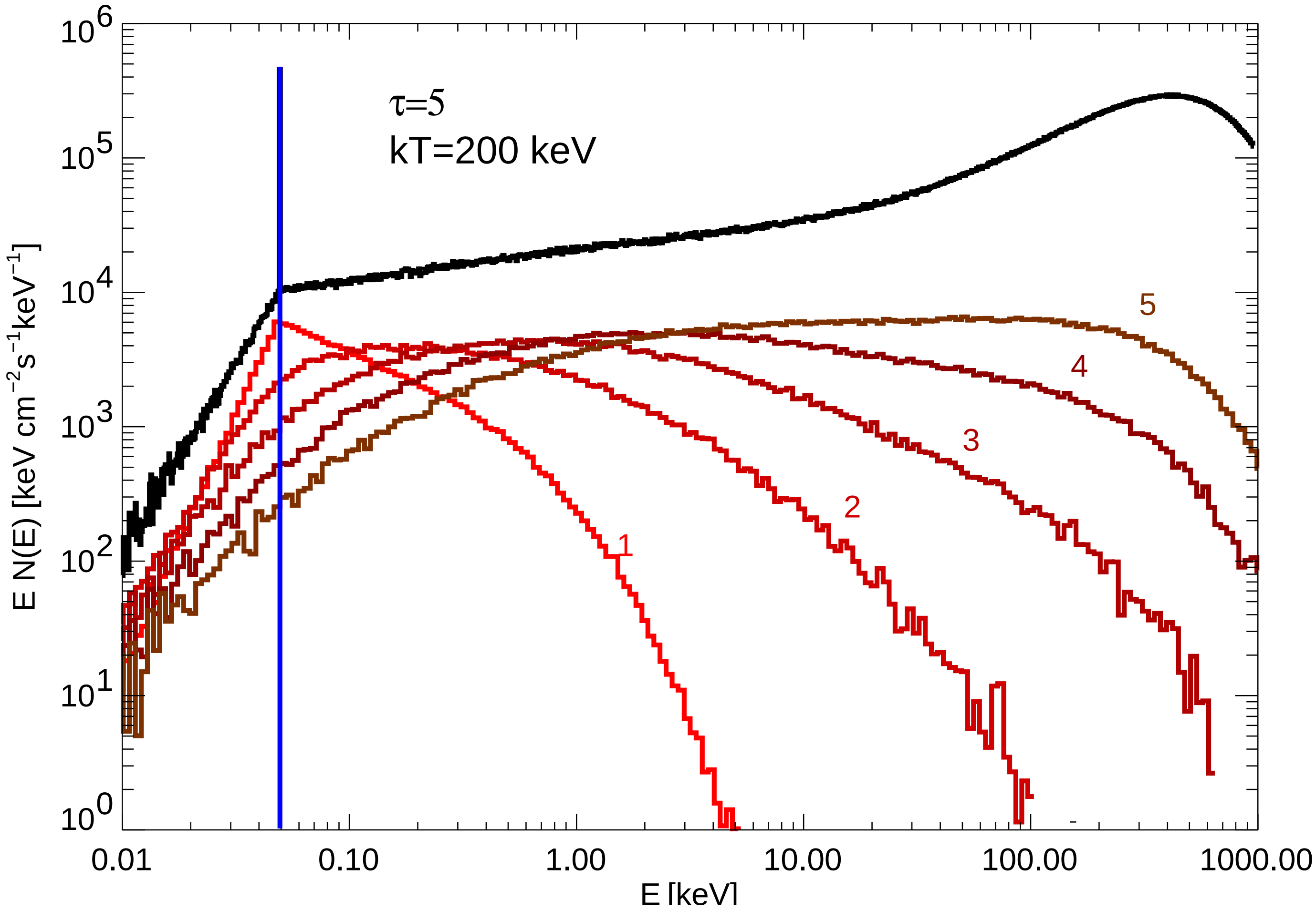


Computation of spectrum either through solution of Kompaneets equation or directly through Monte Carlo simulation

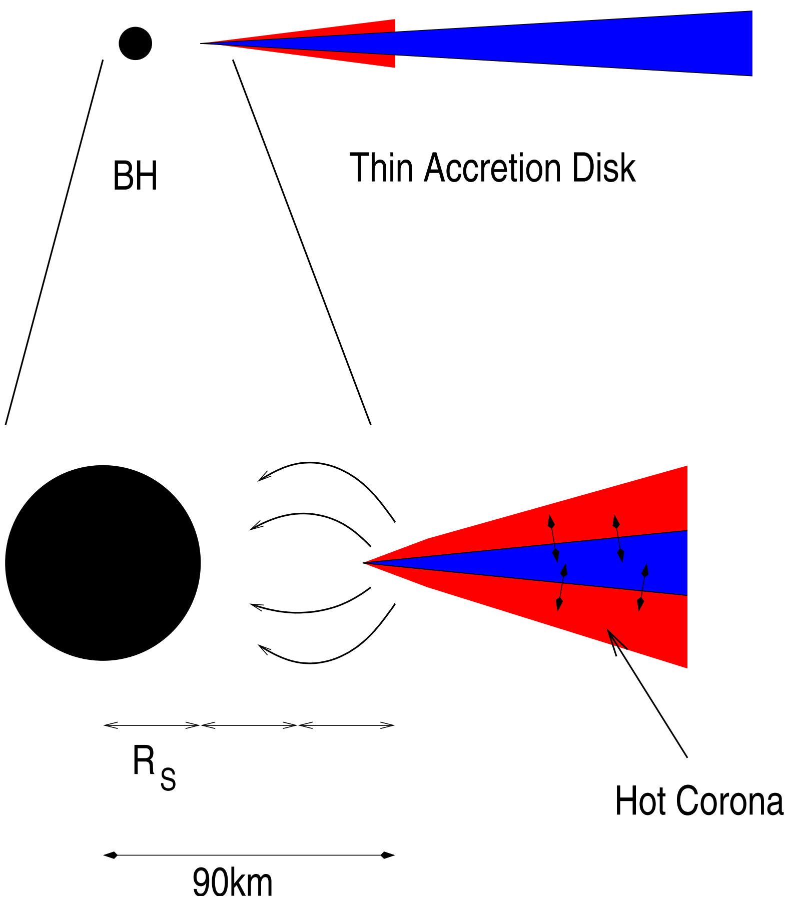
Hard State: Comptonization

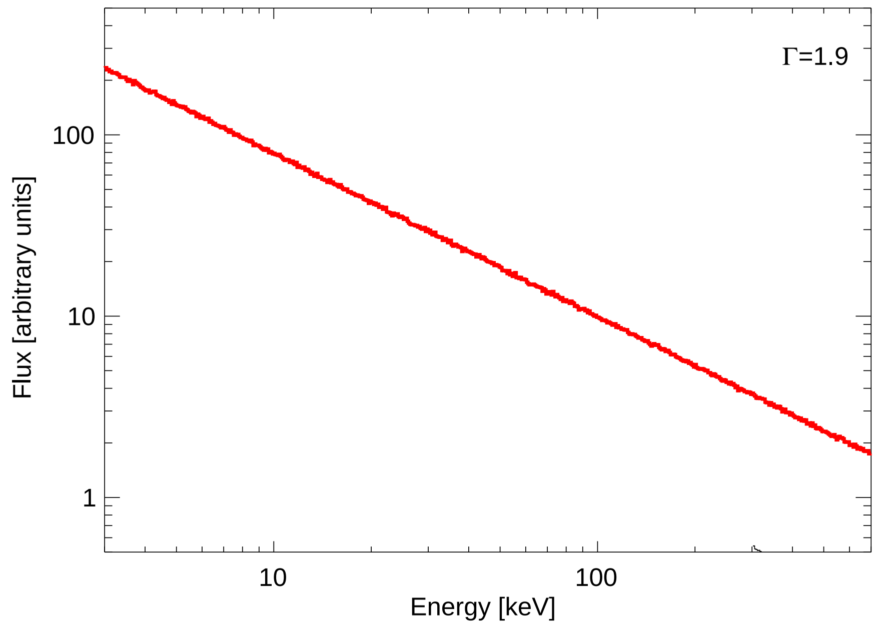


Computation of spectrum either through solution of Kompaneets equation or directly through Monte Carlo simulation

⟹ Power law with exponential cutoff.

Hard State: Comptonization

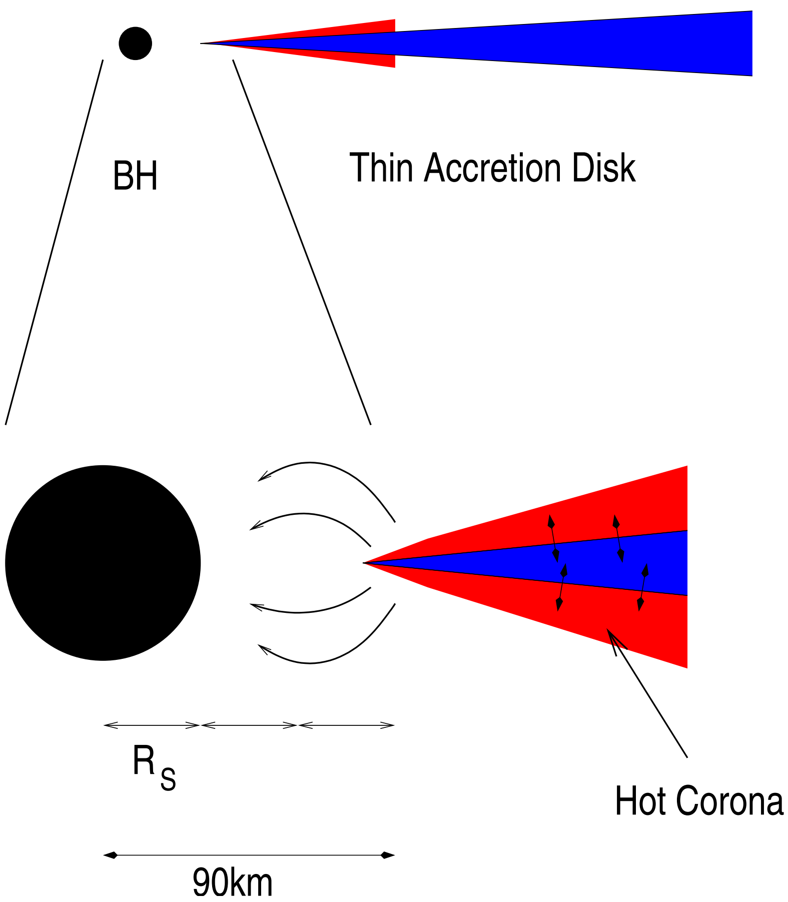


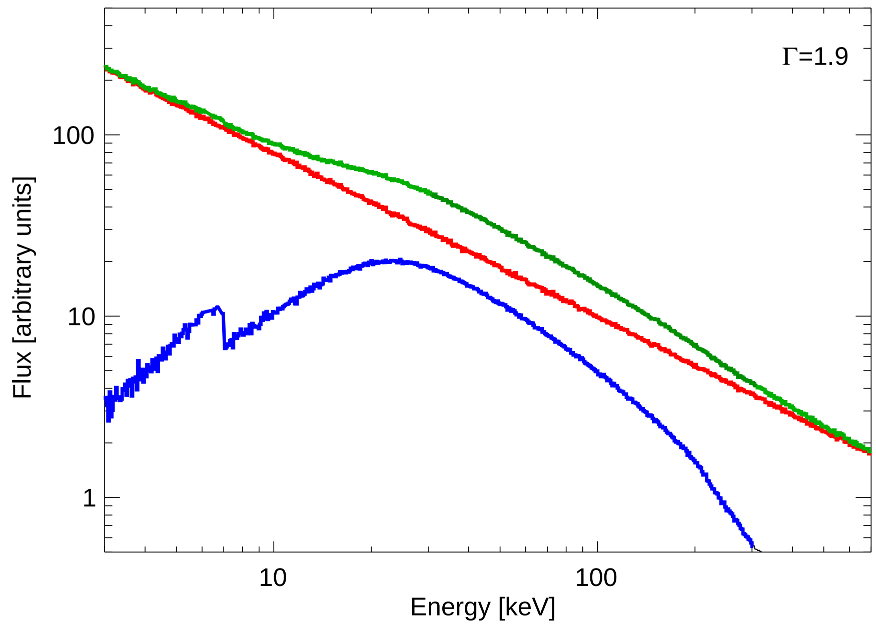


Black Hole X-Ray Spectrum:

- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.

Hard State: Comptonization





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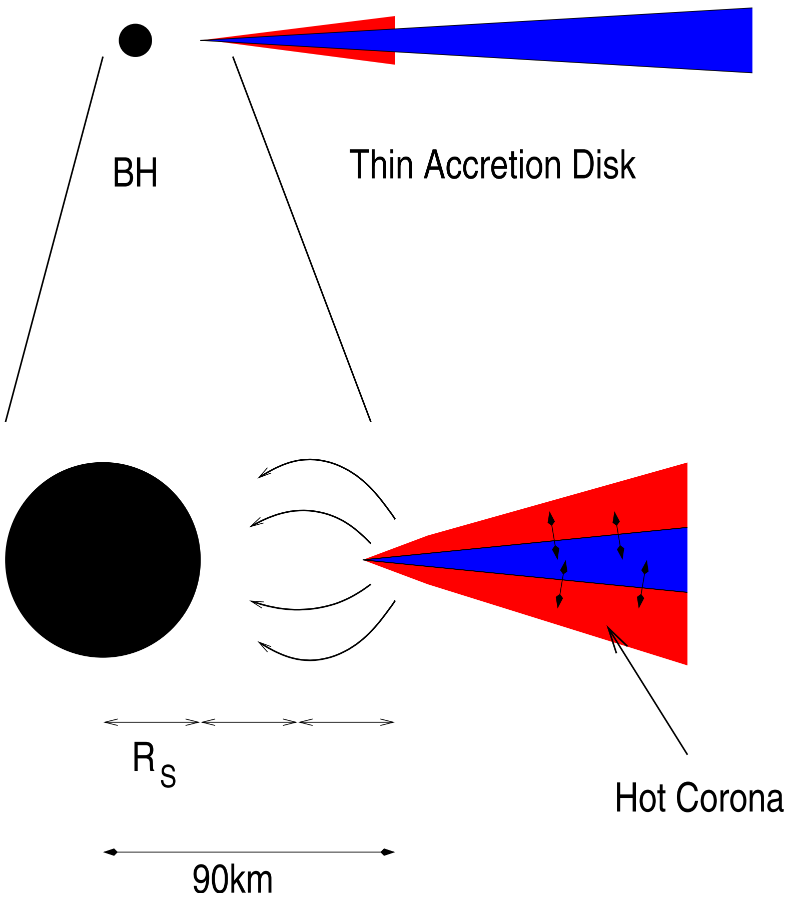
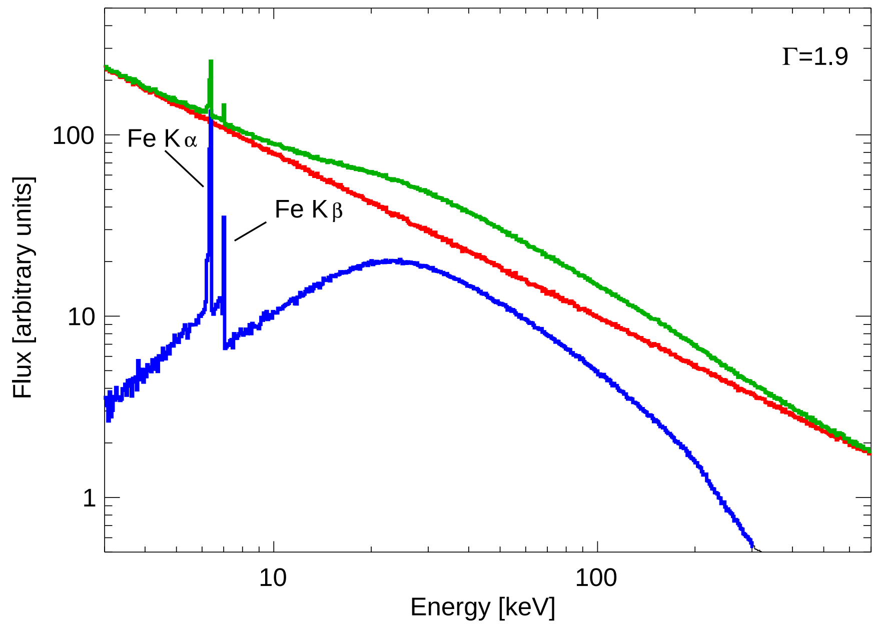
- Thomson scattering of power law photons in disk: Compton Reflection Hump

Hard State: Comptonization



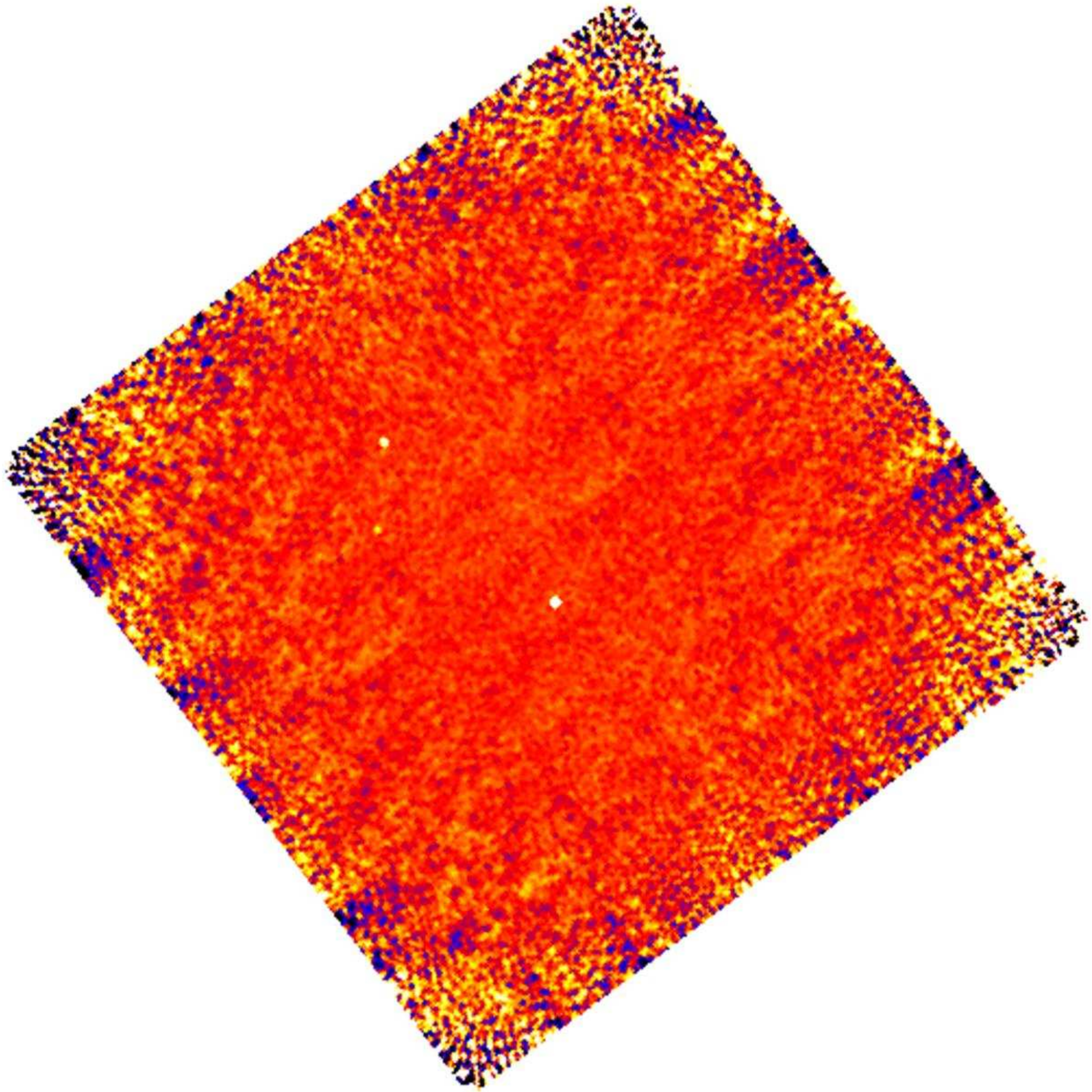


Black Hole X-Ray Spectrum:

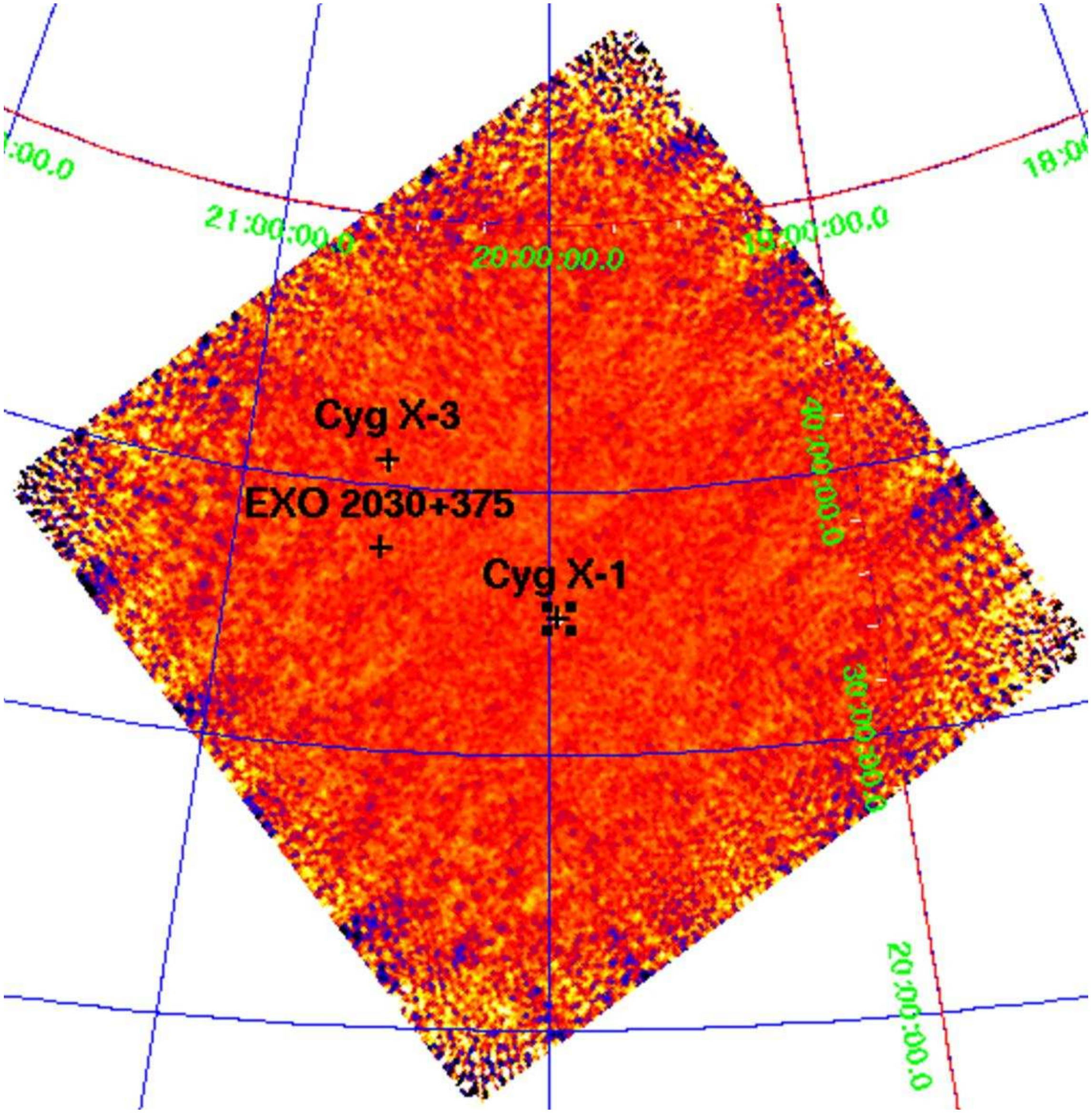
- Comptonization of soft X-rays from accretion disk in hot corona ($T \sim 10^8$ K): power law continuum.
- Thomson scattering of power law photons in disk: Compton Reflection Hump
- Photoabsorption of power law photons in disk: fluorescent Fe Kα Line at $\sim$6.4 keV

INTEGRAL

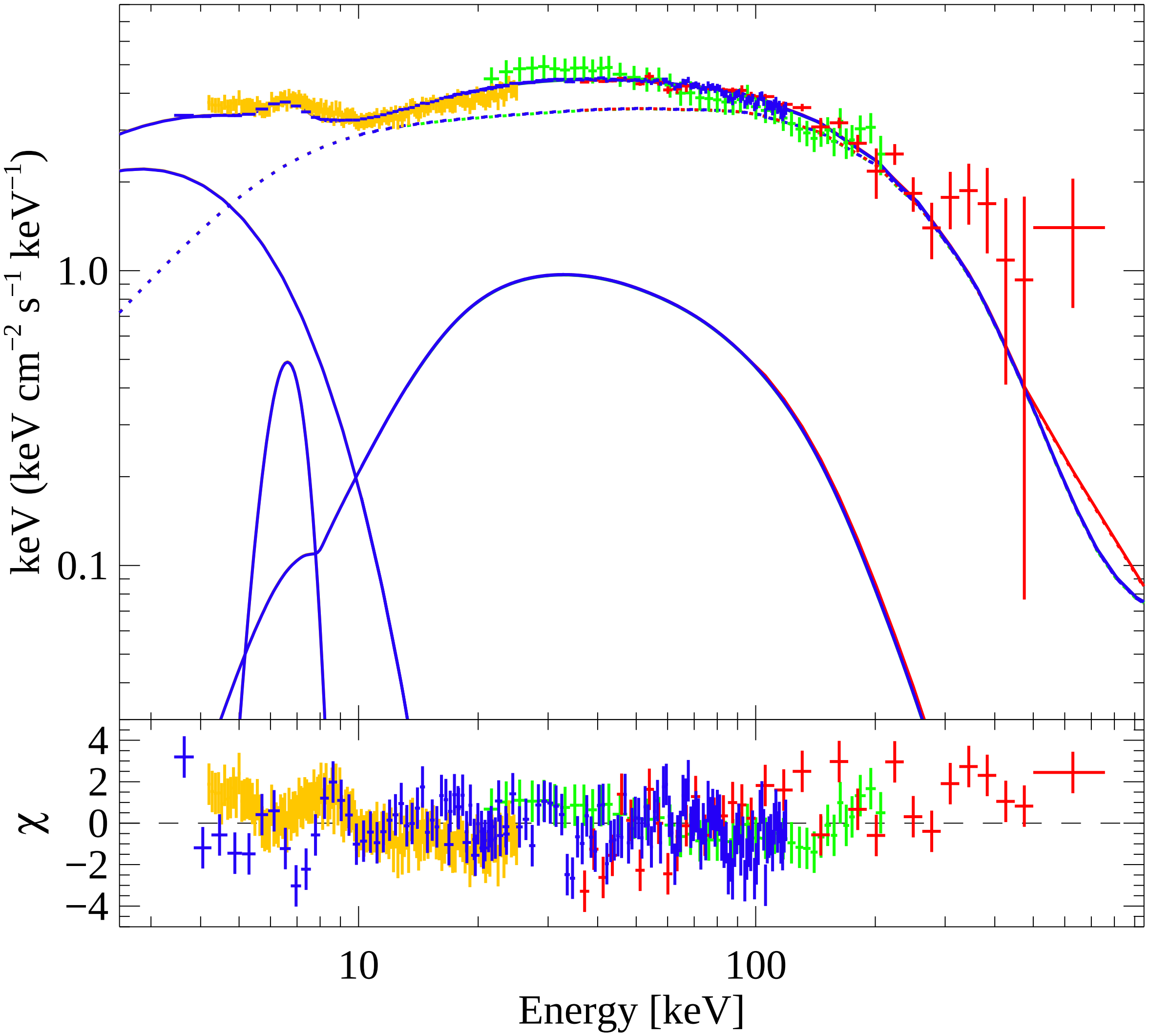
Broad Band Spectrum, II



Broad Band Spectrum, III



Broad Band Spectrum, IV



Fritz et al. (2006)

see also Pottschmidt et al. (2003a)

Fit of Comptonization model to *RXTE*/*INTEGRAL*.

$kT_{\text{max}} = 1.21\,\text{keV}$,

$\tau_{\text{p}} = 1.01$,

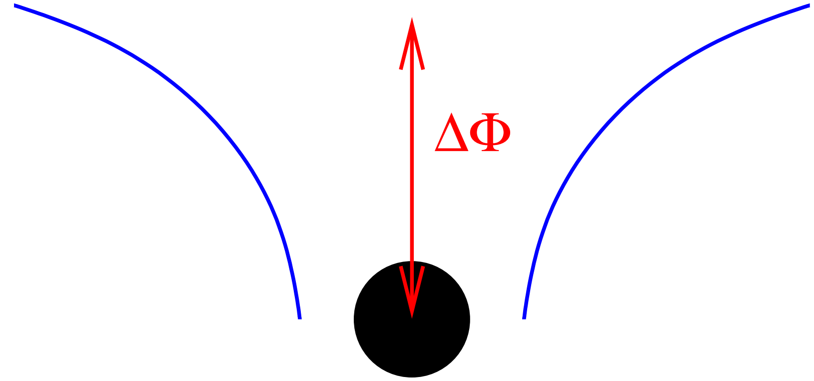
$\ell_{\text{h}}/\ell_{\text{s}} = 2.70$,

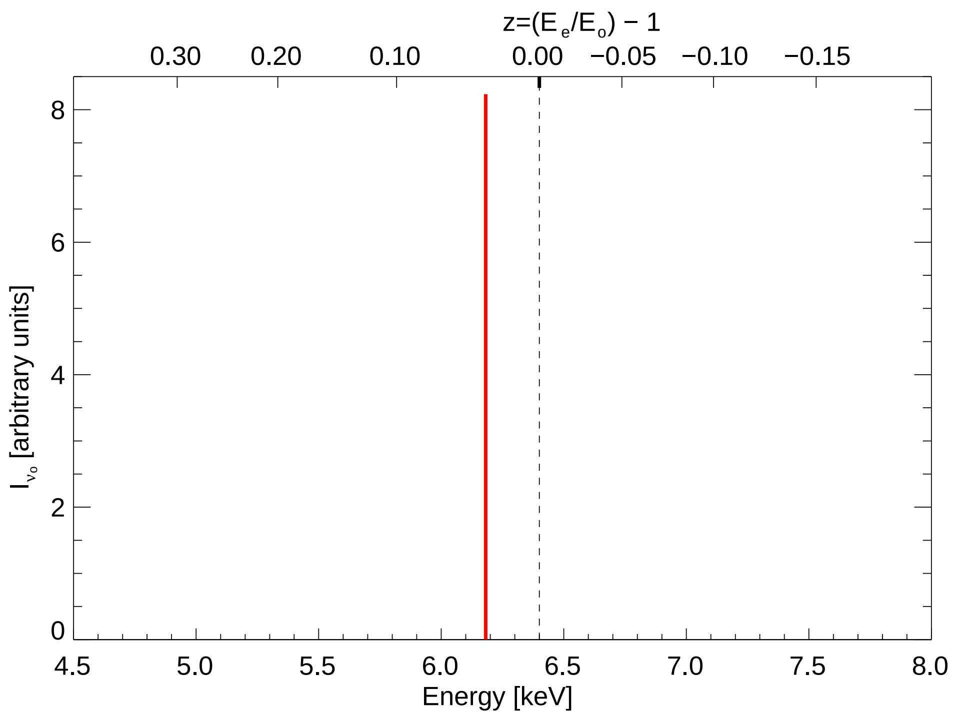
$\ell_{\text{nt}}/\ell_{\text{th}} = 0.05$,

$\Omega/2\pi = 0.3/2$

$\chi^2/\text{dof} = 466/348$

Relativistic Lines

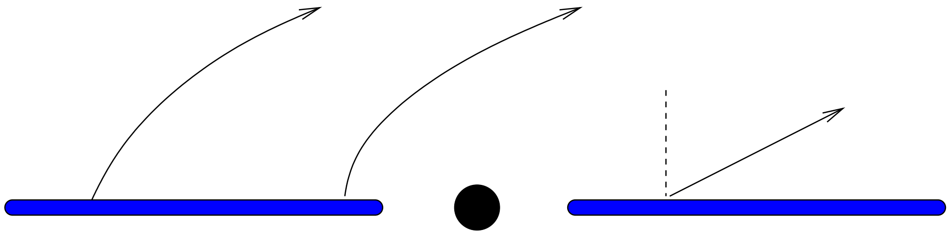


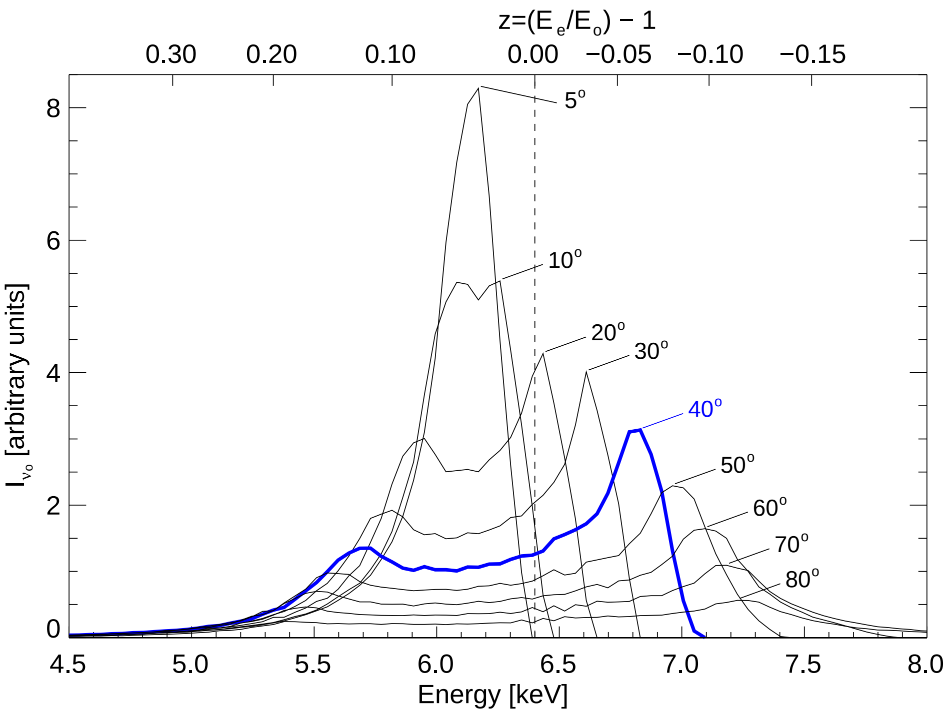


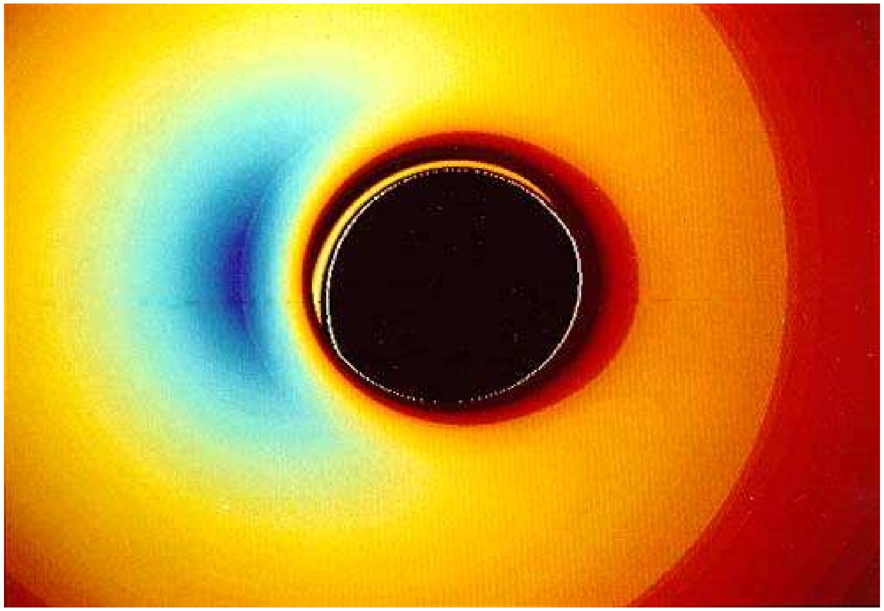
Total observed line profile affected by

- grav. Redshift

Relativistic Lines



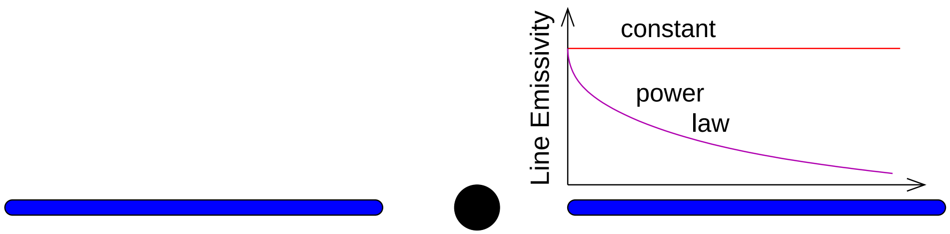


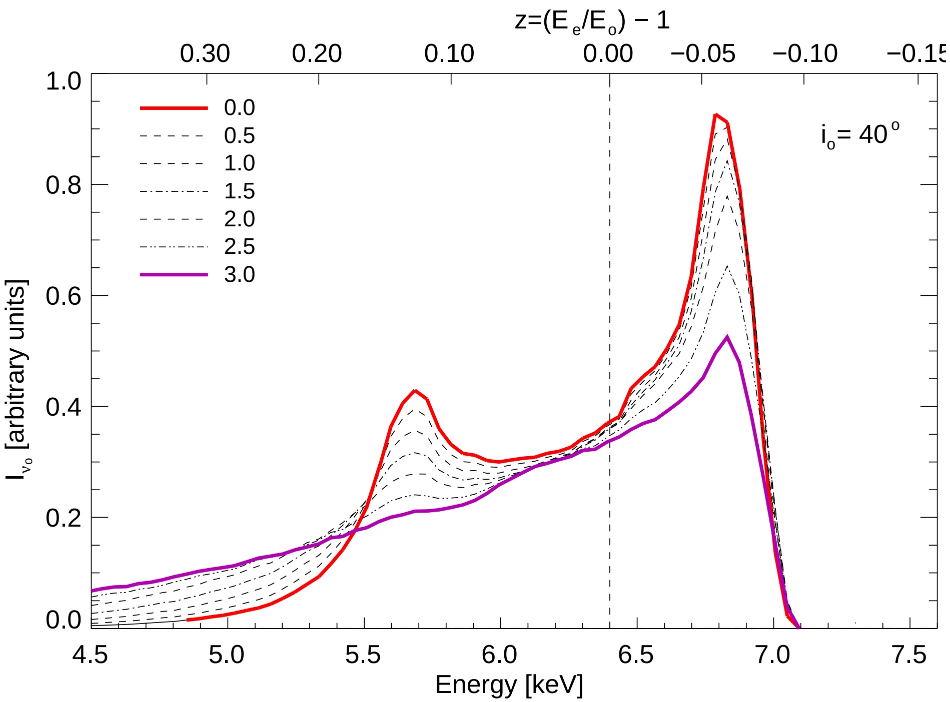


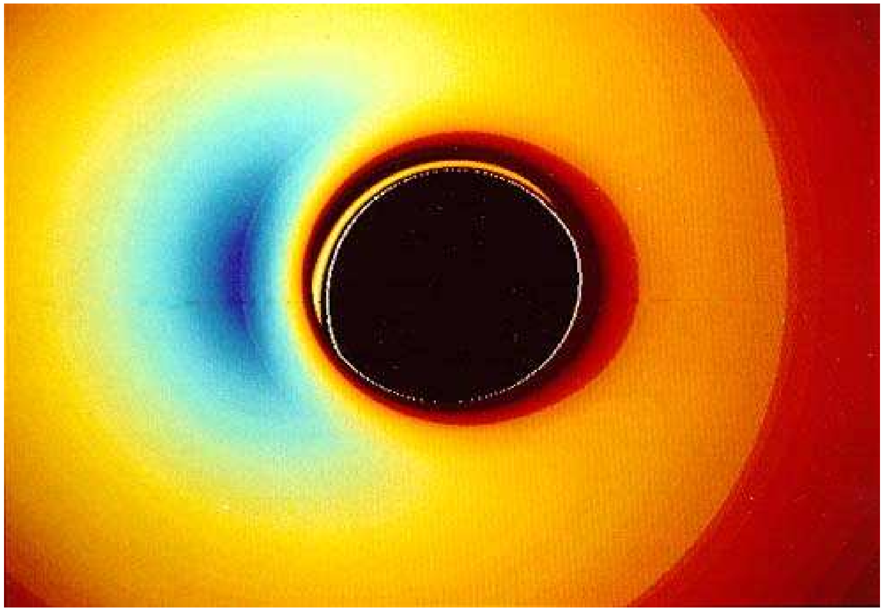
Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift

Relativistic Lines



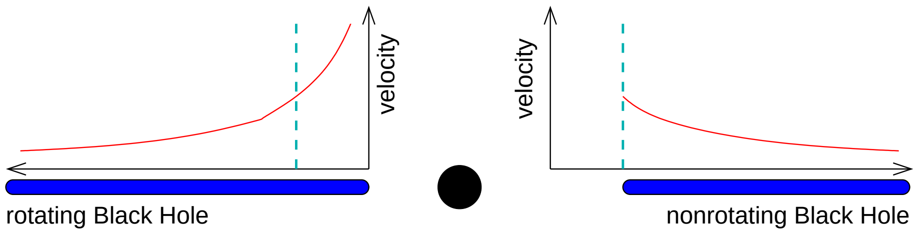


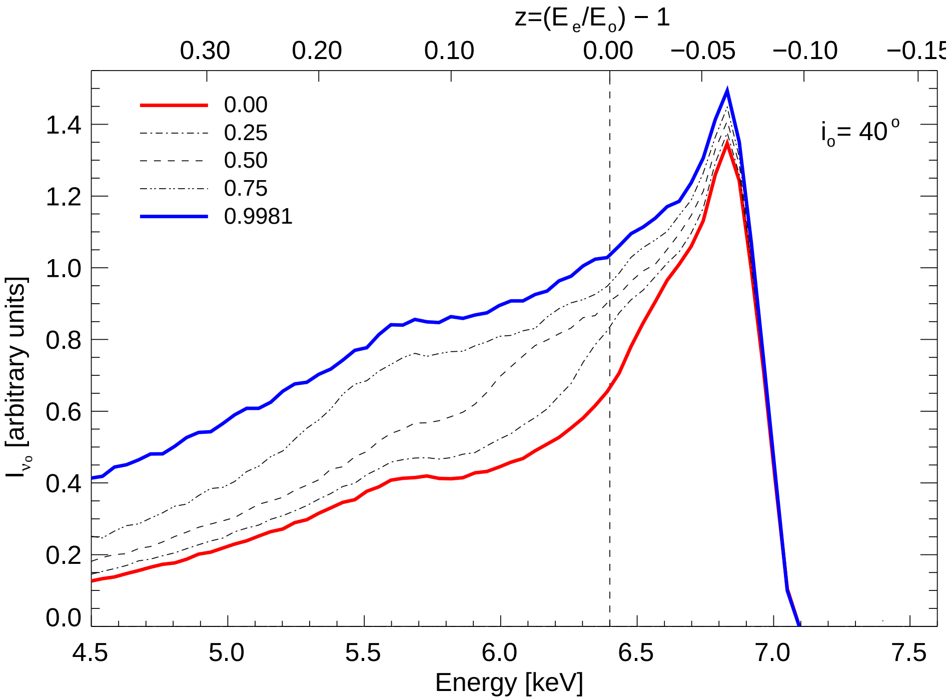


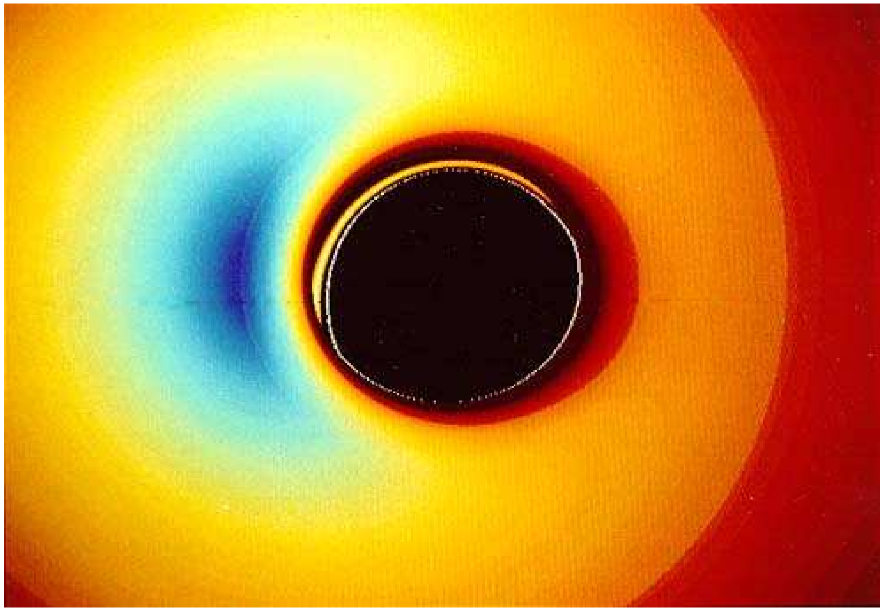
Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile

Relativistic Lines





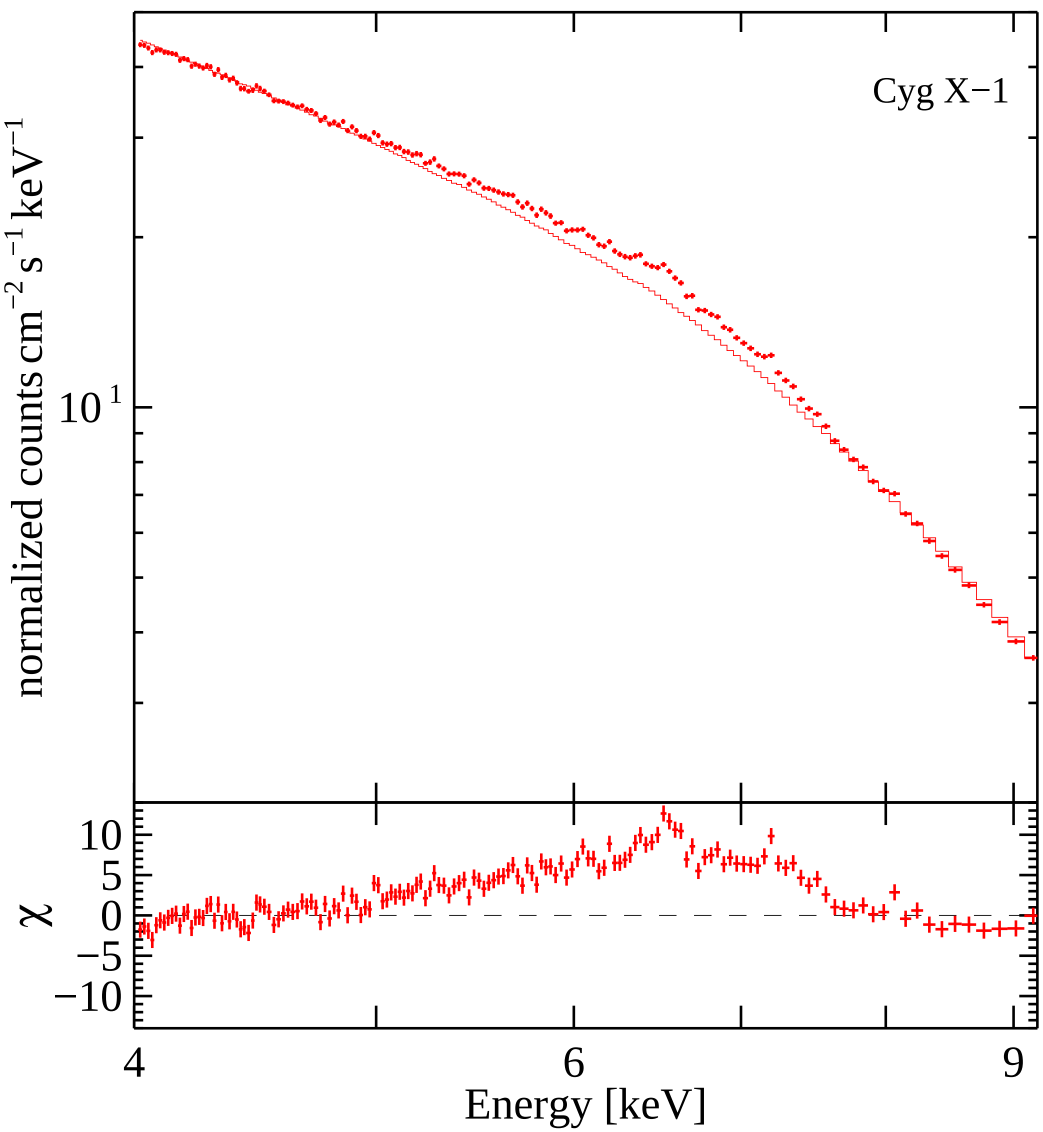


Total observed line profile affected by

- grav. Redshift
- Light bending
- rel. Doppler shift
- emissivity profile
- spin of black hole

XMM-Newton

Relativistic Lines

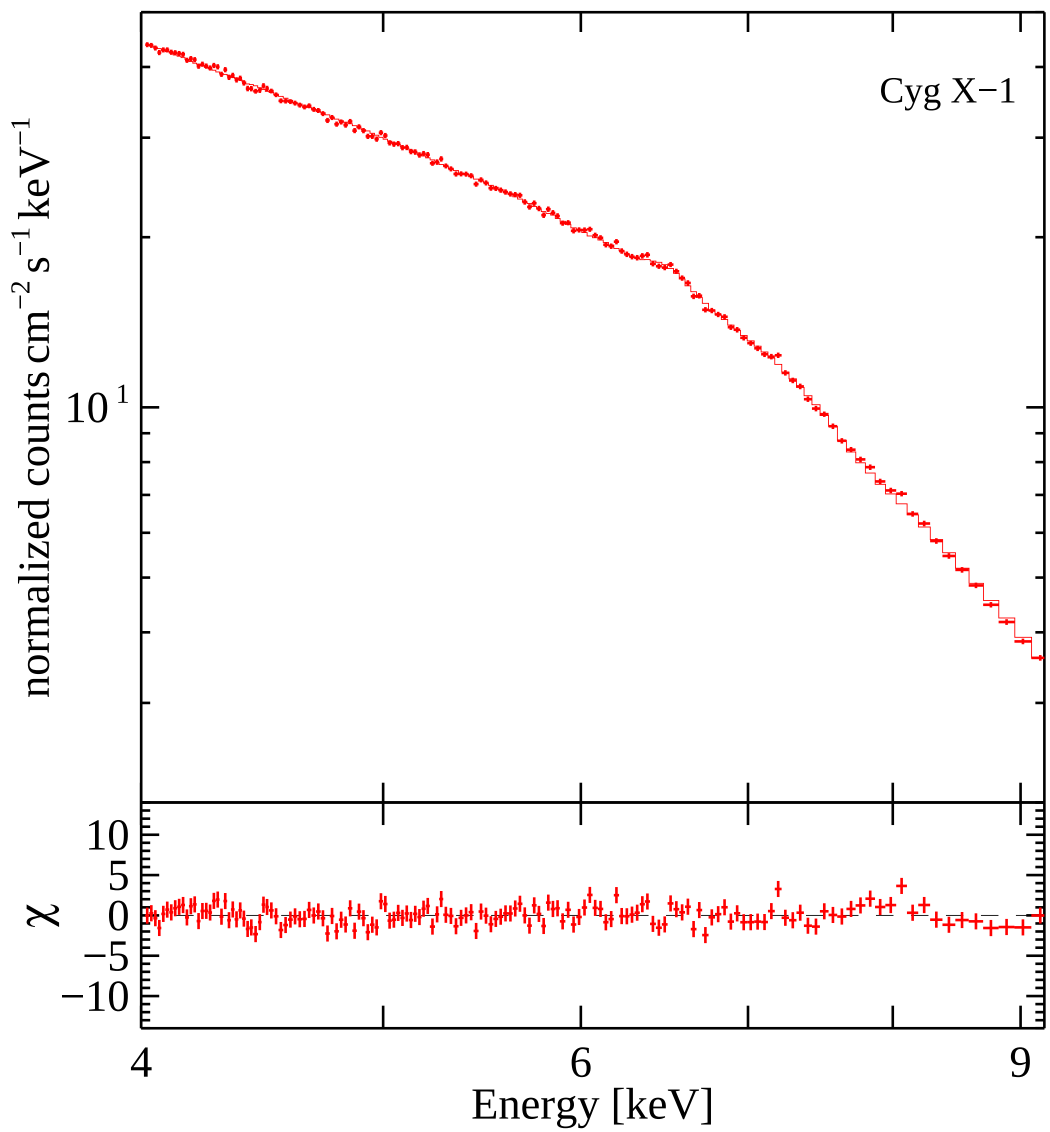


Wilms et al. (2006)

XMM-Newton Observation of Cyg X-1: Power-law fit to $E \leq 5$ keV and $E \geq 8$ keV: strong residuals in Fe Kα region

uses a modifi ed timing mode of the EPIC-pn camera on *XMM-Newton*; inner 3 CCD columns ignored because of pile-up

Relativistic Lines



Wilms et al. (2006a)

4–9 keV spectrum: well explained ($\chi^2_{\text{red}} = 1.3$) with:

- Power law

  $\Gamma = 1.90 \pm 0.01$

- narrow line

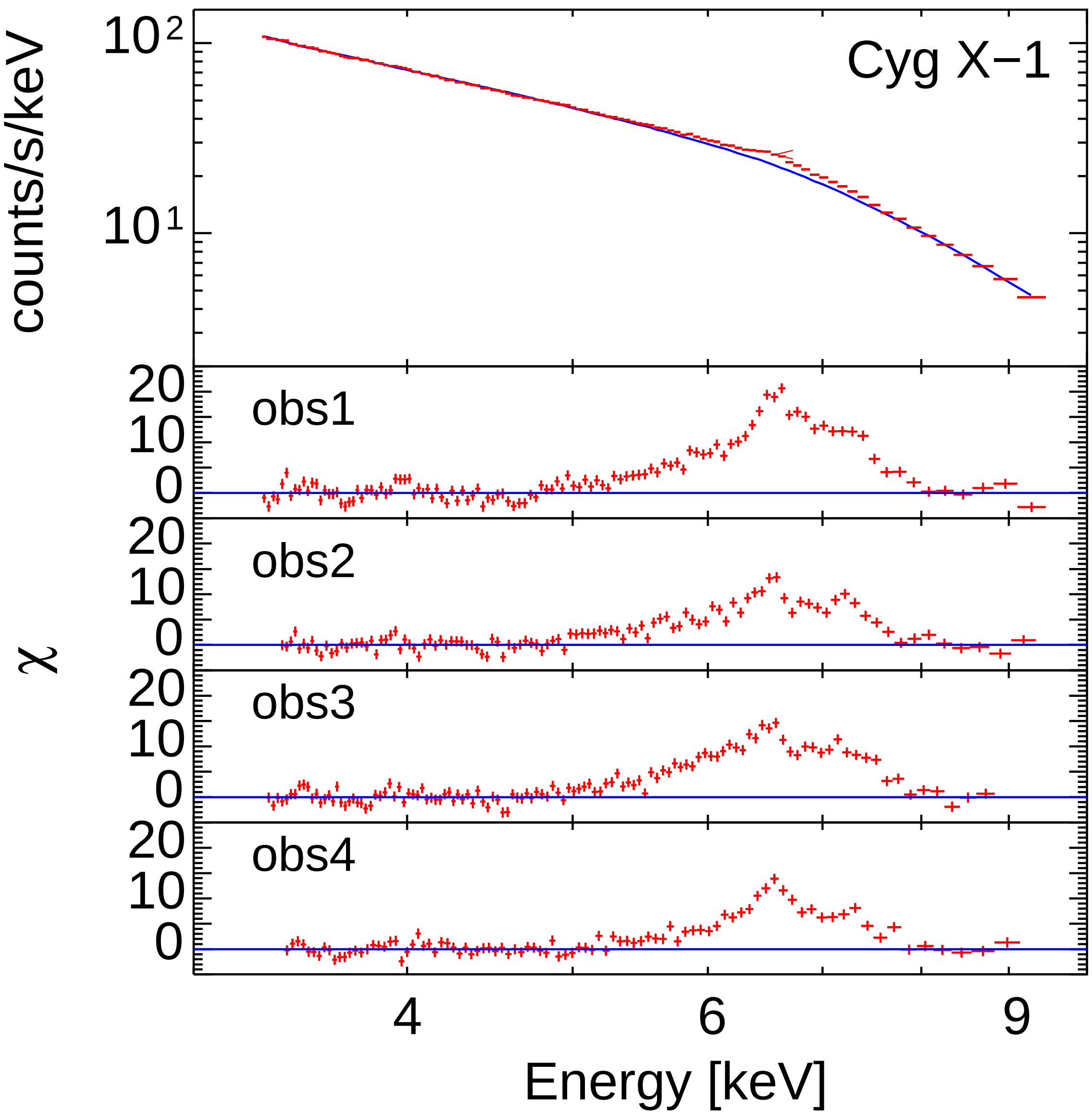
  $E = 6.52 \pm 0.02$ keV,
  $\sigma = 80 \pm 35$ eV,
  EW=14 eV

- relativistic line (Kerr)

  $E = 6.76 \pm 0.1$ keV,
  emissivity $\propto r^{-4.3\pm0.1}$,
  EW=400 eV

Parameters similar (but not equal) to *Chandra* intermediate state observations (Miller et al., 2002)

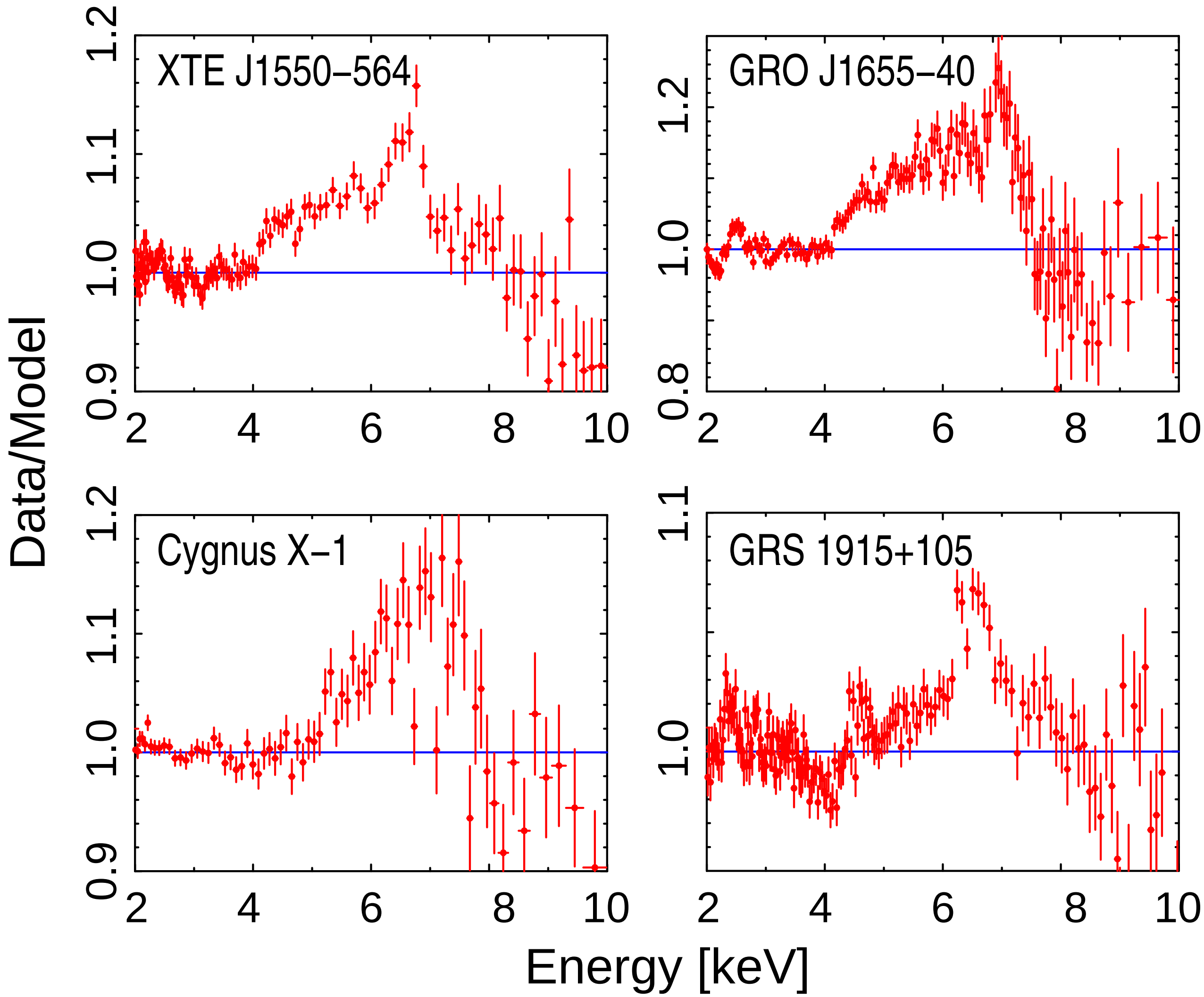
Relativistic Lines



Cyg X-1 (*XMM-Newton*, EPIC-pn modifi ed timing mode, 10–20 ksec each)

(Fritz et al., 2007)

Relativistic Lines



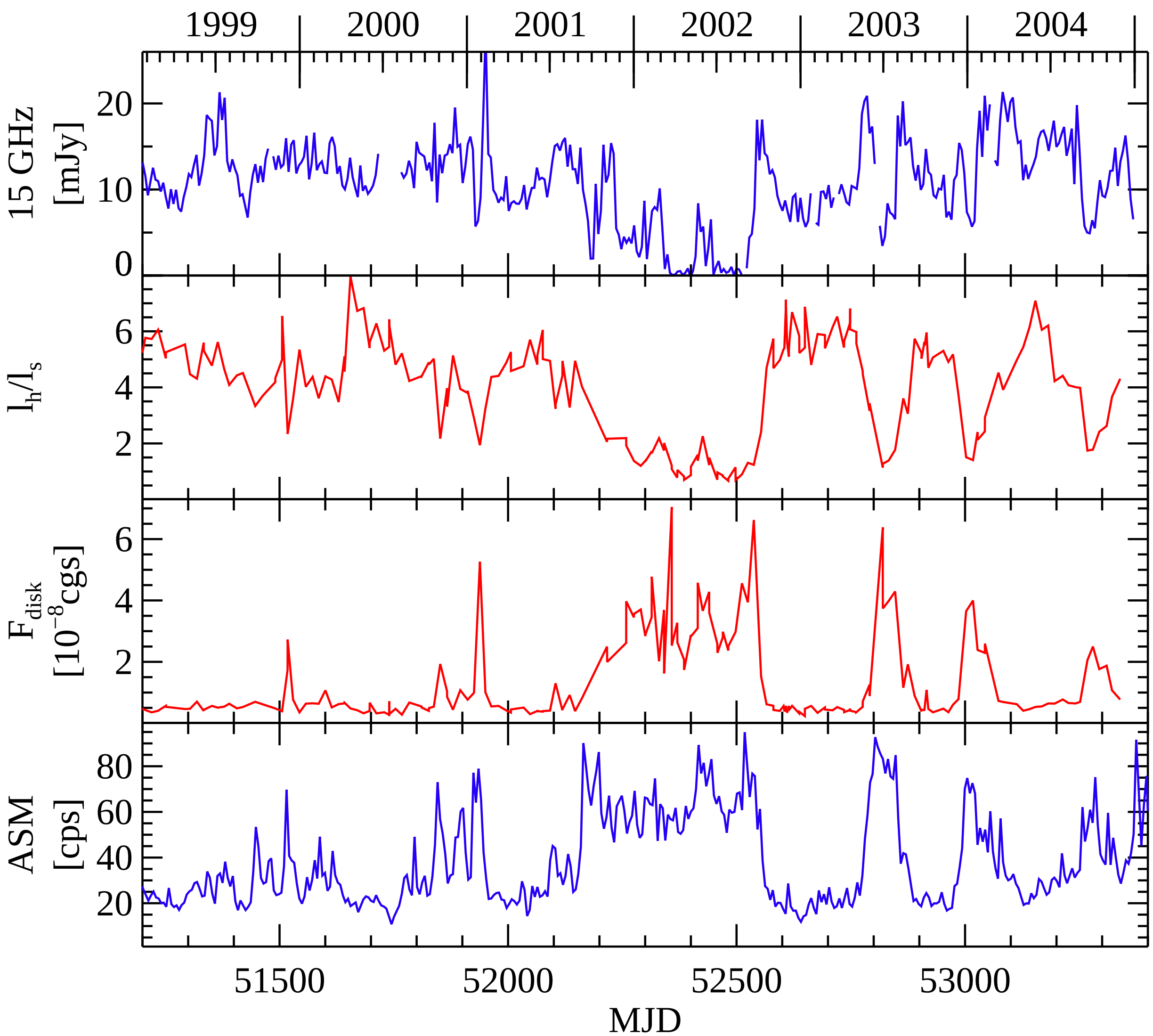
Relativistic lines are seen in many Galactic Black Holes

- GX 339−4: Nowak, Wilms & Dove (2002), Miller et al. (2004)
- GRO J1655−40: Bałucińska-Church & Church (2000)
- Cyg X-1: Miller et al. (2002), Fritz et al. (2007)
- XTE J1650−500: Miller et al. (2002)

. . . and a few more

(*Chandra*; after Miller 2007)

Hard State Monitoring

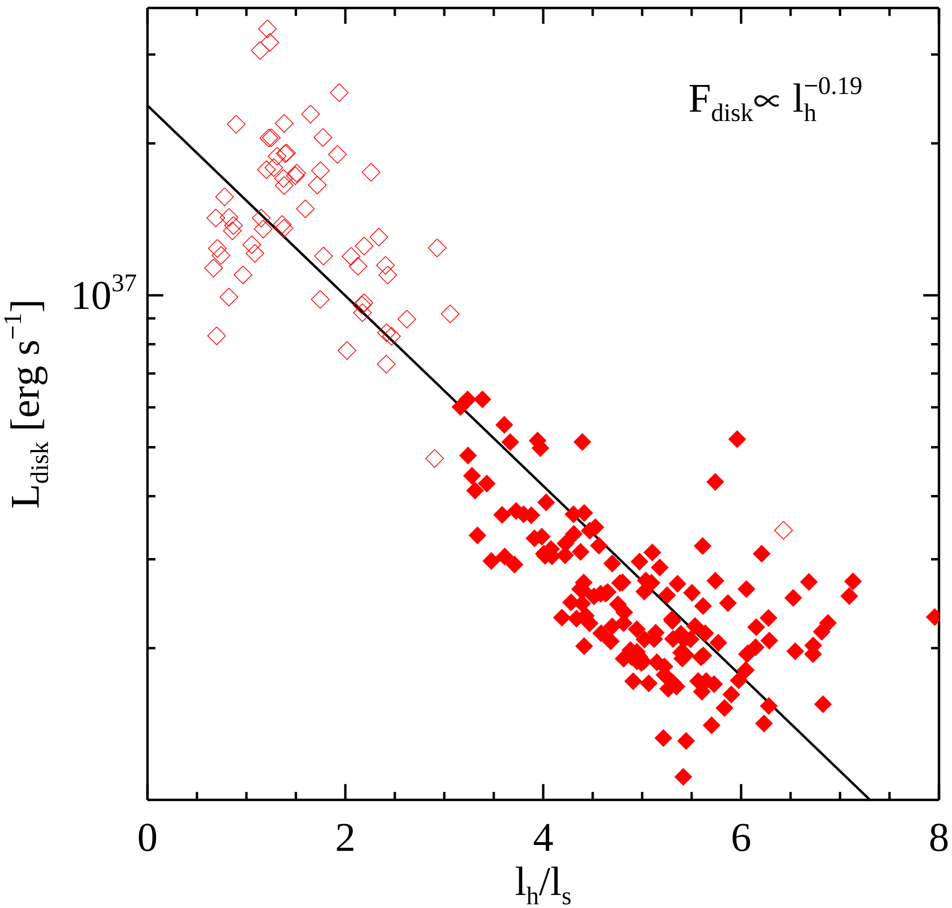


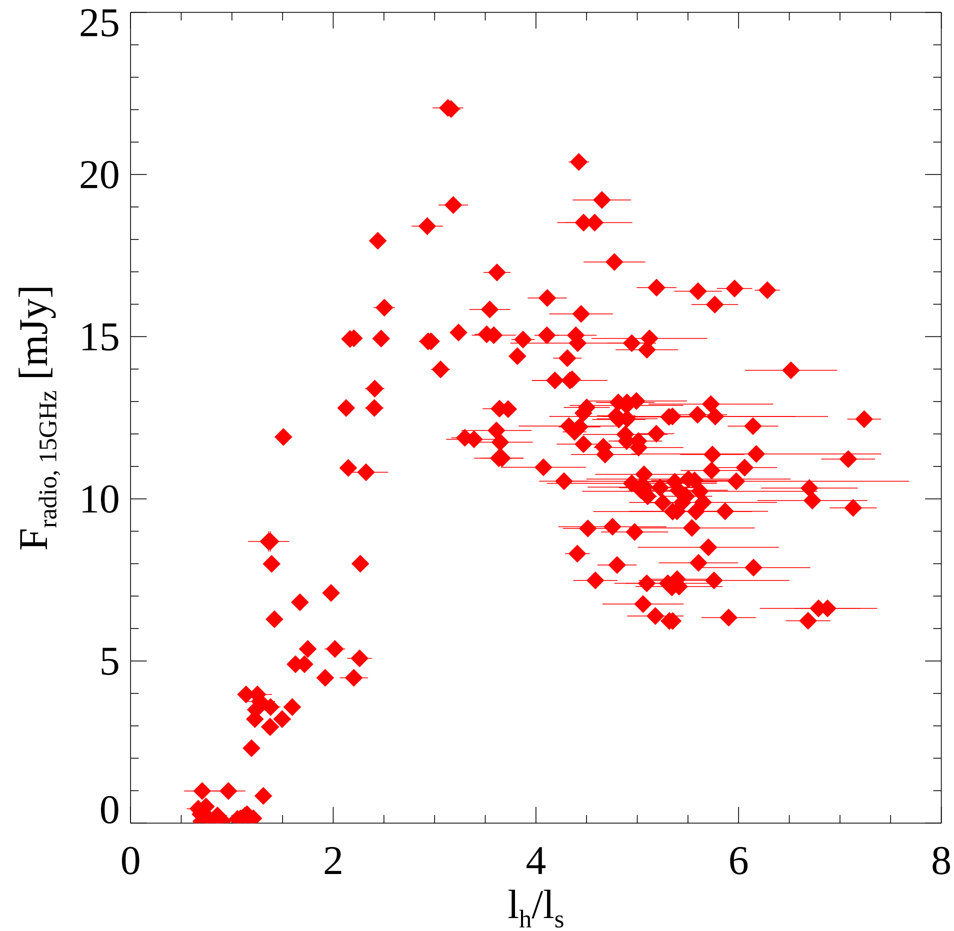
Cyg X-1 (Wilms et al., 2006b)

Never before have BHC been studied with such good coverage and over such a wide energy range.

Compare to pre-RXTE: 1–2 pointings per year!

Hard State Monitoring

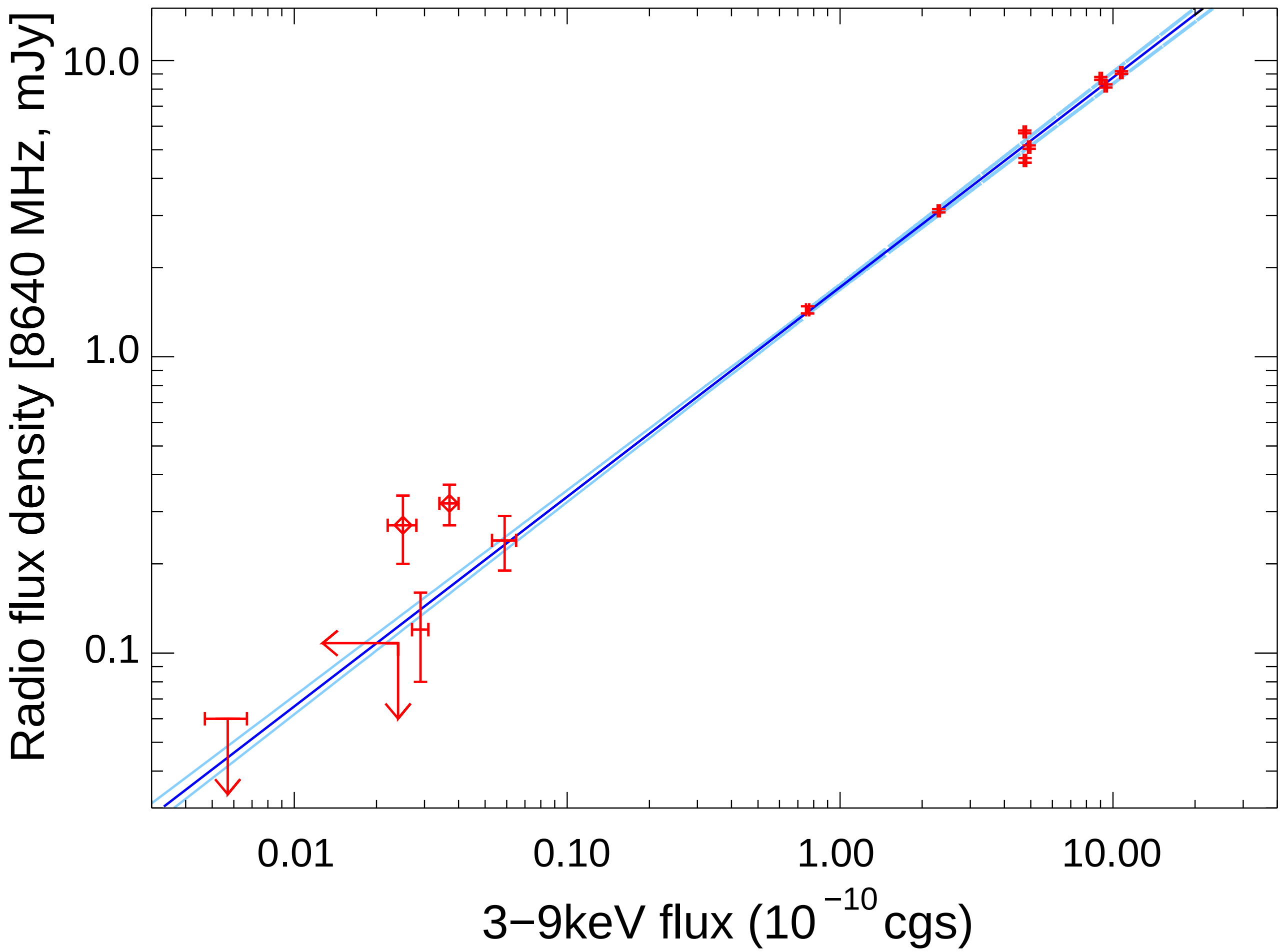




Clear anticorrelation between accretion disk luminosity and coronal compactness ratio, ℓ_h/ℓ_s.

Radio flux is strongest during intermediate states.

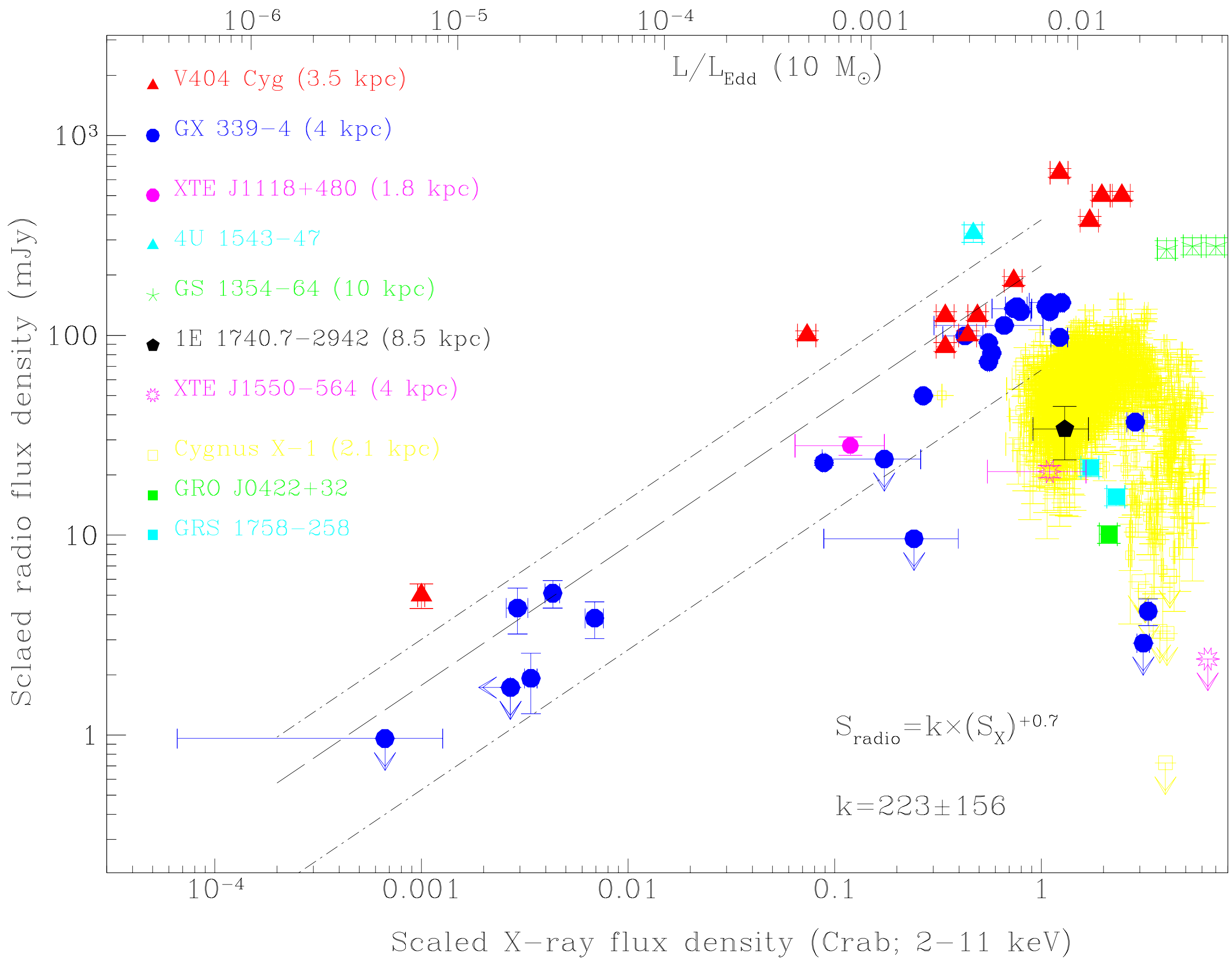
Radio–X-ray connection



Corbel et al. (2003): GX 339−4: During the hard state, there is a clear correlation between X-ray flux and radio flux: $F_{\text{radio}} \propto F_{\text{X, 3–20 keV}}^{0.71}$.

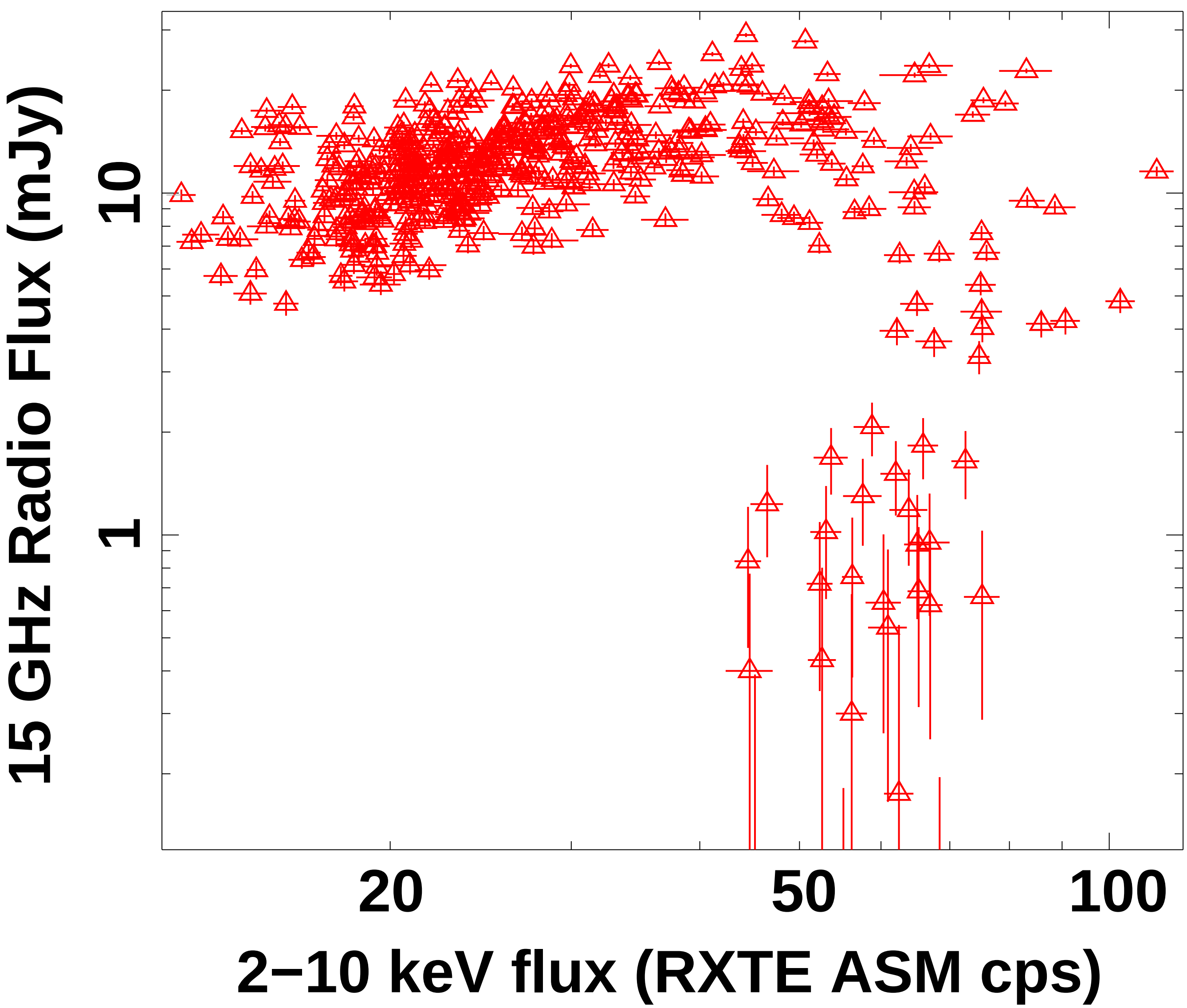
See also Hannikainen et al. (1998), Markoff et al. (2003).

Radio–X-ray connection



Gallo, Fender & Pooley (2003): $L_{\text{radio}} \propto L_{\text{X}}^{0.7}$ also works for sample of GBHs, although there is more scatter (and Cyg X-1 does not work at all).

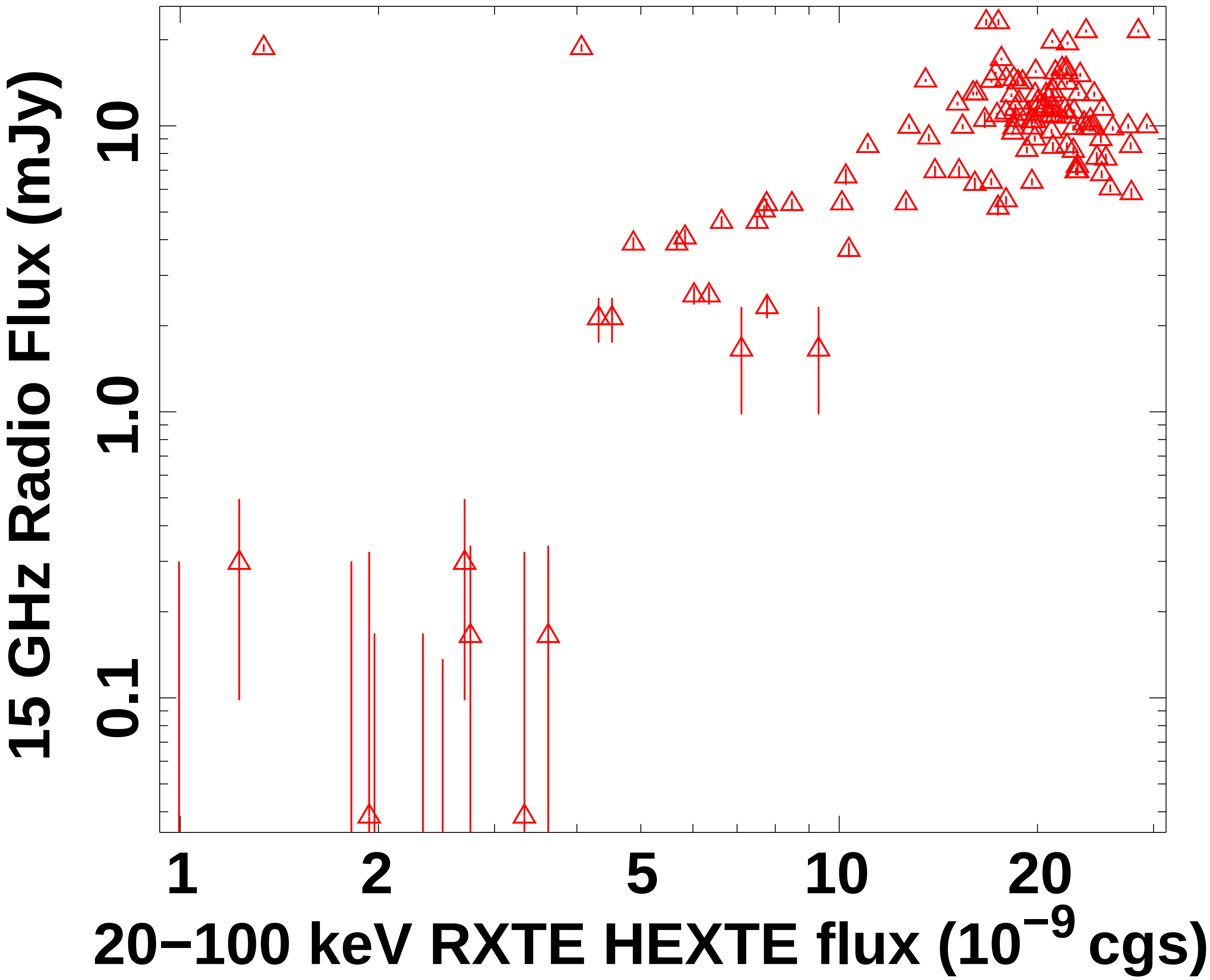
Radio–X-ray connection



Cyg X-1: there is no clear correlation between radio and X-rays in 2–10 keV!

(Nowak et al., 2005)

Radio–X-ray connection



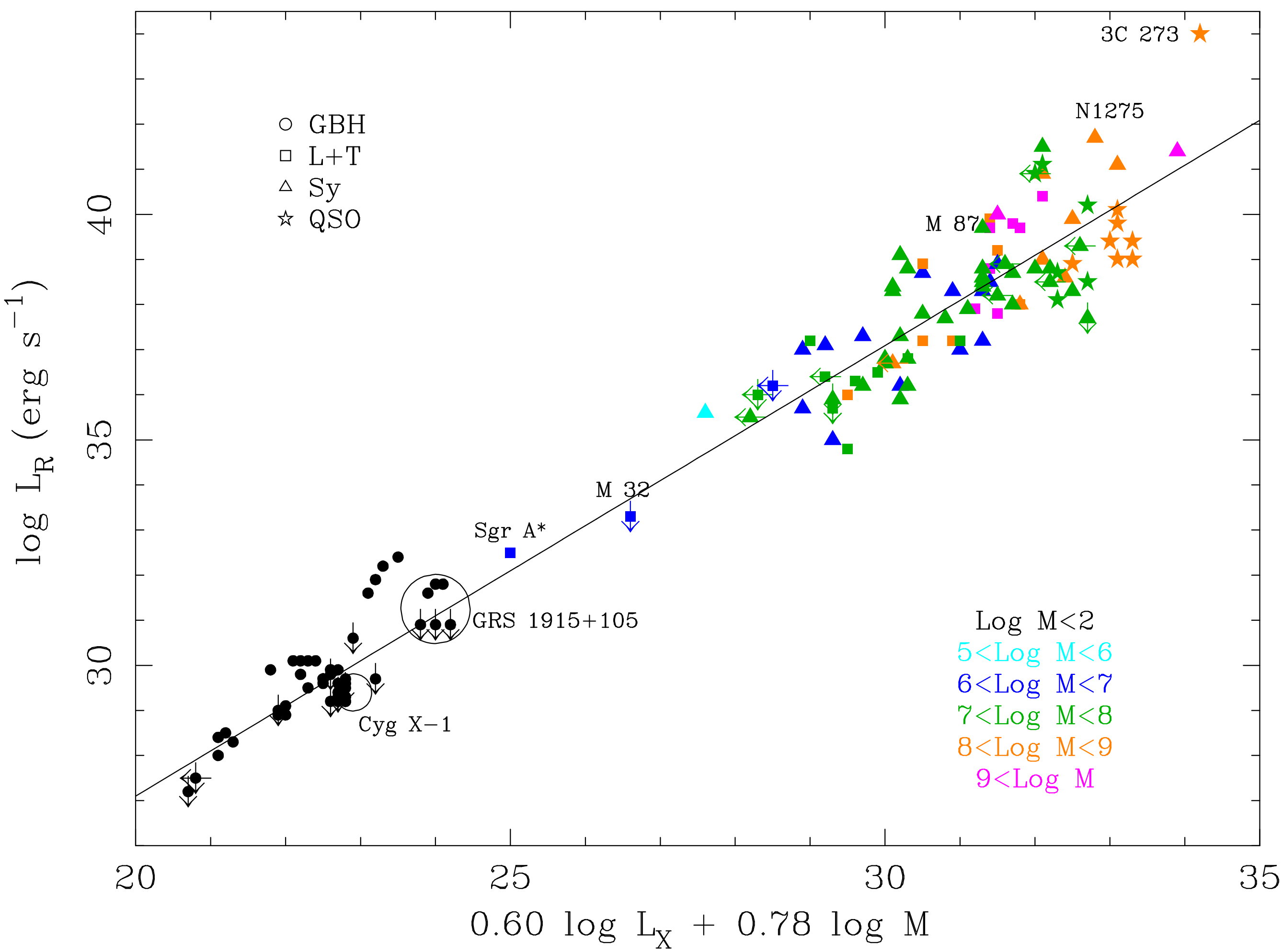
Cyg X-1: there is a clear correlation between radio and X-rays in 20–100 keV.

$\Longrightarrow$ Jet is related to whatever makes the hard spectral component

Not surprising, but illustrates the danger of ignoring pointed observations and only using *RXTE*-ASM.

(Nowak et al., 2005)

Radio–X-ray connection



Merloni, Heinz & di Matteo (2003): for scale-invariant jets (Heinz & Sunyaev, 2003), jet properties only depend on M_{BH}, $\dot{M}$ (, and a).

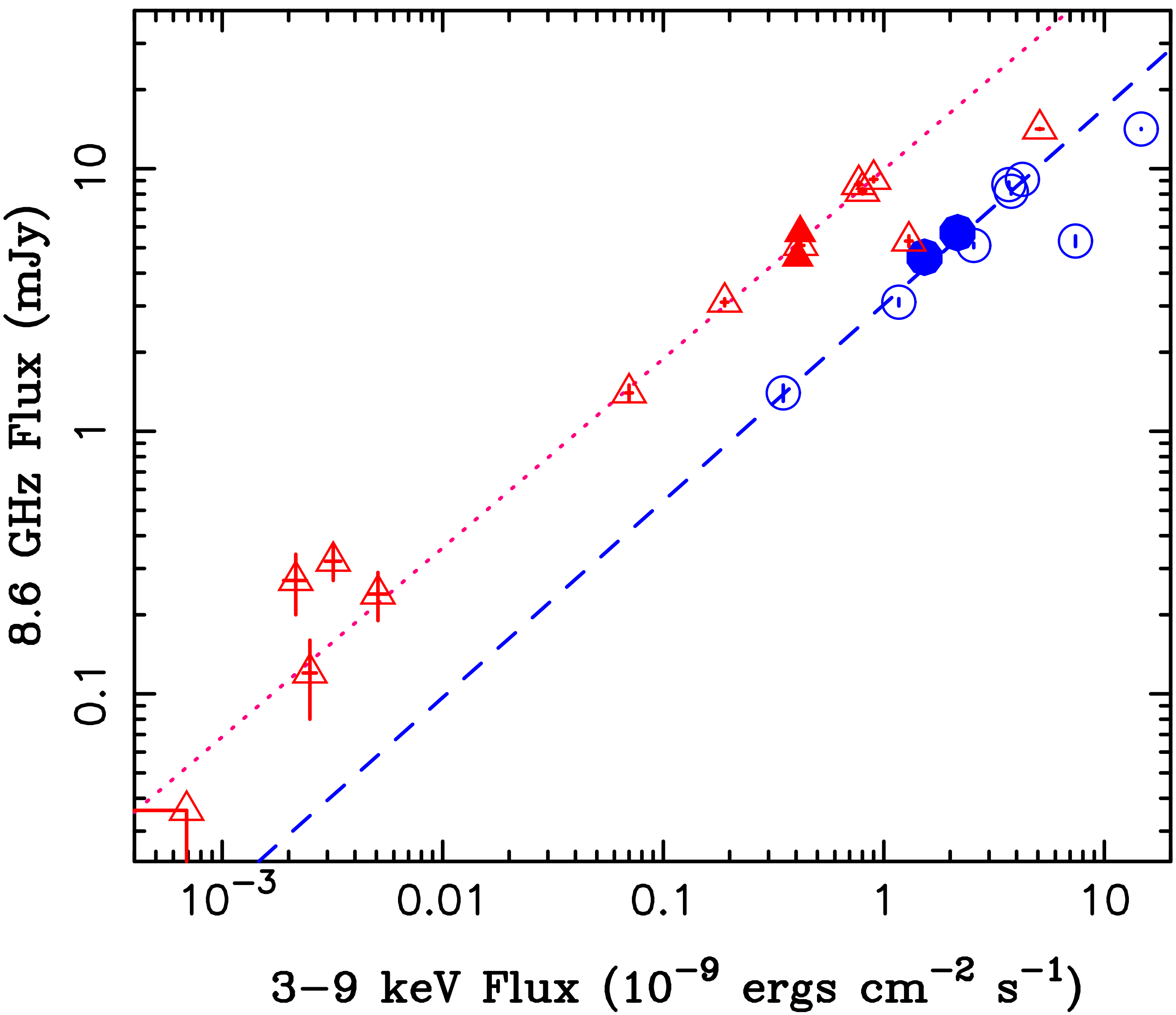
$\Longrightarrow$ scatter due to varying black hole mass

$\Longrightarrow$ "the fundamental plane of black holes" between L_{X}, L_{radio}, and M_{BH}.

see Falcke, Körding & Markoff (2004) for similar results

$$\log L_{\mathrm{radio}} = (0.60 \pm 0.11) \log L_{\mathrm{X}} + (0.78^{+0.11}_{-0.09}) \log M_{\mathrm{BH}} + 7.33^{+4.05}_{-4.07}$$

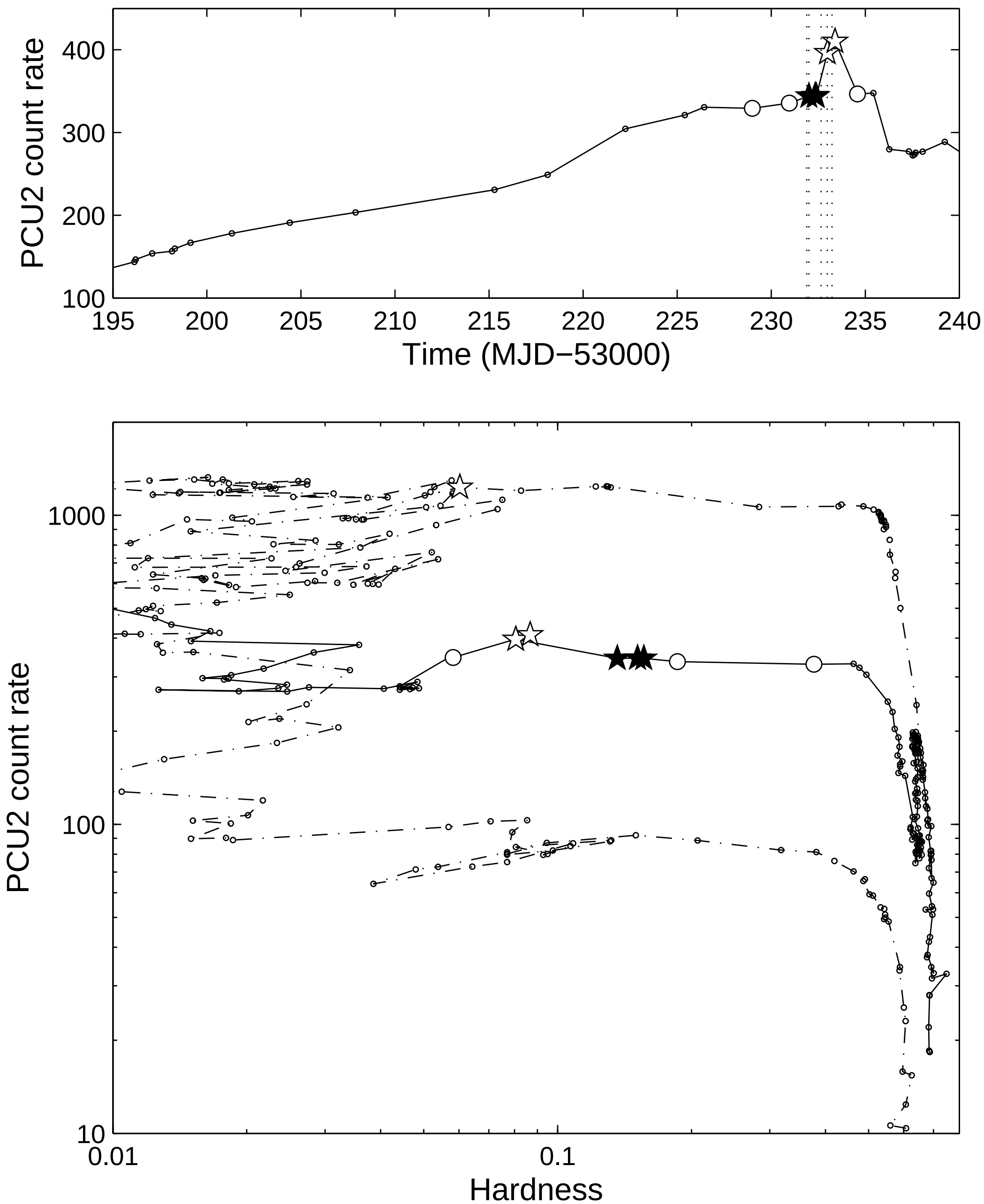
Radio–X-ray connection



But note: while generally $F_{\text{radio}} \propto F_X^{0.7}$, normalization constant *can* change between outbursts of the same object!

In addition, there are four more hard state BHC that are also underluminous in the radio wrt. to the correlation, see Gallo (2007), see also Xue & Cui (2007).

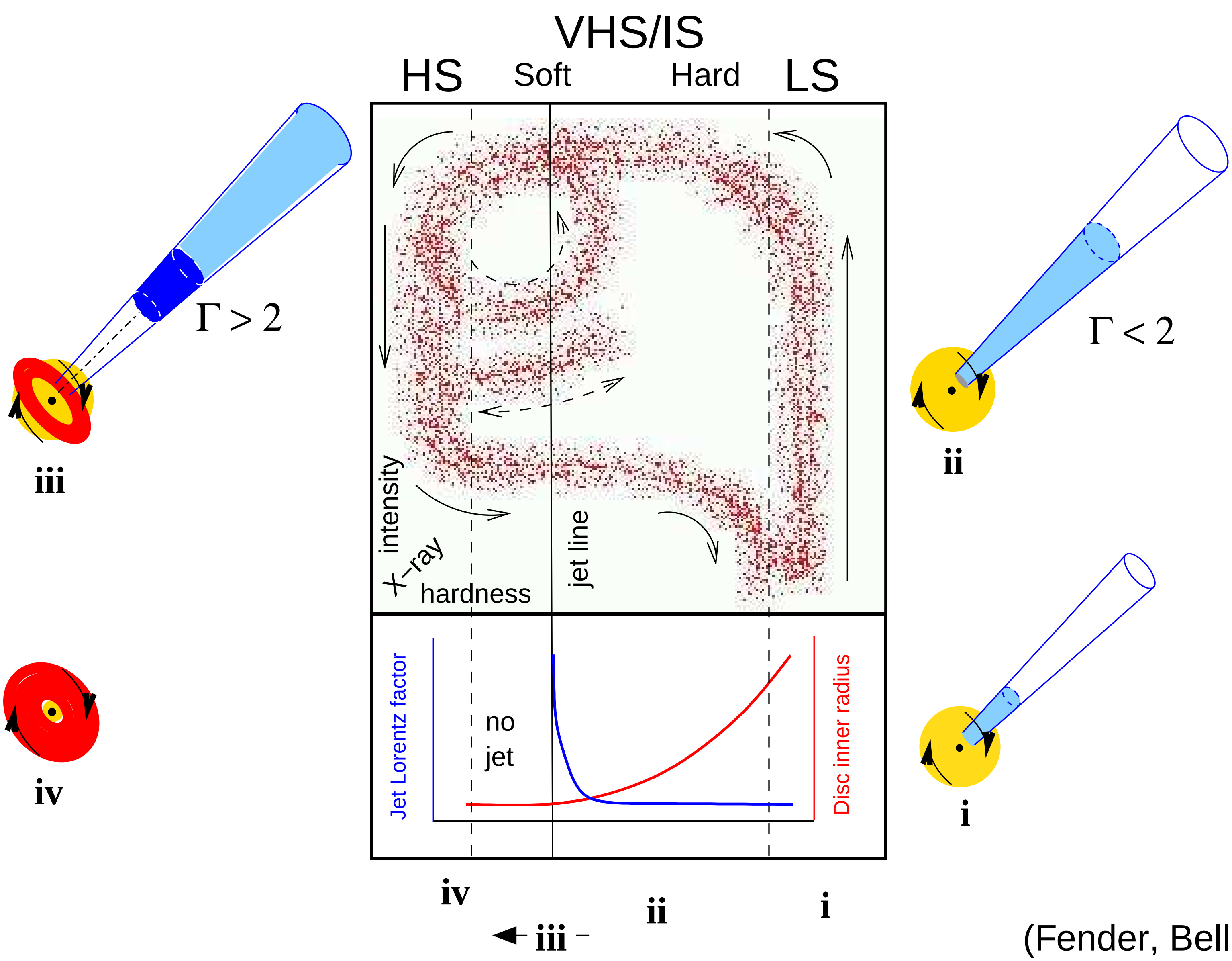
(GX 339−4; Nowak et al., 2005)



Radio-X-ray connection: Radio behavior is strongly correlated with the X-ray behavior (“q-diagram”).

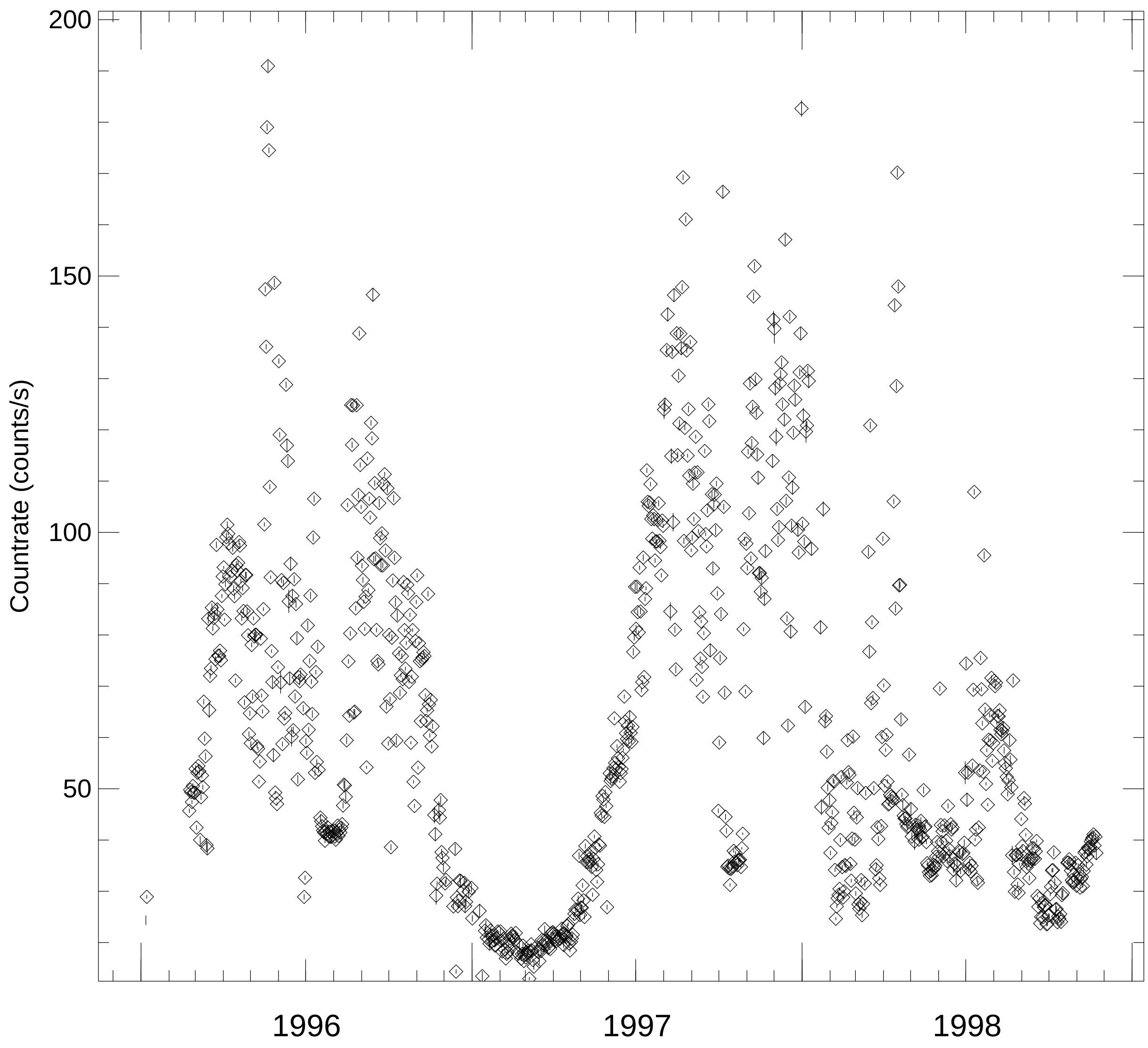
(GX 339−4; Belloni et al., 2006)

Radio–X-ray connection



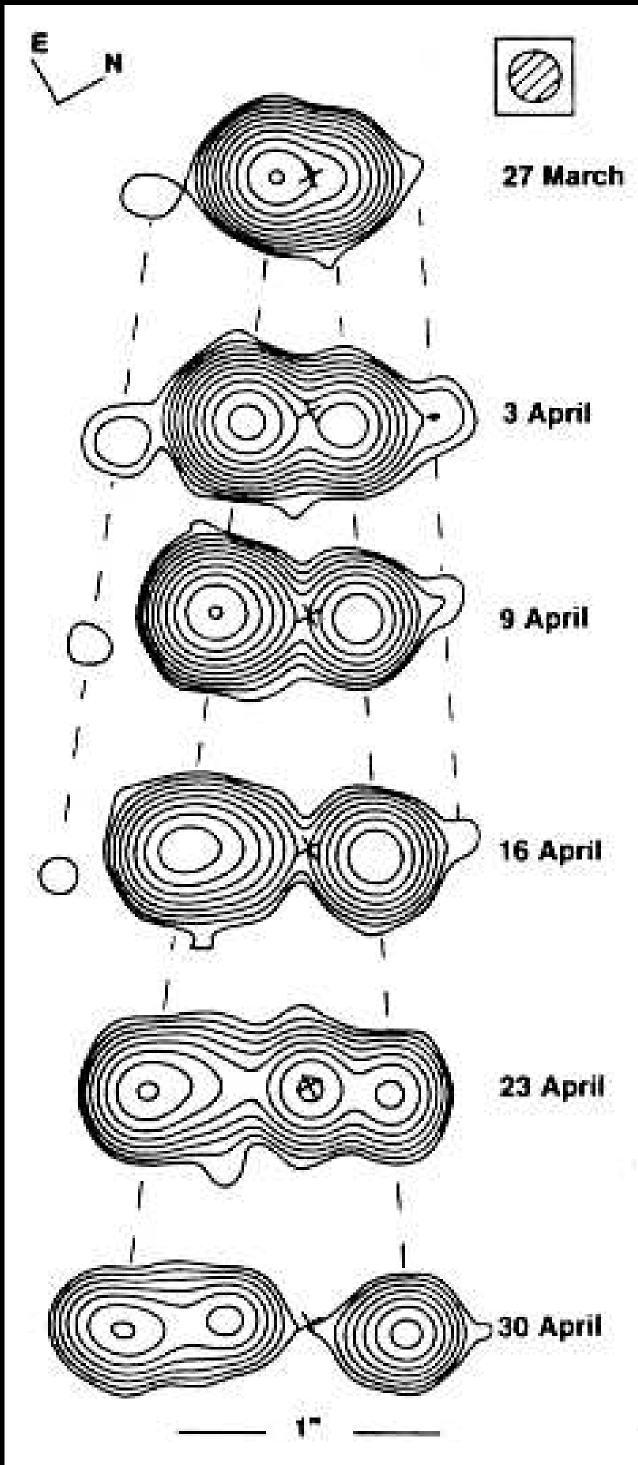
(Fender, Belloni & Gallo, 2004)

Microquasars, I



Some black holes show very interesting long and short term behavior in all wavebands

RXTE-ASM 2–12 keV lightcurve of GRS 1915+105



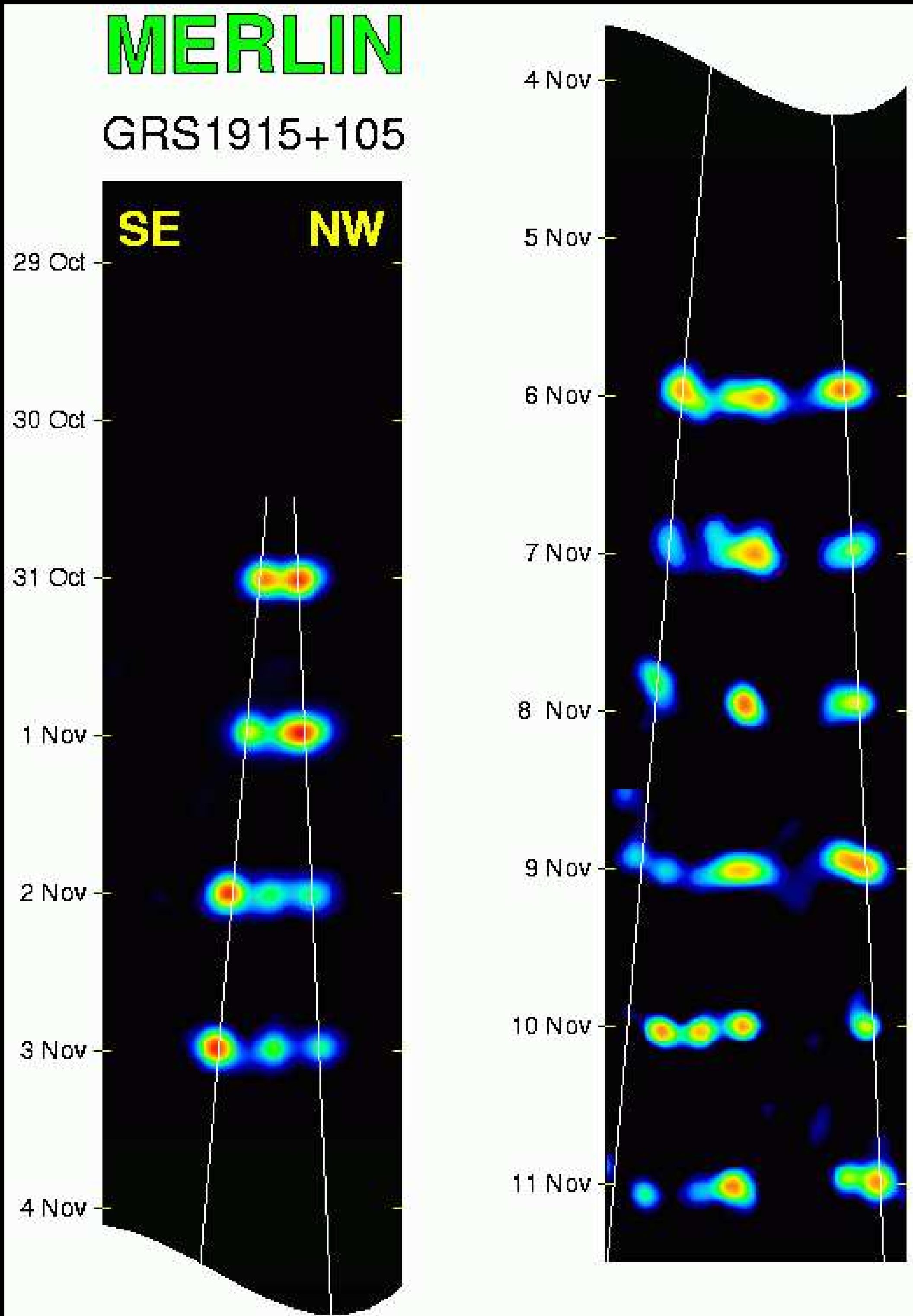
GRS 1915+105 1994 March/April: weekly radio images show blob ejection events.

Scale $\sim$10000 AU

Ballistic motion of events $\Longrightarrow$ no deceleration!

Inferred speeds: $(0.65 \pm 0.08)c$ und $(1.25 \pm 0.15)c$

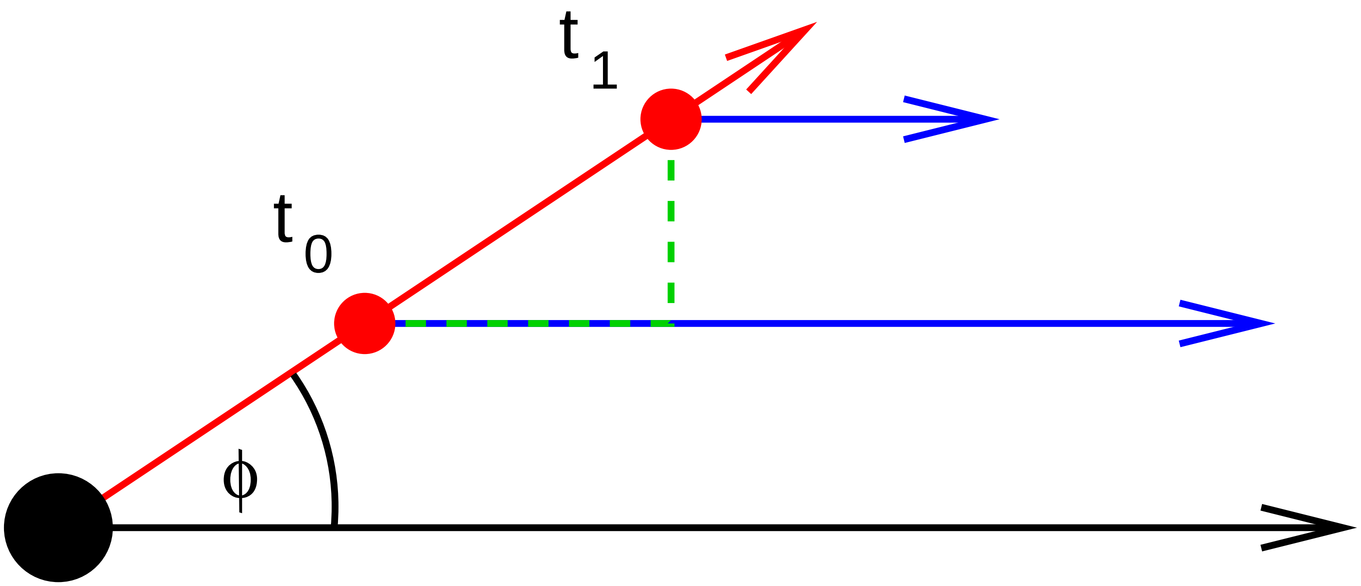
$\Longrightarrow$ superluminal motion!



1997 radio campaign: $\sim$10% higher speeds;

Fender et al. (1998)

Microquasars, IV



Consider blob moving towards us with speed v and angle ϕ with respect to line of sight, emitting light signals at t_0 and $t_1 = t_0 + \Delta t_\mathrm{e}$

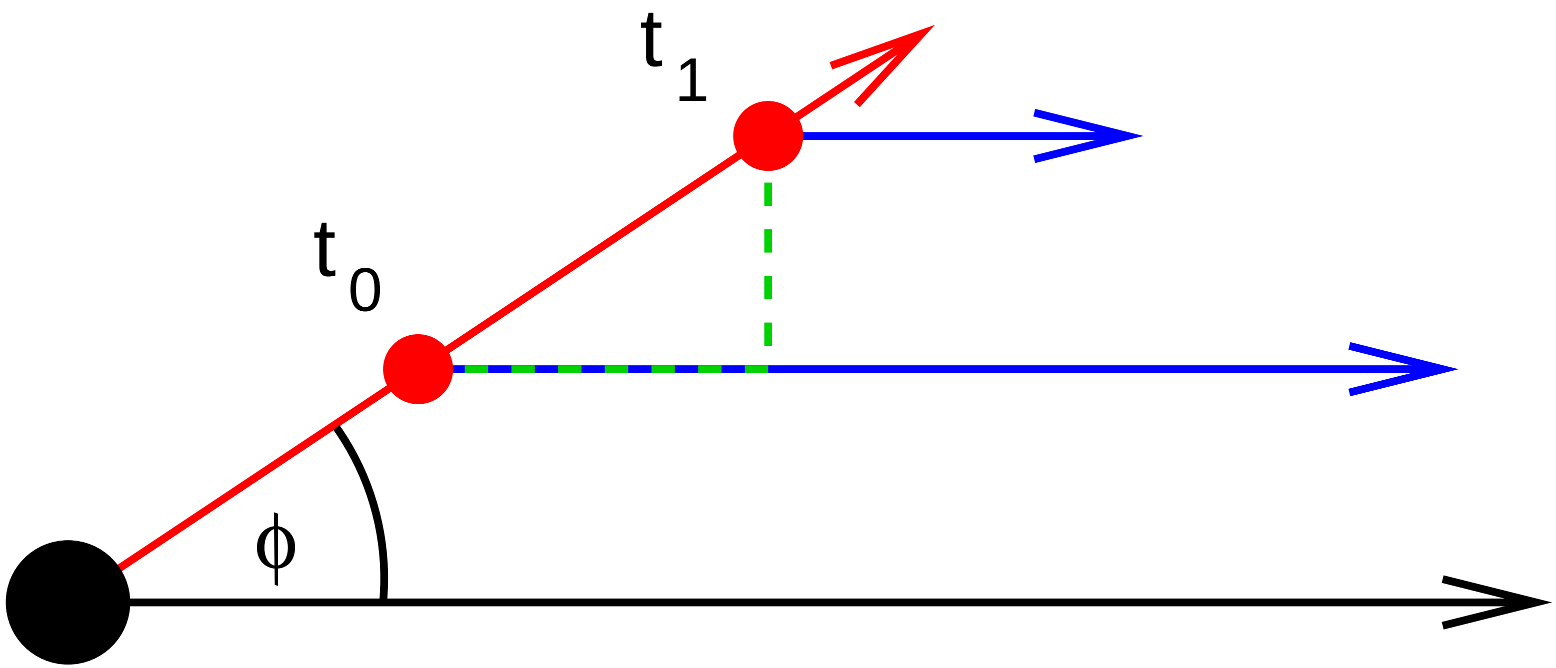
Light travel time: Observer sees signals separated by

$$\Delta t_\mathrm{o} = \Delta t_\mathrm{e} - \Delta t_\mathrm{e} \frac{v}{c} \cos\phi = \left(1 - \frac{v}{c}\cos\phi\right) \Delta t_\mathrm{e} \tag{7.1}$$

Observed distance traveled in plane of sky:

$$\Delta \ell_\perp = v \Delta t_\mathrm{e} \sin\phi \tag{7.2}$$

Microquasars, V



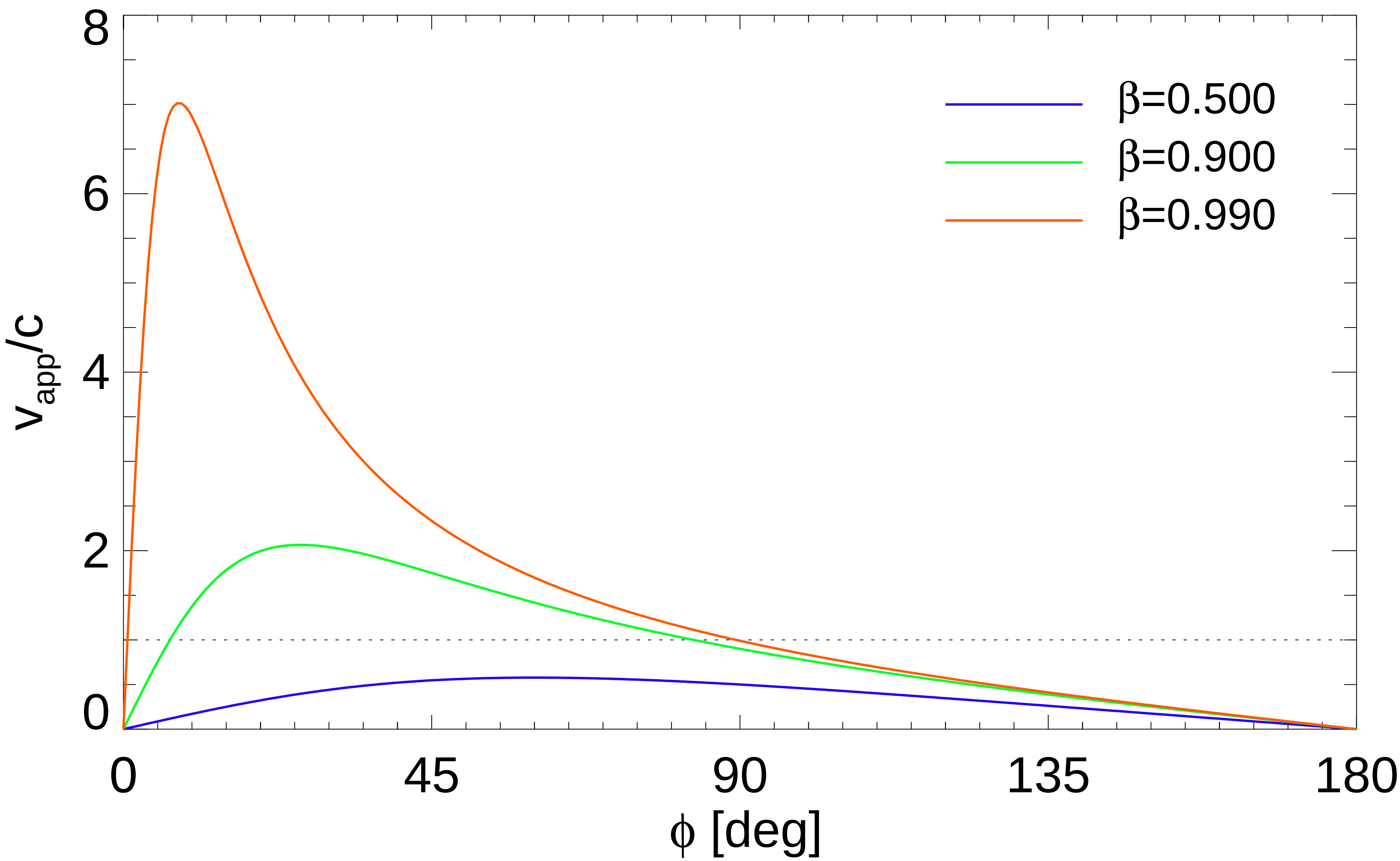
Apparent velocity deduced from observations:

$$v_{\text{app}} = \frac{\Delta \ell_\perp}{\Delta t_{\text{o}}} = \frac{v \Delta t_{\text{e}} \sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right) \Delta t_{\text{e}}} = \frac{v \sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)} \tag{7.3}$$

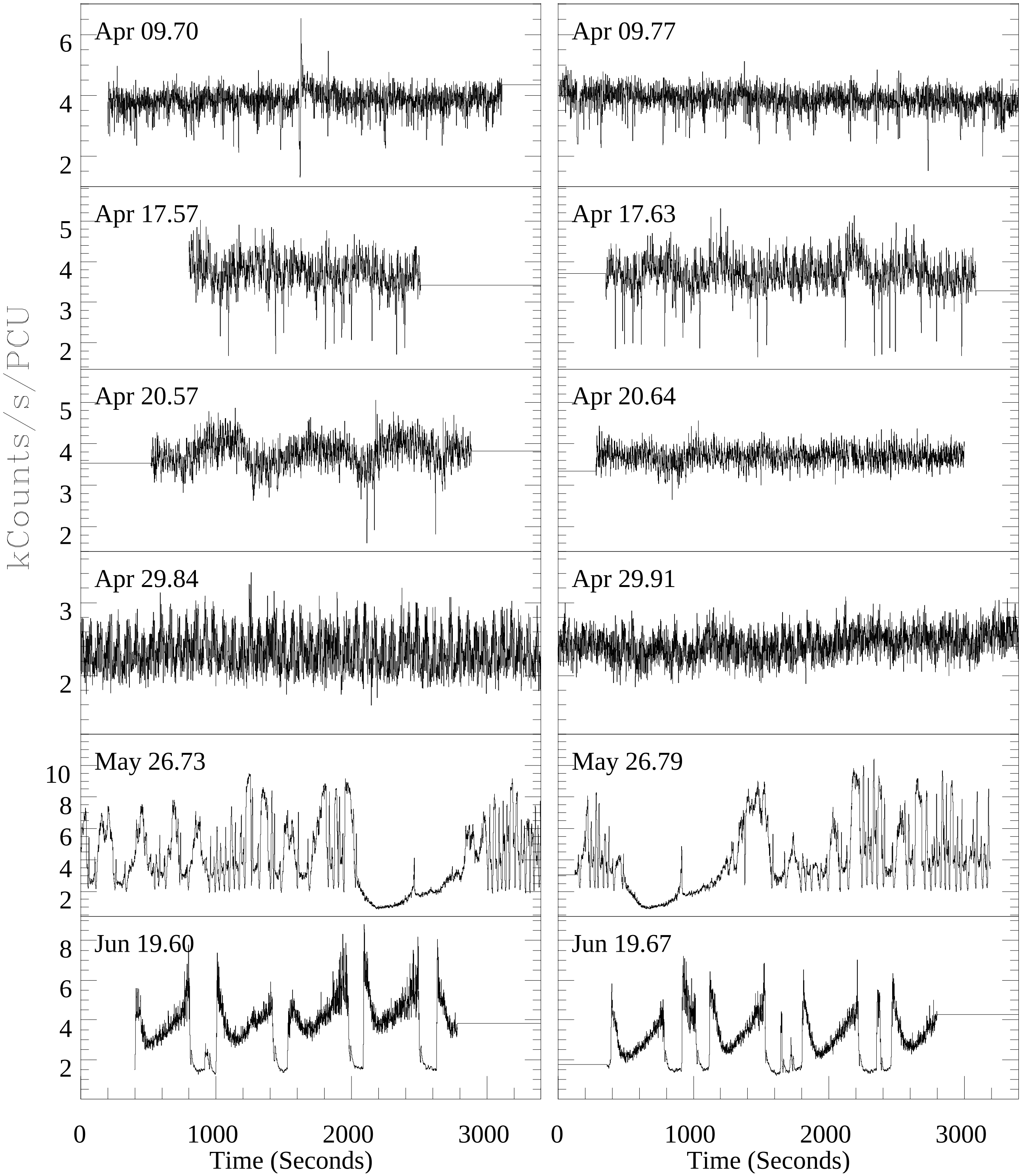
$\Longrightarrow$ For v/c large and ϕ small: $v_{\text{app}} > c$

previously only seen in Active Galaxies ("Quasars") $\Longrightarrow$ Microquasars

Microquasars, VI



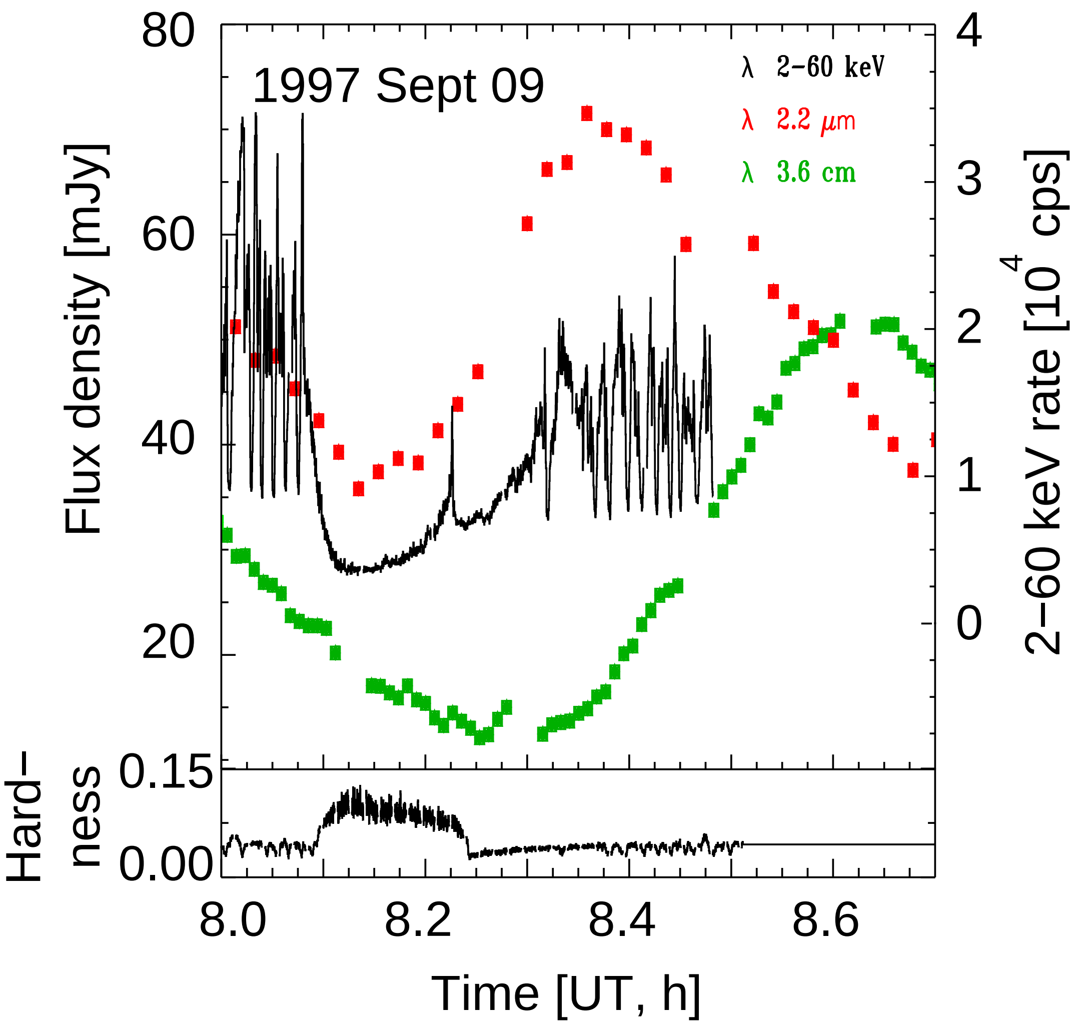
Superluminal motion: Microquasars have jet speeds close to c



GRS 1915+105, RXTE/PCA, 2–60 keV, 1 s resolution lightcurves

Brightness Sputters, Large-Amplitude Oscillations

$\Longrightarrow$ Microquasars show very complex short term variability in the X-rays!



(GRS 1915+105; after Mirabel et al., 1998)

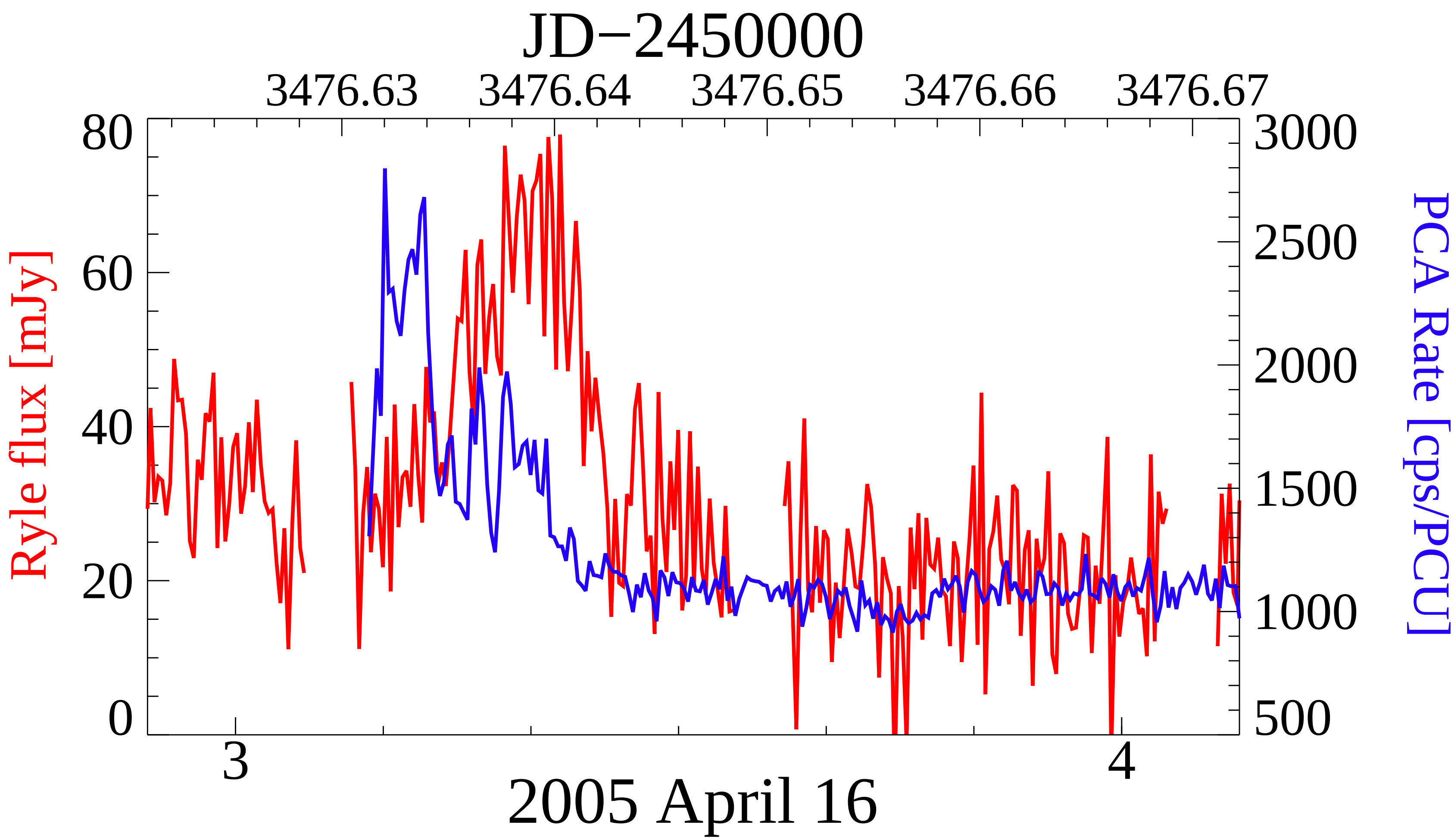
Microquasars allow study of dynamics of jet formation

Works much better than in AGN because of shorter timescales involved.

Flaring episodes: clear radio–X-ray relationship

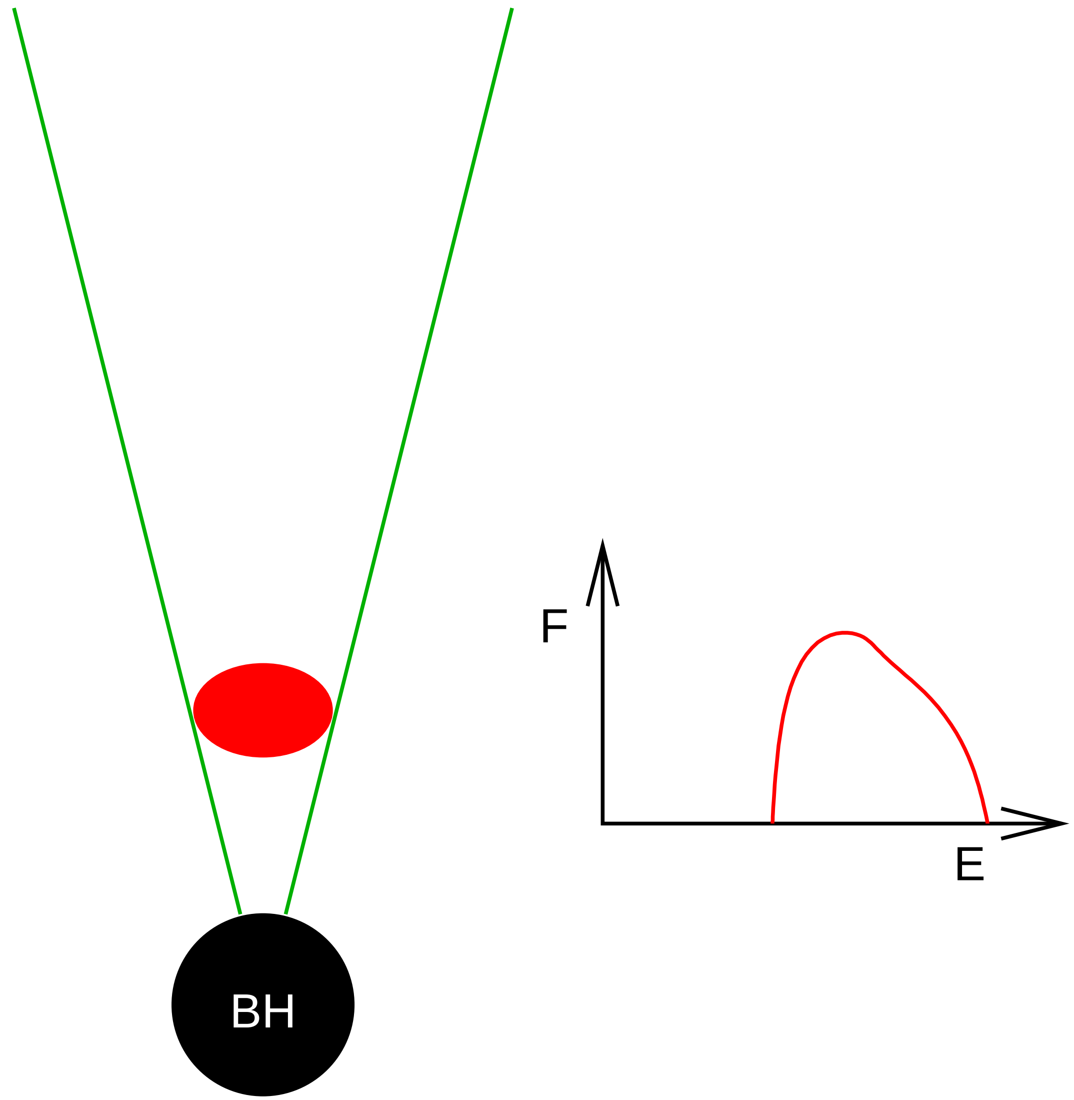
$\Longrightarrow$ "disk-jet-connection"

(cf. Mirabel & Rodríguez, 1994; Pooley & Fender, 1997; Eikenberry et al., 1998; Klein-Wolt et al., 2002; Fender & Belloni, 2004; Rothstein, Eikenberry & Matthews, 2005. . .)



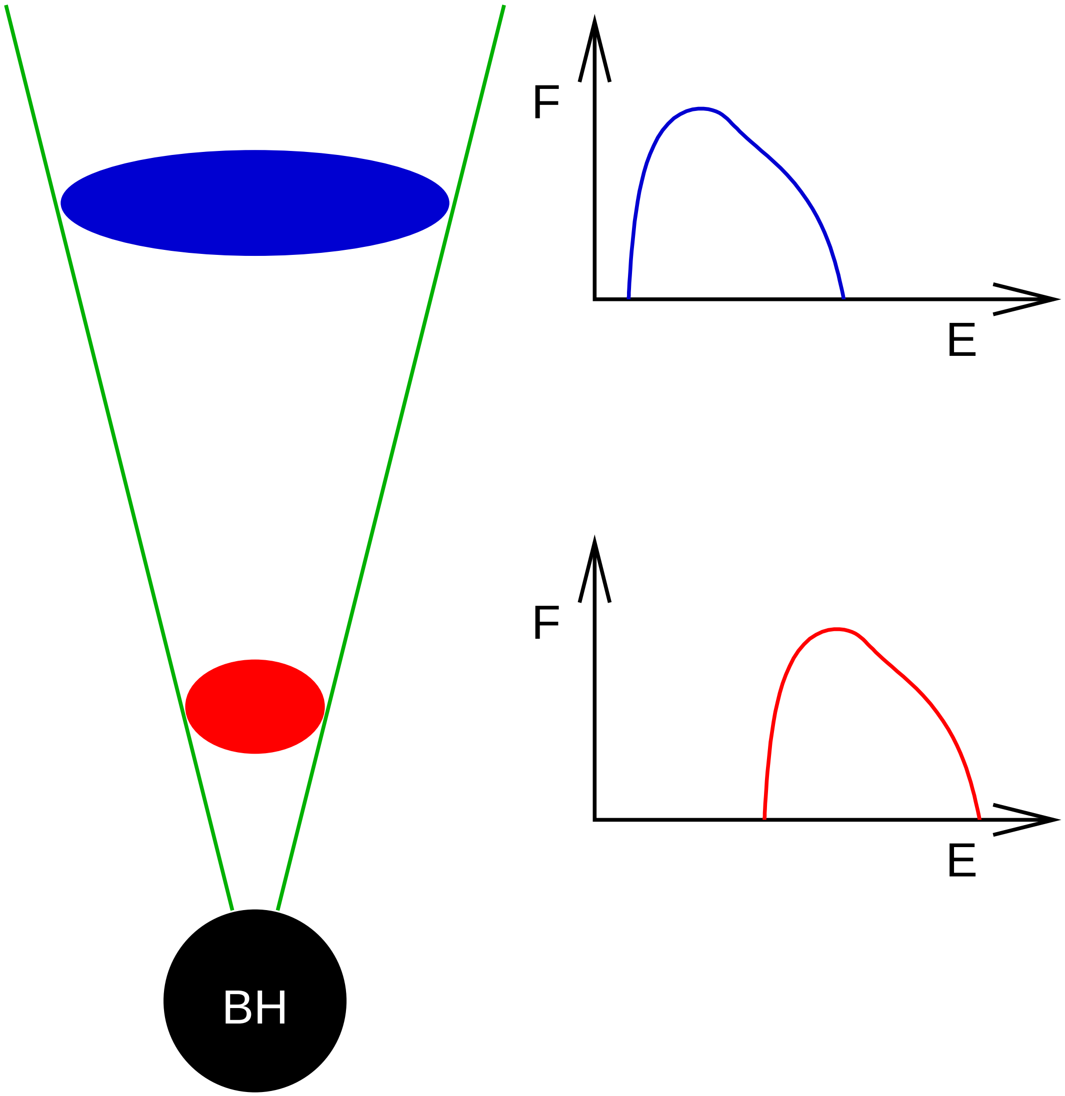
(Cyg X-1, 2005 April 16; Wilms et al., 2007, Ryle: 15 GHz, PCA: 2–60 keV)

Correlated radio–X-ray flaring also seen in “normal” black holes.



Short-term radio–X-ray correlations can be explained with the synchrotron bubble model

(van der Laan, 1966; Hjellming & Johnston, 1988)



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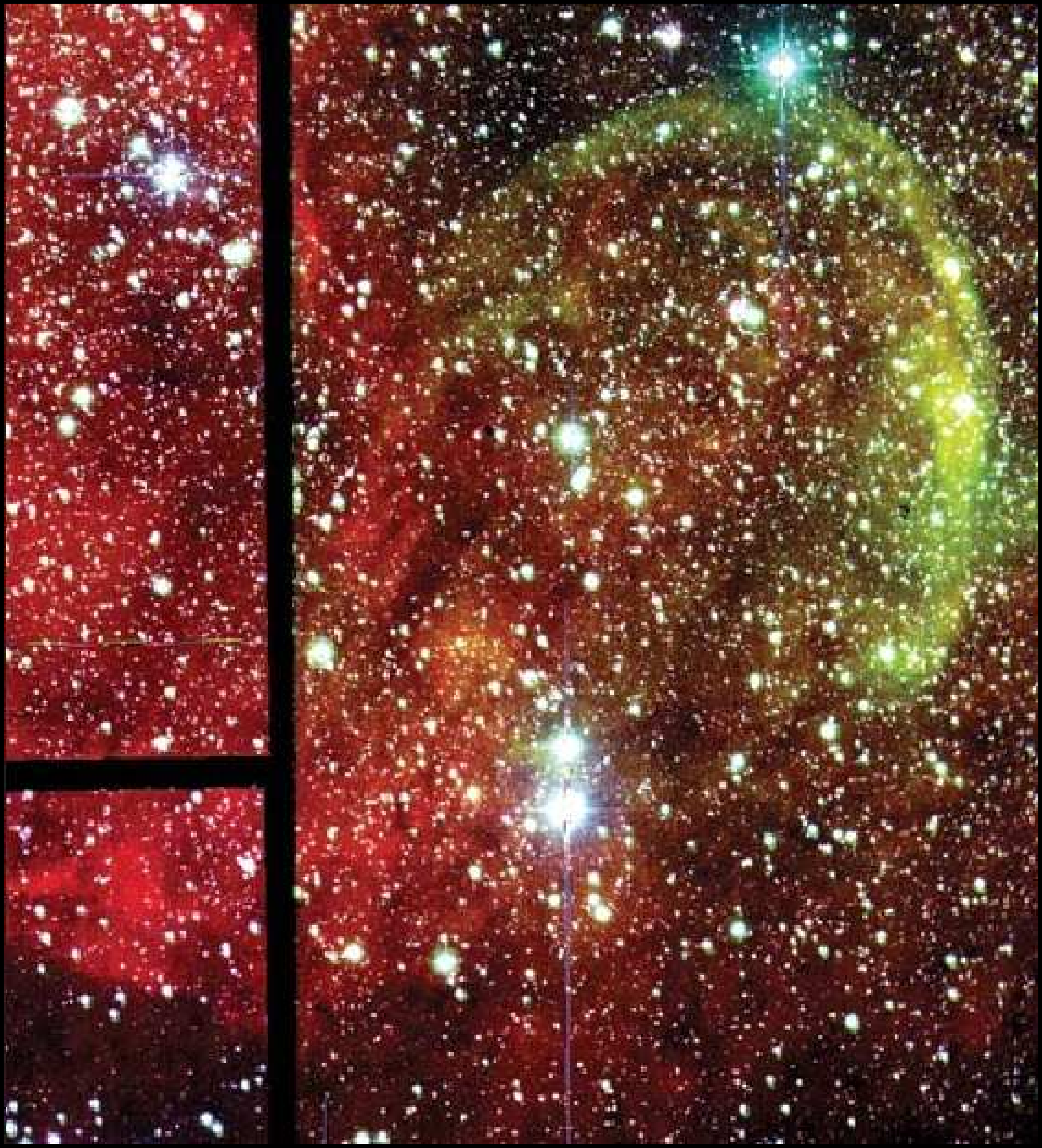
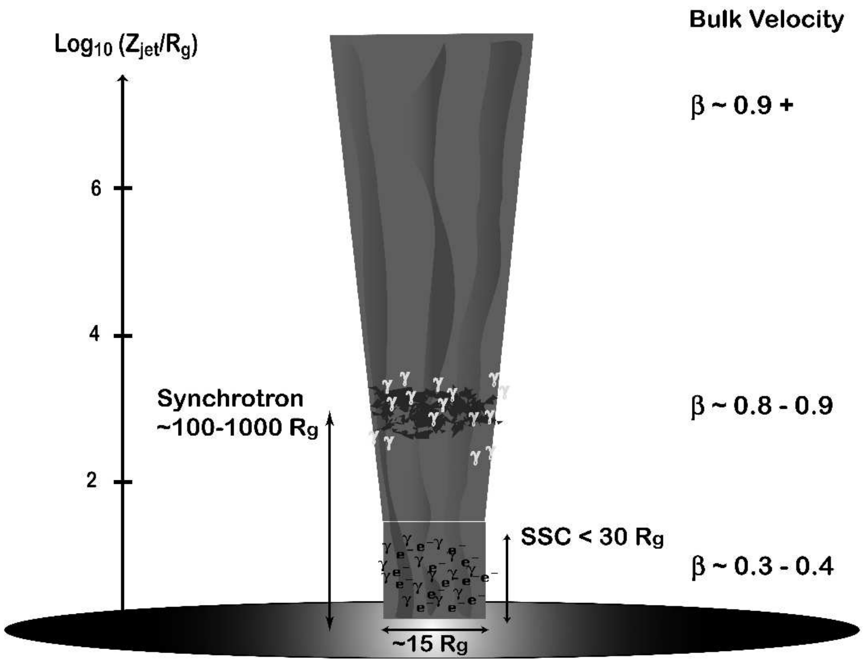


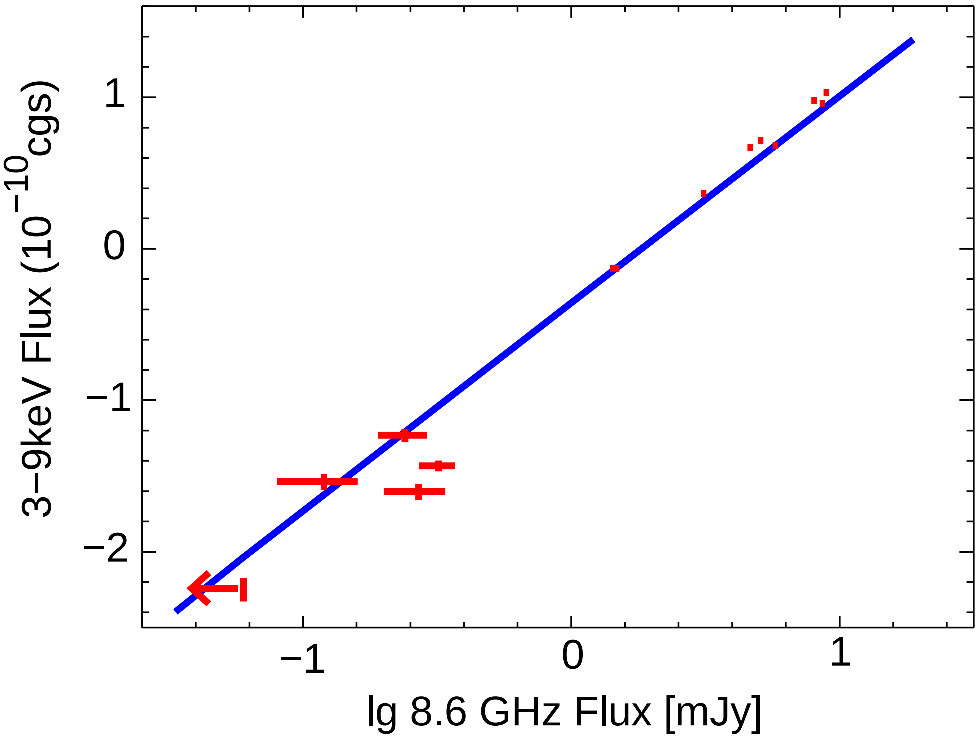
(Maccarone & Koerding, 2006, Figure by D. Russell)

Gallo et al. (2005): Interaction of jet with interstellar medium: galactic black hole jets can be comparable in power to their X-ray luminosity.

Russell et al. (2007)
For Cyg X-1, $L_{\text{jet}} = 0.3 \ldots 1.0\, L_{\text{X}}$.

X-rays: Jet Models?



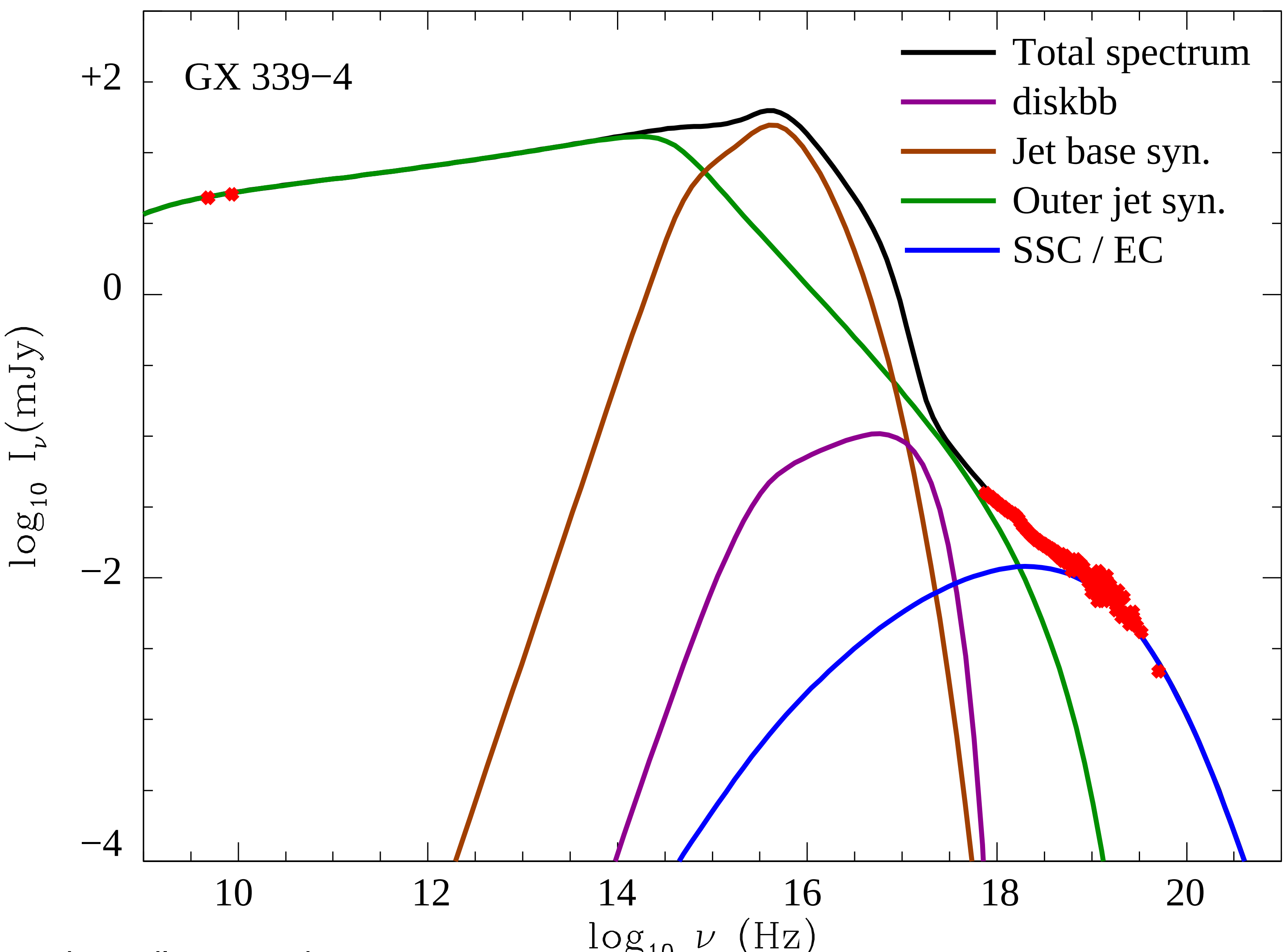


(Markoff & Nowak, 2004)

(Markoff et al., 2003)

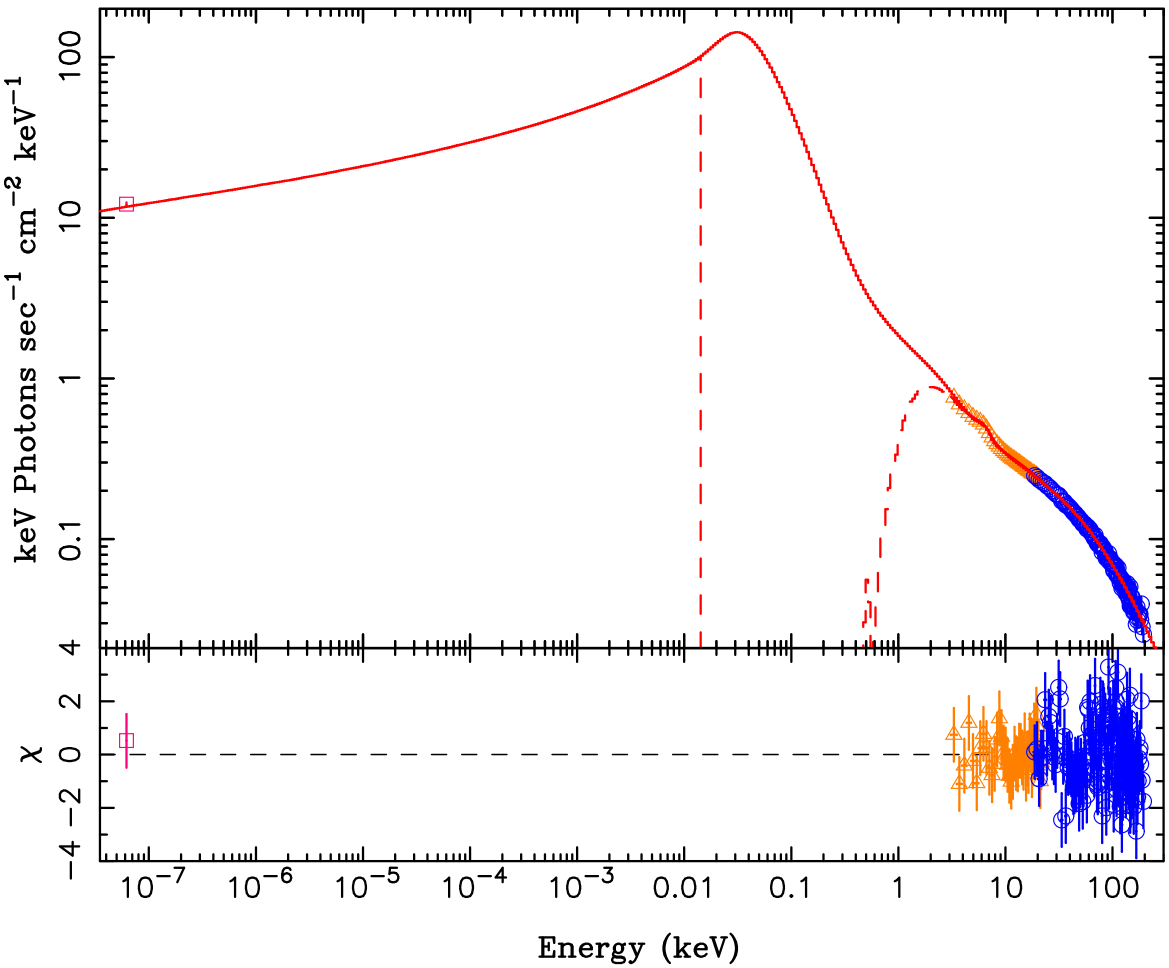
Synchrotron+SSC from a jet can explain observed long-term correlations between radio and X-rays

X-rays: Jet Models?



(Markoff, Nowak & Wilms, 2005)

X-rays: Jet Models?



(Markoff, Nowak & Wilms, 2005)

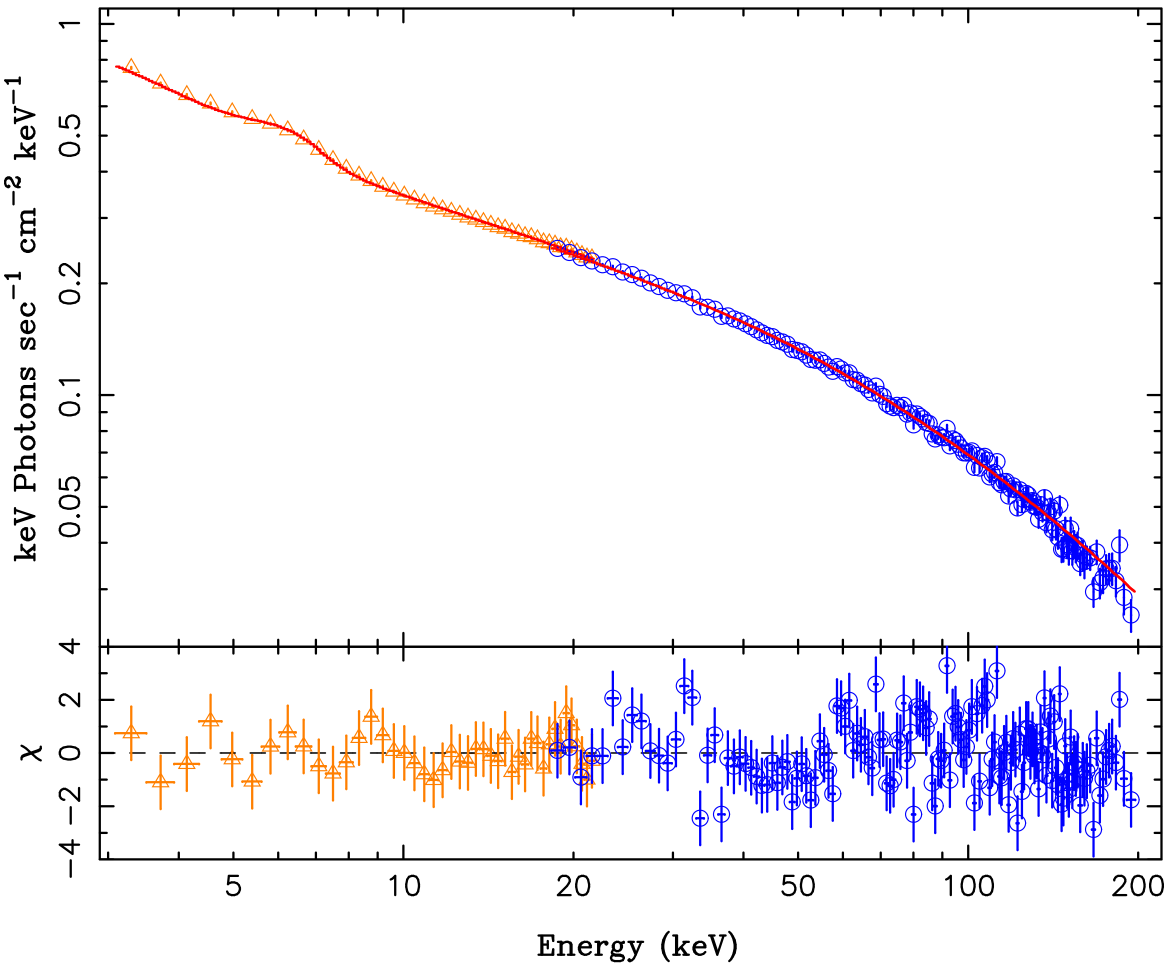
Fit of synchrotron radio jet model gives χ^2 comparable to Comptonization ($\chi^2_{\text{red}} = 1.17$).

X-rays mainly due to synchrotron self-Compton radiation from fairly large jet base (10–15 r_g).

Systematics caused by ionisation or smearing of reflection hump?

Is the Compton corona the base of the jet?

X-rays: Jet Models?



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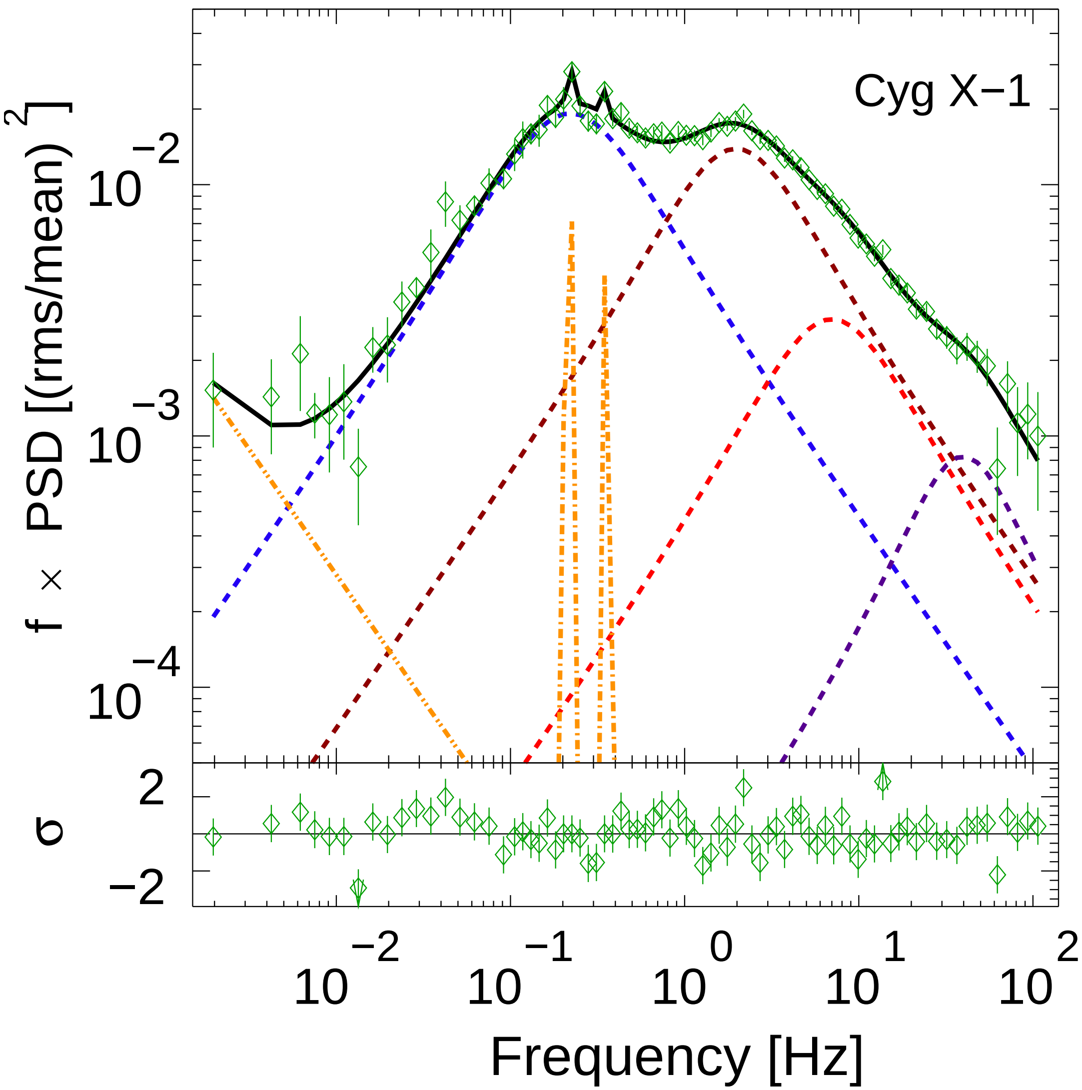
Timing: PSDs, I

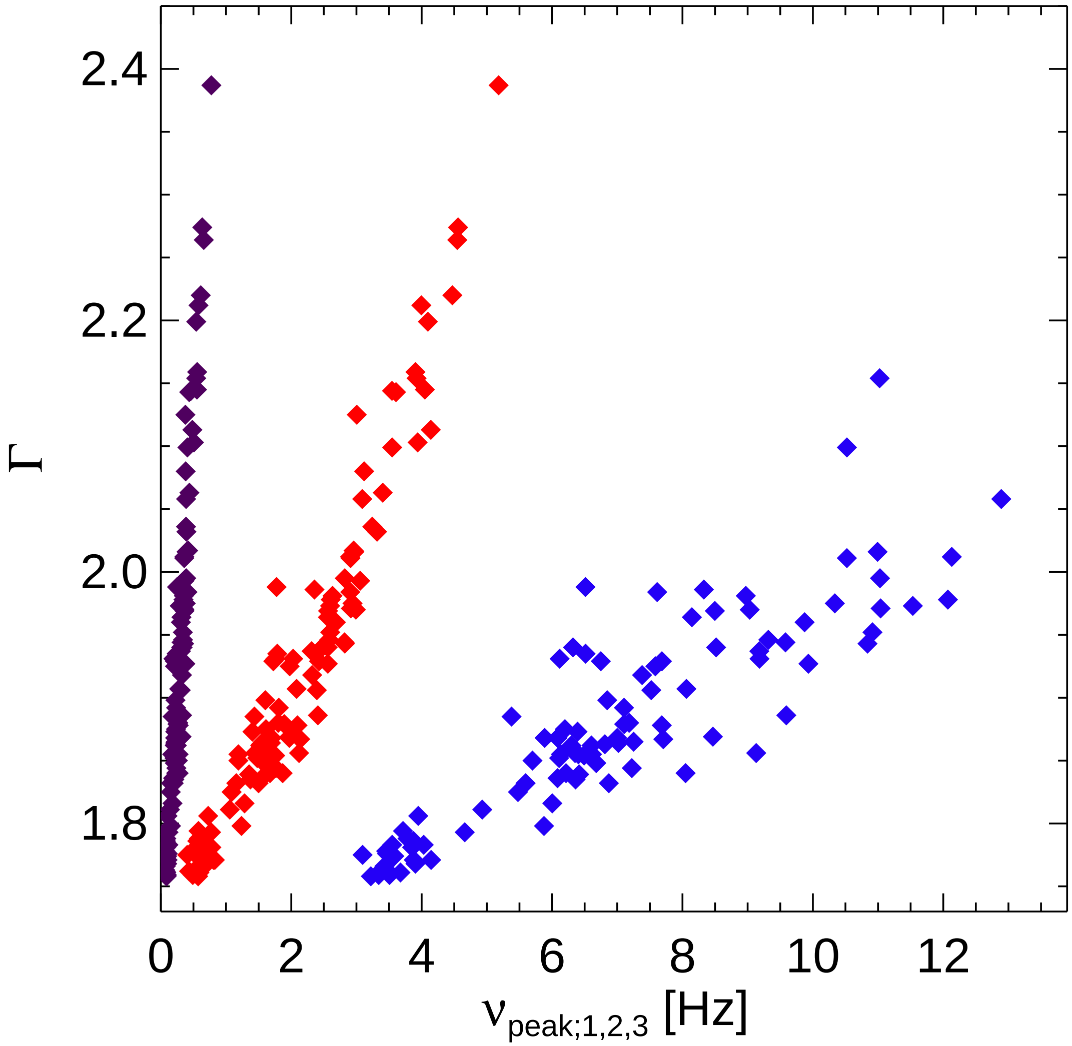


(Pottschmidt et al., 2003b)

Power spectrum in the hard state can be well described as superposition of broad Lorentzians.

(Nowak, 2000)

Timing: PSDs, II

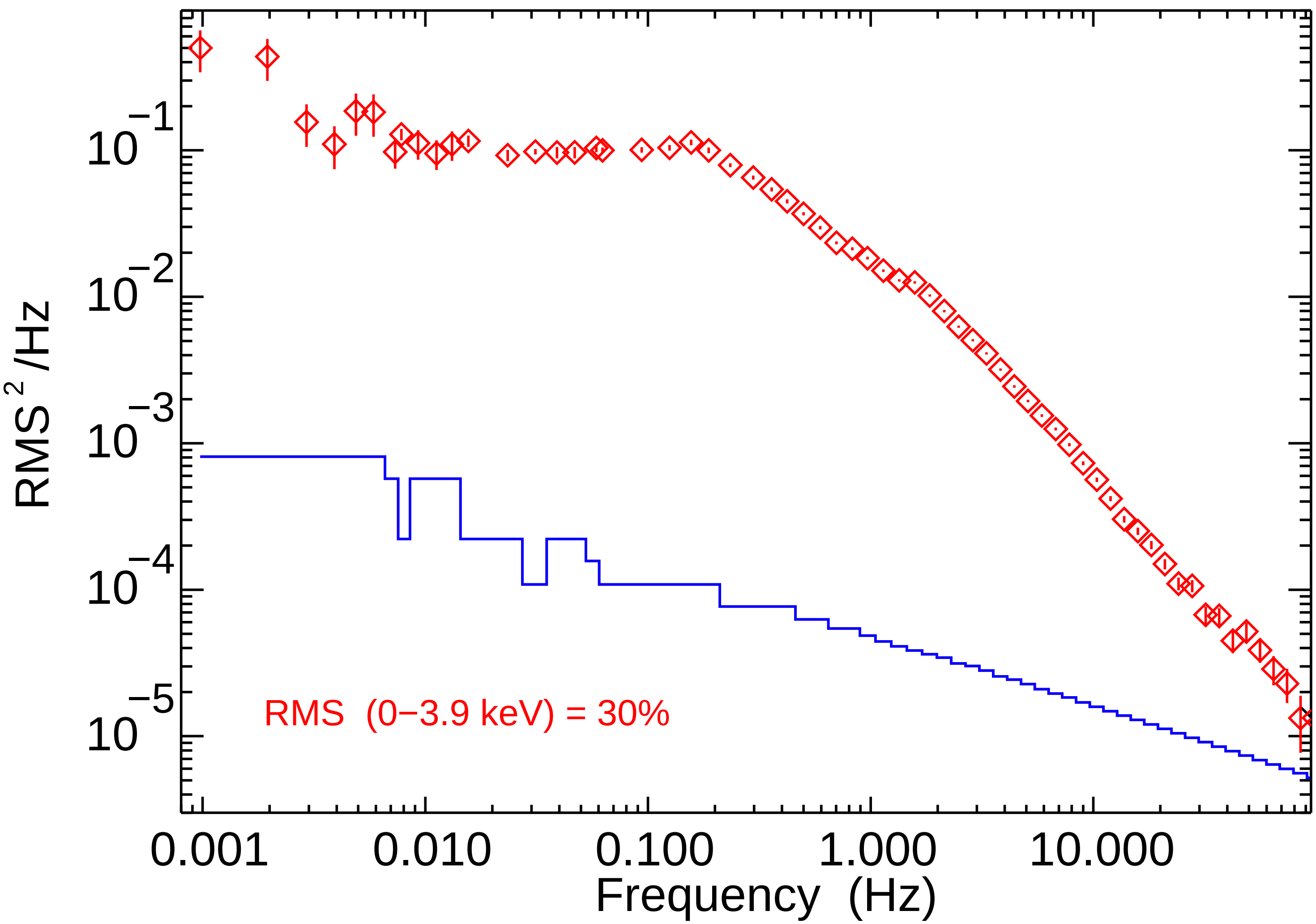


(Pottschmidt et al., 2000)

Peak frequencies are strongly correlated with spectral shape:

Does timing imply a simple disk with a varying radius?

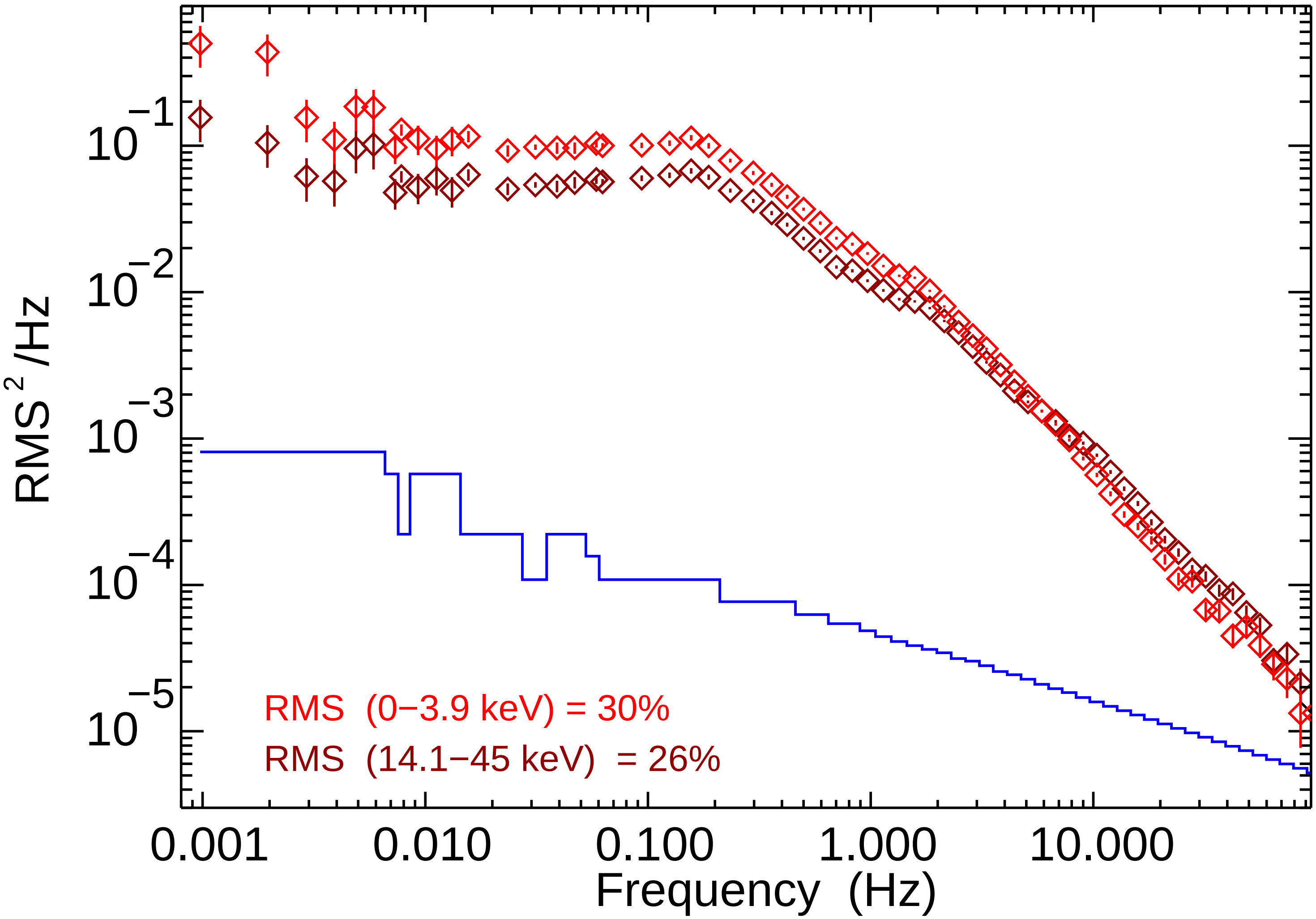
Timing: PSDs: Energy Dependence, I



(Nowak et al., 1999a)

PSD is energy dependent: softer bands: higher rms at *low* frequencies.

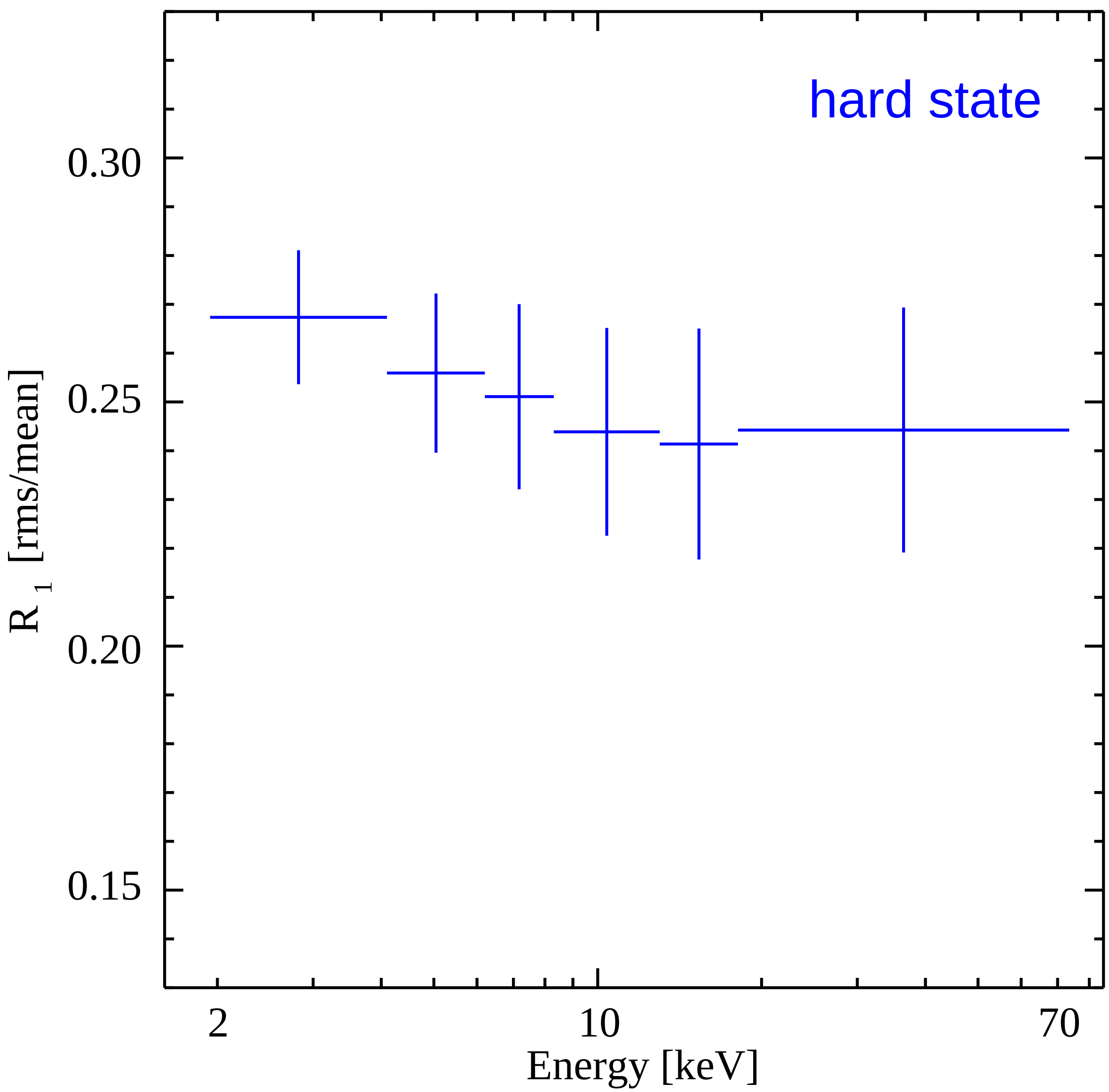
Timing: PSDs: Energy Dependence, II



(Nowak et al., 1999a)

PSD is energy dependent: softer bands: higher rms at *low* frequencies.

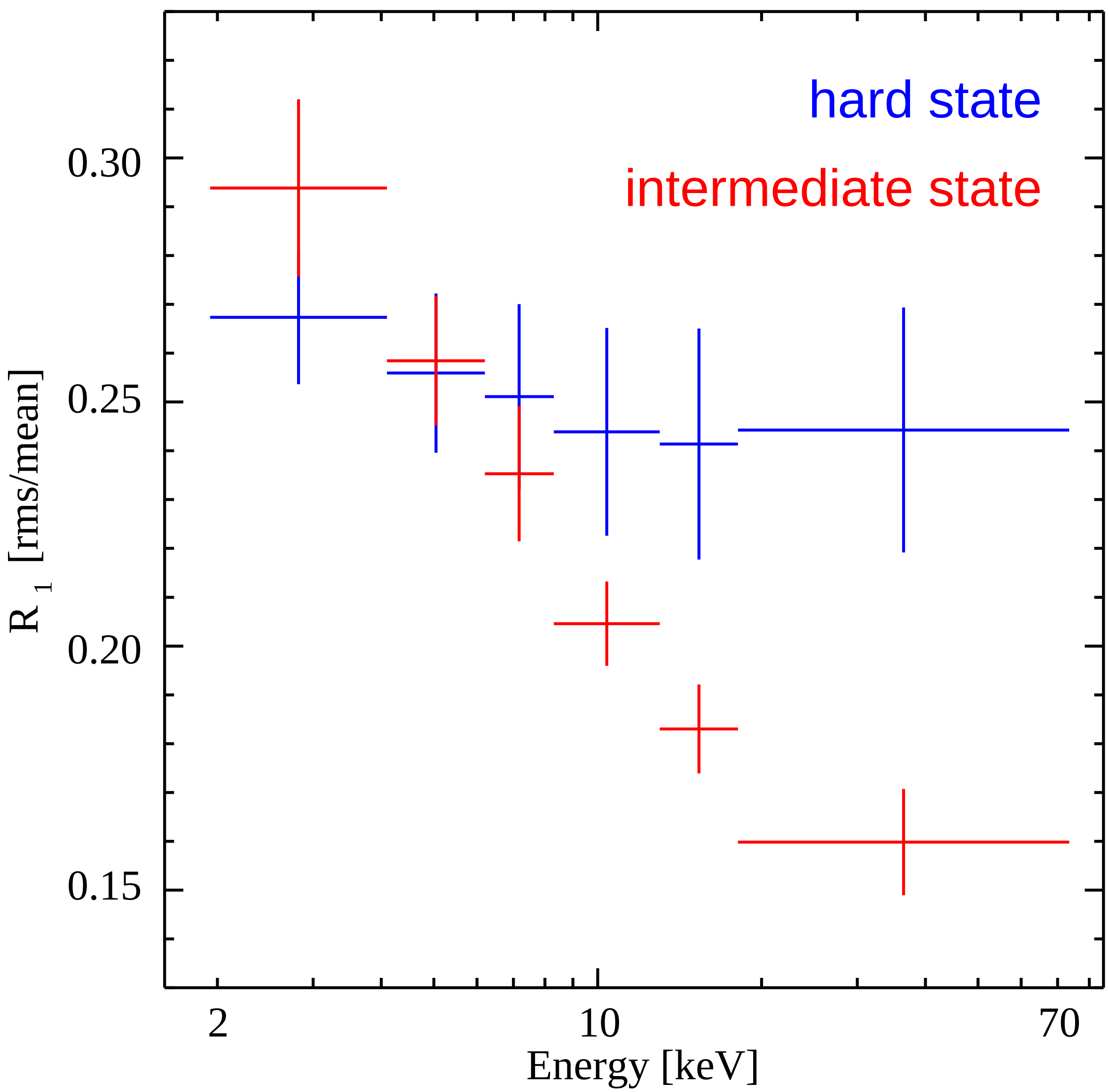
Timing: PSDs: Energy Dependence, III



Amplitude of individual Lorentzians is energy and state dependent

(Pottschmidt et al., 2003b)

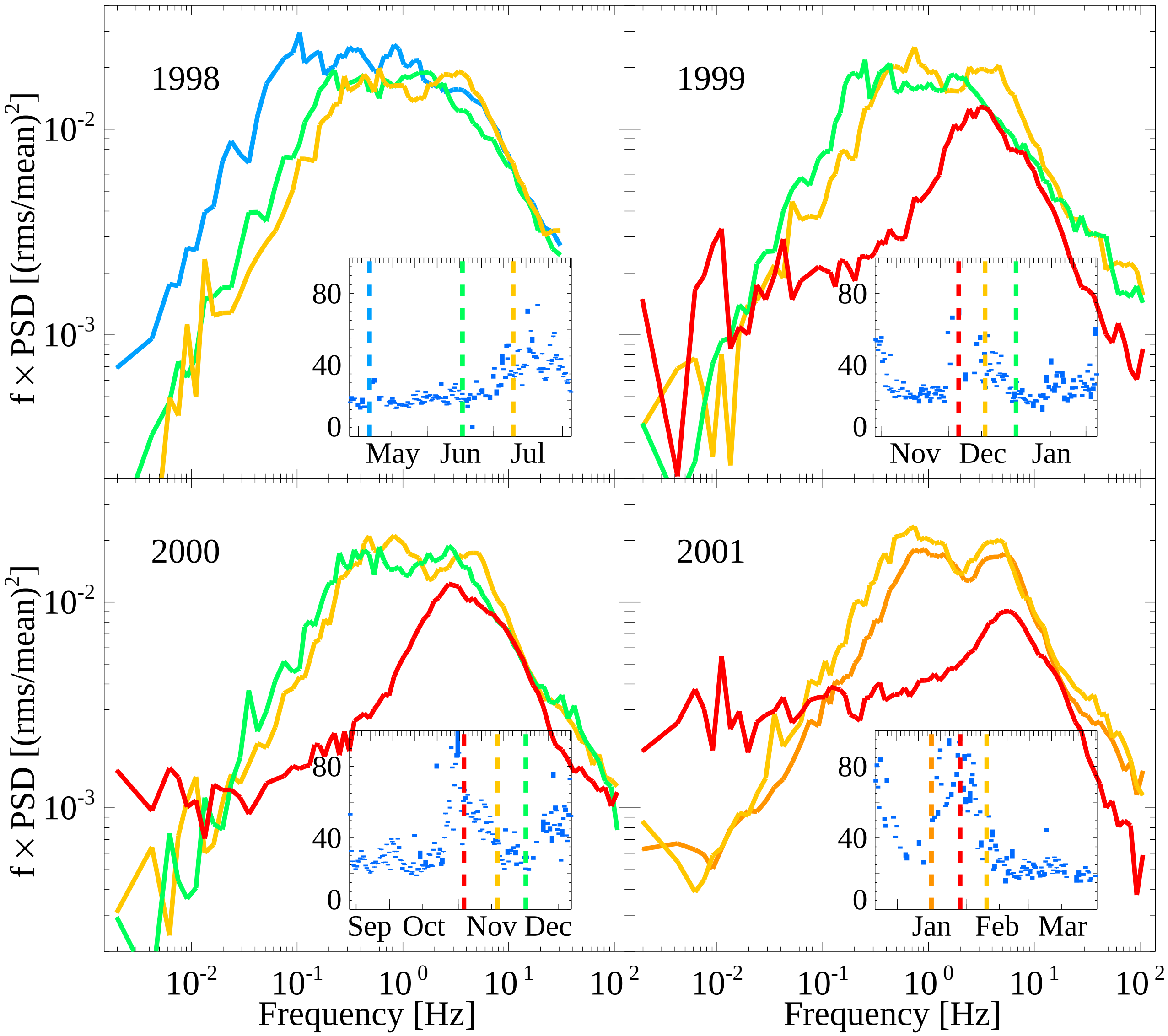
Timing: PSDs: Energy Dependence, IV



Amplitude of individual Lorentzians is energy and state dependent

(Pottschmidt et al., 2003b)

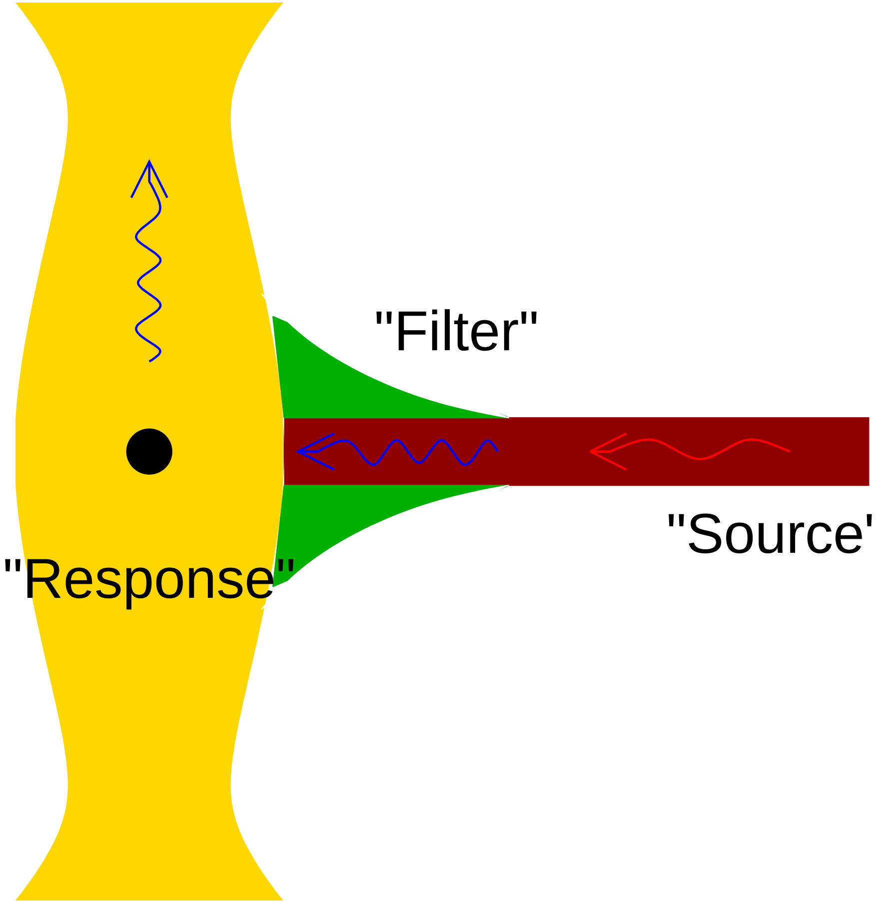
Timing: PSDs: Transitions, I

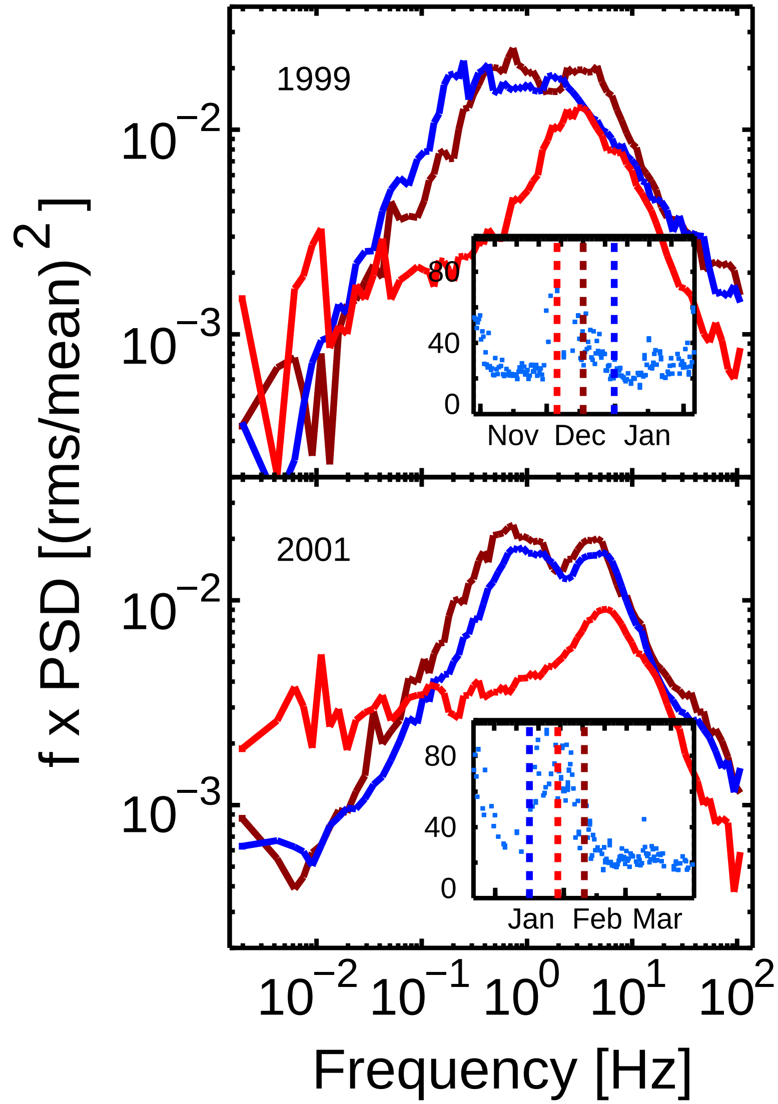


PSD shows dramatic changes during failed state transitions.

(Pottschmidt et al., 2003b)

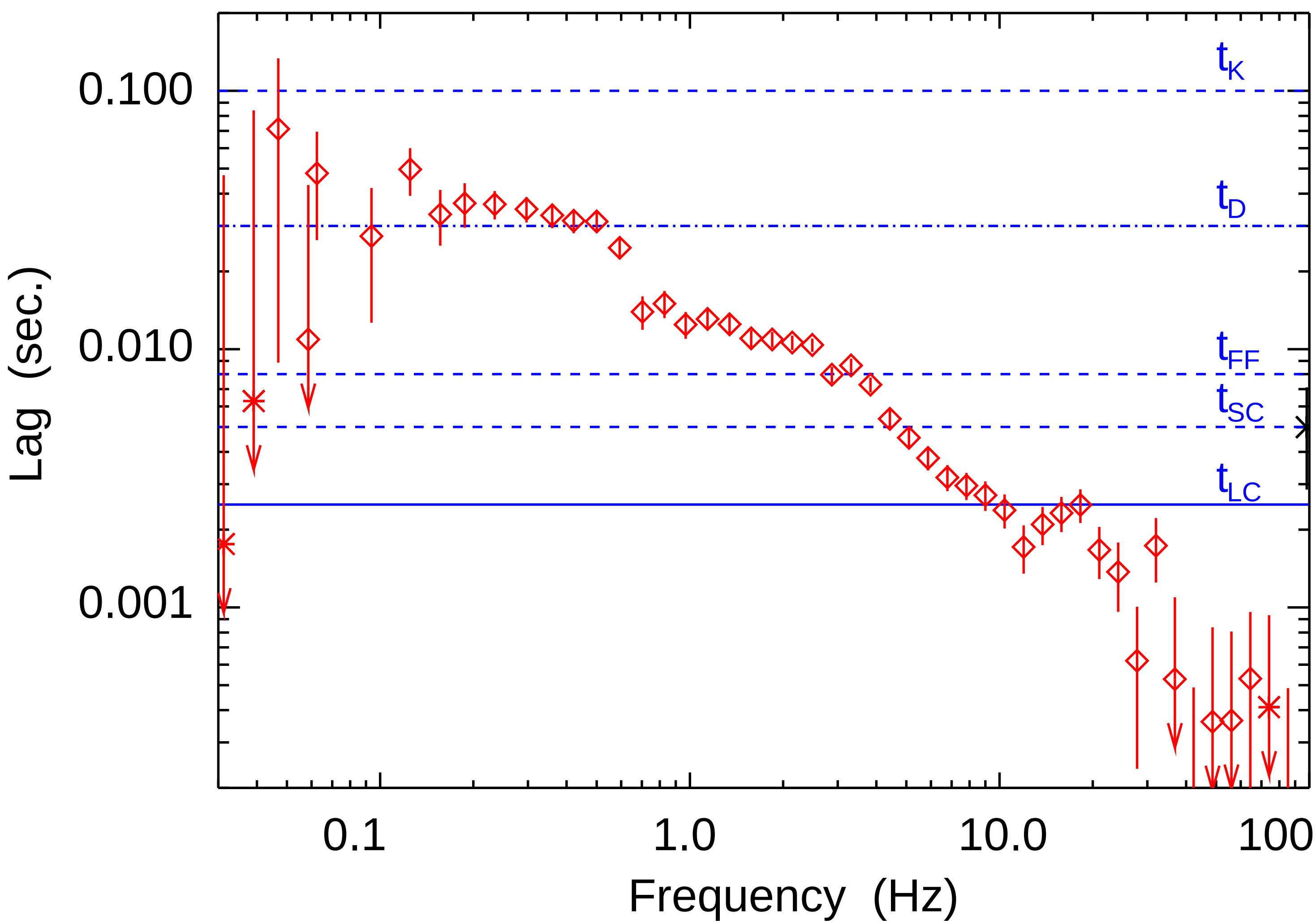
Timing: PSDs: Transitions, II





(Psaltis & Norman, 2001; Nowak et al., 1999b; Miyamoto & Kitamoto, 1989)

Timing: Lags

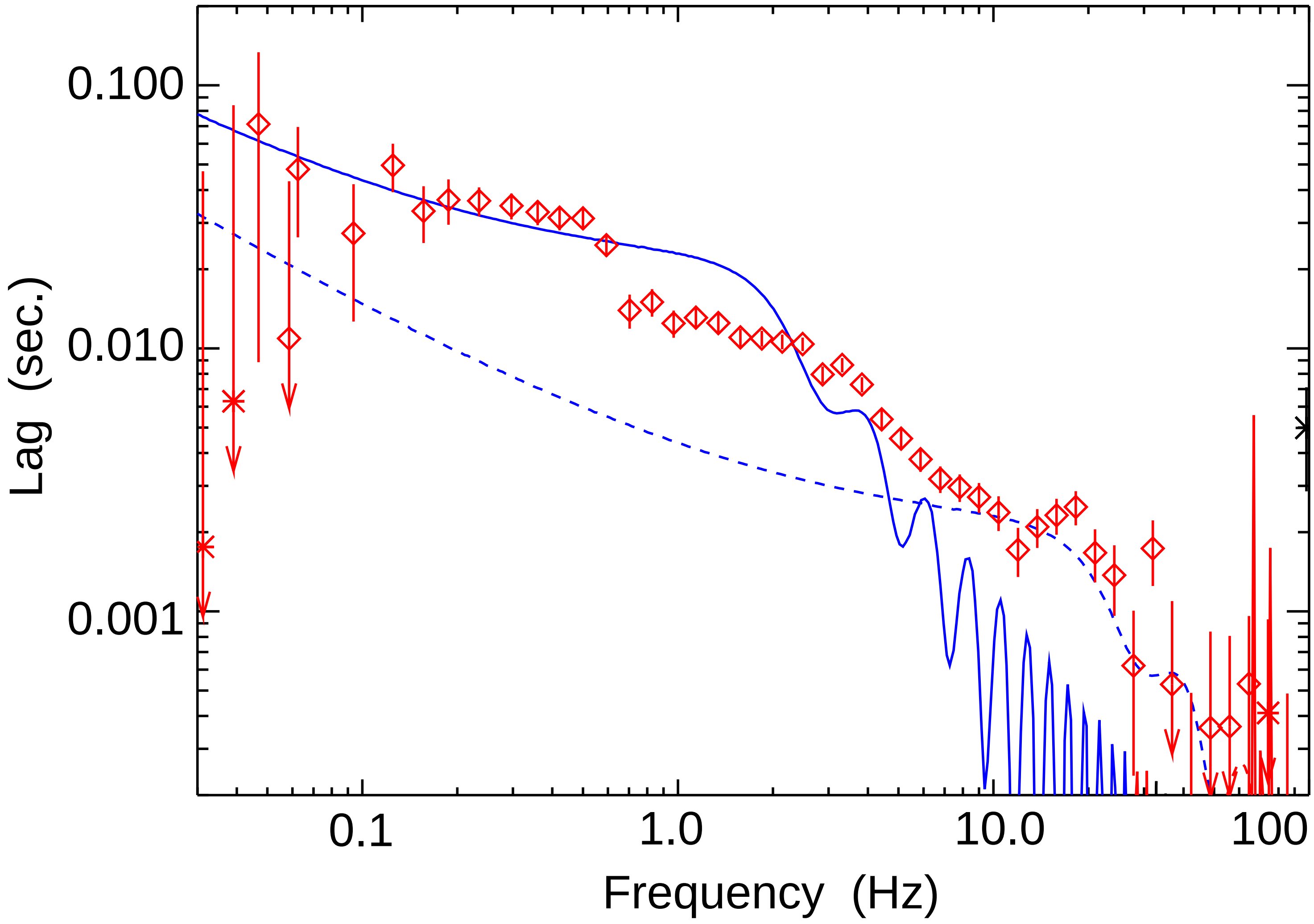


Miyamoto & Kitamoto (1989): Hard X-rays lag soft X-rays

Lag has strong dependence on Fourier frequency: *inconsistent with simple variability models*.

(Nowak et al., 1999b, lines show typical timescales based on coronal radius of $50GM/c^2$ for $M = 10\,M_\odot$)

Timing: Lags



Possible explanation for X-ray lags:

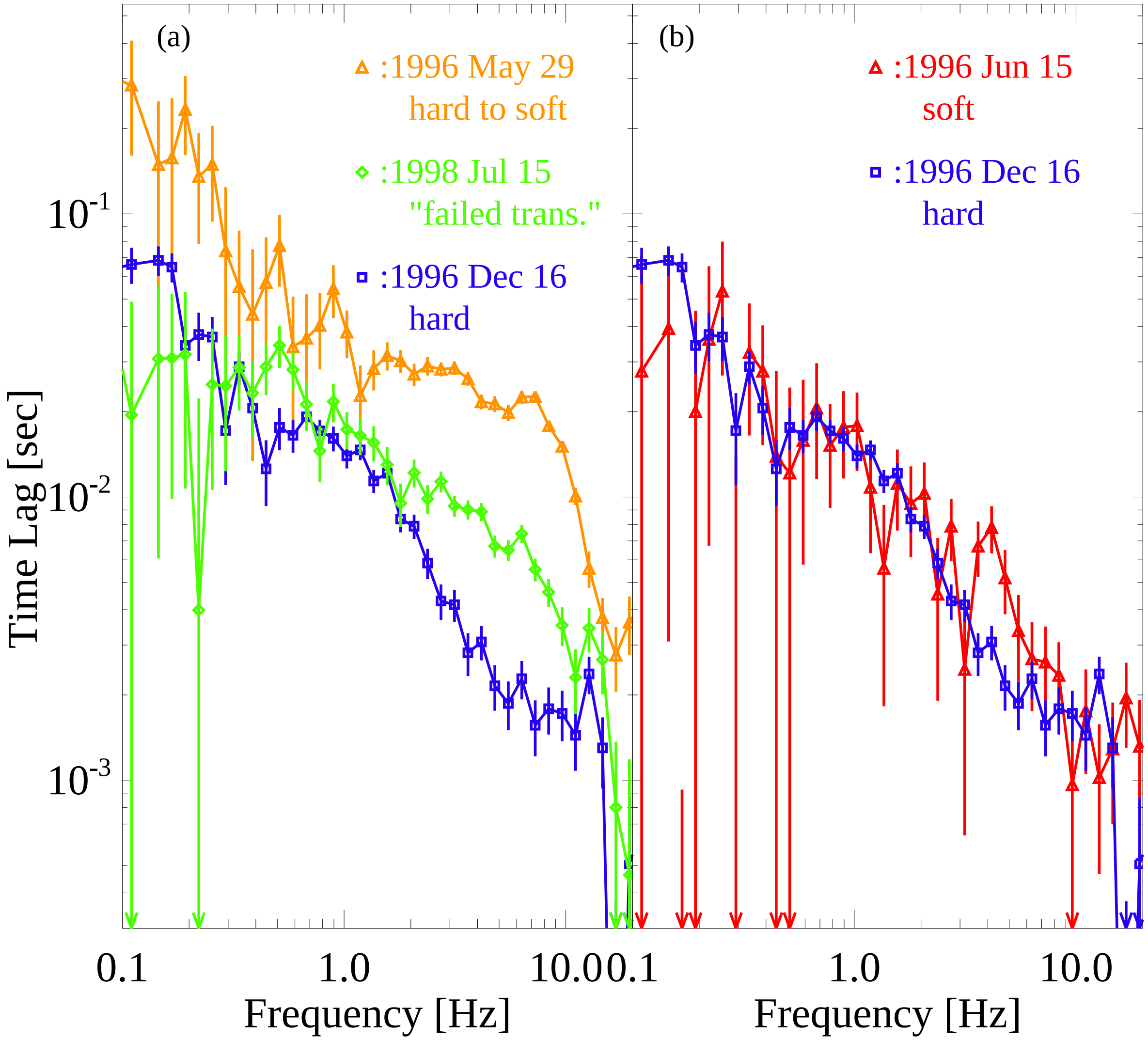
- Nowak et al. (1999b): wave propagation in accretion disk

  See also Manmoto et al. (1996)

- Körding & Falcke (2004): pivoting power law spectra plus Lorentzian PSDs

(Nowak et al., 1999b, solid: time lag for $c_\mathrm{p} = 0.01c$, dashed: $c_\mathrm{p} = 0.1c$)

Timing: Lags



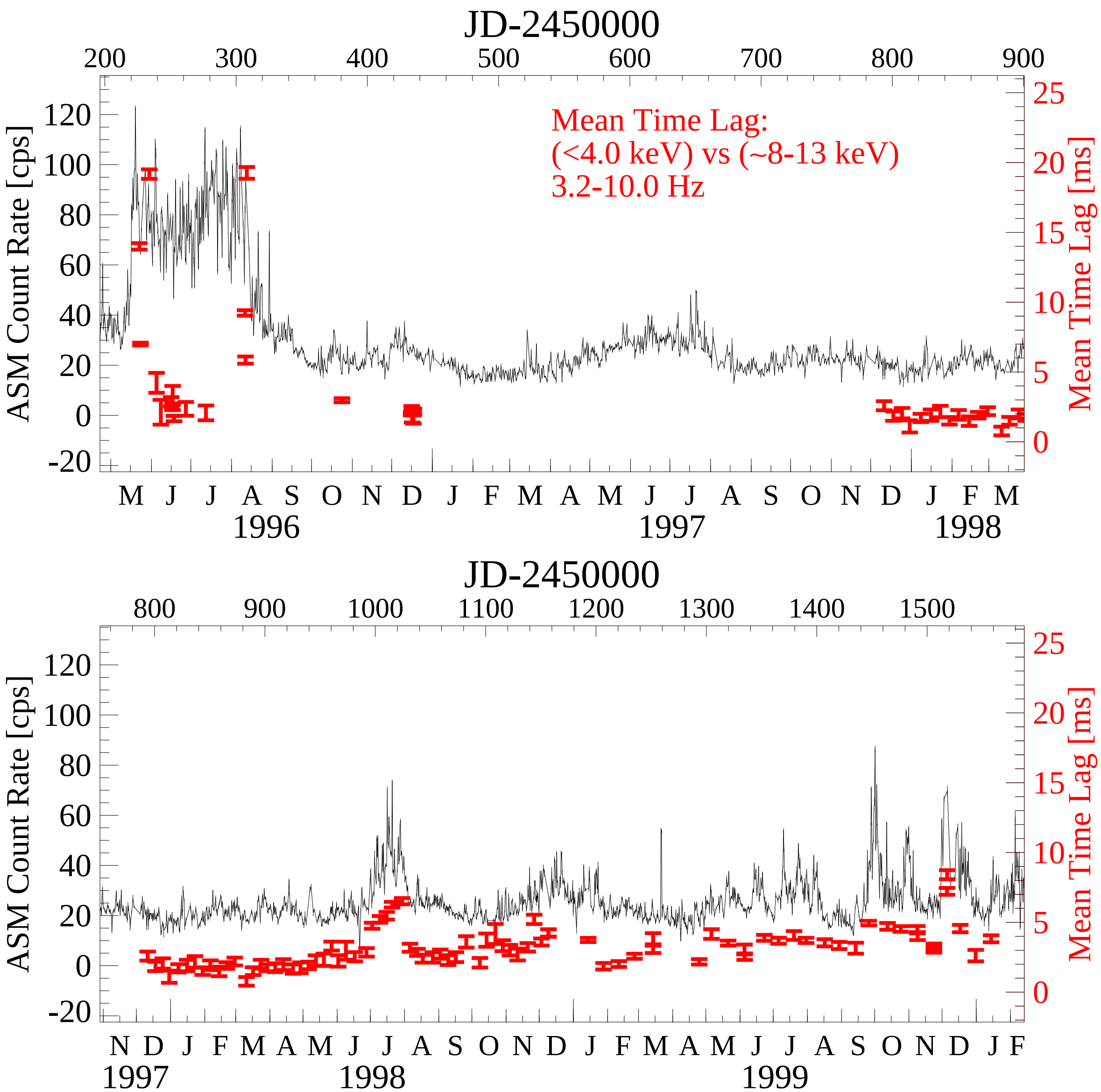
(Pottschmidt et al., 2000)

- Lags are variable: "shelves" consistent with Lorentzians!
- Lags change during transitions

  $\Longrightarrow$ changing geometry?
- Soft state and hard state lag ~similar.

  contradicts geometry change?

Timing: Lags



Enhanced lag during (failed) transitions $\Longrightarrow$ Extremely sharp transition indicator!

Also true in other BHC (e.g., Kalemci et al., 2001, 2003, 2005)

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XRB Evolution