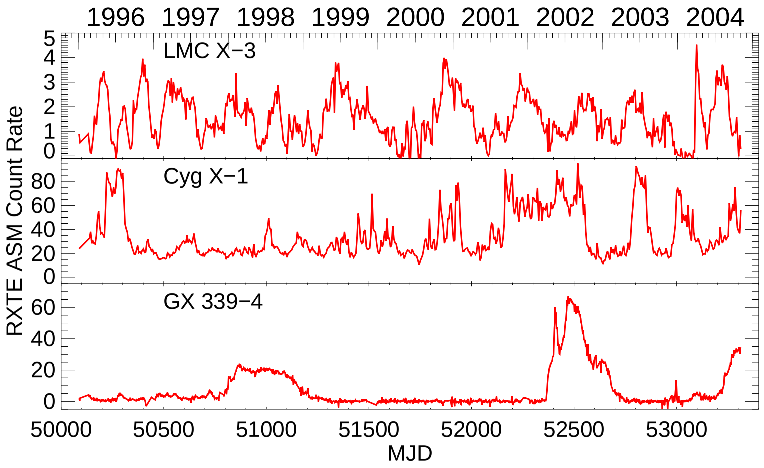
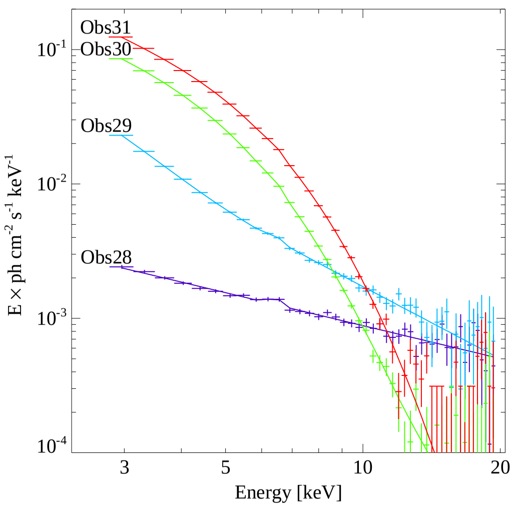
Long-Term Evolution



Black Holes: Variability on all time scales

Spectral States

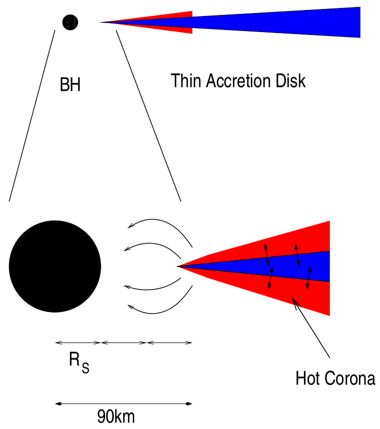


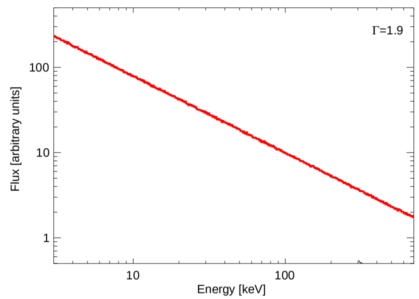
(LMC X-3; Wilms et al., 2001)

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)

Spectral States

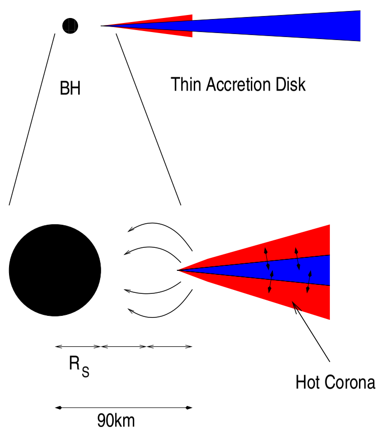


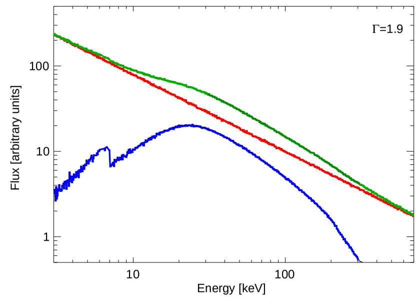


Black Hole X-Ray Spectrum:

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

Spectral States

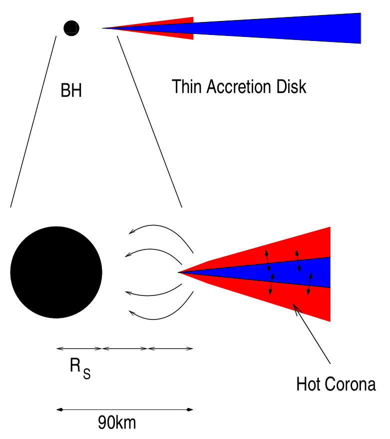


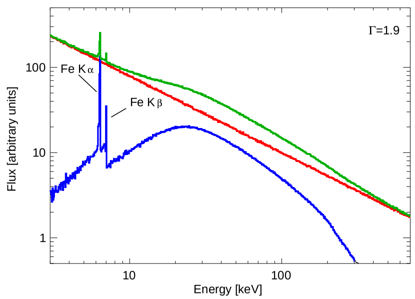


Black Hole X-Ray Spectrum:

- 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

Spectral States

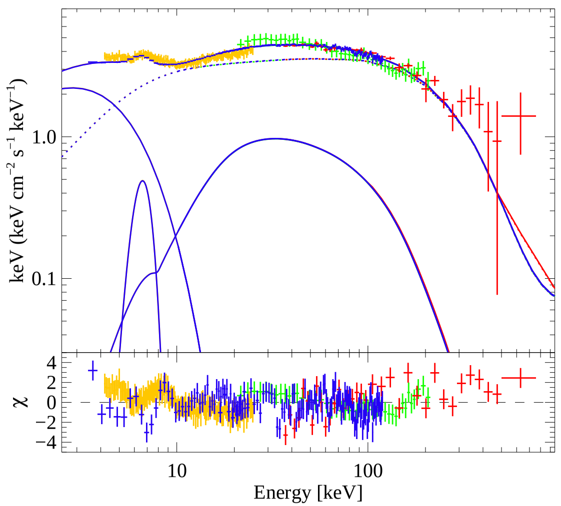




Black Hole X-Ray Spectrum:

- 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 ~6.4 keV

Hard State

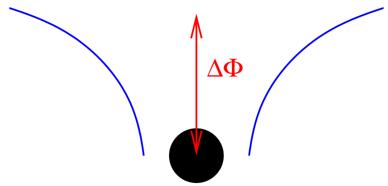


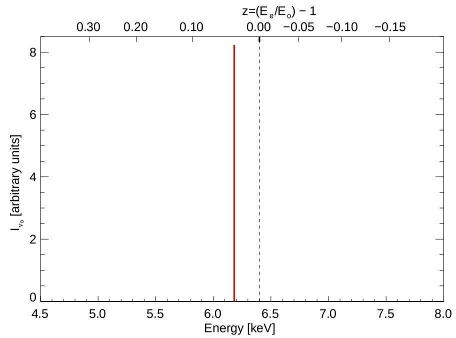
Fritz et al. (2006)
see also Pottschmidt et al. (2003)

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

$kT_{\rm max} = 1.21$ keV,
$\tau_{\rm p} = 1.01$,
$\ell_{\rm h}/\ell_{\rm s} = 2.70$,
$\ell_{\rm nt}/\ell_{\rm th} = 0.05$,
$\Omega/2\pi = 0.3/2$
$\chi^2/{\rm dof} = 466/348$

Relativistic Lines

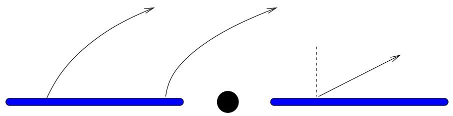


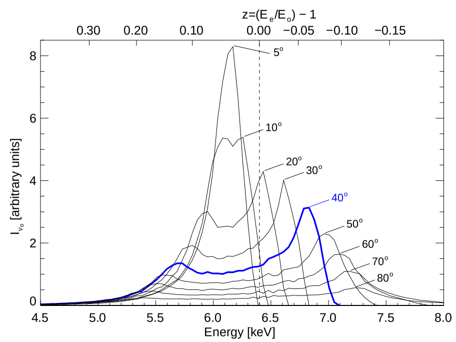


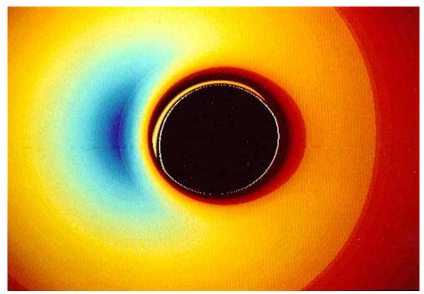
Total observed line profile affected by

- grav. Redshift

Relativistic Lines



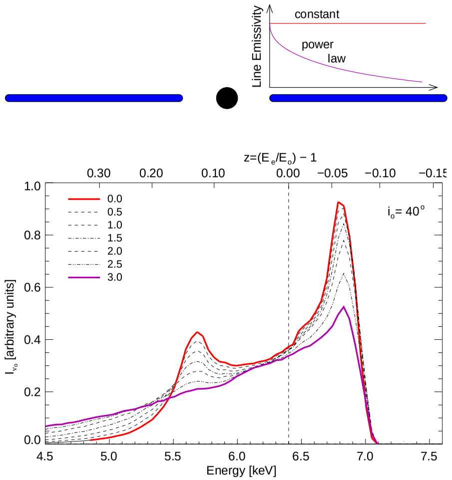


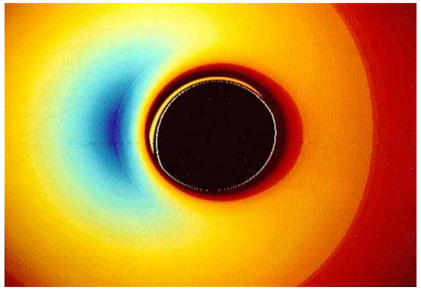


Total observed line profile affected by

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

Relativistic Lines

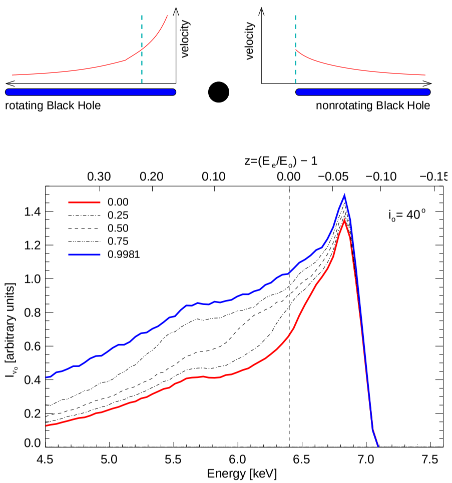


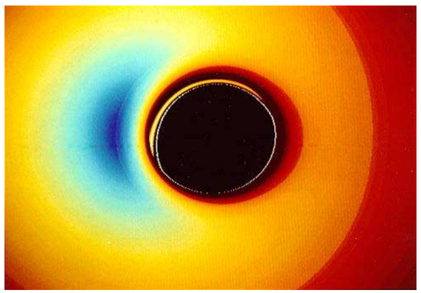


Total observed line profile affected by

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

Relativistic Lines

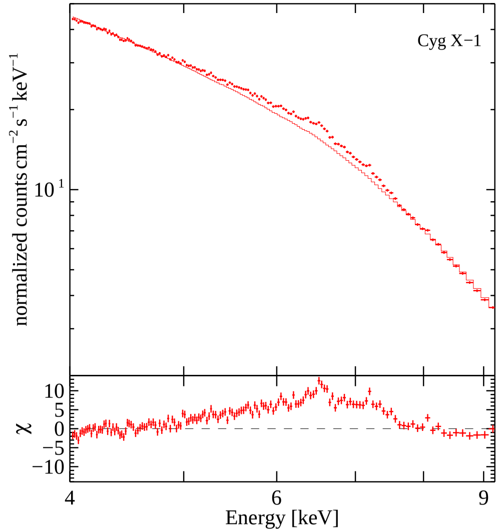




Total observed line profile affected by

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

Relativistic Lines

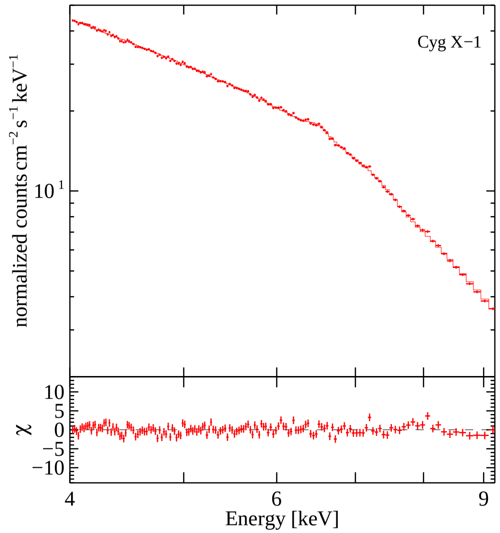


Wilms et al. (2006)

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 modified timing mode of the EPIC-pn camera on *XMM-Newton* which ignores data from below ~3 keV; inner 3 CCD columns ignored because of pile-up

Relativistic Lines



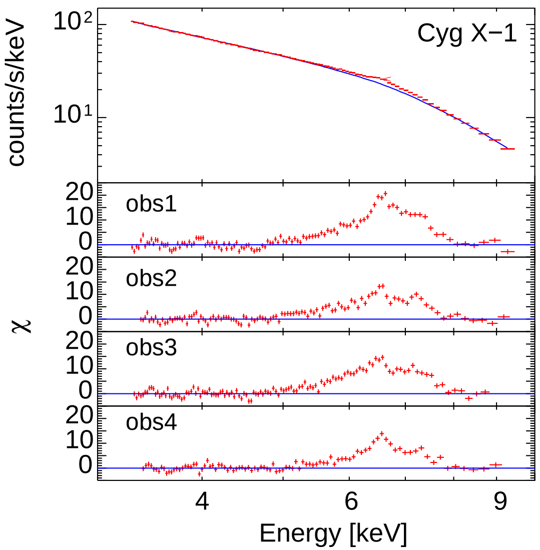
Wilms et al. (2006a)

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

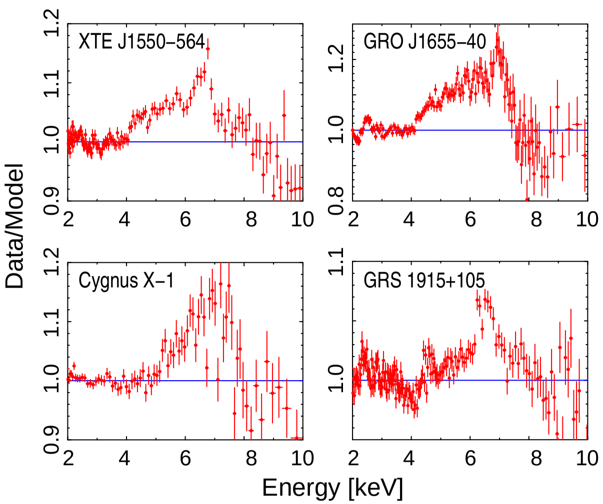
Parameters similar (but not equal) to *Chandra* intermediate state observations (Miller et al., 2002)

Relativistic Lines



Cyg X-1 (*XMM-Newton*, EPIC-pn modified timing mode, 10–20 ksec each)
(Fritz et al., 2007)

Relativistic Lines



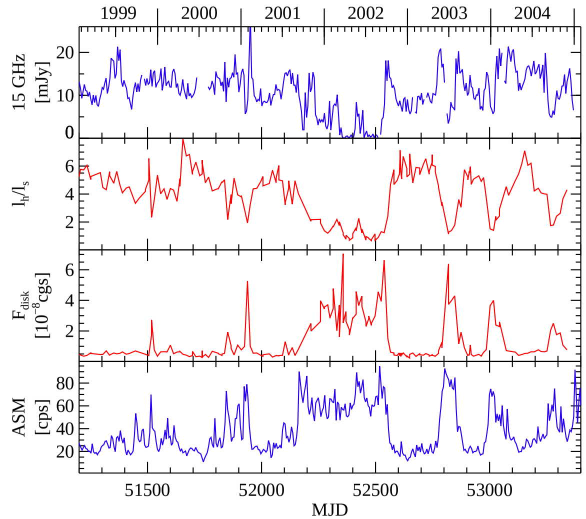
Relativistic lines are seen in many Galactic Black Holes

- 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)

Long-Term Variability

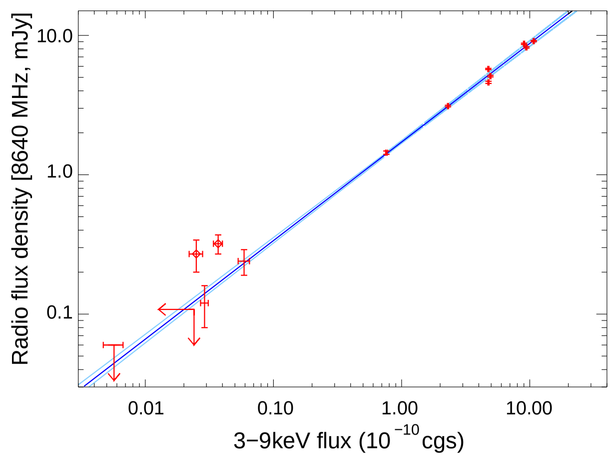


Cyg X-1 (Wilms et al., 2006b)

Correlated variation of the RXTE-ASM count rate, the radio flux, the flux from the accretion disk and the amount of energy dissipated in the Comptonizing plasma relative to the accretion disk (ℓ_h/ℓ_s).

Never before have BHC been studied with such good coverage and over such a wide energy range (e.g., pre-RXTE: 1–2 pointings per year).

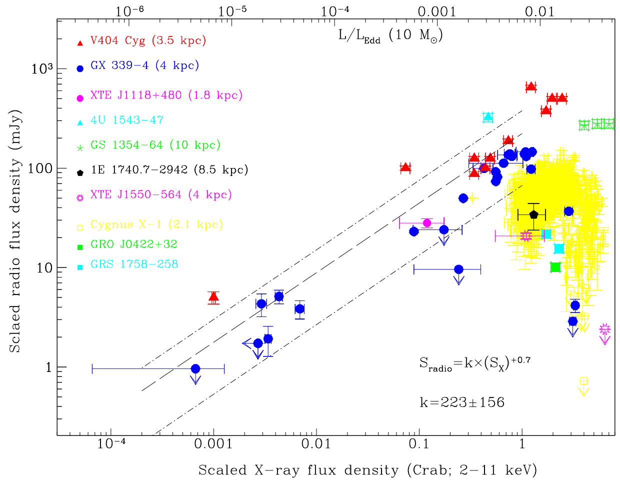
Radio–X-ray connection



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

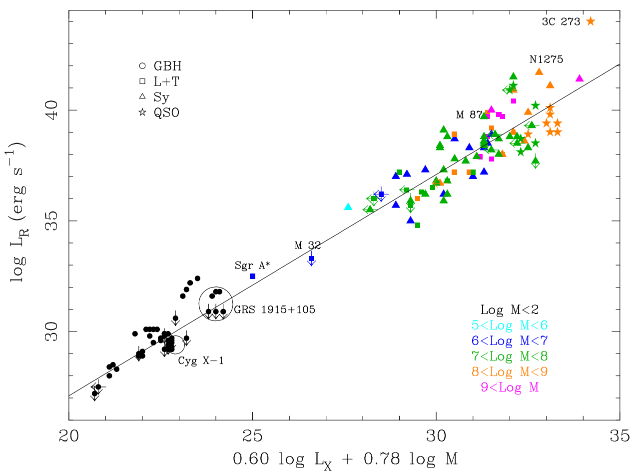
See also Hannikainen et al. (1998), Markoff et al. (2003).

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



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

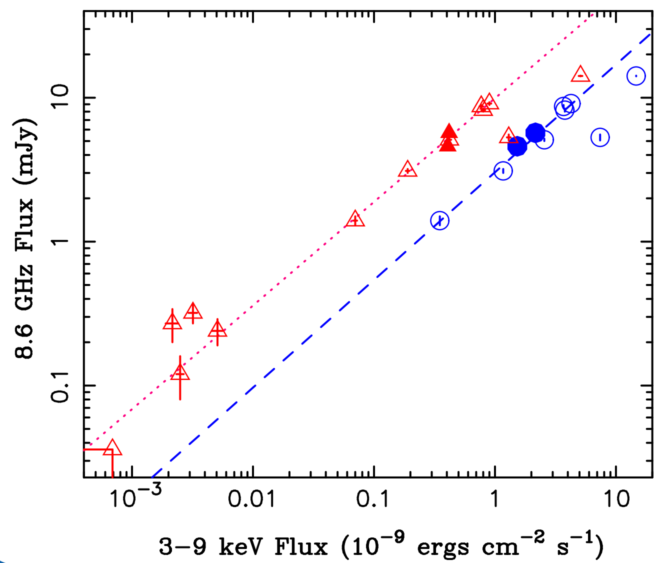
$\Longrightarrow$ scatter due to varying black hole mass

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

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

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

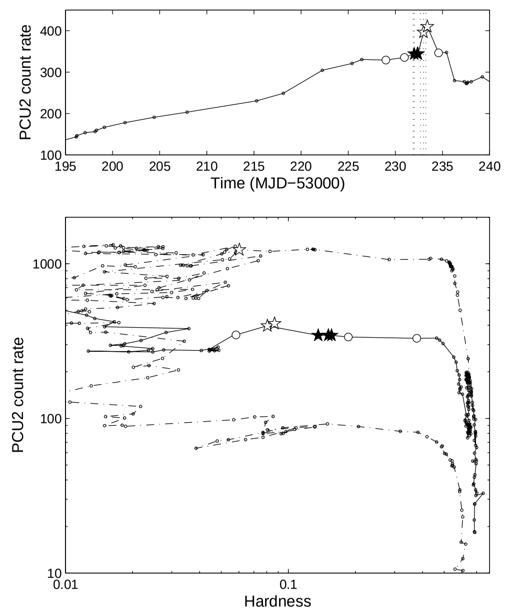
Radio–X-ray connection



But note: while generally $F_{\text{radio}} \propto F_{\text{X}}^{0.7}$, 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).

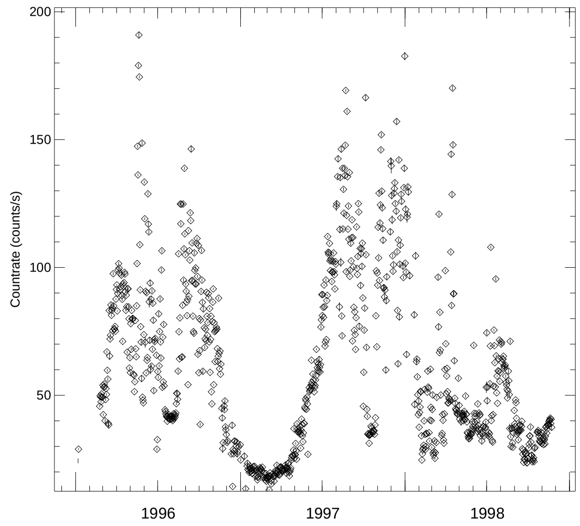
(GX 339−4; Nowak et al., 2005)



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

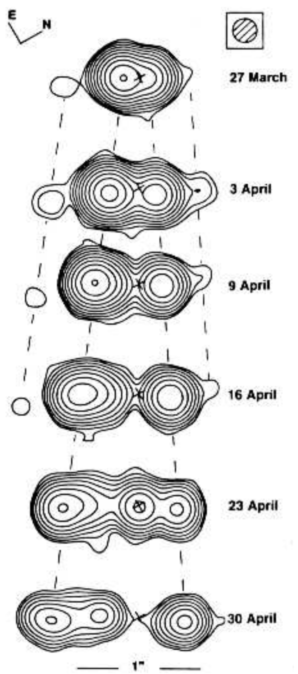
(GX 339−4; Belloni et al., 2006)

Microquasars

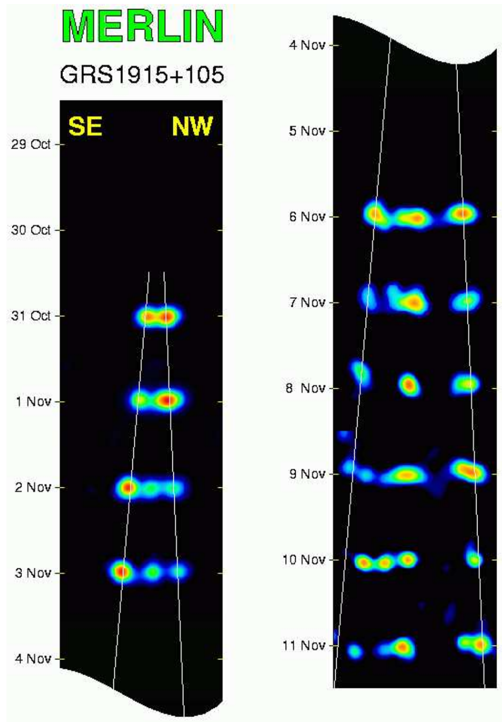


Some black holes show very interesting long and short term behavior in all wavebands

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

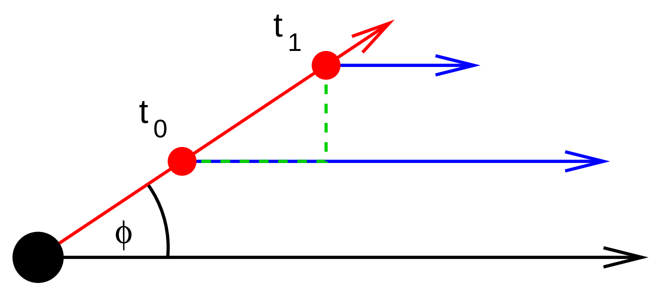


GRS 1915+105 1994 March/April: weekly radio images show blob ejection events.
Scale ~10000 AU
Ballistic motion of events $\Longrightarrow$ no deceleration!
Inferred speeds: $(0.65 \pm 0.08)c$ und $(1.25 \pm 0.15)c$
$\Longrightarrow$ superluminal motion!



1997 radio campaign: ~10% higher speeds;
Fender et al. (1998)

Microquasars



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

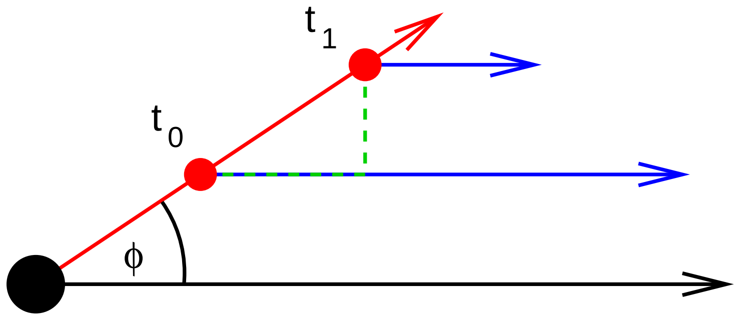
Light travel time: Observer sees signals separated by

$$\Delta t_o = \Delta t_e - \Delta t_e \frac{v}{c}\cos\phi = \left(1 - \frac{v}{c}\cos\phi\right)\Delta t_e \tag{6.73}$$

Observed distance traveled in plane of sky:

$$\Delta\ell_\perp = v\Delta t_e \sin\phi \tag{6.74}$$

Microquasars

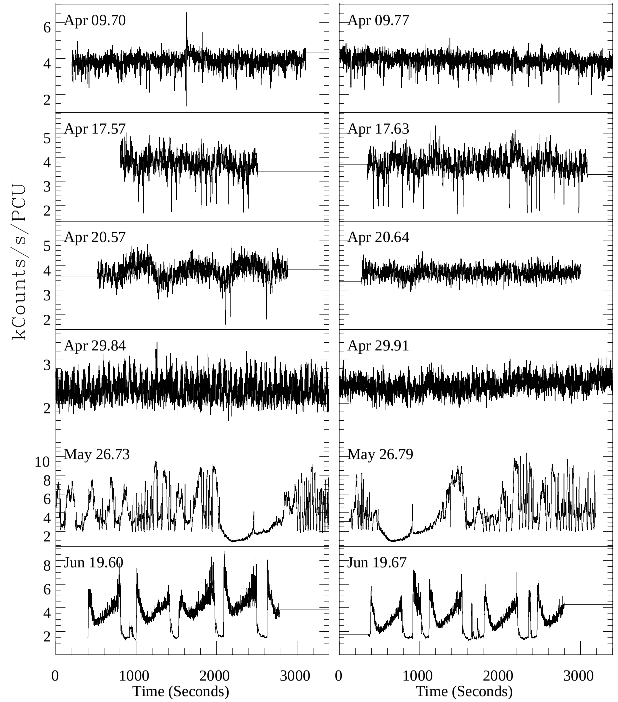


Apparent velocity deduced from observations:

$$v_{\text{app}} = \frac{\Delta \ell_\perp}{\Delta t_{\text{o}}} = \frac{v \Delta t_{\text{e}} \sin\phi}{\left(1 - \frac{v}{c}\cos\phi\right)\Delta t_{\text{e}}} = \frac{v\sin\phi}{\left(1-\frac{v}{c}\cos\phi\right)} \quad (6.75)$$

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

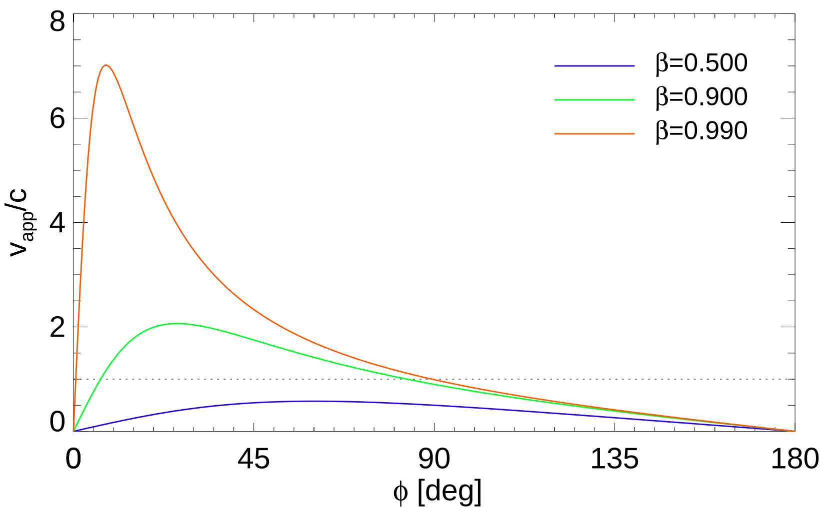
previously only seen in Active Galaxies ("Quasars") $\Longrightarrow$ Microquasars



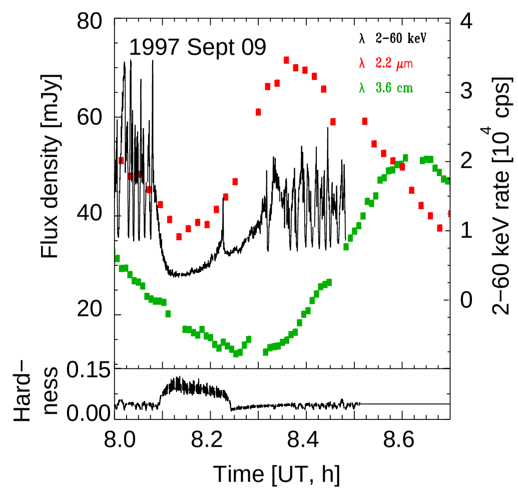
GRS 1915+105, RXTE/PCA, 2–60 keV, 1 s resolution lightcurves Brightness Sputters, Large-Amplitude Oscillations

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

Microquasars



Superluminal motion: Microquasars have jet speeds close to c



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

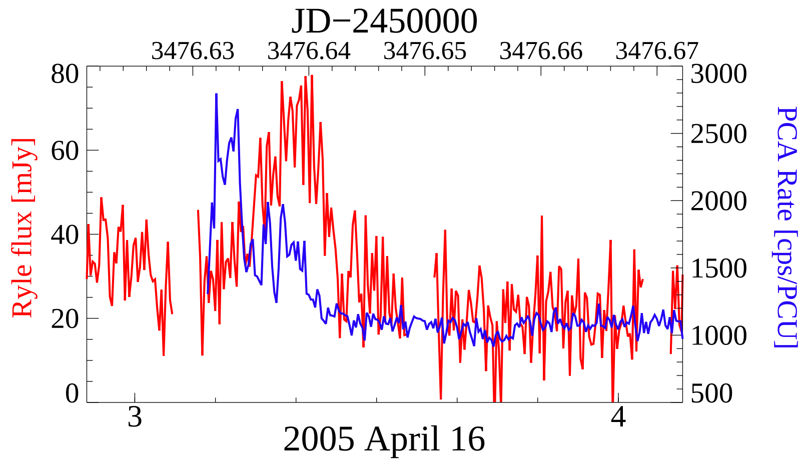
Microquasars allow study of dynamics of jet formation

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

Flaring episodes: clear radio–X-ray relationship

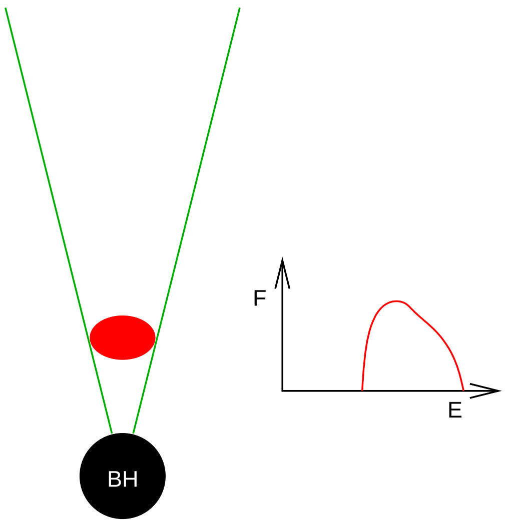
$\Longrightarrow$ "disk-jet-connection"

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



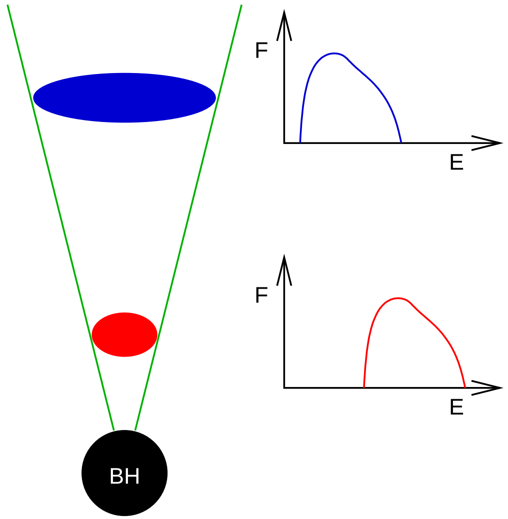
(Cyg X-1, 2005 April 16; Wilms et al., 2007, Ryle: 15 GHz, PCA: 2–60 keV)

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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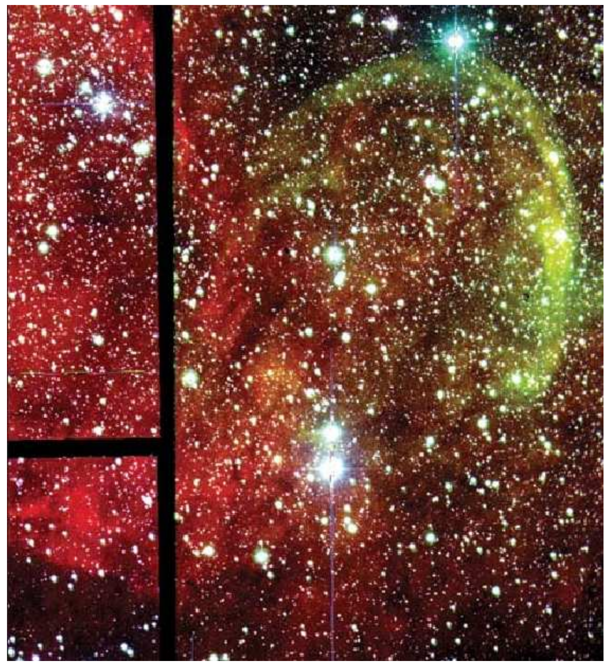
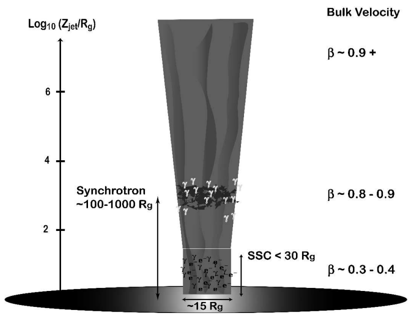


Gallo et al. (2005): Interaction of jet with interstellar medium: galactic black hole jets can be comparable in power to their X-ray luminosity.

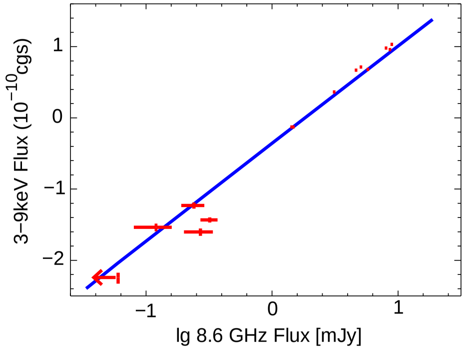
Russell et al. (2007)
For Cyg X-1, $L_{\text{jet}} = 0.3 \ldots 1.0\, L_{\text{X}}$.

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

X-rays: Jet Models?



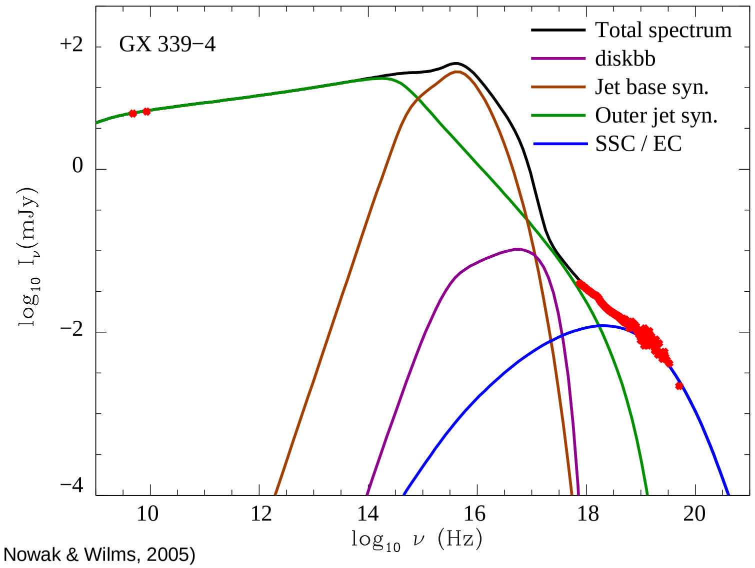
(Markoff & Nowak, 2004)



(Markoff et al., 2003)

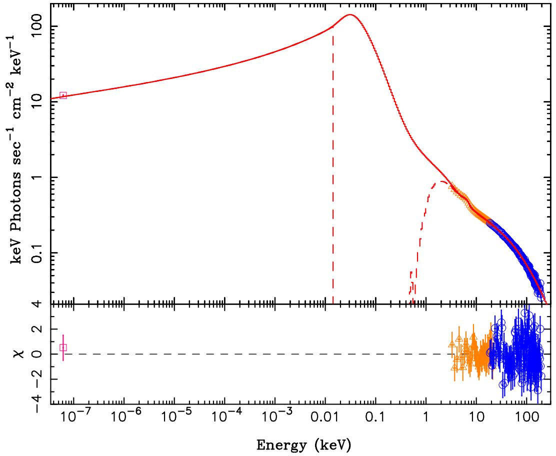
Synchrotron+SSC from a jet can explain observed long-term correlations between radio and X-rays

X-rays: Jet Models?



(Markoff, Nowak & Wilms, 2005)

X-rays: Jet Models?



(Markoff, Nowak & Wilms, 2005)

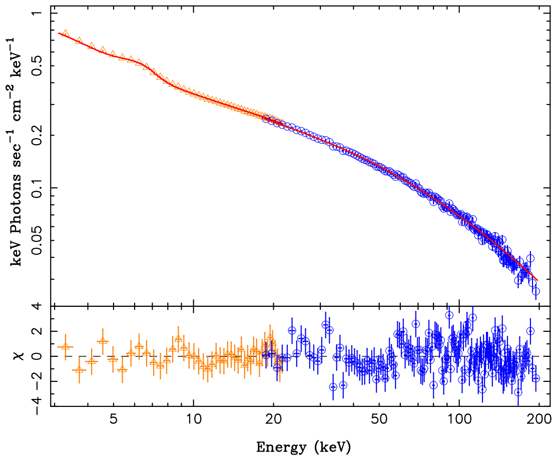
Fit of synchrotron radio jet model gives χ^2 comparable to Comptonization ($\chi^2_{\mathrm{red}} = 1.17$).

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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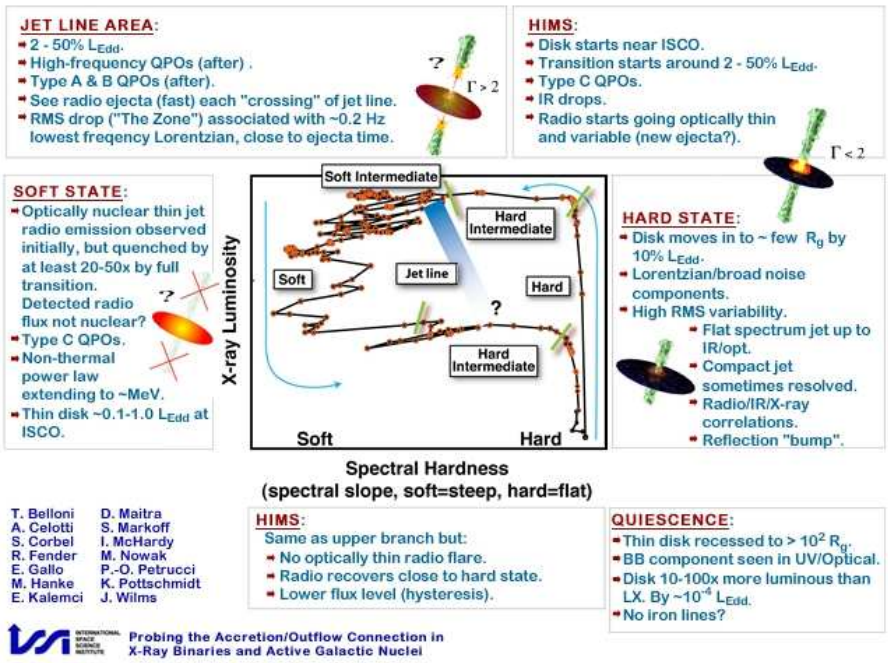

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