Connection between accretion discs and jets in XRBs

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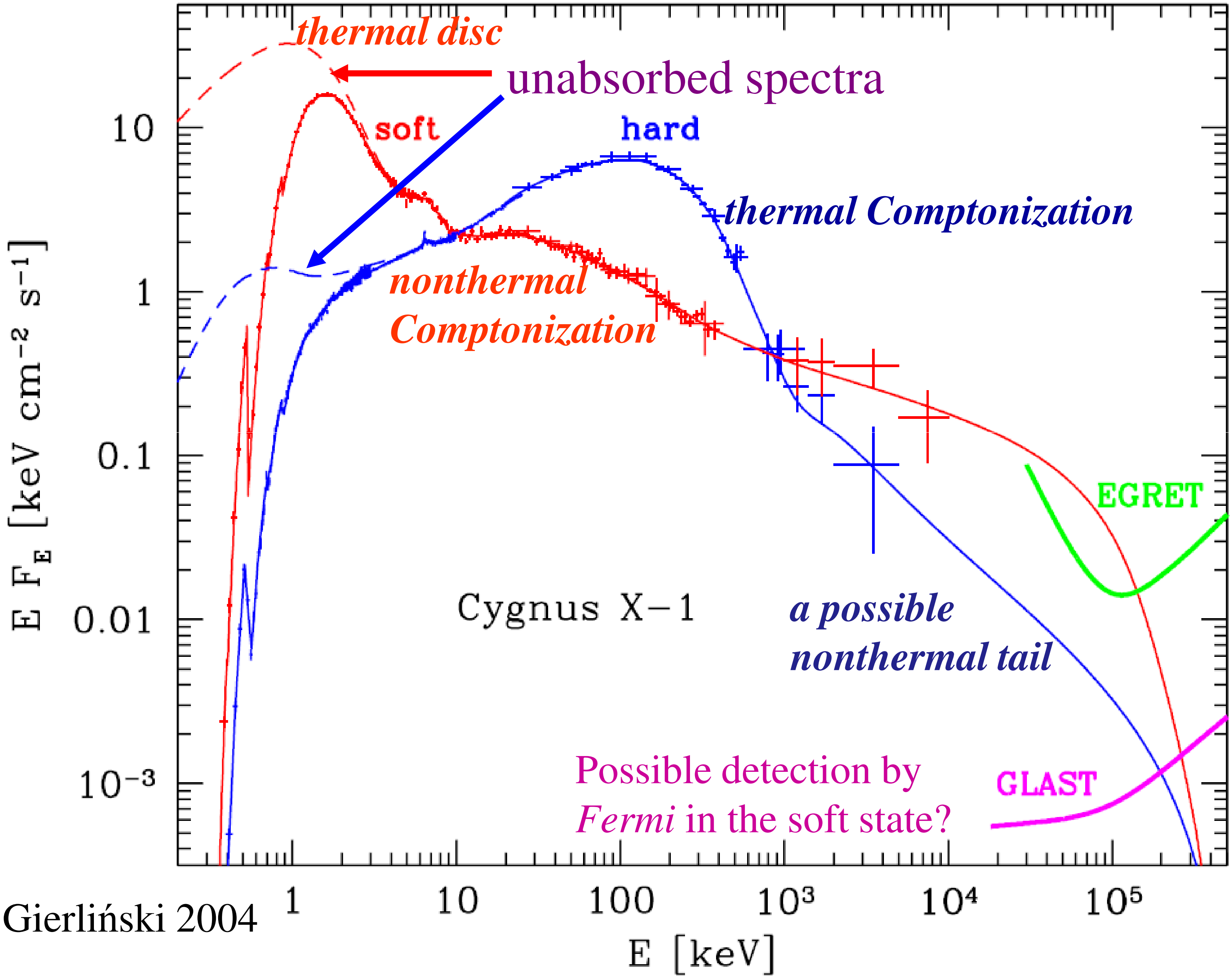
Outline

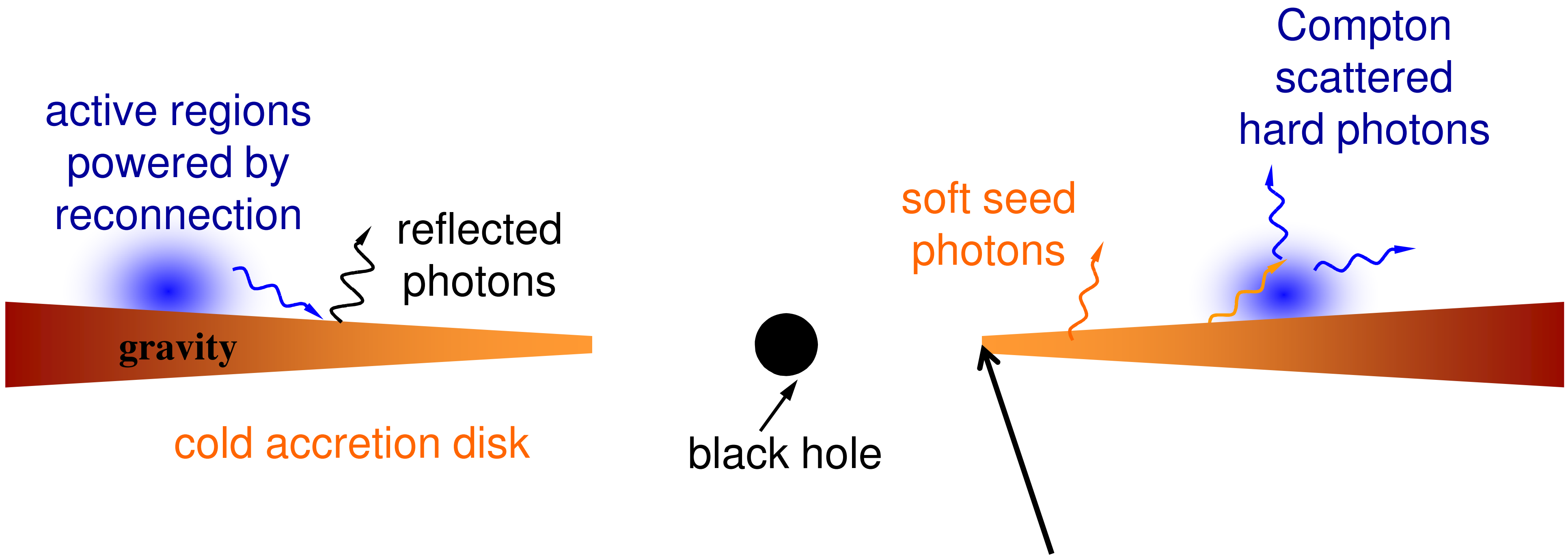
- Spectral states of black-hole binaries
- Radio emission and correlation with X-rays
- Parameters of the jet in Cyg X-1
- Contributions of nonthermal synchrotron emission to X-ray spectra

Two main spectral states of black-hole binaries



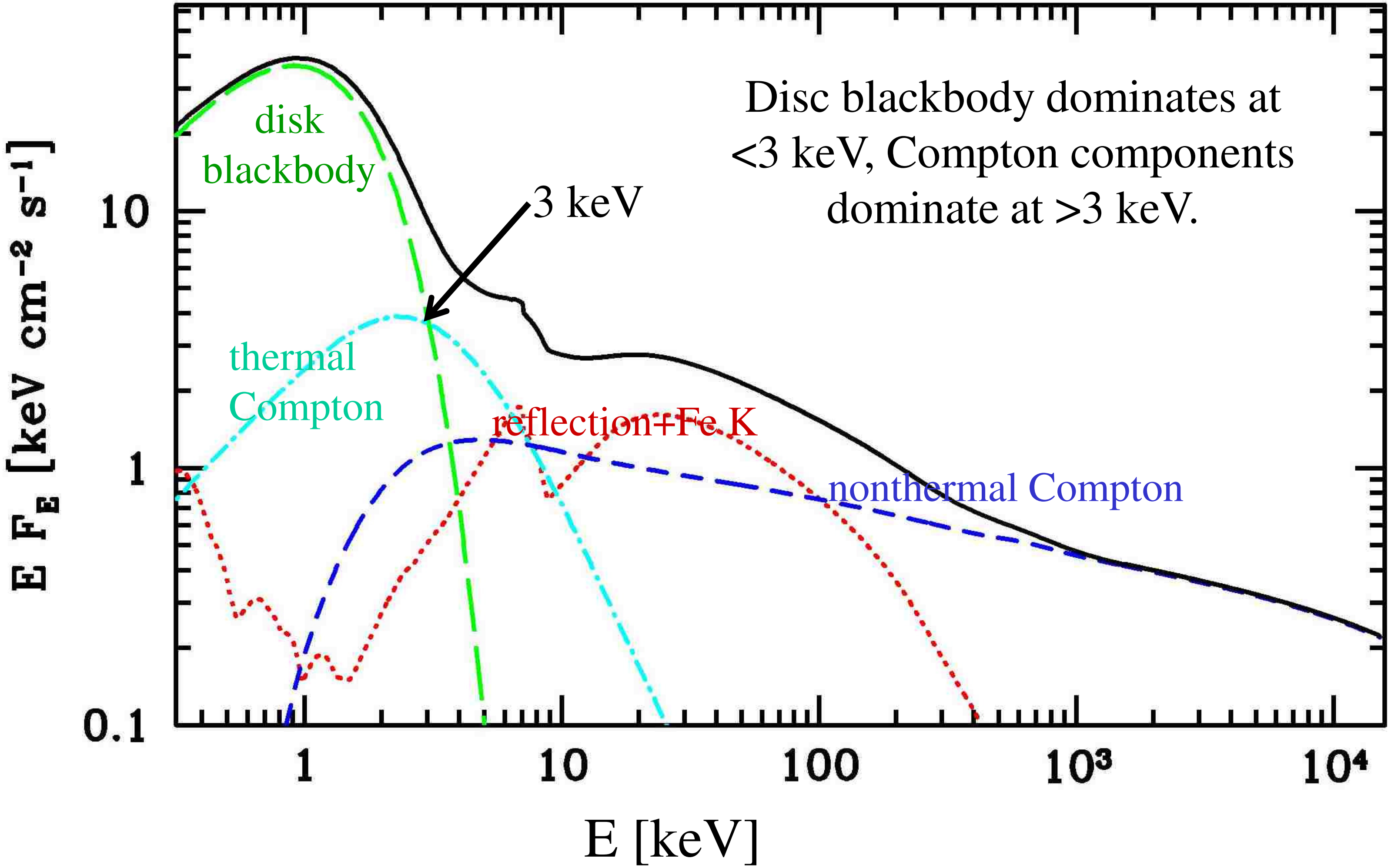
Z. & Gierliński 2004

A likely geometry of the soft state:



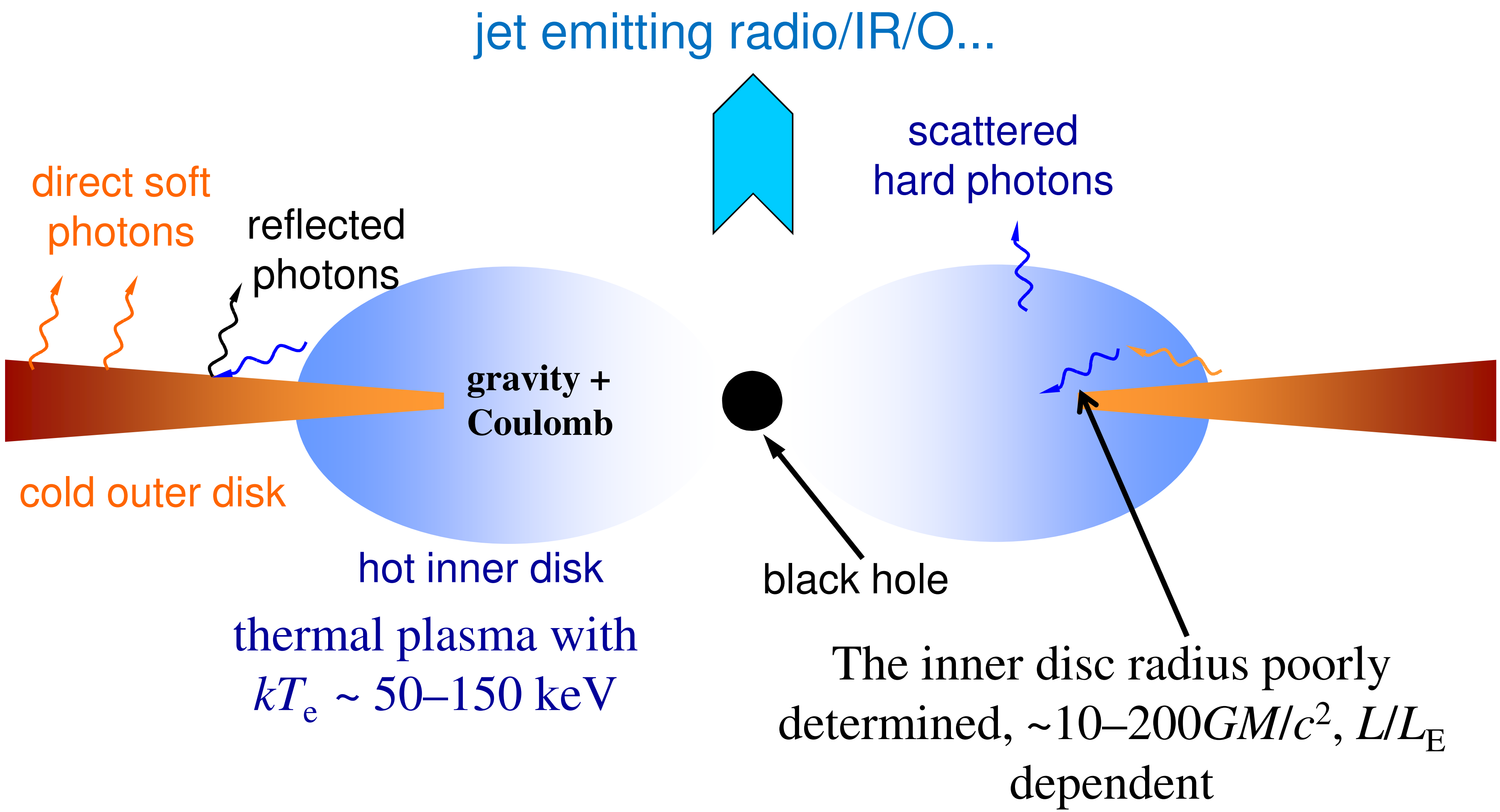
The inner disc radius probably at the innermost stable orbit, $6GM/c^2$ or less for a rotating black hole

Spectral decomposition in the soft state into blackbody and Compton components:



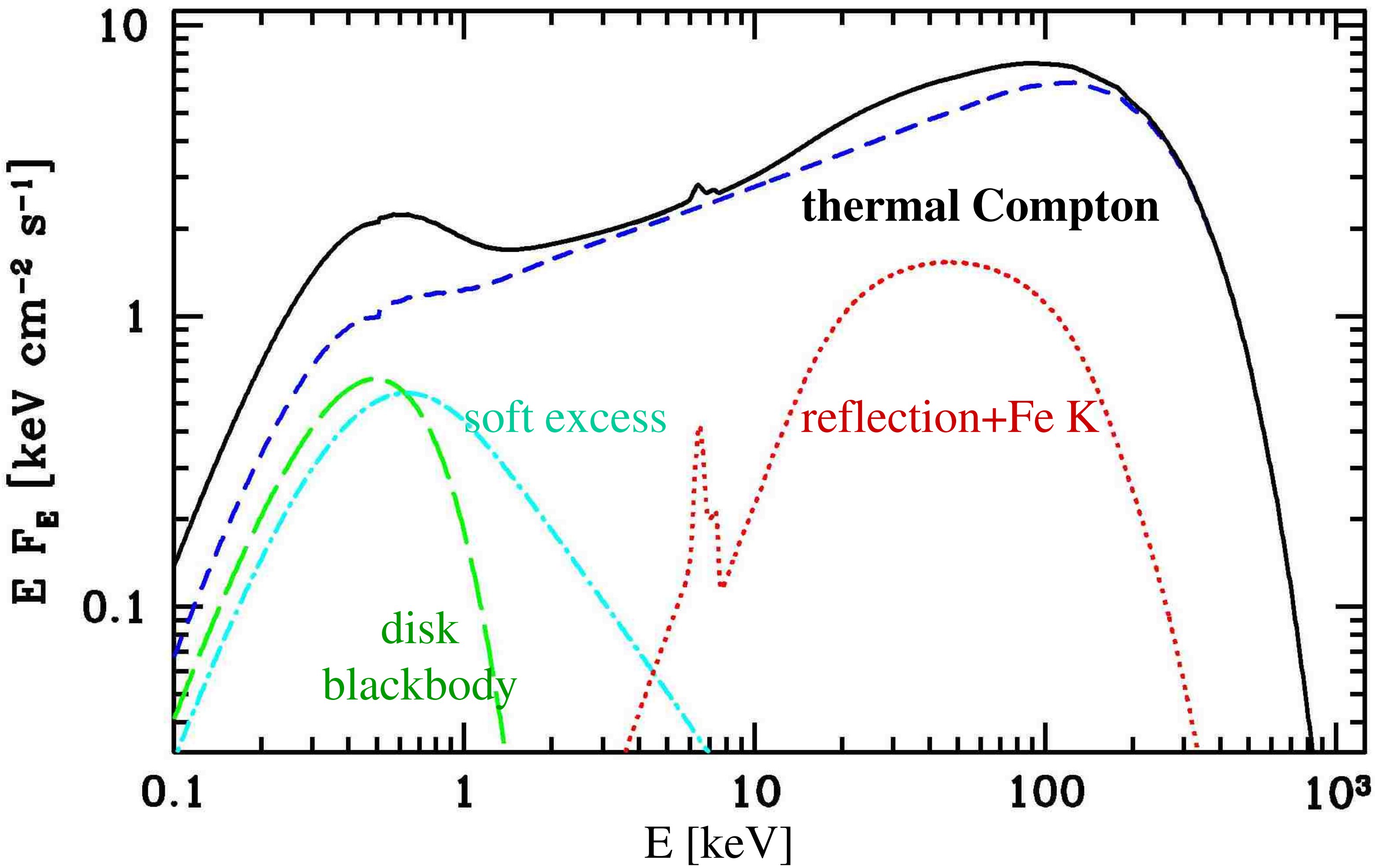
Z. & Gierliński (2004)

A likely geometry of the hard state:



Cyg X-1: typical hard state spectrum

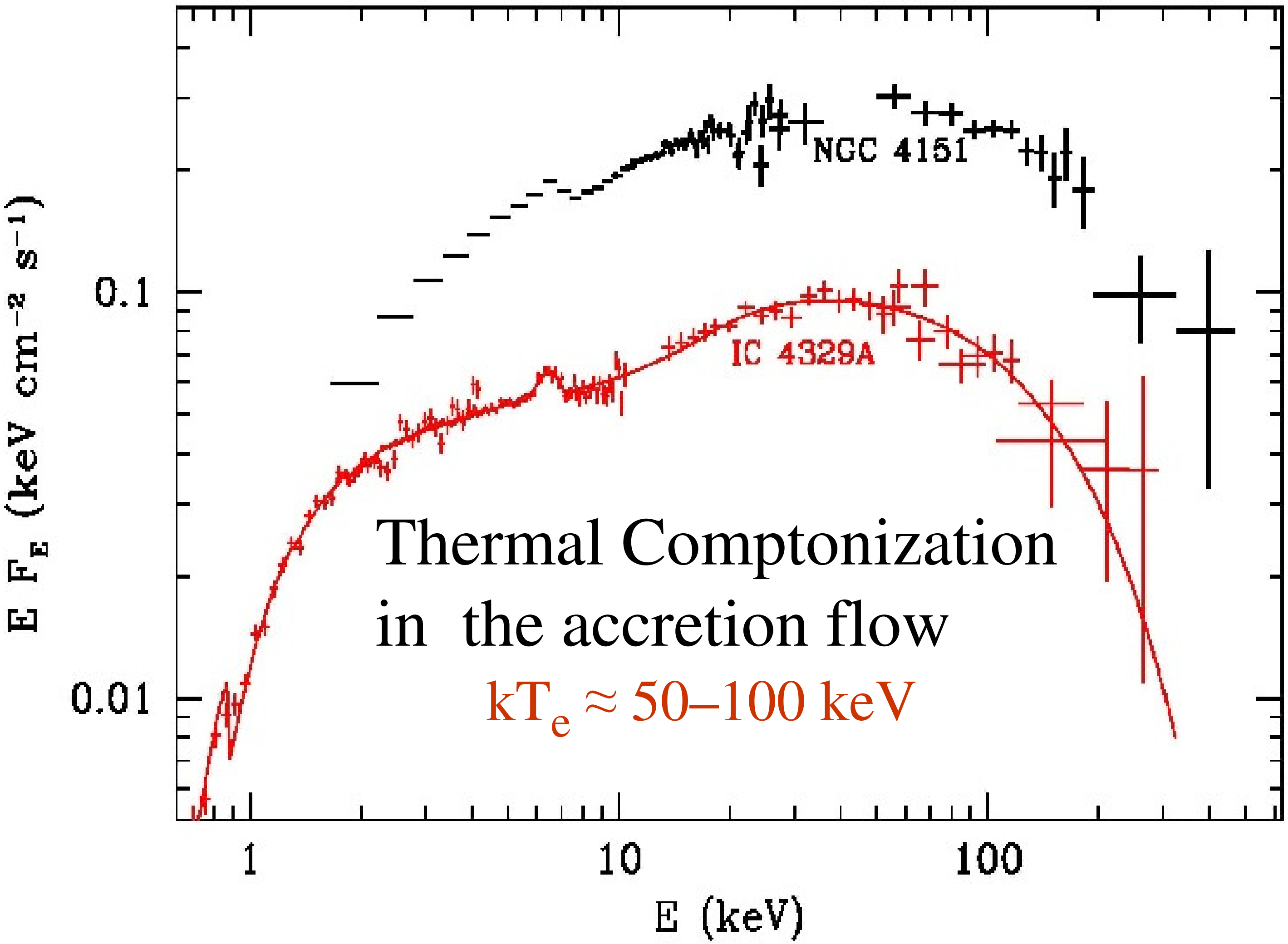
$\frac{L_{hot}}{L_{disk}} \gg 1$



$kT_e \approx 100$ keV, $\tau \approx 1$, L~1–2% of L_E

Z. & Gierliński (2004)

Seyferts: NGC 4151 and IC 4329A

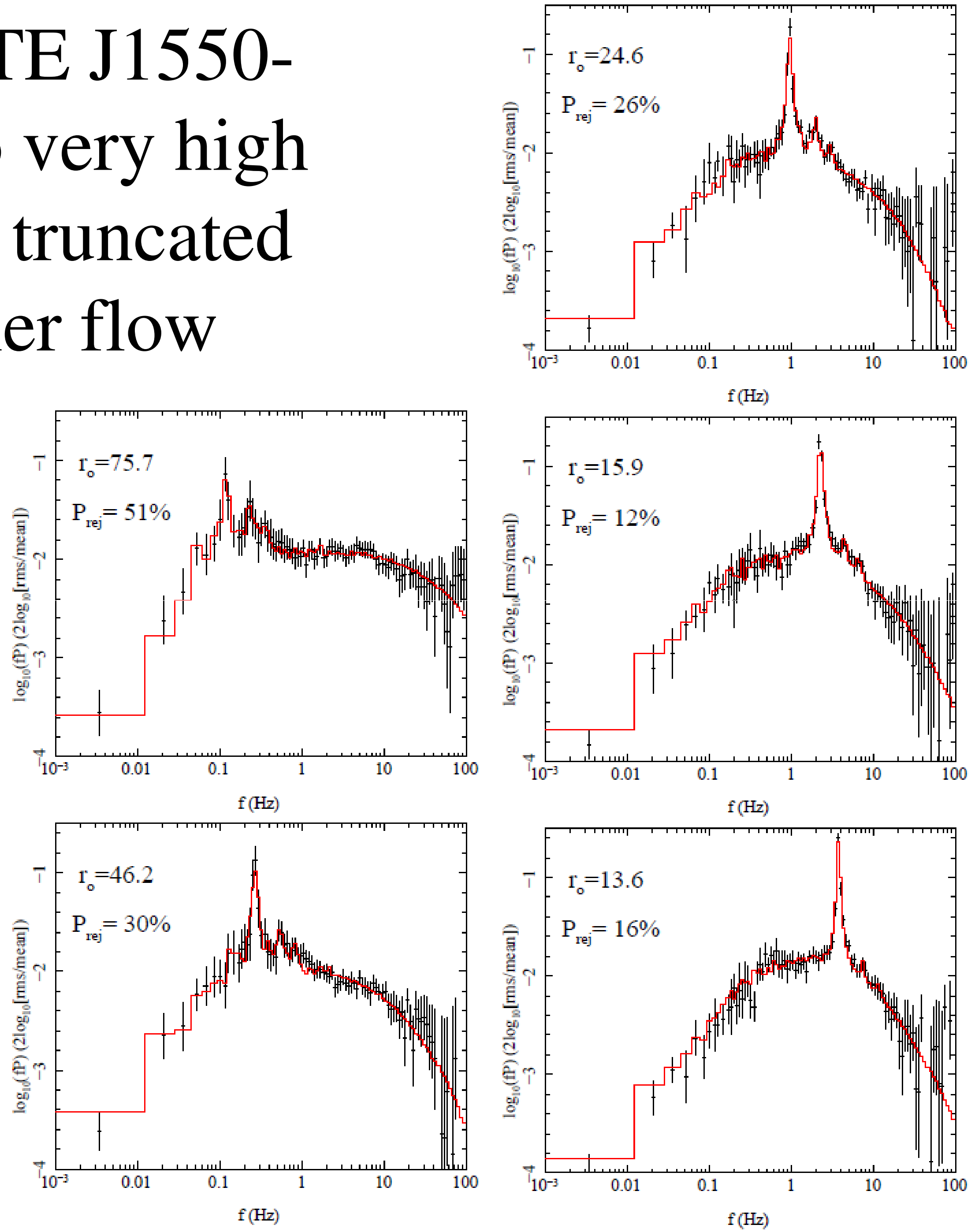


Spectra very similar to those of black-hole binaries in the hard state.

Power spectra of XTE J1550-564 from the hard to very high states modeled by a truncated outer disc/hot inner flow

Ingram & Done 2011

Propagating fluctuations; the disc edge gives the low-f break; QPOs from Lense-Thirring precession

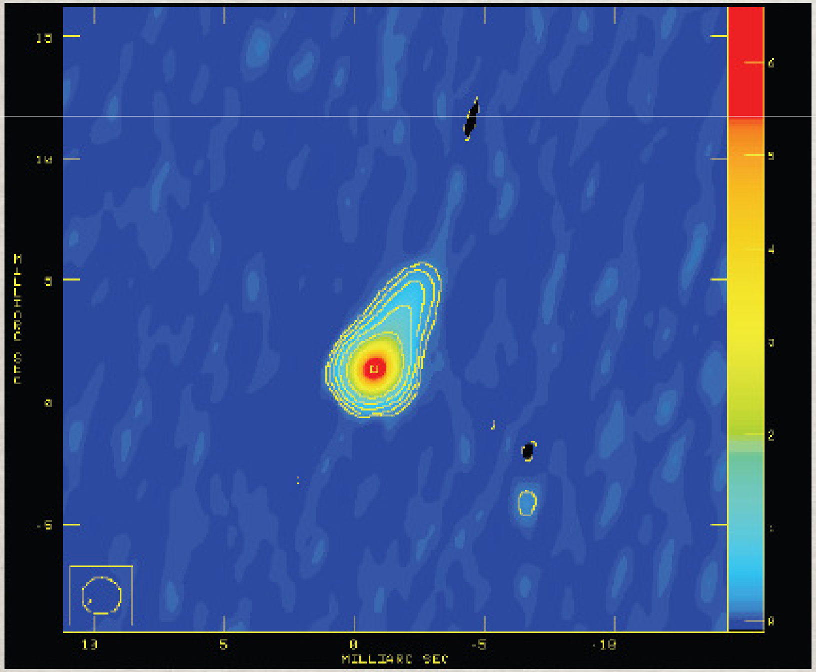


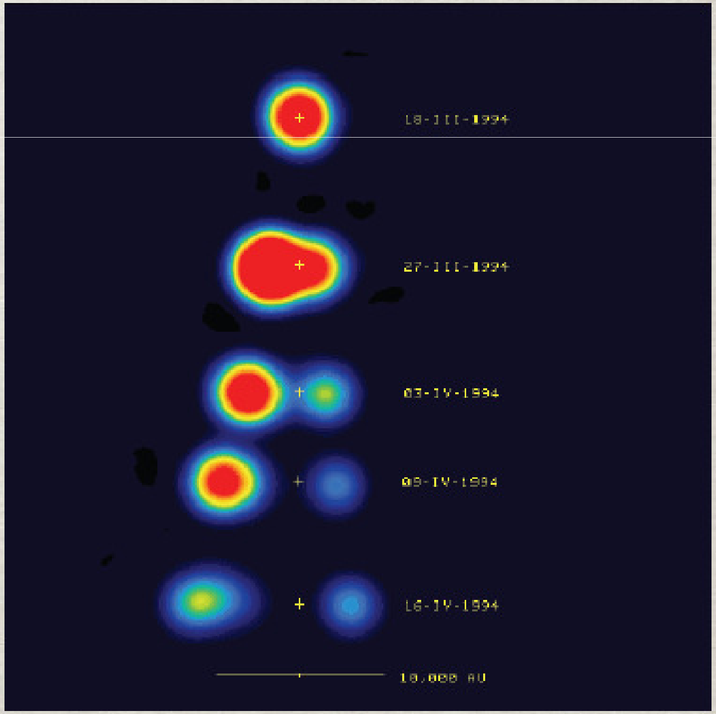
Relativistic jets in black-hole binaries

↙ at low *L*, hard state

↙ at highest *L*, very high state

- Compact, self-absorbed jets (on mas scale = 10s a.u.).
- Discrete ejections events (superluminal, ballistic).

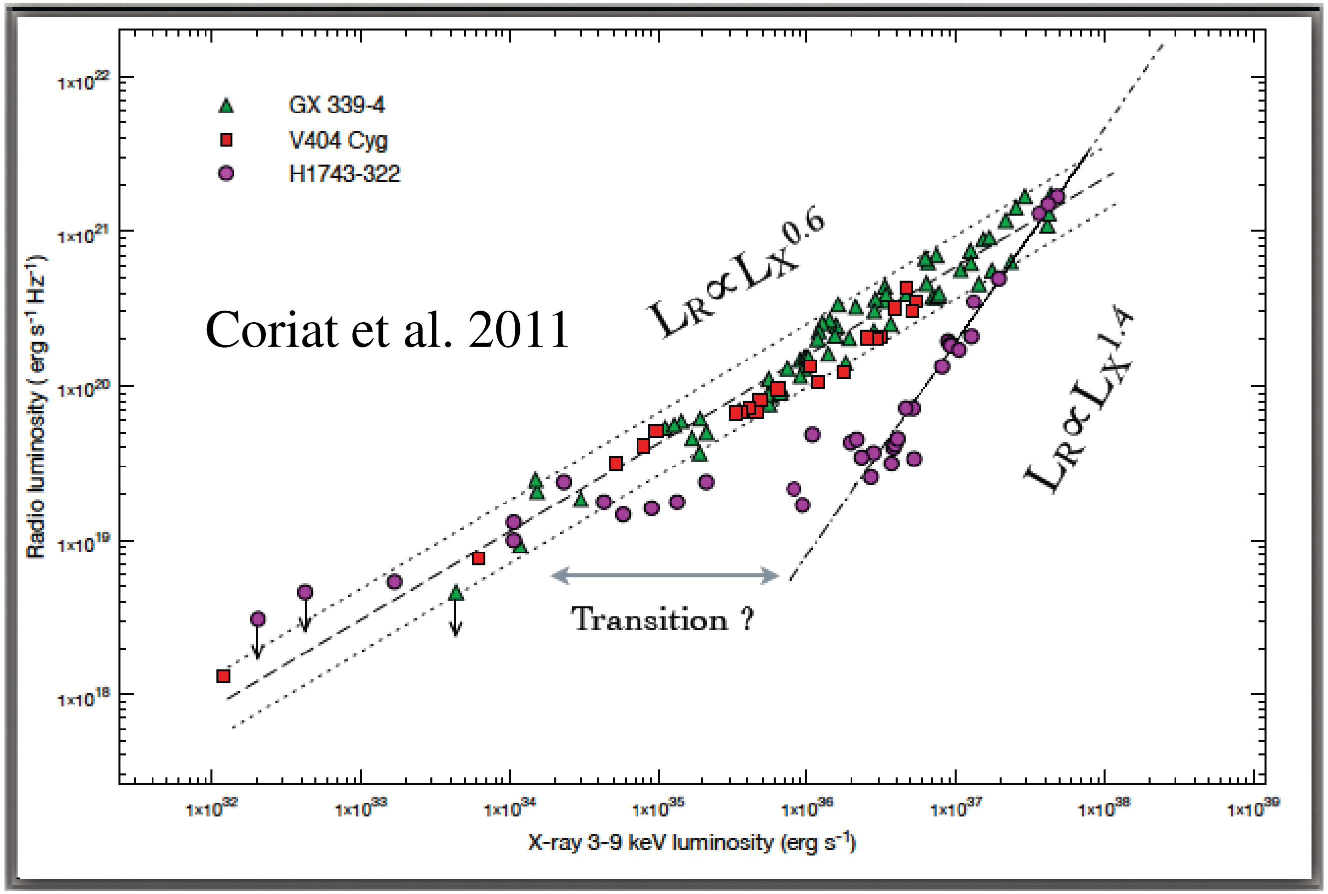




Cyg X-1 Stirling et al. 2001

GRS 1915+105 Mirabel et al. 94

Radio/X-ray correlation in black-hole X-ray binaries in the hard state



The two modes possibly correspond to inefficient, $L_X \propto \dot{M}^2$, and efficient, $L_X \propto \dot{M}$, hot flows, in the class of models in which the accretion rate controls both the disc and jet powers.

Interpretation of the correlation indices:

Radio = Compact Jets

- Conical jet, power-law distribution of electrons, energy losses replenished, etc. (Blandford & Königl 79, Falcke & Bierman 95):

$$L_{\rm radio} \propto Q_{\rm jet}^{1.4}$$

- Power injected is a fraction of the accretion power:

$$Q_{\rm jet} = f_j \; \dot{M} \; c^2$$

- f_j independent of $\dot{M}$ $\Rightarrow$ $\boxed{L_{\rm radio} \propto \dot{M}^{1.4}}$

X-ray component

- Radiatively efficient (e.g. thin disc, ADC...) :

$$L_{\rm X} \propto \dot{M}$$

- Radiatively inefficient (e.g. ADAF, X-ray jet model) : $L_{\rm X} \propto \dot{M}^{2-3}$

$\rightarrow$ $\boxed{L_{\rm X} \propto \dot{M}^{\beta}}$

$$L_{\rm radio} \propto L_{\rm X}^{1.4/\beta}$$

Standard correlation

$L_{\rm radio} \propto L_{\rm X}^{0.6}$ $\rightarrow$ $\beta = 2 - 3$

Radiatively inefficient component

Outliers

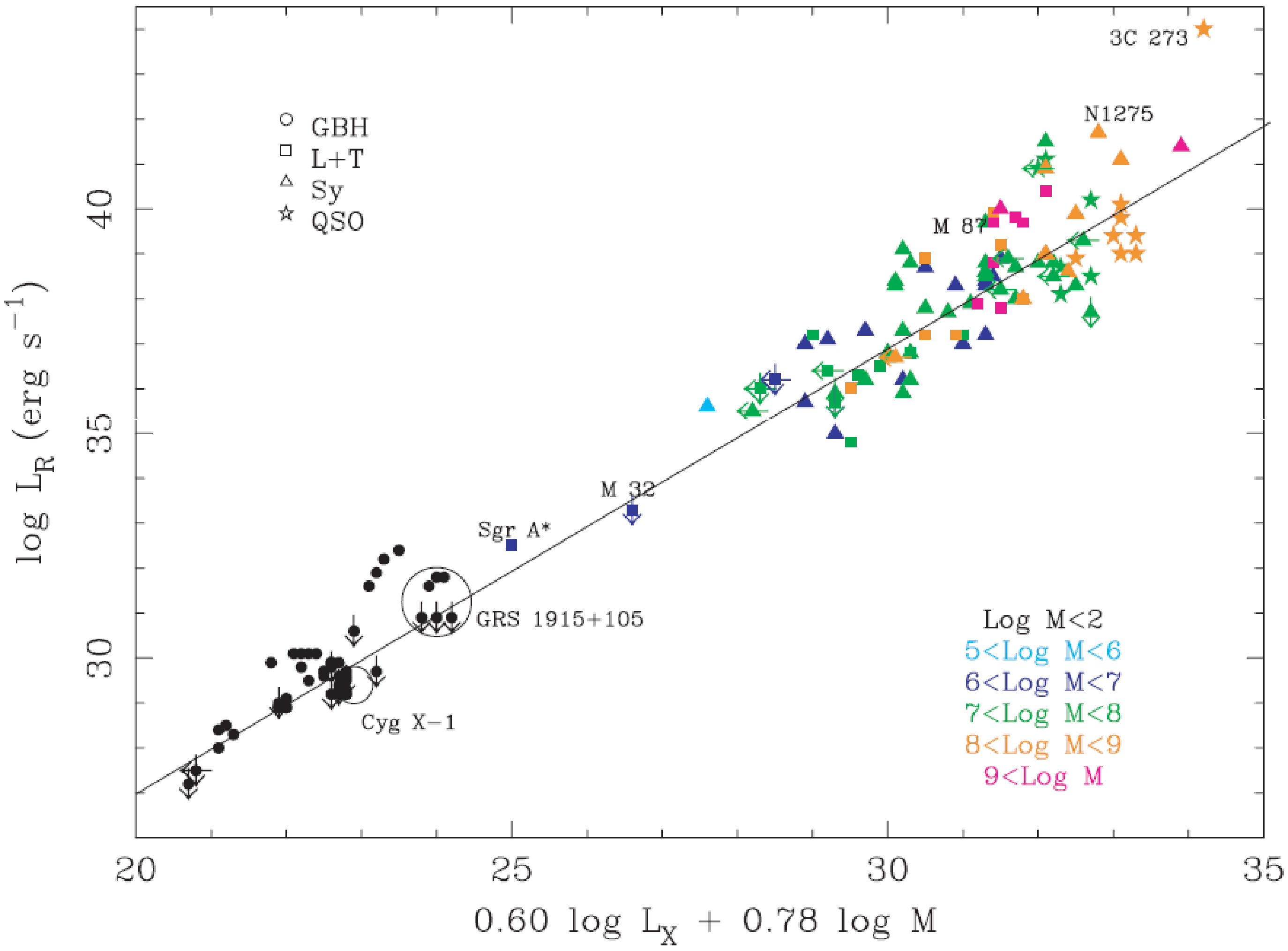
$L_{\rm radio} \propto L_{\rm X}^{1.4}$ $\rightarrow$ $\beta = 1$

Radiatively efficient component

Coriat et al. 2011

The fundamental plane: the radio/X-ray correlation is mass-dependent and extends up to AGNs

The radio to X-ray ratio (∝ to the radio loudness) increases with *M*. More massive systems are more radio loud.



Merloni et al. 2003

$$\log L_R = \left(0.60^{+0.11}_{-0.11}\right)\log L_X + \left(0.78^{+0.11}_{-0.09}\right)\log M + 7.33^{+4.05}_{-4.07}$$

A physical interpretation of the fundamental plane

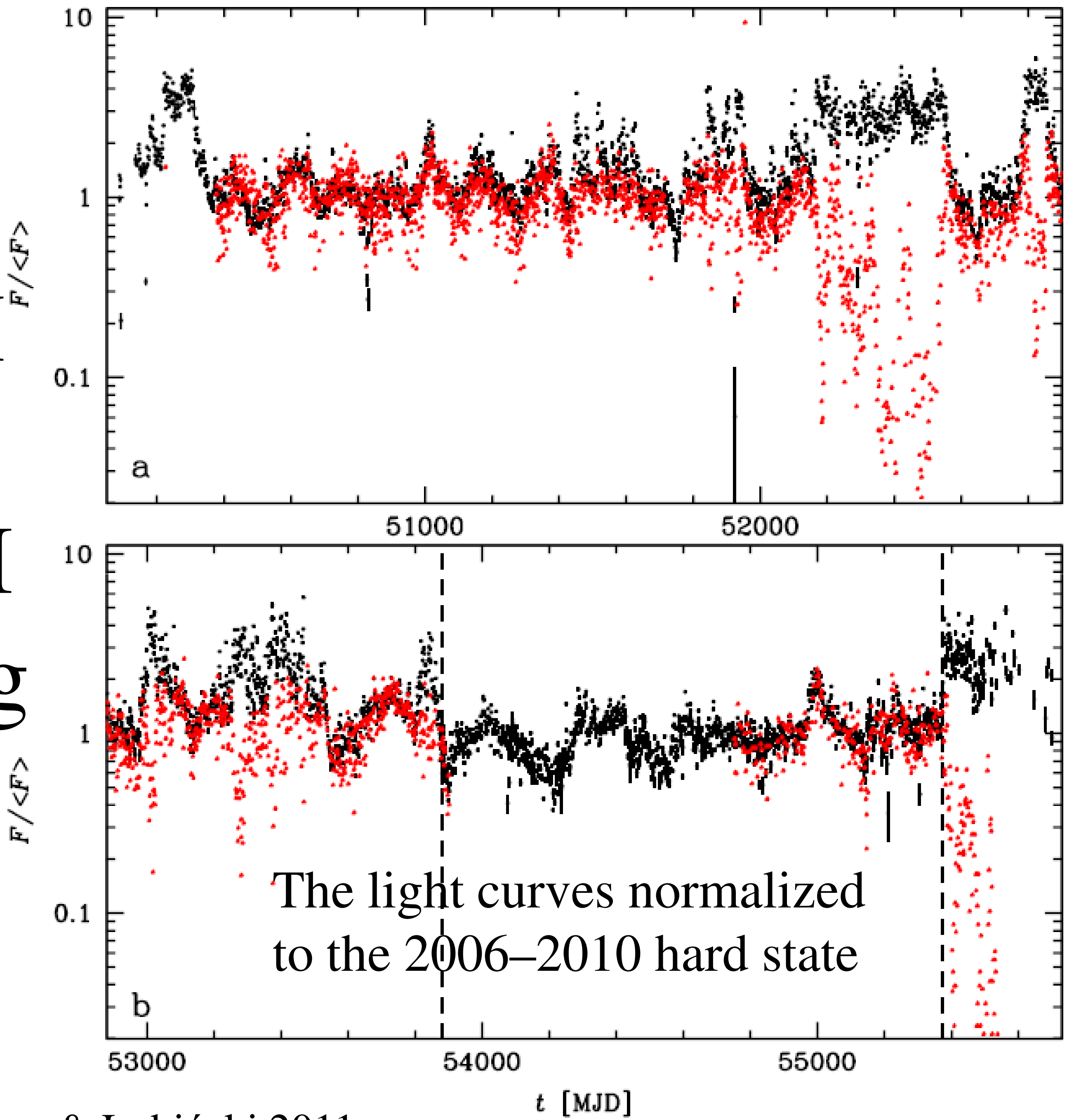
- Both the jet power and the accretion flow luminosity are correlated with the accretion rate. The radio luminosity is due to synchrotron emission from the jet viewed side-ways (i.e, without strong beaming).
- The jets have all properties scale invariant except for the equipartition magnetic field, $B \propto M^{-1/2}$ (Heinz & Sunyaev 2003).
- This generally causes the jet-integrated synchrotron luminosity to peak (in νL_ν, with the peak corresponding to synchrotron self-absorption turnover) at $\nu \propto B \propto M^{-1/2}$.
- Thus, for hard radio spectra, the radio luminosity at a given frequency (below the νL_ν) and a given L/M increases with the mass, explaining the fundamental plane.
- E.g, for flat radio spectra ($\alpha \approx 0$), $L_R/M \propto M^{5/12}$.

Two new aspects: dependence on the spectral state and on the X-ray energy

- How does the correlation at various energies depend on the spectral state? So far, only hard state studied.
- Usually, studies of the correlation considered a narrow X-ray band, e.g., 3–9 keV, and mostly the hard state.
- But how does the correlation depend on the X-ray energy?
- What is the radio flux dependence on the bolometric luminosity or on the luminosity emitted by the relativistic electrons of an accretion flow?

- The chosen object: Cyg X-1, multi-year monitoring by the *RXTE*/ASM, *Swift*/BAT, Ryle/AMI and GBI.
- A complication: high-mass binary, free-free absorption of radio photons by the stellar wind.

The ASM and Ryle/AMI monitoring

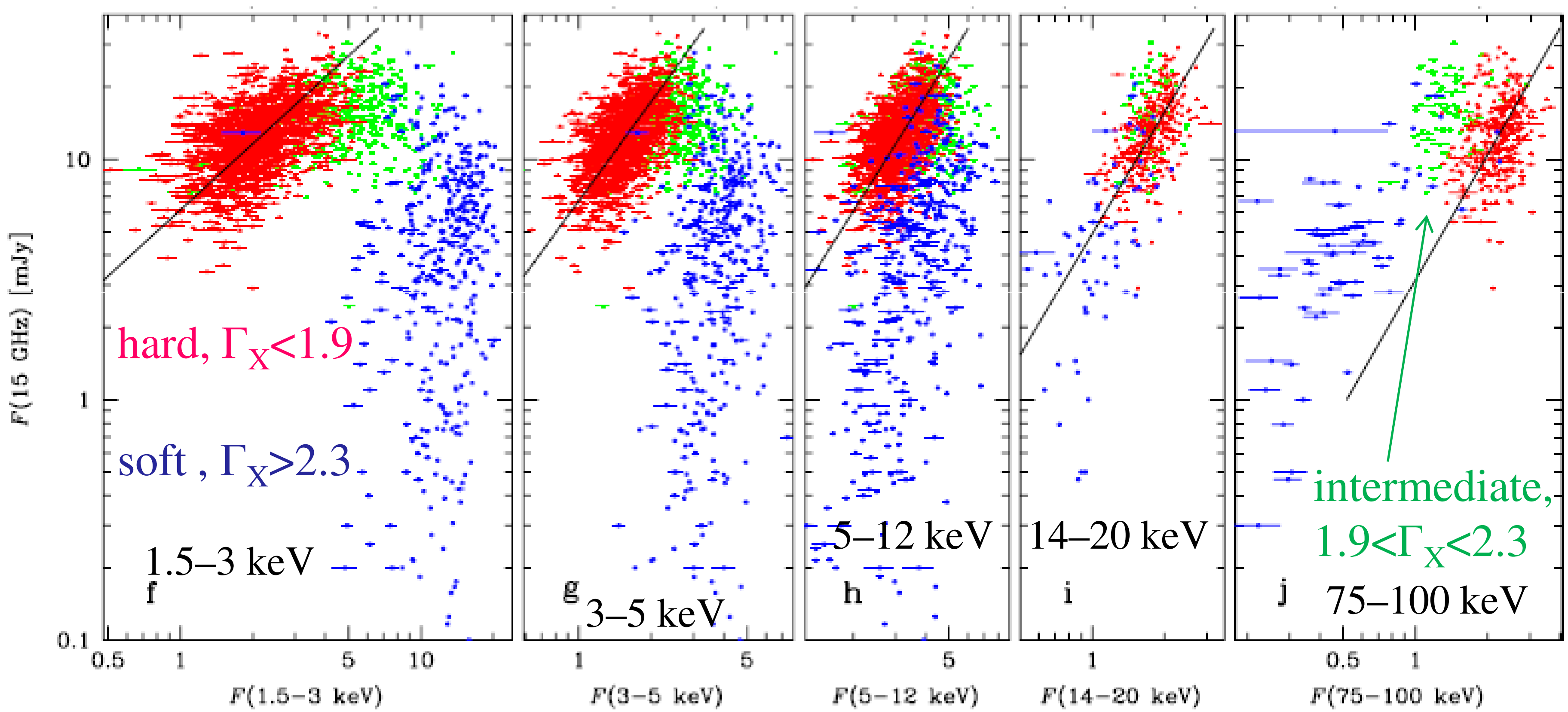


1.5–12 keV

15 GHz

Zdziarski, Pooley, Skinner & Lubiński 2011

The radio/X-ray correlation across X-rays



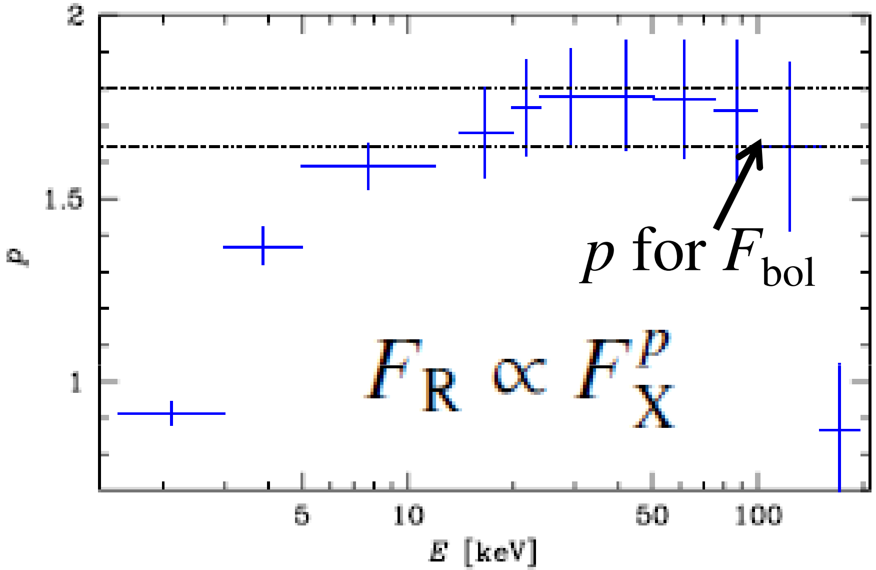
Γ defined by $N(E) \propto E^{-\Gamma}$, thus $EF(E) \propto E^{2-\Gamma}$

Z. et al. 2011

We see that:

- In the soft and intermediate states, the radio flux is proportional to the X-ray flux in the high-energy tail.
- A single correlation in all states in the 14–20 keV band, which is suggestive of the importance of the Comptonization flux but not of the blackbody flux.
- The correlation index depends on E.

Radio flux dependence on the X-ray band



Z. et al. 2011

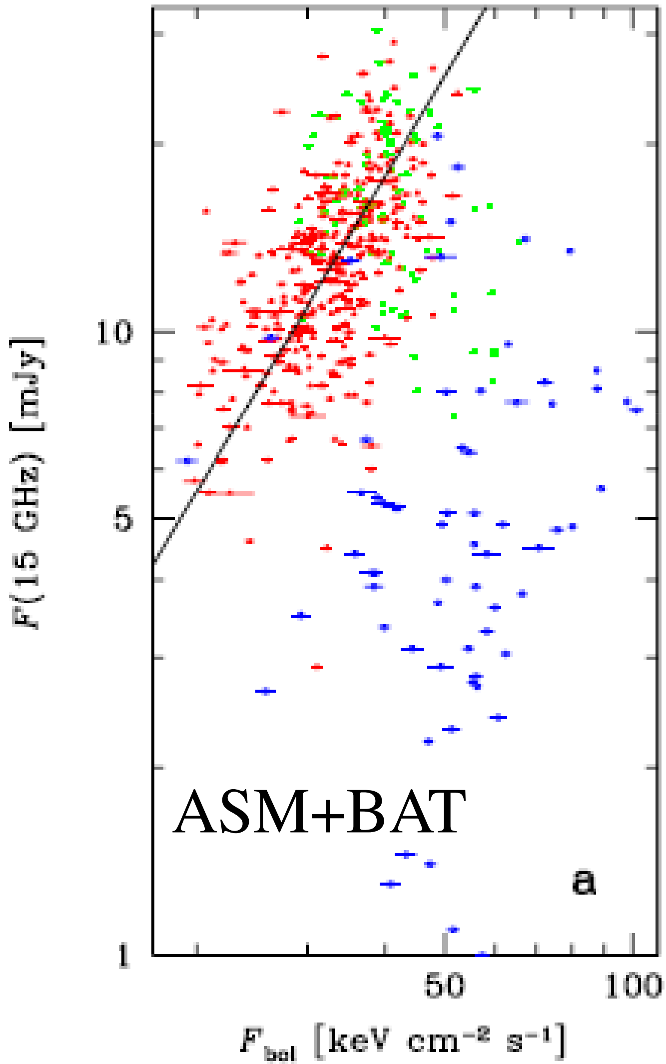
This dependence suggests using the bolometric flux as a measure of the radio/X-ray correlation.

The dependence on the bolometric flux:

$p = 1.7 \pm 0.1$ in the hard state

The hard and intermediate states form a single region, but the soft state forms a parallel correlation. The mismatch occurs because the jet emission is apparently *not* related to the disc blackbody emission.

Z. et al. 2011

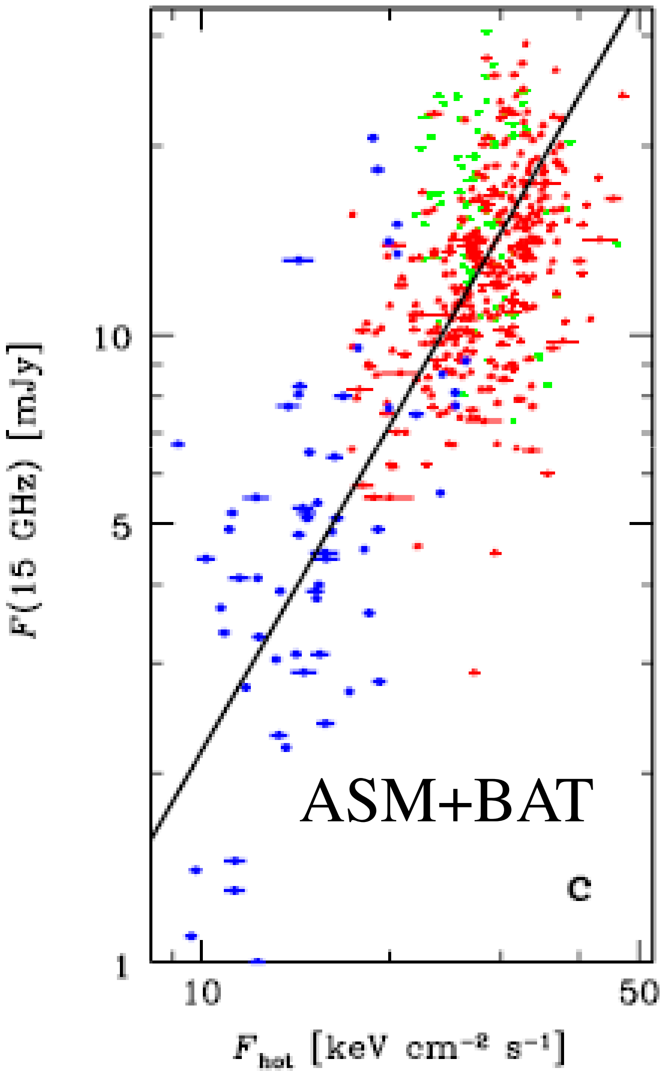


The dependence on the flux from Comptonization only:

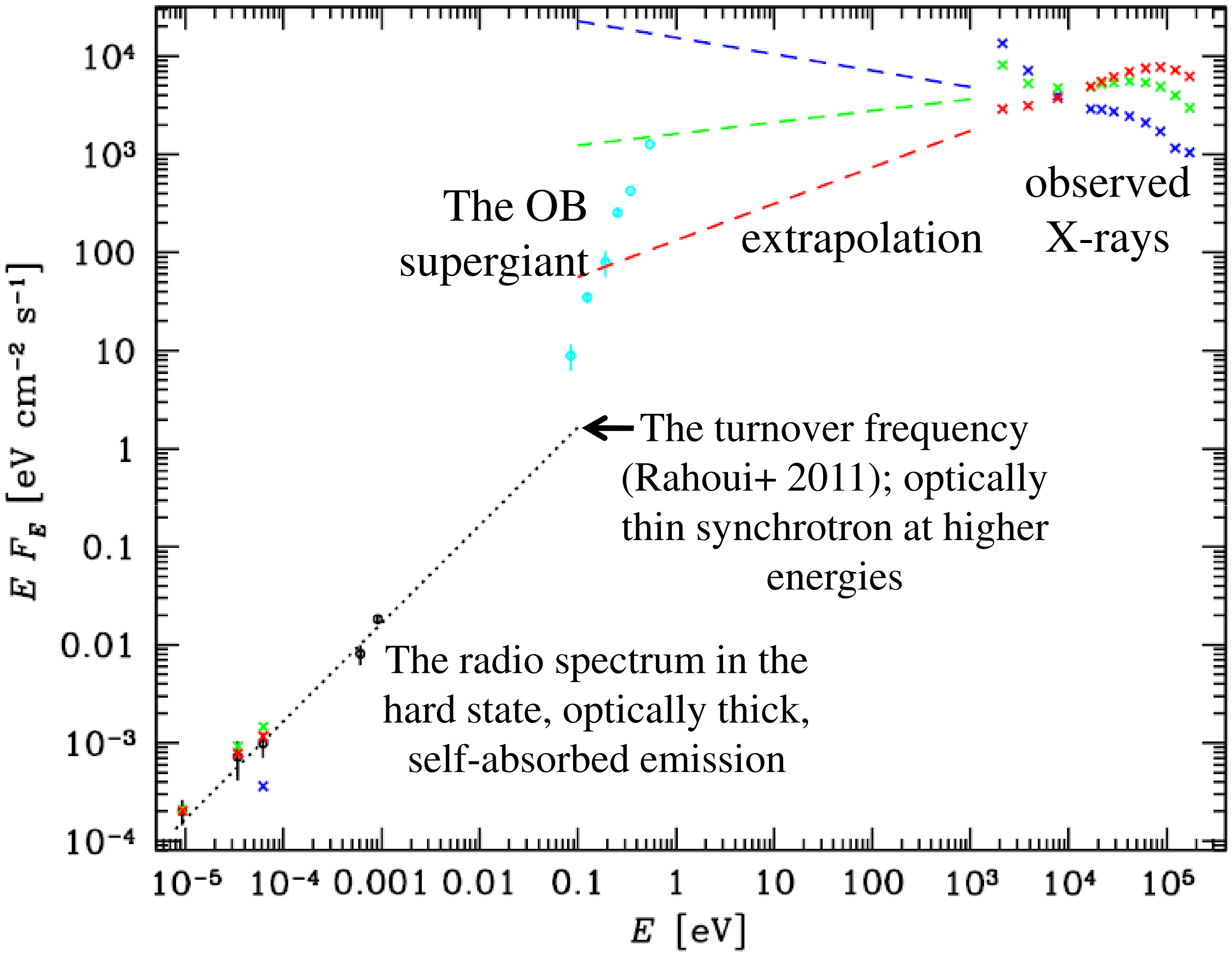
(approximated as the flux >1.5 keV in the hard and intermediate states, and >3 keV in the soft state)

This flux excludes the disc blackbody component.

Now we see $p = 1.7 \pm 0.1$ in all states. In the framework of accretion models, this value is suggestive of a radiatively efficient accretion flow (weak advection). The intermediate and soft states are radiatively efficient.



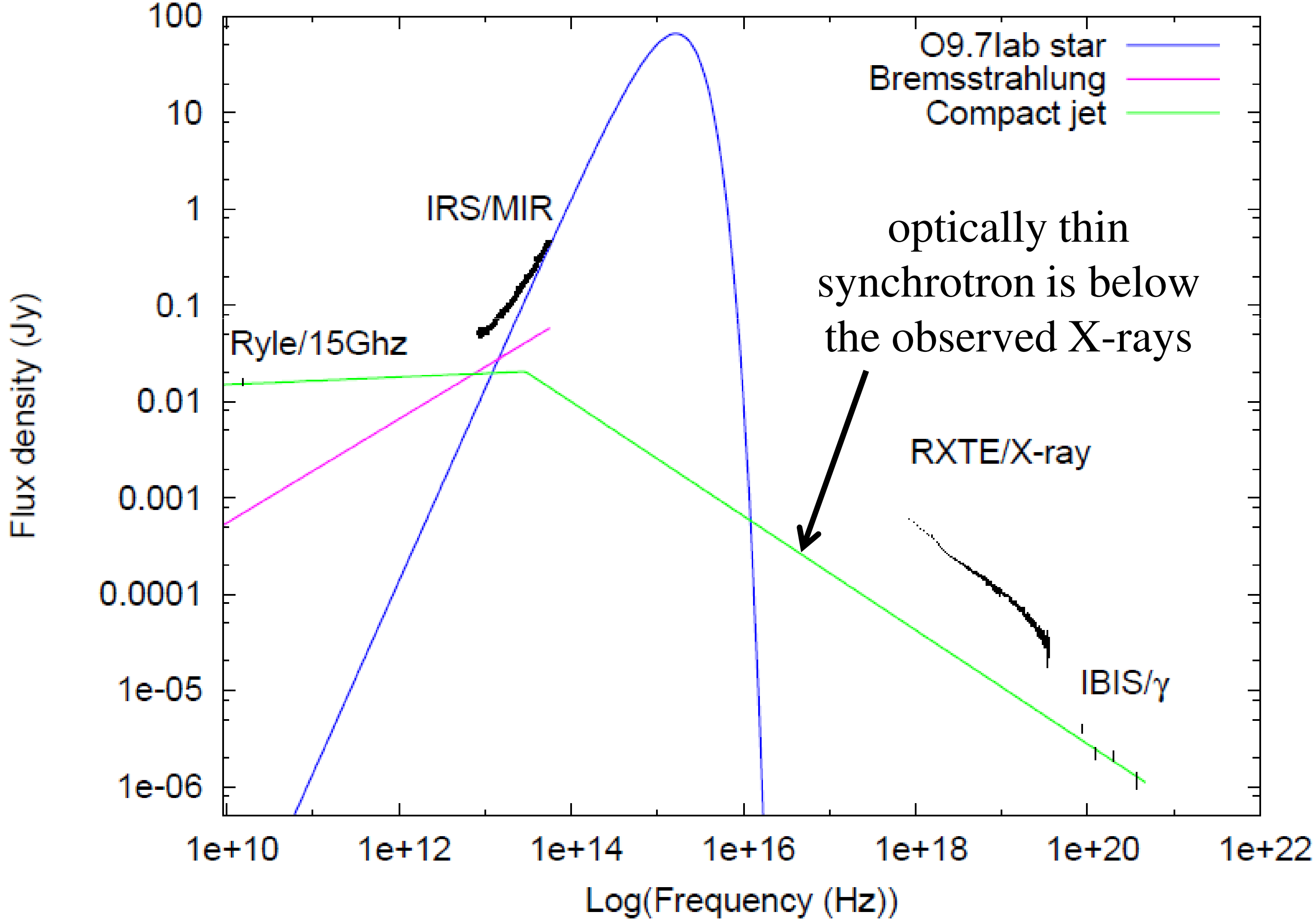
Can the X-rays be from optically-thin jet emission?



No. The X-ray spectra when extrapolated to lower energies do not match the extension of the radio spectra up to the turnover frequency.

Z. et al. 2011

Rahoui et al. 2011 (who determined the synchrotron turnover frequency in Cyg X-1) have reached the same conclusion:

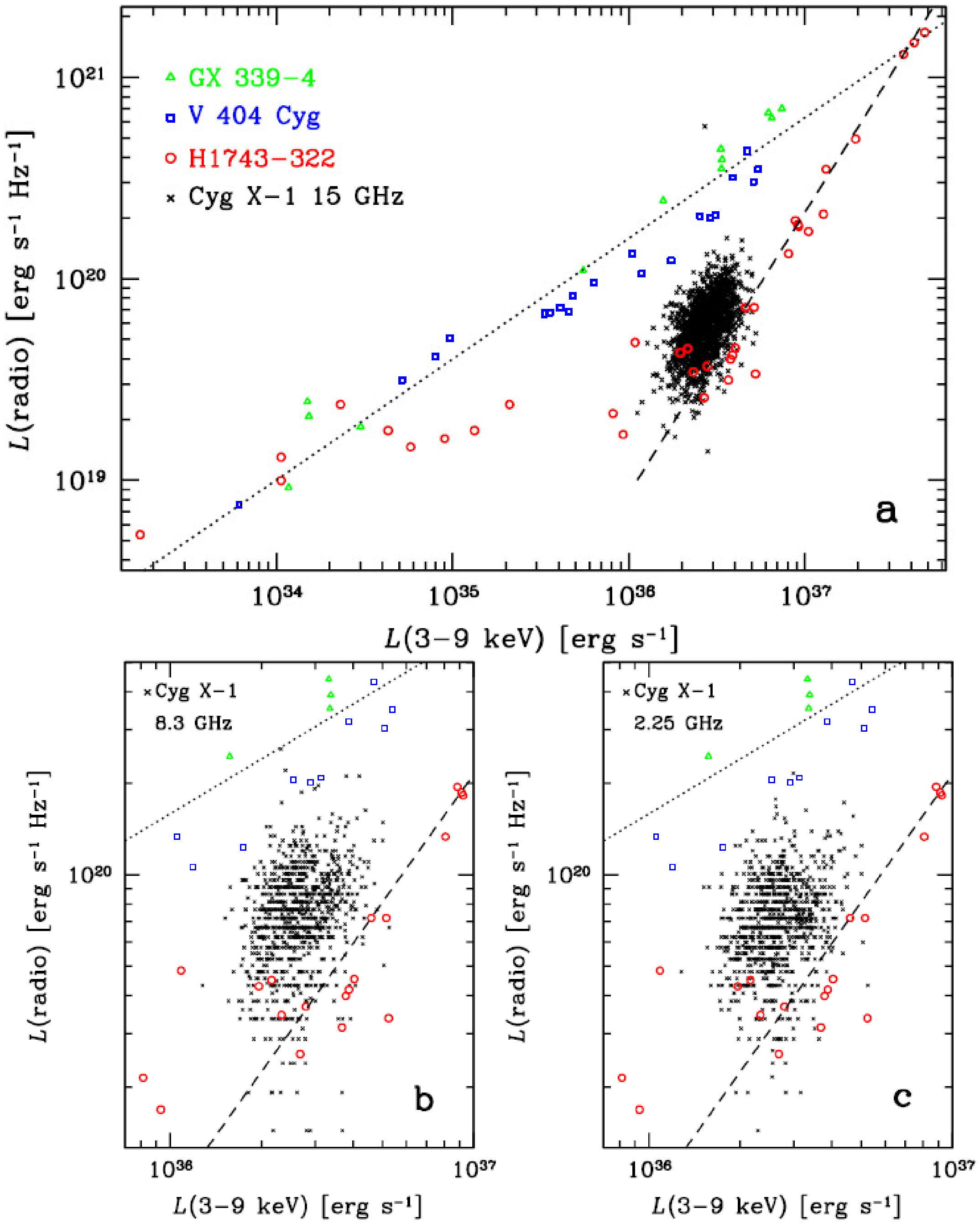


Comparison with other sources

Z. et al. 2011

Cyg X-1 resembles the 'outlier' H1742–322, with $p \approx 1.4$, but not the typical sources.

The radio fluxes from Cyg X-1 are affected by free-free absorption in the wind. However, its effect is unlikely to be very strong given the similarity between the radio/X-ray relationships from 2.25 GHz to 15 GHz and the fact that absorption changes with frequency.

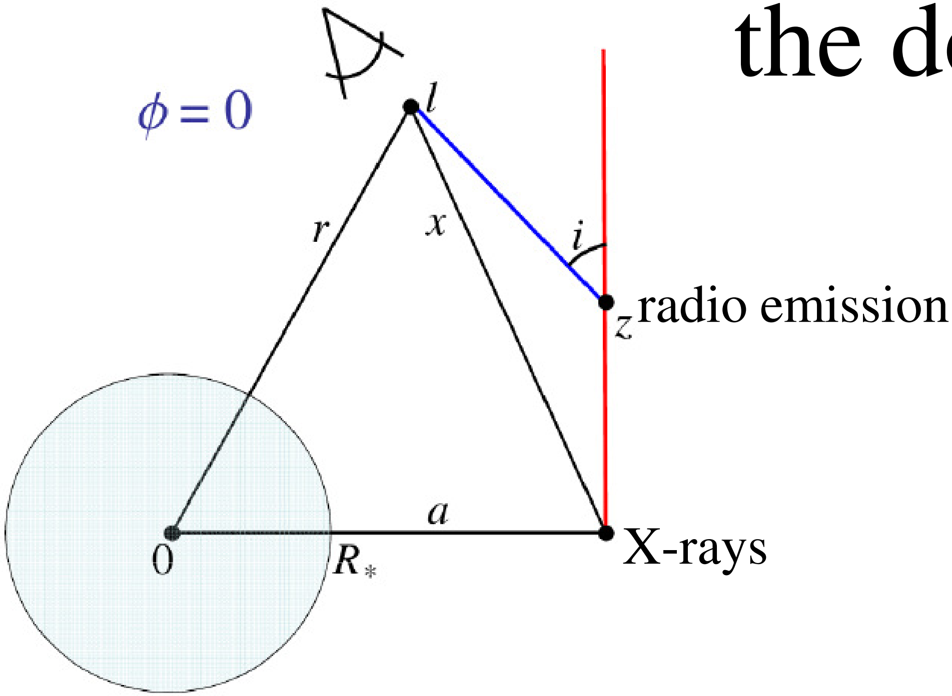


The jet in Cyg X-1

- Cyg X-1 2–15 GHz emission is modulated at the orbital period of 5.6 d.
- The characteristic height at which a given radio frequency is emitted can be determined knowing the wind structure and fitting the theoretical attenuation to the observed modulation.
- The height, corresponding to the jet becoming optically thin to synchrotron self-absorption, is expected to increase with the increasing flux, thus the modulation depth is expected to decrease.

Z. 2011

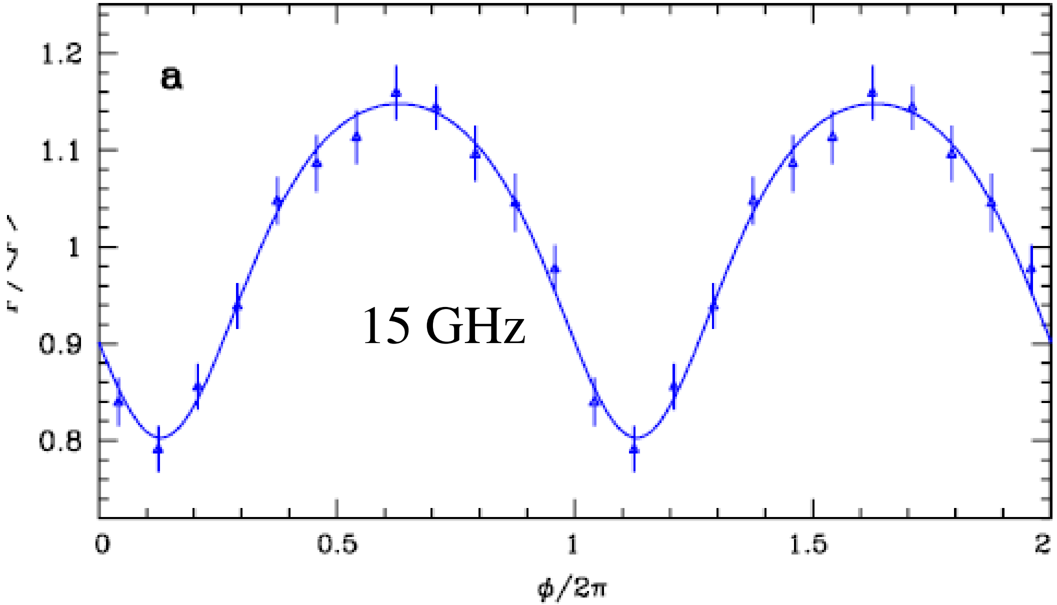
Free-free absorption in the wind of the donor



Knowing the wind parameters and the observed depth of the orbital modulation at a given frequency, we can determine the location along the jet where most of the emission occurs (without having to spatially resolve the radio emission of the jet).

We take into account Compton heating/cooling by both the star and the X-ray source, photoionization, bremsstrahlung, line cooling and advection.

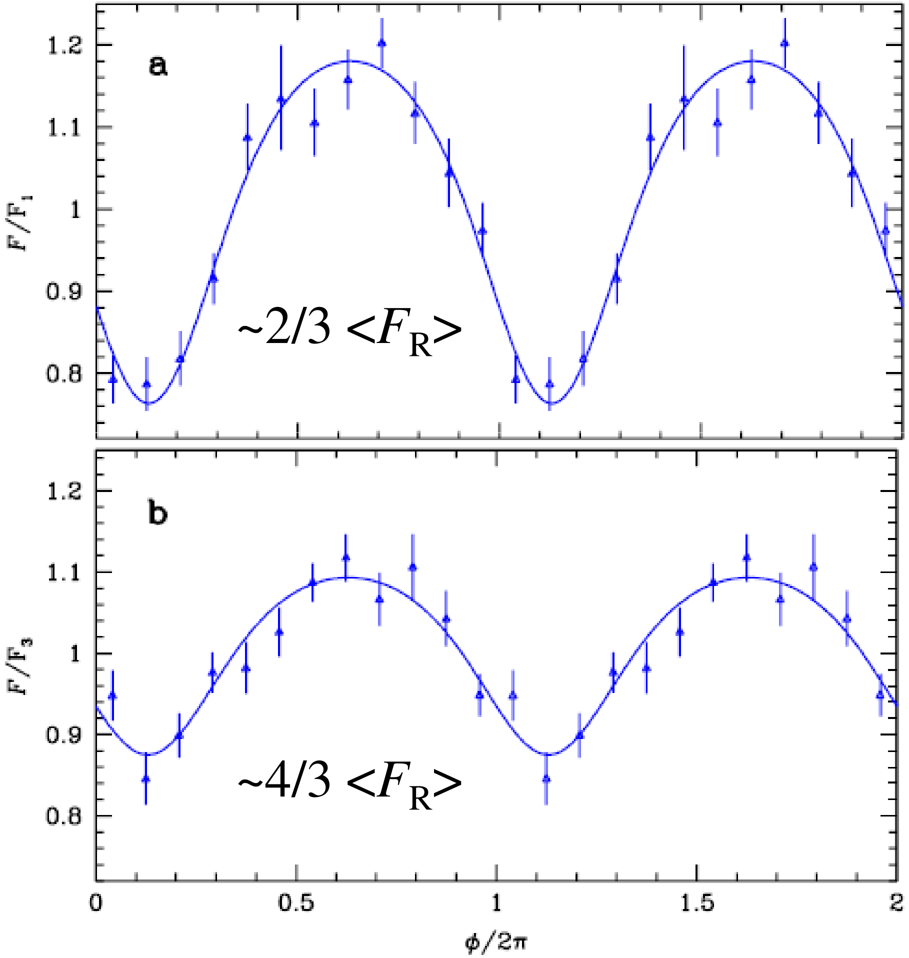
Free-free absorption in the wind of the donor



The observed orbital modulation (with the full fractional depth of ≈ 0.3) fitted by our model. The fit yields $z/a \sim 0.6$ (where a is the orbital separation), i.e., $z \sim 2\times10^{12}$ cm $\sim 10^6\, r_g$. The standard jet model (Blandford & Königl 1979) predicts $z \propto \nu^{-1}$. Given that $\nu_t \approx 3\times10^{13}$ Hz, the jet base is at $\sim 500\, r_g$.

Z. 2011

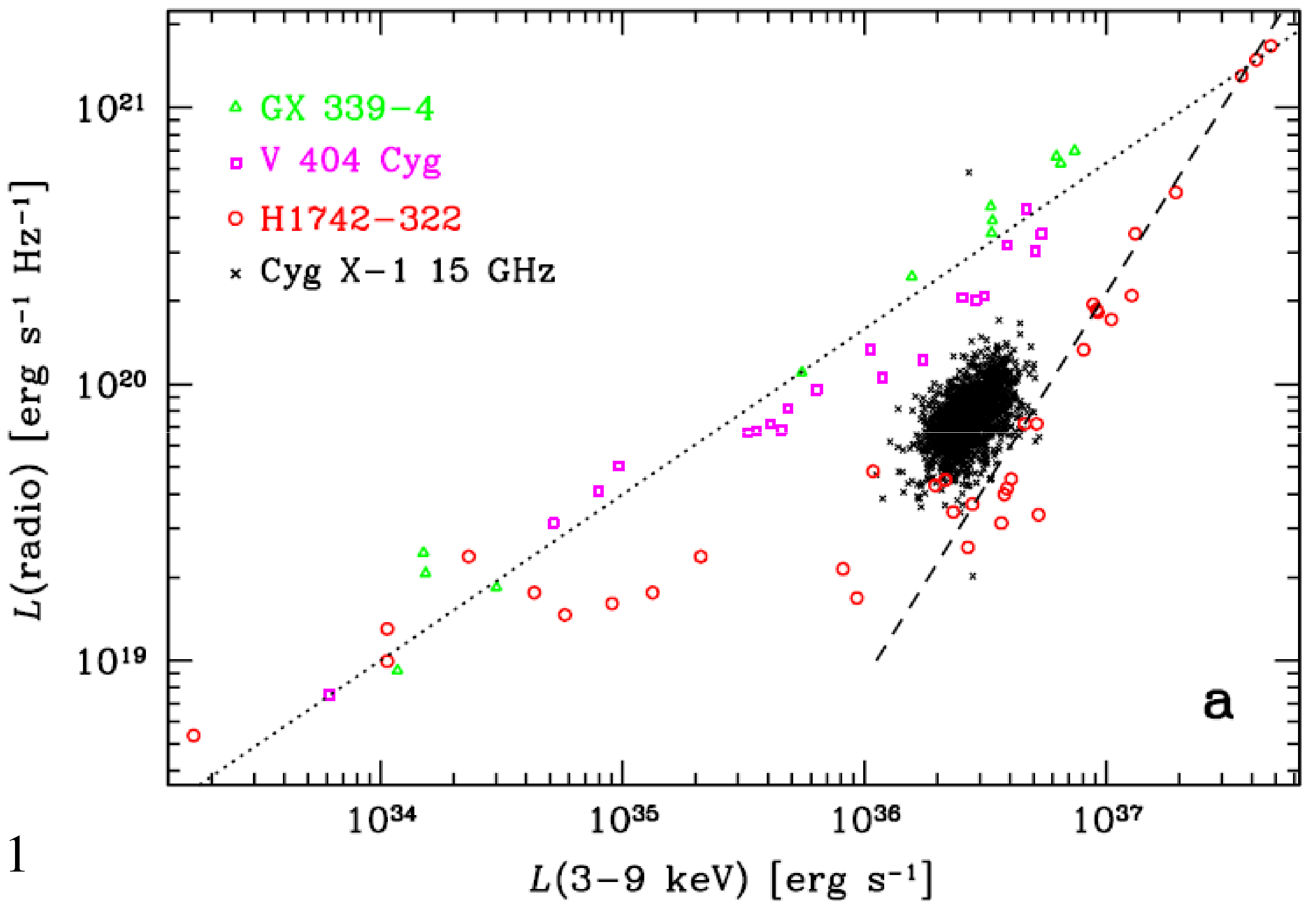
Dependence of the free-free absorption on the radio flux



We see the modulation at high F_R is about a half of that at low F_R. Thus, a high flux is emitted at a higher z, thus less affected by free-free absorption. We find $z \propto F_R^{0.6}$.

This relationship allows us also to determine the intrinsic (corrected for absorption) radio fluxes.

The radio/X-ray correlation in Cyg X-1 corrected for free-free absorption



Z. 2011

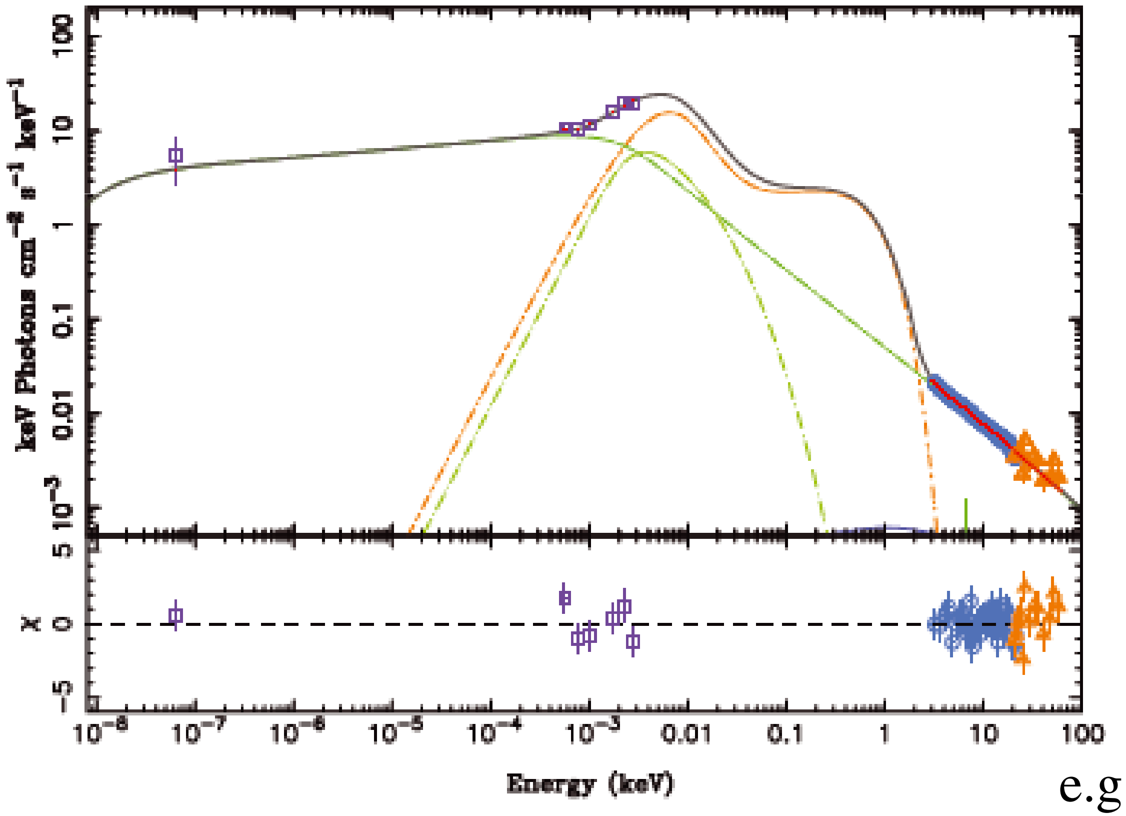
The intrinsic correlation index is $p \approx 1.3$, implying the accretion flow in Cyg X-1 is radiatively efficient.

Accretion models with high radiative efficiency

- Hot accretion flow models at high accretion rates predict a high efficiency, see the *Luminous Hot Accretion Flow* of Yuan (2001), in which compression heating is important. Also, direct electron heating increases the efficiency.
- Coronal models predict 100% local radiative efficiency. This model is applicable to the soft state (but probably not to the hard state). If the fraction of the power released in the corona is constant (as predicted if the disc is dominated by gas pressure), the radio/X-ray correlation index will be the same as for an efficient hot accretion flow (likely present in the hard state), which explains why the index p is the same in both the hard and soft states.

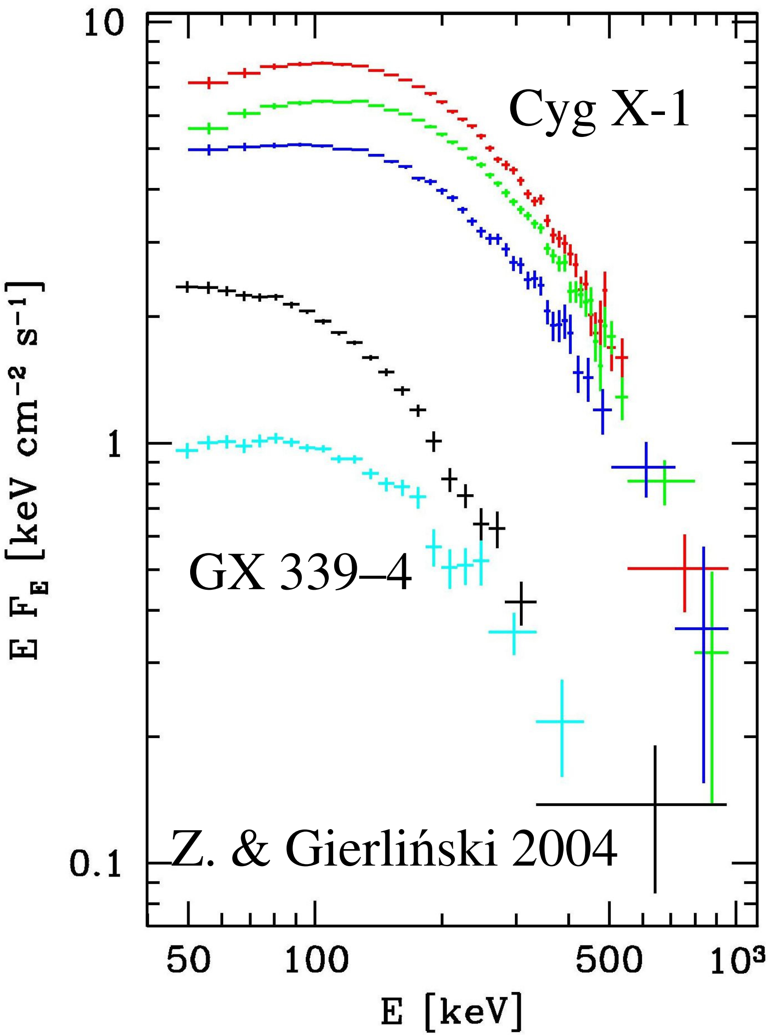
X-ray jet models:

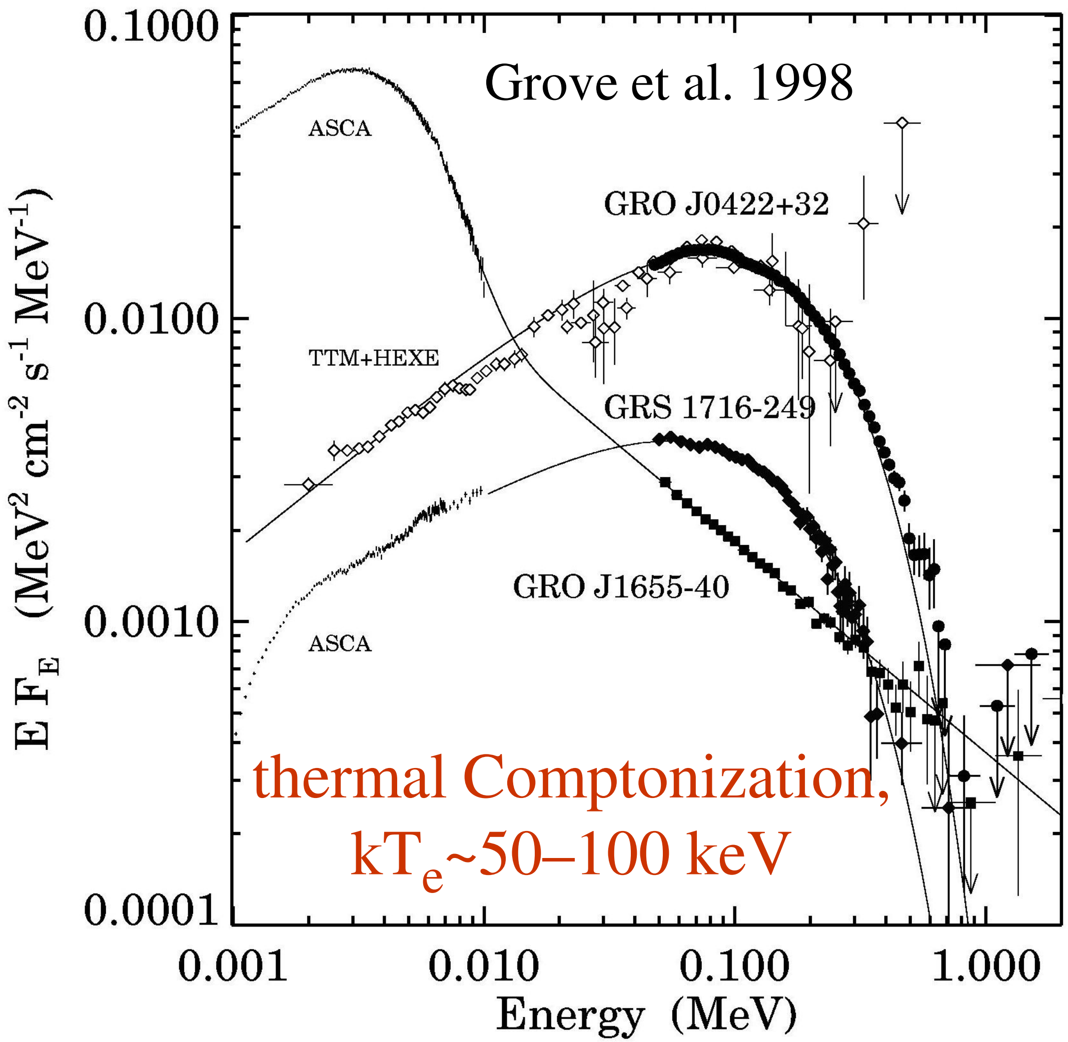
- The X-rays in the hard state are supposed to be emitted by the optically thin nonthermal synchrotron emission of the jet.



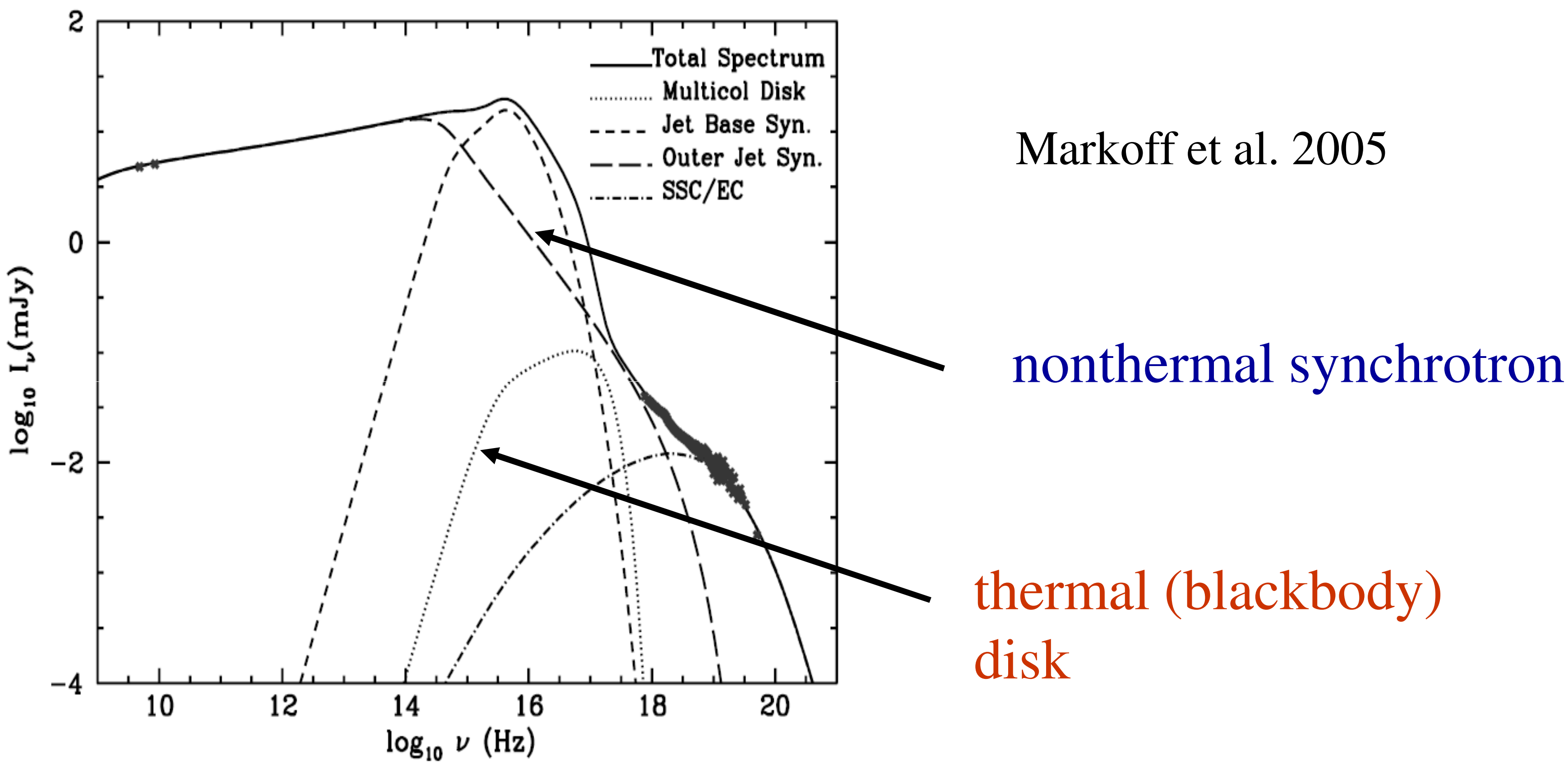
e.g., Maitra et al. 2009 for XTE J1118+480

A major problem for this model: the universal high-energy cutoff in the bright hard state of black-hole binaries, implying the dominance of thermal Comptonization





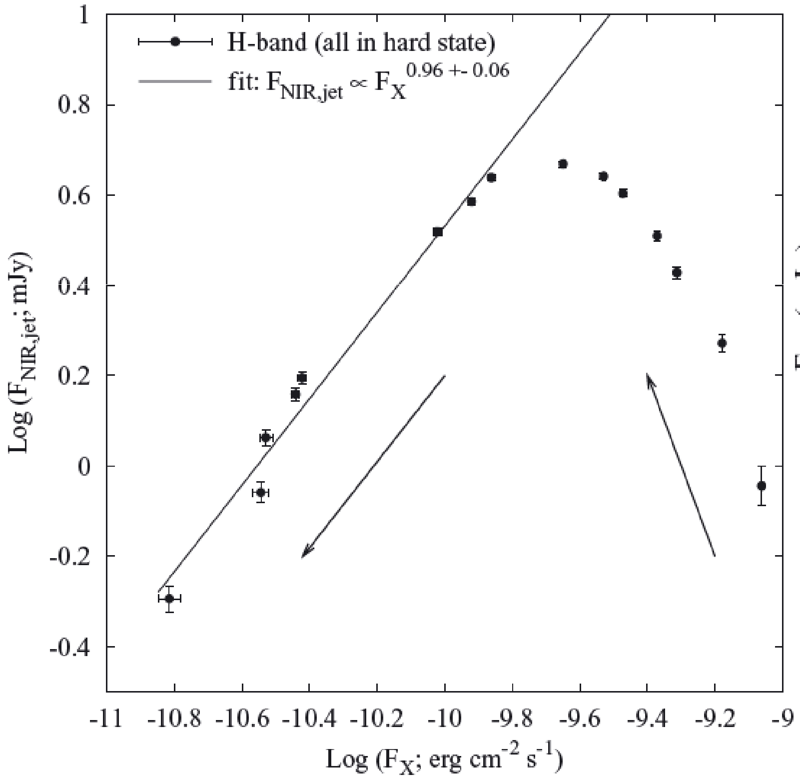
To address the cutoff problem, a thermal Compton jet model was proposed:

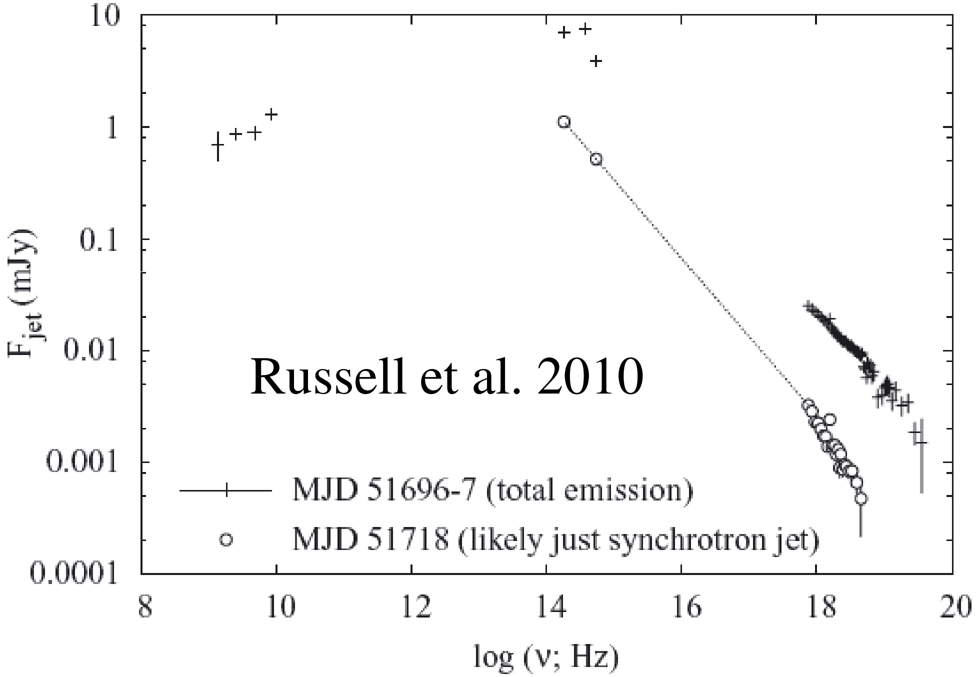


Markoff et al. 2005

Thermal Compton at kT_e ~ **3–5 MeV**; the observed cutoff at ~100 keV from the 1st-order scattering; strong fine-tuning required. Also, the model violates the $e^{\pm}$ pair equilibrium by a factor of 100 (Malzac+09).

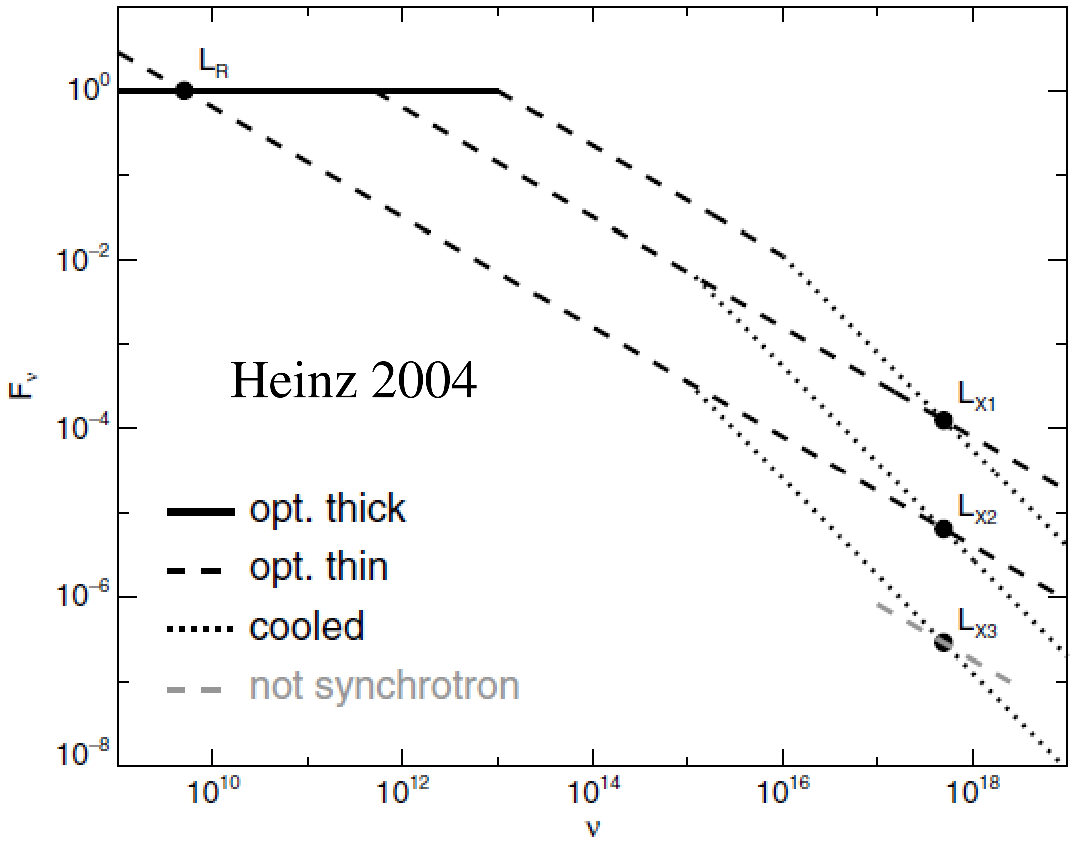
The non-thermal jet emission can possibly account for the X-rays in dim hard states. E.g. XTE J1550-564, where the jet X-ray dominance was claimed below $2\times10^{-3}\ L_E$ (Russell et al. 2010). However, above this L, thermal Comptonization was found to dominate.





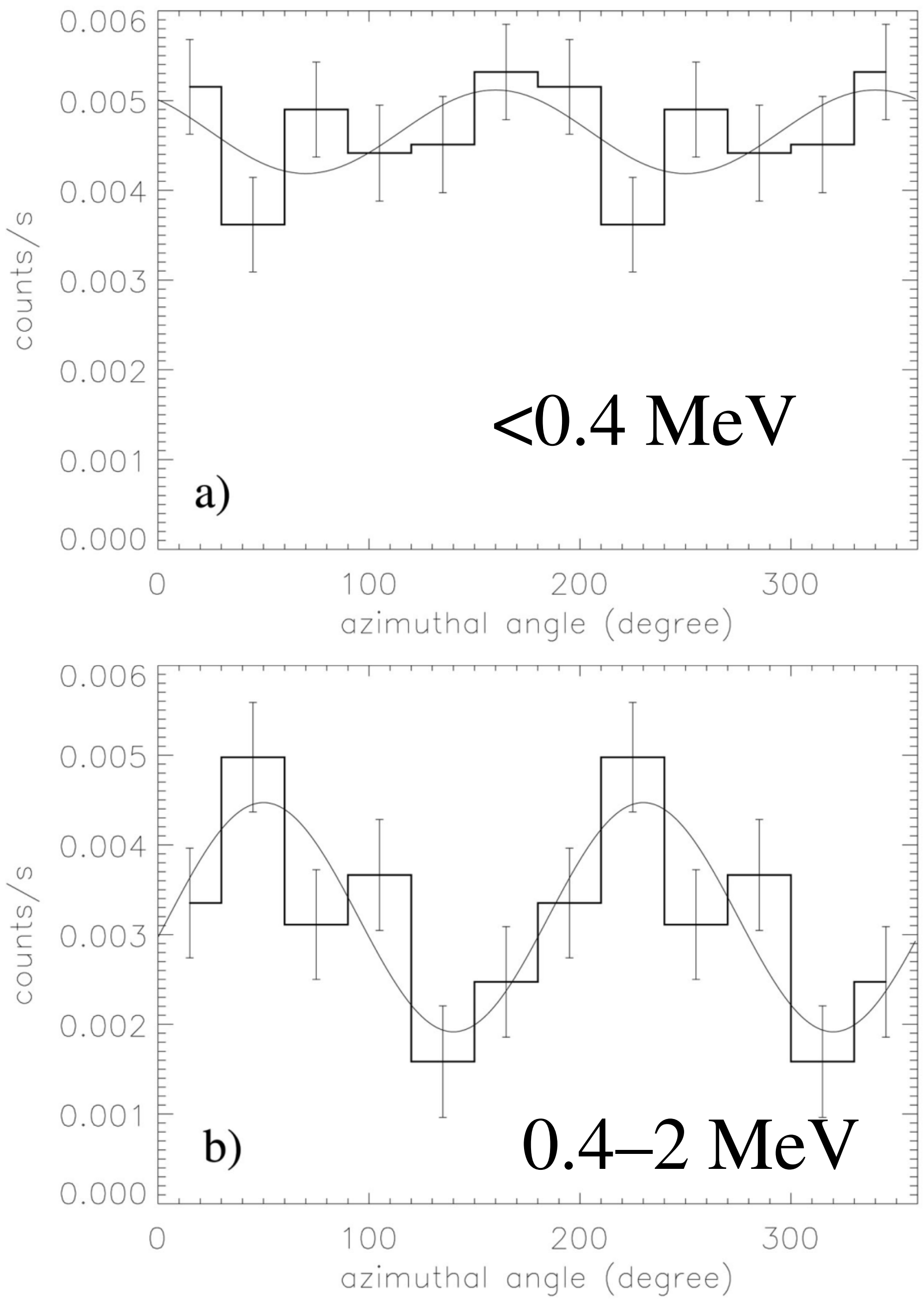
In Cyg X-1, the non-thermal synchrotron can contribute at most several % of the observed X-rays (Rahoui+ 2011; this work).

Further issues: cooling and fast variability



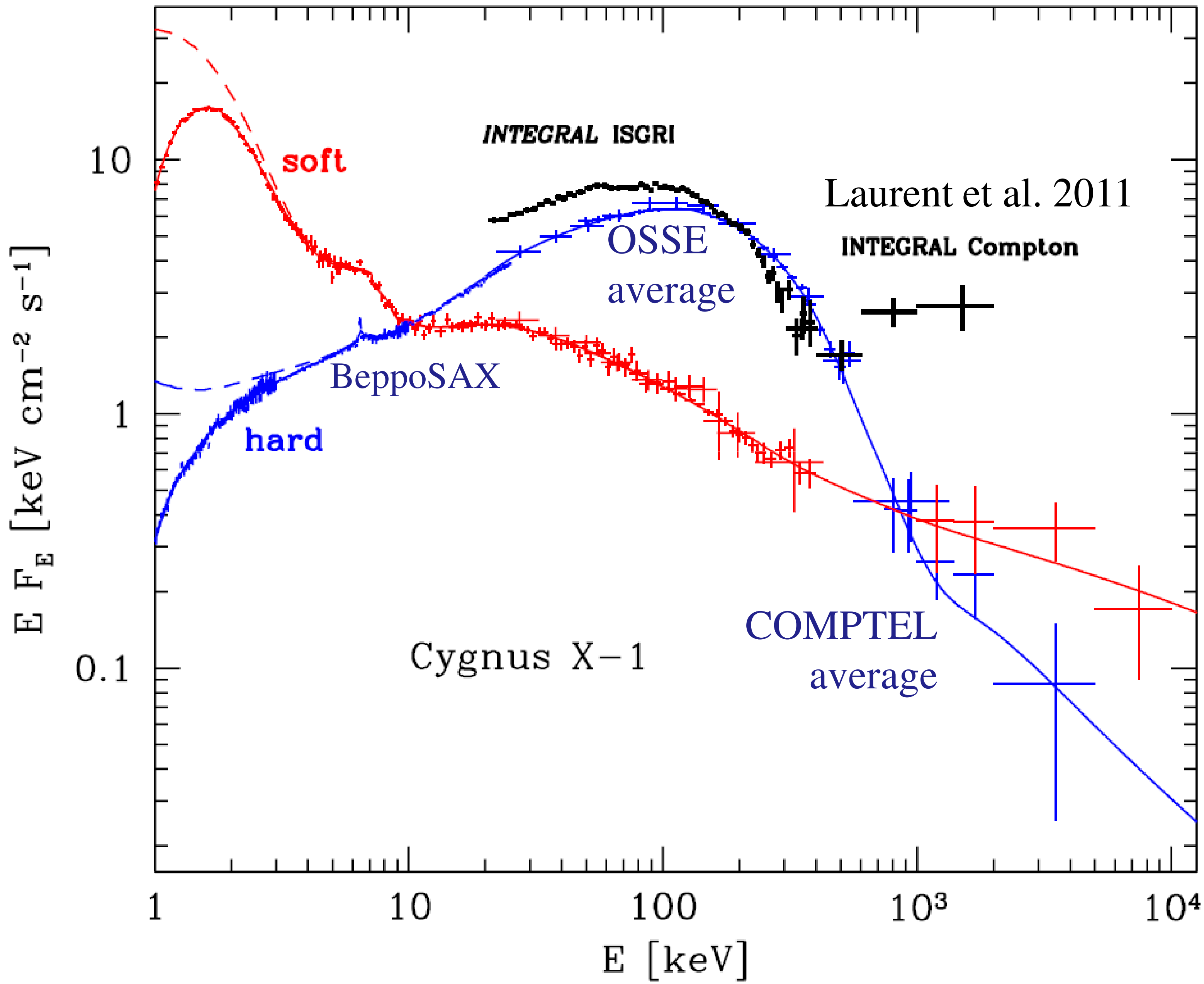
Standard modelling is with a single optically thin nonthermal power law from the turnover frequency to X-rays. But a break with $\Delta\alpha = 0.5$ is expected in the UV due to cooling. This would further reduce the contribution of non-thermal synchrotron to X-rays.

Also, it appears impossible to reproduce the fast X-ray variability observed up to several 100 Hz with the jet synchrotron emission.



Polarization at the level of 70±30% claimed in the 0.4–2 MeV band of Cyg X-1by Laurent et al. 2011 (Science), which would have to be from a jet. But doubts regarding the level of the flux in this band.

A polarized MeV tail in the hard state?



Conclusions

- The radio/X-ray correlation extends from the hard to the soft state.
- The jet is formed by a hot accretion flow, but not by an optically-thick disc.
- X-rays in luminous hard states not dominated by the jet. Some jet contribution possible, anticorrelated with L.
- A determination of the location of the radio-emitting region in Cyg X-1. At 15 GHz, $z \sim 2\times10^{12}$ cm $\sim 10^6\, r_{\rm g}$.
- The intrinsic radio/X-ray correlation index in Cyg X-1 is $p \approx 1.1$–1.4.
- This value of p implies the accretion flow in Cyg X-1 is radiatively efficient in all spectral states.