X-ray Outbursts of Black Holes and the Disk-Jet Connection

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Structure

- Introduction: Why study Black Hole Accretion?
  - AGN feedback and accretion
  - Accretion Geometry: AGN and Galactic Black Holes
- Testing Relativity
  - Relativistic Fe Kα lines
- Variability, Jets, and Radio Emission
  - States
  - Radio – X-ray relations
- Summary and Outlook

Aim of this talk: review of recent results on (dis)similarities of stellar mass and supermassive black holes and where these come from.

Due to time constraints I will ignore intermediate mass black holes and concentrate on the observations. . .

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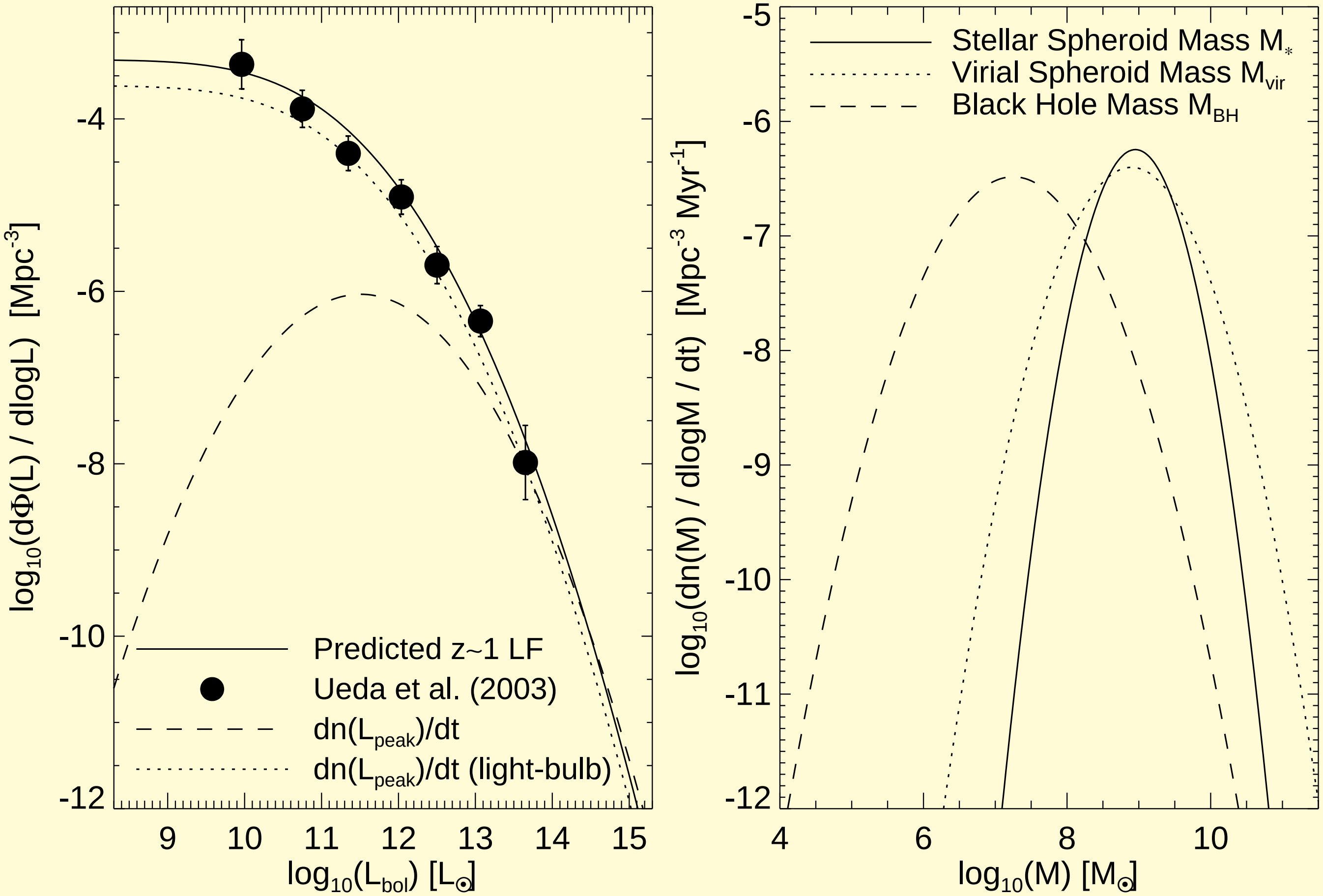
Why study accretion?

Science Vision for European Astronomy (ASTRONET, 2007):

1. Do we understand the extremes of the Universe?
   - Can we observe strong gravity in action?
   - How do black hole accretion, jets and outflows operate?
   - What do we learn from energetic radiation and particles?
2. How do galaxies form and evolve?
   - How did the structure of the cosmic web evolve?
   - How were galaxies assembled?
3. What is the origin and evolution of stars and planets?
   - Do we understand stellar structure and evolution?
4. How do we fit in?

Similar questions also in US Decadal Reports, ESA Cosmic Vision, Denkschrift Astronomie, etc.

AGN Feedback

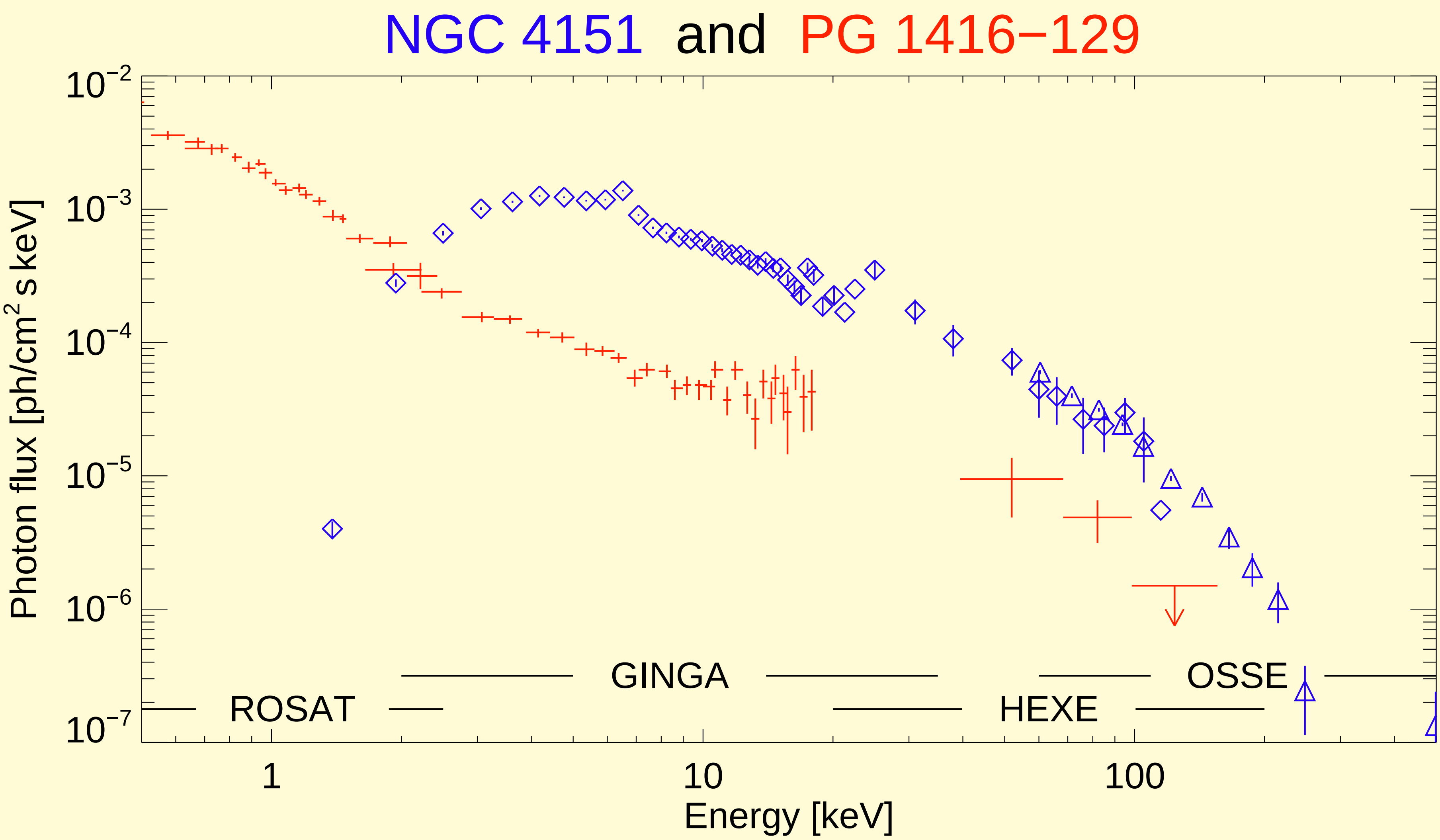


AGN Feedback: Accretion onto Black Holes regulates star formation $\Longrightarrow$ anti-hierarchical structure formation

(Hopkins et al., 2006)

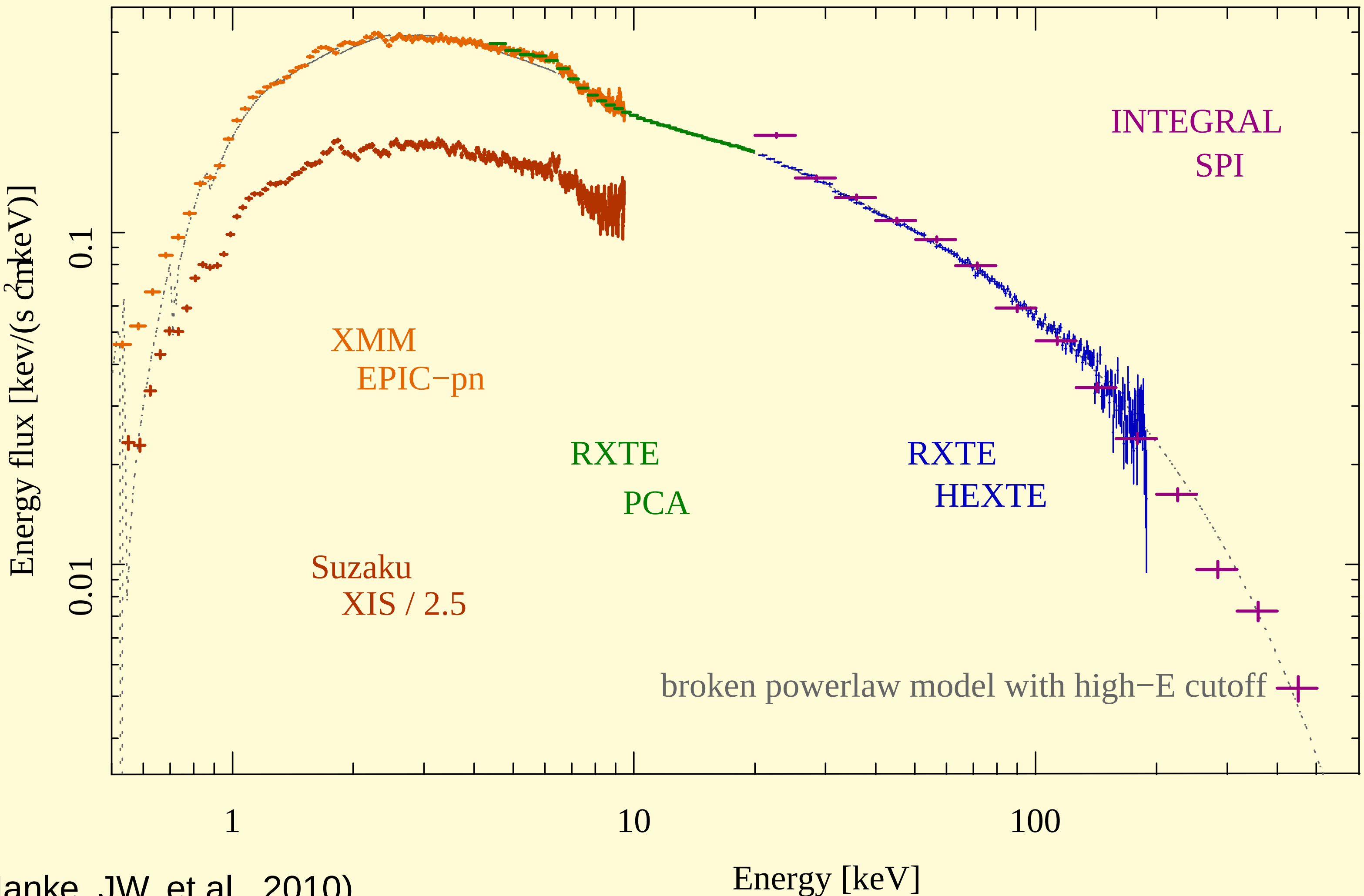
Physics: BH becomes active and grows when gas flows in (e.g., during merger); extended star formation prevented by BH activity.

X-ray Spectra, I



Typical X-ray spectra of Seyfert galaxies ($L \sim 3\% \, L_{\mathrm{Edd}}$).

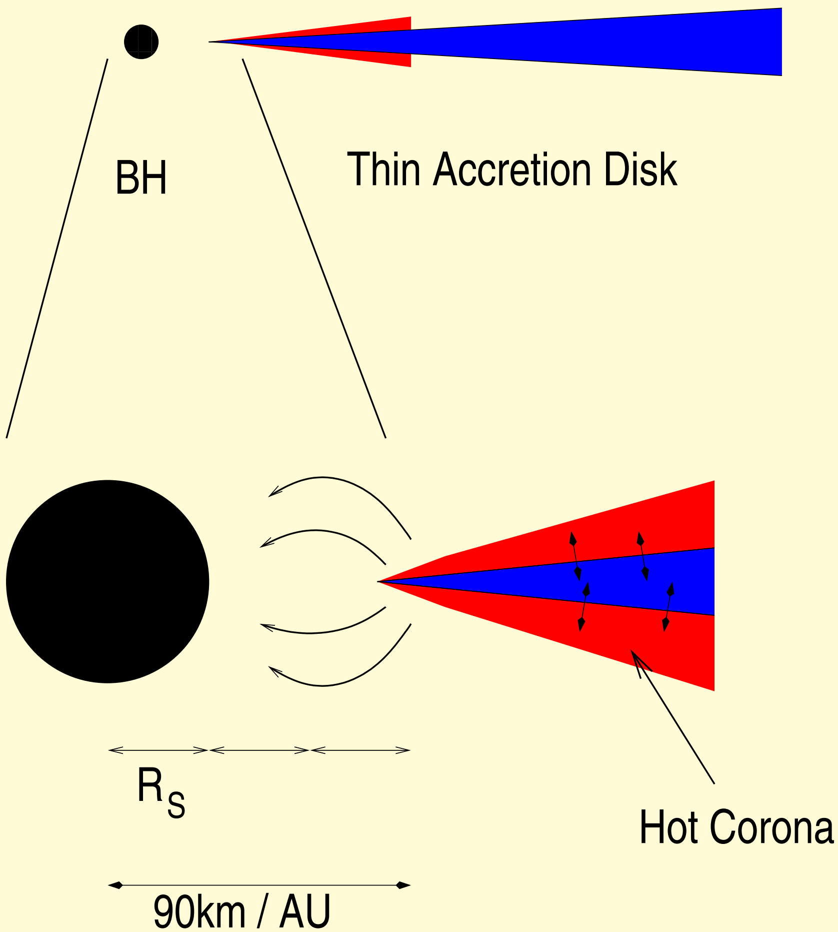
X-ray Spectra, II



Cyg X-1 (Hanke, JW, et al., 2010)

A typical hard state spectrum of a Galactic Black Hole (GBH) ($L \sim 3\% \, L_{\mathrm{Edd}}$)

X-ray Spectra, III



The geometry of the accretion flow is assumed to be very similar in AGN and GBHs

$\Longrightarrow$ expect similar behavior, except for mass scaling:

- Size: $r \propto GM/c^2 \propto M$

  AGN: some AU, GBH: some 10 km

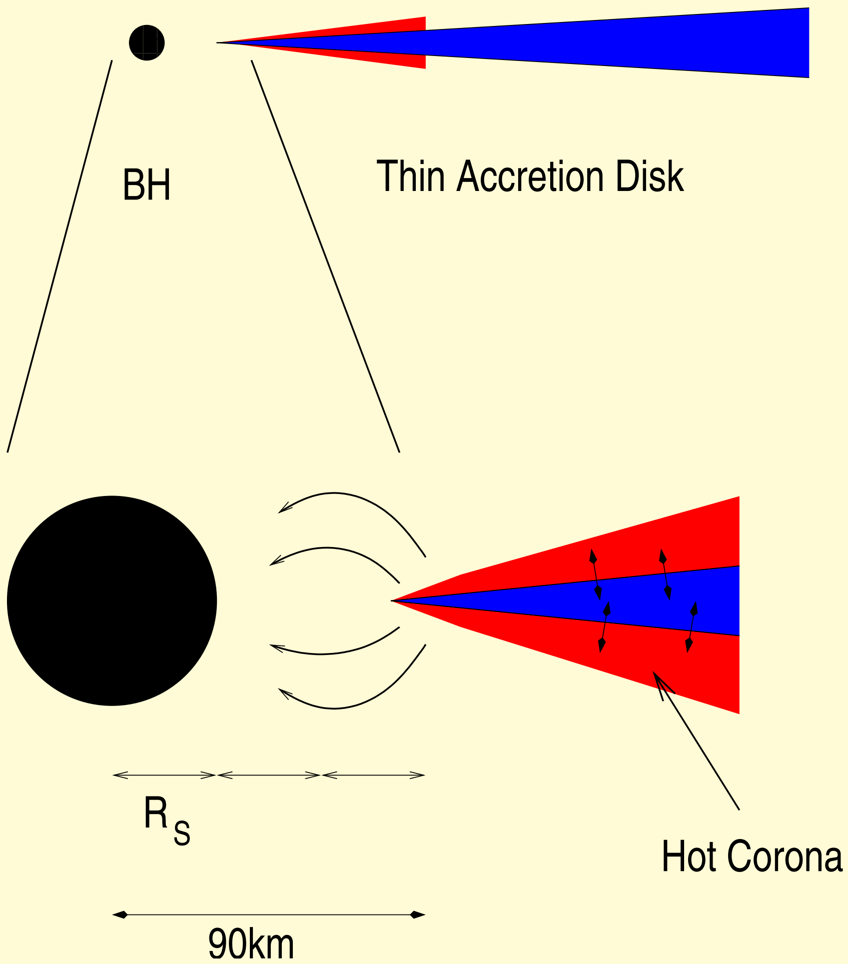
- Variability: $\Delta t \propto M$

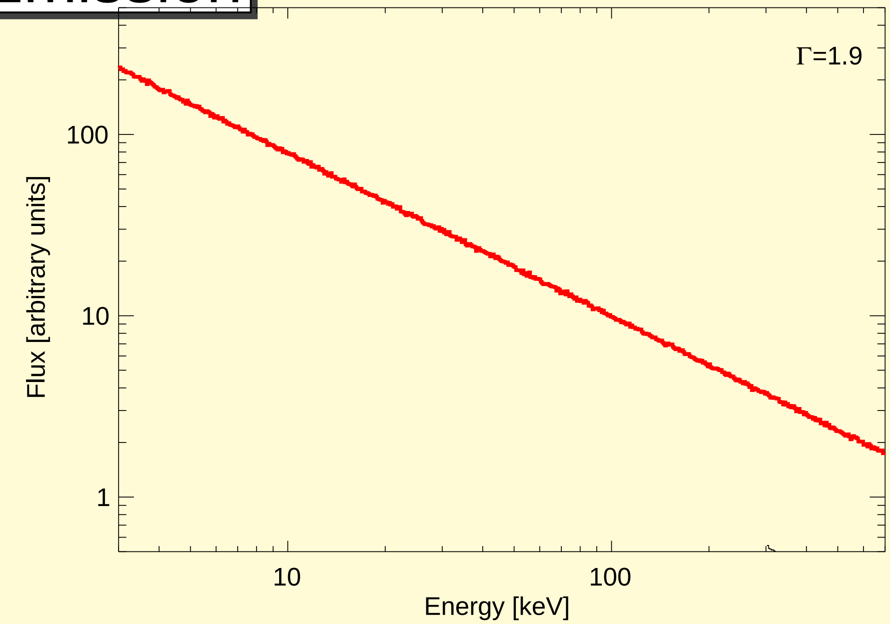
  e.g., Kepler timescale at ISCO: AGN: up to tens of ksec, GBH: a few msec

- Temperature: $kT_{\text{in}} \propto M^{-1/4}$

  AGN disk observed in UV, GBH disk observed in soft X-rays

Continuum Emission

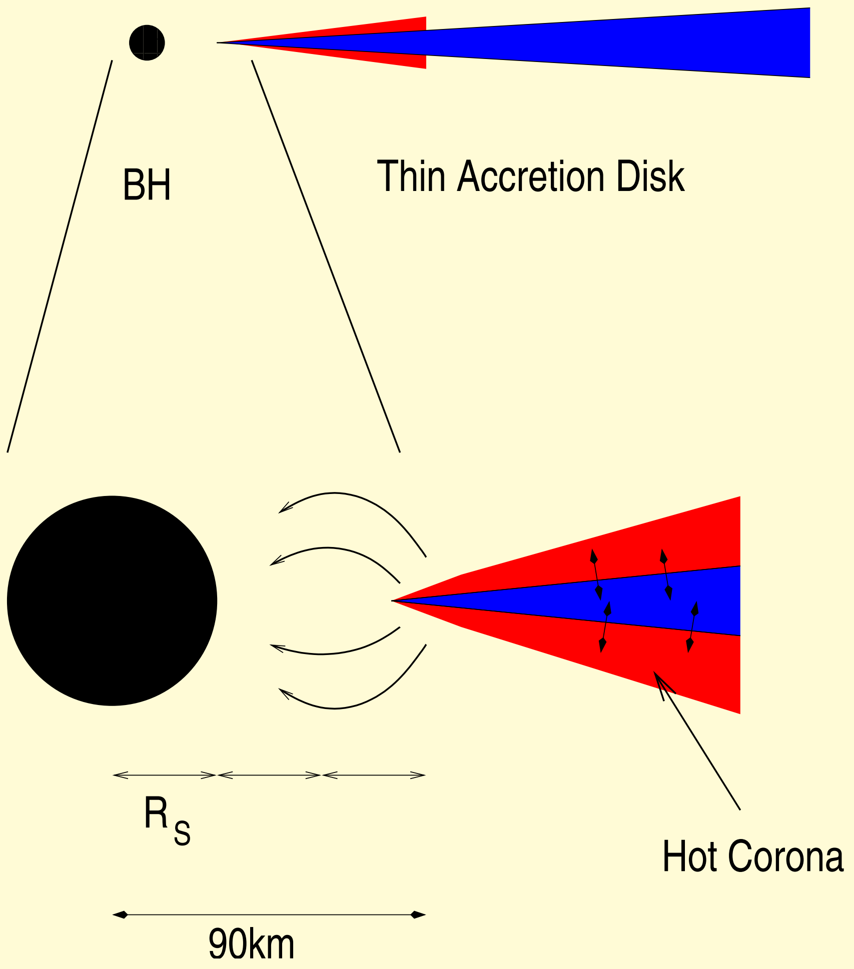


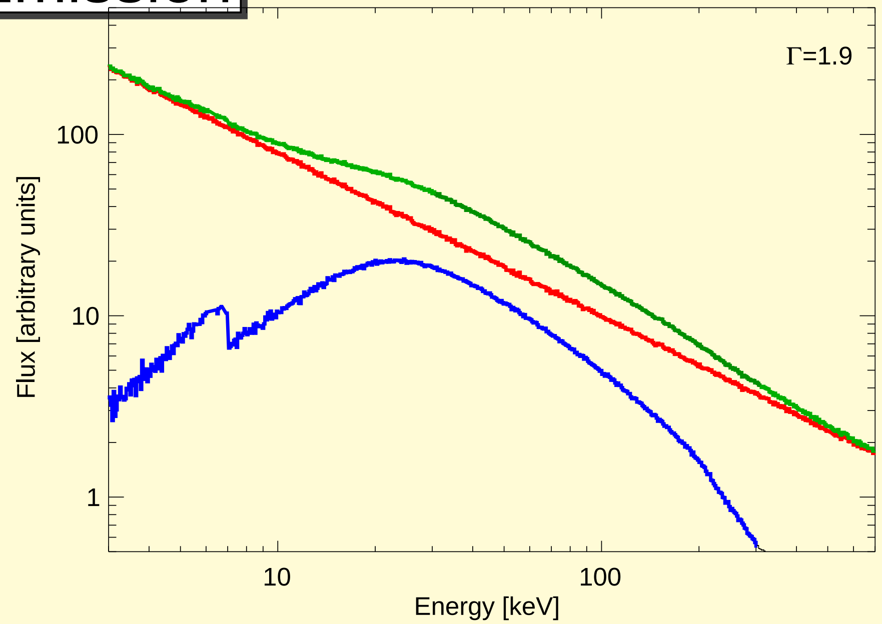


XRB/AGN X-Ray Spectrum:

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

Continuum Emission





XRB/AGN X-Ray Spectrum:

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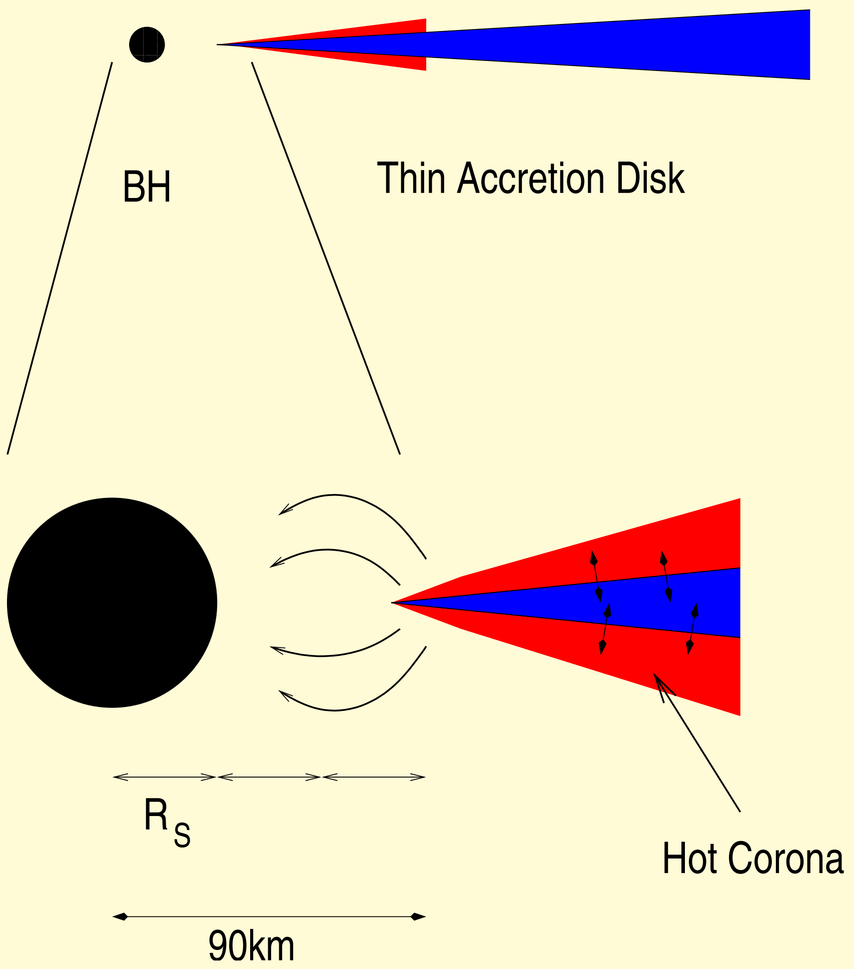
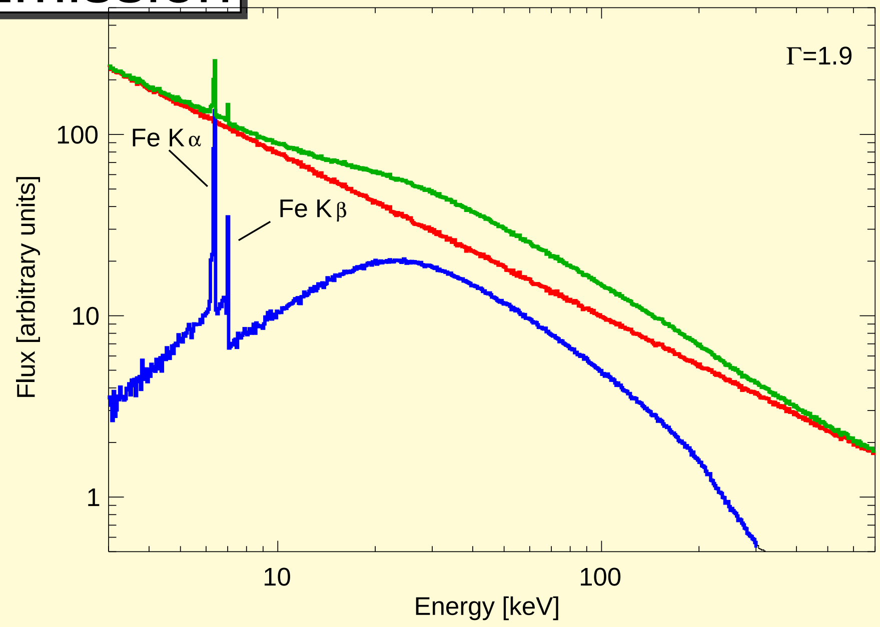
- Thomson scattering of power law photons in disk: Compton Reflection Hump

Continuum Emission



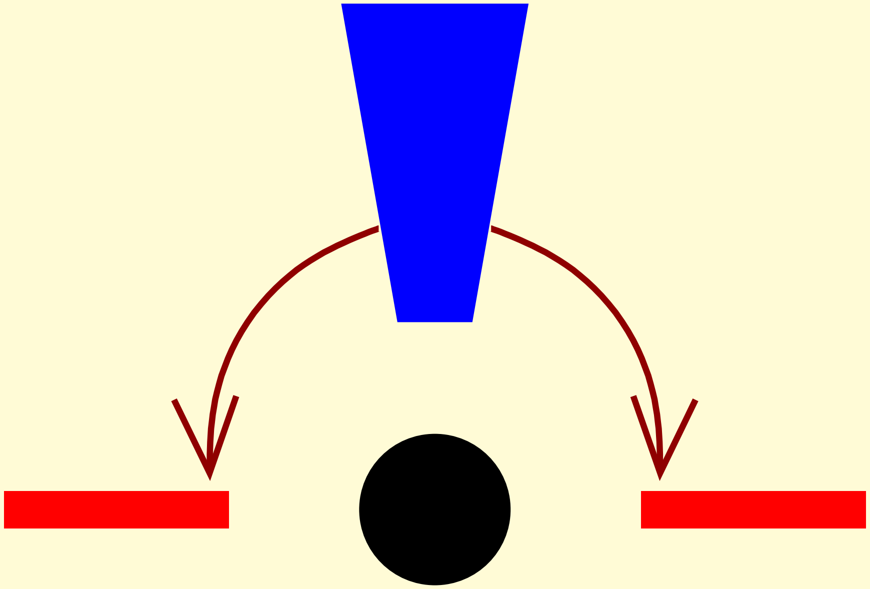


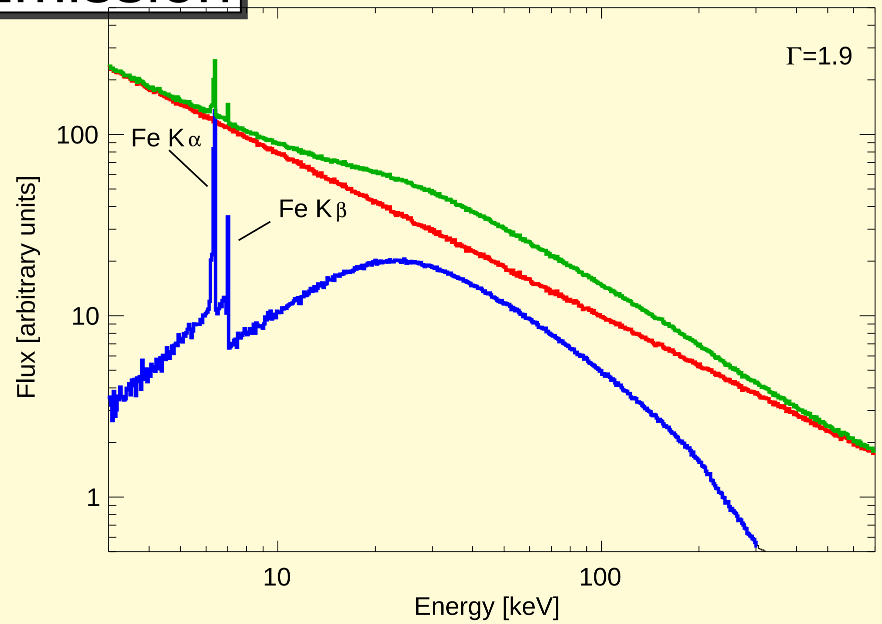
XRB/AGN X-Ray Spectrum:

- 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

for more advanced reflection/disk emission models, see, e.g., Davis et al. (2005), Ross & Fabian (2007)...

Continuum Emission





XRB/AGN X-Ray Spectrum:

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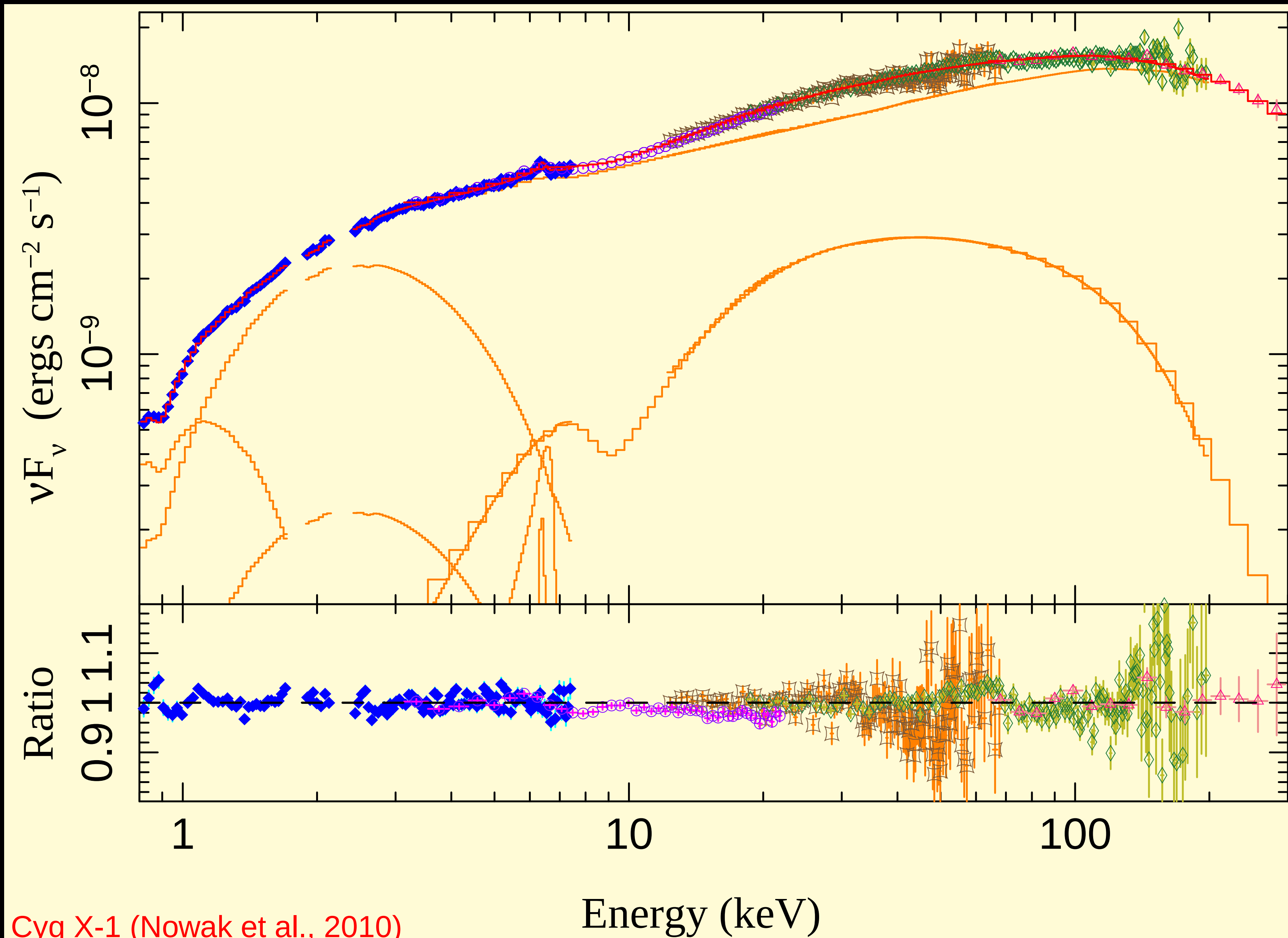
But note:

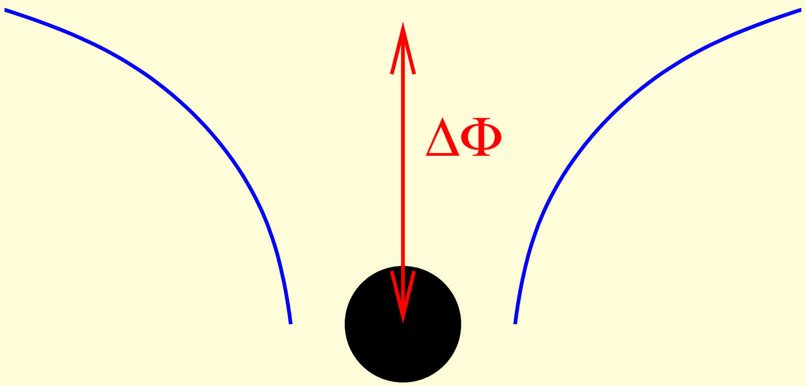
Geometry of accretion flow itself is still debated.

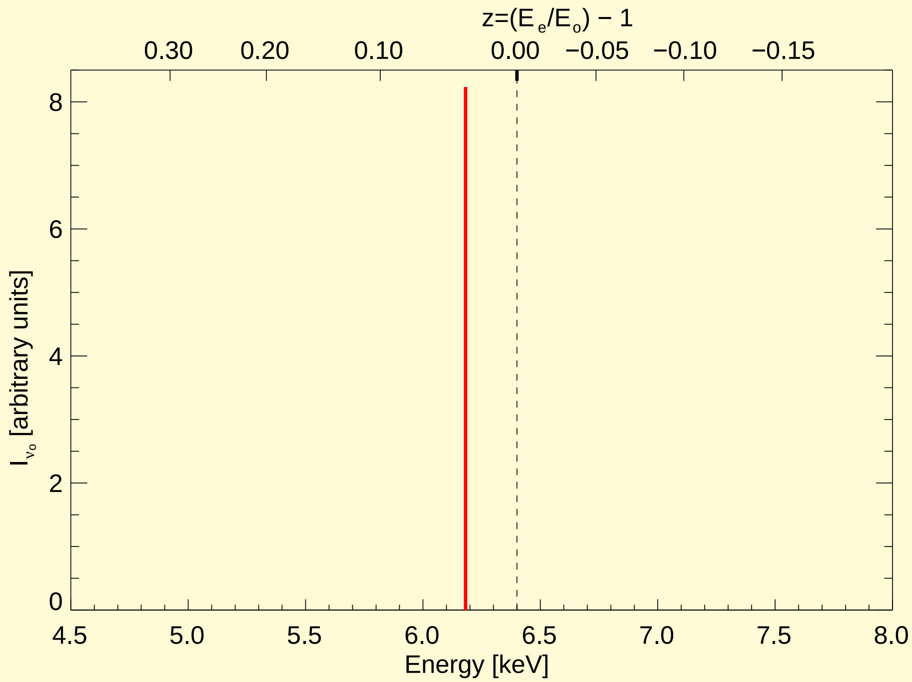
Jets vs. Disks vs. "Lampposts"



Thermal Comptonization plus reflection explain the broad-band spectrum very well.

Kα Line Diagnostics, I

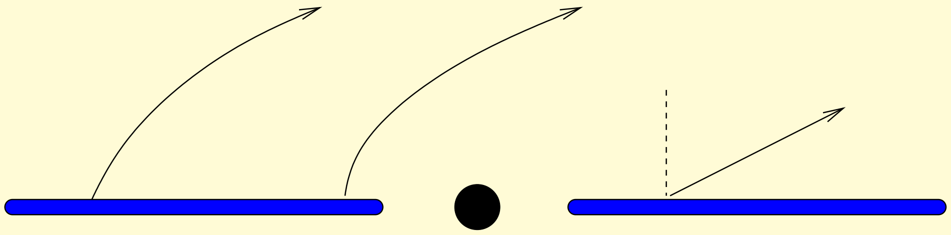


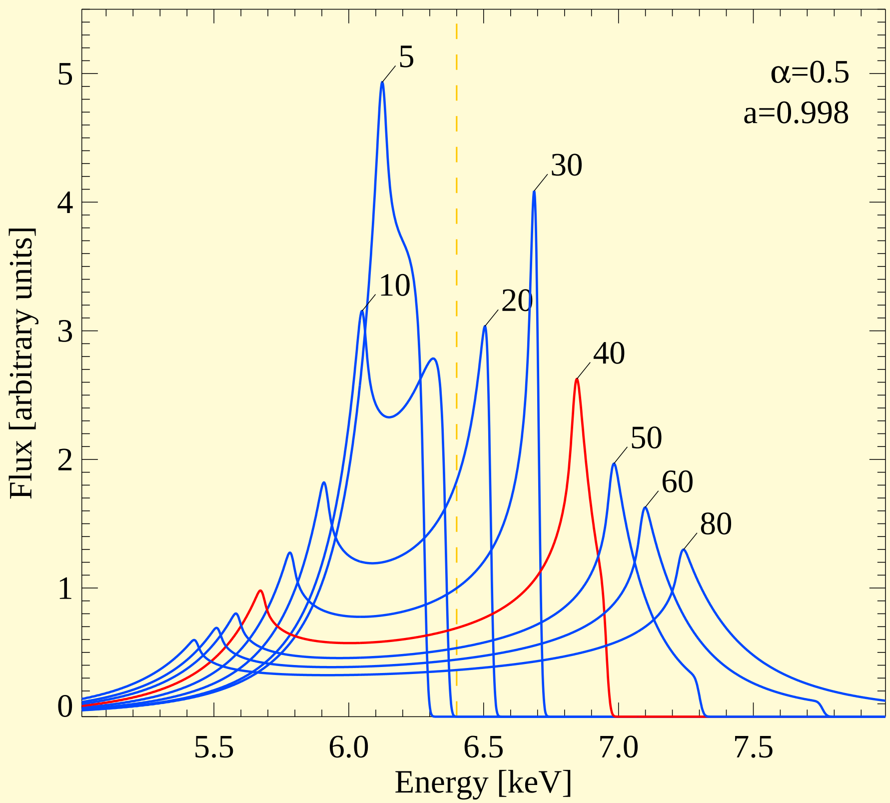


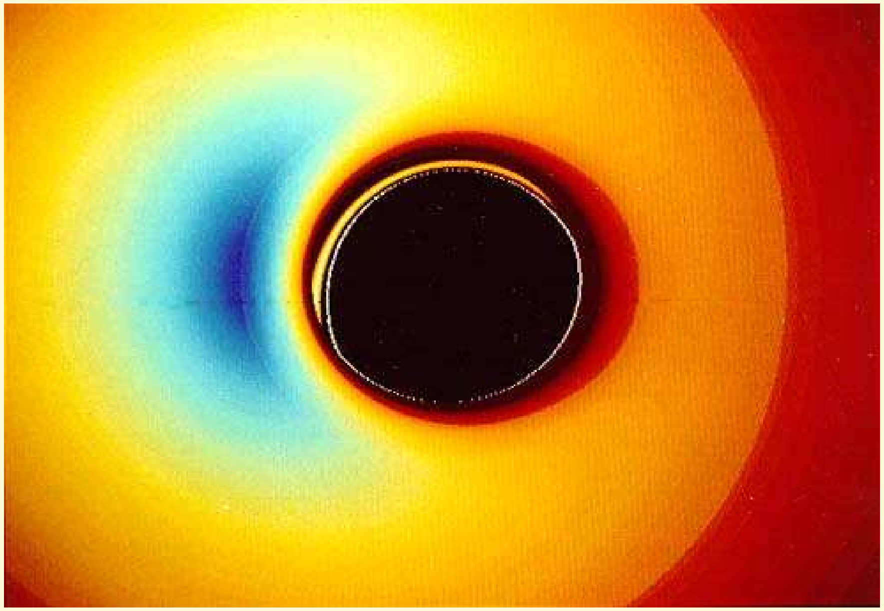
Total observed line profile is affected by

- grav. Redshift

Kα Line Diagnostics, II



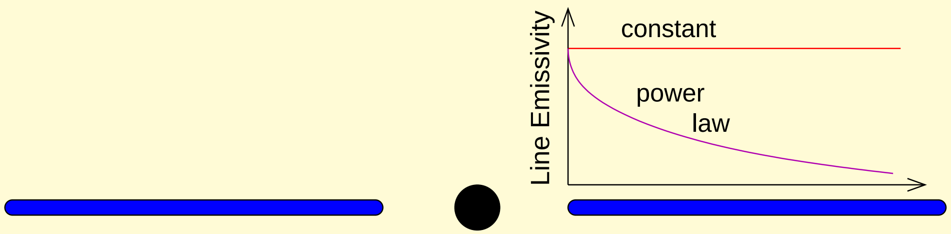


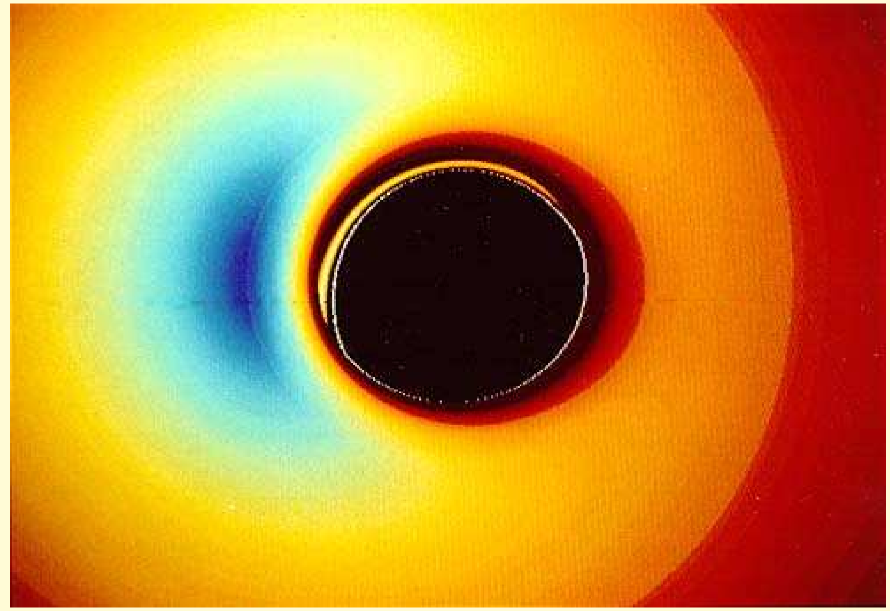


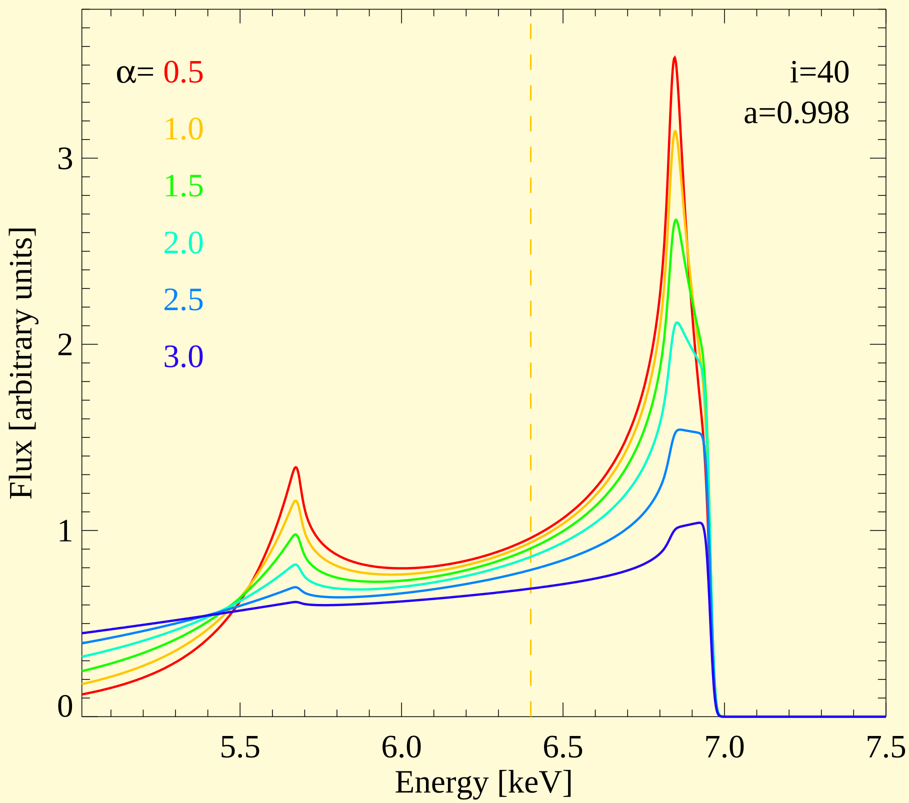
Total observed line profile is affected by

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

Kα Line Diagnostics, III



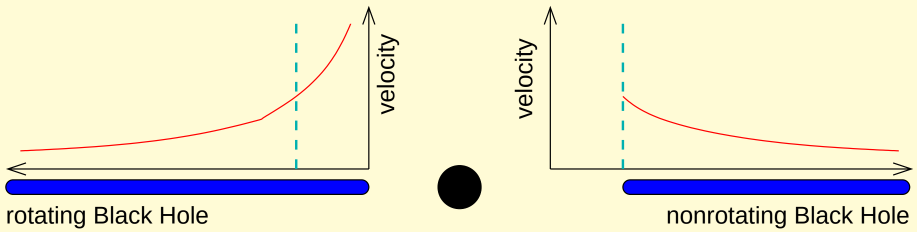


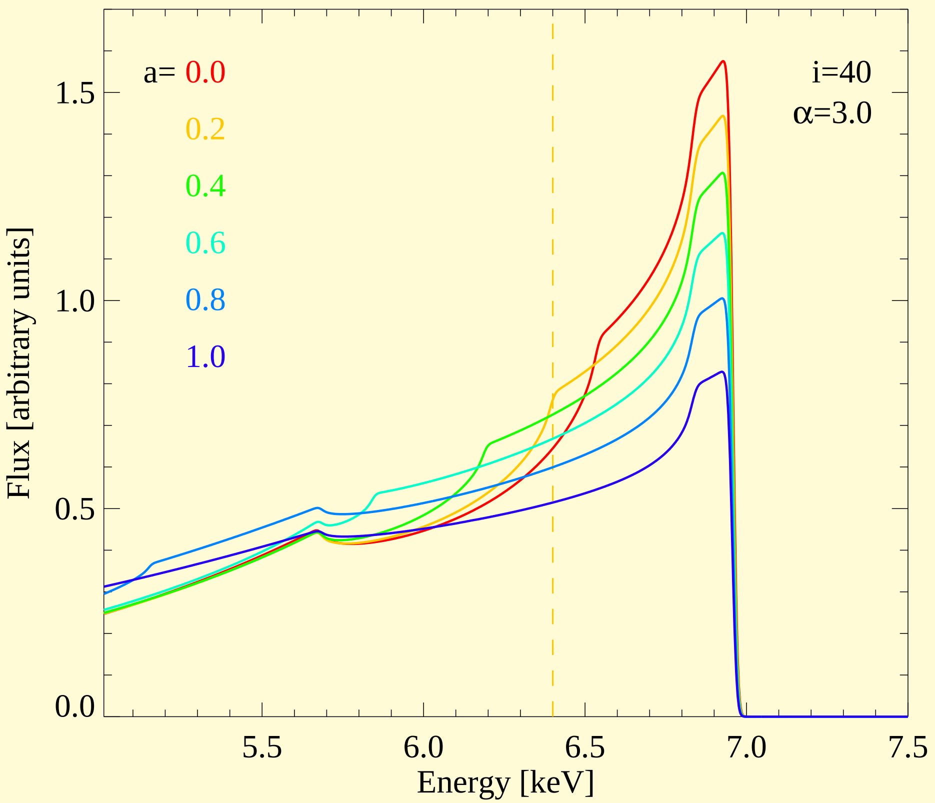


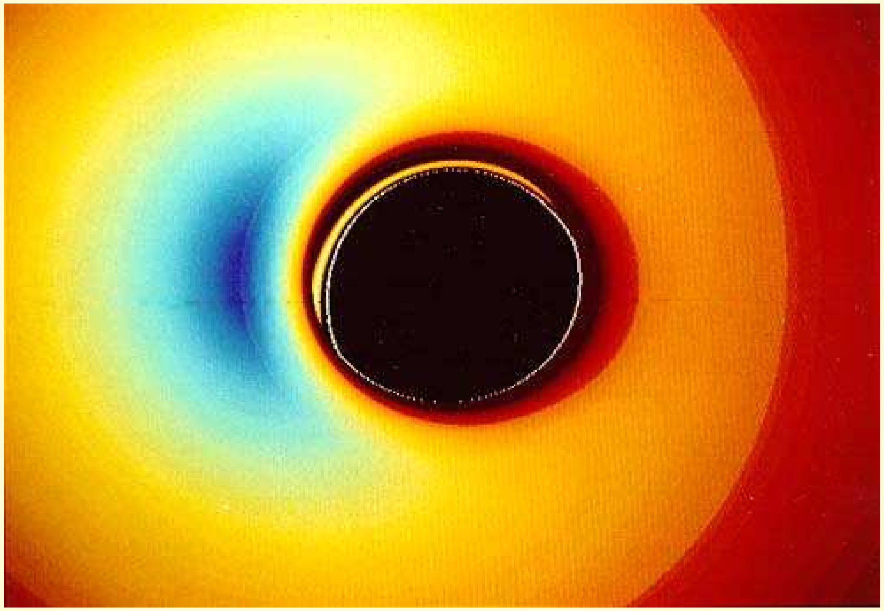
Total observed line profile is affected by

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

Kα Line Diagnostics, IV



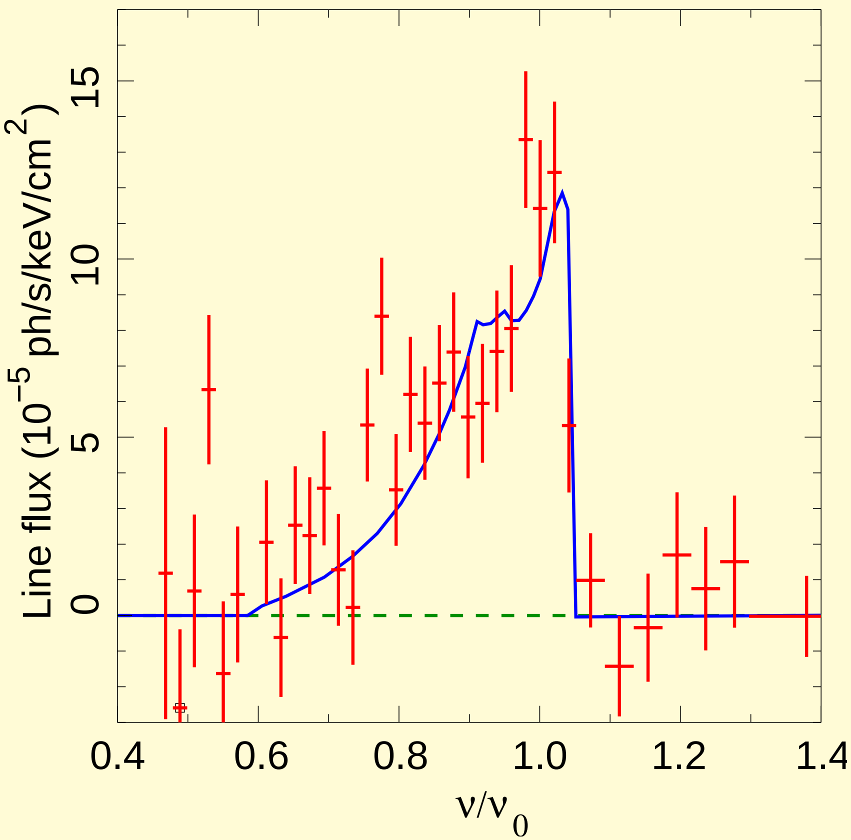


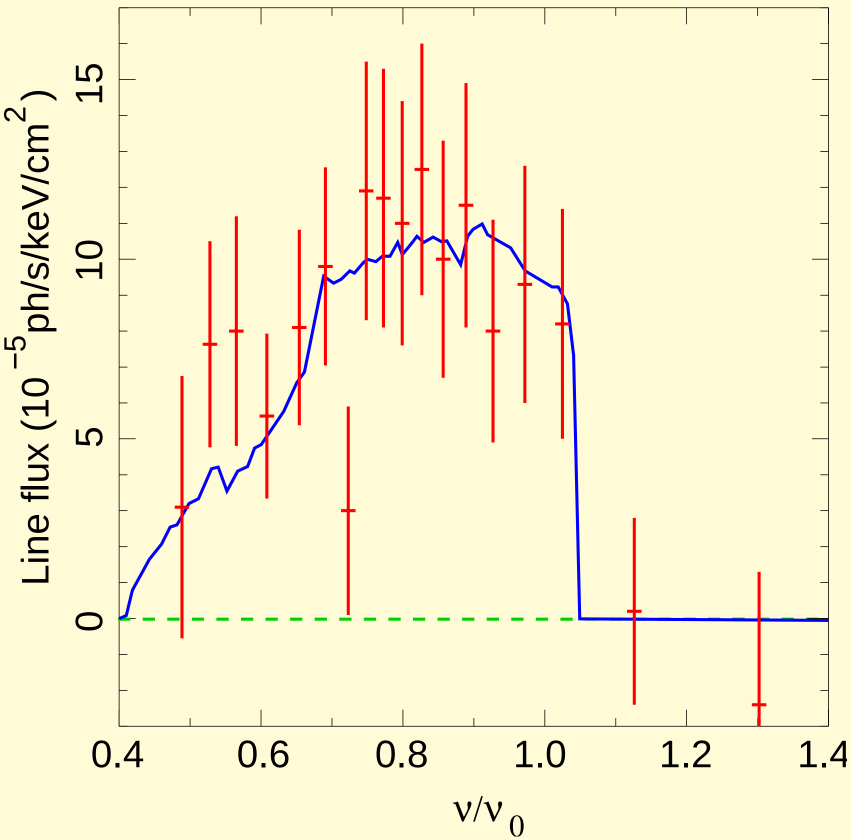


Total observed line profile is affected by

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

AGN, I





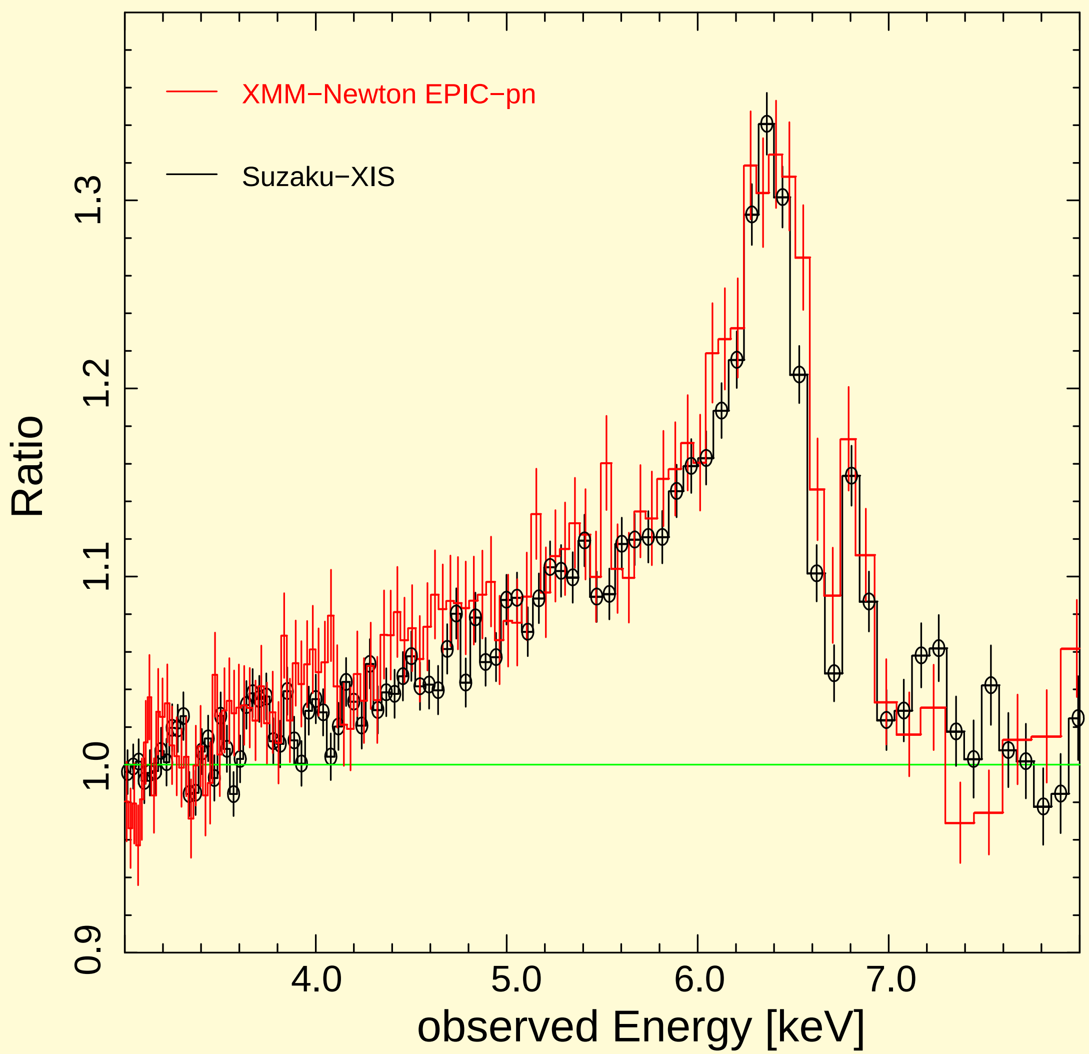
MCG−6-30-15 ($z = 0.008$): first AGN with relativistic disk line

Tanaka et al. (1995): time averaged *ASCA* spectrum: line skew symmetric
$\Longrightarrow$ Schwarzschild black hole.

Iwasawa et al. (1996): "deep minimum state": extremely broad line
$\Longrightarrow$ Kerr Black Hole.

Confirmed by all subsequent X-ray missions.

AGN, II

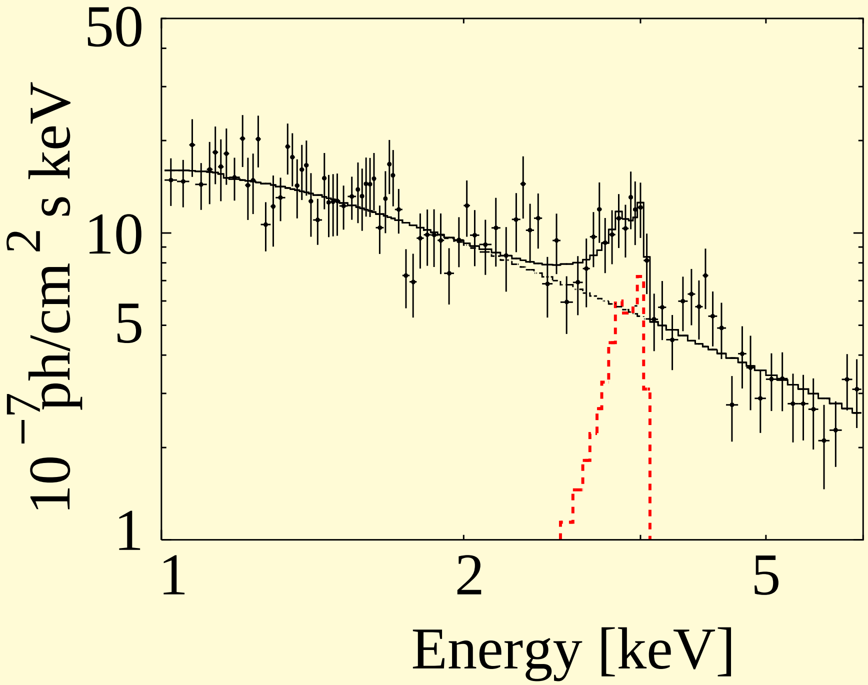


Suzaku (2006 Jan; $\sim$350 ksec; Miniutti et al., 2007)

Brenneman & Reynolds (2006): Angular momentum of BH in MGC$-$6-30-15: $a = 0.989^{+0.009}_{-0.002}$.

Assuming no emission from within innermost stable circular orbit, (too) tightly constrained geometry.

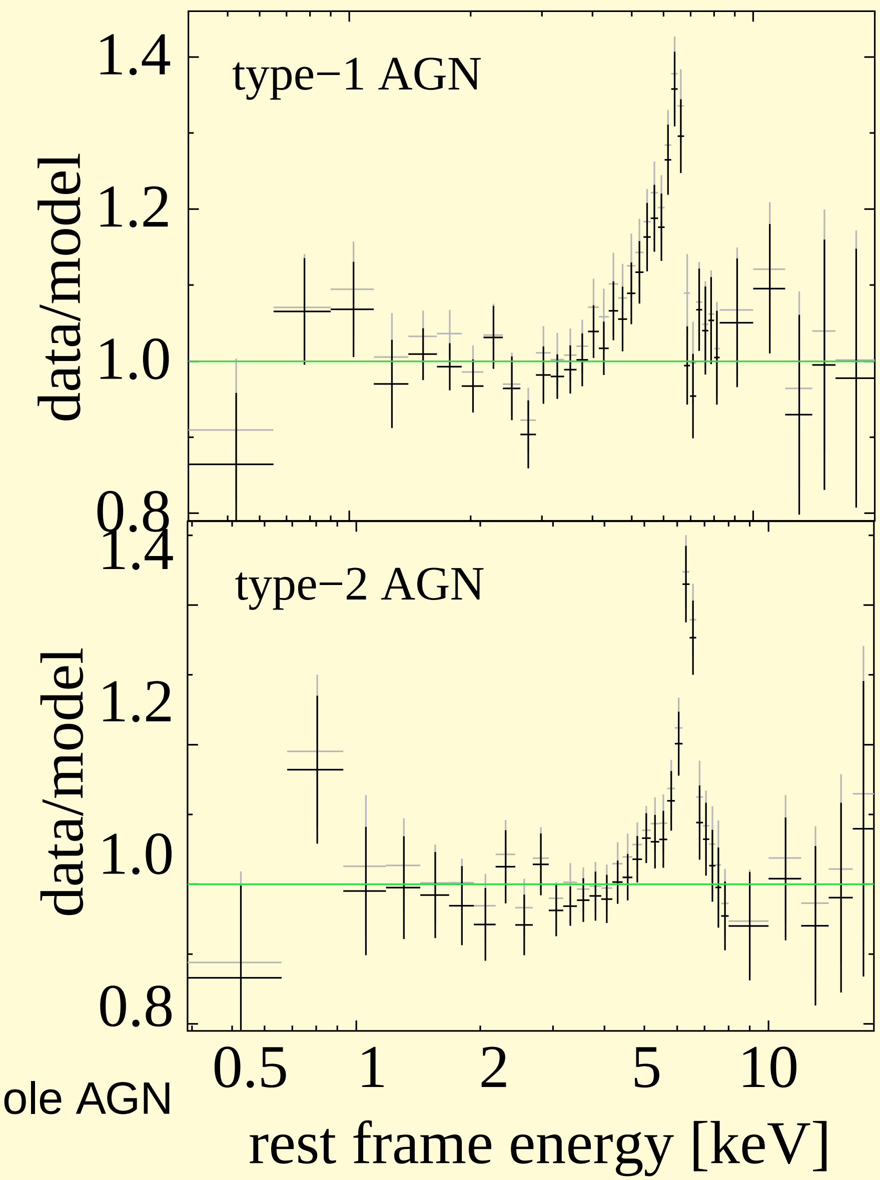
AGN, III



(Comastri, Brusa, Civano, 2004; *Chandra*)

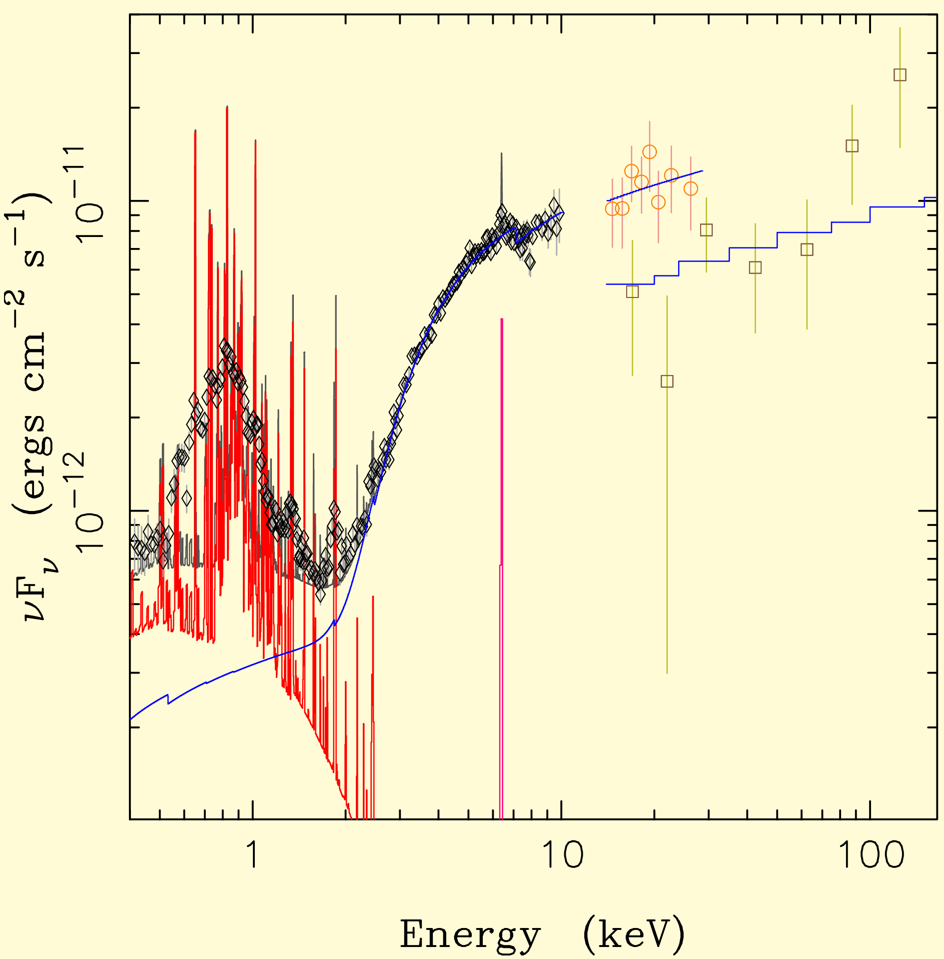
CXO J123716.7+621733 (CDF-N; $z = 1.146$)

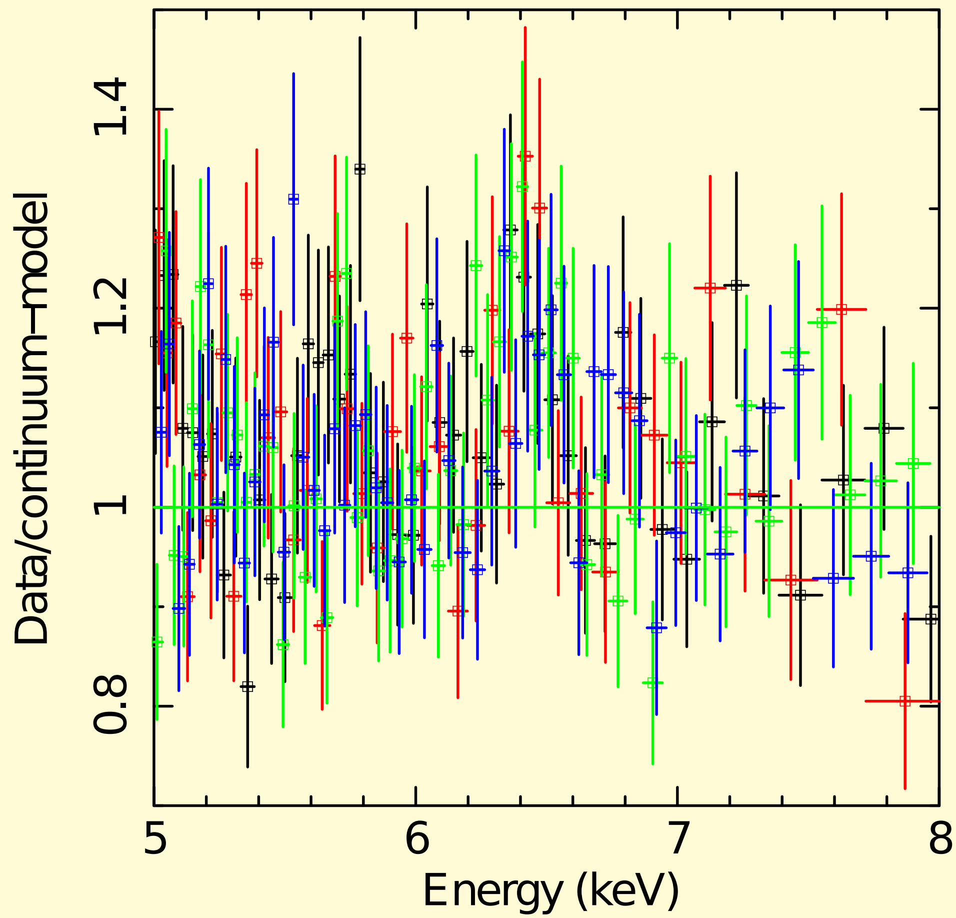
Broad Fe Kα lines already present in high-z universe!



Average Fe line for the Lockman hole AGN (Streblyanska et al., 2005)

AGN, IV

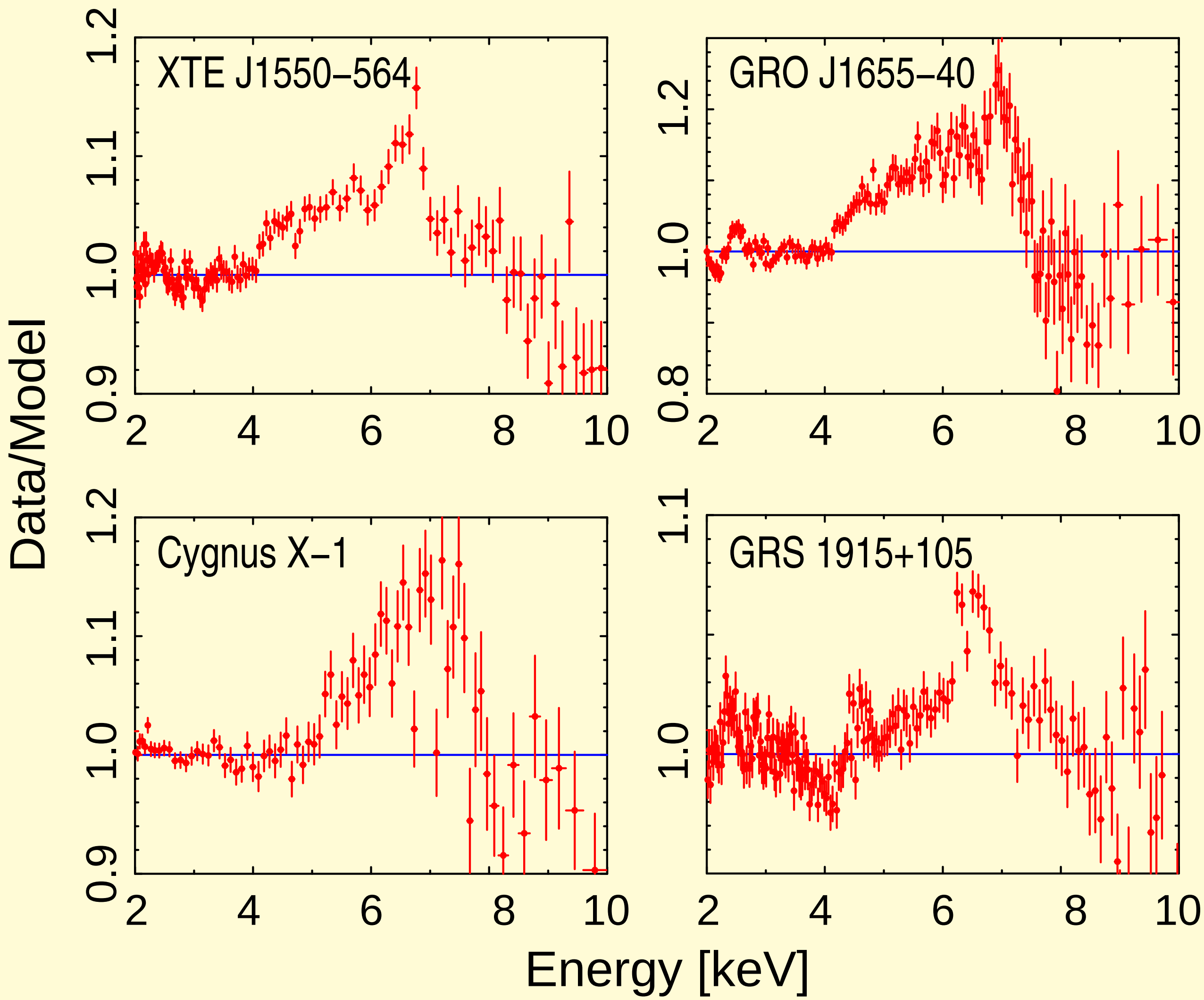




NGC 4258 (Reynolds,. . . ,JW,. . . , 2008; Suzaku, Swift)

But: Many AGN do *not* show relativistic lines!

Galactic BHC

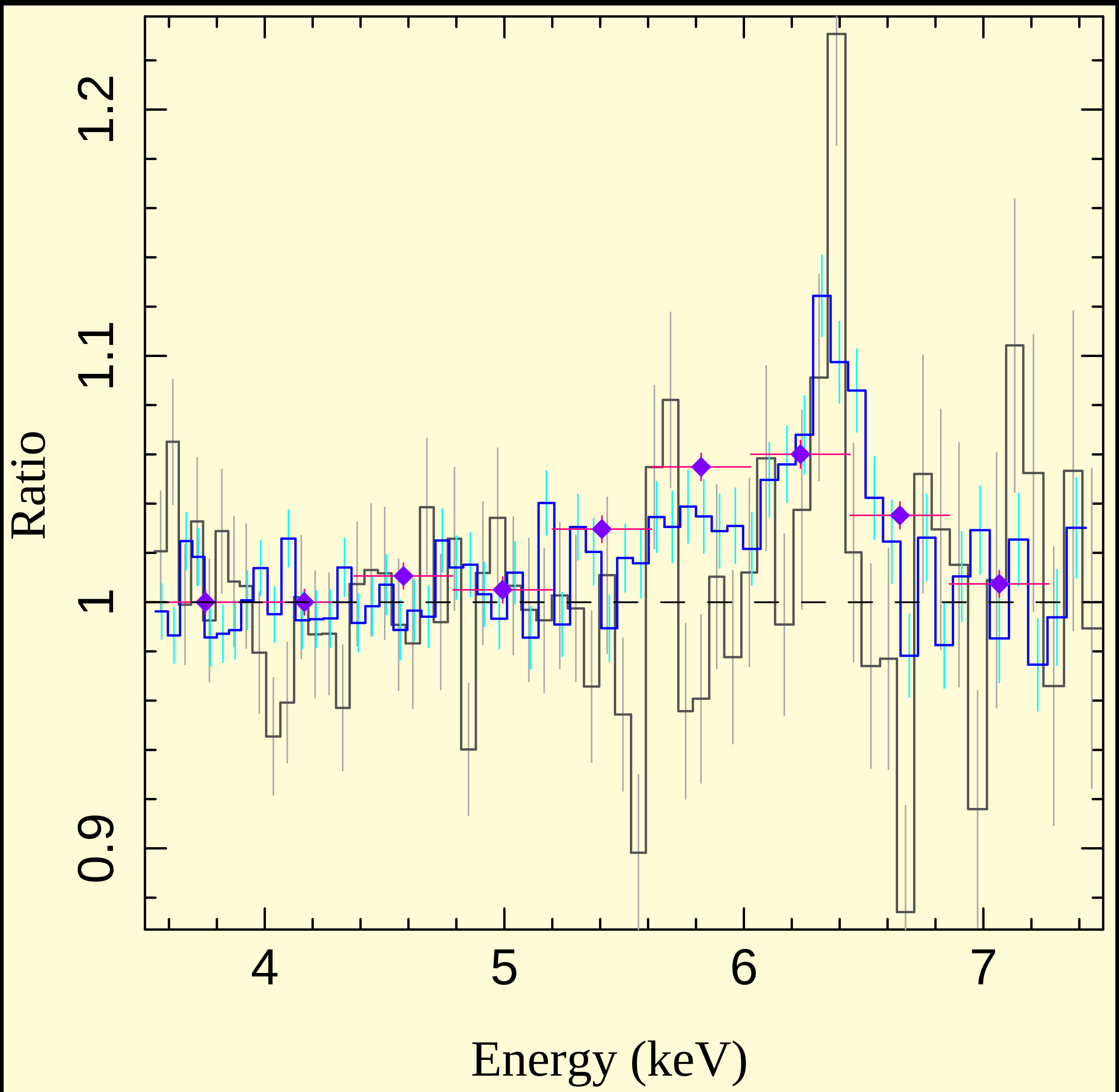


Relativistic lines are also seen in many Galactic Black Holes

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

. . . and a few more

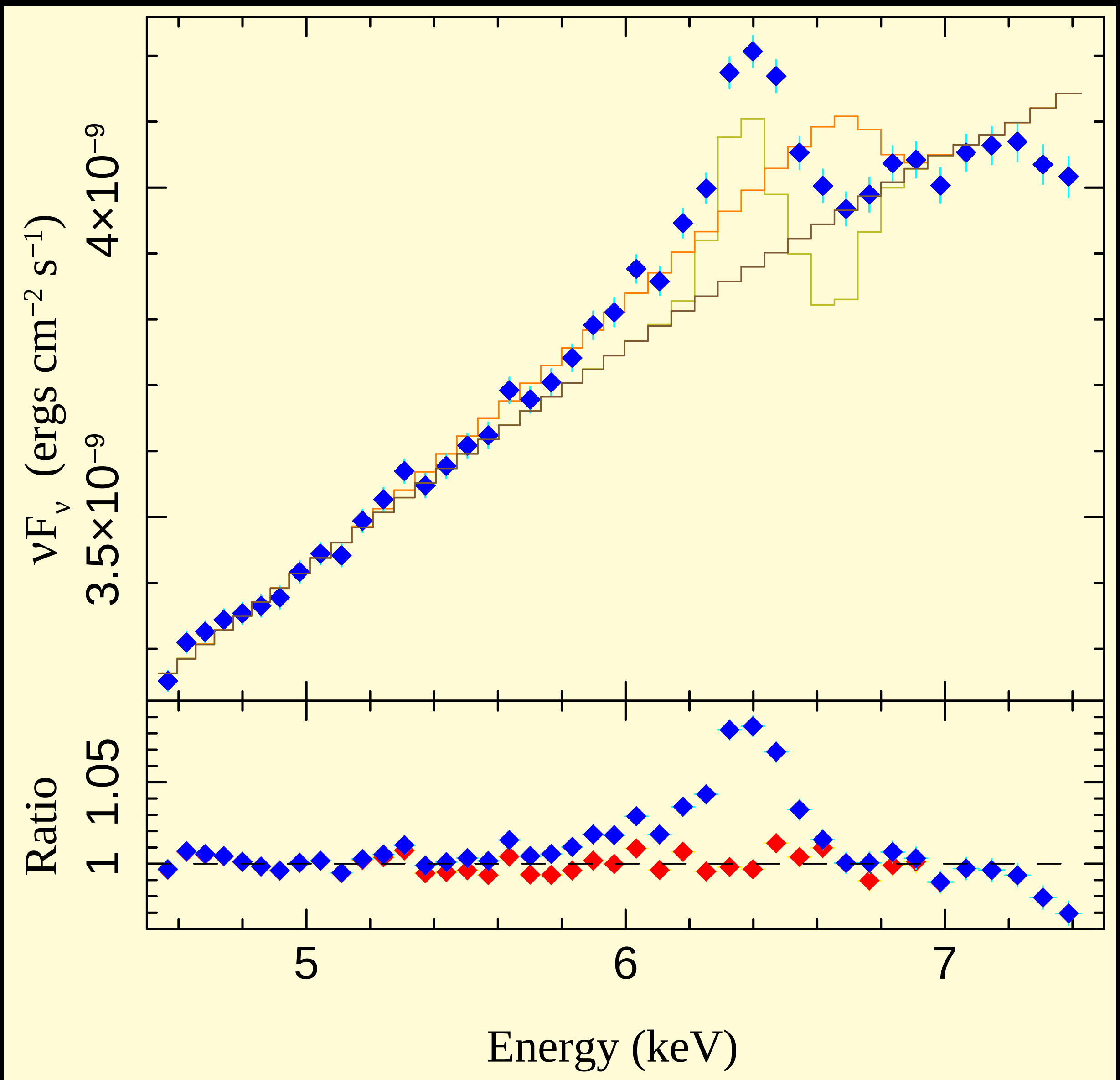
(*ASCA*; after Miller, 2007)



In the hard and intermediate states, galactic black holes show strong and broad Fe Kα lines.

Cyg X-1: $a \sim 1$ (?), $i > 45^{\circ}$, $\epsilon \propto r^{-3}$

Nowak et al. (2010, to be submitted)



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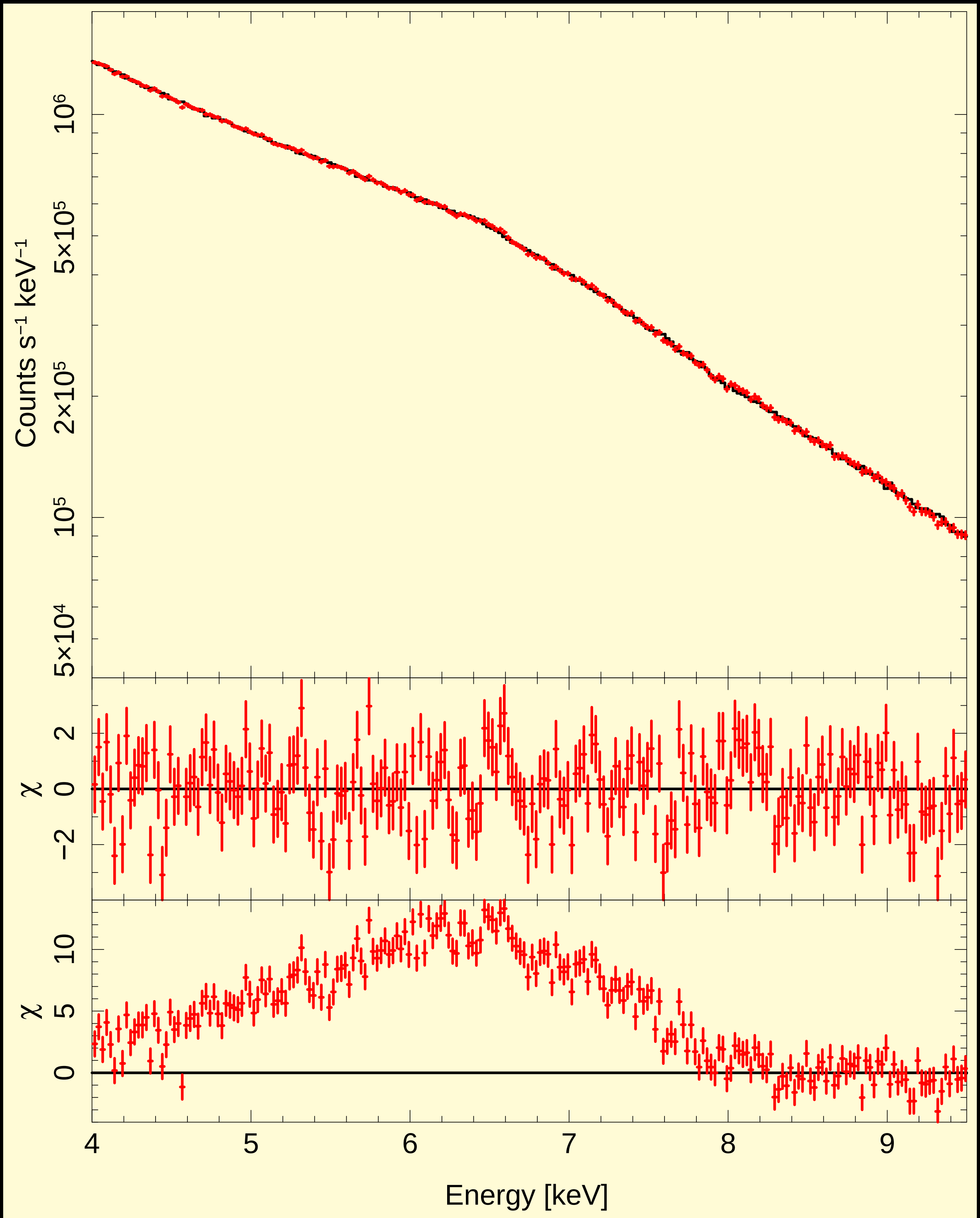

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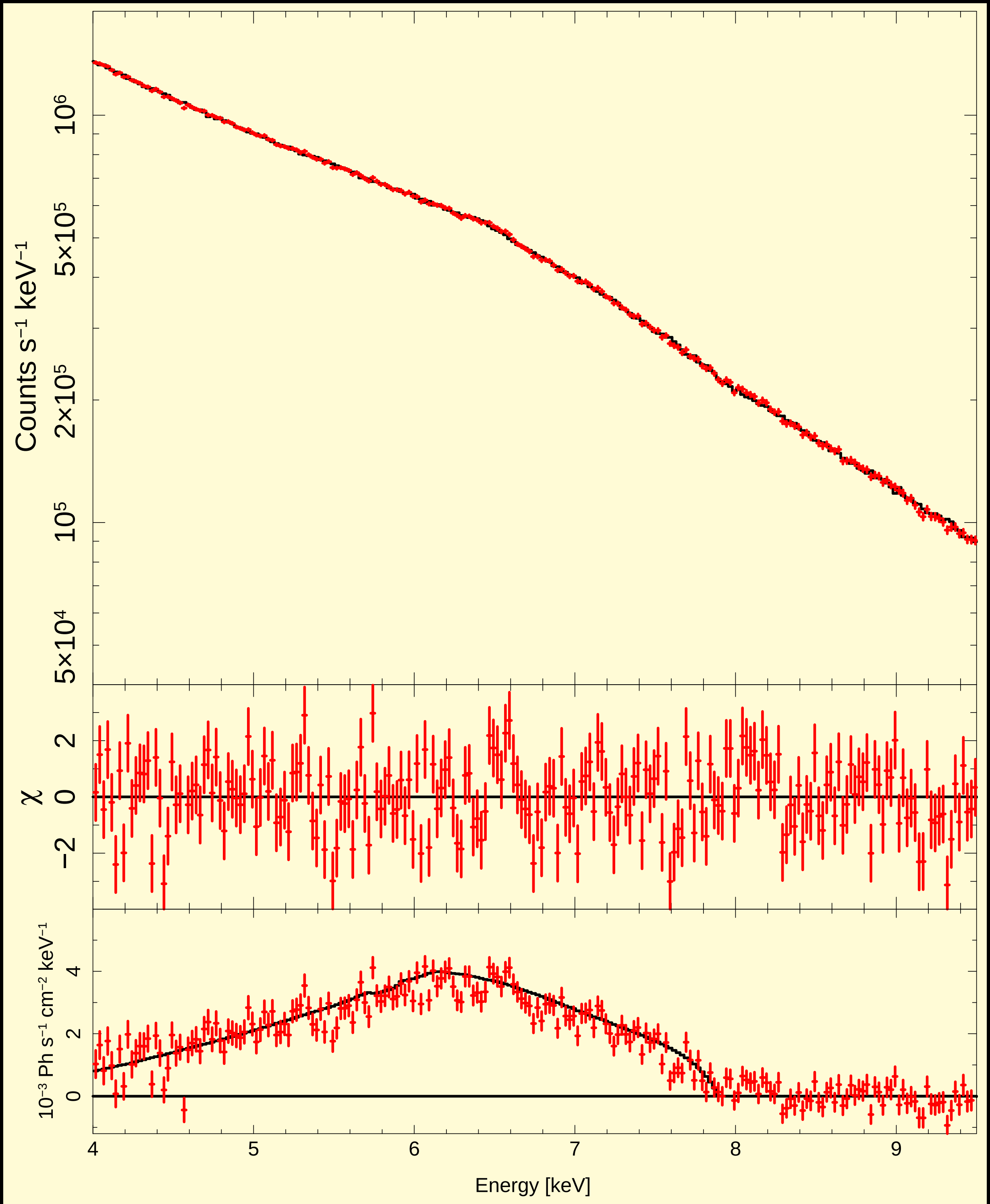
Fritz et al. (2007), Duro et al. (2010)



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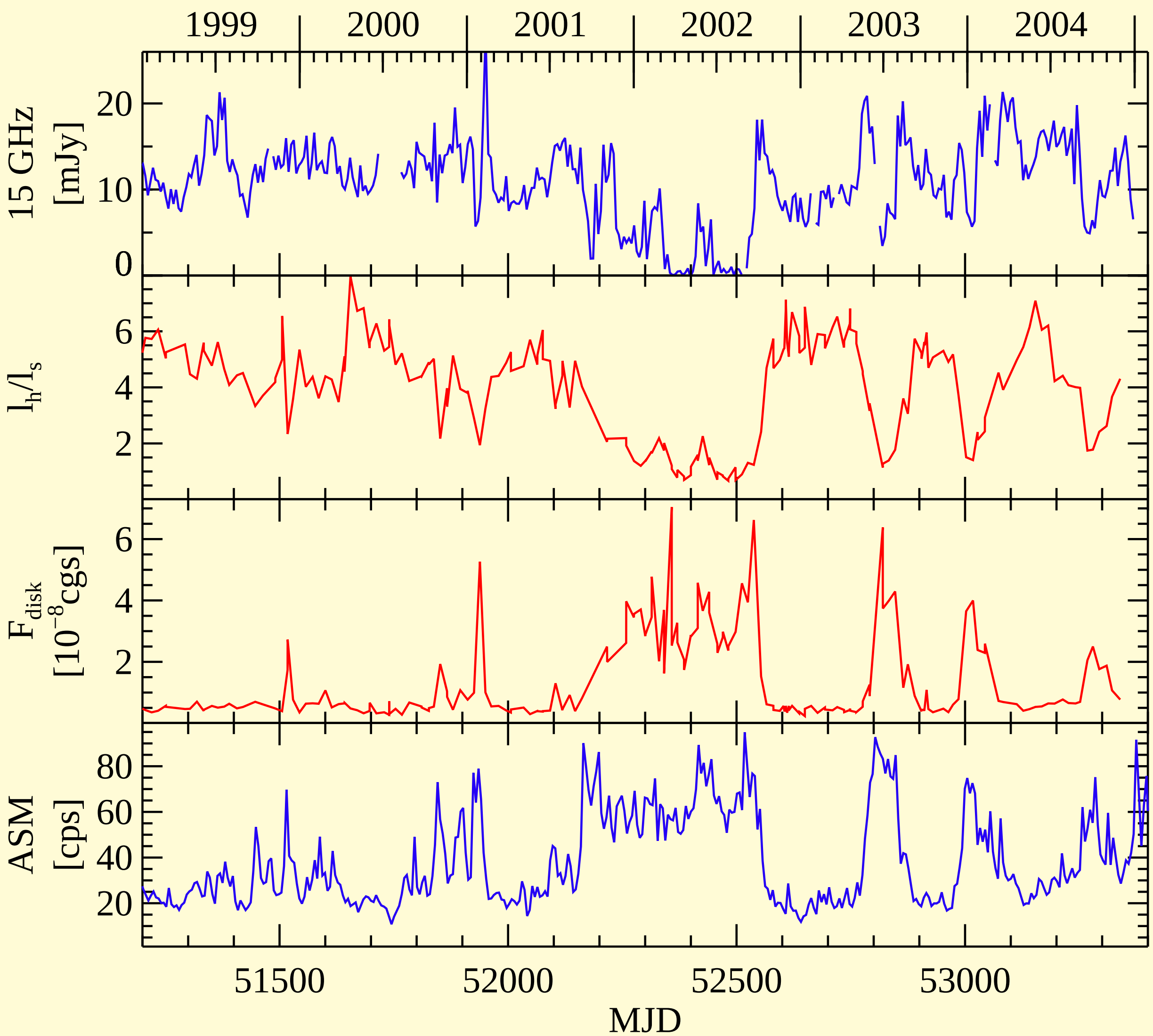
Black Hole States, I

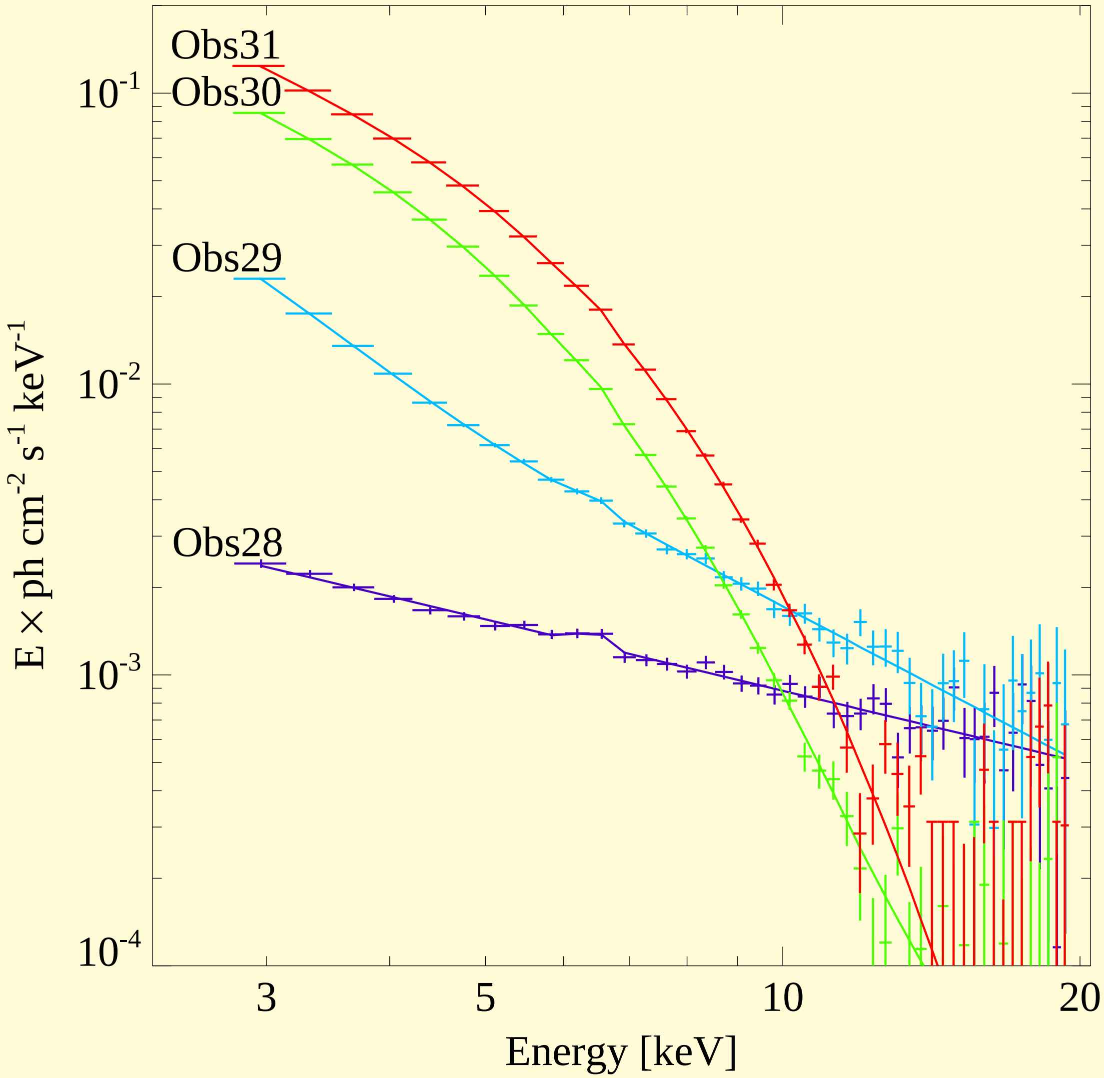


Cyg X-1 (Wilms et al., 2006)

Correlated variation of:

- the radio flux
- the amount of energy dissipated in the Comptonizing plasma relative to the accretion disk (ℓ_h/ℓ_s).
- the accretion disk flux
- the RXTE-ASM 2–10 keV count rate

Black Hole States, II

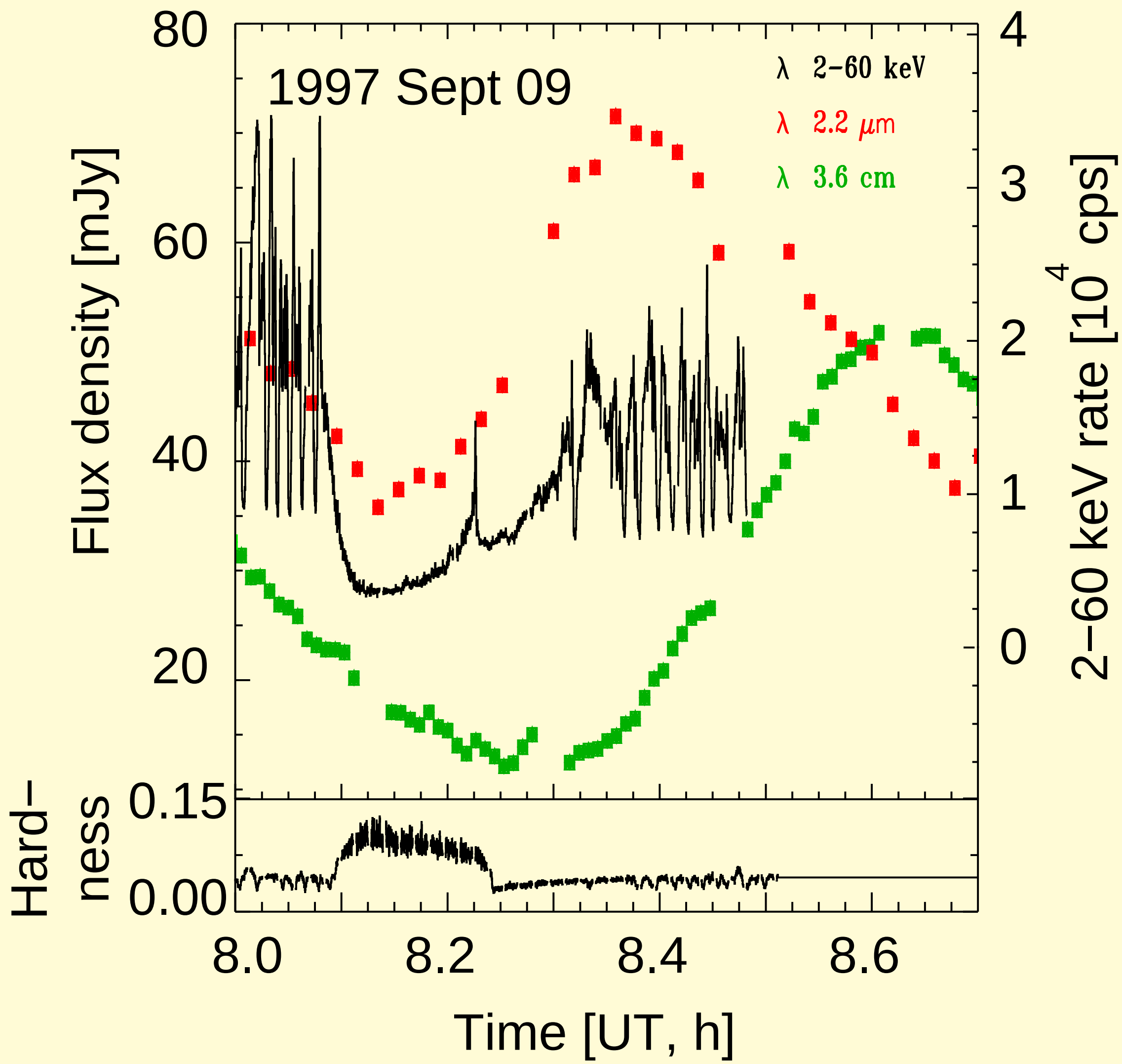


(LMC X-3; Wilms et al., 2001)

X-ray States:

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

Disk-Jet-Connection, I



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

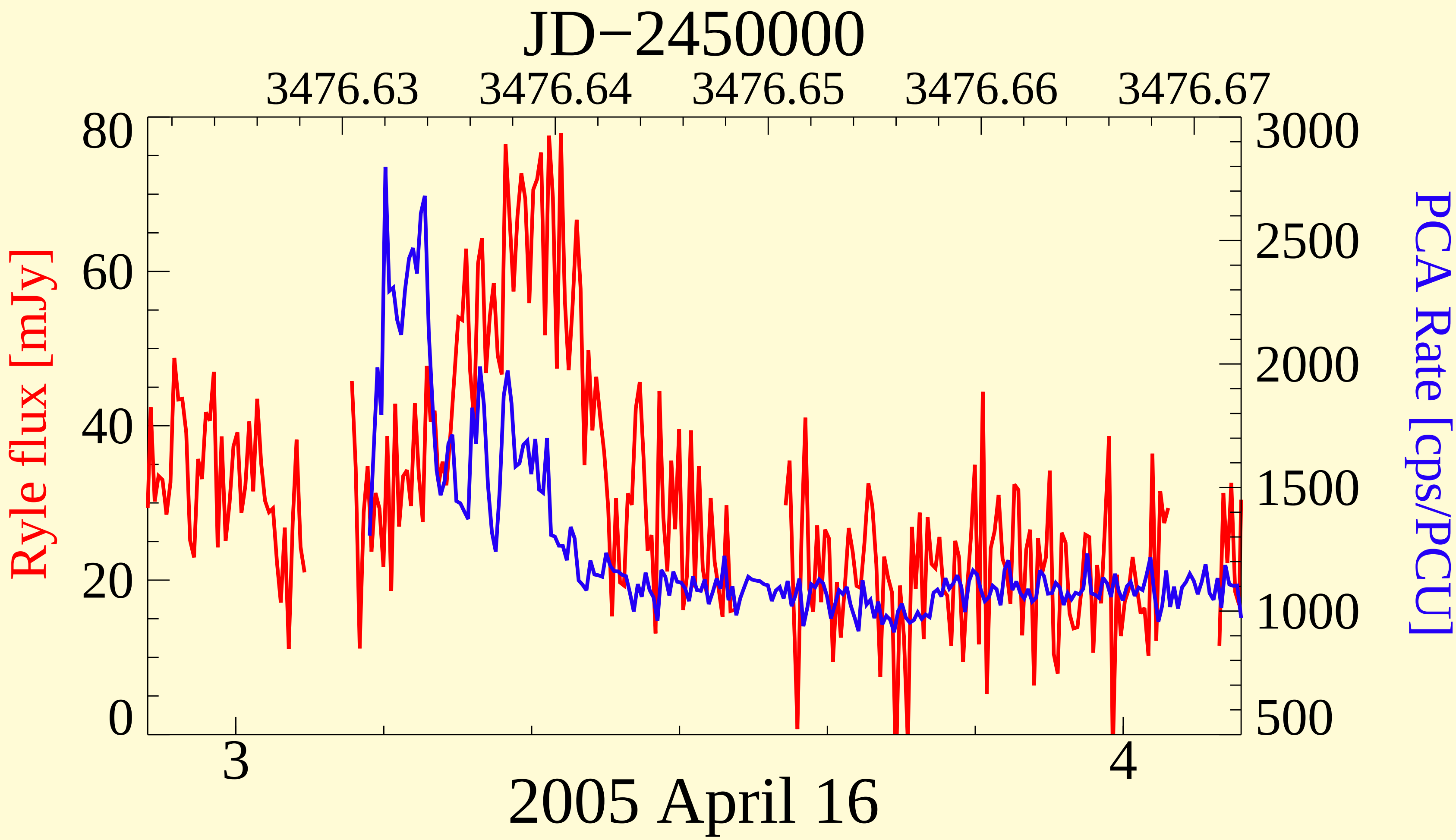
Microquasars allow study of dynamics of jet formation because of shorter timescales compared to AGN.

Flaring episodes: clear radio–X-ray relationship (like in AGN! cf. 3C120, Marscher et al.)

$\Longrightarrow$ "disk-jet-connection"

(cf. Mirabel & Rodriguez, 1994, Pooley & Fender, 1997, Rothstein, Eikenberry & Matthews, 2005,. . .)

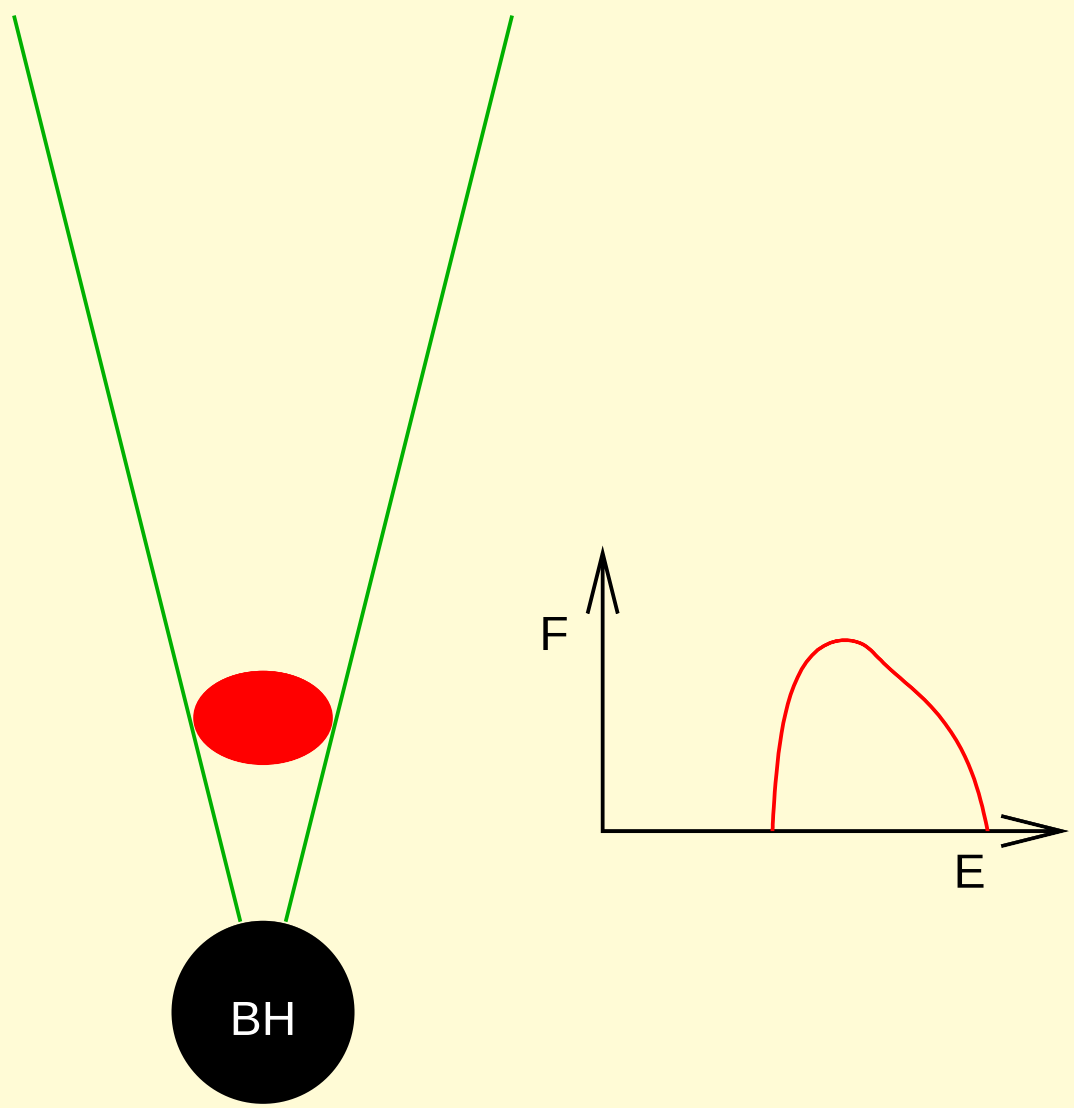
Disk-Jet-Connection, II



(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.

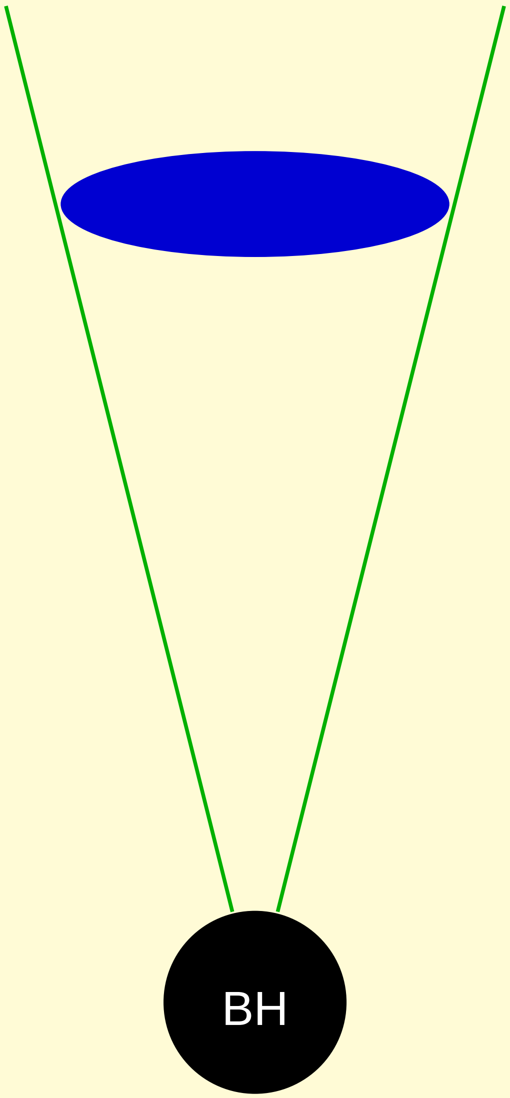
Disk-Jet-Connection, III

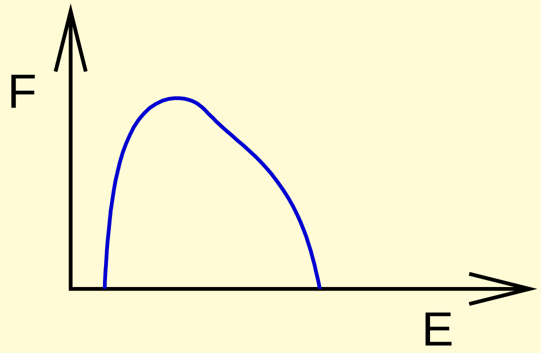


Short-term radio–X-ray correlations can be explained with the synchrotron bubble model

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

Disk-Jet-Connection, IV





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van der Laan (1966)
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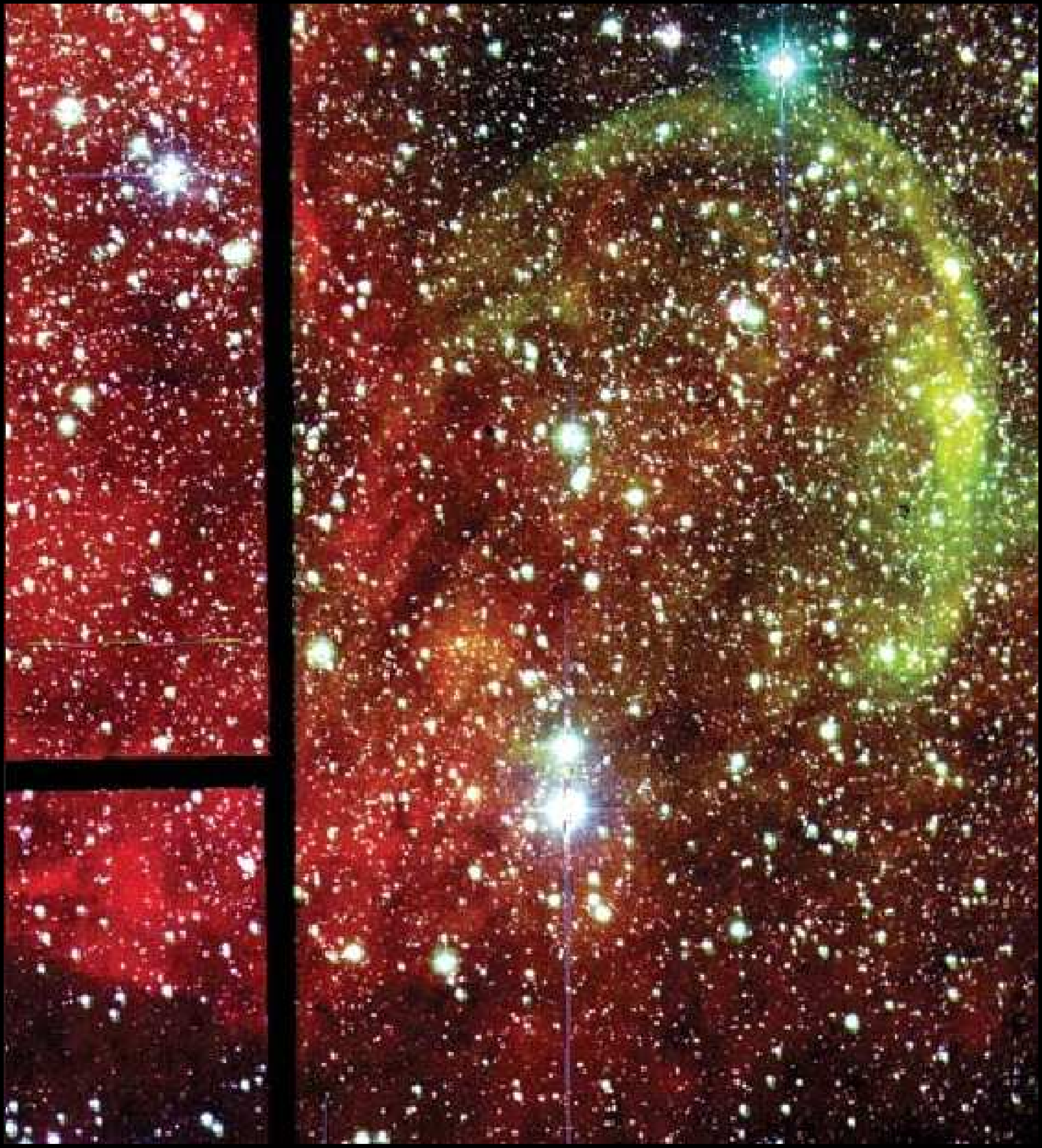
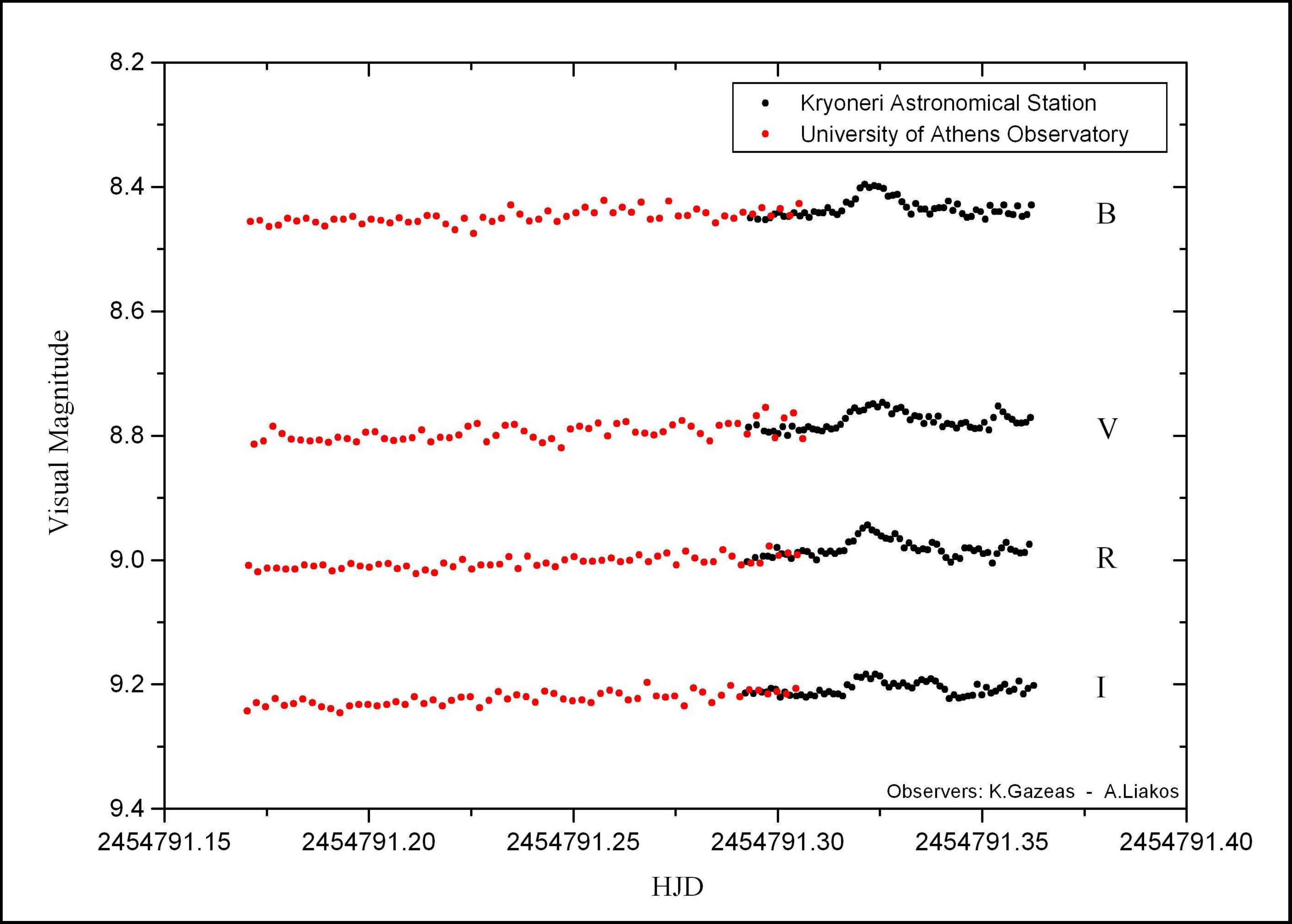


Gallo et al. (2005): Interaction of jet with interstellar medium: galactic black hole jets can be comparable in power to their X-ray luminosity.

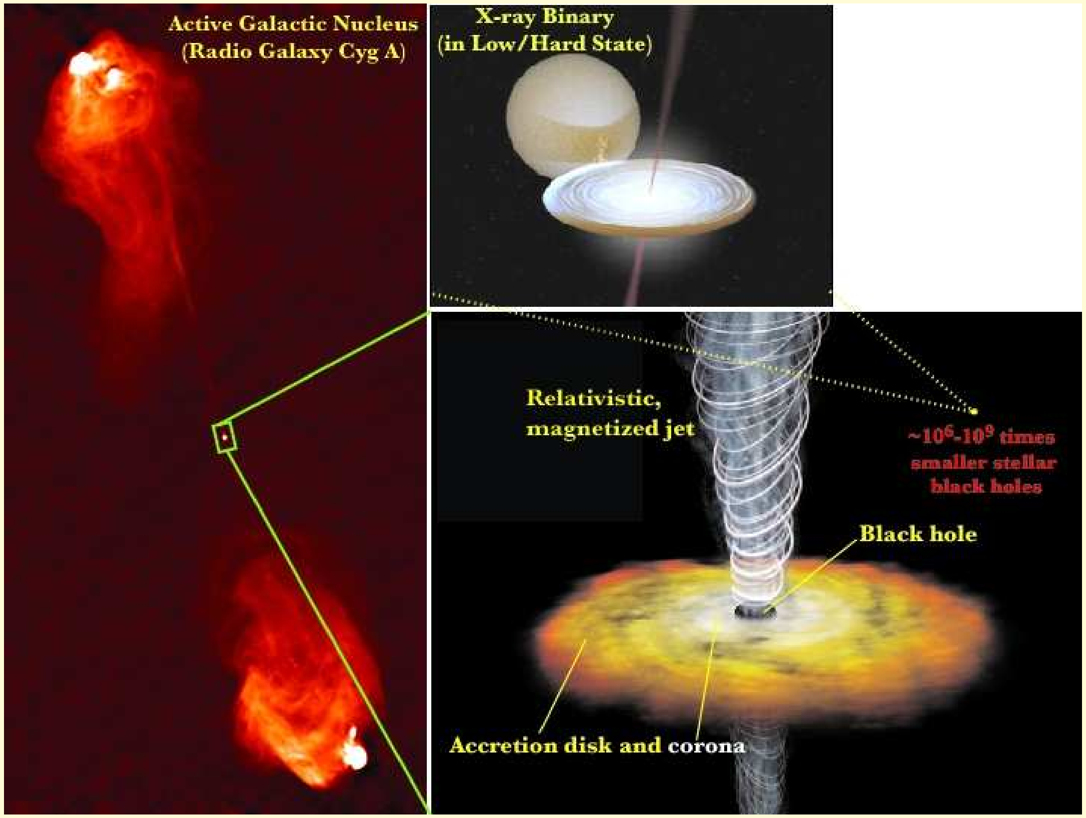
Russell et al. (2007):
for Cyg X-1, $L_{\text{jet}} = 0.3 \ldots 1.0\, L_{\text{X}}$.

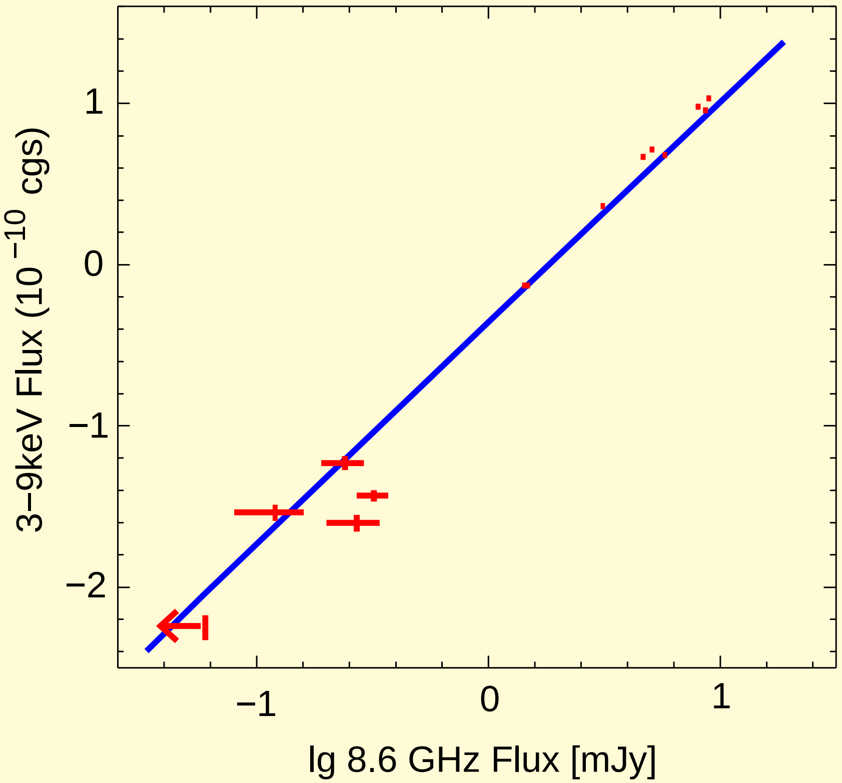
(Maccarone & Körding, 2006; image by D. Russell)



Flaring is also seen in optical (but very rare; no multiwavelength coverage yet).

X-rays: Jet Models?

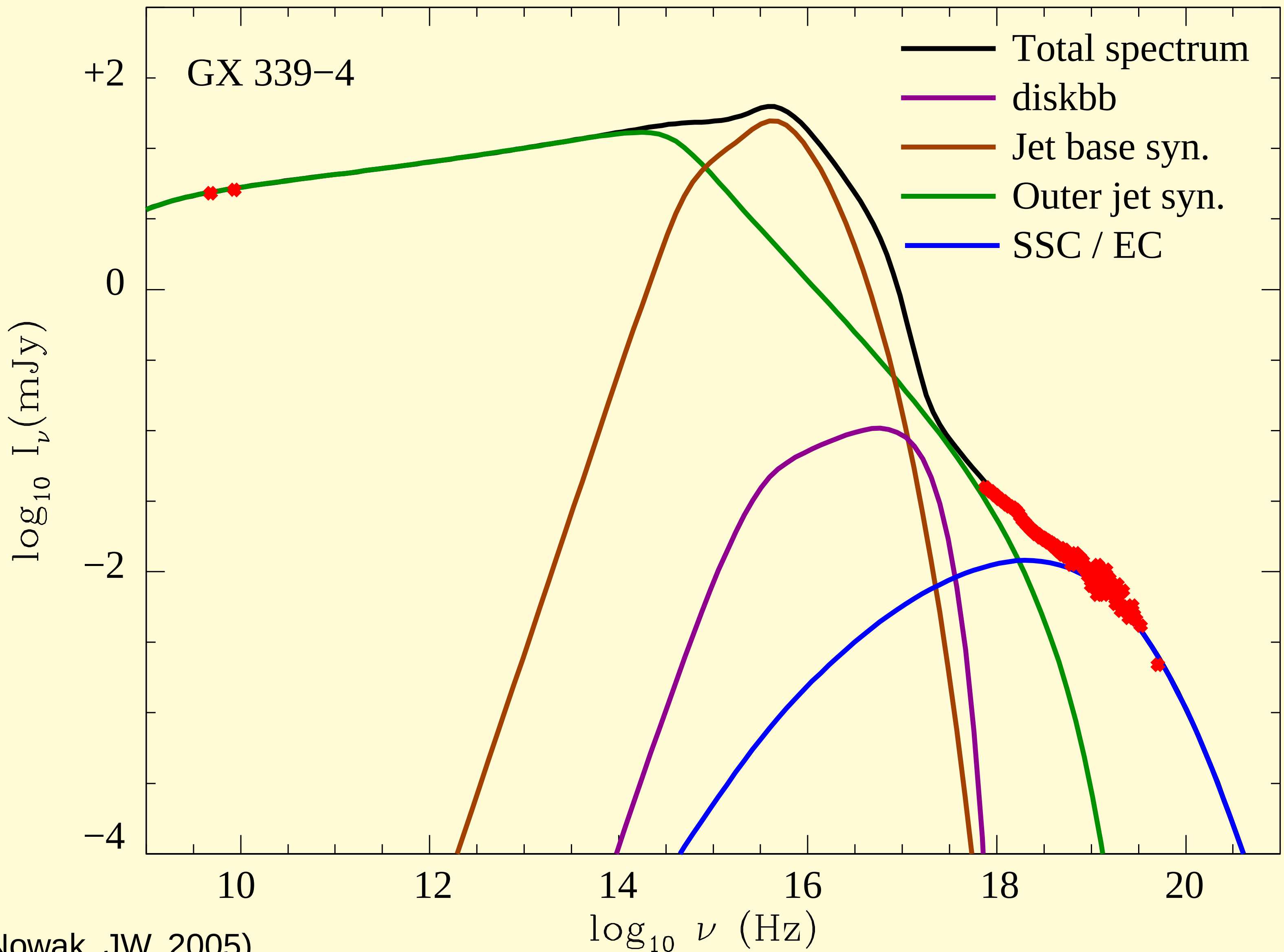




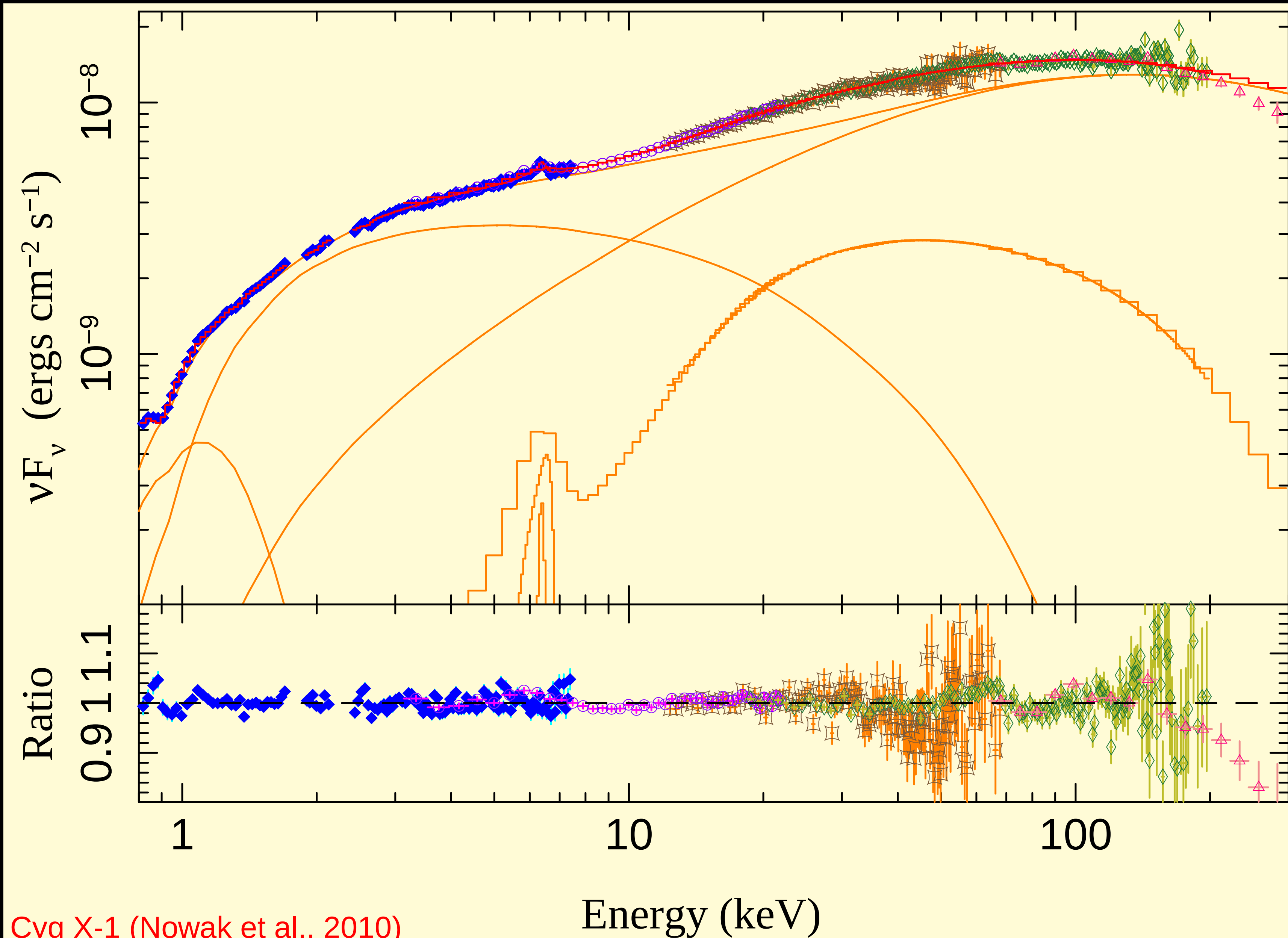
Markoff et al. (2003)

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

X-rays: Jet Models?

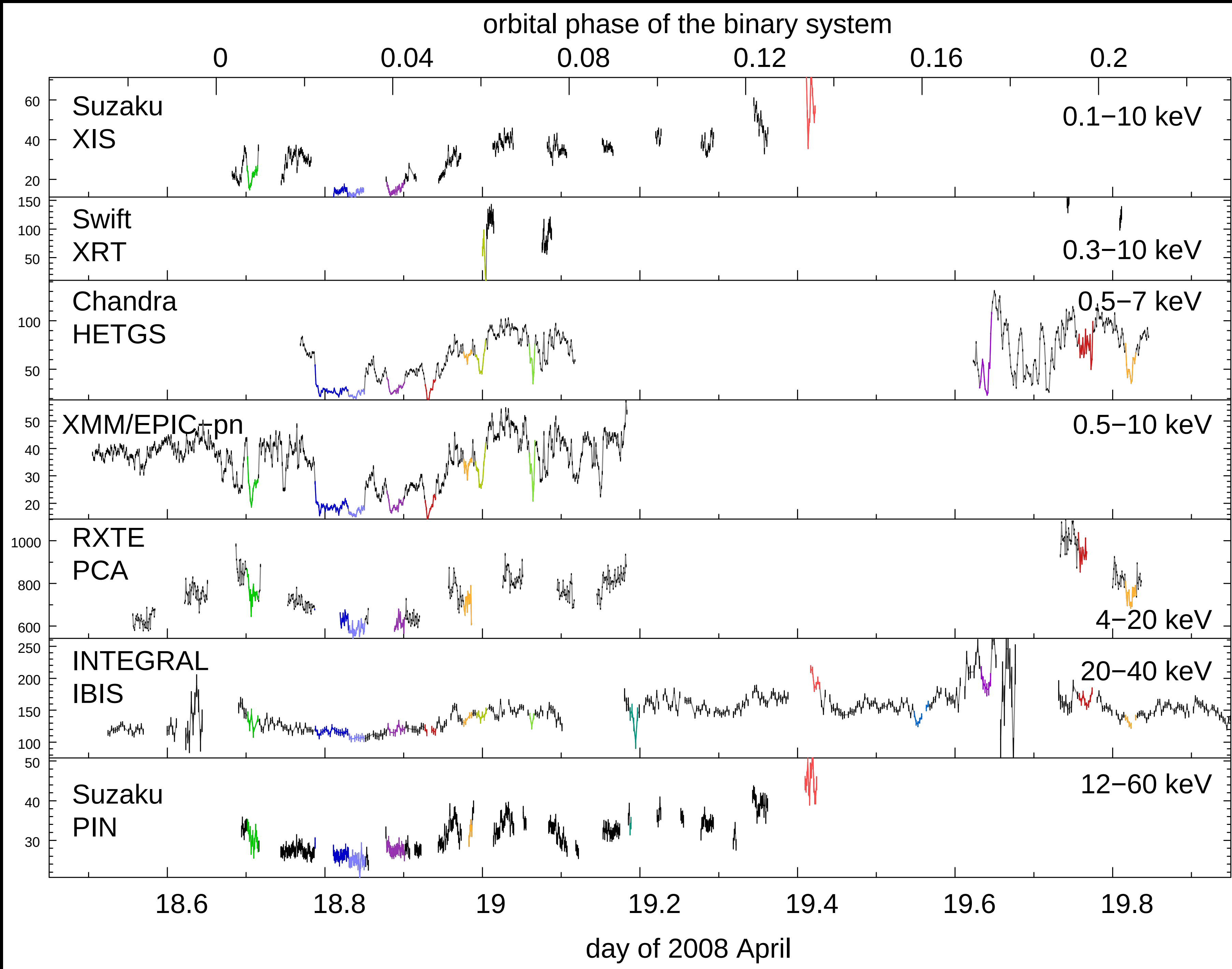


(Markoff, Nowak, JW, 2005)



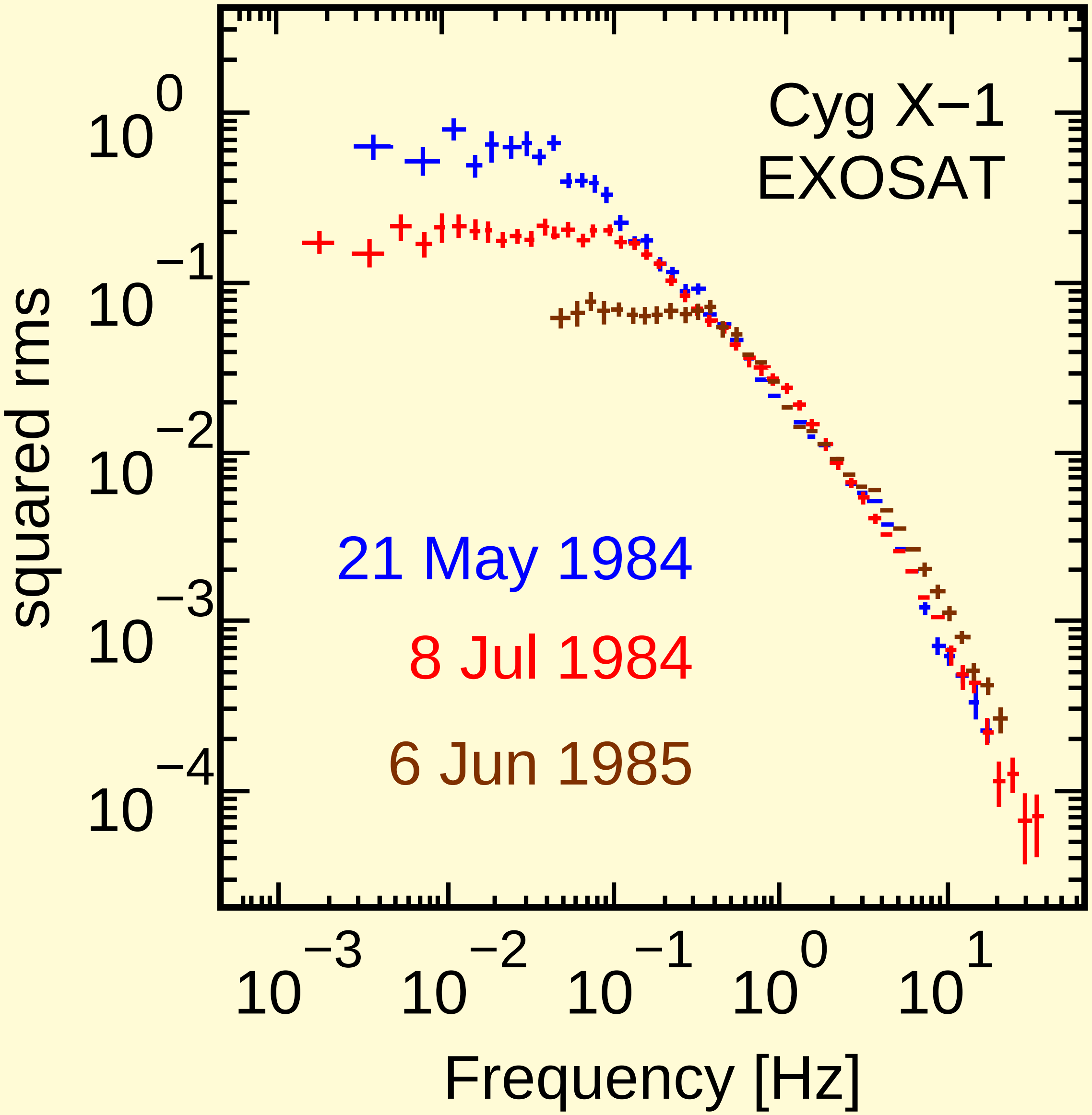
The hard state broad band spectrum can be equally well described with emission from the base of a jet.

Markoff et al. (2005)



Final unifying theme: variability

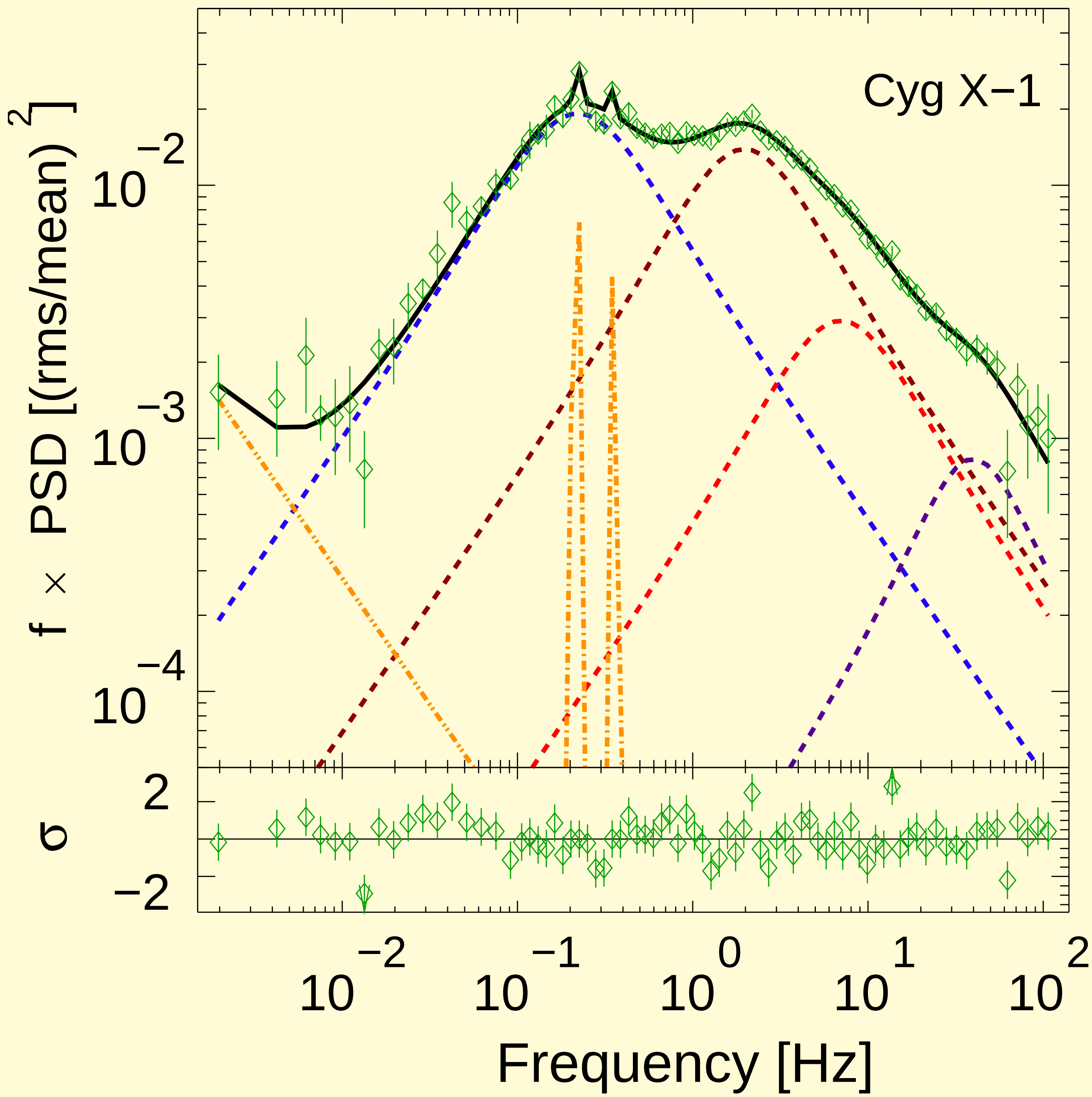
Timing: GBH, II



"Belloni-Hasinger (1990)-effect":

- Power spectrum of Cyg X-1 has a break
- Break frequency depends on source state.

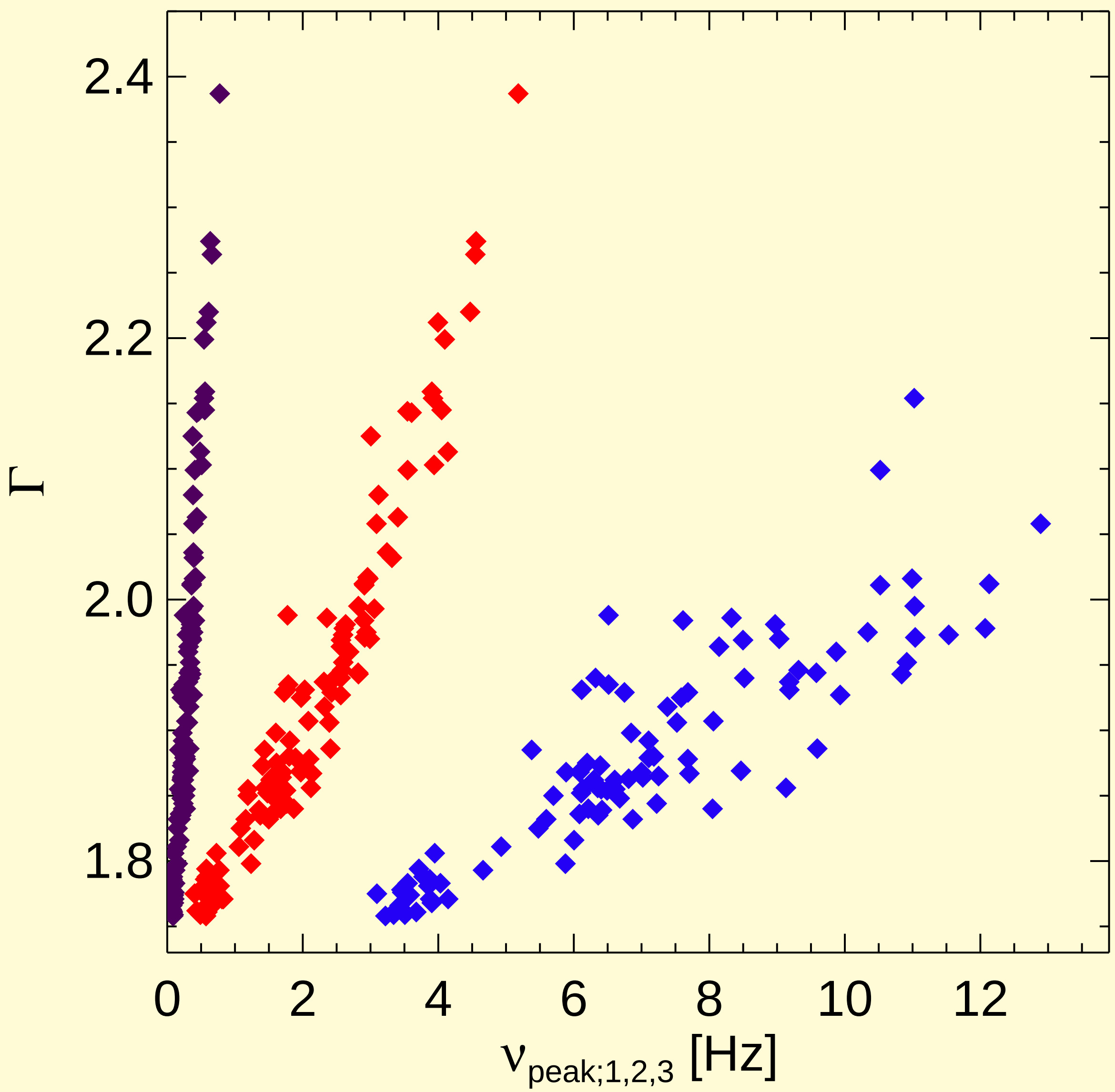
Timing: GBH, III



The power spectral density (PSD) of GBH in the hard state can be well described as sum of four Lorentzians

Nowak (2000),
Pottschmidt, JW, et al. (2002)

Timing: GBH, IV

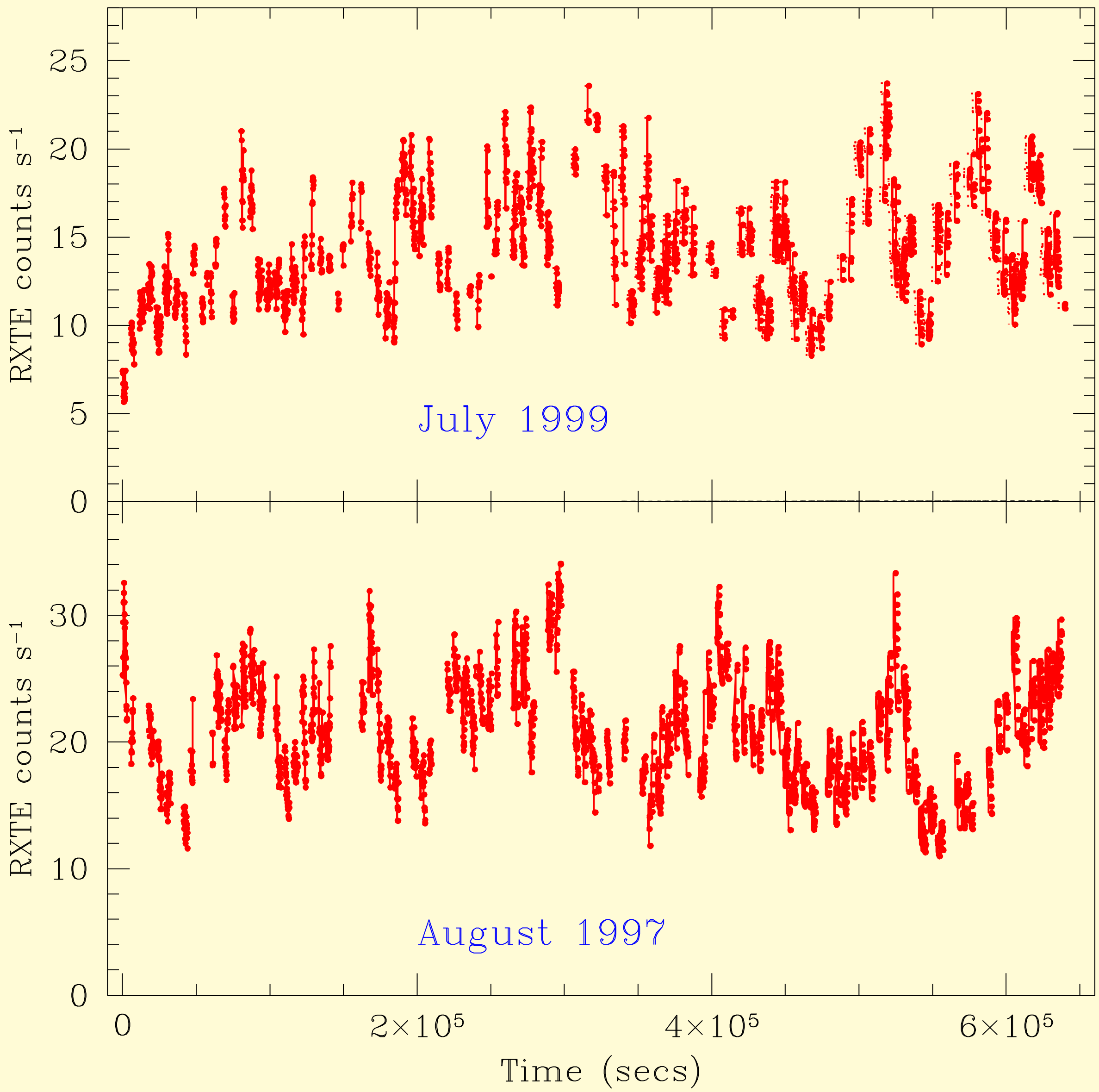


Peak frequencies of Lorentzians depend on source spectrum

. . . and also lie on correlations of Belloni, Psaltis & van der Klis (2002) between characteristic frequencies of *neutron stars*.

(Pottschmidt, JW, et al., 2002)

Timing: AGN, I

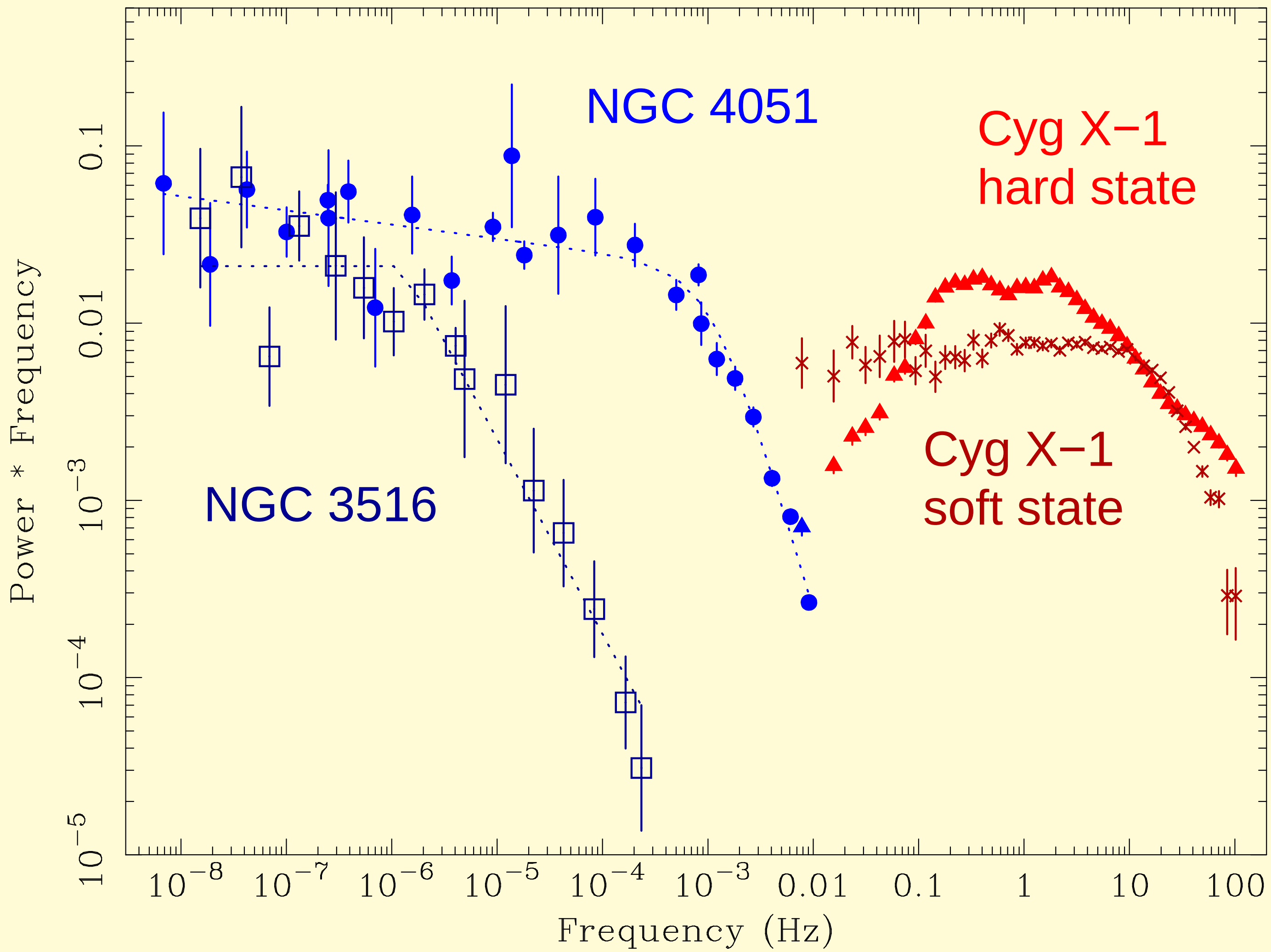


AGN lightcurves are similar to BHC lightcurves.

and their PSDs can often be described by Lorentzians (Pessah, 2007)

(MGC−6-30-15; McHardy et al., 2005)

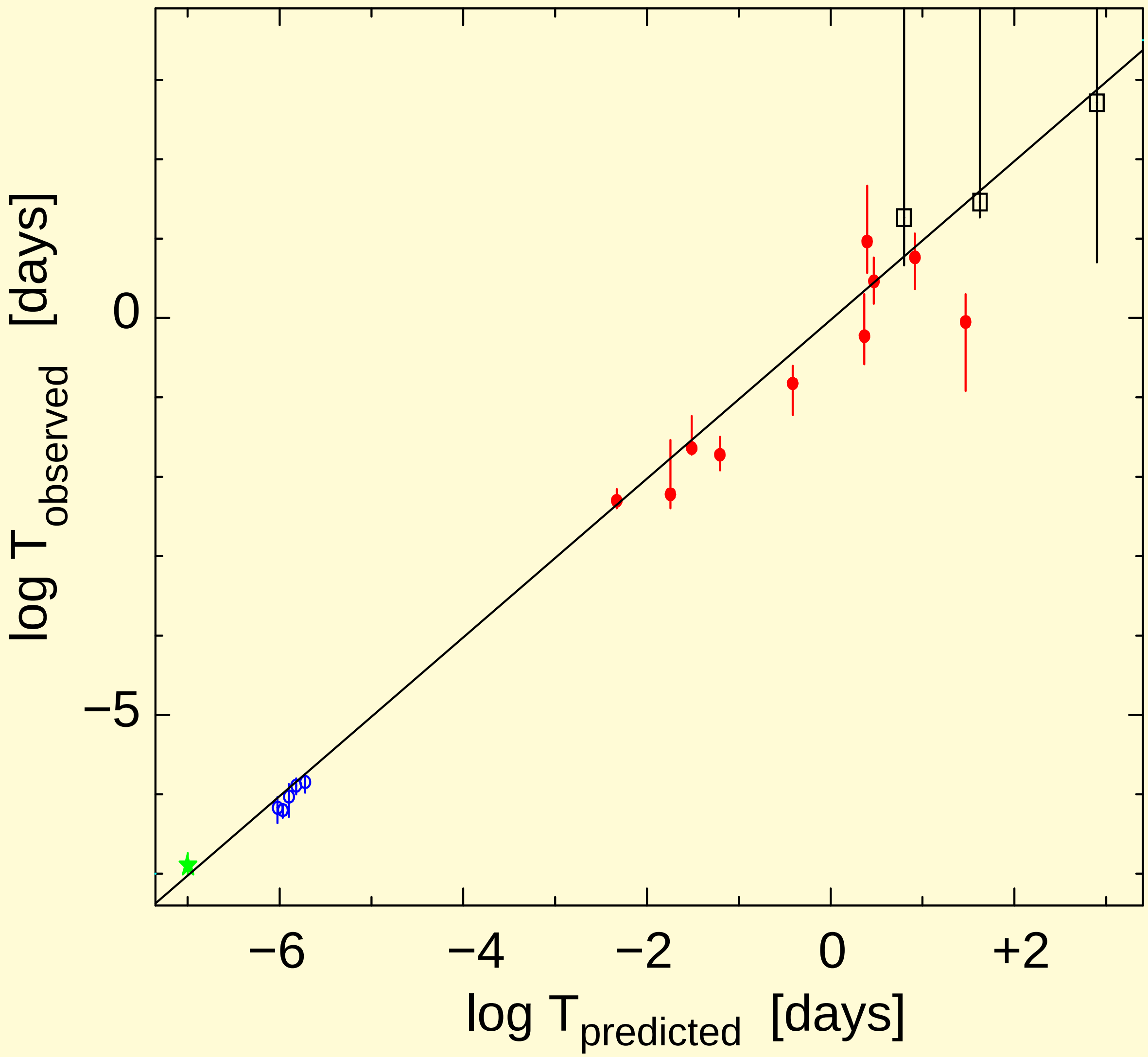
Timing: AGN, II



(McHardy et al., 2004)

Seyfert power spectra are similar to GBH power spectra in the soft state.

Timing: AGN, III



McHardy et al. (2006): Timescale of PSD break scales as

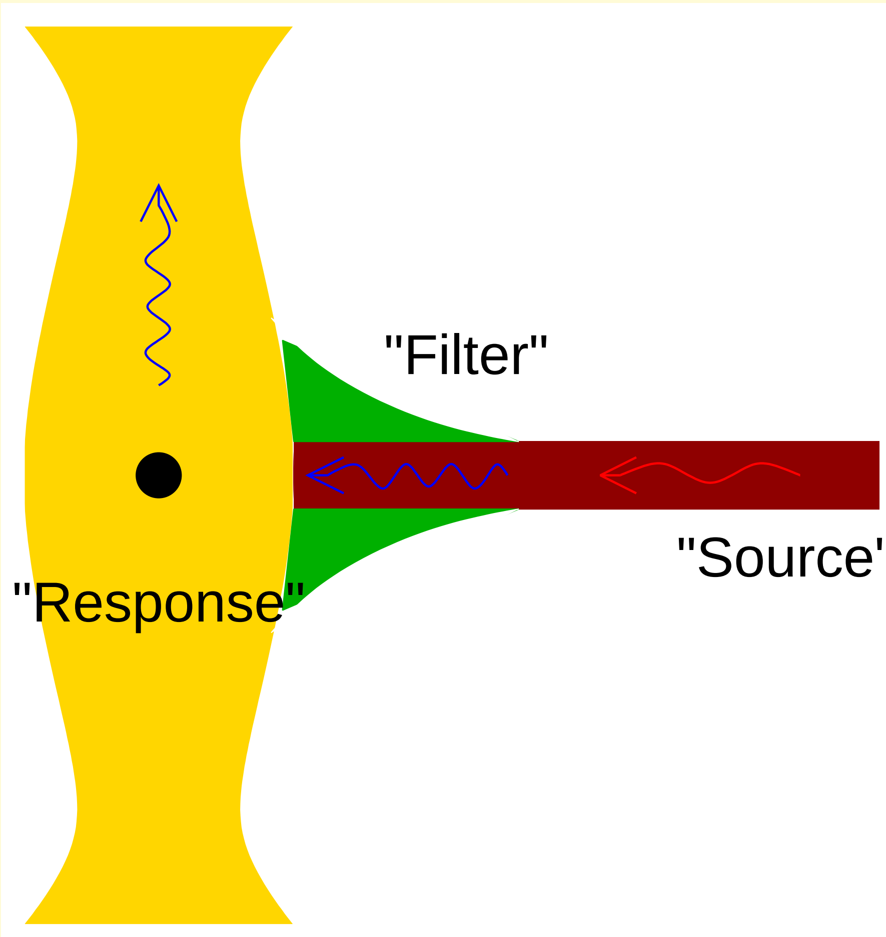
$$\log T_{\text{break}} = (2.10 \pm 0.15) \log M_{\text{BH}} - (0.98 \pm 0.15) \log L_{\text{bol}} - (2.32 \pm 0.20)$$

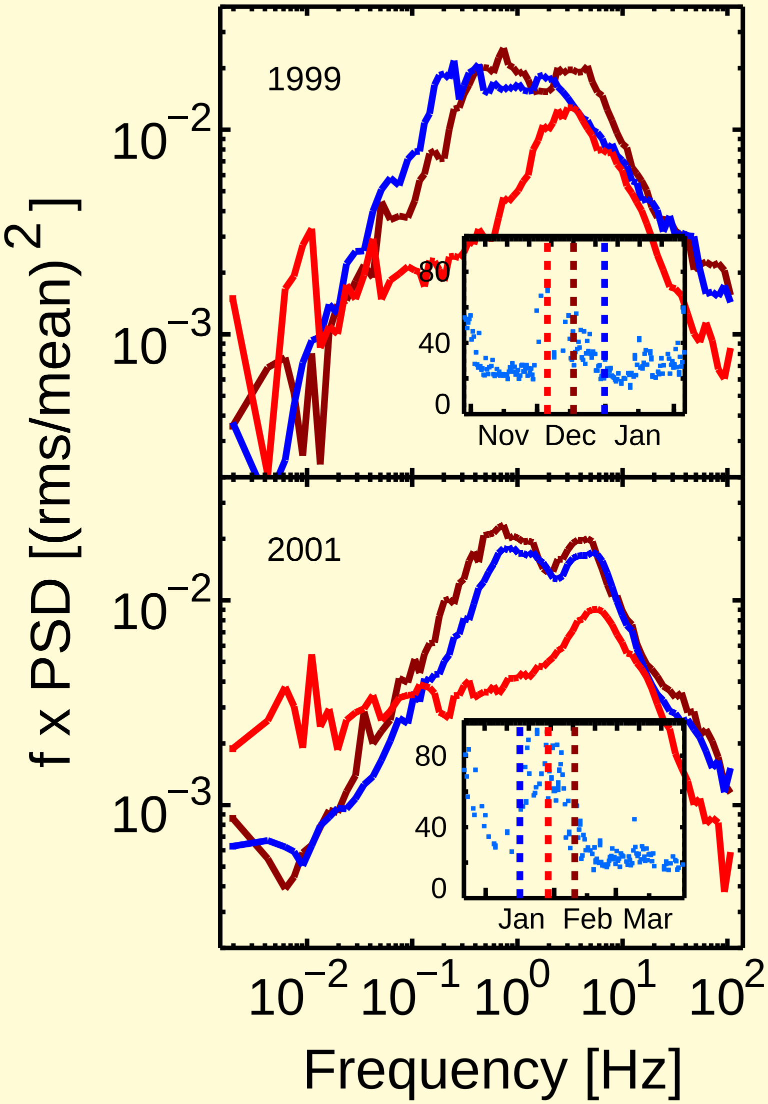
Since $L_{\text{bol}} \sim \dot{m}_{\text{Edd}} \dot{L}_{\text{Edd}}$ where $\dot{m}_{\text{Edd}} = \dot{M} / \dot{M}_{\text{Edd}}$:

$$T_{\text{break}} \propto M_{\text{BH}}^{1.12} \dot{m}_{\text{Edd}}^{-0.98}$$

McHardy et al. (2006)

Timing: Physical Model

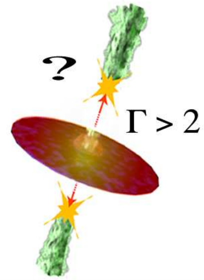




(Psaltis & Norman, 2001; Nowak, JW, et al., 1999; Miyamoto & Kitamoto, 1989)

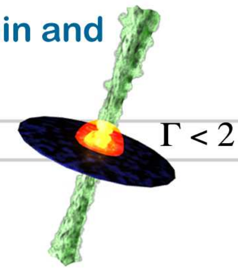
JET LINE AREA:

- 2 - 50% L_{Edd}.
- High-frequency QPOs (after) .
- Type A & B QPOs (after).
- See radio ejecta (fast) each "crossing" of jet line.
- RMS drop ("The Zone") associated with ~0.2 Hz lowest freqency Lorentzian, close to ejecta time.



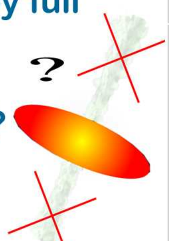
HIMS:

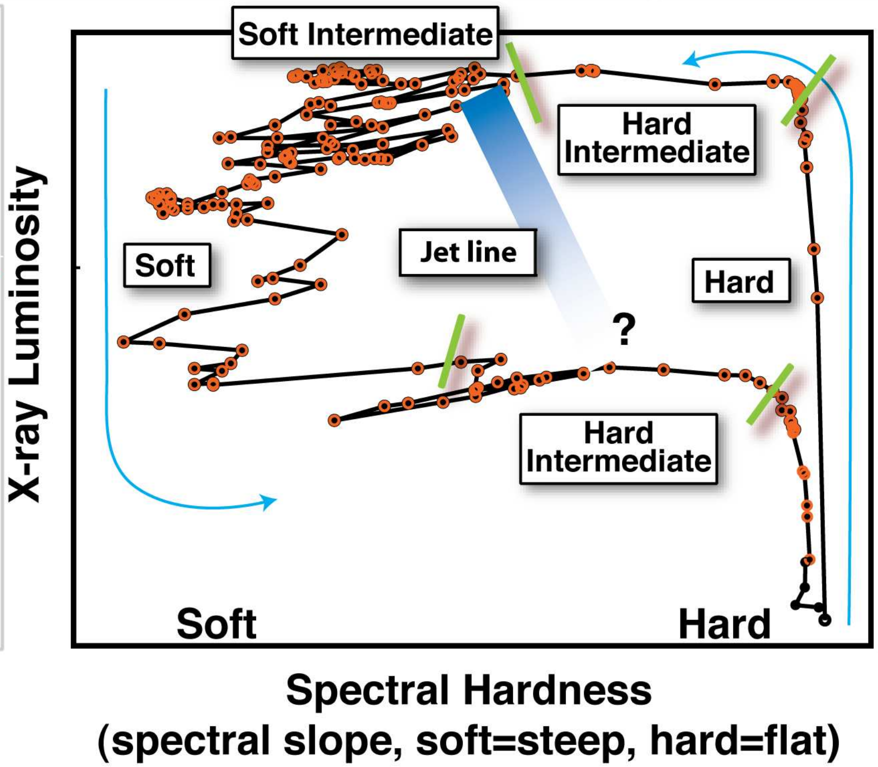
- Disk starts near ISCO.
- Transition starts around 2 - 50% L_{Edd}.
- Type C QPOs.
- IR drops.
- Radio starts going optically thin and variable (new ejecta?).



SOFT STATE:

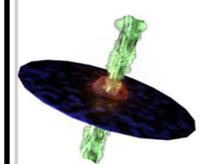
- Optically nuclear thin jet radio emission observed initially, but quenched by at least 20-50x by full transition.
  Detected radio flux not nuclear?
- Type C QPOs.
- Non-thermal power law extending to ~MeV .
- Thin disk ~0.1-1.0 L_{Edd} at ISCO.





HARD STATE:

- Disk moves in to ~ few R_g by 10% L_{Edd}.
- Lorentzian/broad noise components.
- High RMS variability.
  - Flat spectrum jet up to IR/opt.
  - Compact jet sometimes resolved.
  - Radio/IR/X-ray correlations.
  - Reflection "bump".



HIMS:

Same as upper branch but:

- No optically thin radio flare.
- Radio recovers close to hard state.
- Lower flux level (hysteresis).

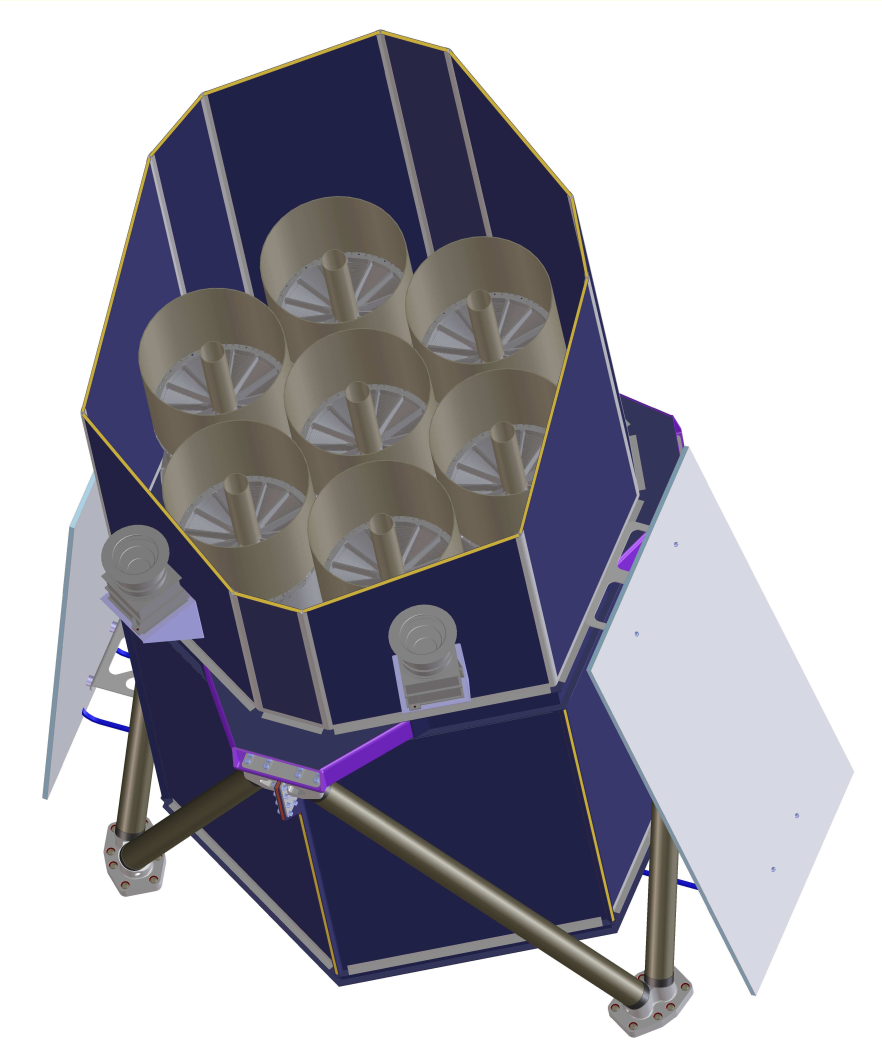
QUIESCENCE:

- Thin disk recessed to > 10^2 R_g
- BB component seen in UV/Optical.
- Disk 10-100x more luminous than LX. By ~10^{-4} L_{Edd}.
- No iron lines?

T. Belloni
A. Celotti
S. Corbel
R. Fender
E. Gallo
M. Hanke
E. Kalemci
D. Maitra
S. Markoff
I. McHardy
M. Nowak
P.-O. Petrucci
K. Pottschmidt
J. Wilms

INTERNATIONAL SPACE SCIENCE INSTITUTE
Probing the Accretion/Outflow Connection in X-Ray Binaries and Active Galactic Nuclei

Outlook, I



eROSITA (courtesy P. Predehl)

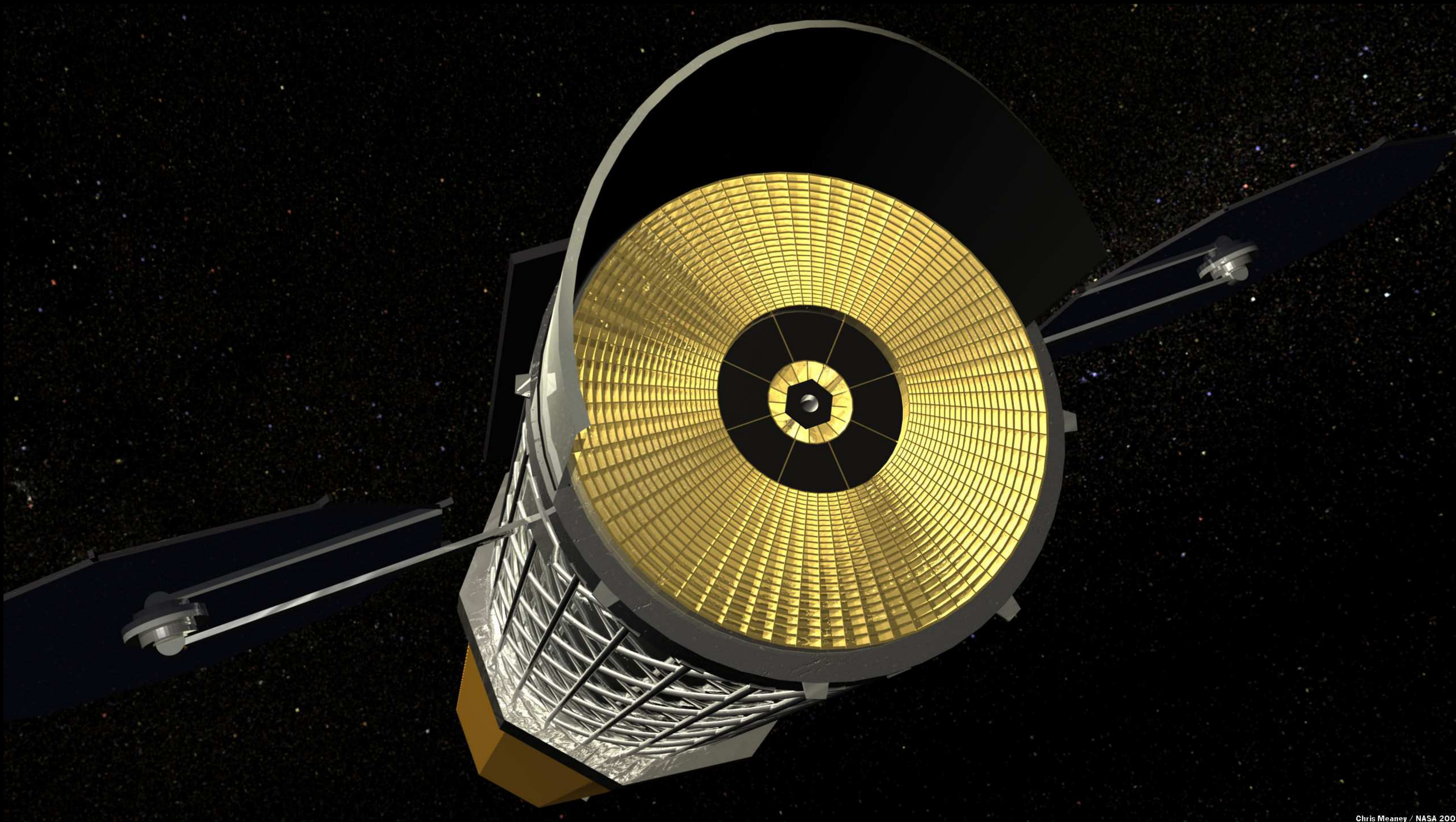
Cosmology: Black Holes play a significant role in structure formation.

"Structures": Galaxies and galaxy clusters

$\Longrightarrow$ *Spectr-RG*:

- X-ray survey of the whole sky (3 years)
- most sensitive survey of black holes ever
- Russian satellite bus, experiments:
  - *eROSITA* (CCDs): MPE, IAA Tübingen, Potsdam, Hamburg, FAU, Bonn, industry
  - *ART-XC*: Roscosmos
- Launch: 2012/2013, Operations until 2016–

2 Million AGN, 100000 Galaxy clusters,...



IXO (ESA/NASA/JAXA; 2020/2021)

WFI: Deep observations of high-z AGN & HTRS for Galactic sources

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