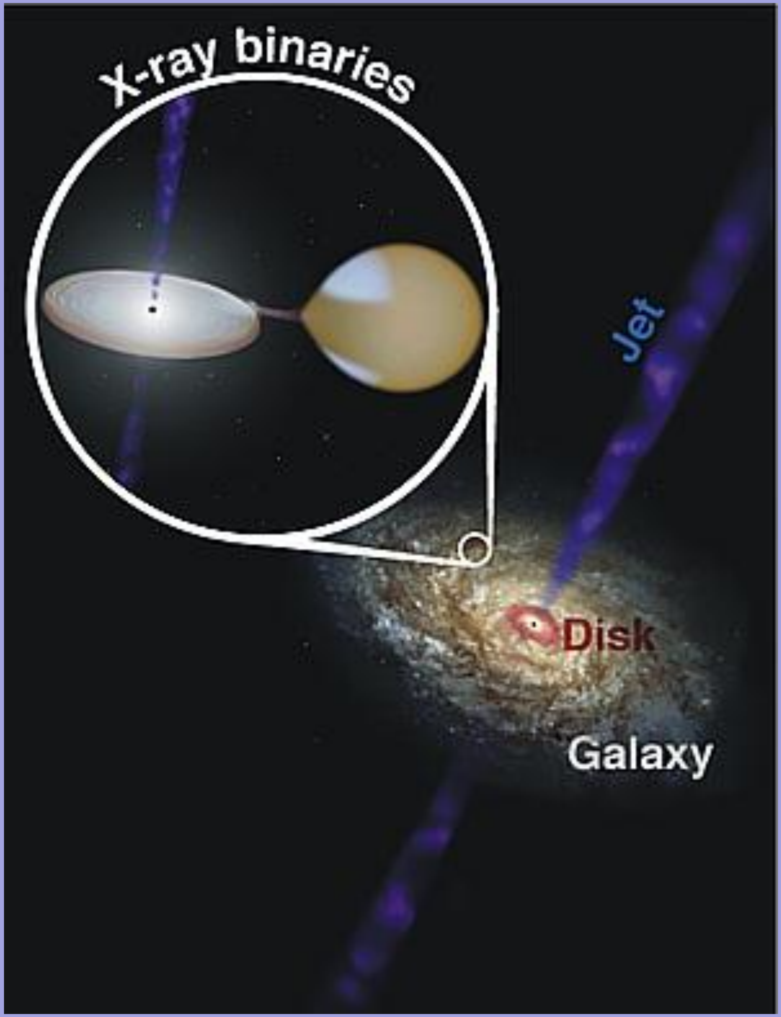
X-ray spectral variability

a scrapbook collection

Simon Vaughan

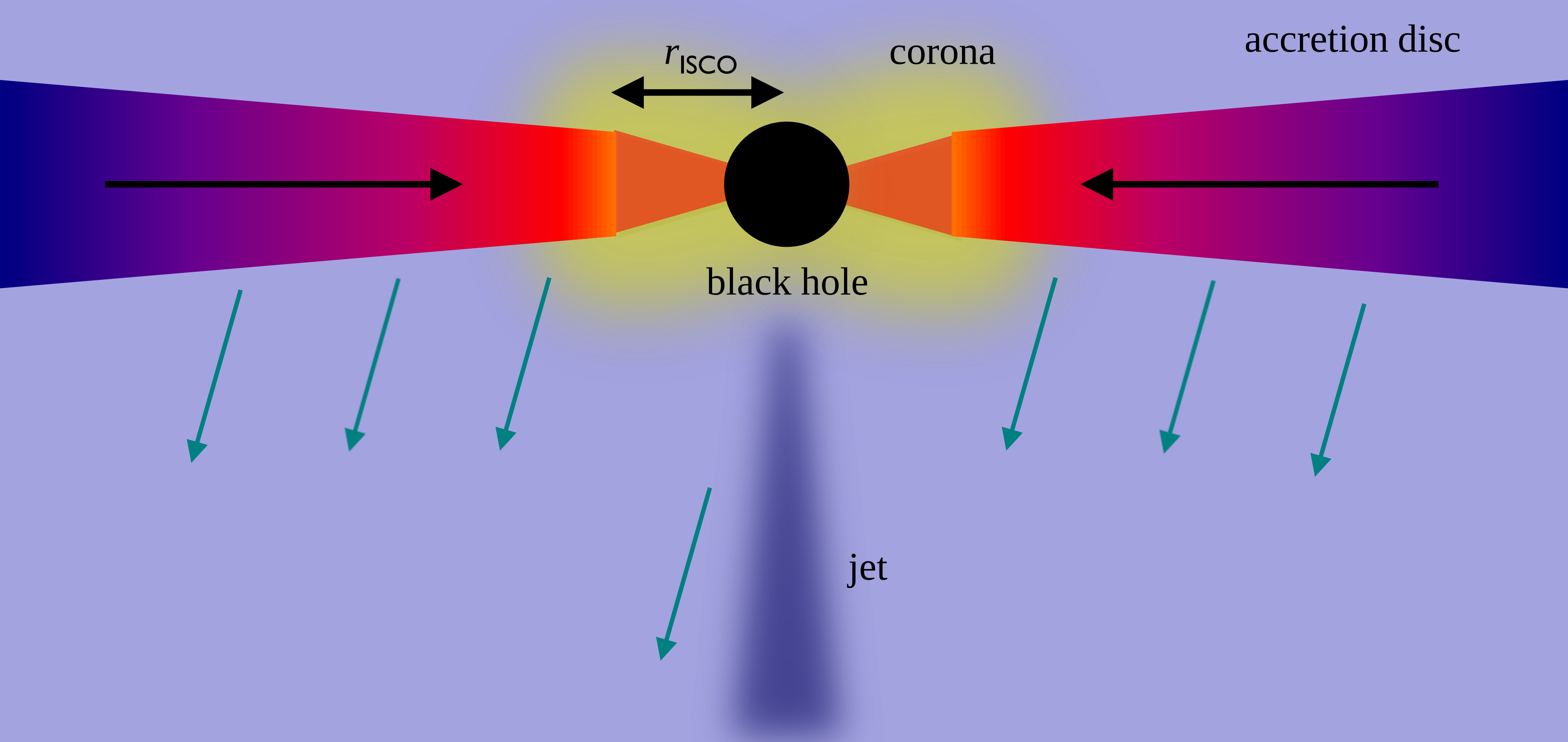
(University of Leicester)



I will aim to provide

- Some motivation for examining X-ray spectral variability
- Predictions of "toy models" for atomic features and continua
- Data sources past, present and future
- Different ways to look at spectral variability
- Plenty of references for further reading

Observations of the black hole region



Photons (mainly EUV + X-rays) { Spatial (x,y) – unresolved (until interferometry)
Time (t) } this is what we have
Energy (E)
Polarization (PA) – possible with future missions

A priori ... timescales or frequencies

$$f_{lc} \sim 2\times10^5\left(\frac{r}{r_g}\right)^{-1}\left(\frac{M}{M_\odot}\right)^{-1}\mathrm{Hz} \qquad \left[\left(\frac{GM_\odot}{c^3}\right)^{-1} = 2\times10^5\right]$$

$$f_{dyn} \sim 2\times10^5\left(\frac{r}{r_g}\right)^{-3/2}\left(\frac{M}{M_\odot}\right)^{-1}\mathrm{Hz} \sim 2\pi f_\phi$$

$$f_{therm} \sim f_{dyn}\alpha \sim 2\times10^4\left(\frac{\alpha}{0.1}\right)\left(\frac{r}{r_g}\right)^{-3/2}\left(\frac{M}{M_\odot}\right)^{-1}\mathrm{Hz}$$

$$f_{visc} \sim f_{dyn}\alpha\left(\frac{h}{r}\right)^2 \sim 2\times10^2\left(\frac{\alpha}{0.1}\right)\left(\frac{h/r}{0.1}\right)^2\left(\frac{r}{r_g}\right)^{-3/2}\left(\frac{M}{M_\odot}\right)^{-1}\mathrm{Hz}$$

Timescale	10 M_{sun}	10^6 M_{sun}
Light crossing	0.3 ms	30 s
Dynamical	1 ms	100 s
Thermal	0.1 ms	1000 s
Viscous	1 s	100 ks

[assuming $\alpha \sim 0.1$, $h/r \sim 0.1$, $r/r_g \sim 6$]

A different figure of merit: count/timescale

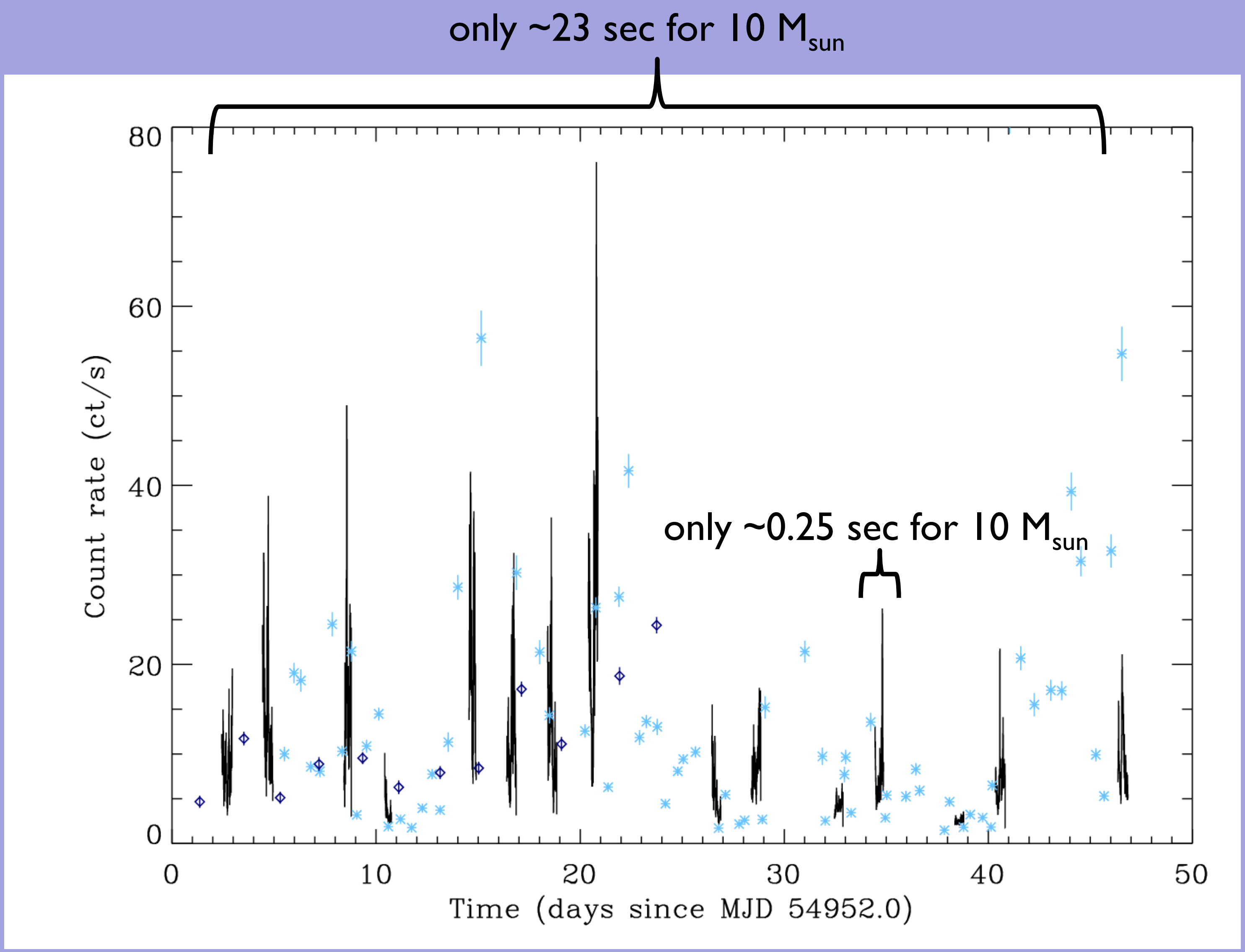
For example: *XMM-Newton* (EPIC pn)

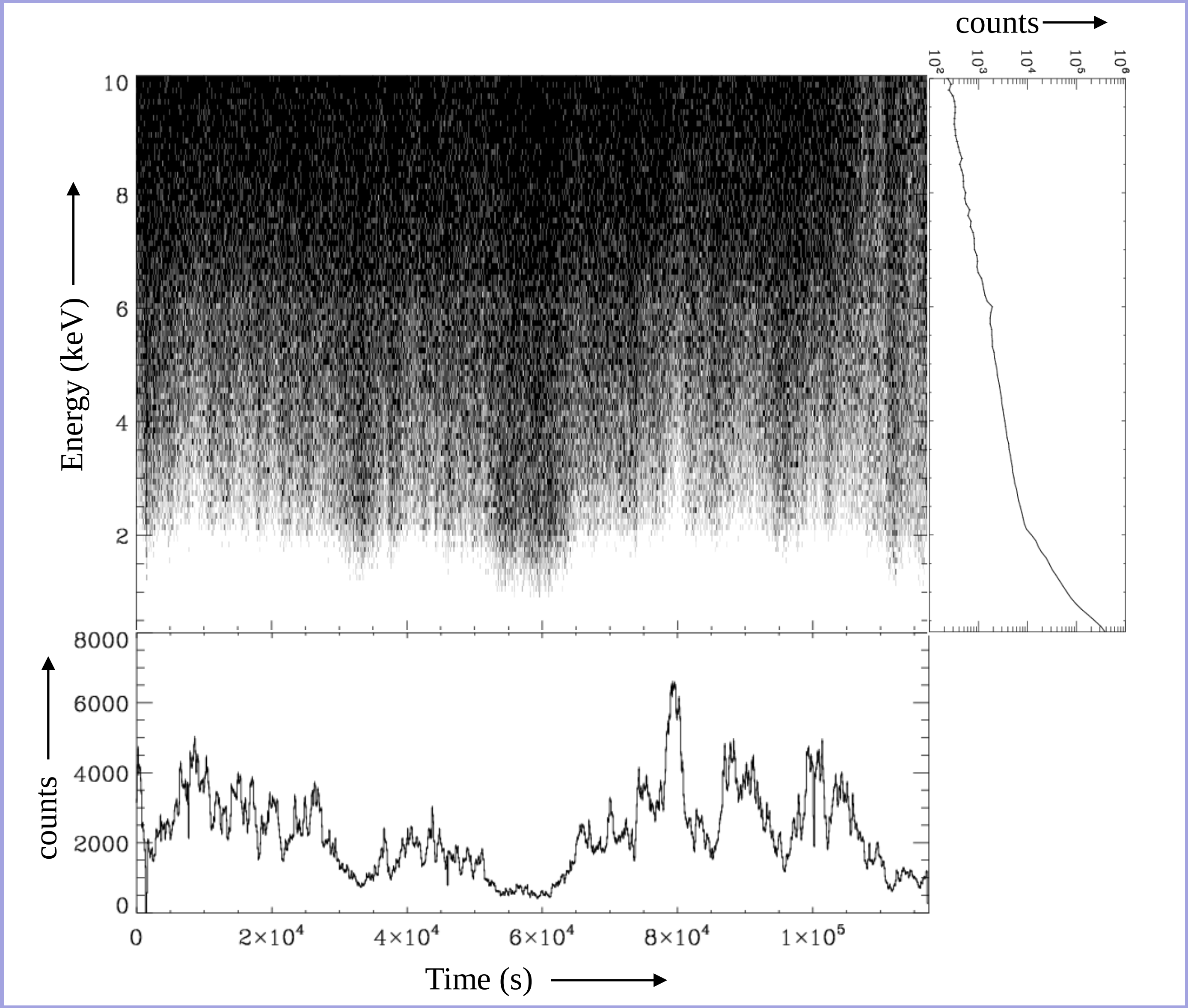
XRB: ~1000 ct/s → ~1 ct/dynamical time
AGN: ~10 ct/s → ~1000 ct/dynamical time

Timescale	$10\ M_{sun}$	$10^6\ M_{sun}$
Light crossing	0.3 ms	30 s
Dynamical	1 ms	100 s
Thermal	0.1 ms	1000 s
Viscous	1 s	100 ks

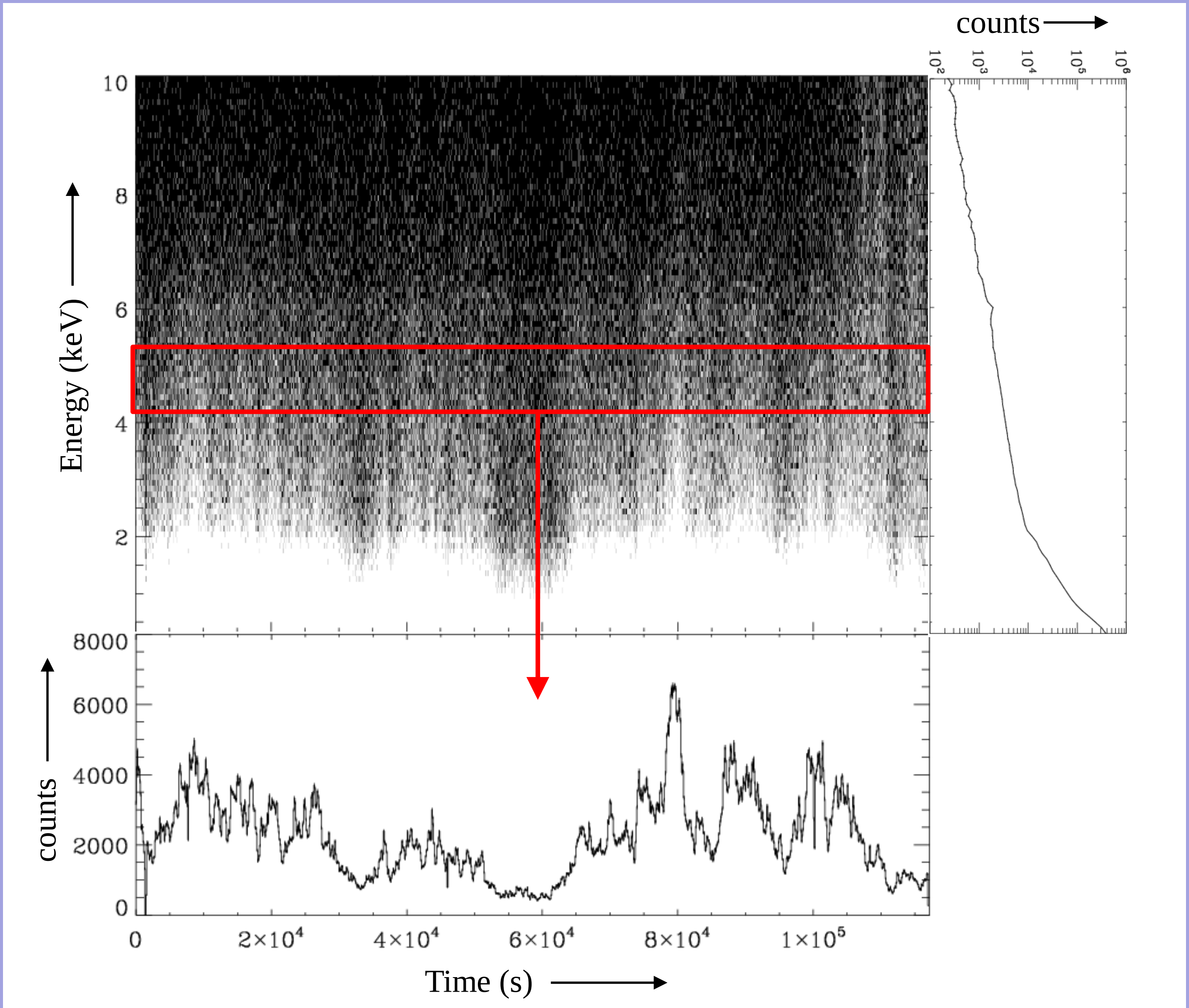
[assuming α ~ 0.1, h/r ~ 0.1, r/r_g ~ 6]

Take care when interpreting AGN data in terms of XRB "states"

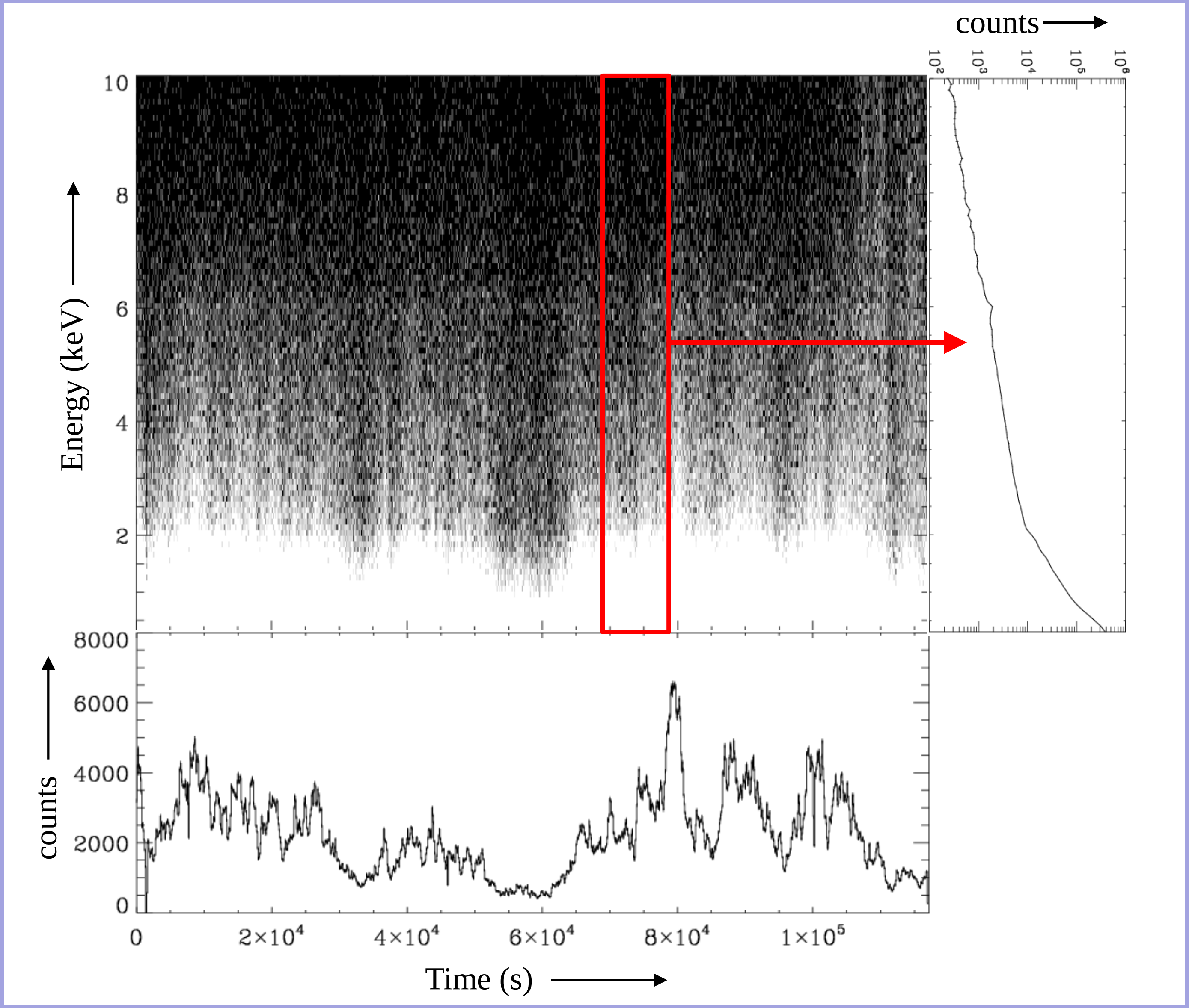



counts
10^2 10^3 10^4 10^5 10^6
10
8
6
4
2
Energy (keV)
8000
6000
4000
2000
0
counts
0 2×10^4 4×10^4 6×10^4 8×10^4 1×10^5
Time (s)

What can be done with this much data? Time series analysis

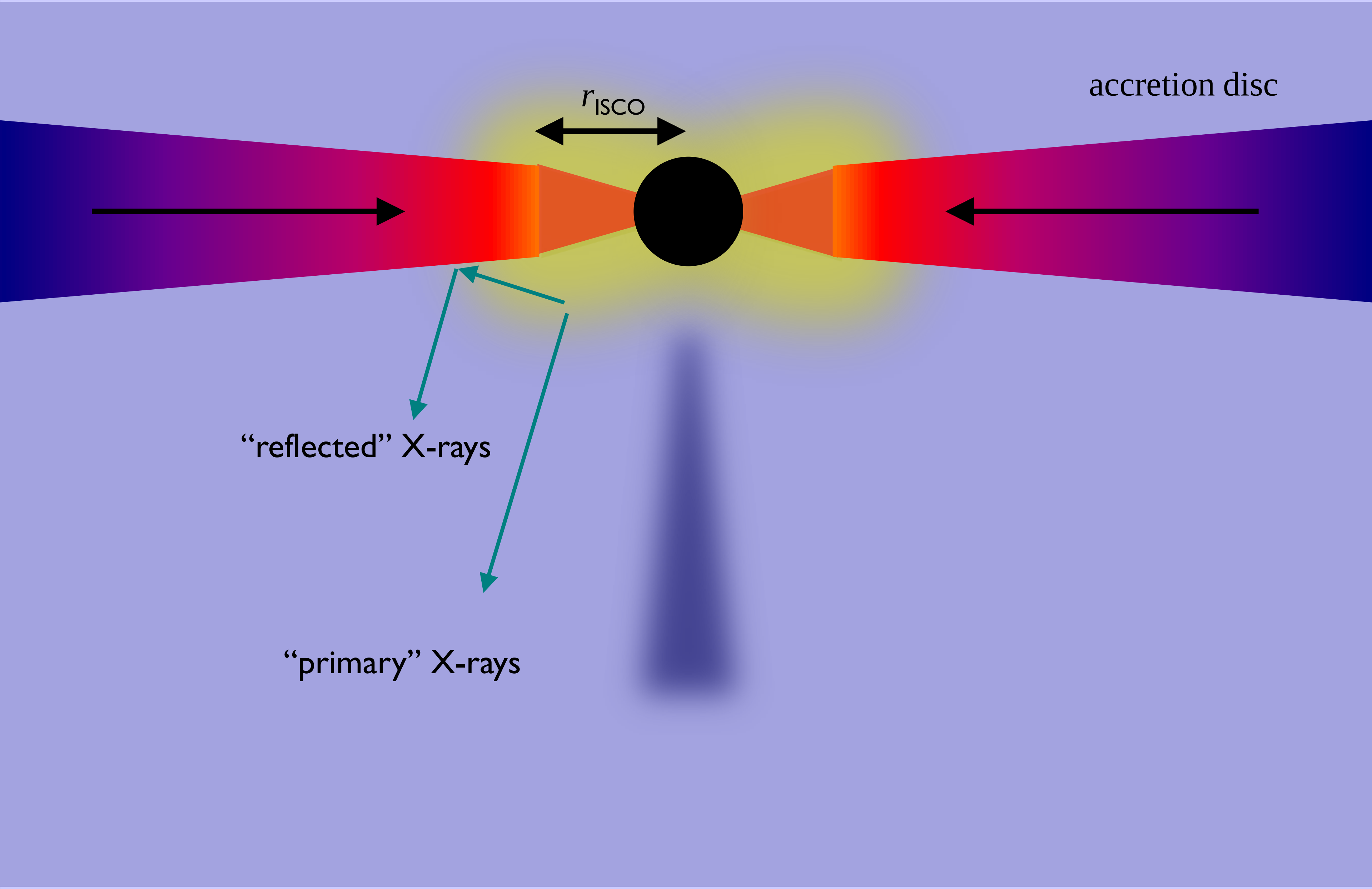


What can be done with this much data? X-ray spectral fitting



X-ray reflection and reverberation

Spectral variability "toy models": disc reflection & reverberation



Compton reflection:

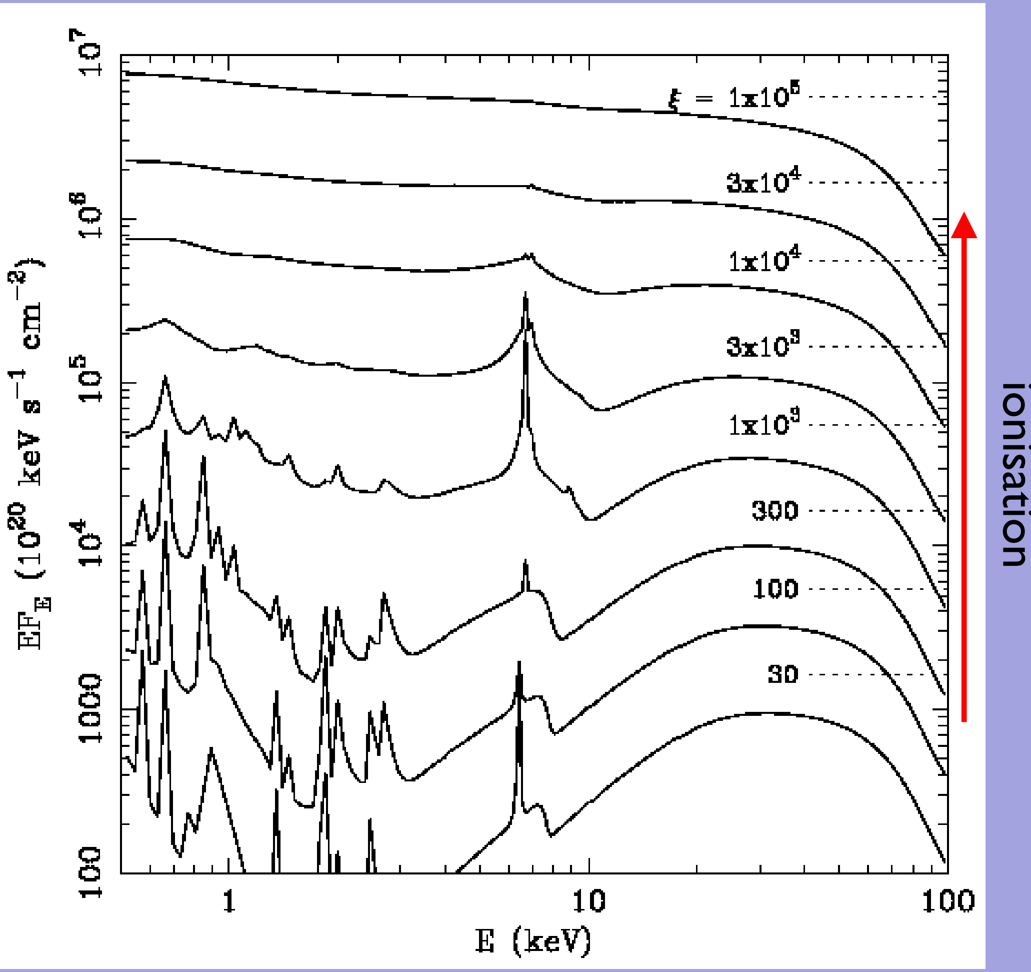
Lightman & White (1988)
White, Lightman & Zdziarski (1988)
George & Fabian (1991)

Continuum reflection model:

Magdziarz & Zdziarski (1995)
[PEXRAV]

Ionised reflectors

Ross et al. (1999)
Ballantyne et al. (2001)
Nayakshin et al. (1999)
Ross & Fabian (2005) [REFLIONX]



The “diskline” model

“thick” accretion flow at ~few r_{g}

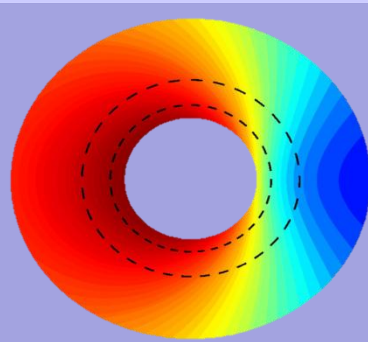
+

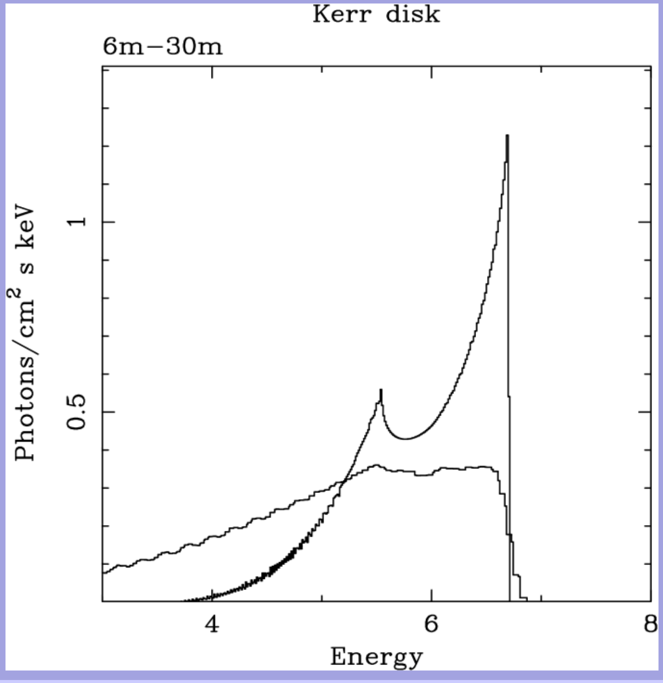
X-rays at ~few r_{g}

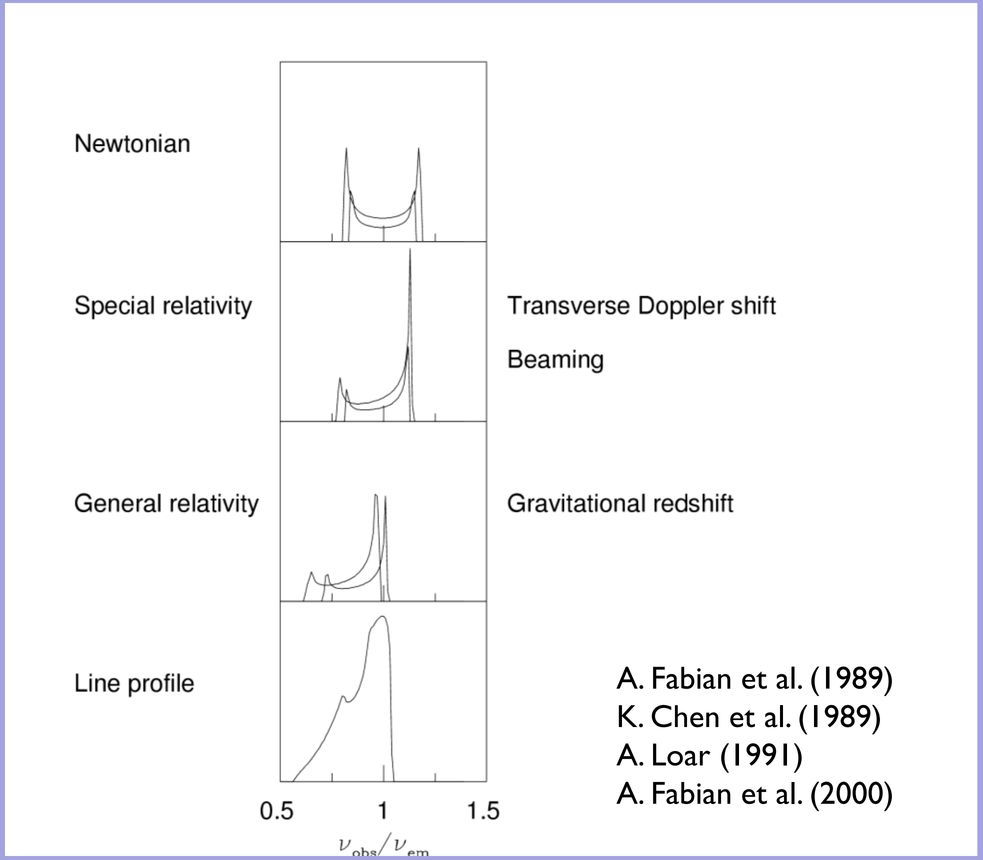
=

“diskline”

Fe features are our “probe” near BH

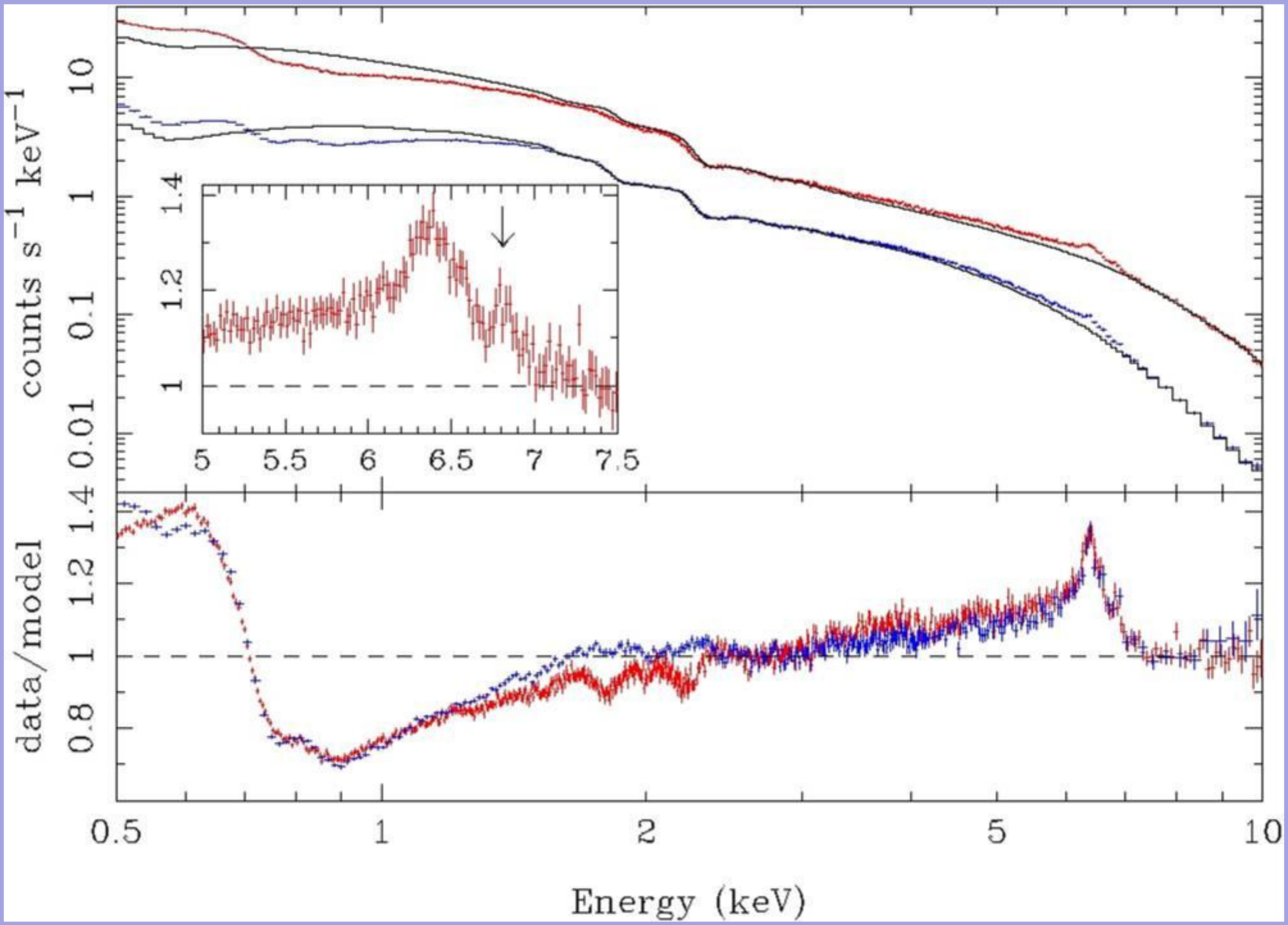






A. Fabian et al. (1989)
K. Chen et al. (1989)
A. Loar (1991)
A. Fabian et al. (2000)

A long look with *XMM-Newton* (circa 2002)



Wilms et al. (2001); Fabian et al. (2002); Vaughan & Fabian (2004)

Response matrix

Observed (ct s^{-1})

Effective area (cm^2)

Source spectrum ($ct\ s^{-1}\ cm^{-2}\ keV^{-1}$)

$$C(i) = \int R(i,E)A(E)S(E)dE$$

Discrete version (channel i energy j)

$$C_i = \sum_{j=1}^{N} R_{ij} A_j S_j$$

$$\hat{S} = C_i / \sum_{j=1}^{N} R_{ij} A_j$$

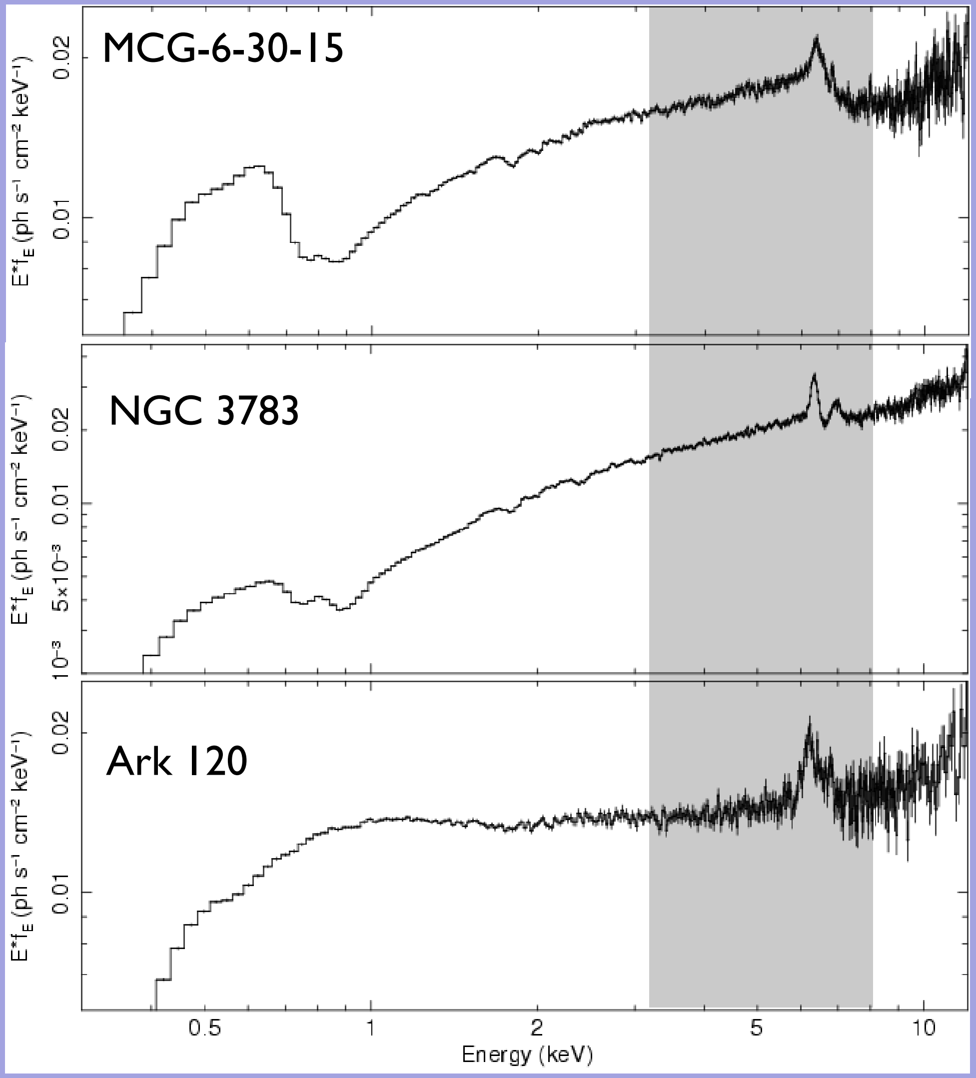
A "best efforts" unfolded spectrum

```
xspec> model powerlaw
         Index: 0
         Norm:  1
xspec> plot eeuf
```

for a νF_ν style plot

Or see SAS task EFLUXER
Or use ISIS

Some *XMM-Newton* (EPIC) spectra of bright Seyfert 1s



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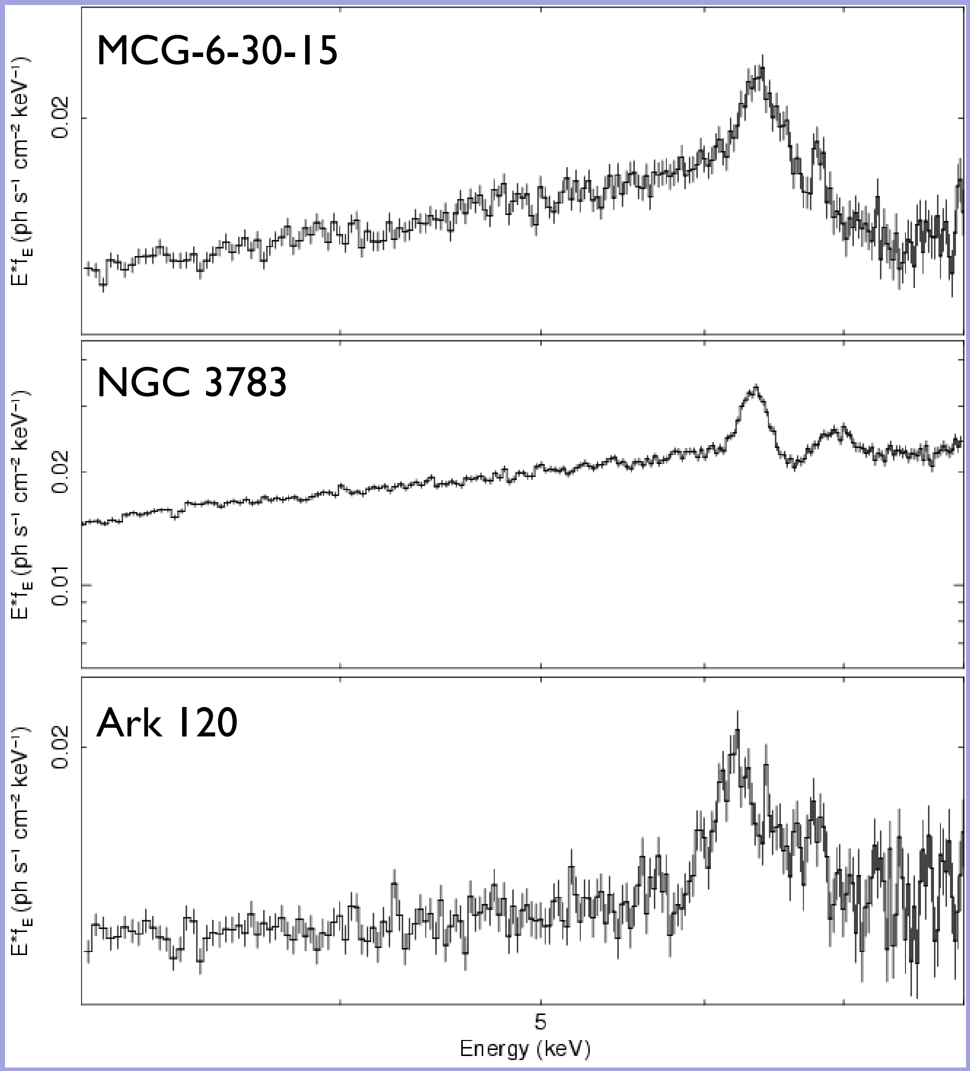
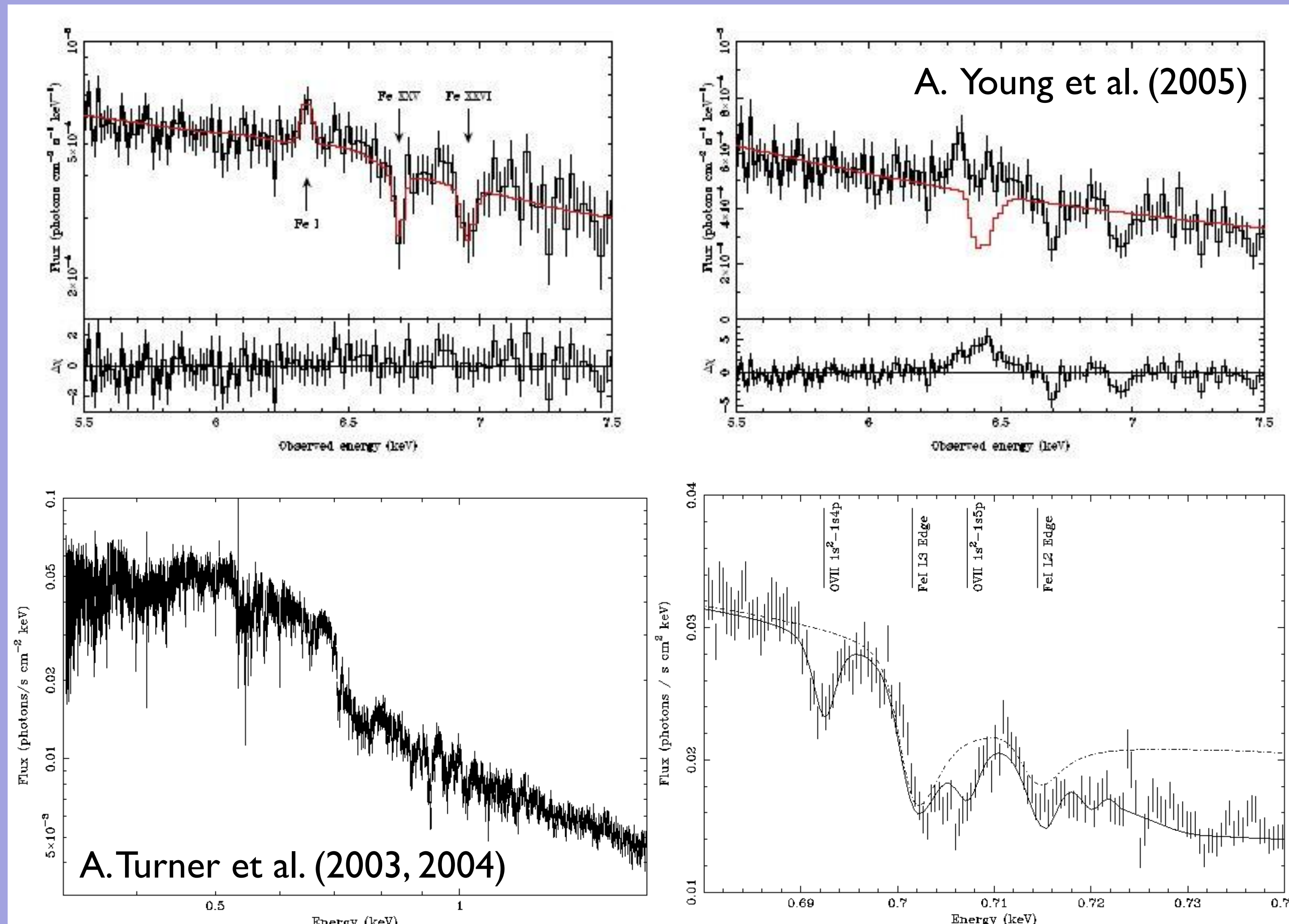


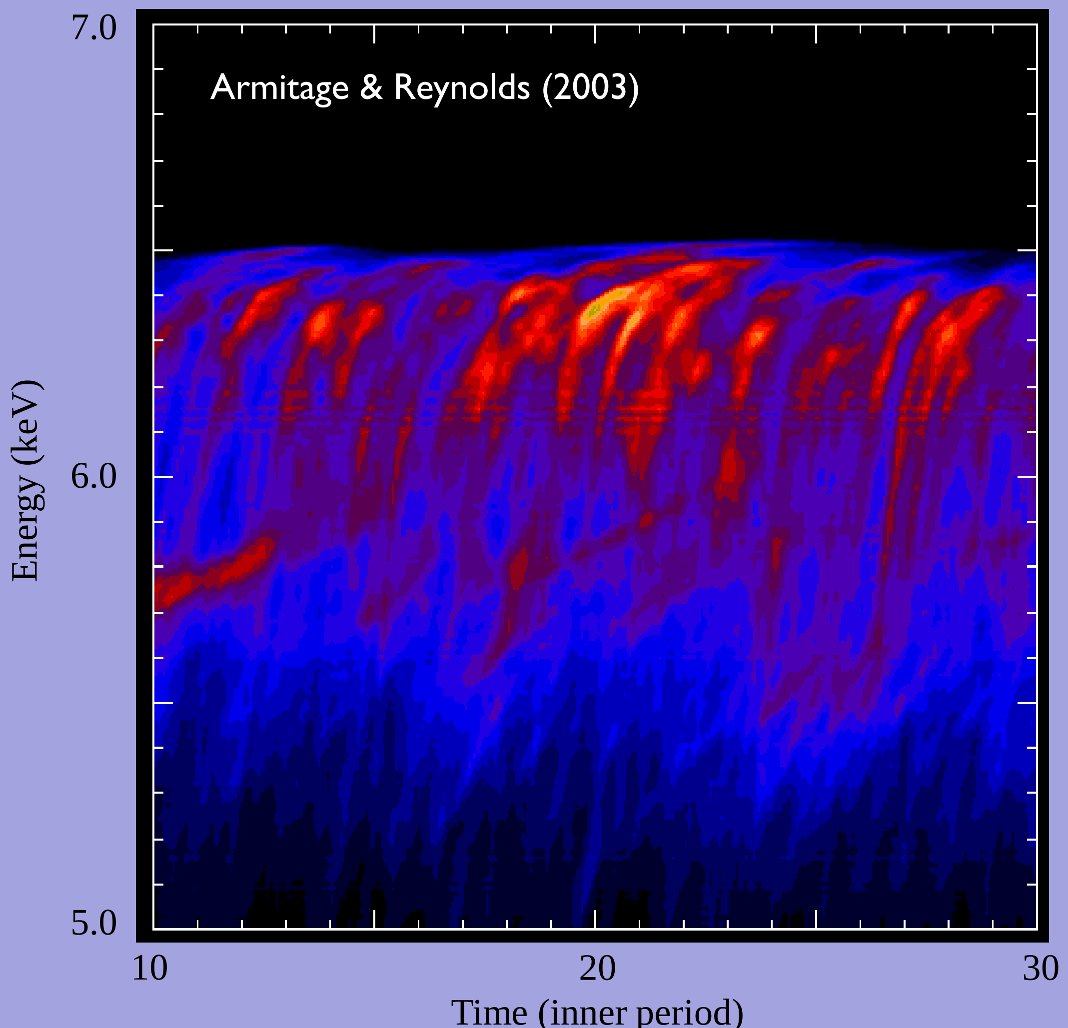
Higher resolution (Chandra/HETGS and XMM/RGS) spectra of bright Seyfert 1s

Chandra/HETGS
(0.5-8 keV)

XMM/RGS
(0.3-2 keV)



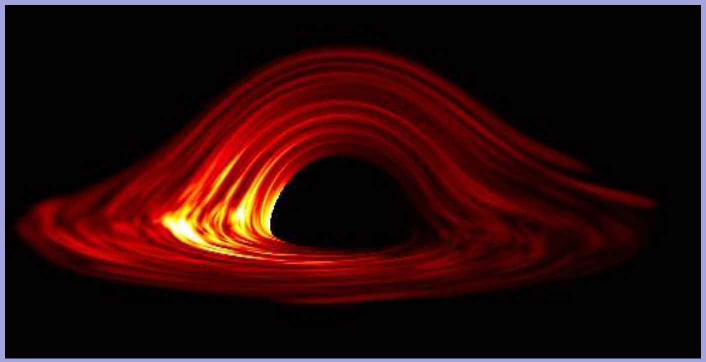
Iron line "reverberation"



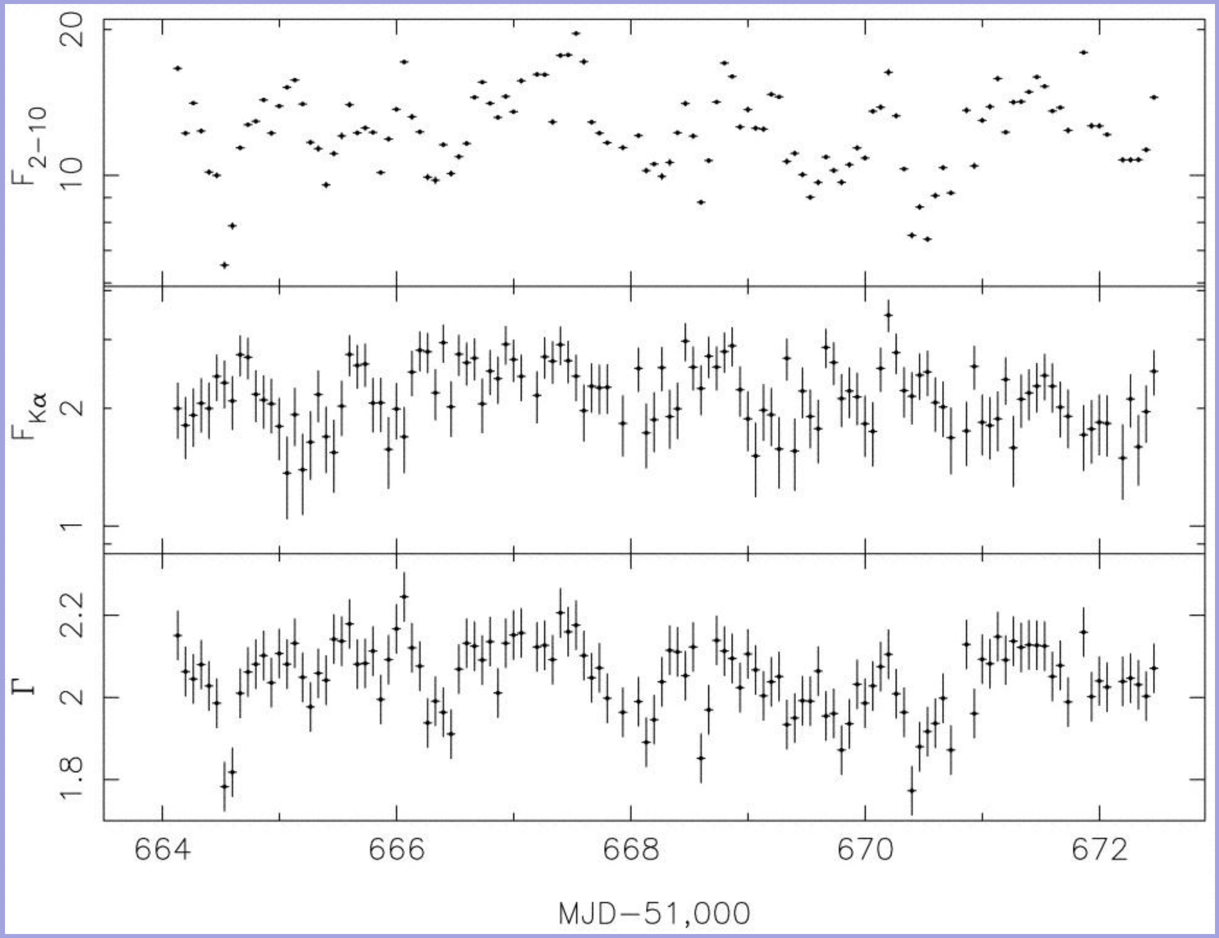
reverberation - the X-ray light echo that propagates across the accretion disk due to the finite speed of light.

These reverberation signatures encode detailed information about the spacetime geometry, and might allow for a quantitative test of General Relativity in the very strong field limit.

Reynolds & Nowak (2003)



Iron line "reverberation" … not quite



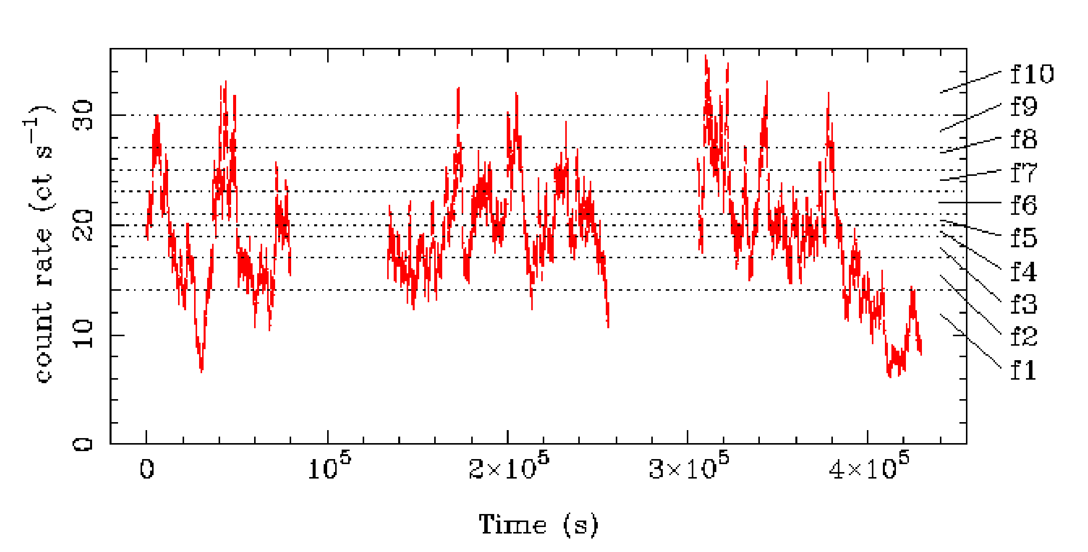
RXTE data from MCG-6-30-15
Vaughan & Edelson (1999)
See also Iwasawa et al. (1996, 1999); Reynolds (1999);
Shih et al. (2002); Fabian & Vaughan (2003)

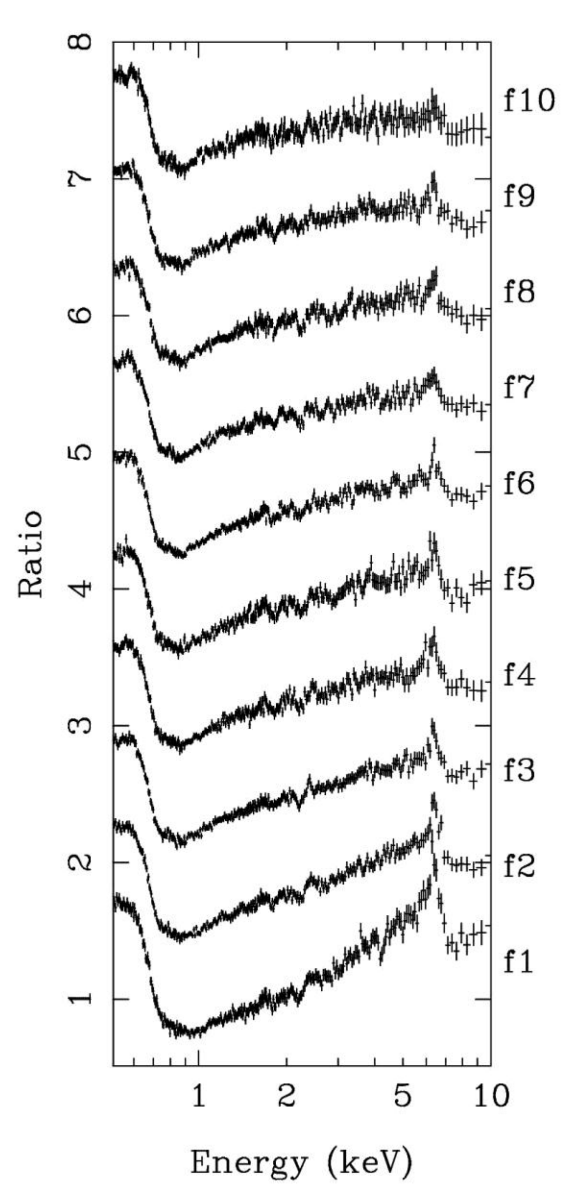
Good for revealing flux-correlated spectral changes

(Averages out spectral changes not correlated
with flux on relevant timescale)

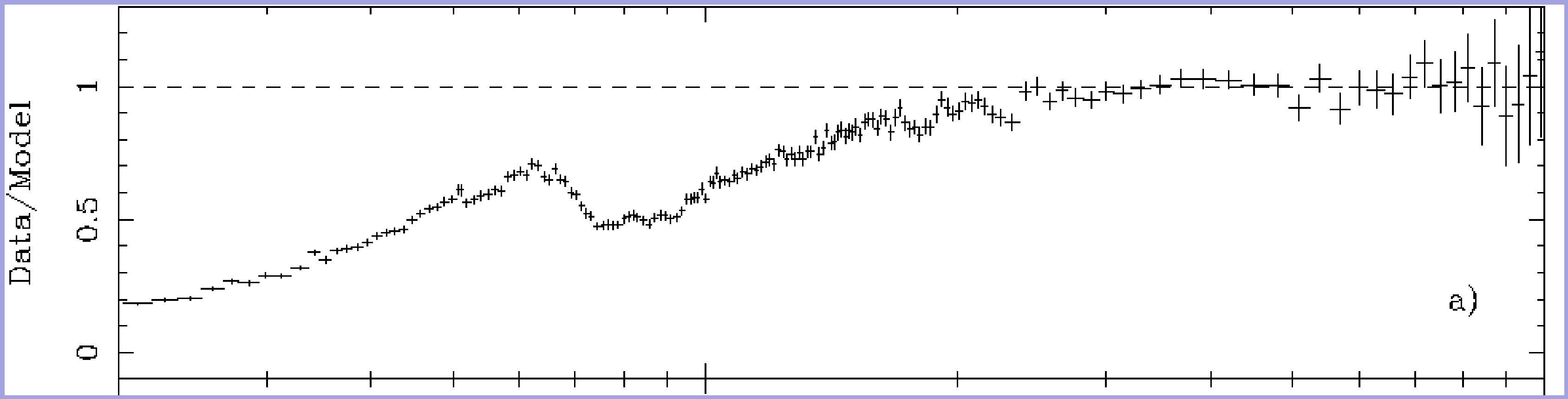
Reveals known trend for Fe line EW to decrease with flux

Vaughan & Fabian (2004): XMM-Newton data of MCG-6-30-15





Vaughan & Fabian (2004); Fabian & Vaughan (2003)



Assume "two component" model:

F(E; t) = N(t)*varb(E) + cons(E)

Therefore

F(E; t1) = N(t1)*varb(E) + cons(E)

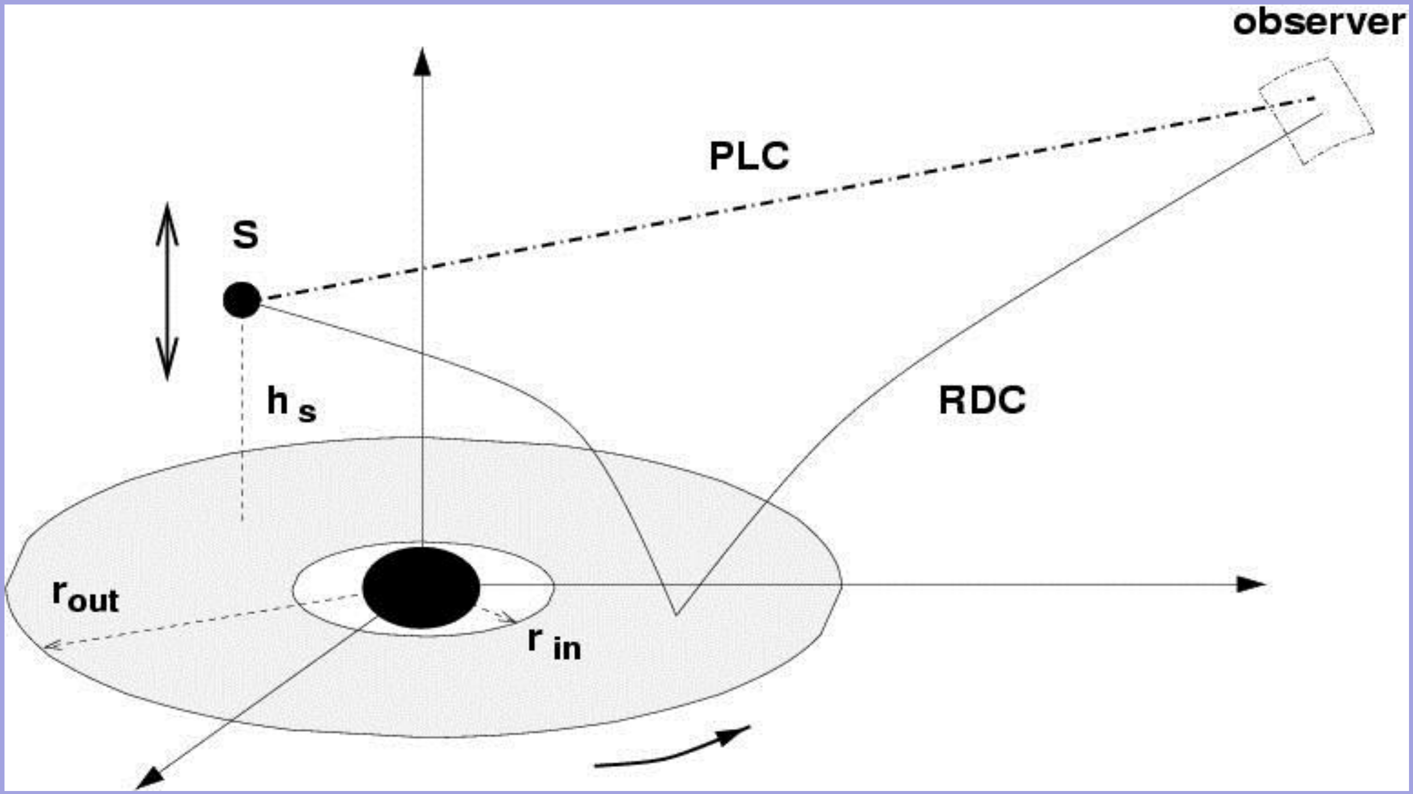
F(E; t2) = N(t2)*varb(E) + cons(E)

And so

F(E; t1) – F(E; t2) = [N(t1)-N(t2)]*varb(E)

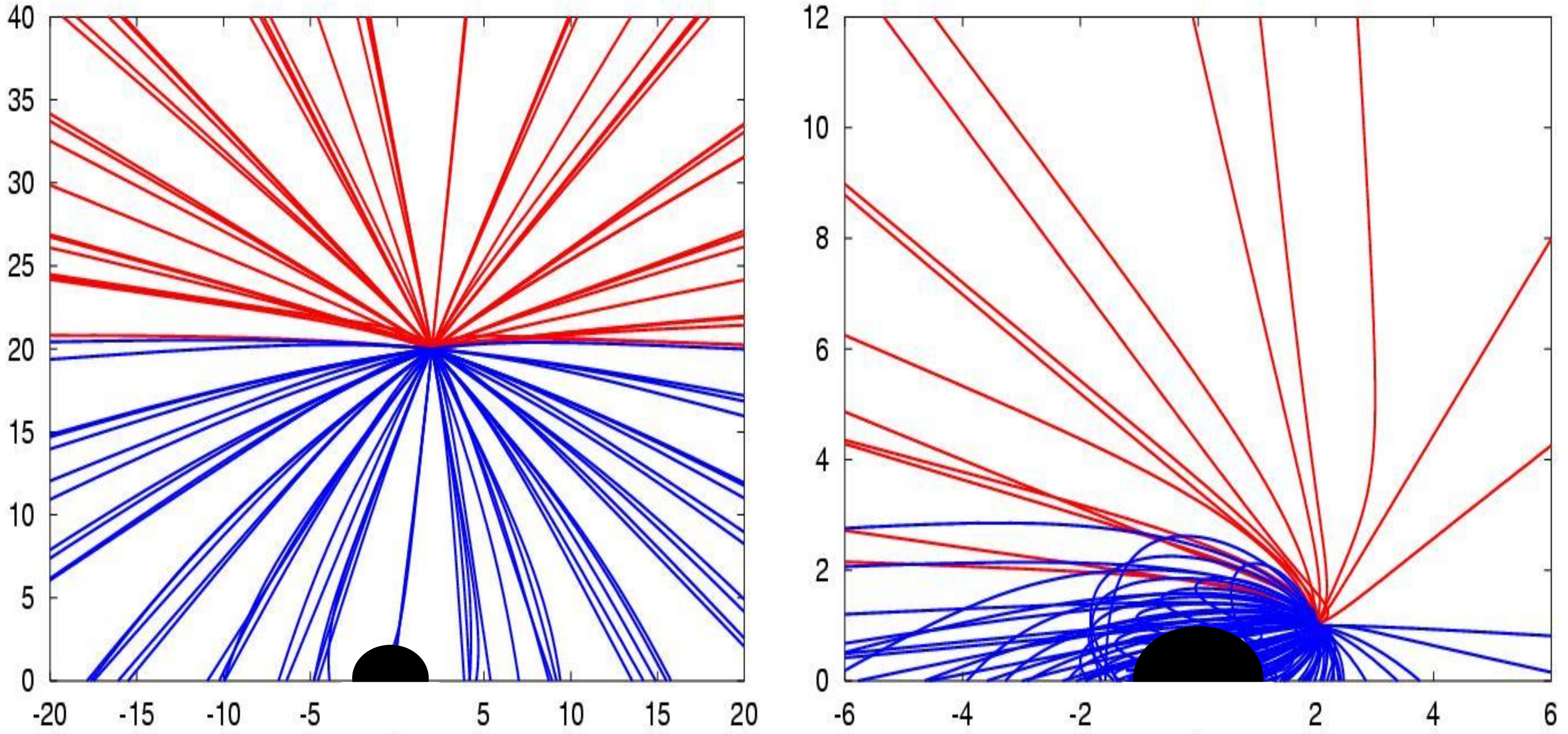
Measure and fit high-low flux difference spectra

Light bending model in Kerr spacetime



Miniutti et al (2003); Miniutti & Fabian (2004)

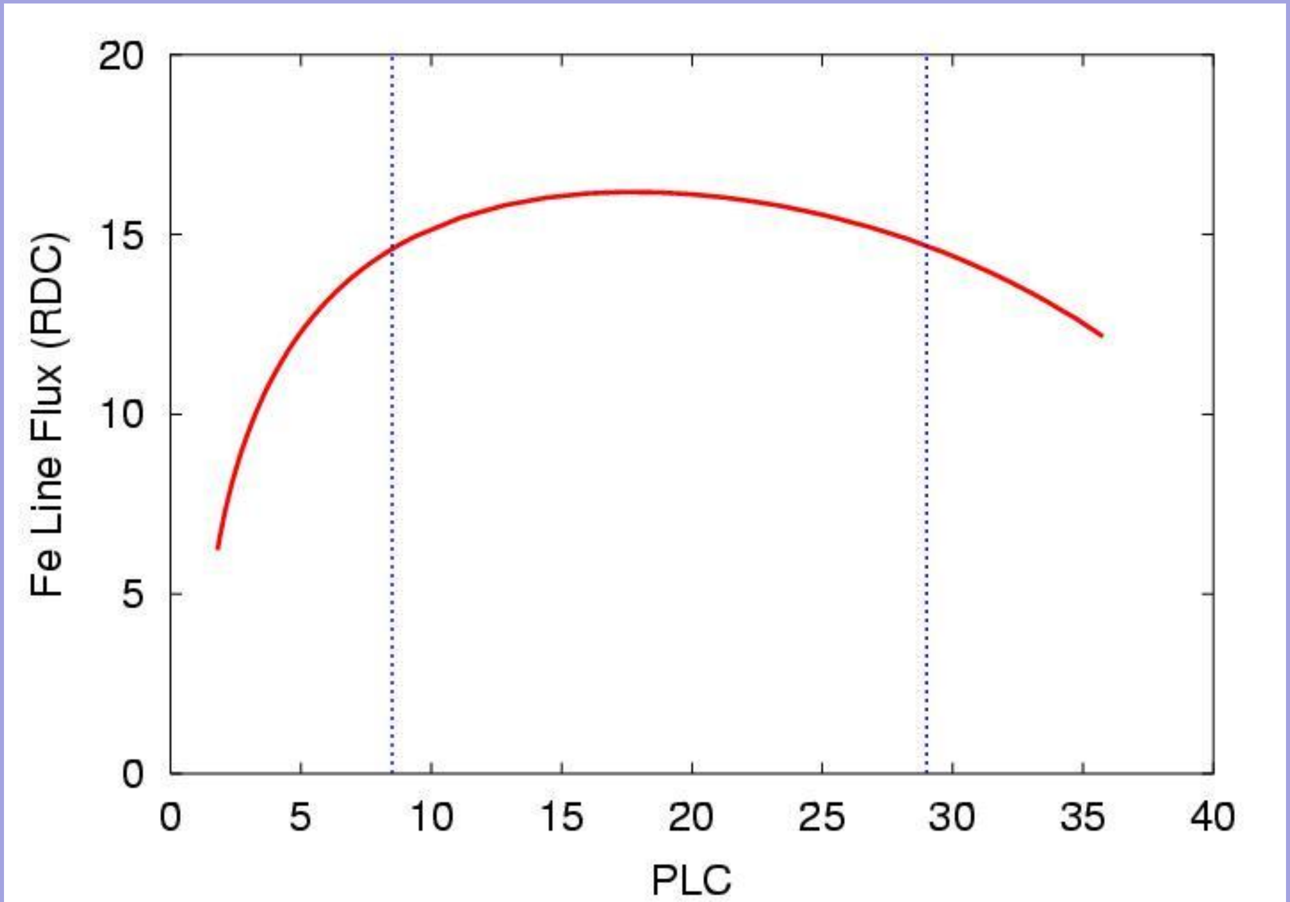
•Light bending model in Kerr spacetime



A source of constant intrinsic luminosity will appear to vary if it changes position within the strong gravity regime close to the black hole

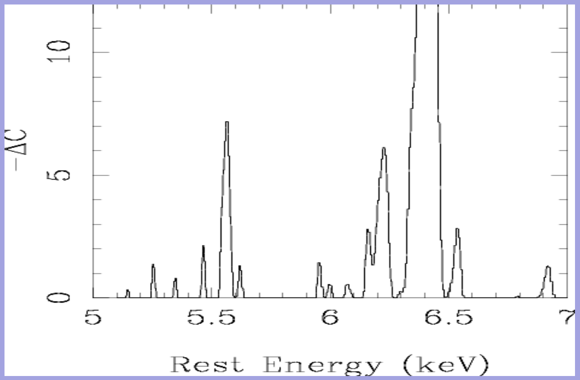
Miniutti et al (2003); Miniutti & Fabian (2004)

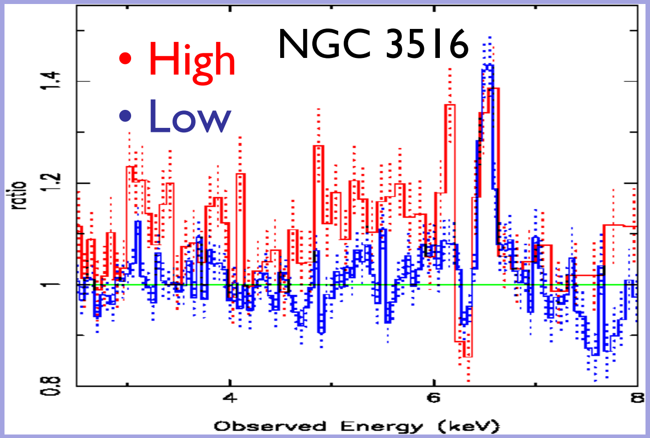
Light bending model in Kerr spacetime: line-continuum relation

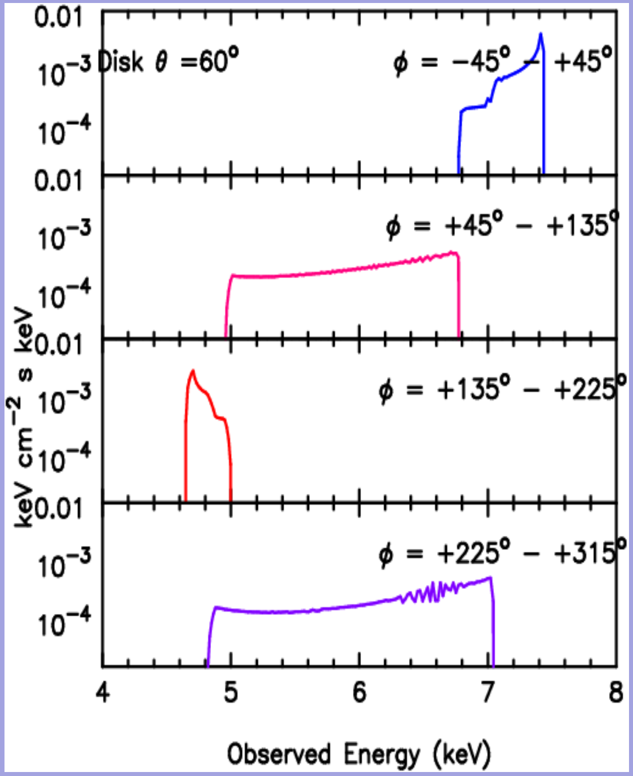


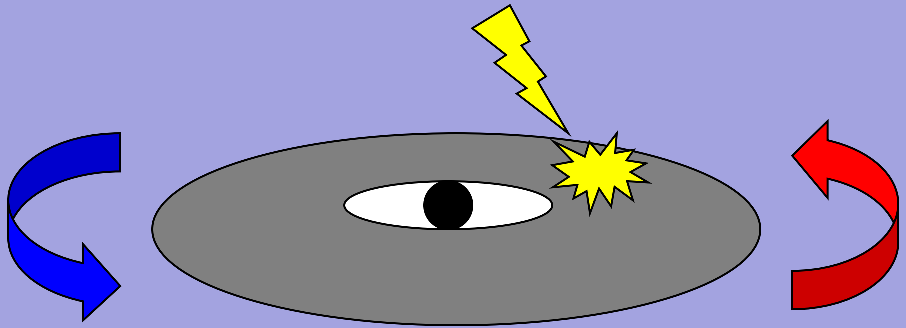
Miniutti et al (2003); Miniutti & Fabian (2004)

Narrow and shifted iron lines





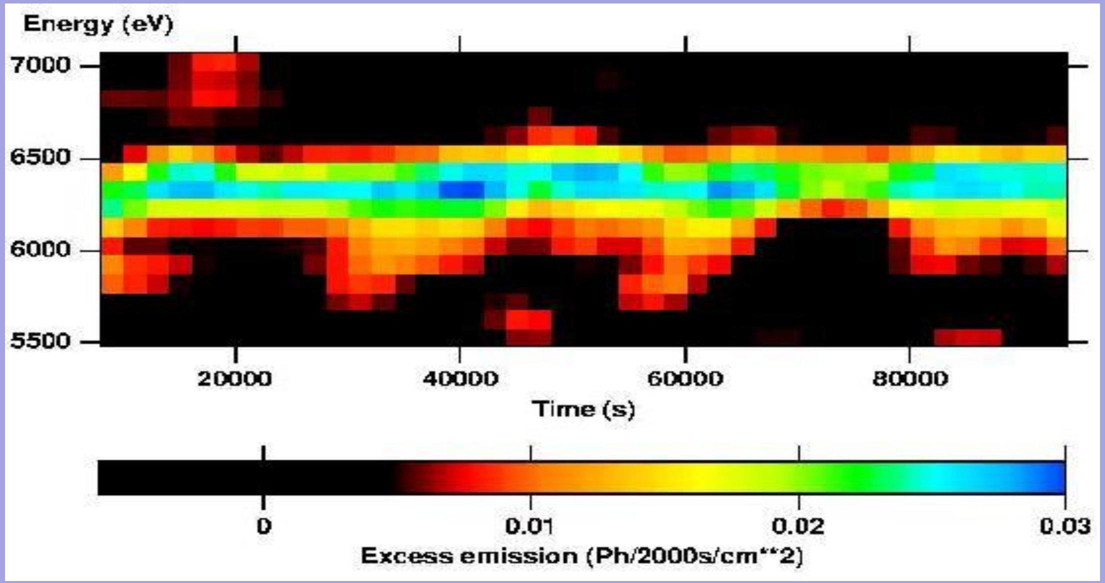


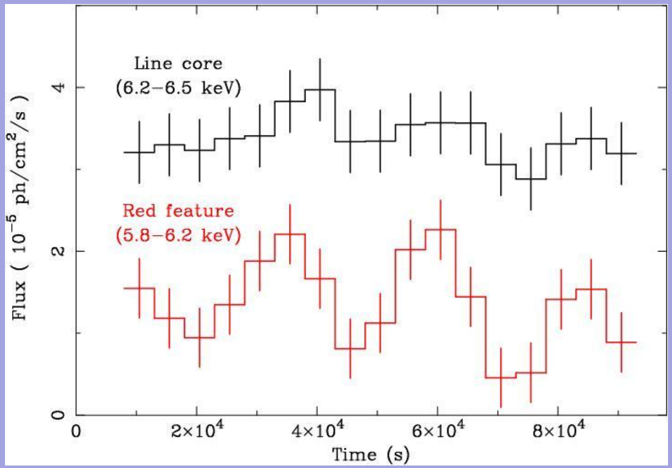


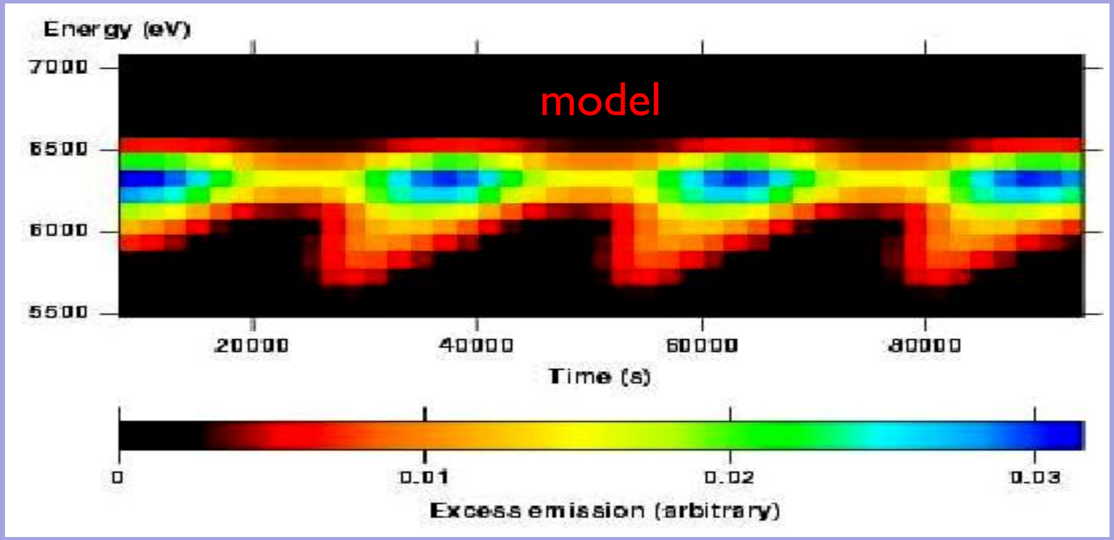
Emission from disk hotspots integrated over partial orbits at ~10-100 r_g? (T. J. Turner et al 2002, 2004)

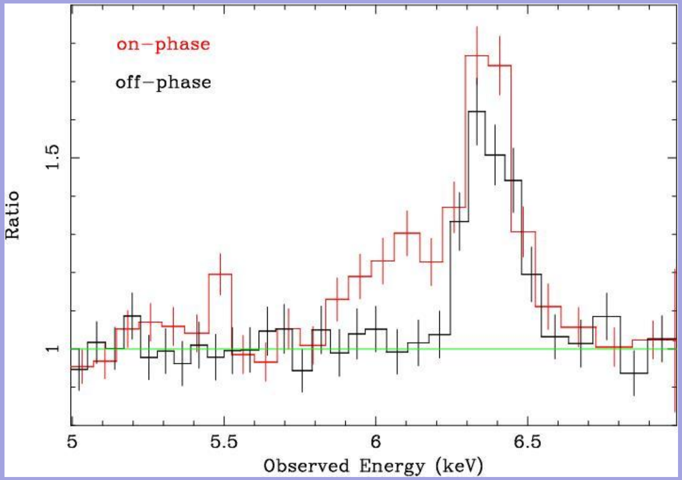
For critical discussion see Vaughan & Uttley (2008)
Also Longinotti et al. (2007)

NGC 3516 (K. Iwasawa et al., 2004)









Fourier resolved spectroscopy

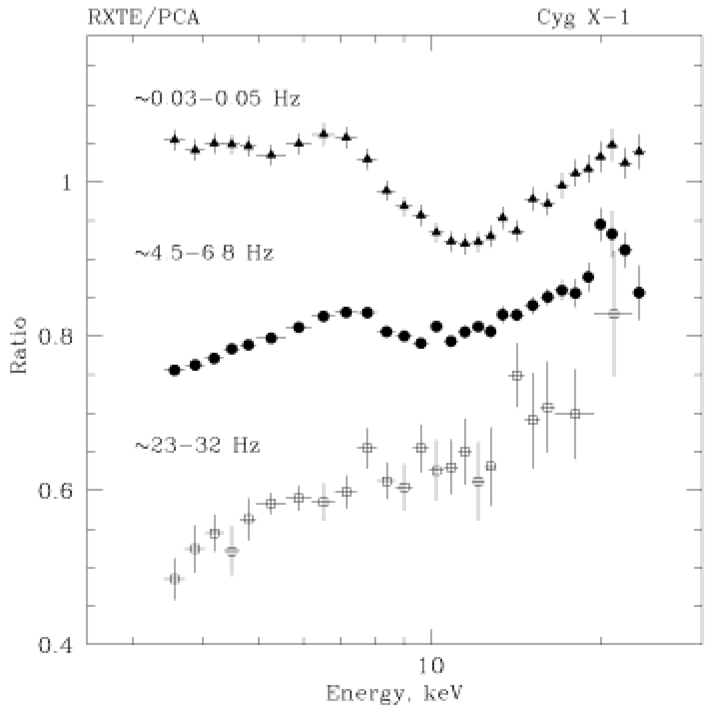


Fig. 1. The ratio of the energy spectra of Cyg X-1 in different frequency bands to a power law model with the photon index $\alpha = 1.8$. Spectra corresponding to 0.03–0.05 Hz and 23–32 Hz were rescaled for clarity.

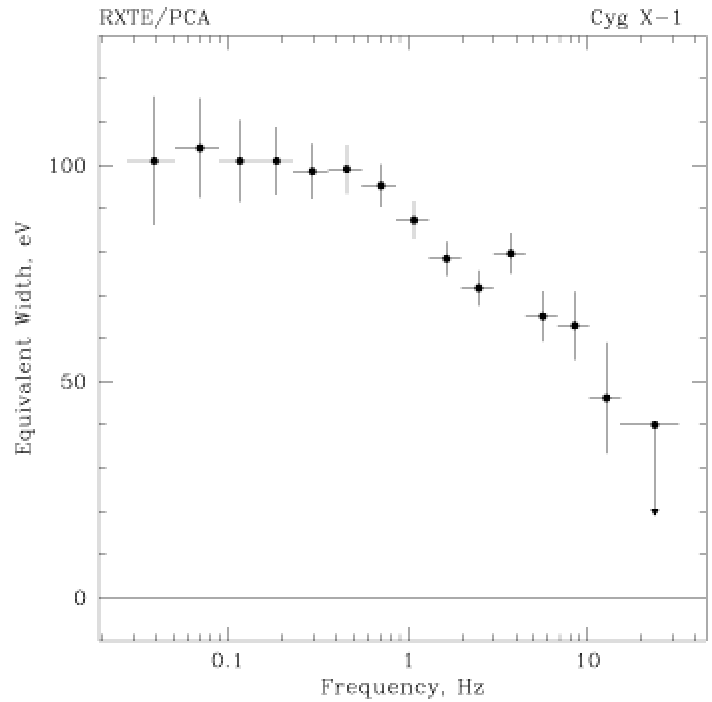


Fig. 2. Dependence of the equivalent width of the fluorescent Fe line on the frequency. For the spectral approximation the powerlaw+gaussian line model was used (3–13 keV energy band, the centroid energy and the width of the line were frozen at the values 6.4 keV and 0.1 keV respectively).

in fractional units

Cyg X-1: Revnivtsev et al. (1999)

$$P = \int_{f_1}^{f_2} psd(f)\,\mathrm{d}f \qquad S(E) = \sqrt{P(E)}F(E)$$

Broad-band X-ray spectral variability

$$P = \int_{f_1}^{f_2} psd(f)\,\mathrm{d}f \qquad S(E) = \sqrt{P(E)}$$

$$V = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2 \qquad rms(E) = \sqrt{V(E) - bias(E)}$$

rms spectrum –
equivalent to Fourier-resolved spectrum

[See Vaughan et al. (2003) for details of measuring rms.]

Result for “ultrasoft” Seyfert Ton S180:

- Bending X-ray spectrum
- But flat rms/mean: soft & hard variability very similar
- Simple to state; difficult to explain!

Ton S180: Vaughan et al. (2002)

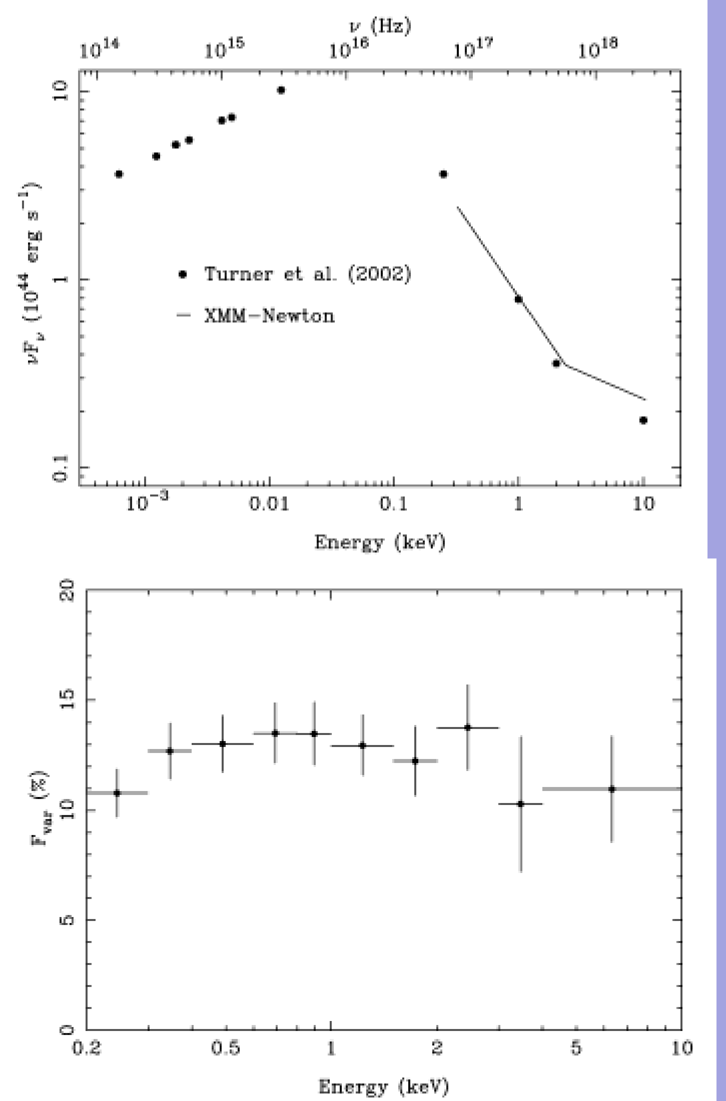
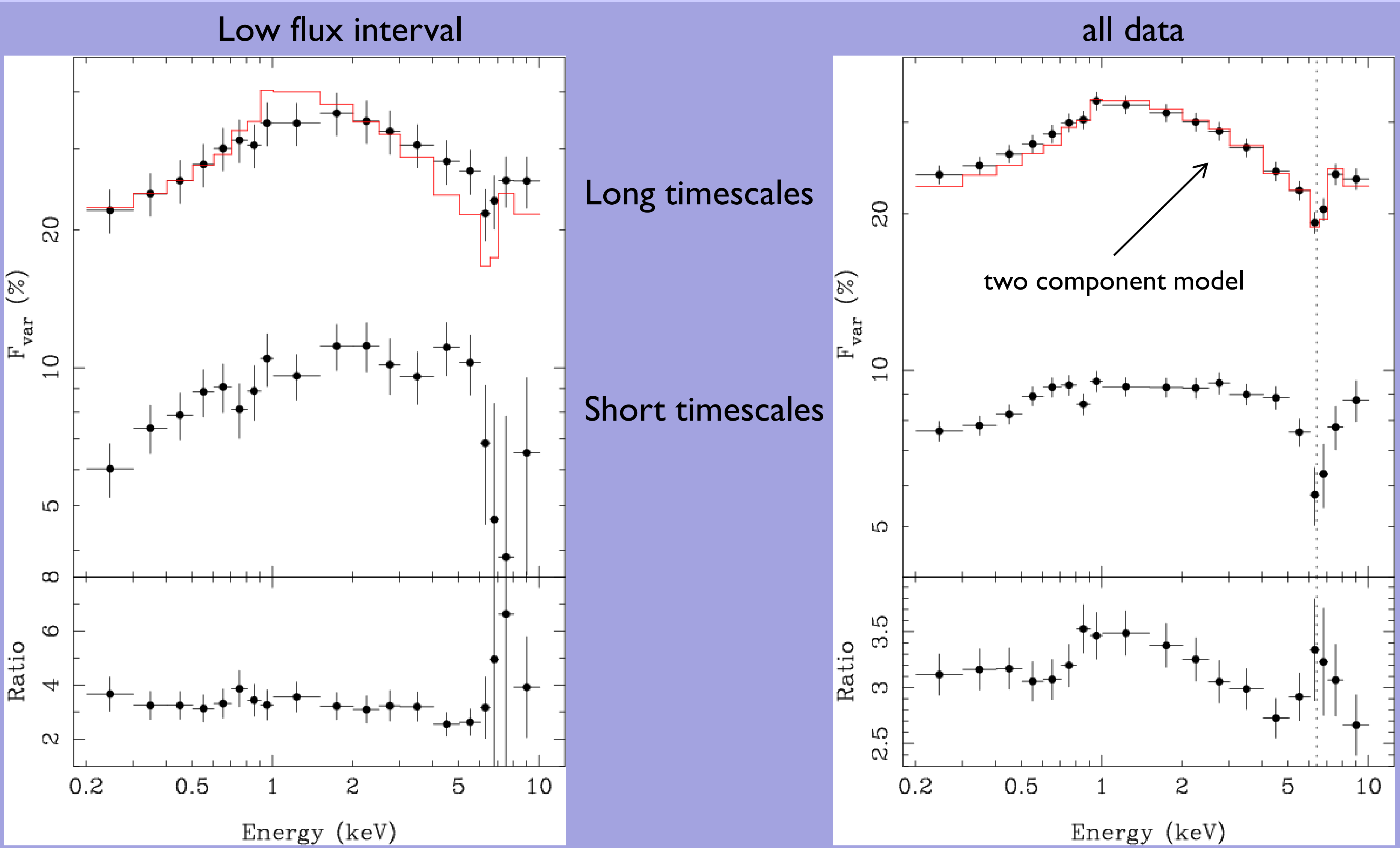


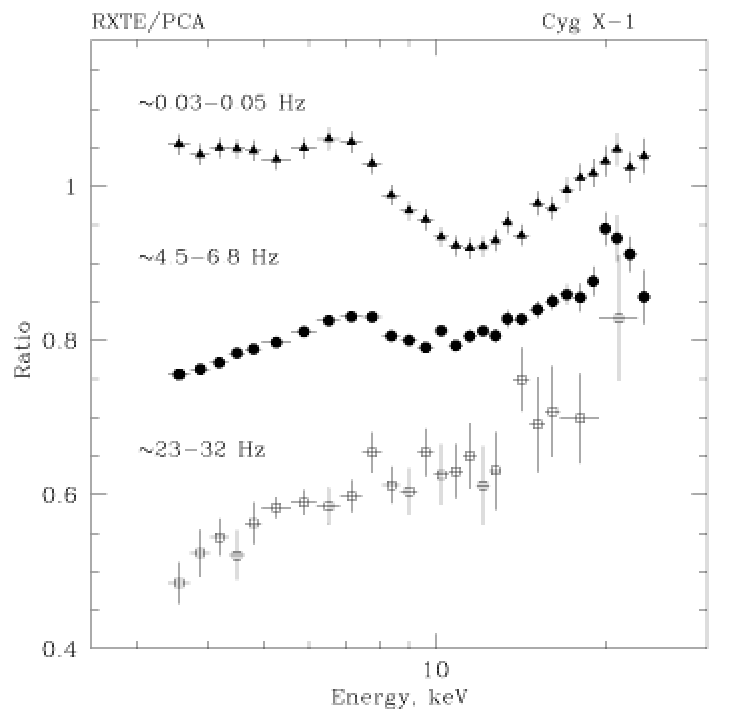
Figure 8. Normalized rms spectrum based on EPIC pn light curves. The F_{var} values were calculated using 500-s binned data.



MCG-6-30-15: Vaughan & Fabian (2004)

Mrk 766: Papadakis et al. (2007)

Approx. same as rms spectrum but using Fourier methods



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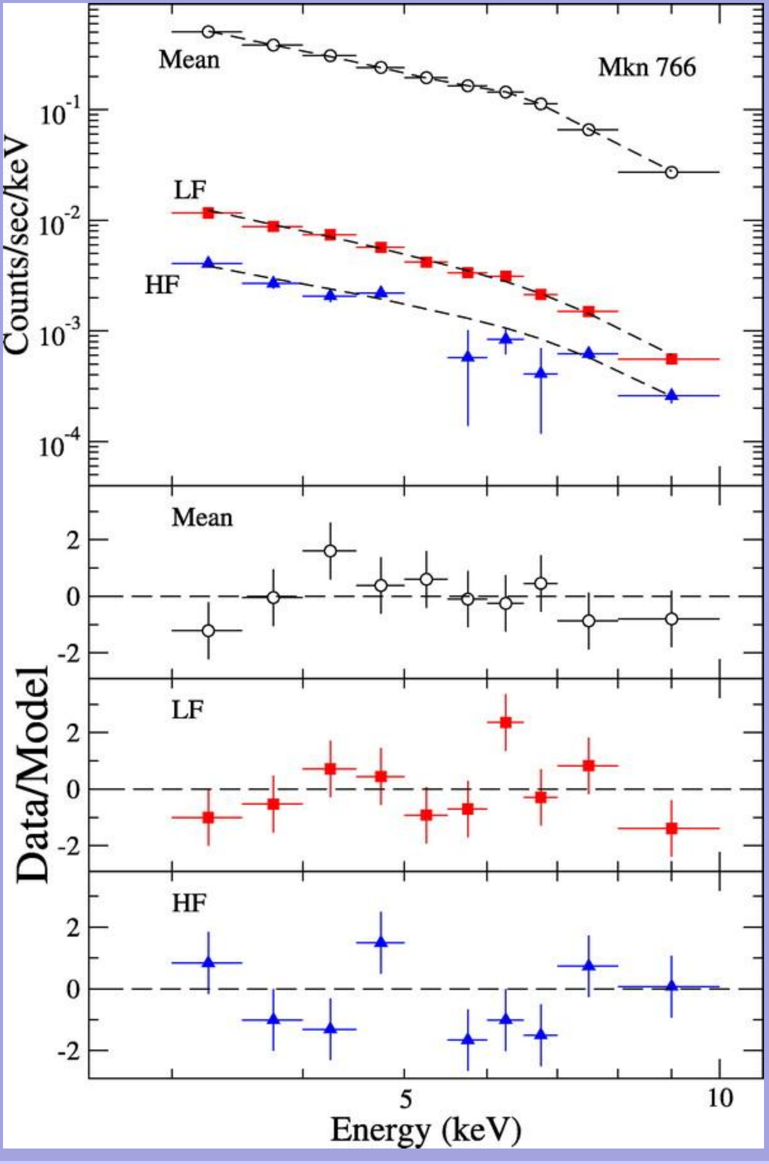


Flux-flux plots

Assume "two component" model:

$$F(E) = N(t)*varb(E) + cons(E)$$

Therefore

$$F(E1) = N(t)*varb(E1) + cons(E1)$$
$$F(E2) = N(t)*varb(E2) + cons(E2)$$

And so

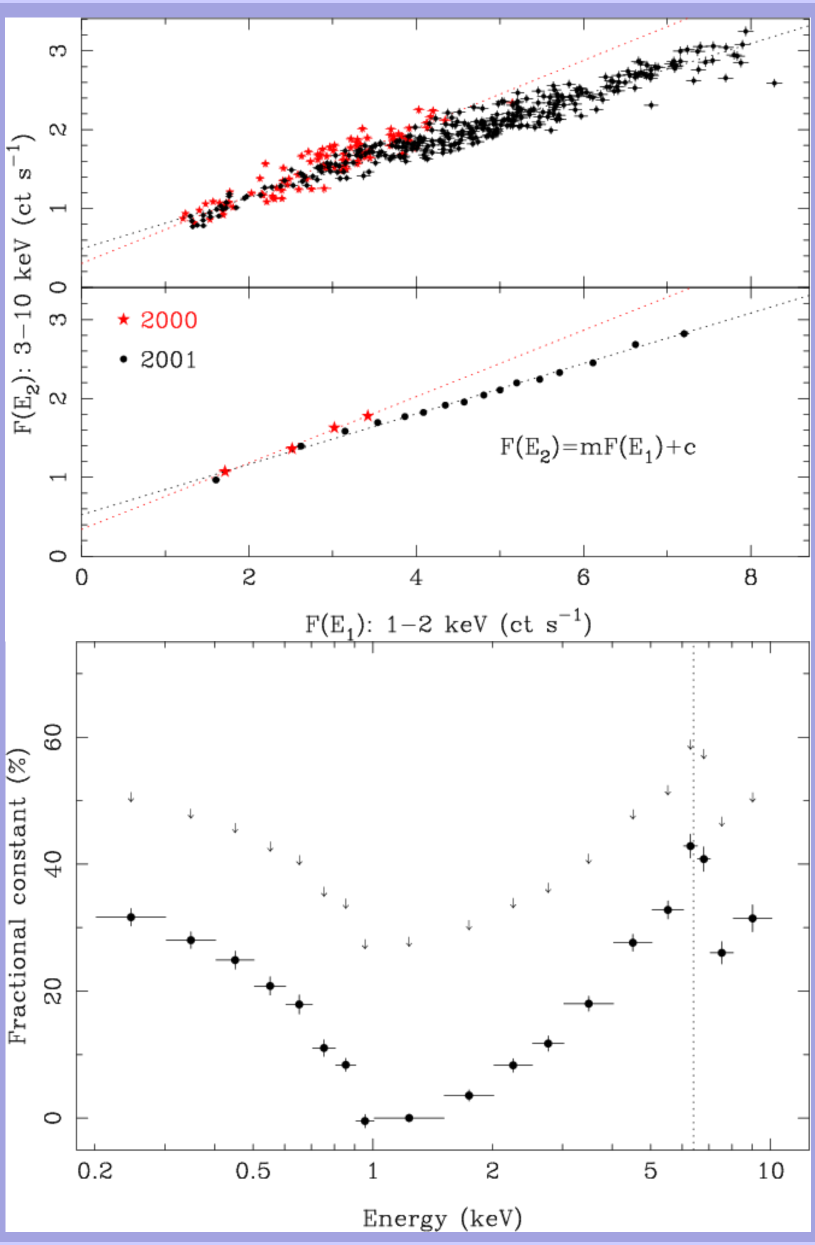
$$F(E2) = m*F(E1) + c$$

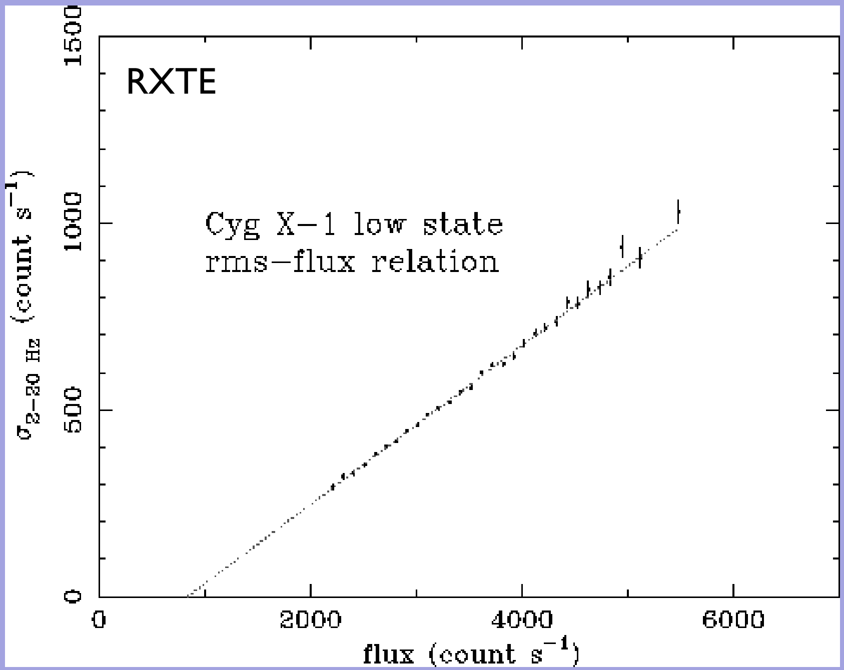
where

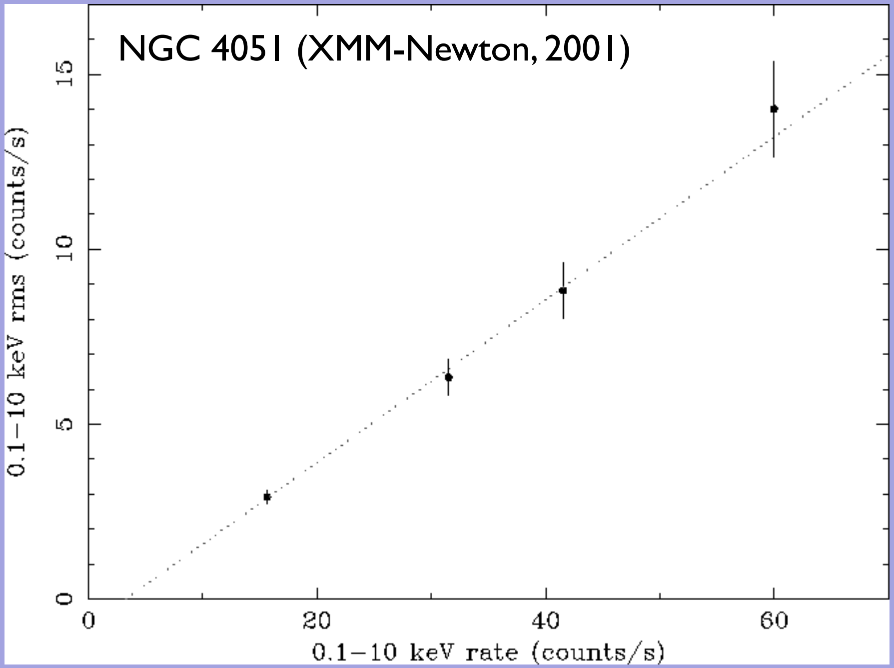
$$m = varb(E2)/varb(E1)$$
$$c = cons(E2) – m*cons(E1)$$

Measure m(E) and c(E)

Taylor et al. (2003)
Vaughan et al. (2004)
Ponti et al. (2006)







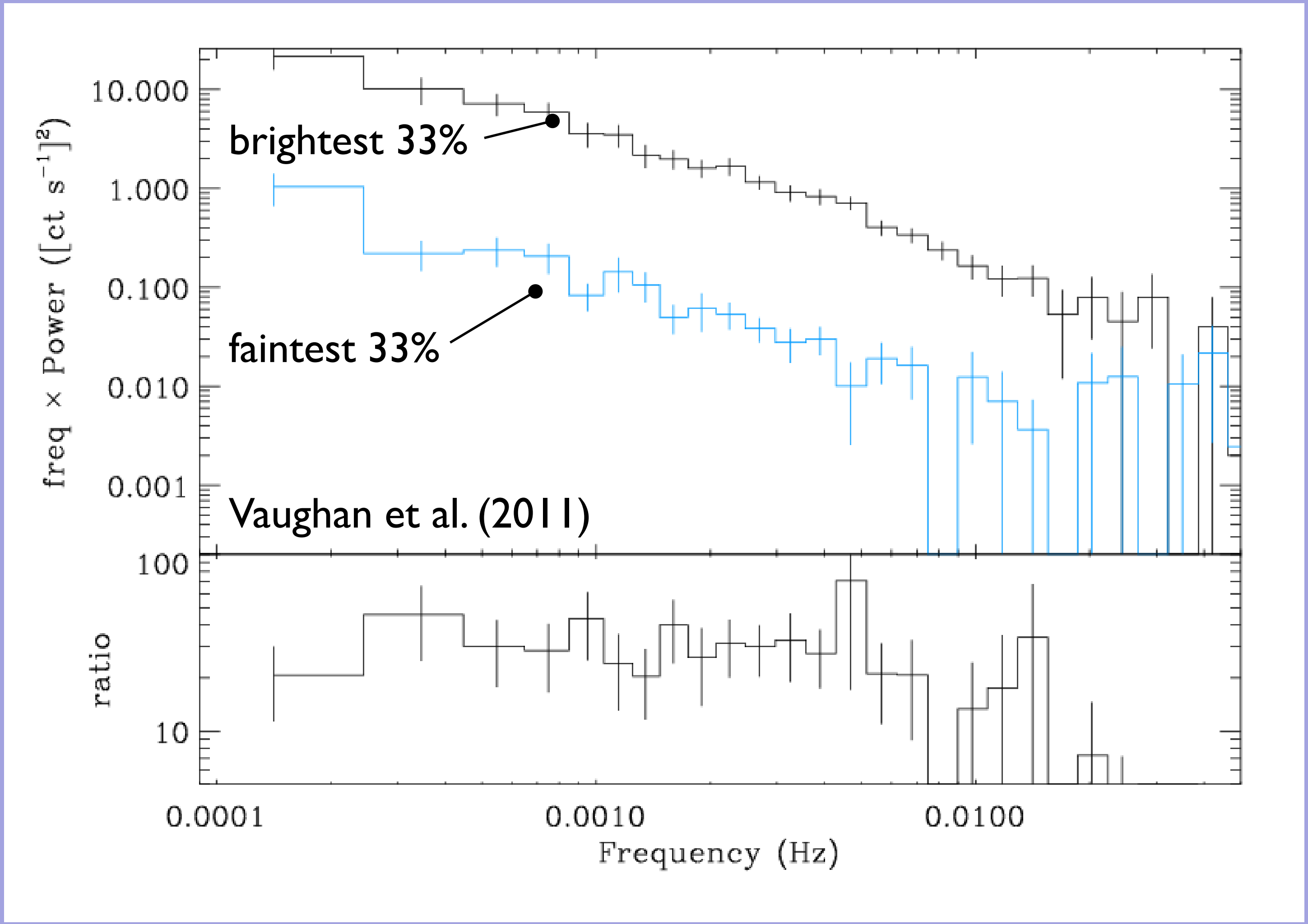
Amplitude of short timescale variations responds to long timescale average flux.

Same in XRBs and AGN (Seyfert 1s): seen in ***all*** (stationary) states

Uttley and McHardy (2001), Gleissner et al. (2004); **Uttley, McHardy & Vaughan (2005),** Vaughan & Uttley (2007); Heil (2011, PhD thesis)

Simple power spectrum

PSD amplitude (but not shape) is flux-dependent



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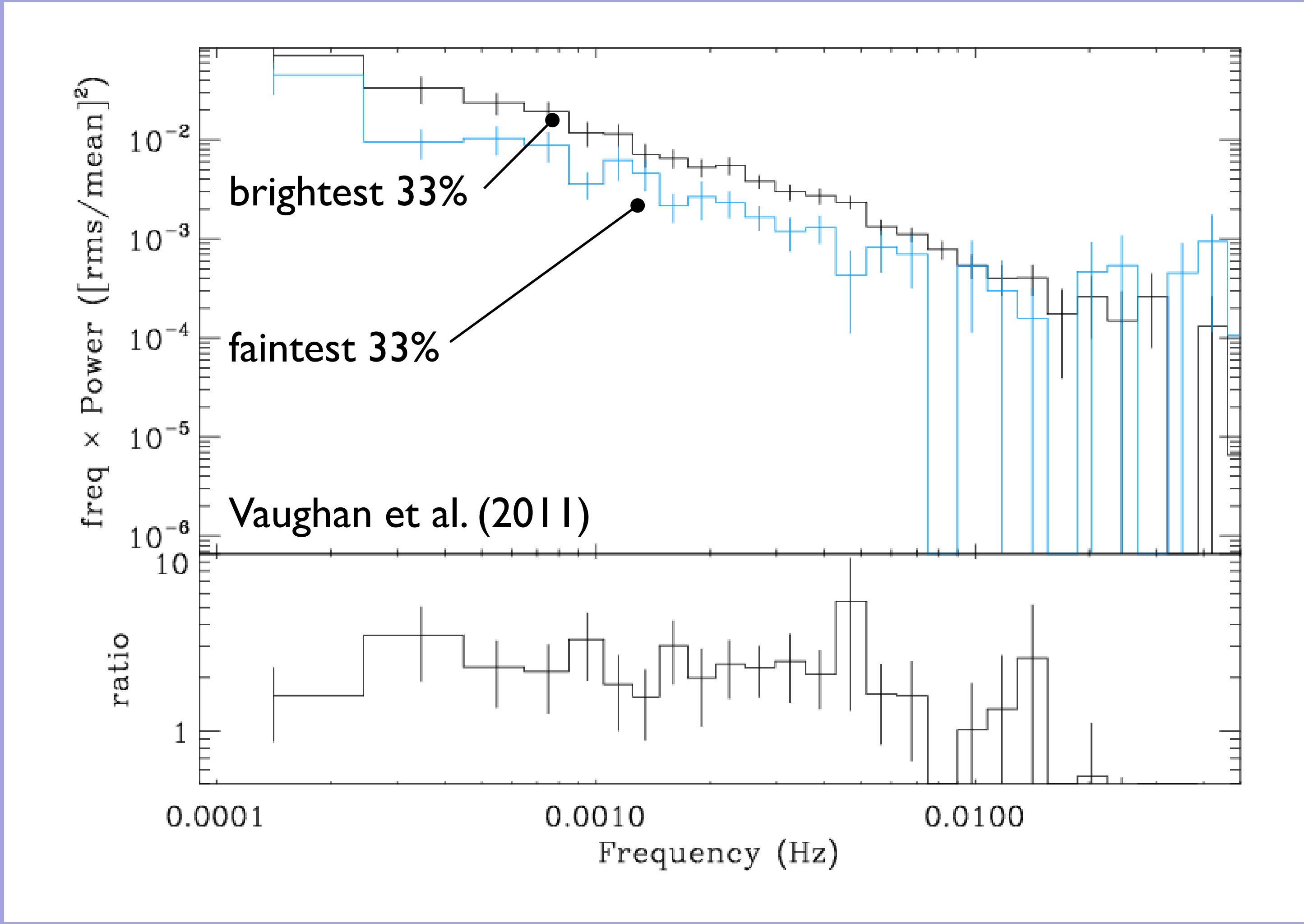
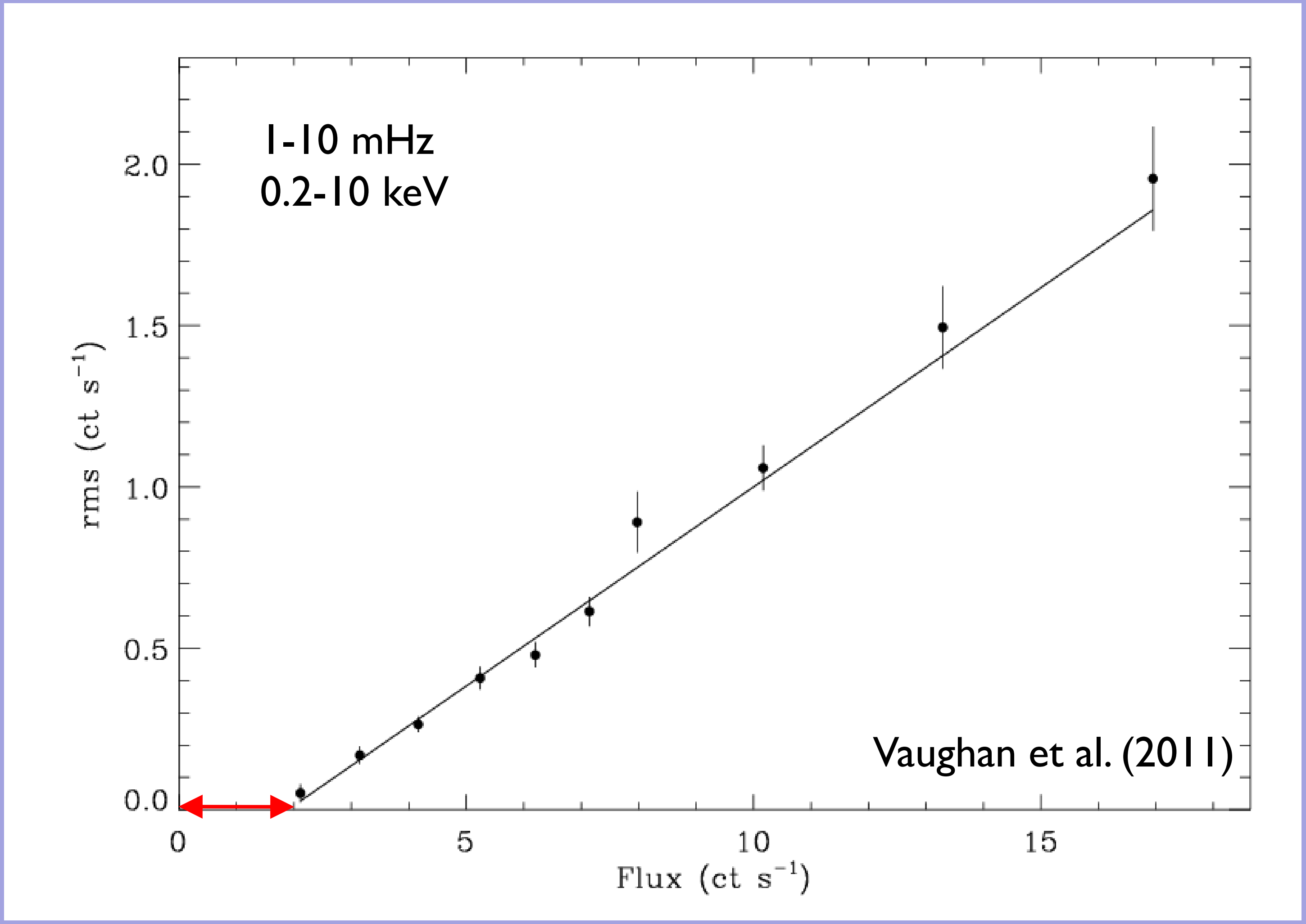


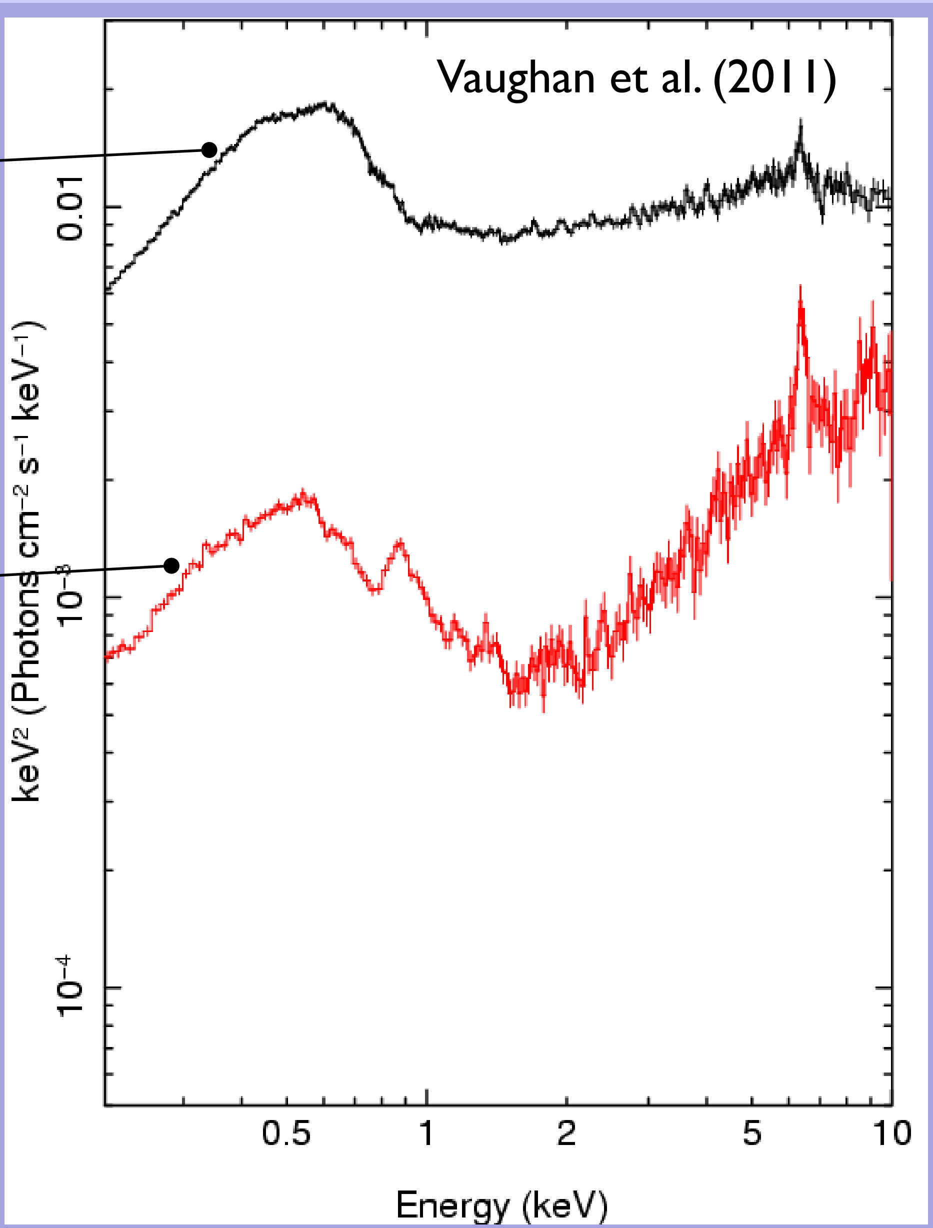
NGC 4051 shows linear rms-flux relation (with high accuracy)
PSD amplitude (but not shape) is flux-dependent



rms-flux relation... a tool in spectral dissection

High flux spectrum

Low flux spectrum

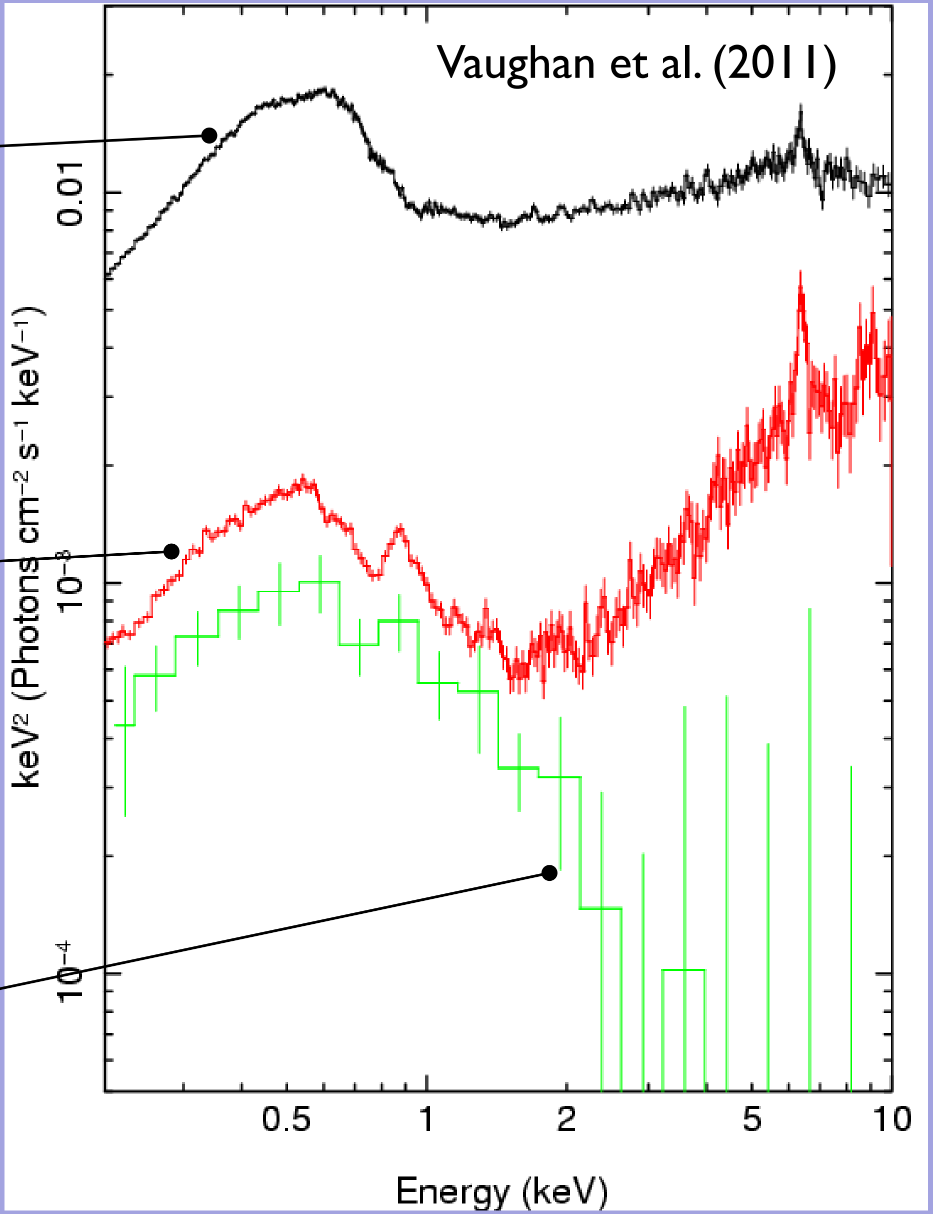


These are '*fluxed*' spectra (**not** '*unfolded*'!)
See Vaughan et al. (2011), Nowak (2005)
And **`EFLUXER`** task in XMM/SAS

High flux spectrum

Low flux spectrum

rms-flux offset



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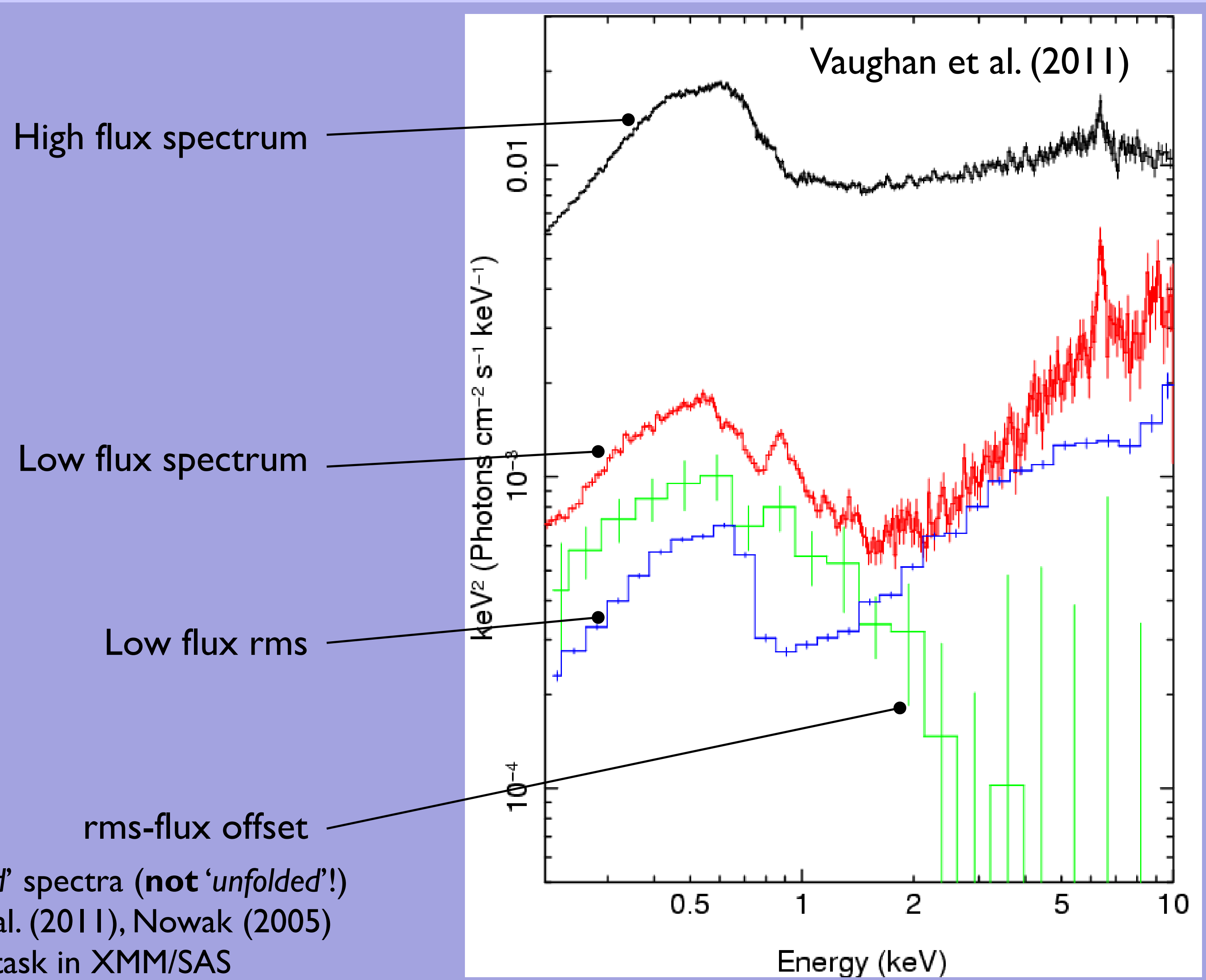

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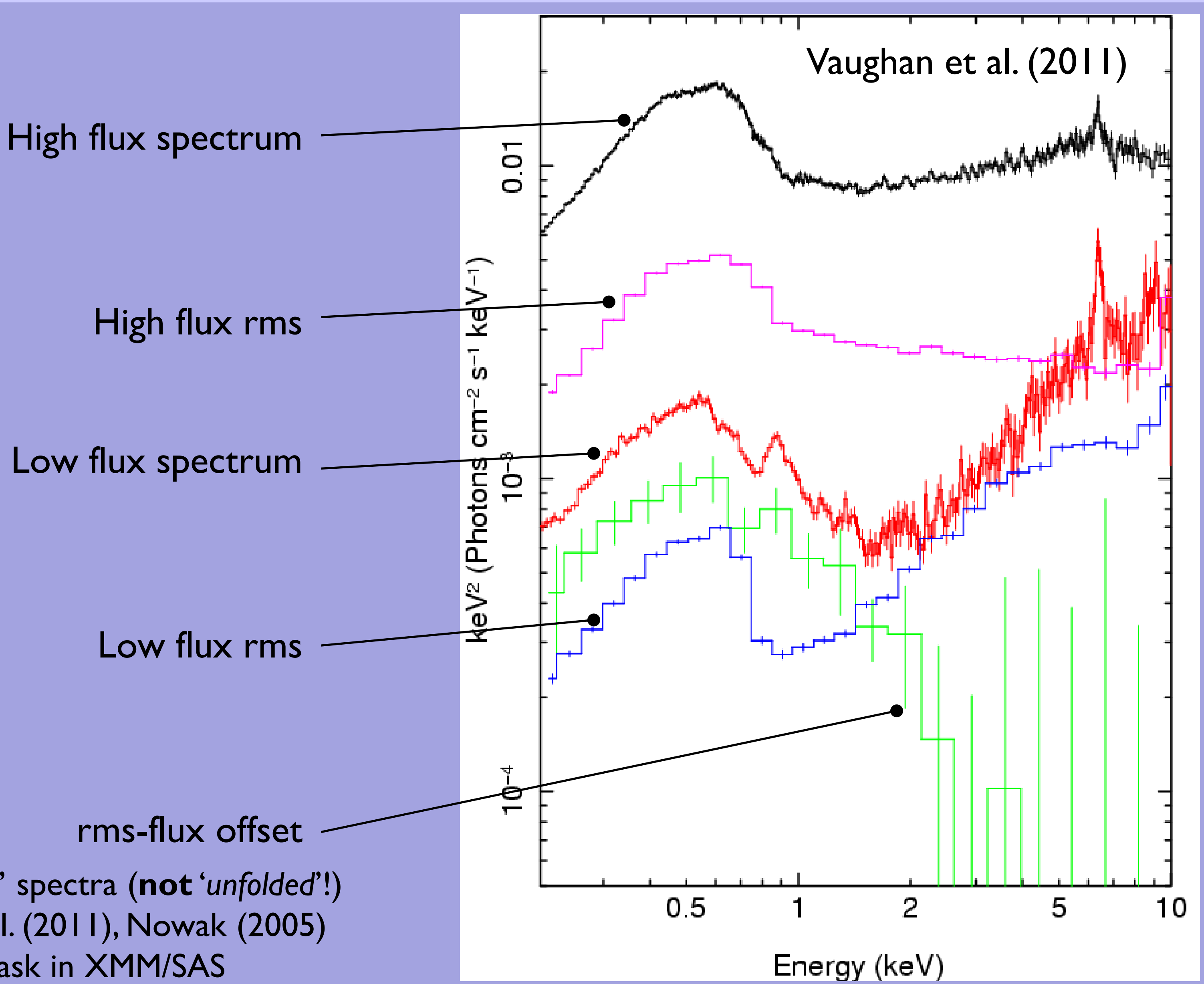
And EFLUXER task in XMM/SAS

rms-flux relation... a tool in spectral dissection



These are '*fluxed*' spectra (**not** '*unfolded*'!)
See Vaughan et al. (2011), Nowak (2005)
And EFLUXER task in XMM/SAS

Cross spectral methods

Consider two time series x(t) and y(t) – e.g. from "soft" and "hard" energy bands

Compute their FTs: X(f) and Y(f)

How are these two related? (Compare with cross-correlation in the "time domain")

$$C(f) = \langle X^*(f) Y(f) \rangle$$

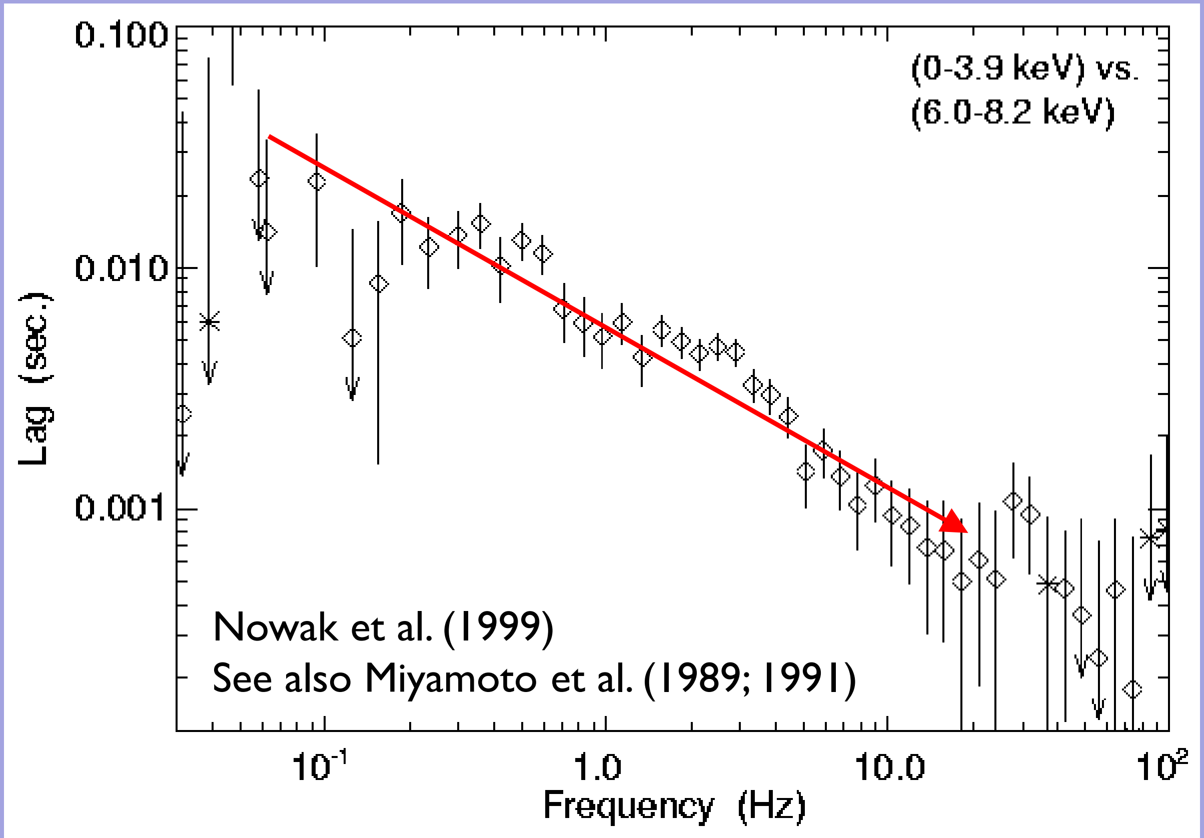
$$\phi(f) = \arg[C(f)] = \arctan\left(\frac{-\mathrm{Im}[C(f)]}{\mathrm{Re}[C(f)]} \right)$$

$$\tau(f) = \phi(f) / 2\pi f$$

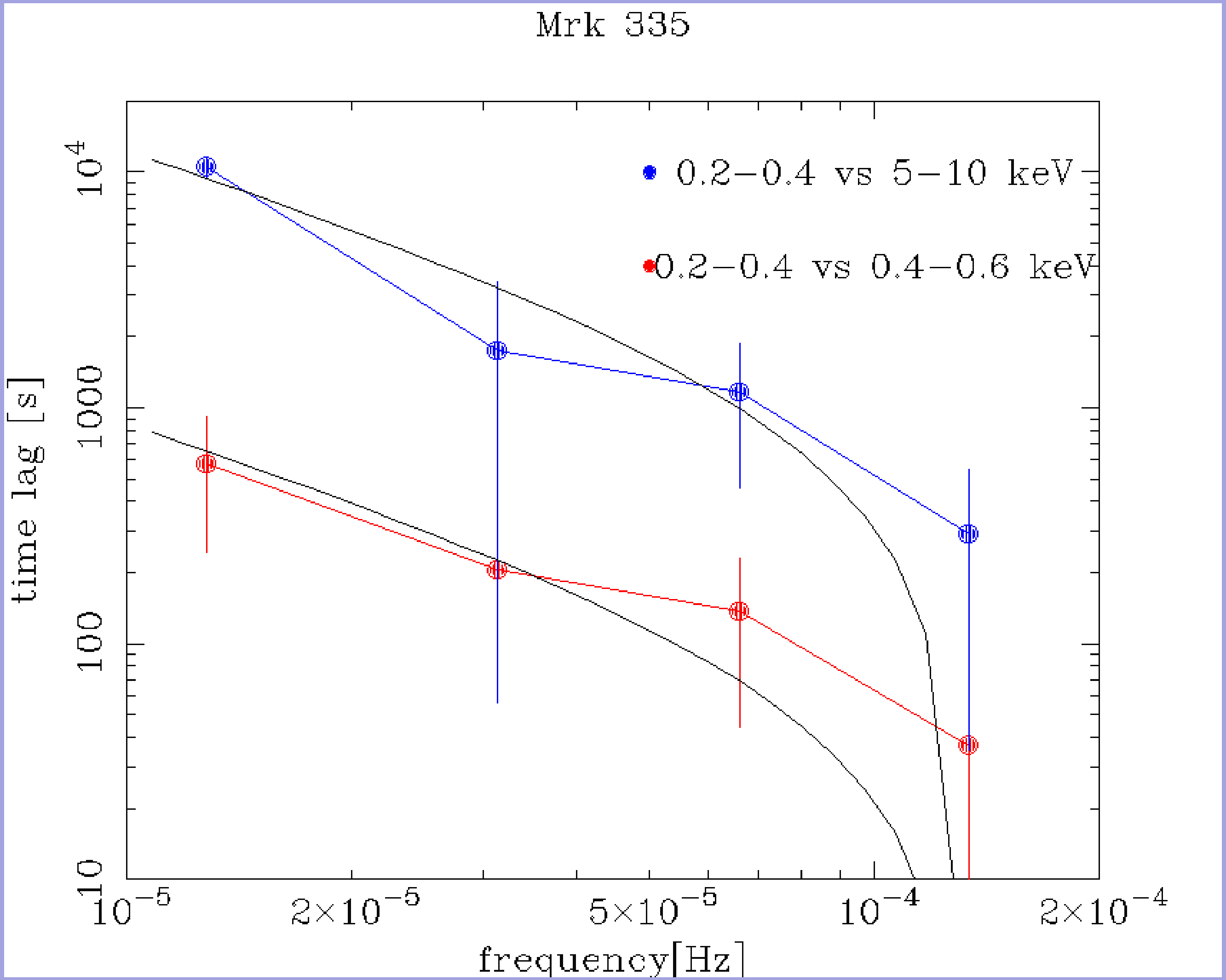
$$\gamma^2(f) = \frac{|C(f)|^2}{\langle |X(f)|^2 \rangle \langle |Y(f)|^2 \rangle}$$

Bendat & Piersol (1986) *Random Data*
Nowak et al. (1999): Cyg X-1
Vaughan et al. (2003): MCG-6-30-16

- Relates two light curves x(t) and y(t)
- Measures (average) time (phase) delay between as a function of freq
- Origin of hard lag ~ freq relation still unclear
  (e.g. Nowak & Vaughan 1996; Kylafis et al. 2008)
- Some promise from “propagation fluctuation” models
  (Kotov et al. 2001
  Arevalo & Uttley 2008)

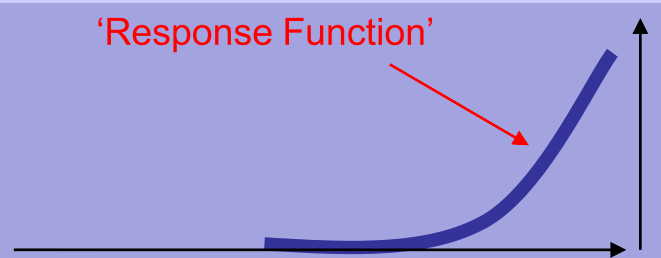


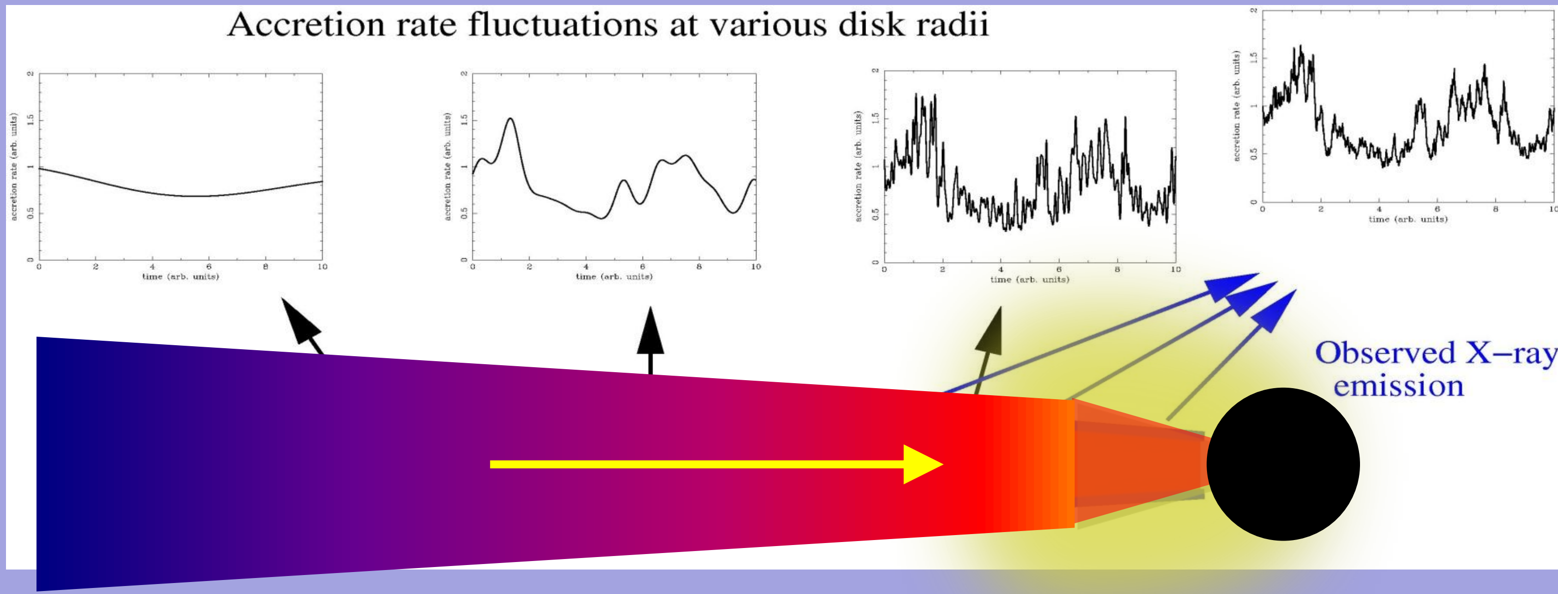
Papadakis & Nandra (2001), Vaughan et al. (2003), Arevalo et al. (2008), McHardy et al. (2004)



The emitting region as a variability filter

Kotov, Churazov & Gilfanov (2001)
Arevalo & Uttley (2008)

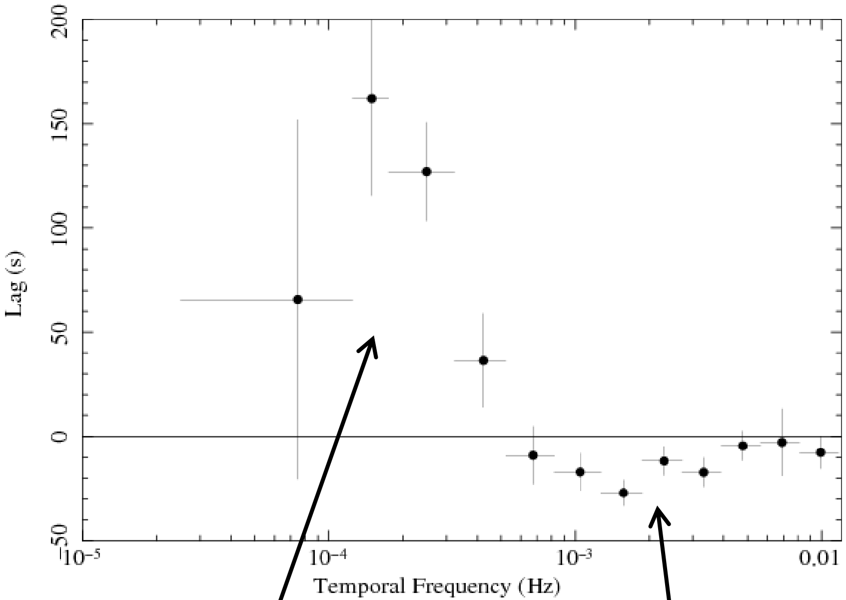


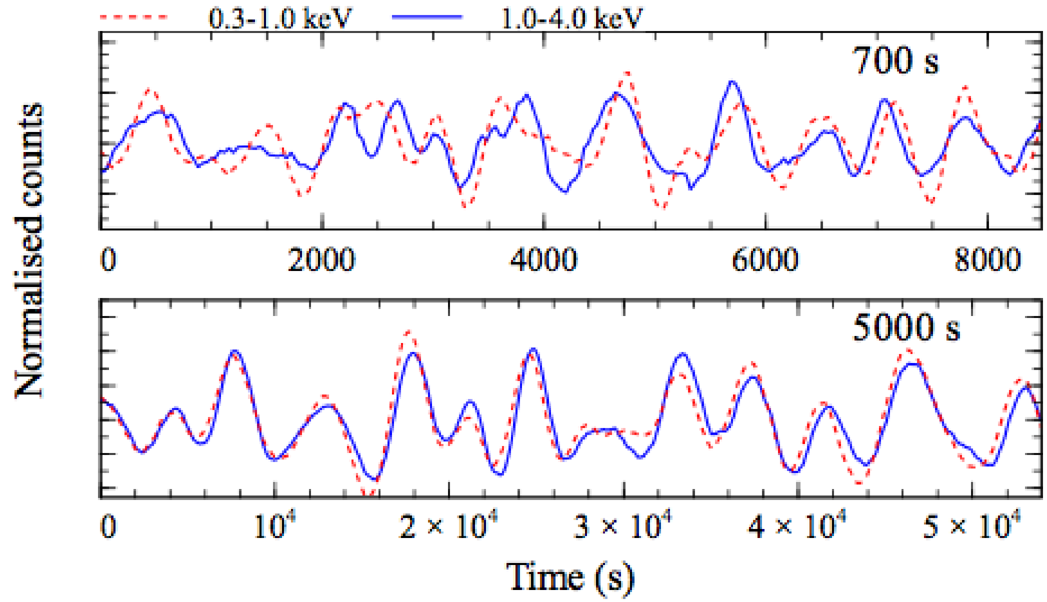


In any type of propagation model, the signal must be convolved with the response function of the emitting region. This will:

- Suppress signal at high frequencies due to travel time across region
- Introduce Fourier-frequency dependent time lags between bands if different bands have different emissivity profiles

Reverberation/lags in AGN and BH XRBs





"hard" lag
(1-4 keV) power law

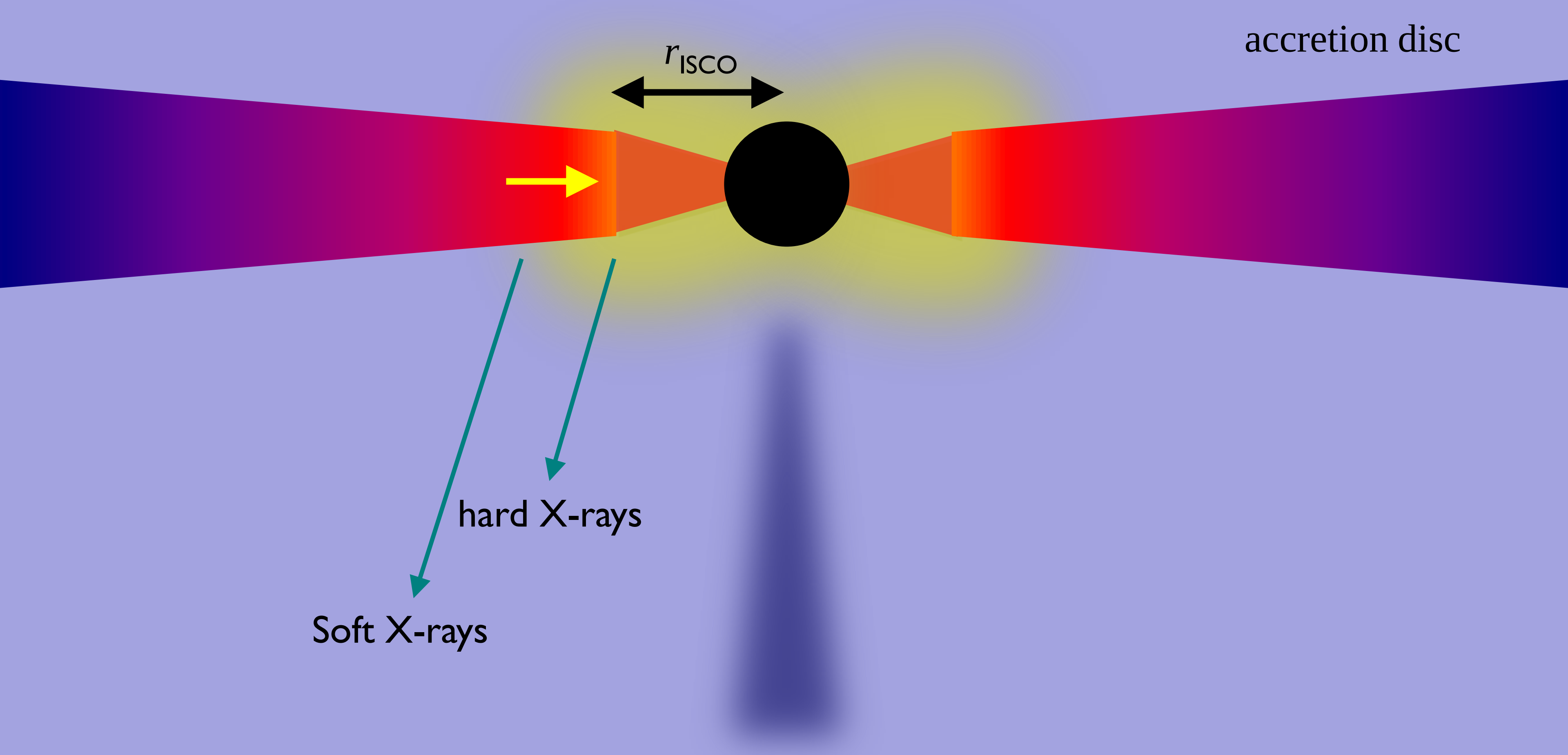
"soft" lag
(0.3-1 keV) PL+refln

Fabian et al. (2010); Zoghbi et al. (2010)
Also L. Miller et al. (2010)
Emmanoulopoulos et al. (2011)

AGN – lag due to reflection on timescales of τ ~ few 10s ~ few r_g/c
– "intrinsic" hard lag within PL continuum at lower freq
– Optical–X-ray (disc – power law) correlation on long timescales (+limits on lag)

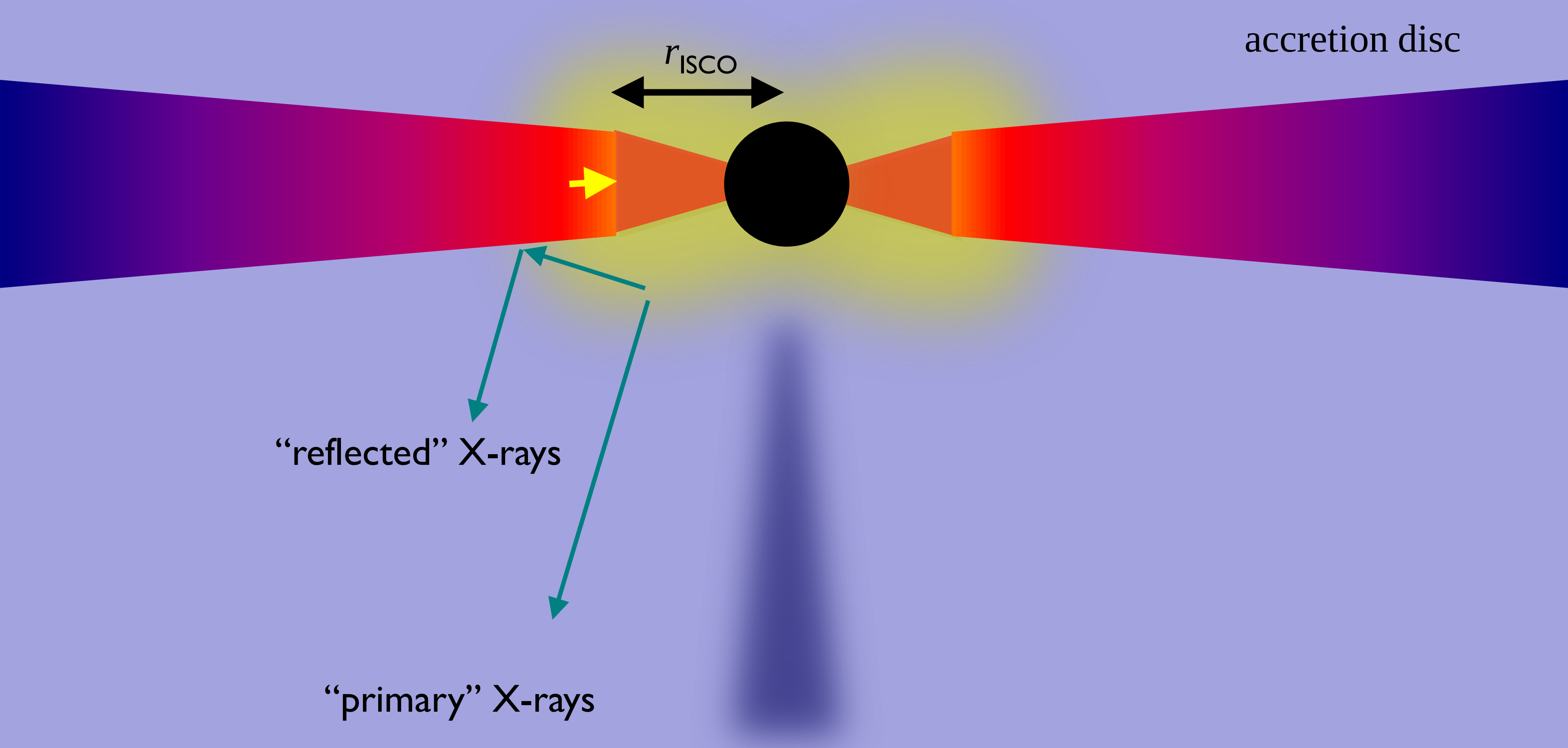
XRBs – Disc – power law lags at low freq [Wilkinson & Uttley (2009), Uttley et al. (2011)]
– "intrinsic" hard lag within PL continuum at lower freq
– reflection signal at higher freqs?

At low frequencies: disc fluctuation propagation



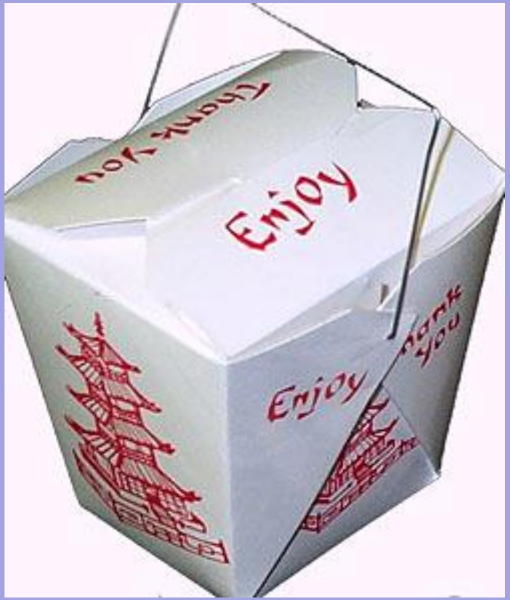
At **low frequencies**, variations in mdot are produced at larger radius in disc, modulating disc emission before propagating in to the corona on the disc viscous time-scale; a graduated corona produces soft ***before*** hard emission

At high frequencies: disc reflection & reverberation



At **high frequencies**, variations in mdot are produced at small radius in disc or corona. Only a fraction of disc emission can respond, but all of corona does, and coronal heating dominates variability ➔ disc reverberation

What to take away from this talk



Time-Energy analysis contains all the information we can get

Many different methods to try:

- spectral fitting – split by time, flux (phase)
- flux-flux analysis
- rms spectra → Fourier resolved spectra
- rms-flux offset
- cross-spectral time delays and coherence
- Principal Components [Vaughan & Fabian 2004]
- covariance spectra [Wilkinson & Uttley 2009]

Much to be gained if we combine what we know and can do with AGN with XRBs
(more counts/cycle vs. more cycles)

Beginning to understand two competing effects (reverberation and fluctuation propagation) in some objects

But important details still an open problem in many cases (e.g. lack of Fe line response in MCG-6-30-15 etc…)

Much more to do: new methods, models, missions.