FOURIER FREQUENCY RESOLVED X-RAY SPECTROSCOPY OF AGN USING XMM-NEWTON DATA

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Outline:

- The Method and how it works
- Application to RXTE observations of GBHs
- Application to XMM-Newton light curves of AGN
- Conclusions and summary

Fourier Frequency Resolved X-ray spectroscopy

A) The theory

Suppose we study the X-ray emission from an AGN which is variable with time. Let us denote with ***X(t)*** the flux at time ***t***. Let us also suppose that ***X(t)*** is a stationary process.

Then X(t) can be represented as the sum of cosine and sine functions. In other words, we can write that:

$$X(t) = \int_0^{\infty} [\cos \omega t \, dU(\omega) + \sin \omega t \, dV(\omega)]$$

for all t.

It turns out that:

$$E[|dU(\omega)|^2]=E[|dU(\omega)|^2]=h(\omega)d\omega$$

where $h(\omega)d\omega$ is the contribution to the total variance of the components with frequency $\boldsymbol{\omega}$

So, in other words...

The amplitude of the Fourier components of a stationary process is equal to $\sqrt{[h(\omega)d(\omega)]}$

B) In practice (Revnivtsev et al 1999)

Suppose we have a light curve with N observations, $X(E_i, t_i)$ $(i=1,2,...,N)$. Then, at frequencies $f_j = j/(N\Delta t)$, $j=1,...,N/2$, we can estimate the power spectral density function, $h(\omega)$, as follows:

$$P(E_i, f_j) = (2\ddot{A}t/N)\left|\sum_{i=1}^{N} X(E_i, t)e^{(-i2\pi f_j t)}\right|^2$$

where $\Delta t = t_i - t_{i-1}$. Consequently,

$$R(E_i, f_j) = \sqrt{P(E_i, f_j)\ddot{A}f}$$

is an estimate of the amplitude of the Fourier component with frequency f_j in the energy band E_i.

The plot $R(E_i, f_j)$ vs E_i, gives the "energy spectrum" of the amplitudes of this Fourier component.

The FR spectra are NOT like the observed energy spectra of the sources.

Nevertheless, they can help us understand the variability properties of compact objects

For example: Suppose the iron line profile is given by:

$$f(E,t)=A(t)exp[-(E-E_0)^2/2\sigma^2]$$

In this case, we expect to detect a line-like feature in the FRS at E_0, at all frequencies.

…or: Suppose the X-ray continuum varies as:

$$f(E,t)=A(t)E^{-\Gamma}$$

In this case, the FR spectra should also have a power law like shape, with the same slope, at all frequencies.

…or: The X-ray continuum varies as above, but the line is constant. In this case, there will be no line in the FR spectra, which will have a power-law like shape.

Fourier Resolved spectroscopy of GBHs

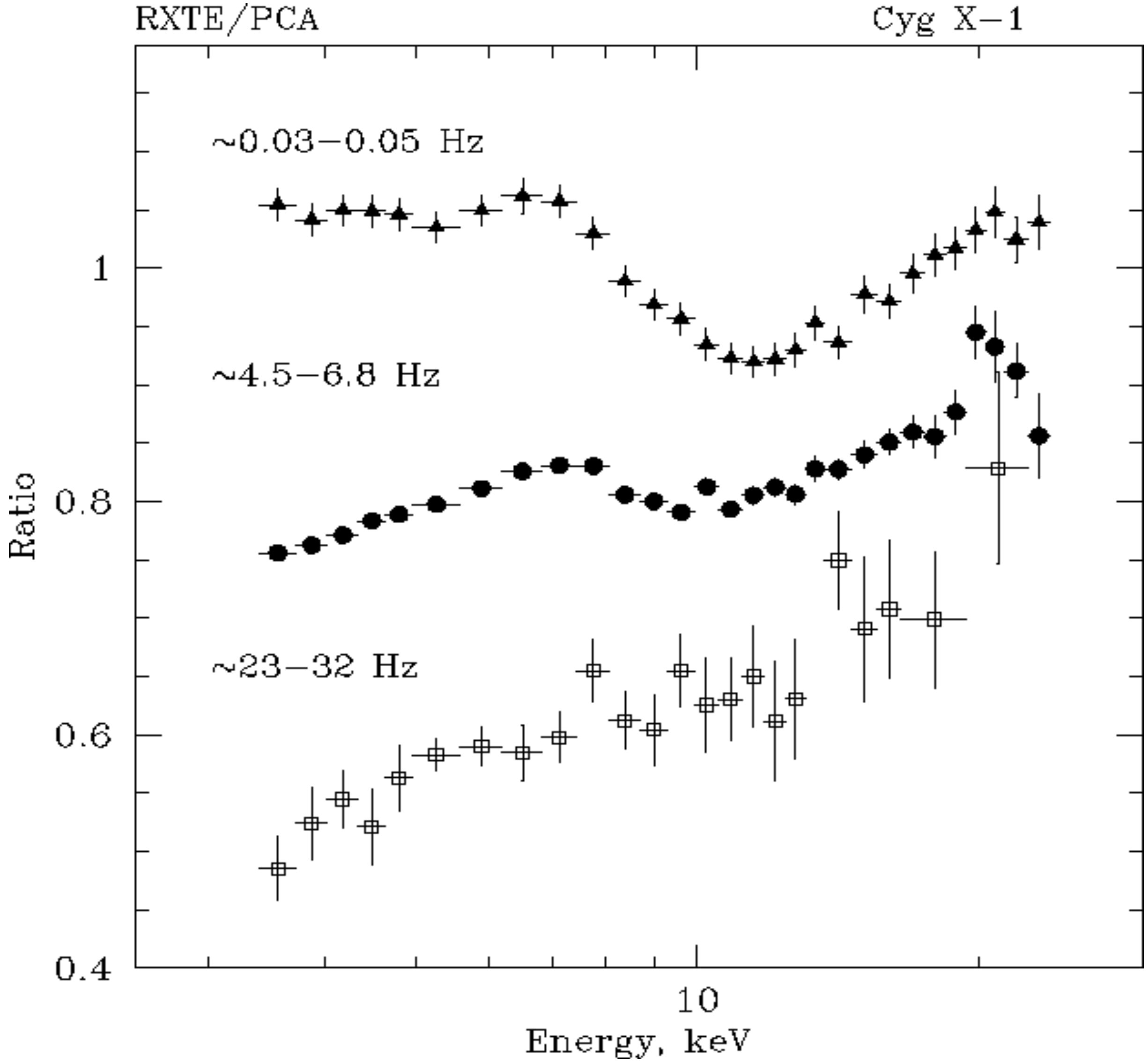
Using RXTE observations,

a) Revnivtsev et al (1999) studied the FRS of Cyg X-1 in its Low/Hard State.

b) Gilfanov et al. (2000) studied the FRS of Cyg X-1 in its High/Soft Sate.

c) Revnivtsev et al (2001) studied the FRS of GX 339-4 in its Hard/Low state.

d) Reig et al. (2005) studied the FRS spectra of 4U 1543-47 during its 2002 outburst.



RXTE/PCA
Cyg X−1
~0.03−0.05 Hz
~4.5−6.8 Hz
~23−32 Hz
Ratio
1
0.8
0.6
0.4
10
Energy, keV

Results

A) *In almost all cases, an iron line at ~ 6.4 keV is detected.*

⬇

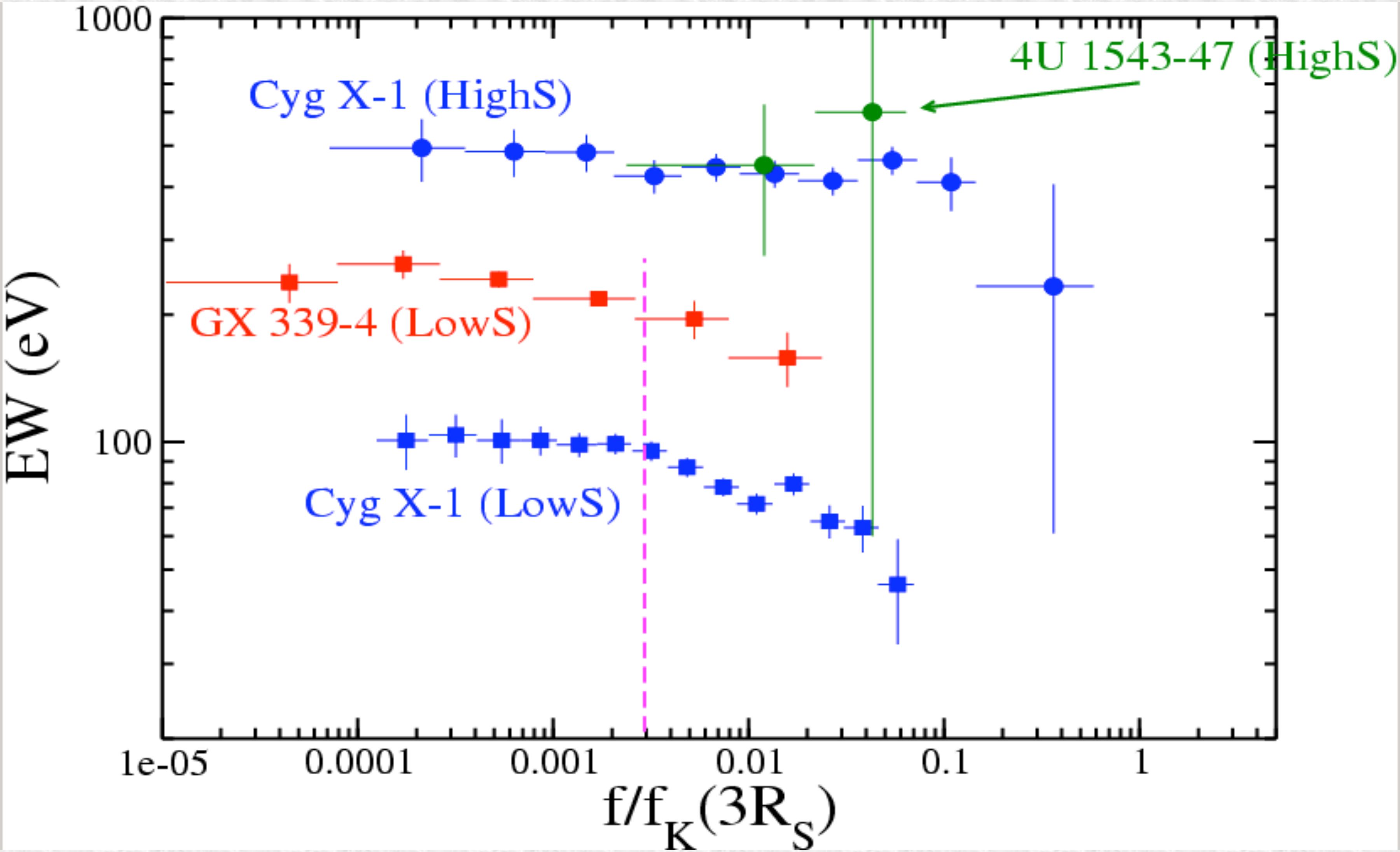
The line is variable. The EW is larger when the systems are in their Soft/High State.

B) *The FRS spectra are well fitted by a simple Power Law model.*

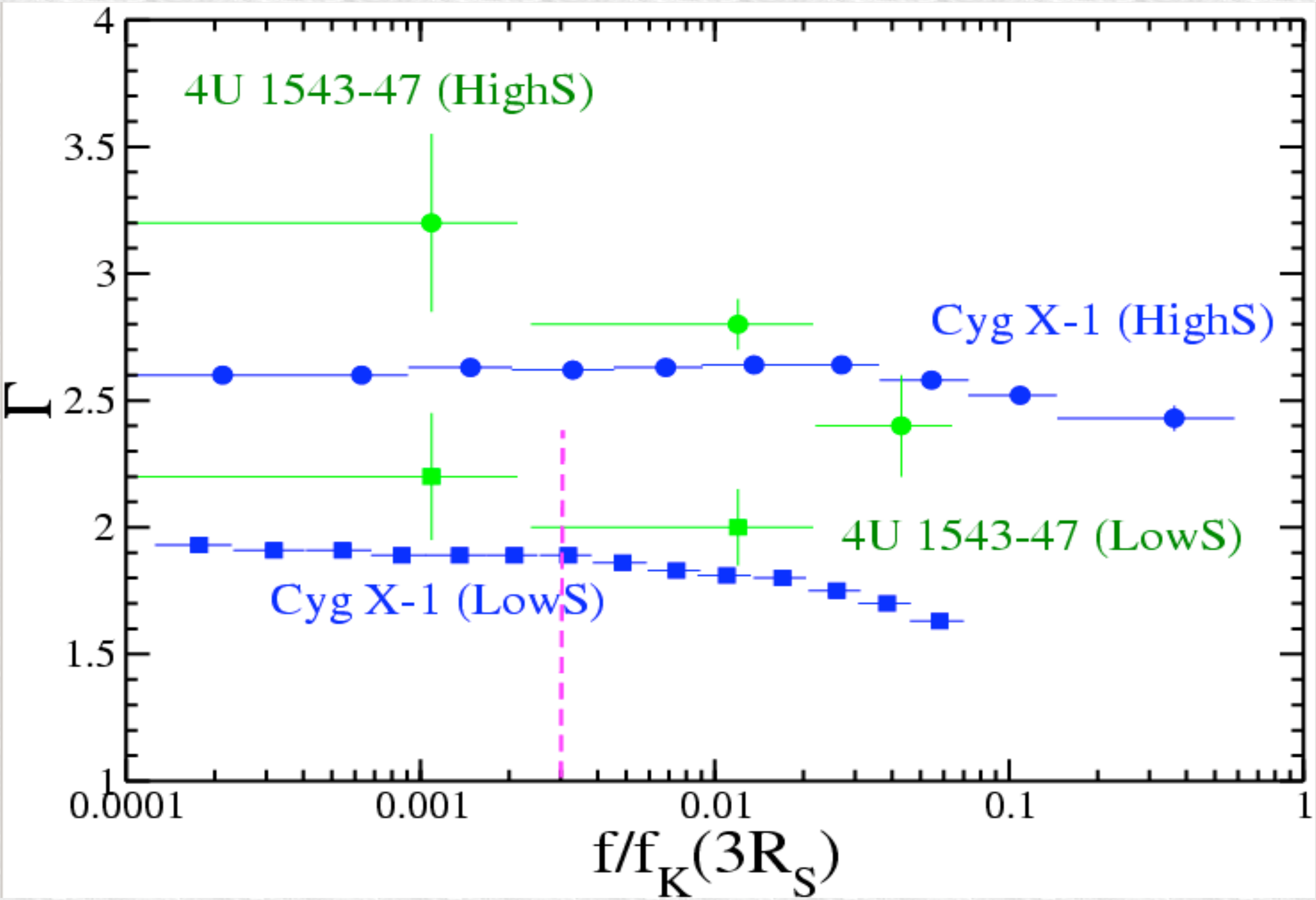
⬇

The hard band Power Law component is variable while the disk emission is not variable on time scales < 100s.

C) *The line's EW and Γ decreases (i.e. the spectrum hardens) with increasing frequency.*



1000
100
EW (eV)
1e-05
0.0001
0.001
0.01
0.1
1
f/f_K(3R_S)
Cyg X-1 (HighS)
4U 1543-47 (HighS)
GX 339-4 (LowS)
Cyg X-1 (LowS)



4U 1543-47 (HighS)
Cyg X-1 (HighS)
4U 1543-47 (LowS)
Cyg X-1 (LowS)
Γ
4
3.5
3
2.5
2
1.5
1
0.0001
0.001
0.01
0.1
1
$f/f_K(3R_S)$

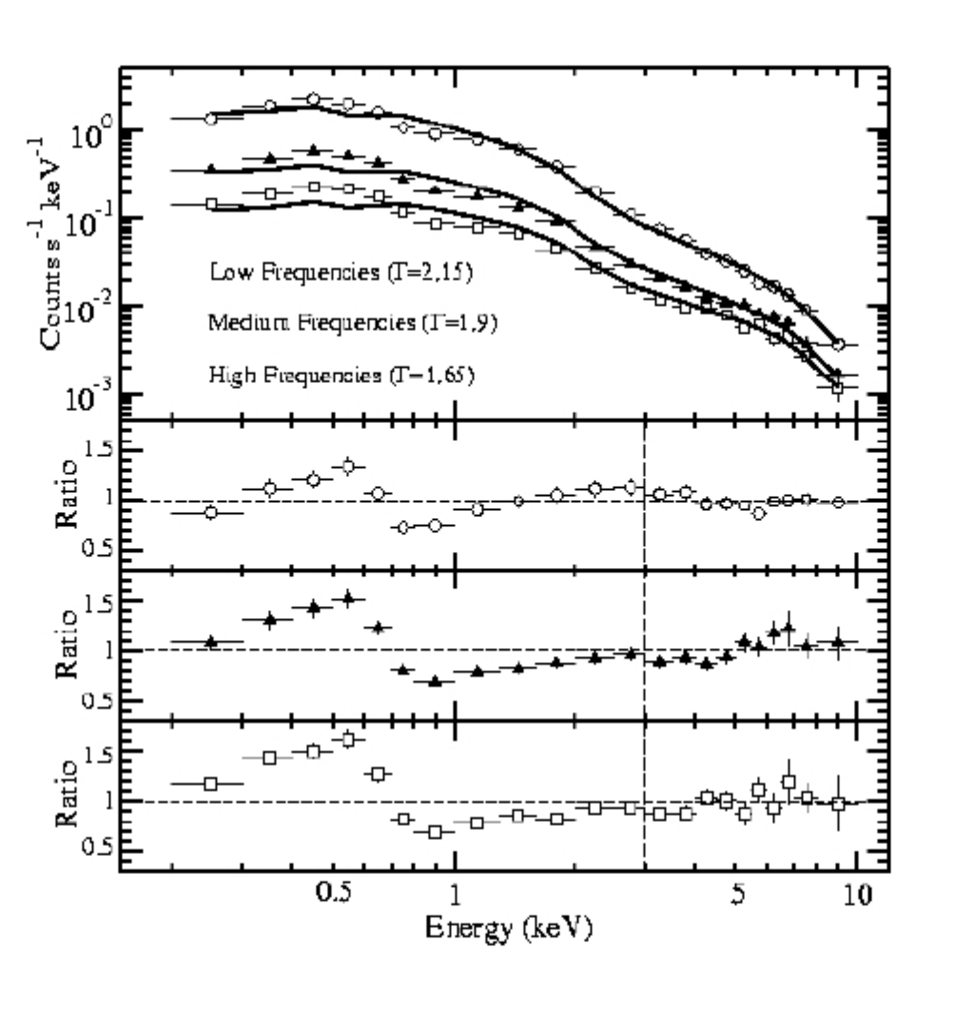
Application to AGN: MCG -6-30-15

Papadakis et al. (2005) studied the FRS of MCG -6-30-15, using EPIC pn data from the two XMM-Newton observations of the source.

They found that the,

8.3*10^{-6}–10^{-4} Hz,
1-3*10^{-4} *Hz*, and
3-7*10^{-4} Hz

FRS are well fitted by a simple Power Law model, with Γ decreasing with increasing frequency.



Application to other AGNs

We searched the XMM-Newton archive for AGN with observations longer than 100 ksec.

We used EPIC pn data, and created lightcurves in 10 energy bands:

8 from 3 to 7 keV with $\Delta E=0.5$ keV, and *7-8*, *8-10* keV.

We accepted objects which show significant variations in all energy bands.

There are 5 AGN with observations that satisfy these criteria:

NGC 3516, NGC 3783, NGC 4051,

Akn 564, Mkn 766

We considered the FRS in two broad frequency bands:

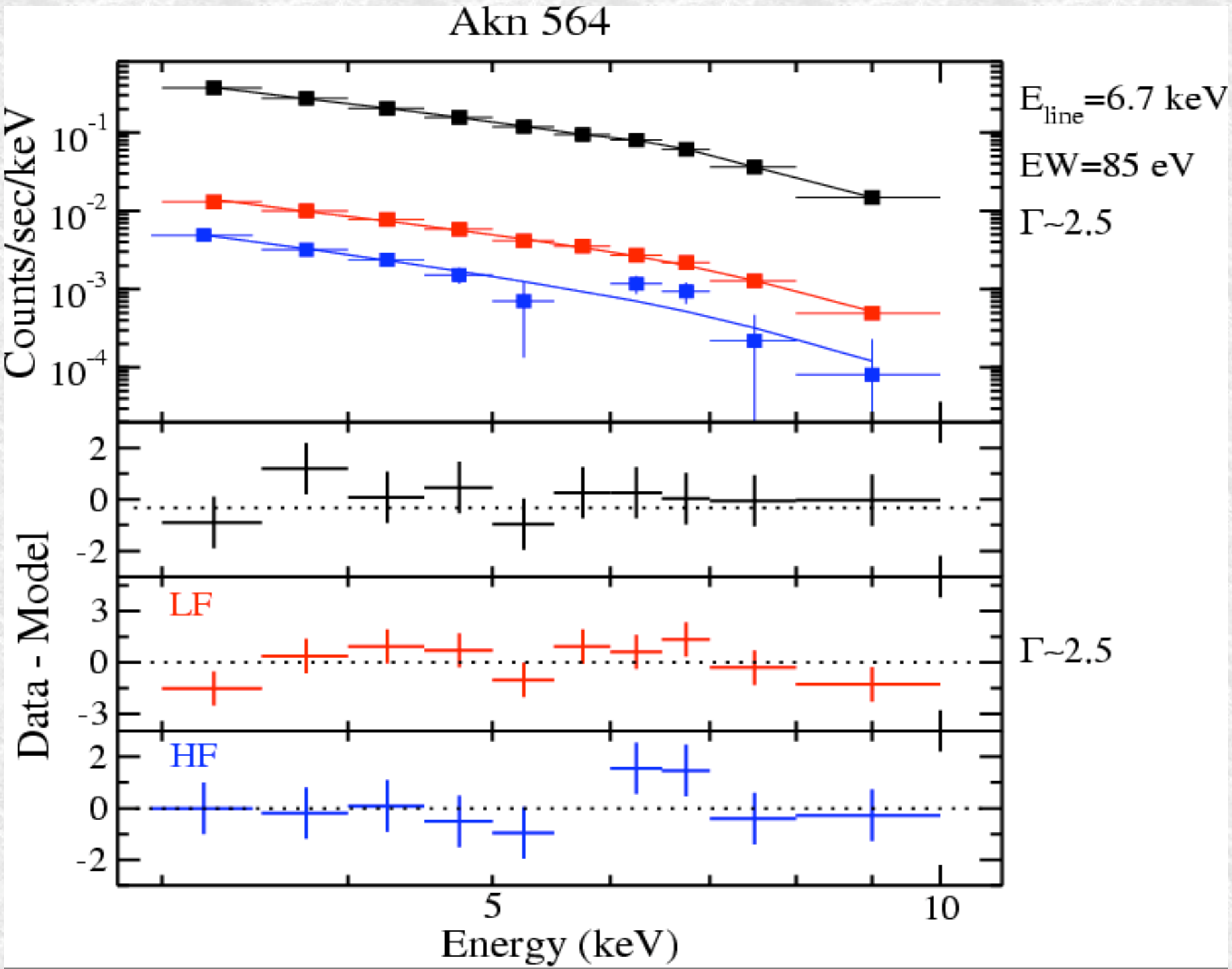
a) *10^{-5} - $5*10^{-4}$ Hz (**LF**)*

and

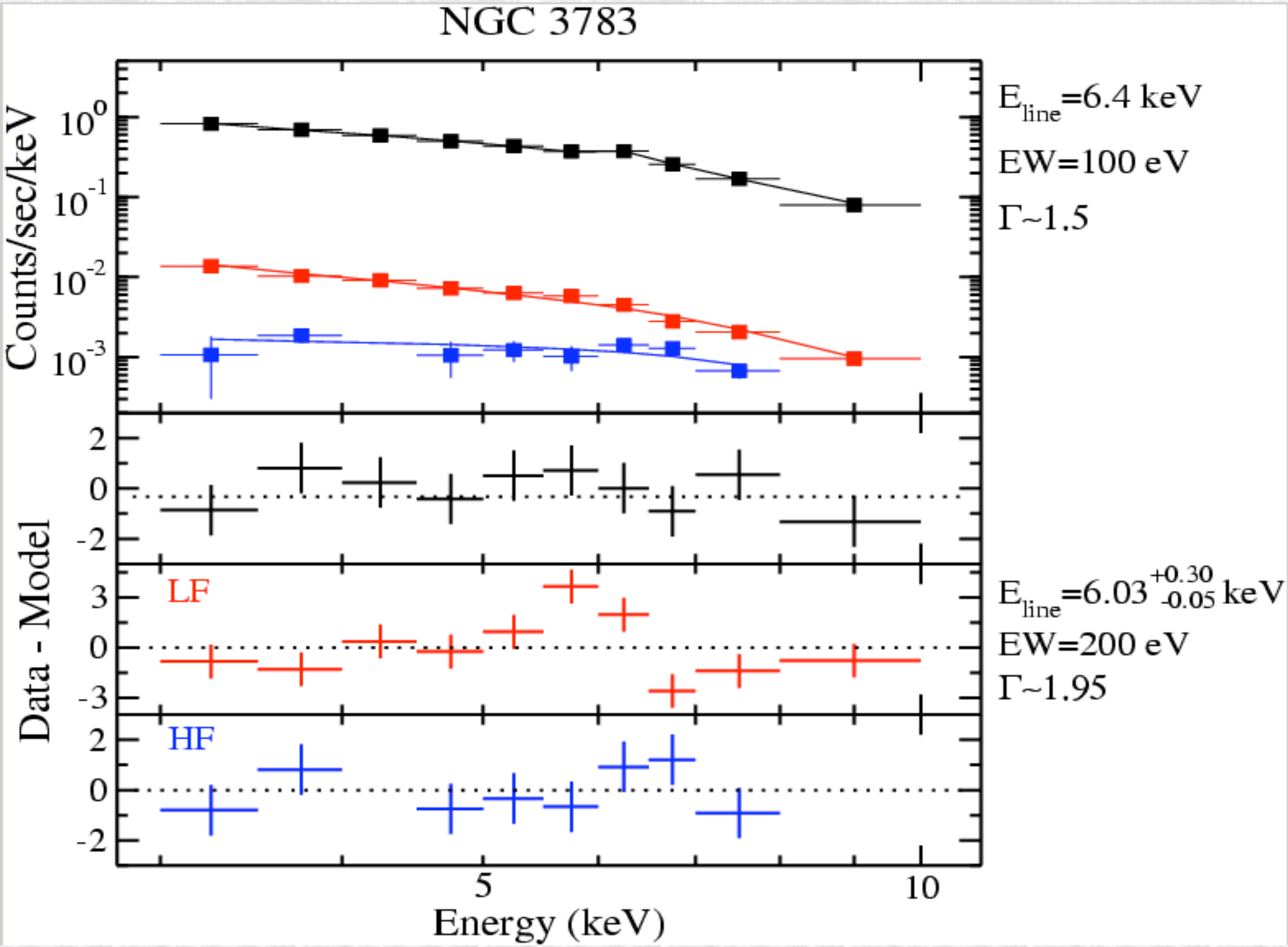
b) *$5*10^{-4}$ - 10^{-3} Hz (**HF**)*

A) A line at ~ 6.4 keV is detected in the LF spectrum of three sources (NGC 3783, Mkn 766 and NGC 4051).

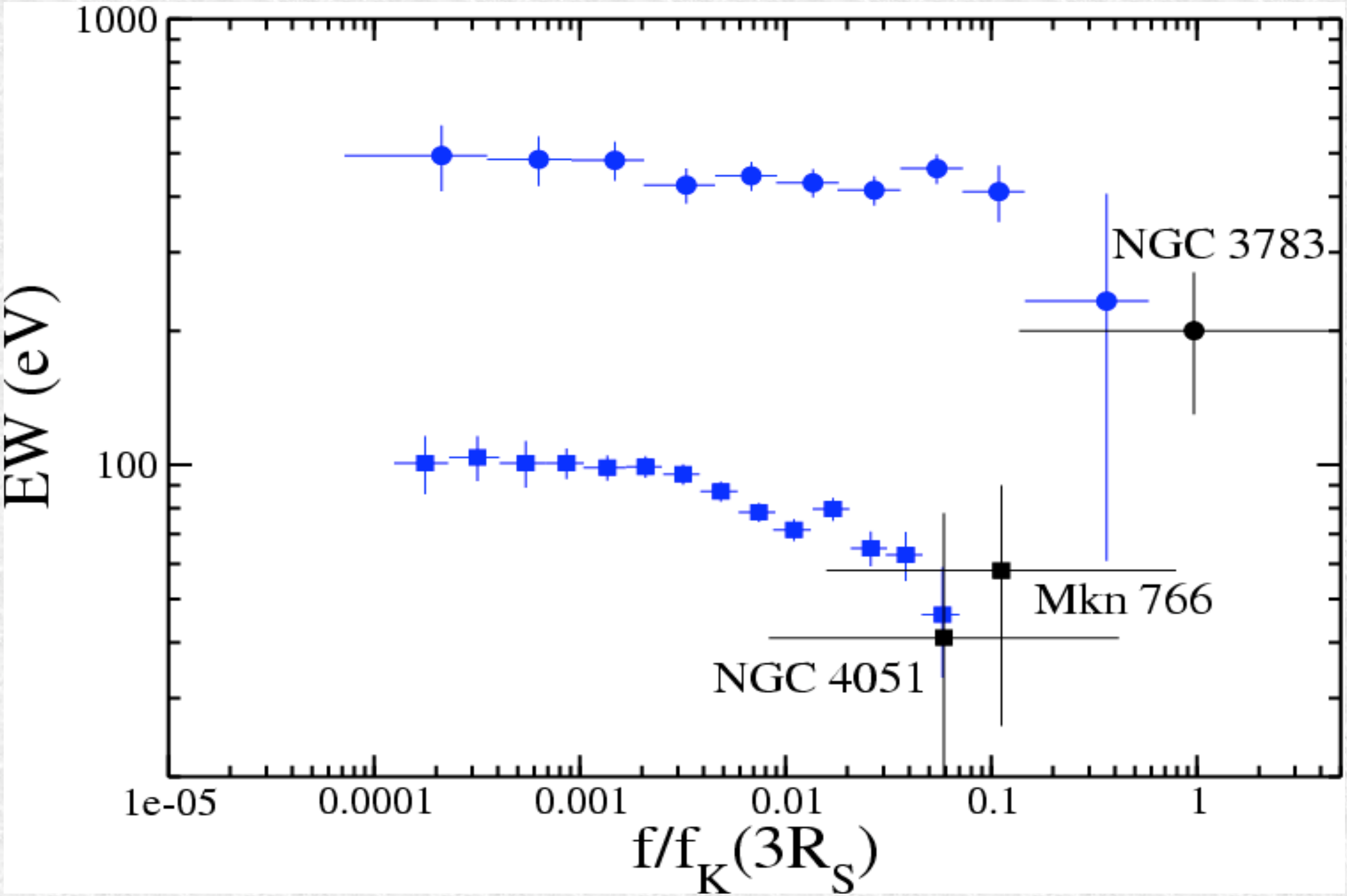
B) The FRS are well fitted by a simple Power Law model. The spectral slope Γ decreases with increasing frequency.



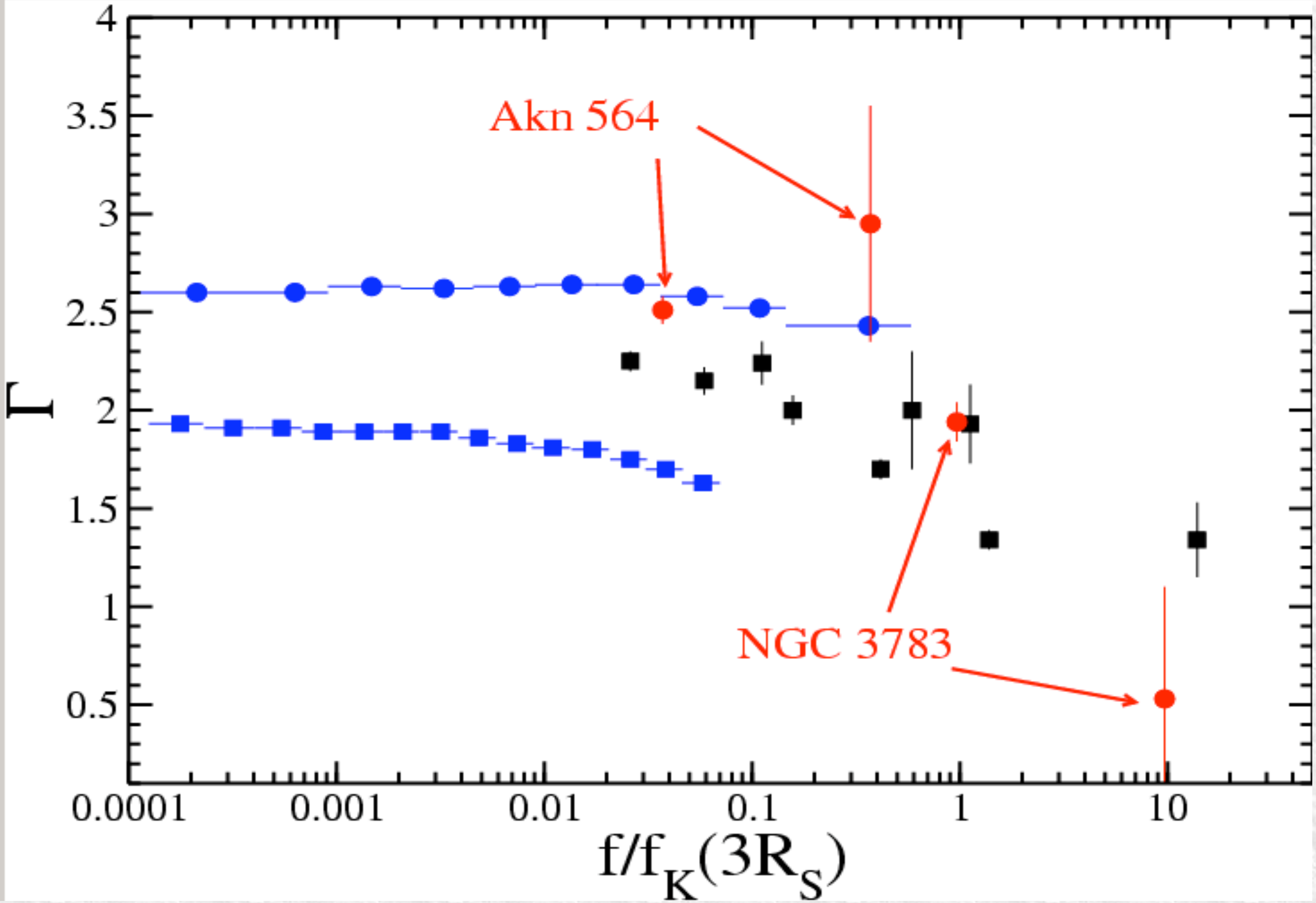
Akn 564
Counts/sec/keV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
E_{line}=6.7 keV
EW=85 eV
Γ~2.5
Data - Model
2
0
-2
LF
3
0
-3
Γ~2.5
HF
2
0
-2
5
10
Energy (keV)



NGC 3783
Counts/sec/keV
Data - Model
Energy (keV)
E_{line}=6.4 keV
EW=100 eV
Γ~1.5
LF
HF
$E_{line}=6.03^{+0.30}_{-0.05}$ keV
EW=200 eV
Γ~1.95



1000
100
EW (eV)
1e-05
0.0001
0.001
0.01
0.1
1
$f/f_K(3R_S)$
NGC 3783
Mkn 766
NGC 4051



Akn 564
NGC 3783
Γ
f/f_K(3R_S)
4
3.5
3
2.5
2
1.5
1
0.5
0.0001
0.001
0.01
0.1
1
10

RESULTS:

A line at ~ 6.4 keV appears in many FRS of a few GBHs and AGN.

This result implies that the iron line in these objects responds to the continuum variations, but not in the same way at all time scales, since …

The line's EW decreases with increasing frequency.

At least in the case of Cyg X-1 in the "Hard/Low" and "Soft/High" state, the EW of the line decreases at frequencies

$$> 2*10^{-3} \text{ and } 10^{-1}\ \Omega_K(R=3R_S)$$

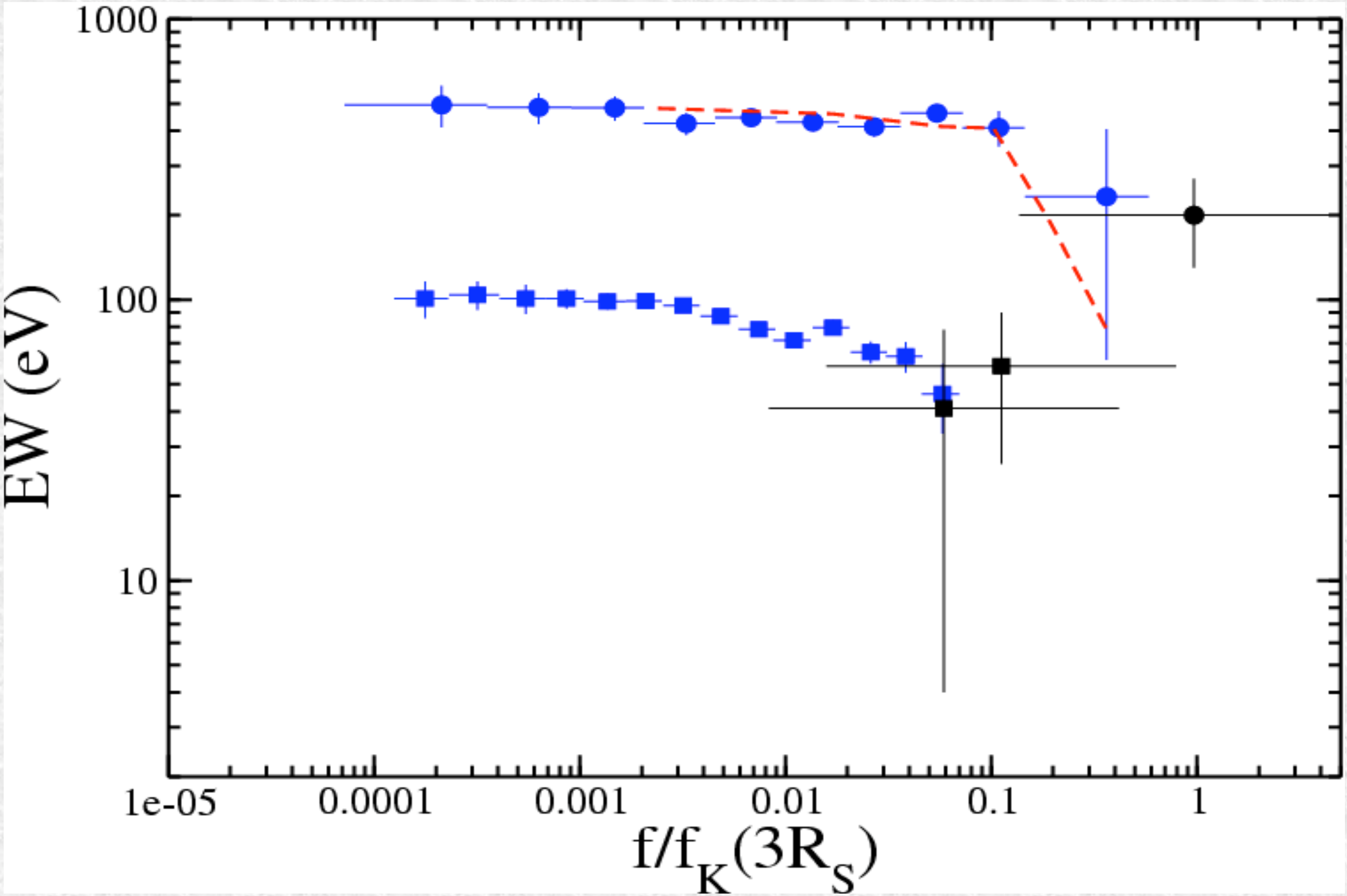
respectively.

If we assume the simplified geometry of an isotropic point source above a flat disc, these results imply that:

a) the reflection component in GBHs and AGN is variable,

BUT,

b) the inner radius of the “reflective” part of the disc the case of systems in their Hard/Low State is $R_{\text{"}in\text{"}}$***~100*** R_s as opposed to $R_{\text{"}in\text{"}}$***~10*** R_s, in the Soft/High state (Gilfanov et al, 2000).



1000
100
10
EW (eV)
1e-05
0.0001
0.001
0.01
0.1
1
f/f_K(3R_S)

The FR spectra become progressively harder (Γ decreases) as the frequency increases.

This results implies complex intrinsic spectral variations, and is not consistent with the idea that the flux variations in AGN are associated with a Power Law component which varies only in amplitude.

Interestingly, Γ changes above the same frequencies that the iron's line EW decreases.

In summary

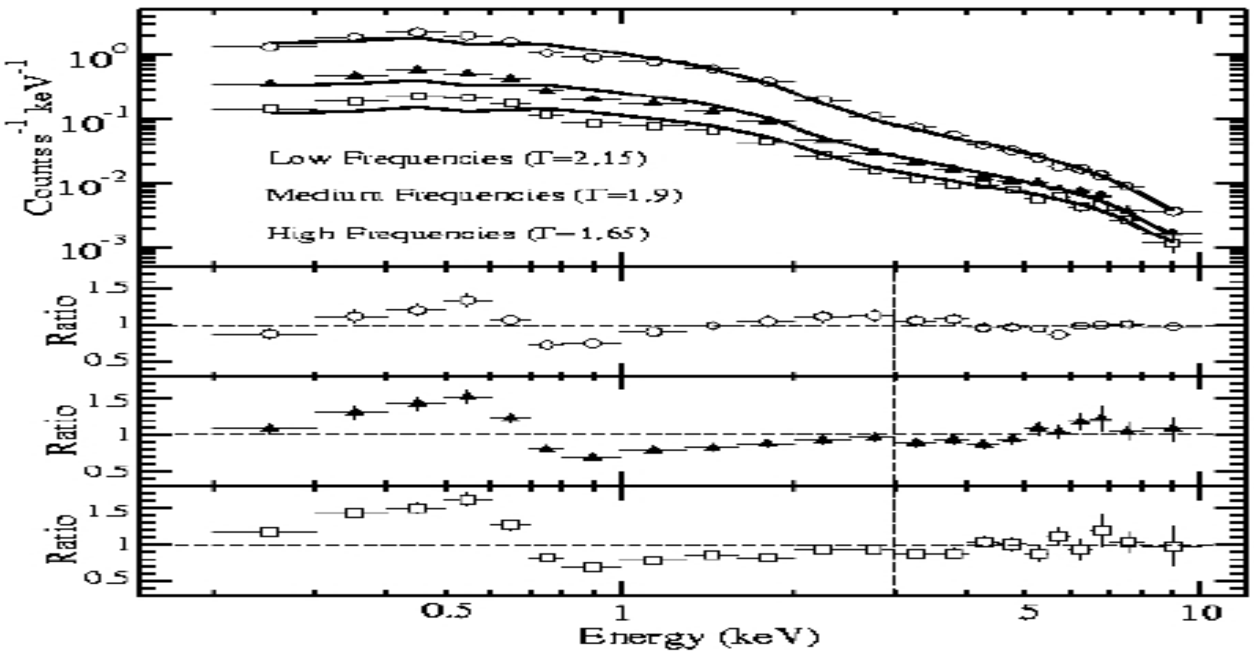
The FRS technique is a powerful new method that can help us understand better the X-ray spectral variability in AGN, and probe the geometry of the accretion flow.

In the near future, we plan:

A) To study the FRS of AGN using long (weeks and years long) RXTE light curves.

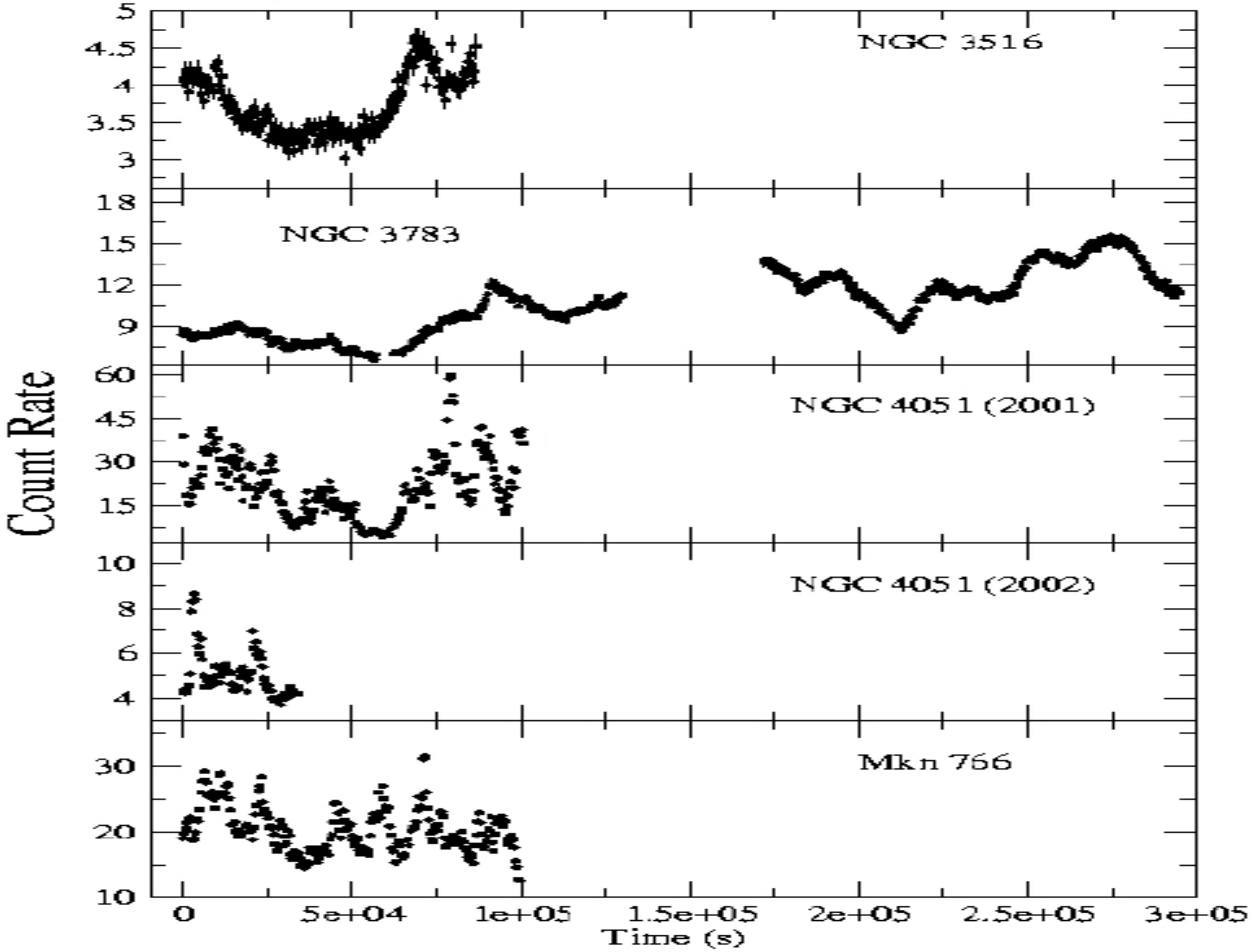
B) Model the disc response in detail and perform a better comparison with the data (taking into account the EW of the line in each object, and the Γ variations with frequency).

MCG -6-30-15



Counts s^{-1} keV^{-1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
Low Frequencies (Γ=2.15)
Medium Frequencies (Γ=1.9)
High Frequencies (Γ=1.65)
Ratio
1.5
1
0.5
0.5
1
5
10
Energy (keV)

The 0.2-10 keV light curves



Possible scenarios that can be tested with the use of the FRS.

Iron Line variability: Suppose the iron line profile is given by:

$$f(E,t)=A(t)\exp[-(E-E_0)^2/2\sigma^2]$$

In this case, we expect to see the same shape line in the FRS, at all frequencies. On the other hand, the amplitude of the line does depend on the geometry of the emitting region, since:

$$F_{refl}(E,t)=\int_0^\infty F_0(E,t-\tau)T(\tau)d\tau$$

Where, F_{refl} and F_0 are the reflected and primary flux, while $T(\tau)$ is the transfer function. This function depends on the geometry and accounts for the propagation time of the photons from the source to different parts of the

Continuum Variability:

A) Suppose the X-ray continuum varies as:

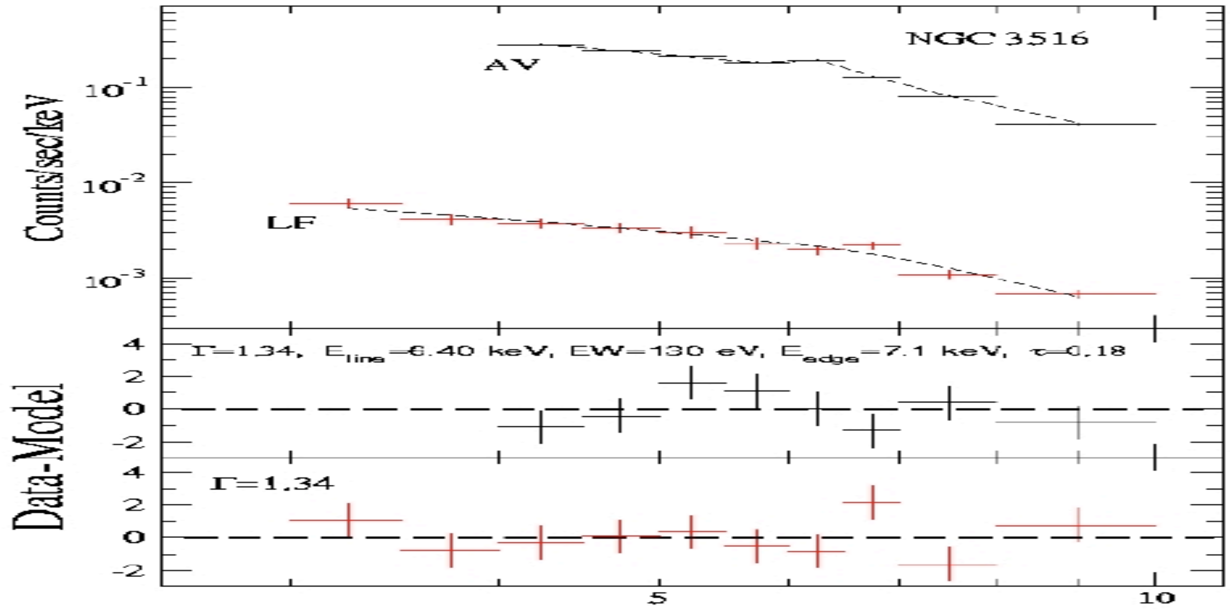
$$f(E,t)=A(t)E^{-\Gamma}$$

In this case, the X-ray continuum in the FR spectra should also have a power law shape, with the same slope, ***at all frequencies.*** The same holds true in the case there exists a constant reflection component as well.

B) Suppose now that the spectral slope Γ changes with time, i.e. Γ increases or decreases with $A(t)$. In the former case, the FR spectra should be steeper than Γ_{ave}, while in the latter case they will be flatter, ***at all frequencies.***

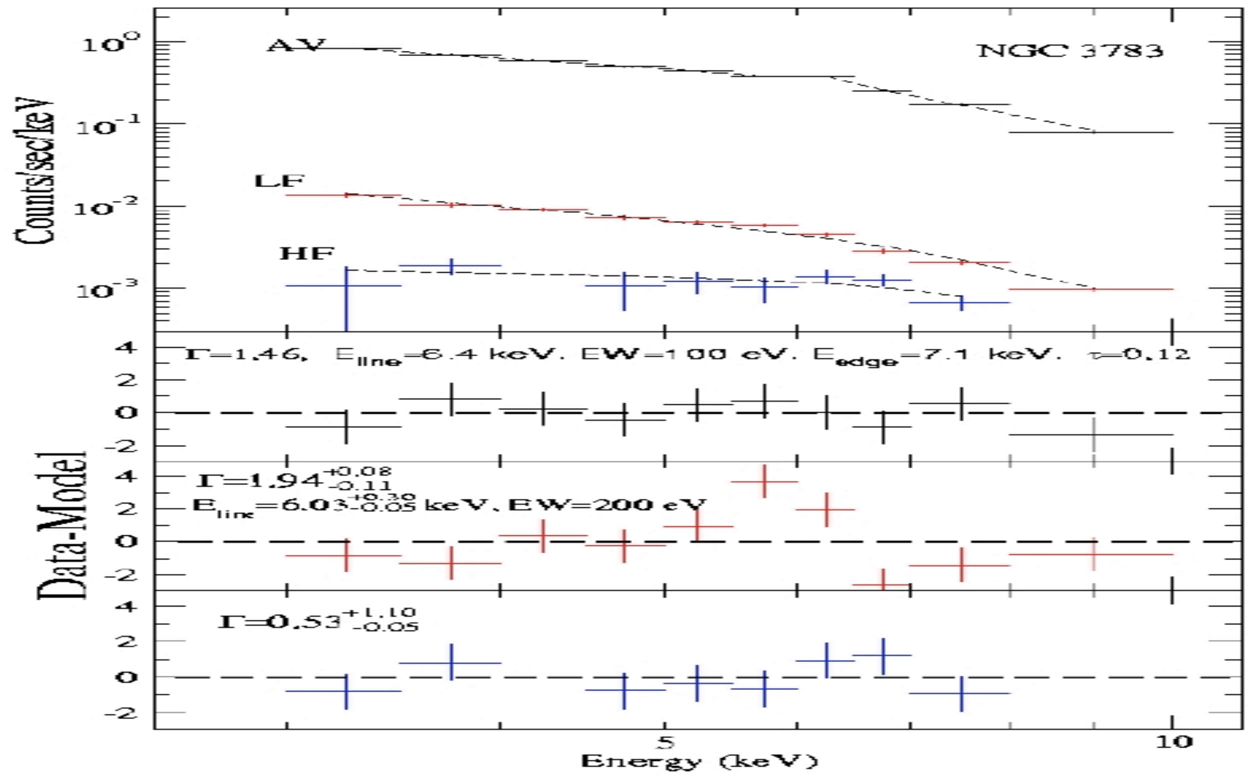
In both cases we do not expect frequency dependent spectral slope

NGC 3516

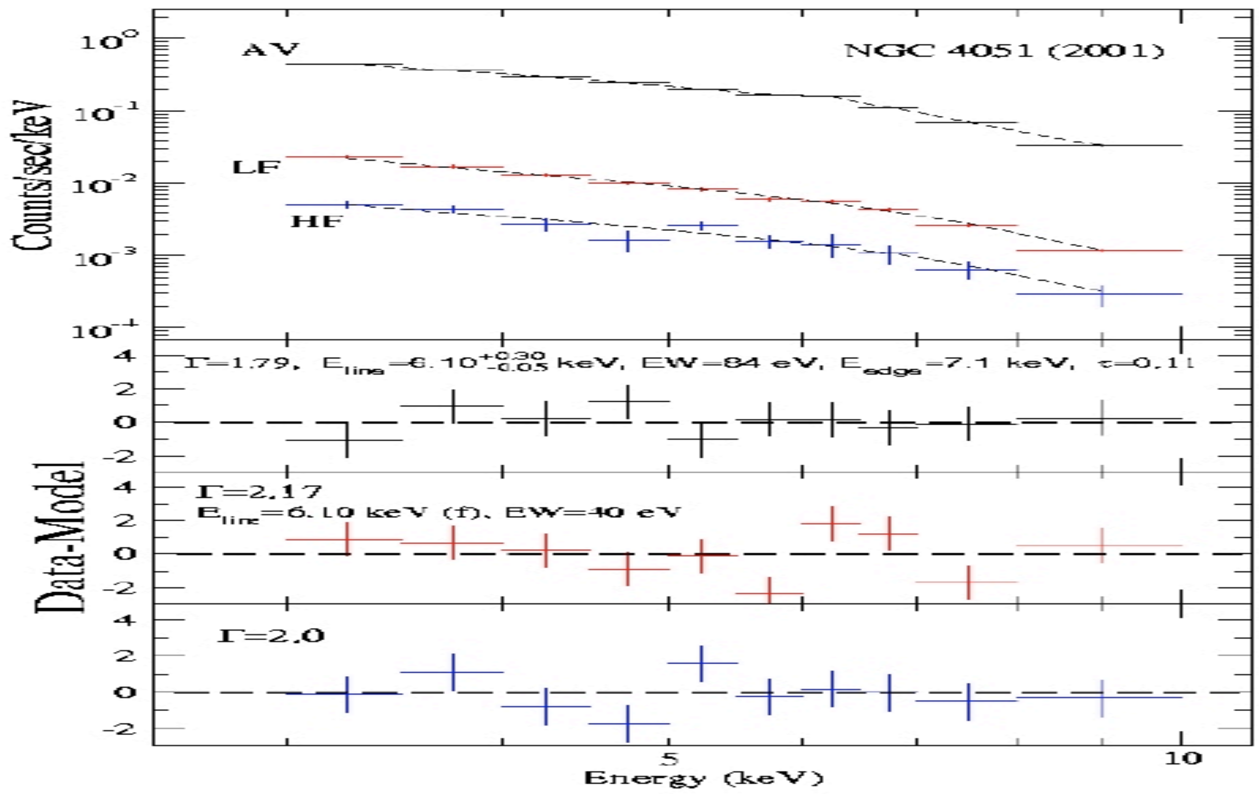


NGC 3516
AV
LF
Counts/sec/keV
Data-Model
Γ=1.34, E_{line}=6.40 keV, EW=130 eV, E_{edge}=7.1 keV, τ=0.18
Γ=1.34

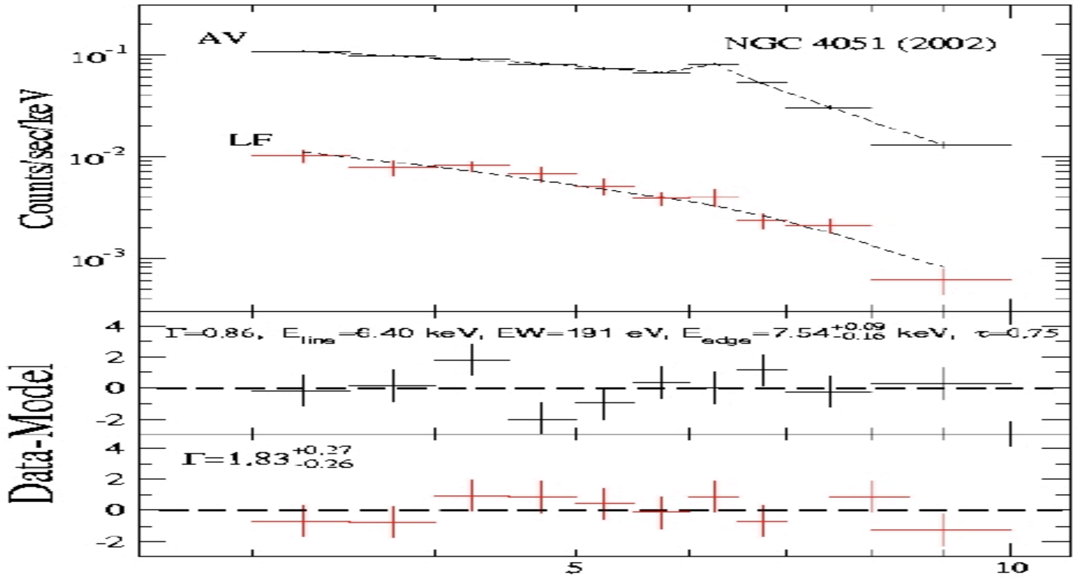
NGC 3783



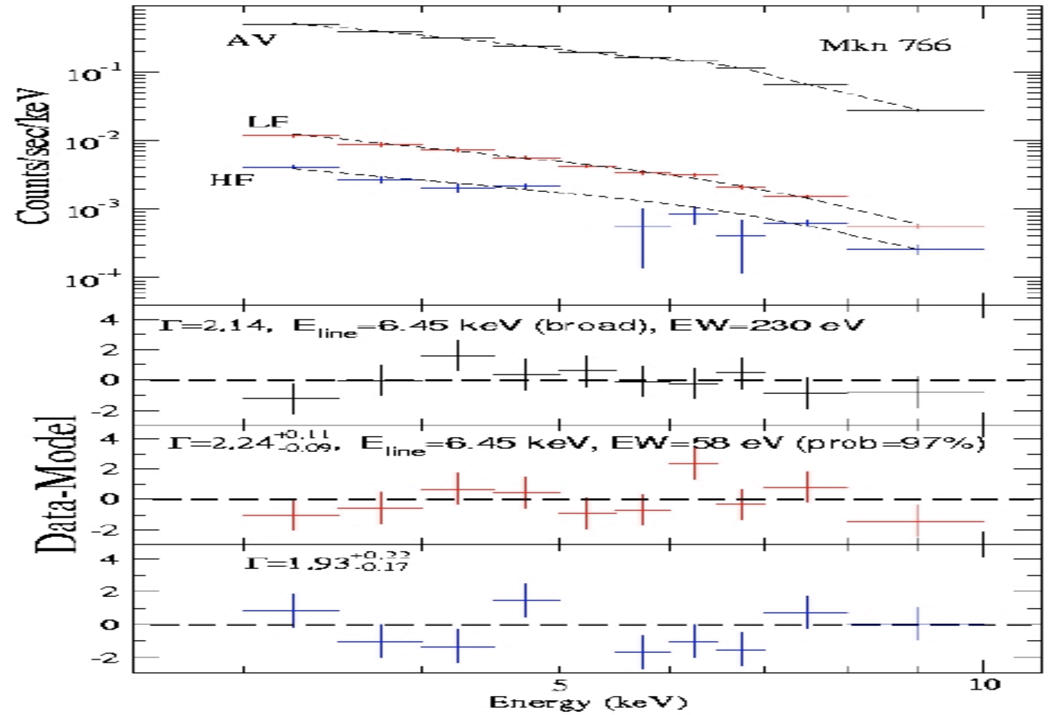
NGC 4051 (2001)



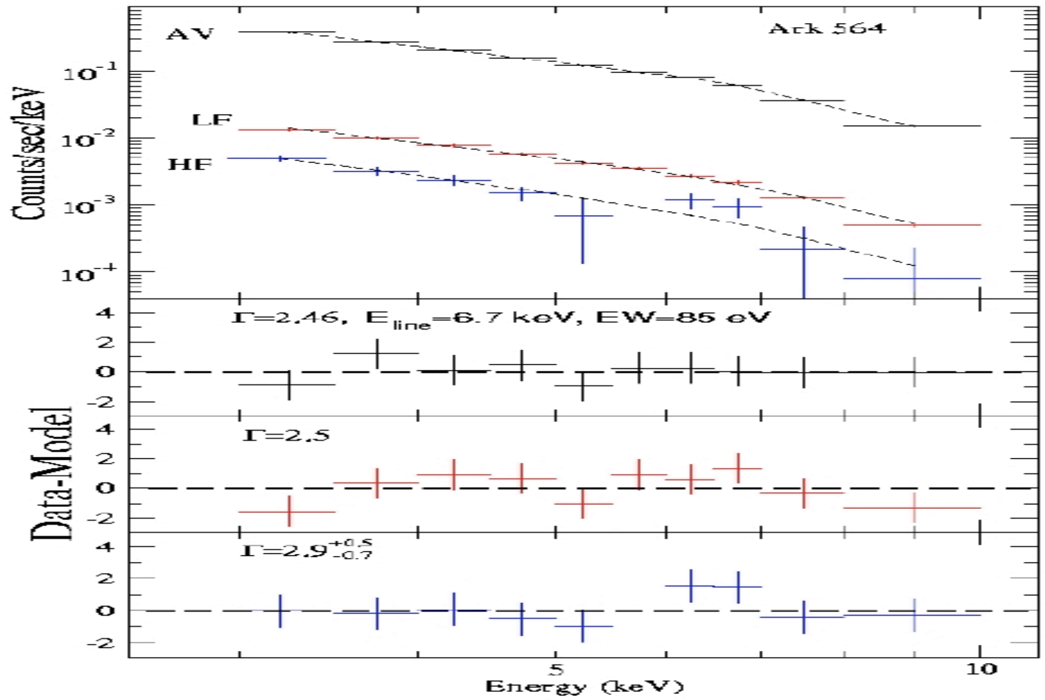
NGC 4051 (2002)



Mkn 766


AV
Mkn 766
LF
HF
Counts/sec/keV
Data-Model
Γ=2.14, E_line=6.45 keV (broad), EW=230 eV
Γ=2.24+0.11-0.09, E_line=6.45 keV, EW=58 eV (prob=97%)
Γ=1.93+0.22-0.17
Energy (keV)

Ark 564



AV
Ark 564
LF
HF
Counts/sec/keV
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Γ=2.46, E_{line}=6.7 keV, EW=85 eV
Γ=2.5
$\Gamma=2.9^{+0.5}_{-0.7}$
Data-Model
Energy (keV)

Summary and comparison with Cyg X-1