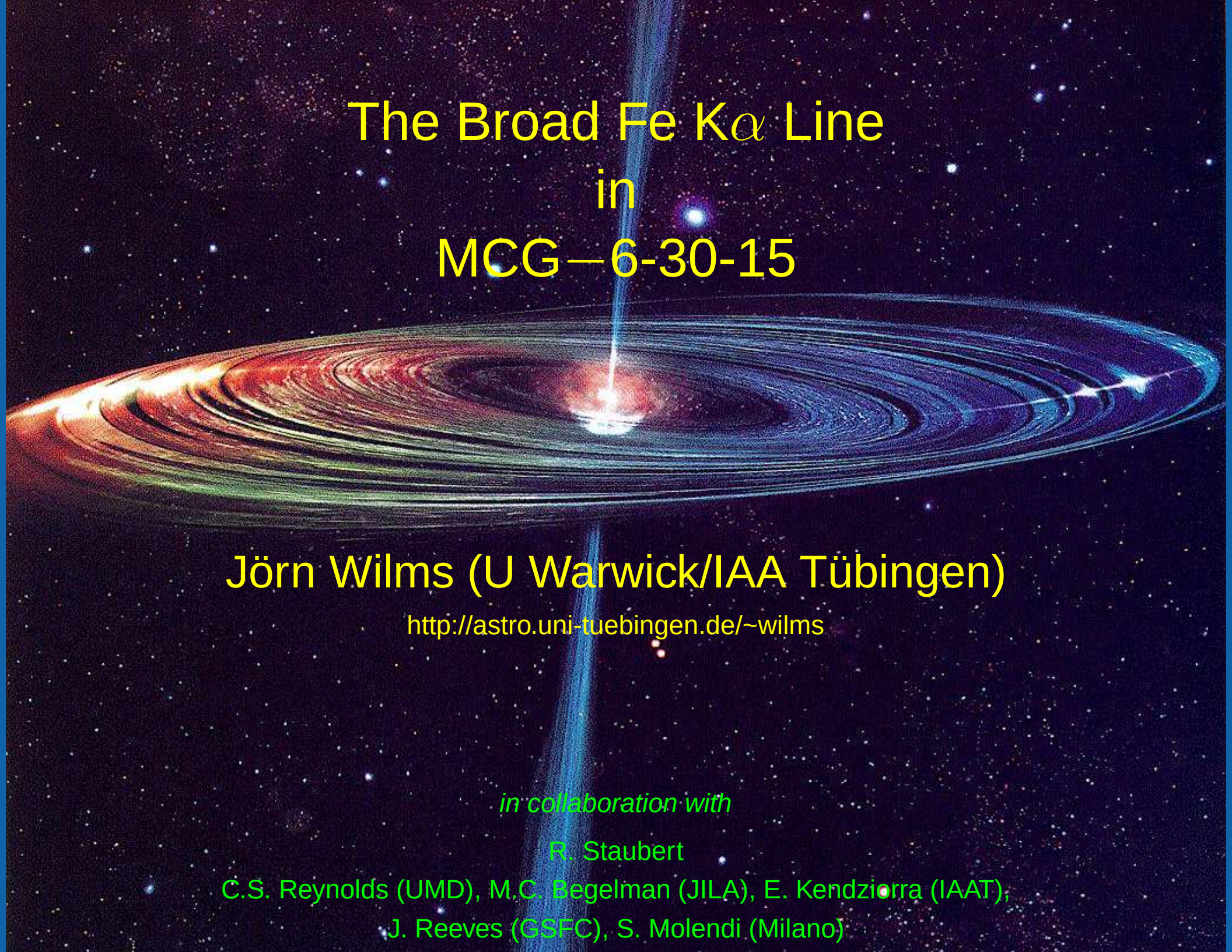

# The Broad Fe K$\alpha$ Line in MCG$-$6-30-15


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*in collaboration with*

R. Staubert

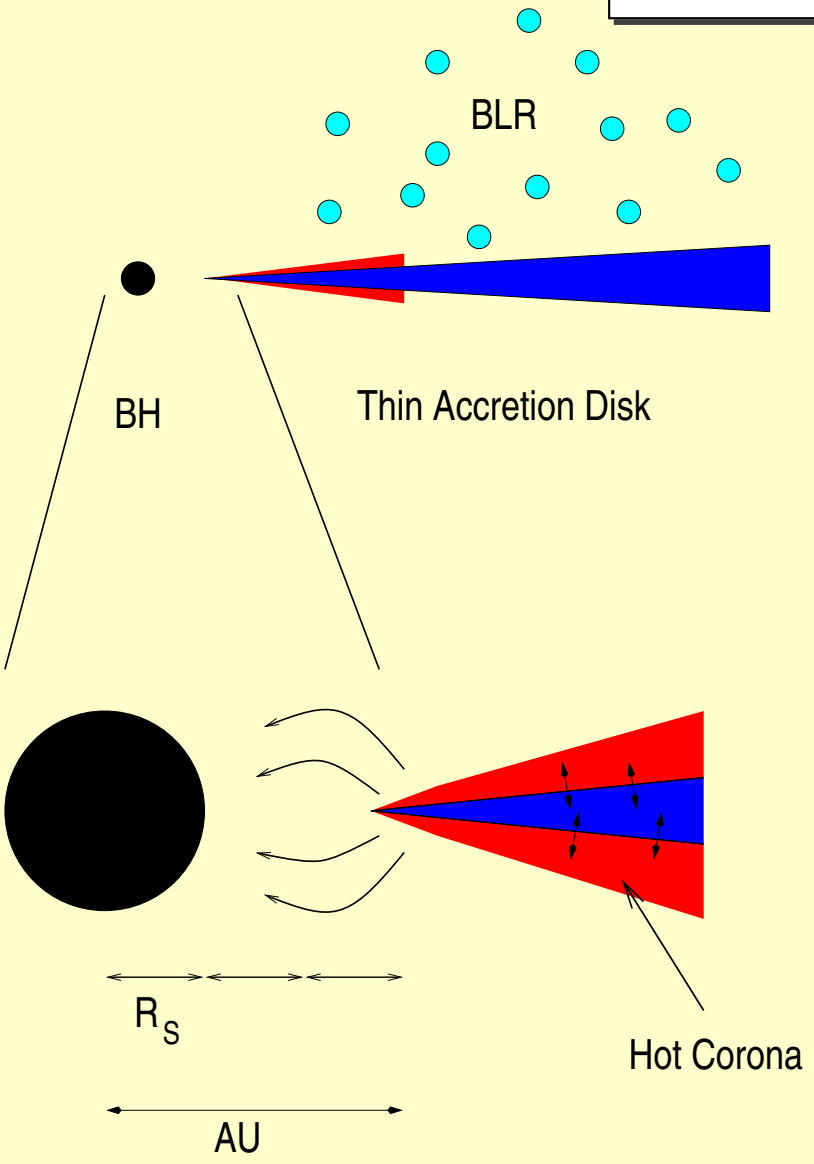
C.S. Reynolds (UMD), M.C. Begelman (JILA), E. Kendziorra (IAAT),

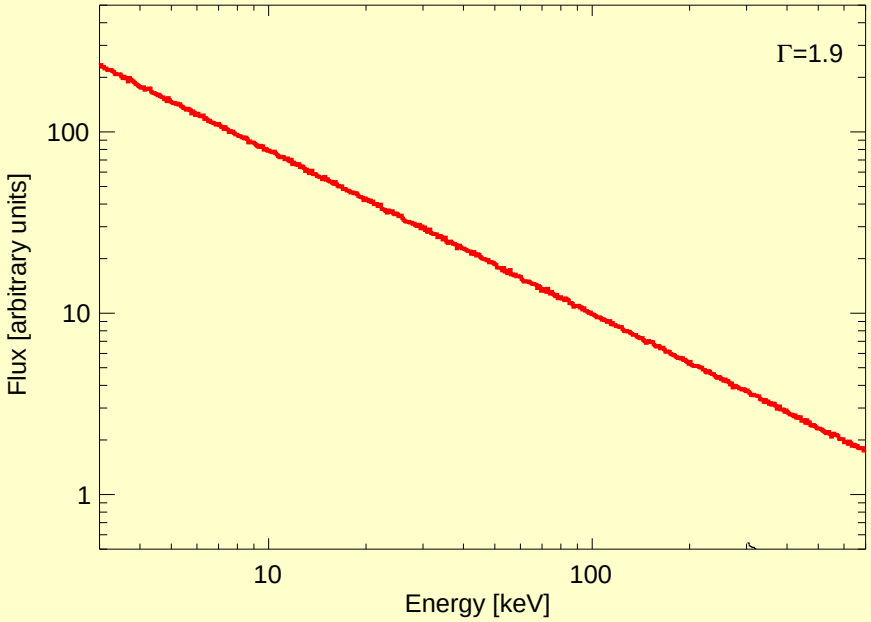
J. Reeves (GSFC), S. Molendi (Milano)

# Structure

- K$\alpha$ Line Diagnostics
  - Accretion geometry
  - Compton reflection and Fe K$\alpha$ generation
  - Line transfer close to the BH
- MCG$-$6-30-15
  - Simultaneous *XMM-Newton*/*RXTE* Observations
  - Soft X-ray spectrum
  - Observations of a Broad Line
  - Interpretation and Caveats
- Summary

# K$\alpha$ Line Diagnostics

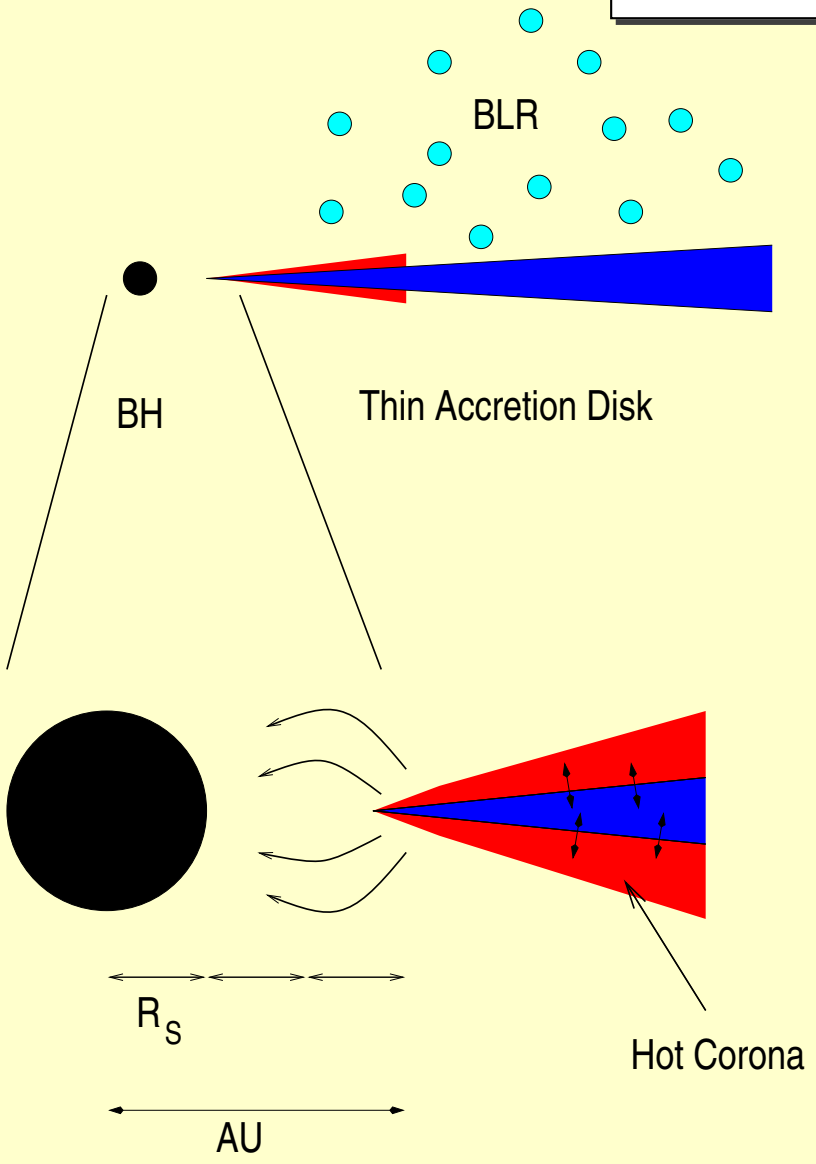


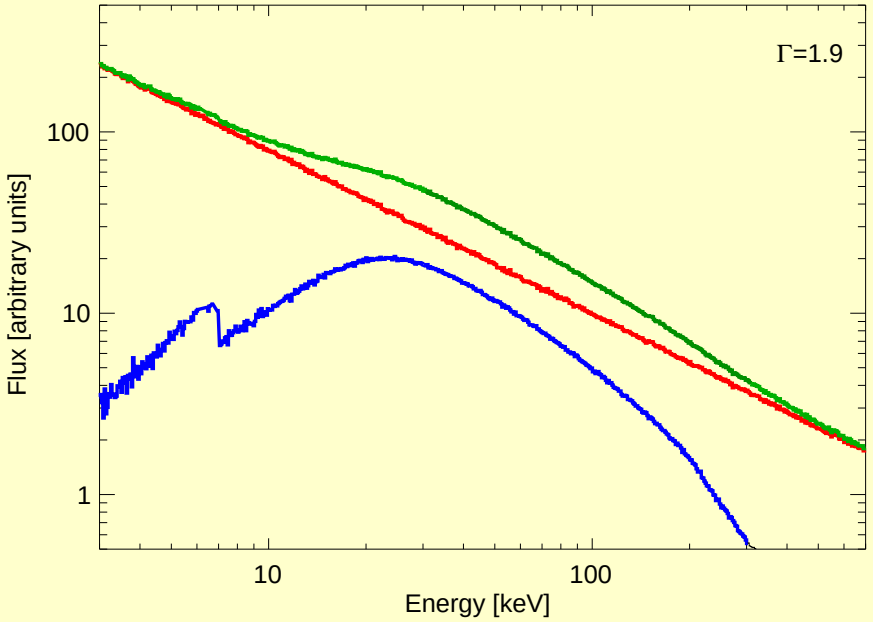




AGN X-Ray Spectrum:

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

# K$\alpha$ Line Diagnostics

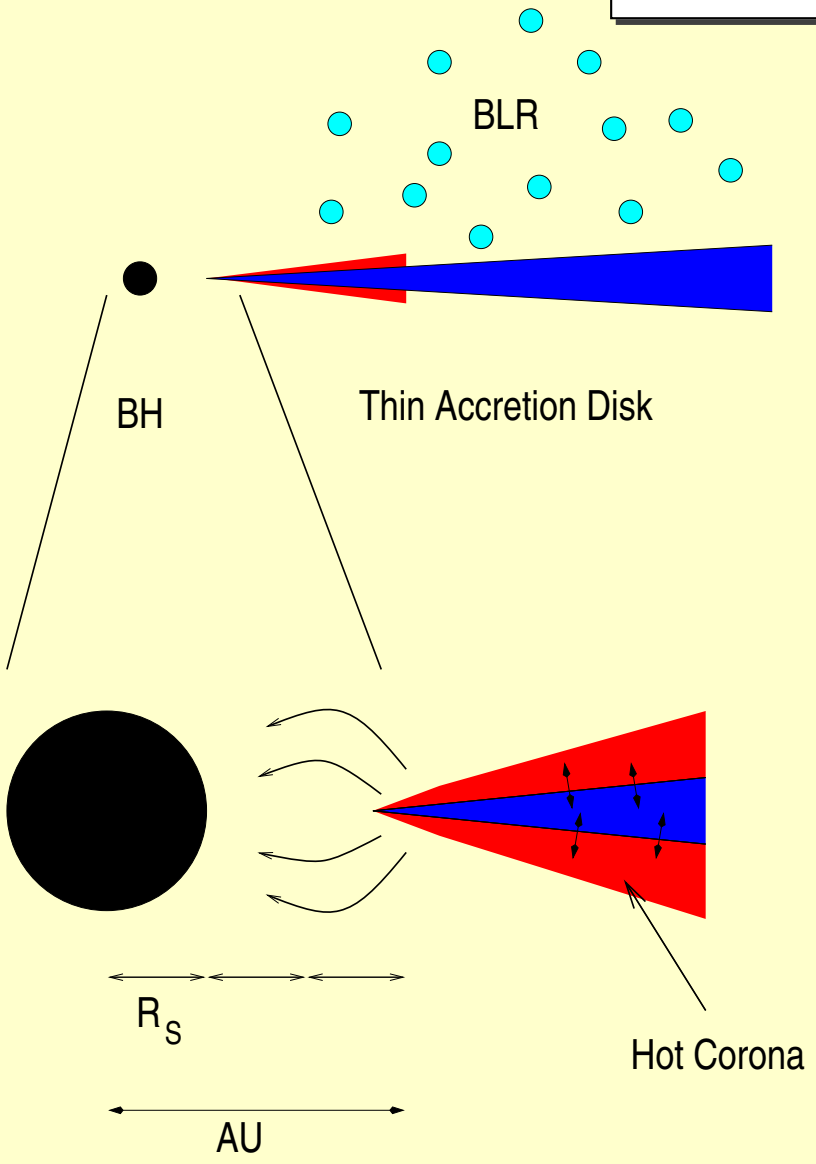


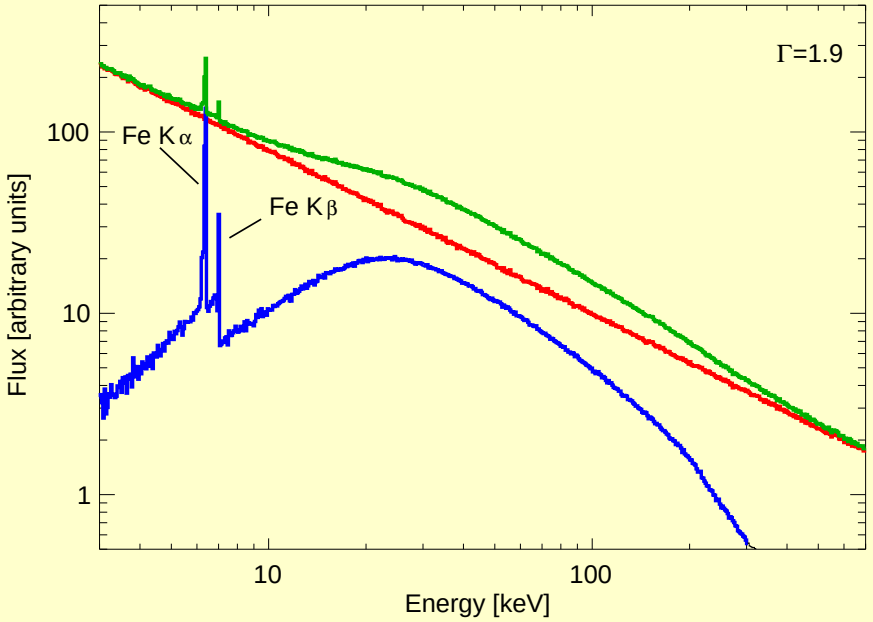




AGN X-Ray Spectrum:

- 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

# K$\alpha$ Line Diagnostics

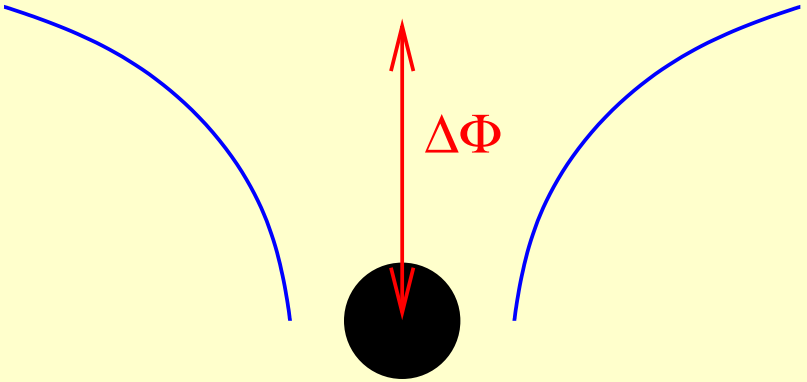


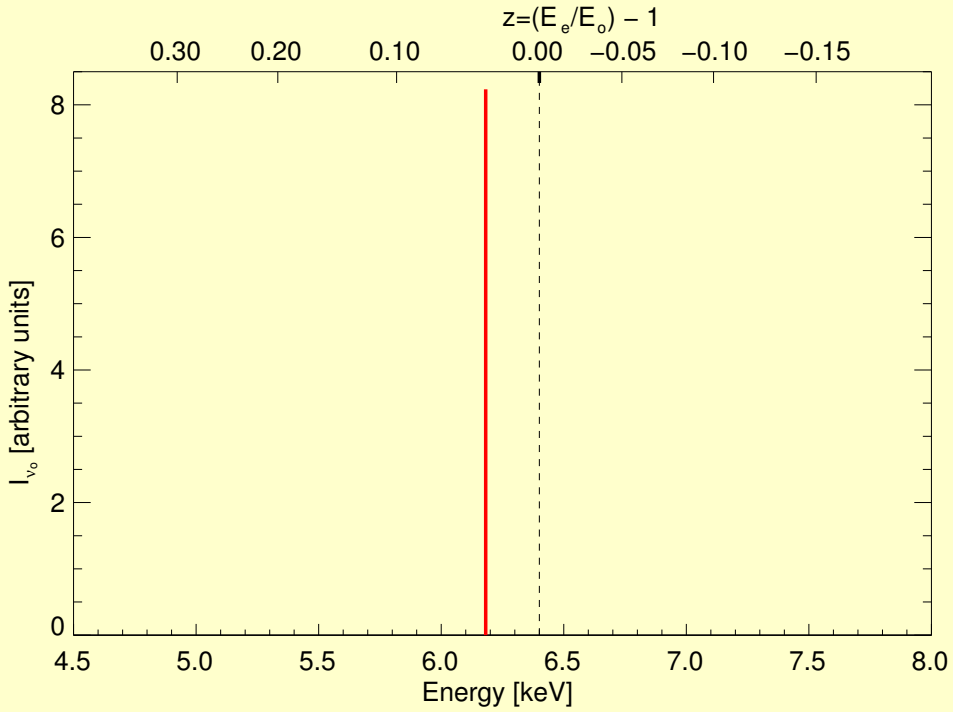




AGN X-Ray Spectrum:

- 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 K$\alpha$ Line at $\sim$6.4 keV

# K$\alpha$ Line Diagnostics

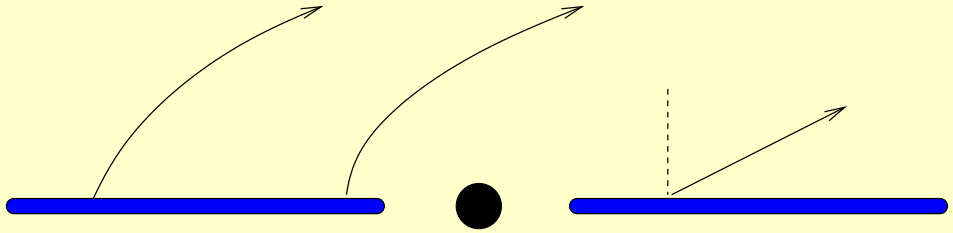


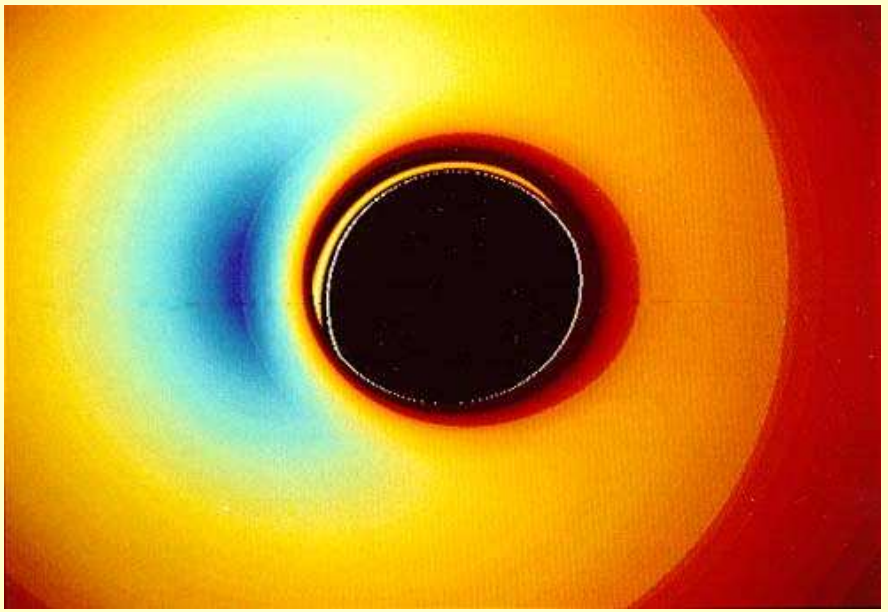



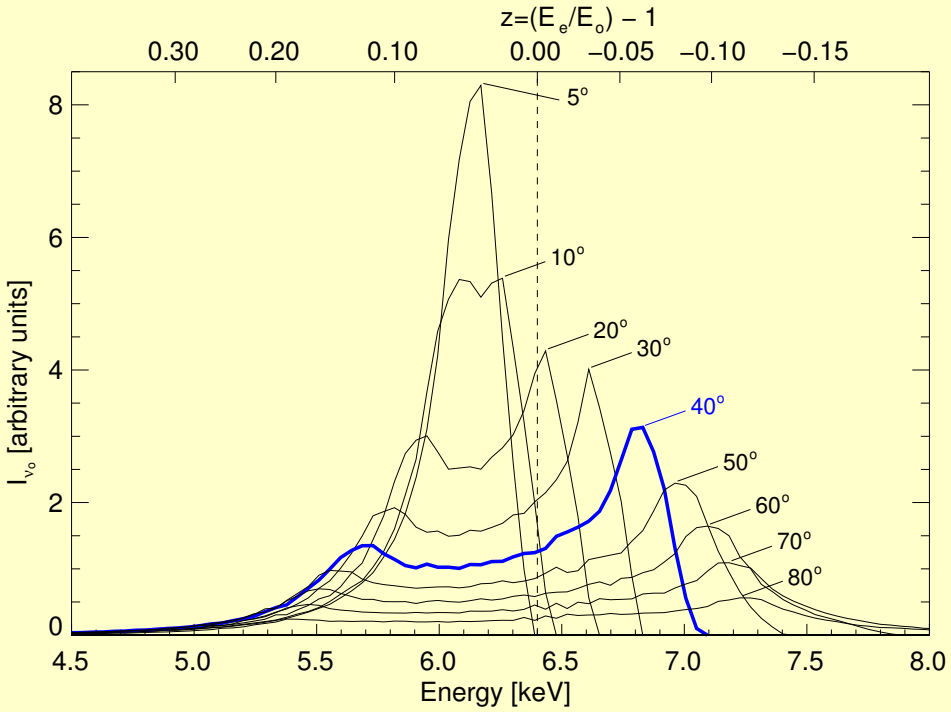

Total observed line profile affected by

- grav. Redshift

# Kα Line Diagnostics



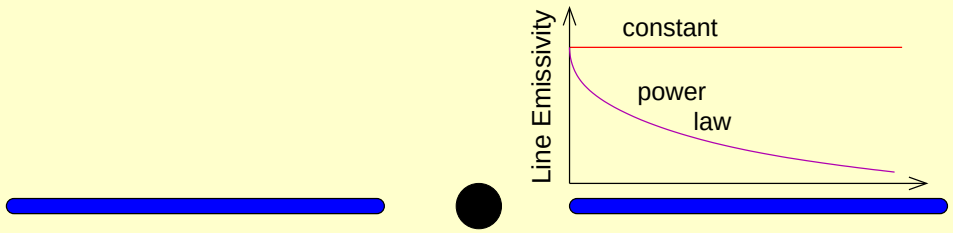


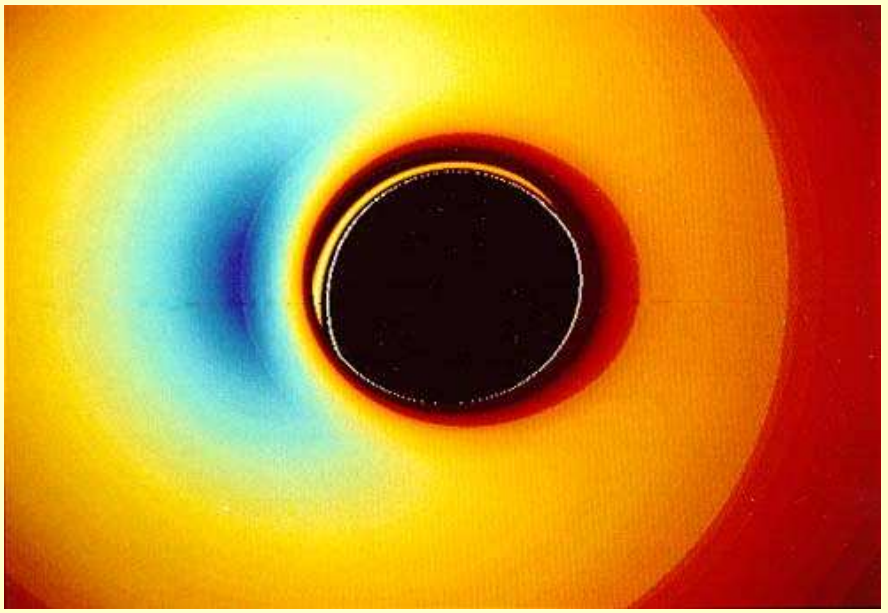


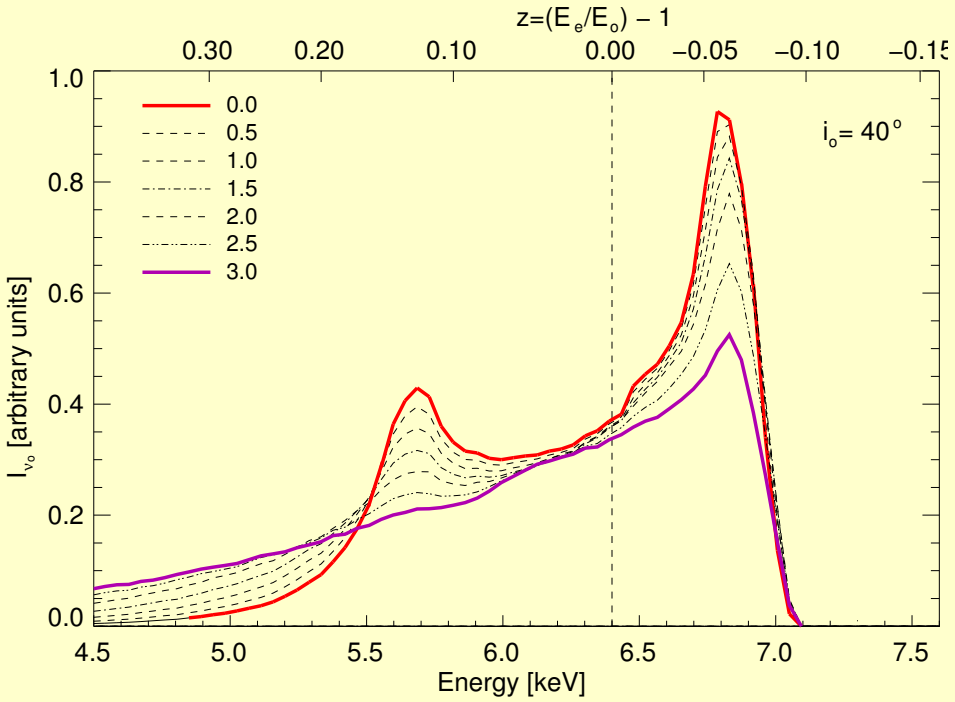

Total observed line profile affected by

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

# K$\alpha$ Line Diagnostics



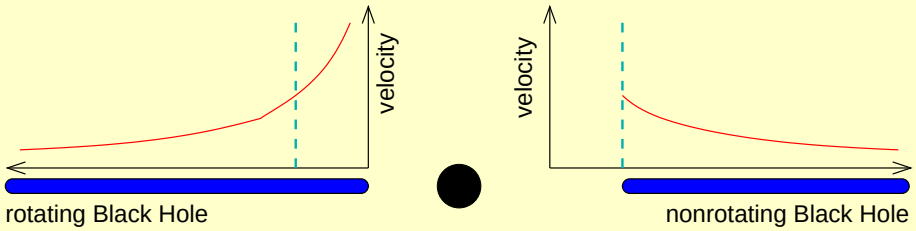



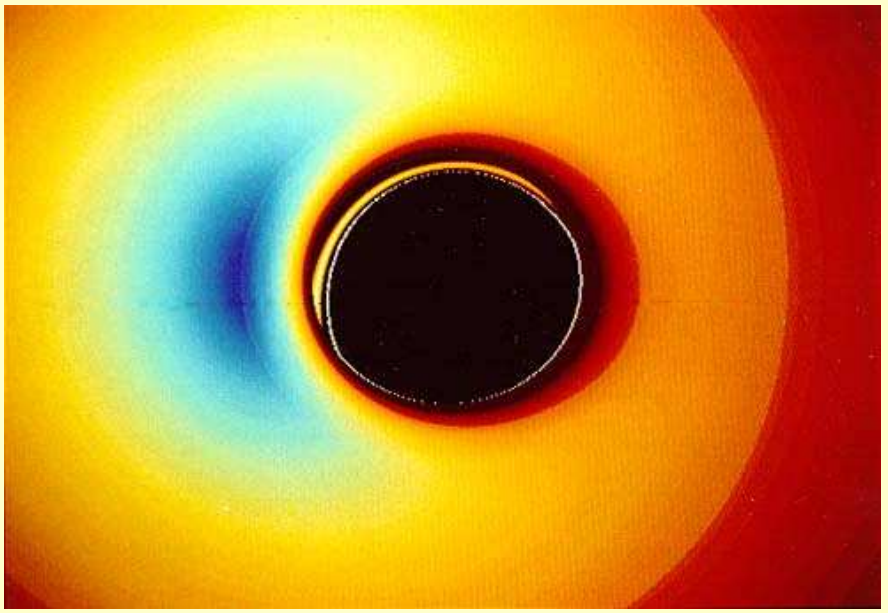


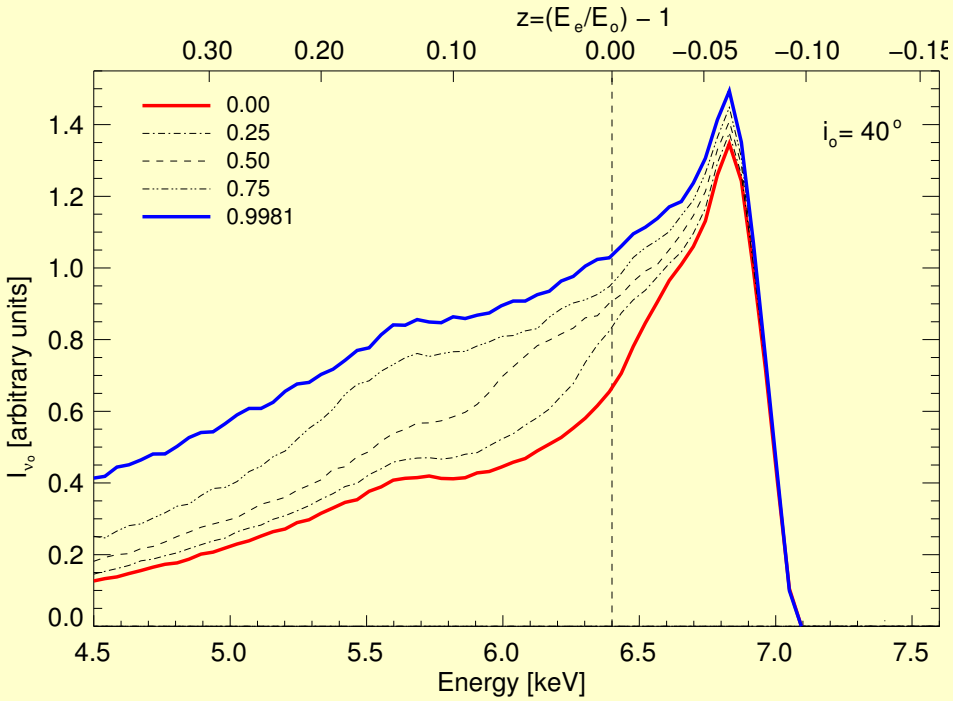

Total observed line profile affected by

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

# K$\alpha$ Line Diagnostics



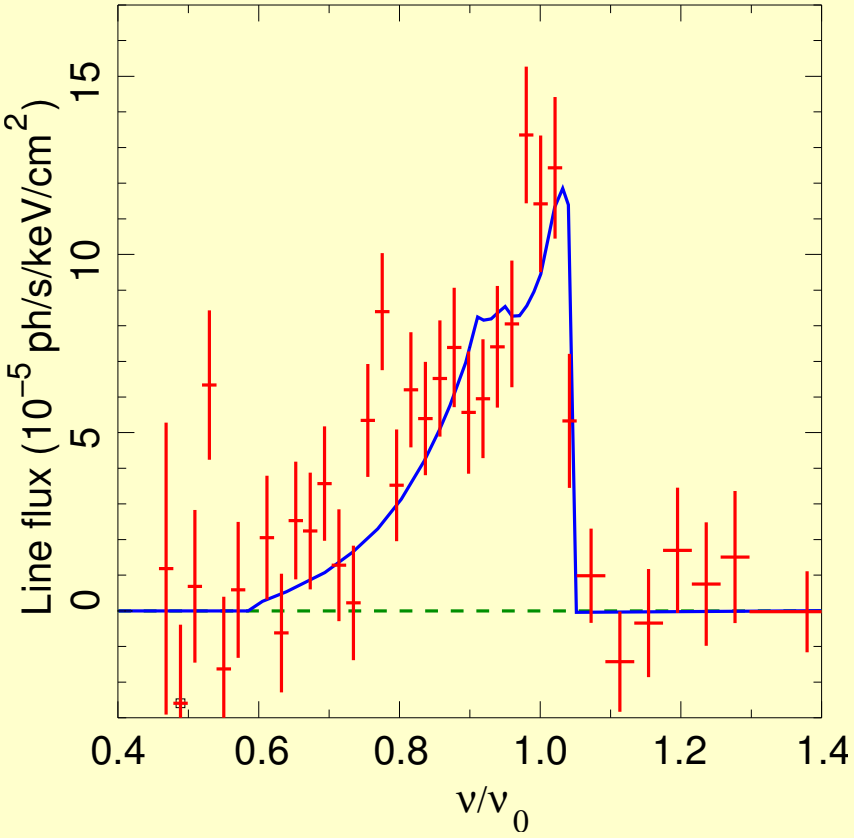






Total observed line profile affected by

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

# MCG−6-30-15, I

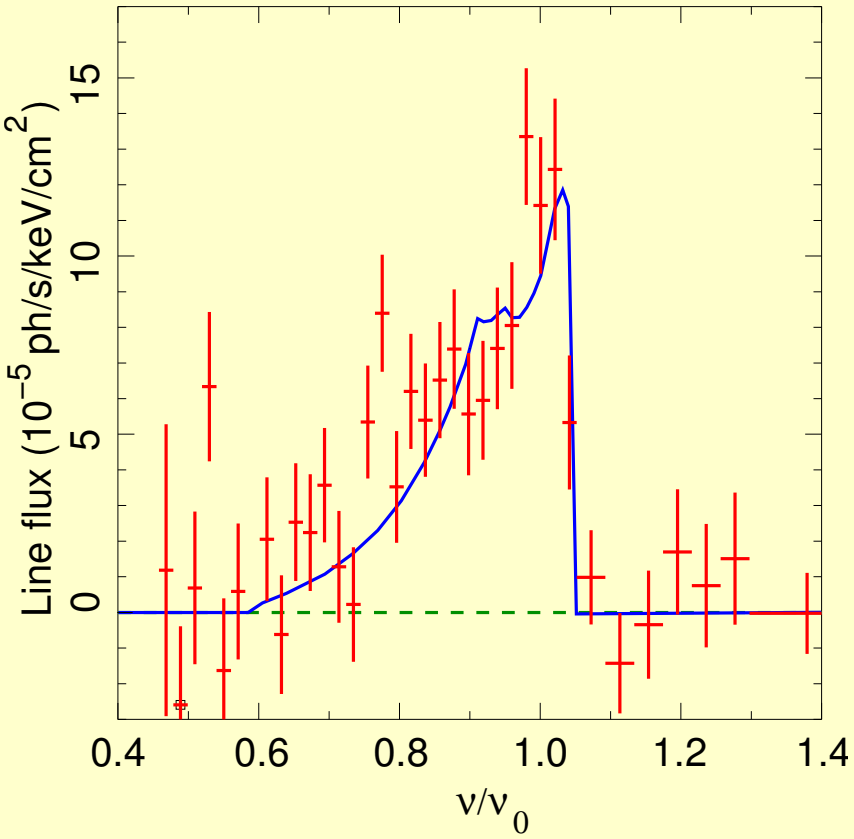


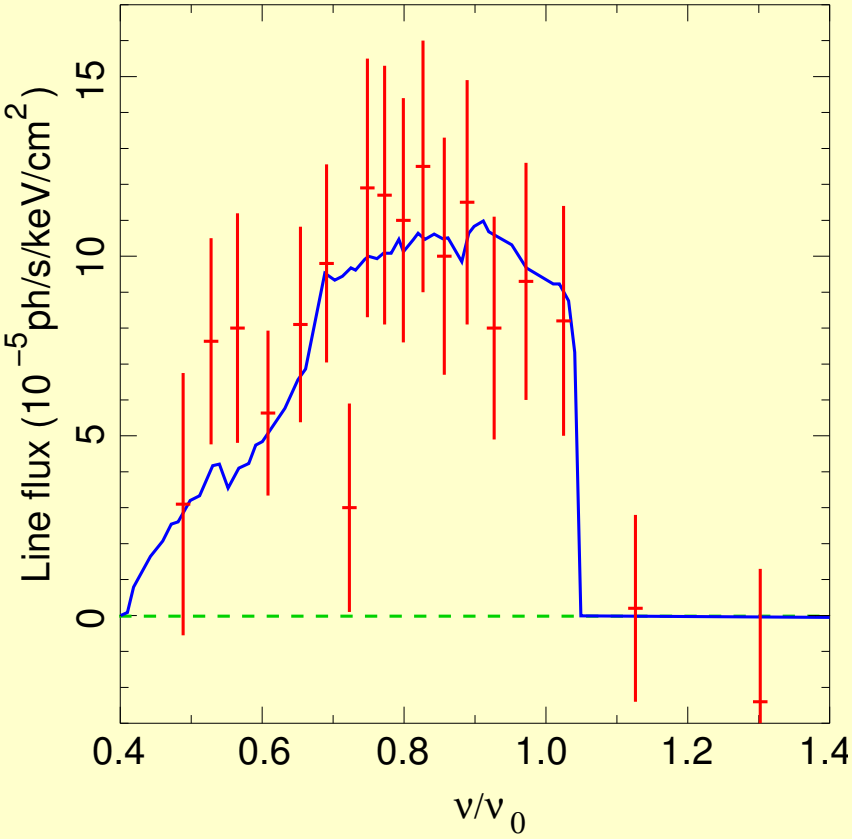

MCG−6-30-15 ($z = 0.008$): first AGN with relativistic disk line

Tanaka et al. (1995): time averaged *ASCA* spectrum: line skew symmetric

$\Longrightarrow$ Schwarzschild black hole.

# MCG−6-30-15, II



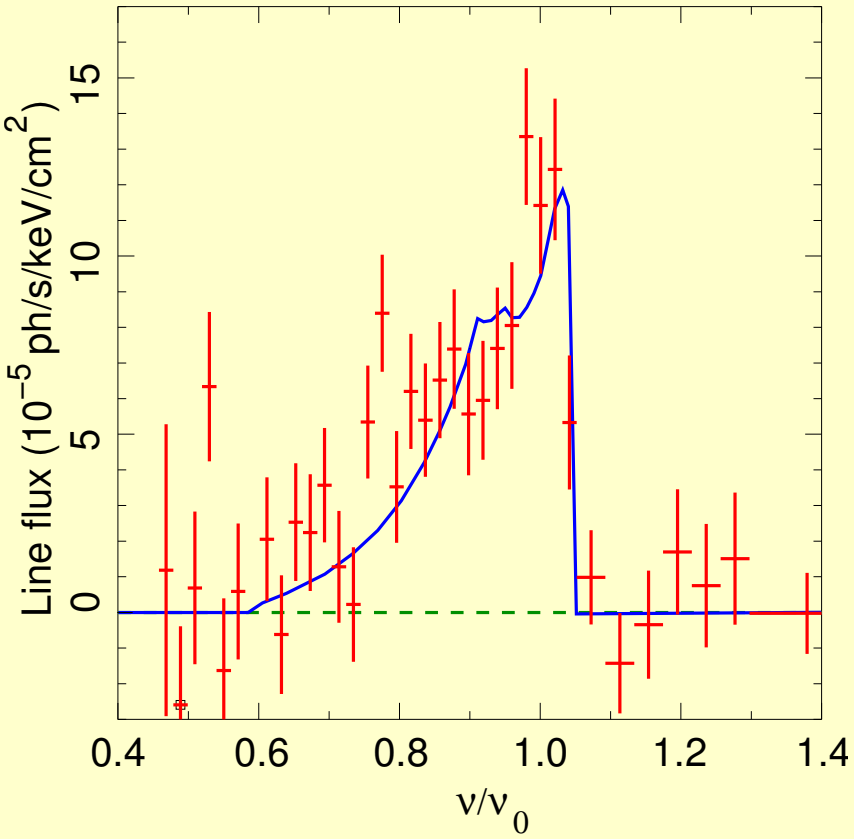



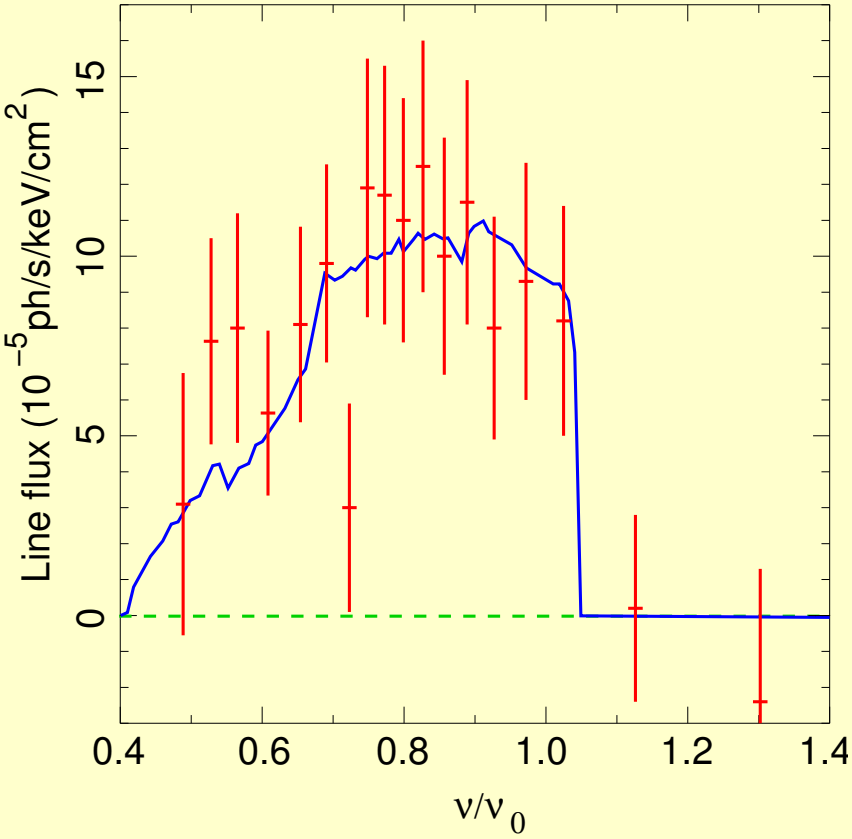

MCG−6-30-15 ($z = 0.008$): first AGN with relativistic disk line

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.

# MCG−6-30-15, III




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.

Later confirmed with *BeppoSAX* (Guainazzi et al., 1999) and *RXTE* (Lee et al., 1999).

# XMM-Newton Data, II

Two long *XMM-Newton* Observations of MCG−6-30-15 available:

**June 2000** : (rev 108), 100 ksec

(Wilms et al. 2001, Reynolds et al., 2003)

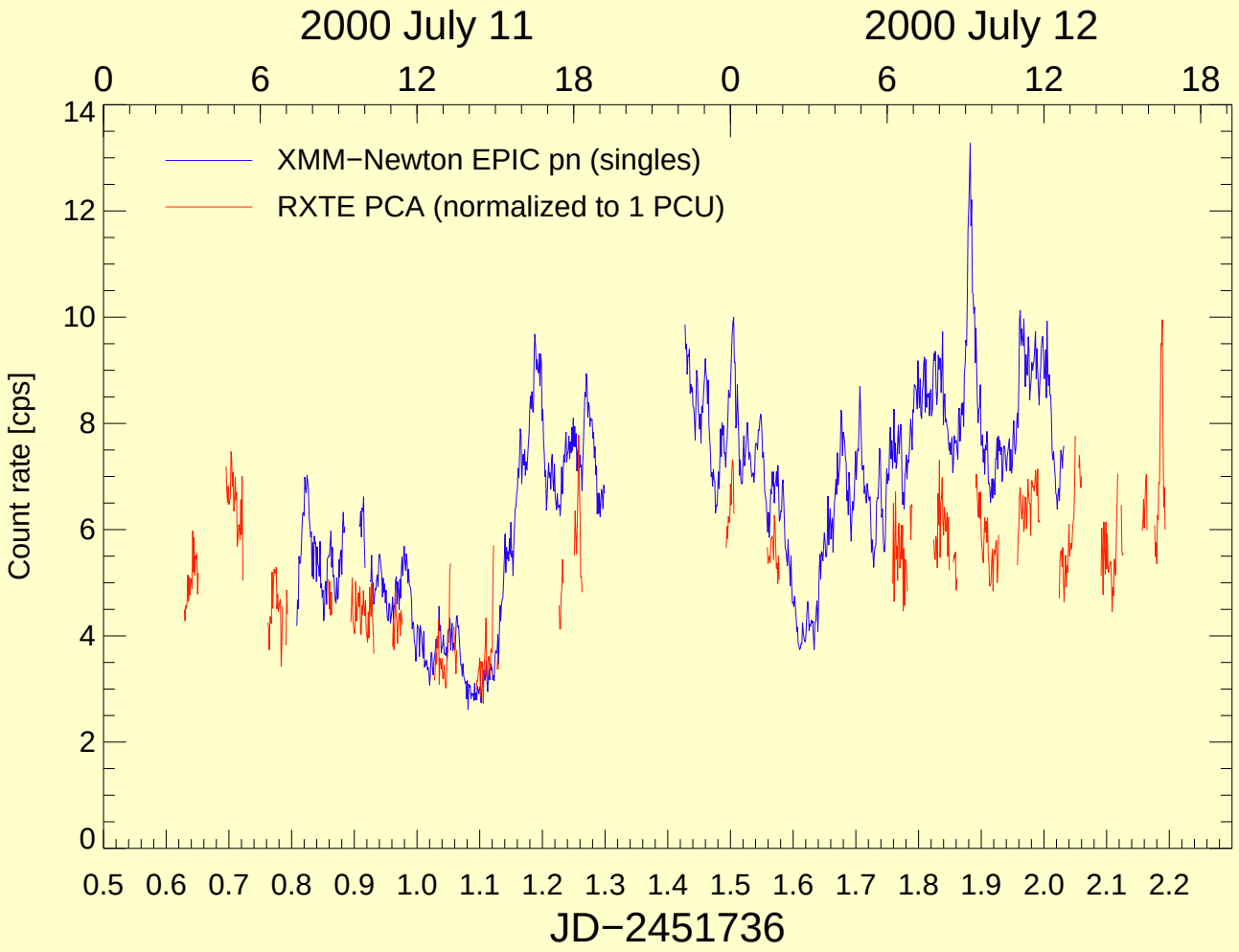
- overall flux $\sim$ *ASCA* "deep minimum"
- source strongly variable
- broad Fe K$\alpha$ line

**July/August 2001** : (rev 301–303), 315 ksec

(Fabian et al. 2002, Vaughan et al. 2003, Ballantyne et al. 2003)

- source 70% brighter than in June 2000
- similar variability
- broad Fe K$\alpha$ line

# Data Extraction

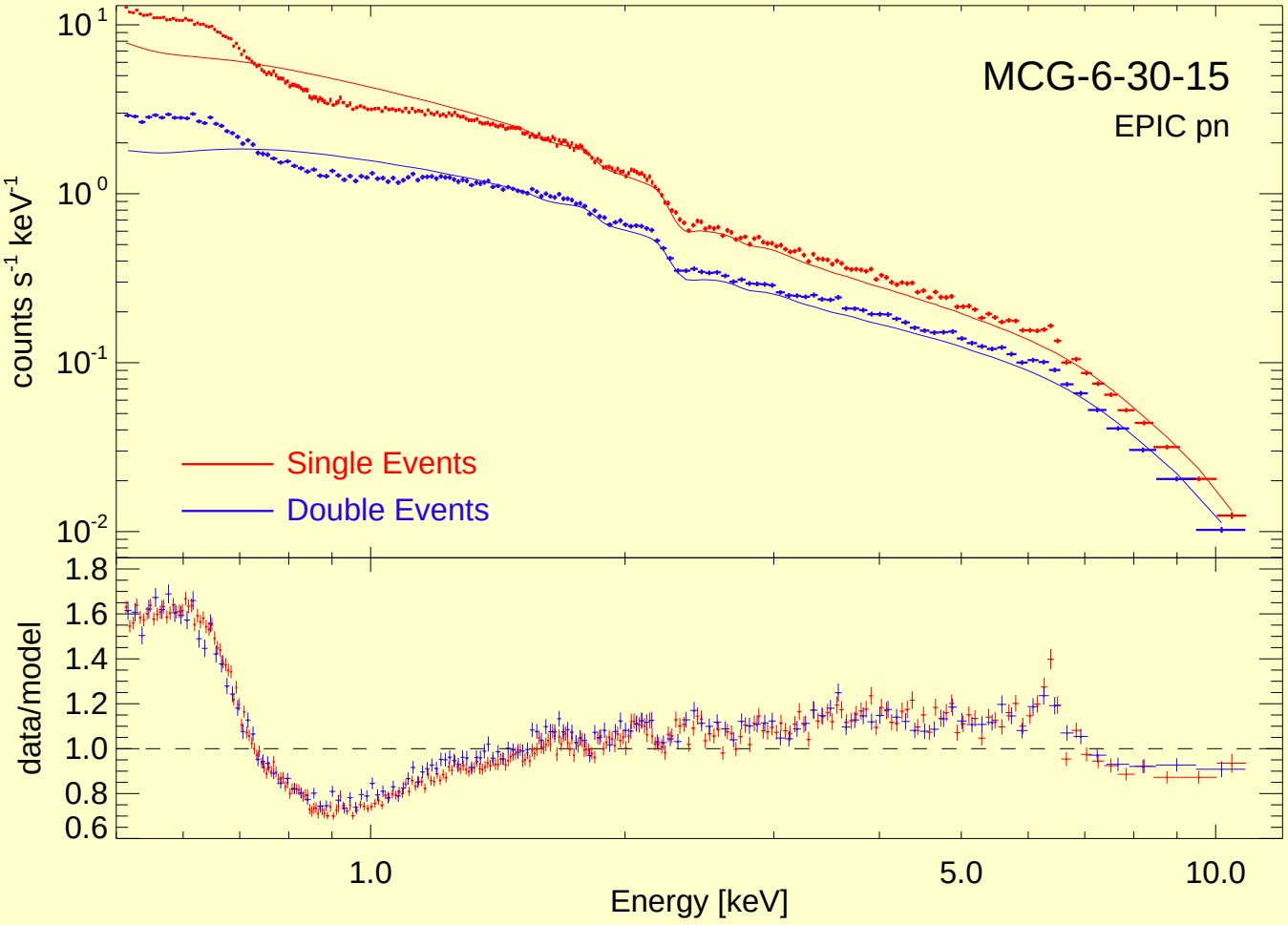



*XMM-Newton* and *RXTE* light curves, $\Delta t = 100$ s.
Total *XMM-Newton* exposure $\sim$100 ksec.

Overall flux $\sim$ *ASCA* "deep minimum" ($F_{2-10} = 2.3 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$)

To avoid possible pile-up, use data from $< 14$ cps in EPIC pn only
for MOS: Ring 10″, 35″, pattern 0–12.

# Spectral Analysis



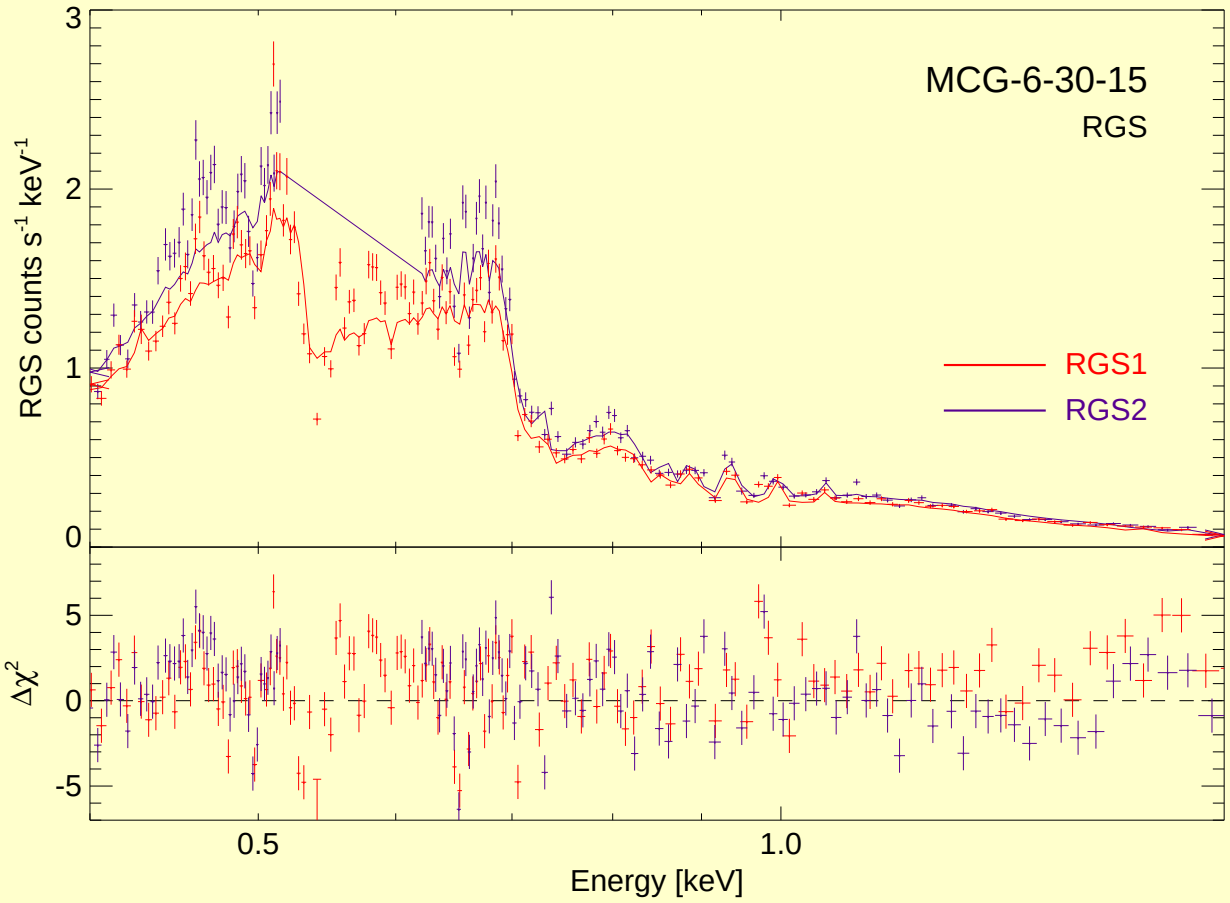

X-ray spectrum very complex:

- warm absorber at $\lesssim 1.5$ keV
- power-law continuum
- reflection continuum
- relativistic iron line
- narrow iron line

Low energy end of spectrum: warm absorber $\Longrightarrow$ RGS.

Then Fe line analysis with EPIC data.

# RGS Data



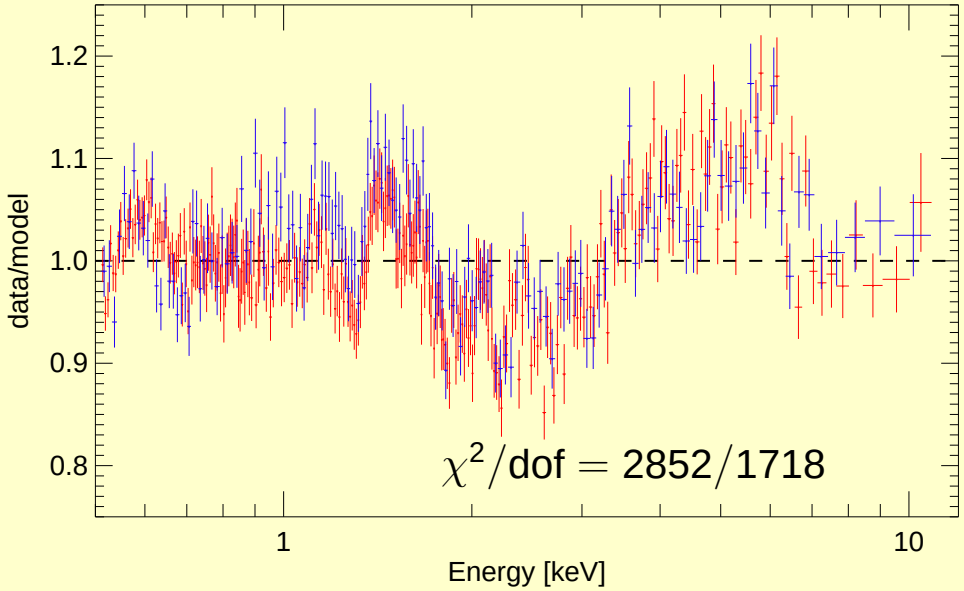

- absorption edges of C V (400), O VII (740), O VIII (870), and Ne X (1362 eV),
- blended resonance absorption lines below O VII and O VIII edges,
- four moderately broad, weak Gaussian emission features at 0.885 keV, 0.935 keV, 0.995 keV, and 1.06 keV (lab frame; no interpretation).

(red: RGS1, blue: RGS2; $\chi^2_{\rm red} = 1.4$).

(model similar to Lee et al. 2001)

Analysis à la Branduardi-Raymont et al. (2001) gives similar results for Fe line.

# Iron Line, I



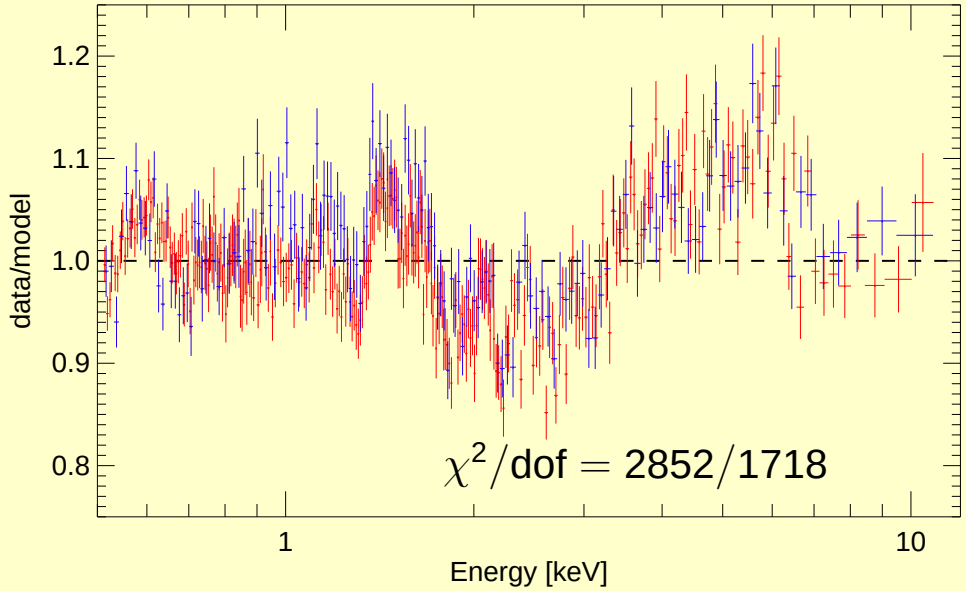

*Continuum model:*

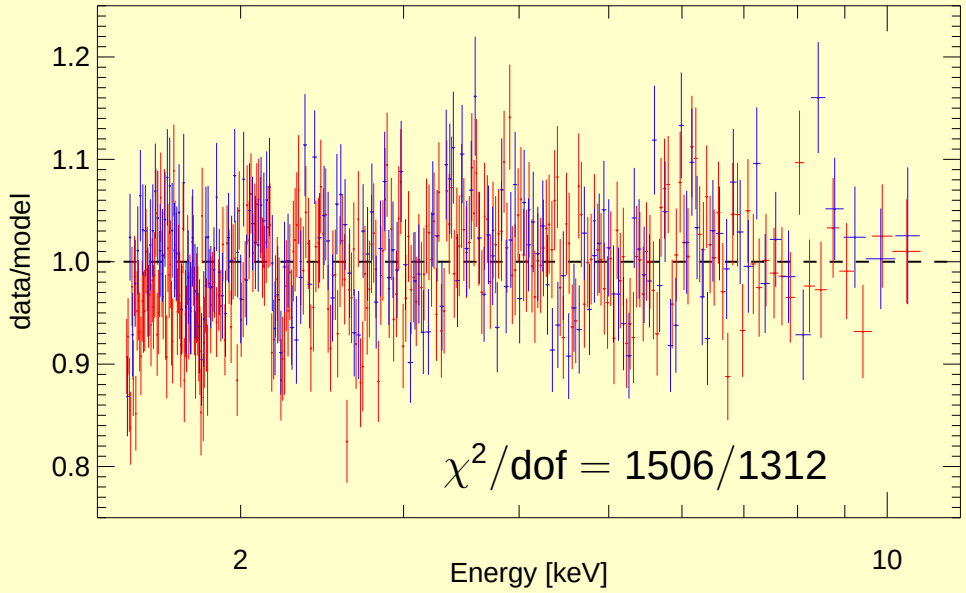
1. empirical “warm absorber model”,
2. power law ($\Gamma = 1.94 \pm 0.02$),
3. relativistically smeared reflection from a possibly ionized accretion disk ($i = 30^\circ$, $\Omega/2\pi = 1$–$1.5$).
4. narrow Fe line (EW $\sim 40$ eV)

$\Longrightarrow$ Clear deviations in the 2–7 keV band

$\Longrightarrow$ relativistically broadened iron line.

# Iron Line, II

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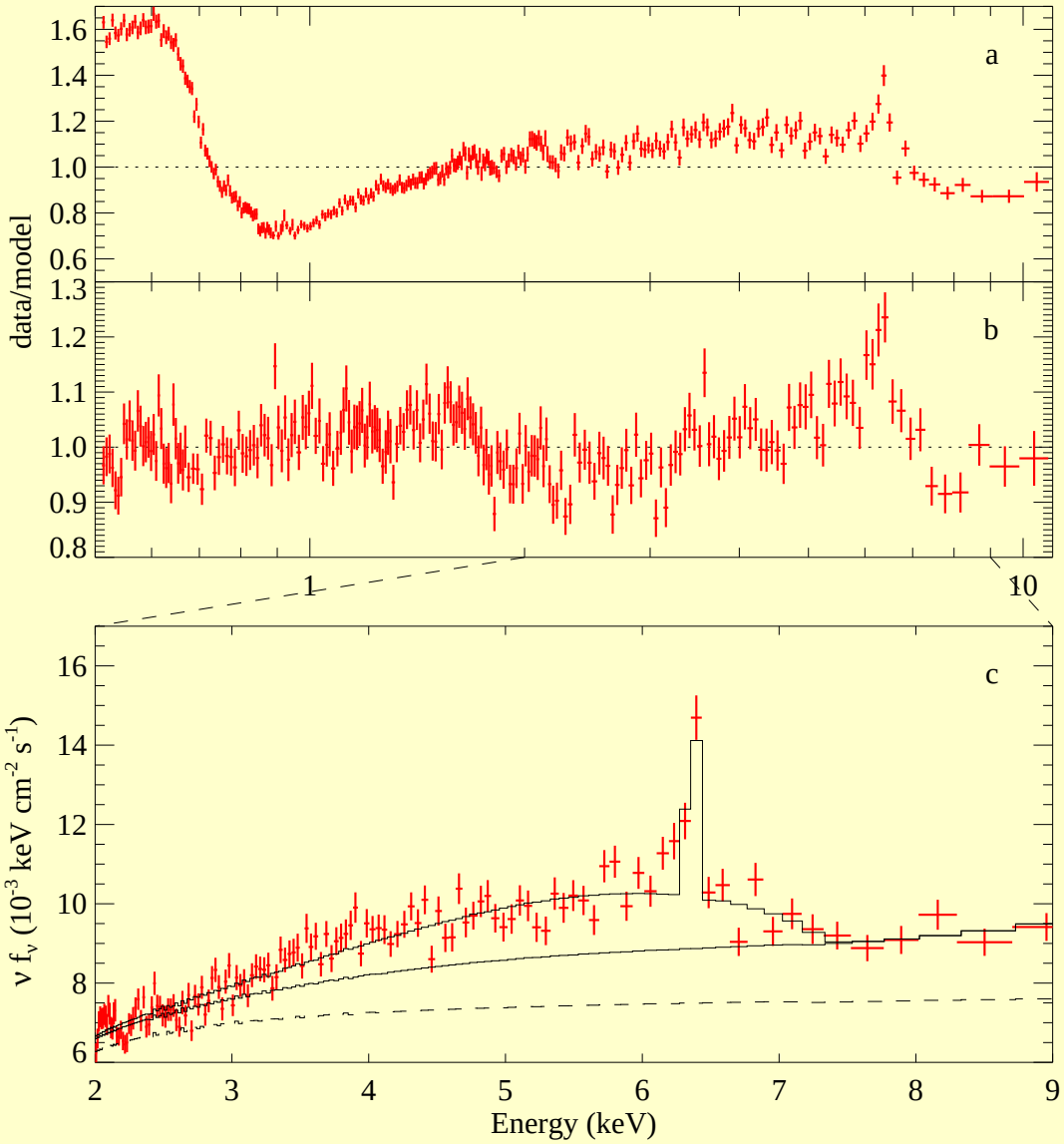
4. narrow Fe line (EW $\sim 40$ eV)

$\Longrightarrow$ Clear deviations in the 2–7 keV band

$\Longrightarrow$ relativistically broadened iron line.

5. relativistically broadened Gaussian: $E = 6.95^{+0}_{-0.15}$ keV, $W_{\mathrm{K}\alpha} = 582$ eV; with emissivity $I_{\mathrm{Fe}}(r) \propto r^{-\beta}$: $\beta = 4.6 \pm 0.3$

# Observational Summary

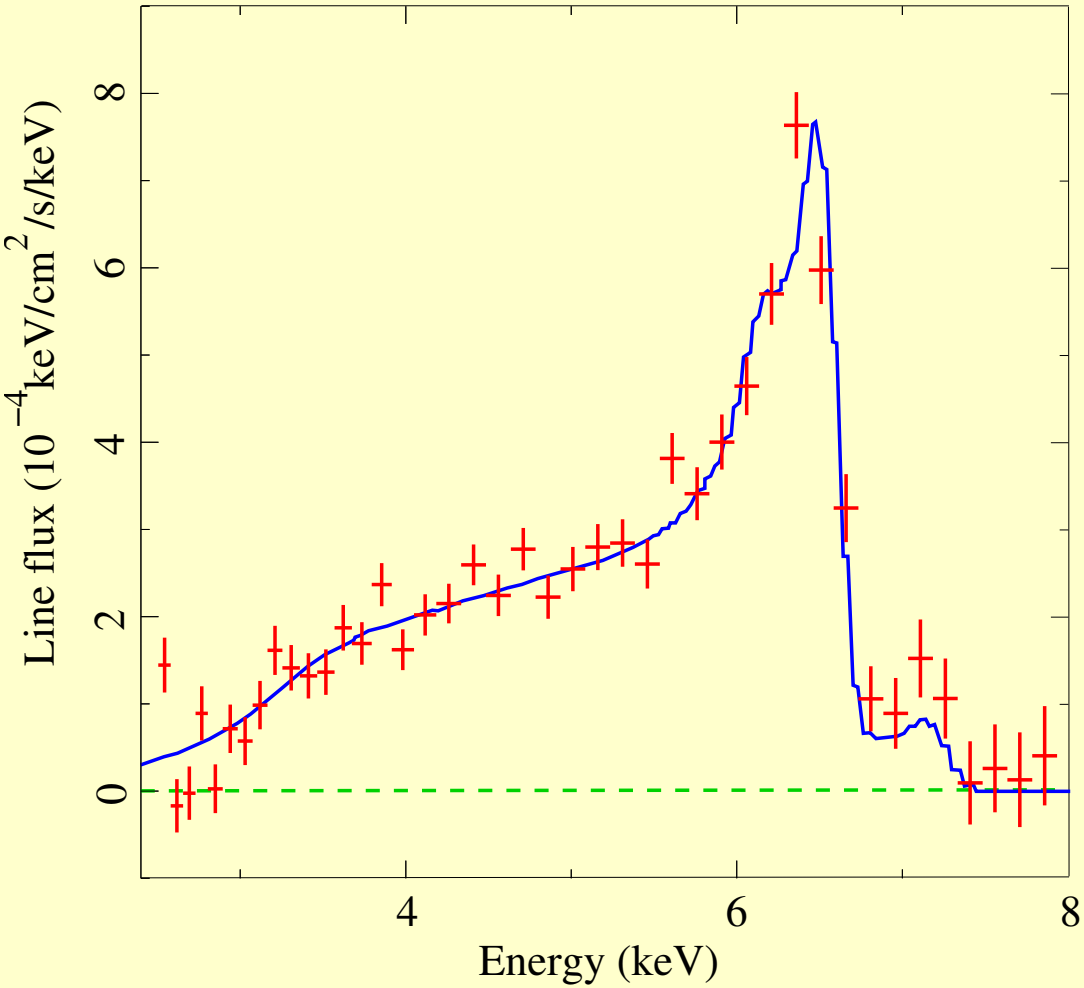



**a** pure PL fit,

**b** Setting the normalization of the lines to zero reveals the extreme width and skewed profile of the Fe line,

**c** Components of the final fit

# Other XMM Observations




after Fabian et al. (2002)

July/August 2001 315 ksec observation

(Fabian et al., 2002)

- Strong narrow line
- broad line clearly present
- emissivity profile very steep for radii close to $r_{\rm in}$

$$I_{\text{Fe K}\alpha} \propto \begin{cases} r^{-5.5\pm0.3} & \text{for } r < 6.1^{+0.8}_{-0.5} r_{\rm g} \\ r^{-2.7\pm0.1} & \text{outside} \end{cases}$$

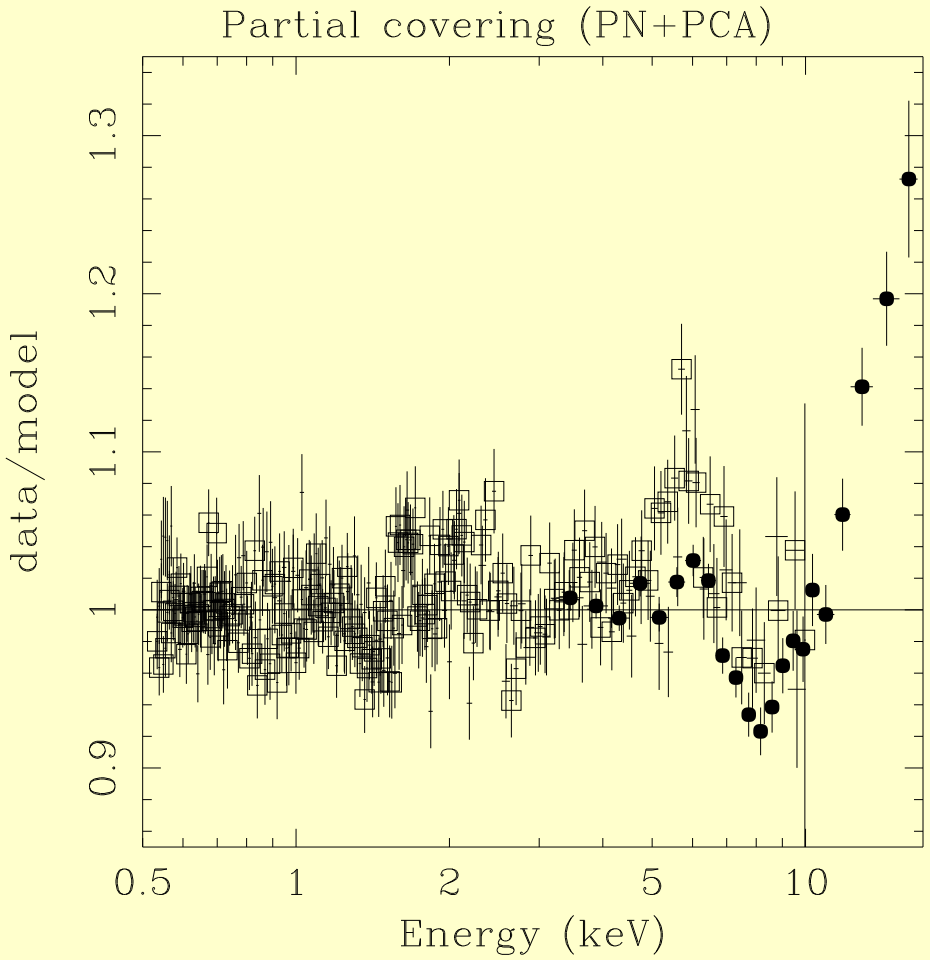
(Fabian & Vaughan, 2003)

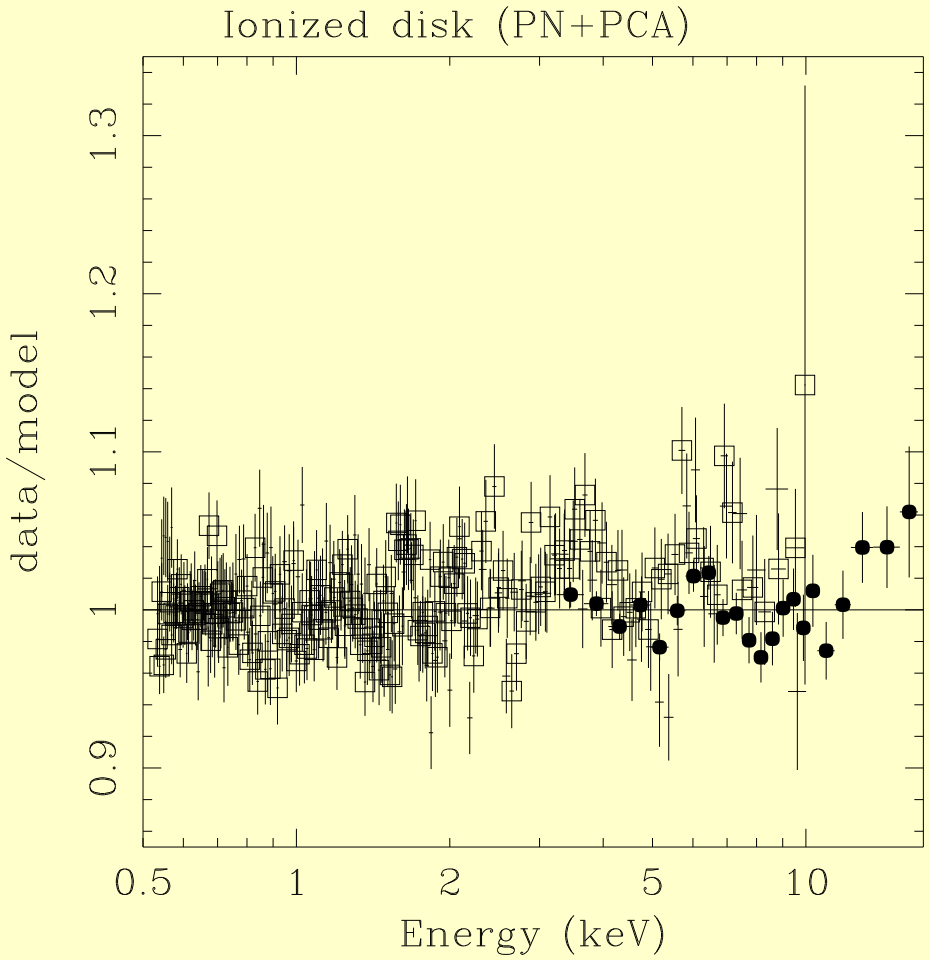
# Caveats

**Broad line obviously depends on assumed continuum**

- ionized reflection models not yet very realistic!
  but would require *big* change at low $E$, rather improbable...
  $\Longrightarrow$ Ballantyne & Fabian models give same result for line!
- absorption in ionized gas? attempts of including this generally unsuccessful...
- partial covering? so far, all partial covering models we tried failed in the *RXTE*-PCA...
- simple PL continuum used
  expected from Comptonization; fitting realistic Comptonization models to *XMM*/*RXTE* data results in large $\beta$ and $kT_{\rm e} \gtrsim 70\,\mathrm{keV} \Longrightarrow$ PL
- Continuum variability
  $\Gamma$ changes with flux, might mimic broadening
  $\Longrightarrow$ time dependent analysis shows line remains broad

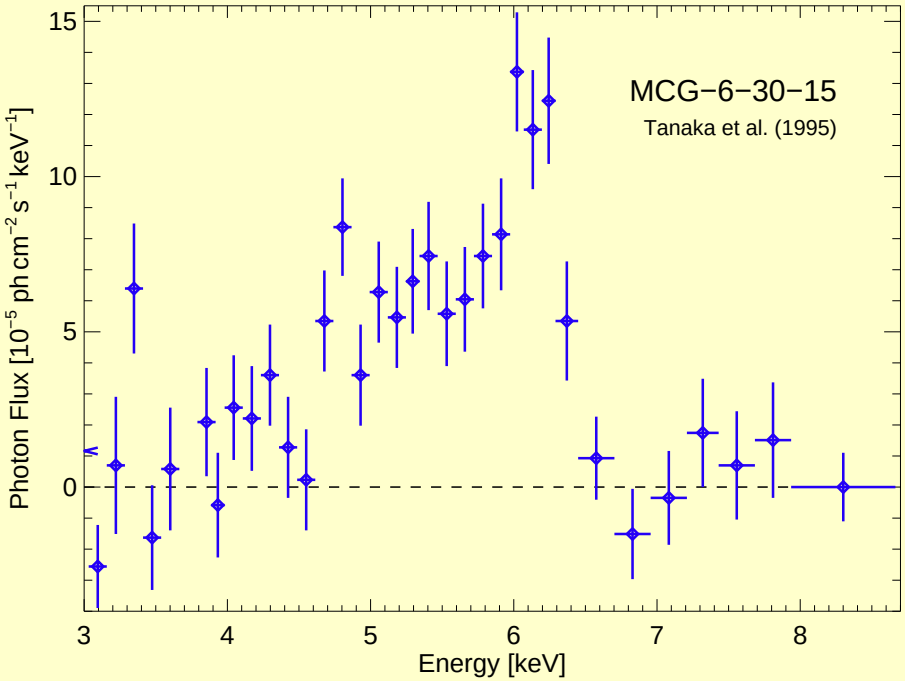
# Alternative Continuum Models



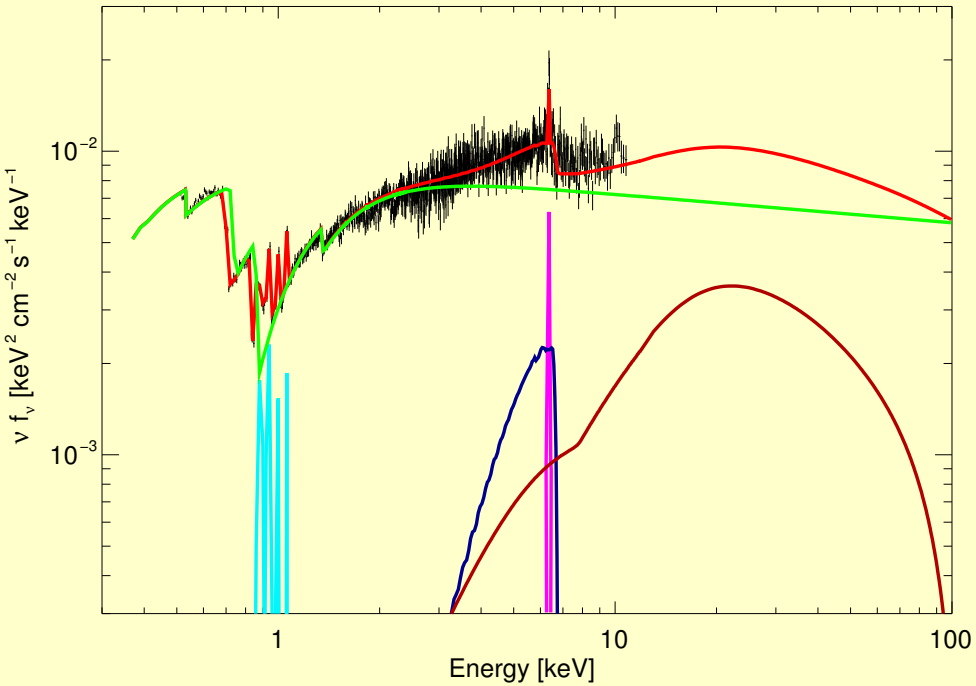




- Partial covering à la Pounds et al. (2002) does not work with PCA!
- ionized reflection, as assumed here, works with PCA!

# Observational Summary




Tanaka et al., 1995




Wilms et al., 2001, 2003

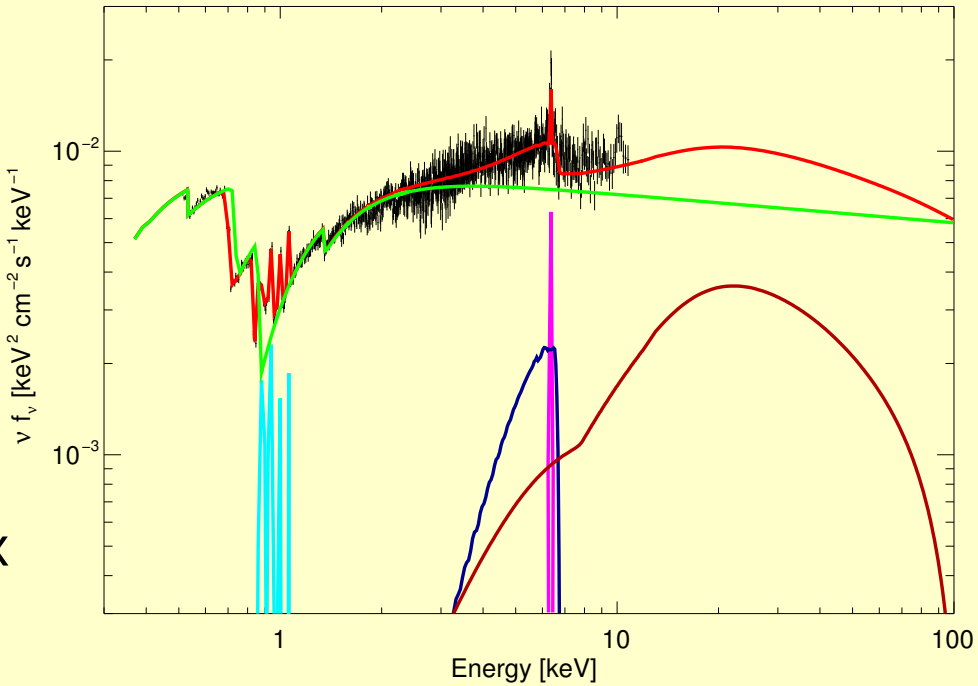
*XMM-Newton*: MCG−6-30-15 has broadest Fe K$\alpha$ line seen in all AGN

Width of the line: Kerr Black Hole is required (Confirming *ASCA* and *BeppoSAX*)

The emissivity index, $\beta$, is large $\Longrightarrow$ Line from centralmost regions!

# Interpretation

Shape of line profile depends on radial line emissivity




*XMM-Newton:* $I_{\text{Fe K}\alpha} \propto r^{-4.6}$

line emissivity $\propto$ flux irradiated on disk

$\propto$ downward coronal flux

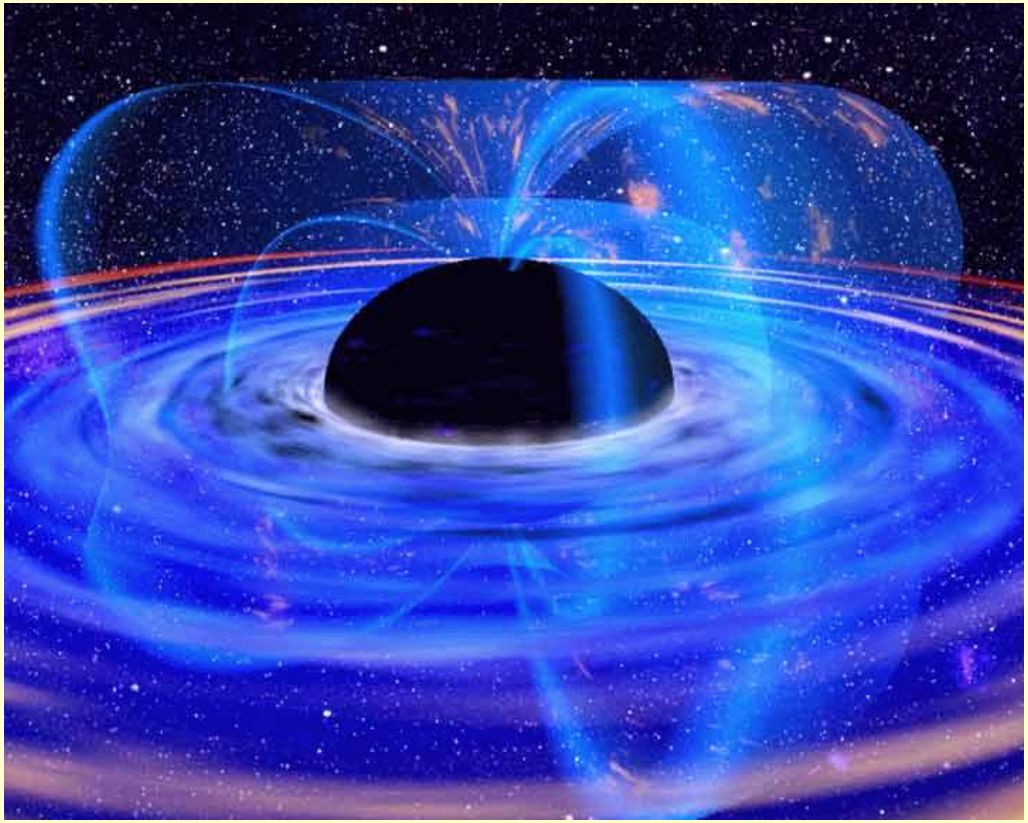
$\propto$ local disk emissivity

$\propto$ local energy dissipation rate

*BUT:* Accretion theory: dissipation rate $\propto r^{-3}$!

*XMM-Newton* observations show that more energy dissipated in disk than predicted from theory $\Longrightarrow$ additional energy source required!

# Interpretation



*Hypothesis:* Magnetic couple between BH and accretion disk:

1. Magnetic connection between inner disk and plunging region (Agol & Krolik, 2000)
2. Magnetic connection between inner disk and rotating event horizon (Li, 2000, 2002, 2003).

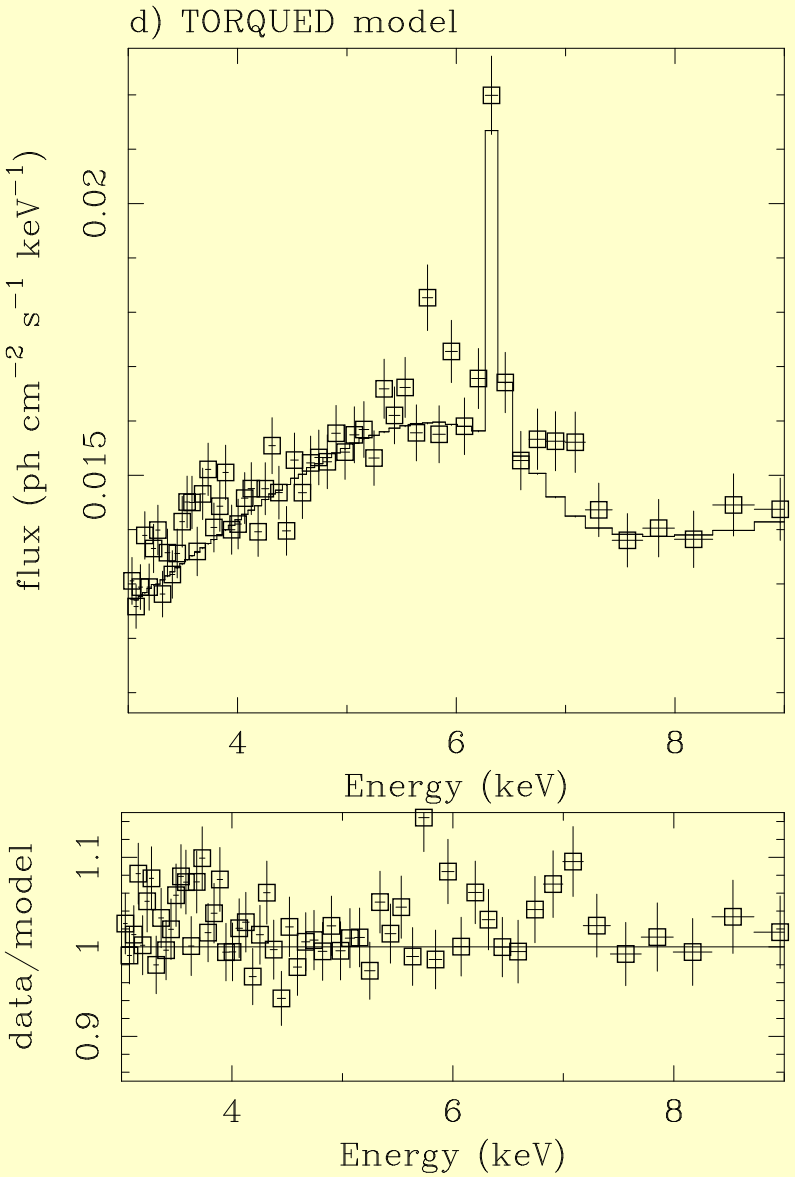
"torqued disks"

Complications:

- Magnetic field structure for $r < r_{\mathrm{in}}$: connection btw. plunging region and disk too weak for energy release required? (Li, 2003) [but: contradicts numerical simulations, e.g., Hawley & Krolik, 2001]

- Corona might be suppressed by torquing (Merloni & Fabian, 2003)
- gravitational focussing of X-rays? Petrucci & Henri (1997) show that in this case central source needed as well (but see Martocchia, Matt & Karas 2002).
- relativistic outflow? Proposed by Titarchuk, no comparison with data yet...
- limb darkening law of accretion disk? (Beckwith & Done, 2004, no fits yet).

# Realistic (?) Line Profiles




Payne & Thorne (1994) accretion disk, torqued at $r = r_{\mathrm{ms}}$ (Agol & Krolik, 2000), including returning radiation

$\chi^2/\mathrm{dof} = 2075/2104$

$\Longrightarrow$ Fits need large increase of inner disk radiative efficiency to explain line profile, are dominated by torquing.

Reynolds, Wilms, et al. (2004)

# Summary

- *XMM-Newton* observations show extremely broad line.
- Line profile implies very steep emissivity profile.
- Steep emissivity profile also seen in longer observation of Fabian et al. (2002).
- Shakura & Sunyaev type disks cannot explain inferred emissivity profile.
- Plausible explanation by elimination of other alternatives:
  spin extraction from a magnetized black hole

$\Longrightarrow$ More theoretical work on line emissivity profiles from (Kerr) black holes is needed!

And the future?

- more deep AGN observations with *XMM-Newton*
- Simbol-X
- XXX-XEUS

$\Longrightarrow$ enough to do for age 65 – 85. . .

*

Agol, E., & Krolik, J. H., 2000, ApJ, 528, 161

Branduardi-Raymont, G., Sako, M., Kahn, S. M., Brinkman, A. C., Kaastra, J. S., & Page, M. J., 2001, A&A, 365, L140

Fabian, A. C., et al., 2002, MNRAS, 335, L1

Guainazzi, M., et al., 1999, A&A, 341, L27

Iwasawa, K., et al., 1996, MNRAS, 282, 1038

Lee, J. C., Fabian, A. C., Brandt, W. N., Reynolds, C. S., & Iwasawa, K., 1999, MNRAS, 310, 973

Lee, J. C., Ogle, P. M., Canizares, C. R., Marshall, H. L., Schulz, N. S., Morales, R., Fabian, A. C., & Iwasawa, K., 2001, ApJ, 554, L13

Martocchia, A., Matt, G., & Karas, V., 2002, A&A, 383, L23

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