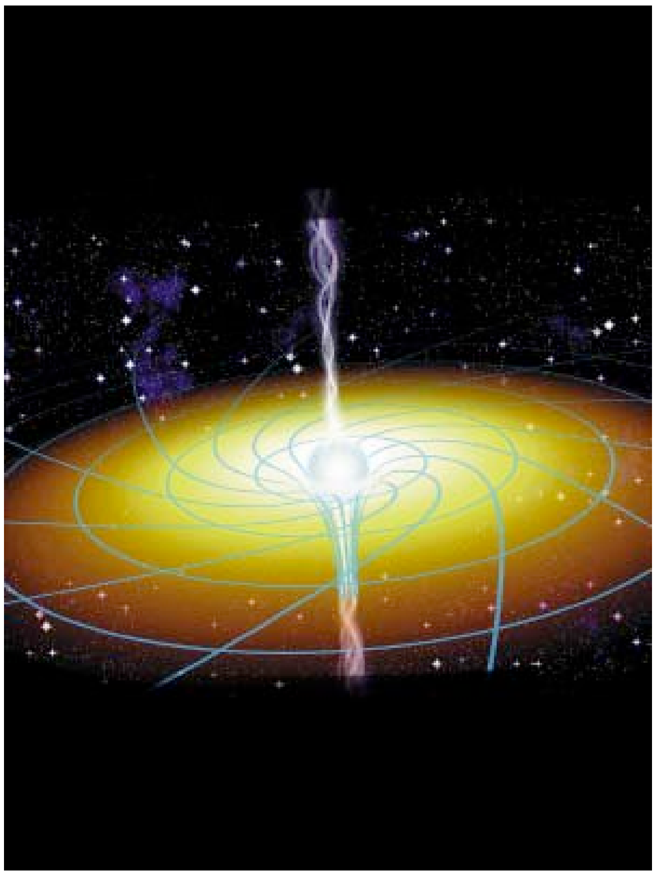
Iron K Line Diagnostics in AGN

Tahir Yaqoob (JHU/GSFC)



(Collaborators: Kendrah Murphy (JHU/GSFC), J. Reeves (JHU/GSFC), Y. Tersashima (Ehime U.), P. Serlemitsos (GSFC), & the Suzaku Team).

Overview

- Background: Goals for studying relativistic Fe K emission lines.
- High resolution observations, deconvolution of the "distant-matter'' Fe K emission line.
- The case of NGC 2992: highly sensitive measurements of the relativistic and distant matter Fe K line components. Flaring from the inner disk accompanied by gravitational redshifting.
- Demographics of broad Fe K lines. Limits on the broad line in a prototype with no detection.
- The broad Fe K line in high-luminosity and high-redshift quasars (from individual sources & samples).
- Artificial broadening from spectral adding.
- How to measure black hole angular momentum.

Black Holes Have No Hair

* *Characterized by Mass, Angular momentum (spin) & Charge only*
* *Hawking radiation immeasurabley tiny*

"Black holes, by definition, are structures involving strong field general relativity and can only be properly described in these terms.

Nevertheless, it is a feature of (and perhaps a sad commentary on) current progress in black hole astrophysics that virtually all physical processes that are likely to be observable can be described with adequate precision using pre–general relativity (although not entirely non–Newtonian) models. Indeed, in most of the relevant astrophysical literature metrics, horizons, etc. are avoided and calculations are performed in a flat spacetime terminated when necessary at the Schwarzschild radius. Much of the discussion that follows will be couched in this language, not as a reactionary attack on general relativity, but instead as a means of emphasizing that astronomical observations of black holes are not very promising ways to verify that general relativity is the correct theory of gravitation."

– R. Blandford, 1987 [in '300 Years of Gravitation']

Kerr Metric: Frame Dragging

Black Hole angular momentum or spin, a=J/M = 0 –> 0.9982.

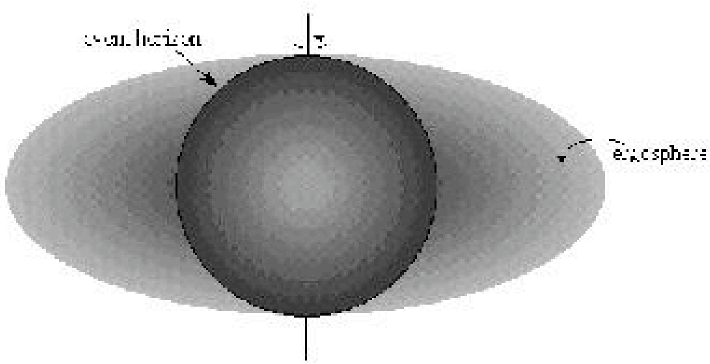
[Maximal spin for accretion onto 'standard' thin disk].

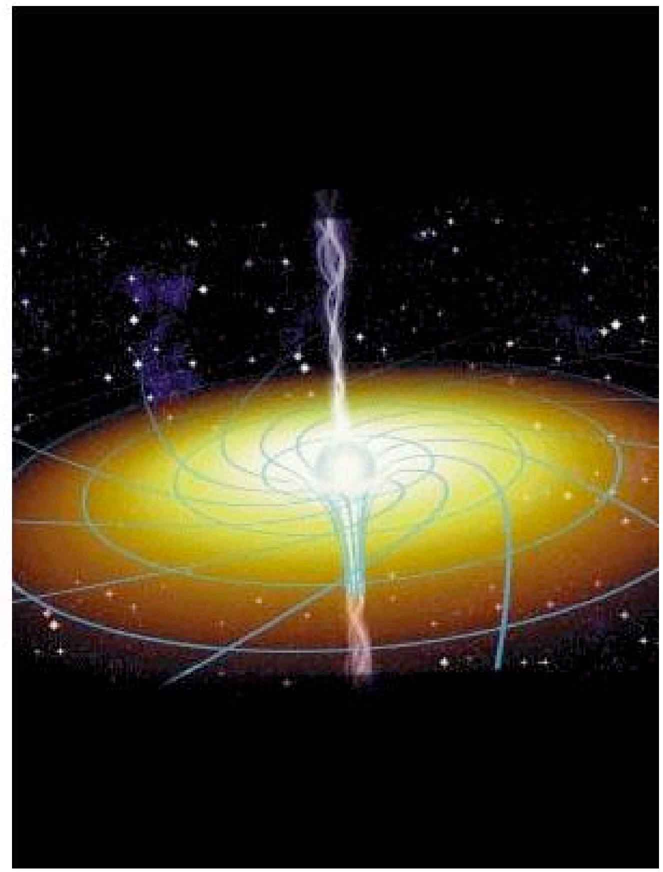
All interial frames inside ergosphere rotate with the hole.

$$R_{\mathtt{horizon}} = 1 + (1 - a^2)^{1/2}$$

$$R_{\mathtt{ergo\,sphere}} = 1 + (1 - a^2 \cos^2\theta)^{1/2}$$

(Angle measured from equatorial plane).



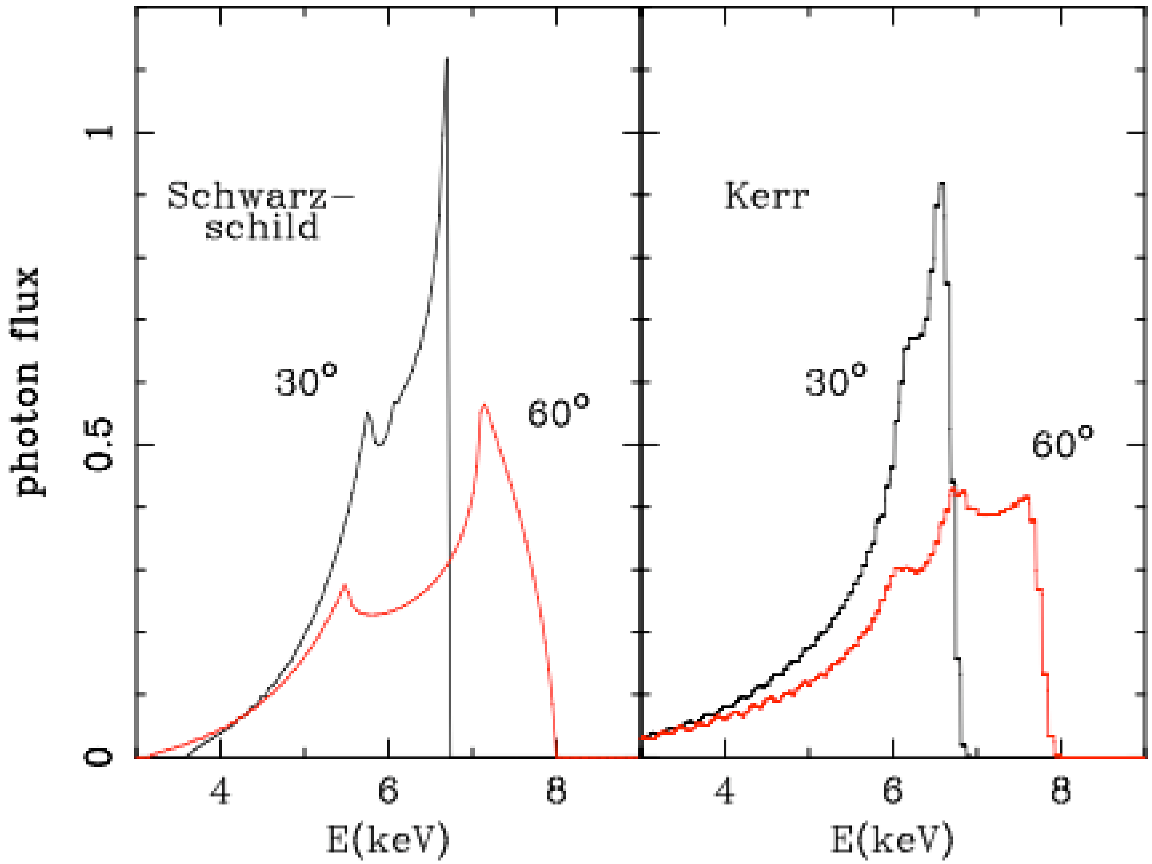


Keplerian Orbital Time versus Mass

$$\frac{\text{Orbital Timescale}}{\text{Hydrostatic Timescale}} = \pi$$

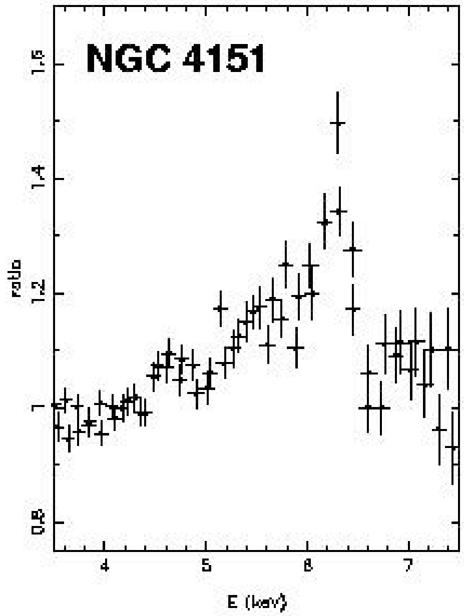
	$10^6 M_\odot$	$10^7 M_\odot$	$10^8 M_\odot$	$10^9 M_\odot$
$6r_g$	140 s	1.4 ks	0.17 d	1.7 d
$10r_g$	320 s	3.2 ks	0.37 d	3.7 d
$20r_g$	894 s	8.9 ks	1.0 d	10.4 d
$100r_g$	10 ks	1.2 d	11.6 d	115.7 d
$1000r_g$	3.7 d	36.6 d	366 d	10 years

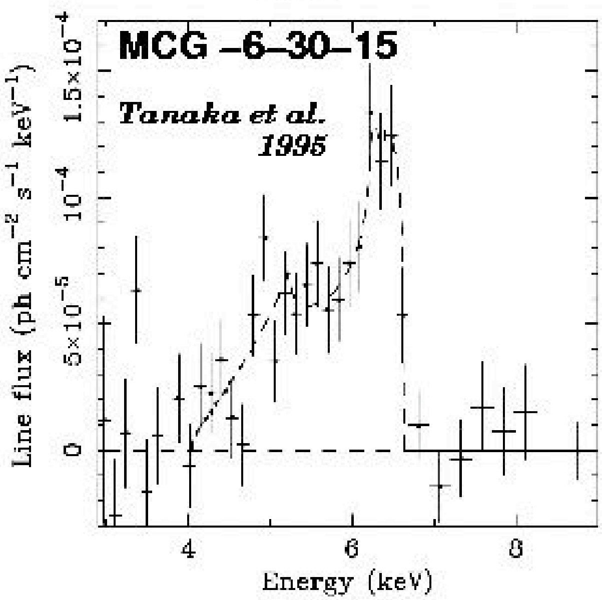
Typical Fe K Emission Line Profiles from Disks

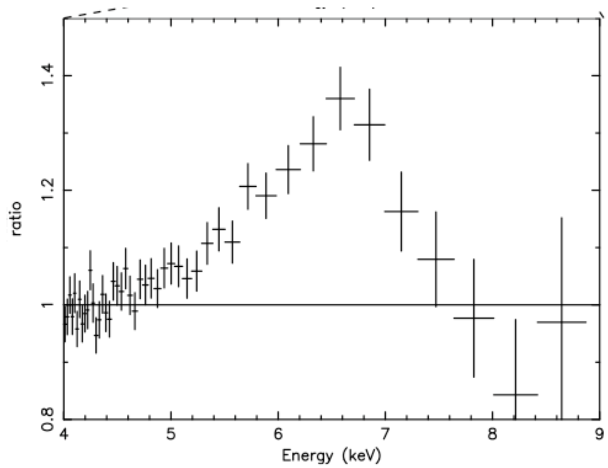


ASCA Finds the Relativistic Fe K Lines

Yaqoob et al. 1995



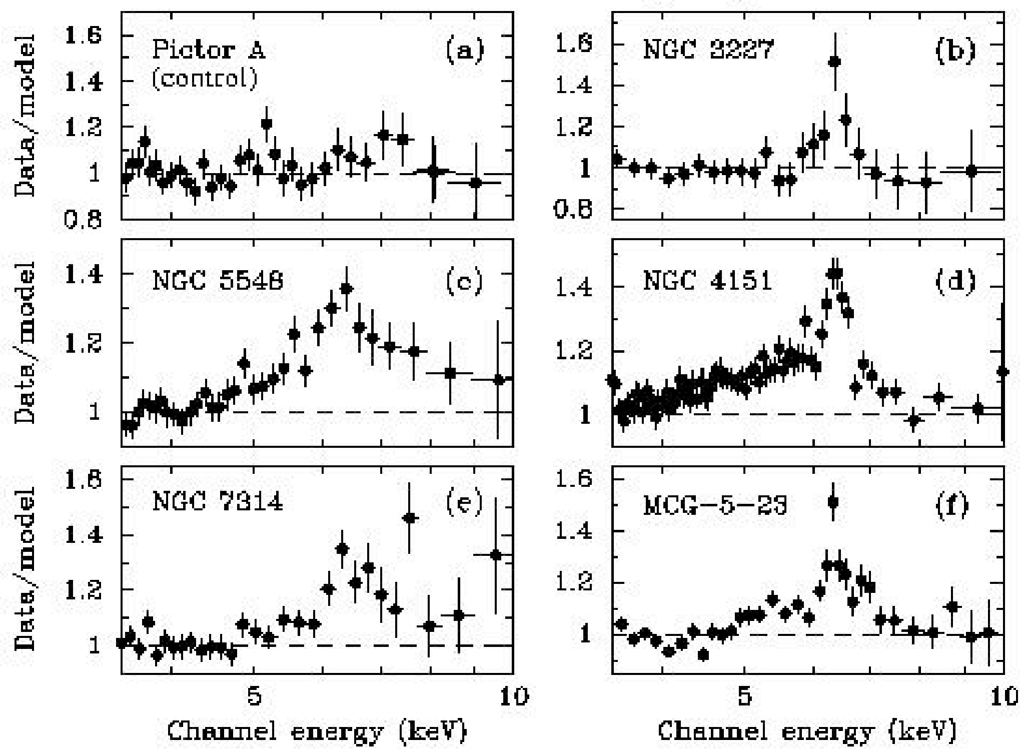


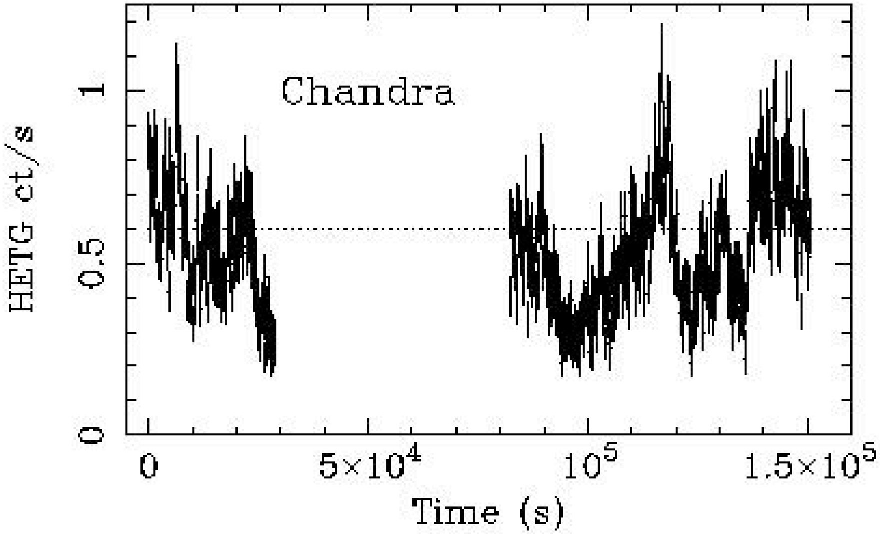


In X–ray Binaries too (although this line profile measured by Chandra).

GX 339-4
Miller et al. 2004

Yaqoob, Weaver 1996





NGC 7314: Fe XXV & Fe XXVI
Narrow, rapidly variable, unresolved lines from an accretion disk.

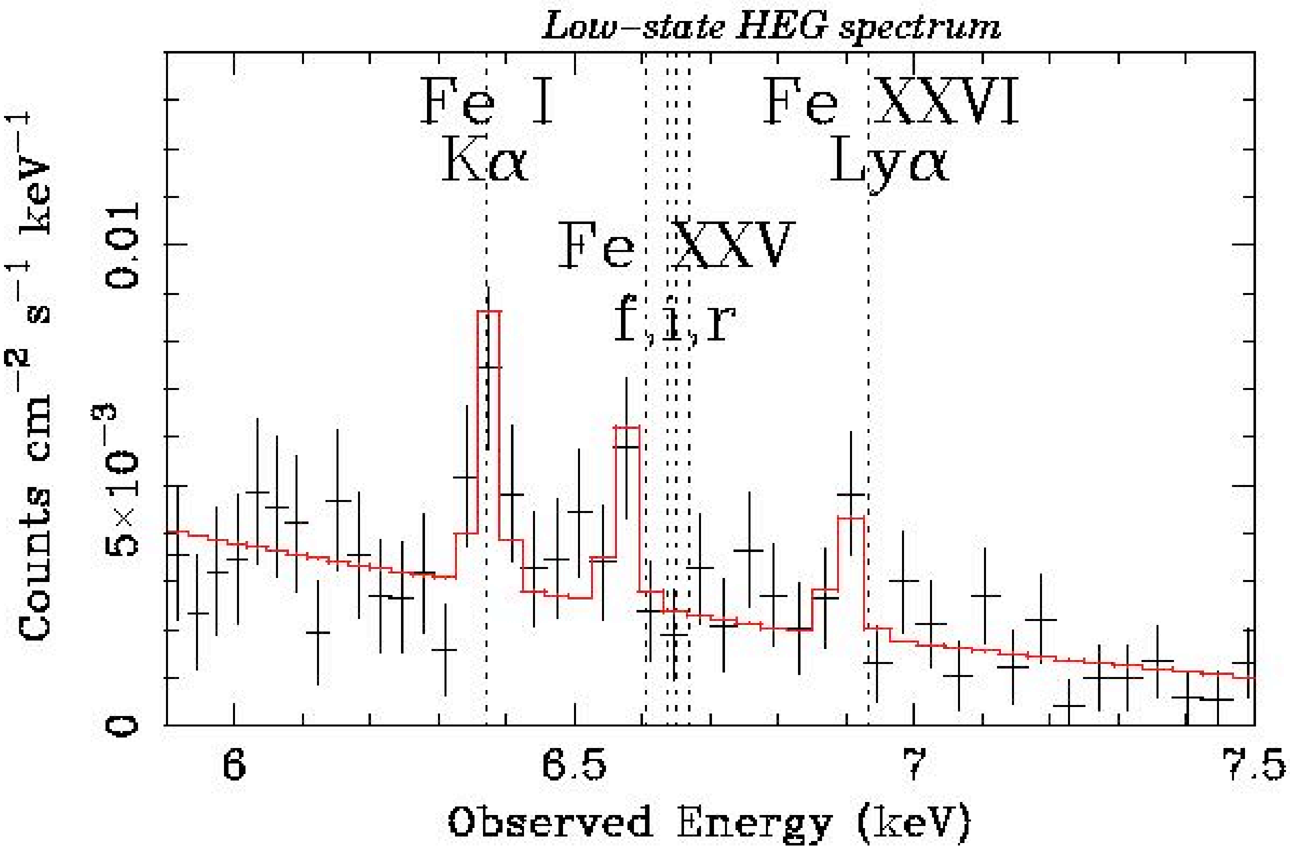
Variable narrow 6.4 keV line found in Mkn 841 - Petrucci et al. (2002).

He–like & H–like lines are redshifted, Fe I K line is not.

Redshift is ~1500 km/s, greater than systematic & statistical uncertainty.

Is He–like line f,i, or r? HEG cannot resolve.

Consistent redshift with H–like line if forbidden.

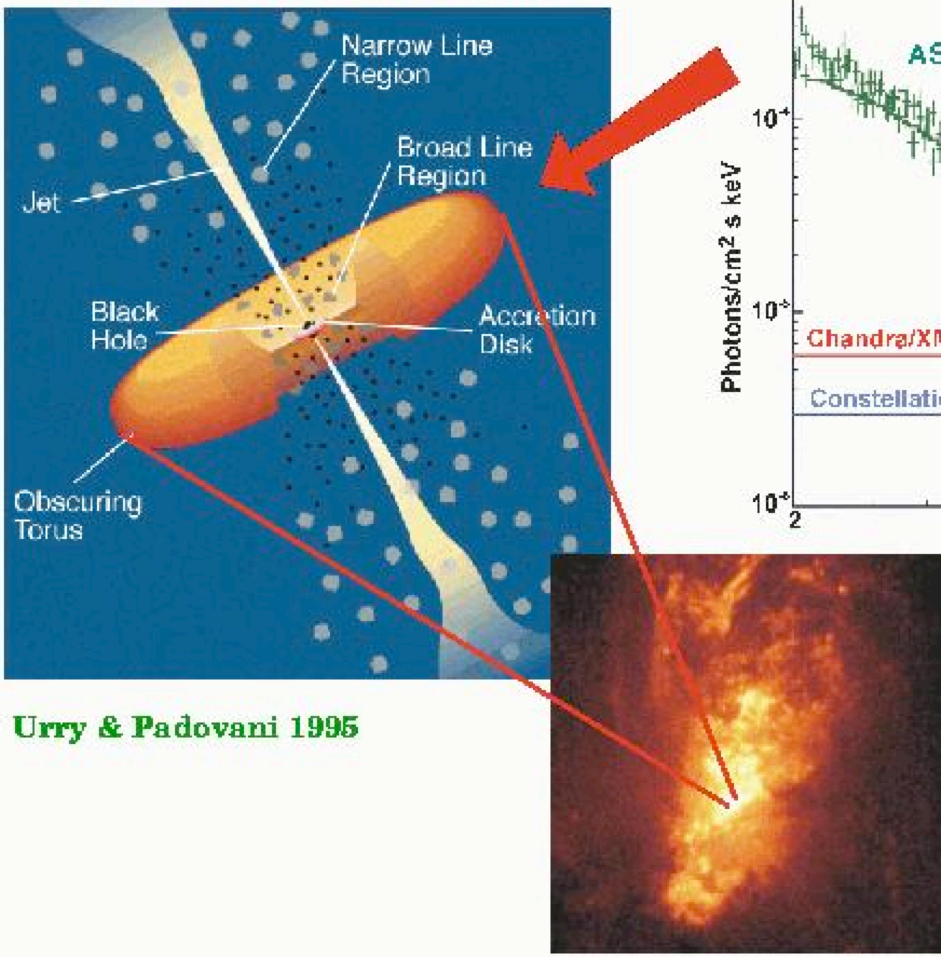


Yaqoob 2003

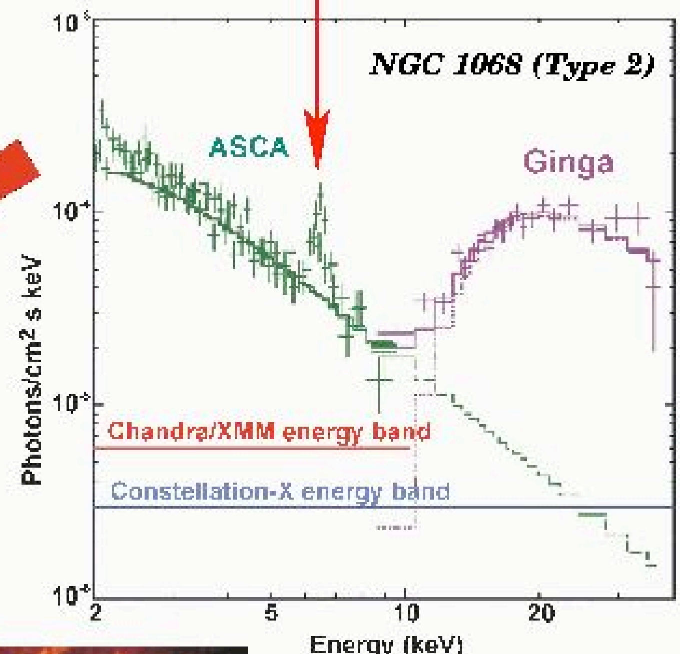
Confusion of Disk & Distant–Matter Fe K Lines

Non–Disk Fe K line may be present in Type 1 AGN:
CCD resolution cannot resolve disk component

AGN unification model: Disk might only be seen directly in Type 1 AGN



Urry & Padovani 1995

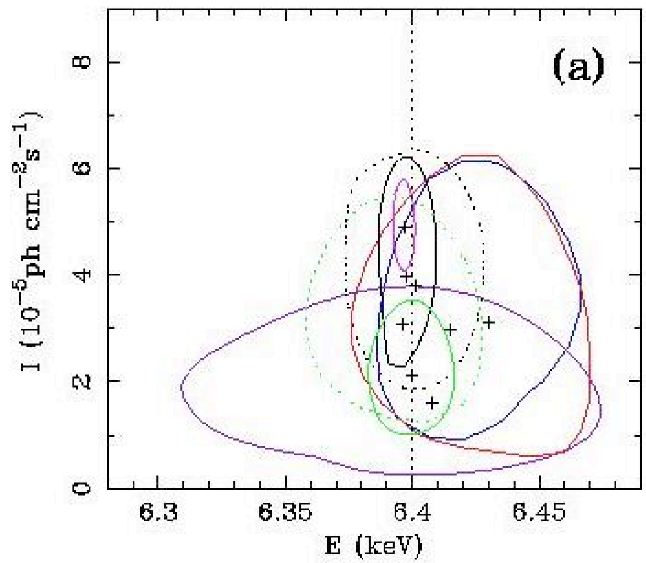


Done, Madejski, Smith 1996

Type 2 AGN:

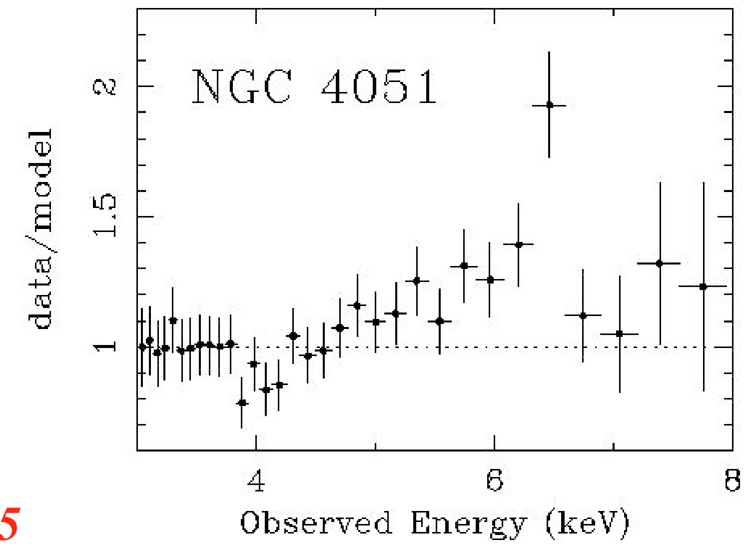
NGC 1068

Peak Energy & FWHM of Fe-K Line Core

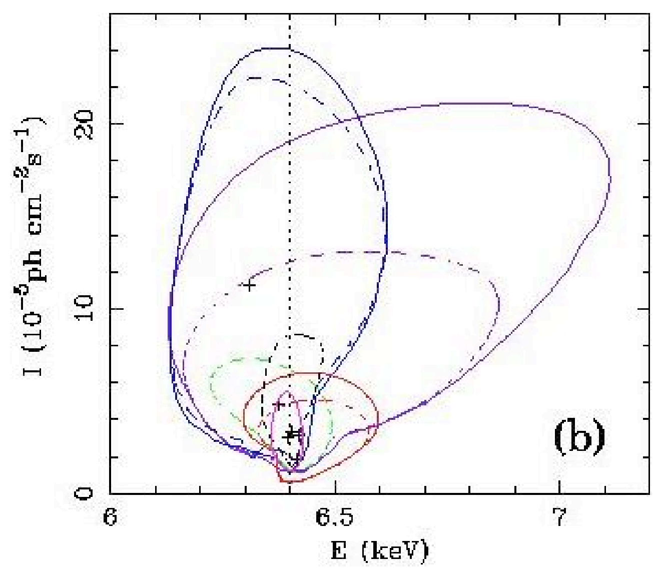


Mean peak energy: 6.404 +/- 0.005 keV

HEG resolution is ~1800 km/s FWHM.

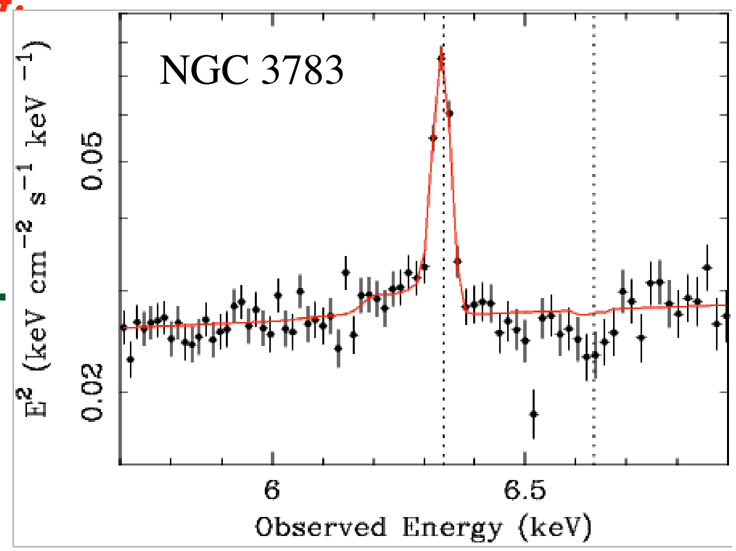


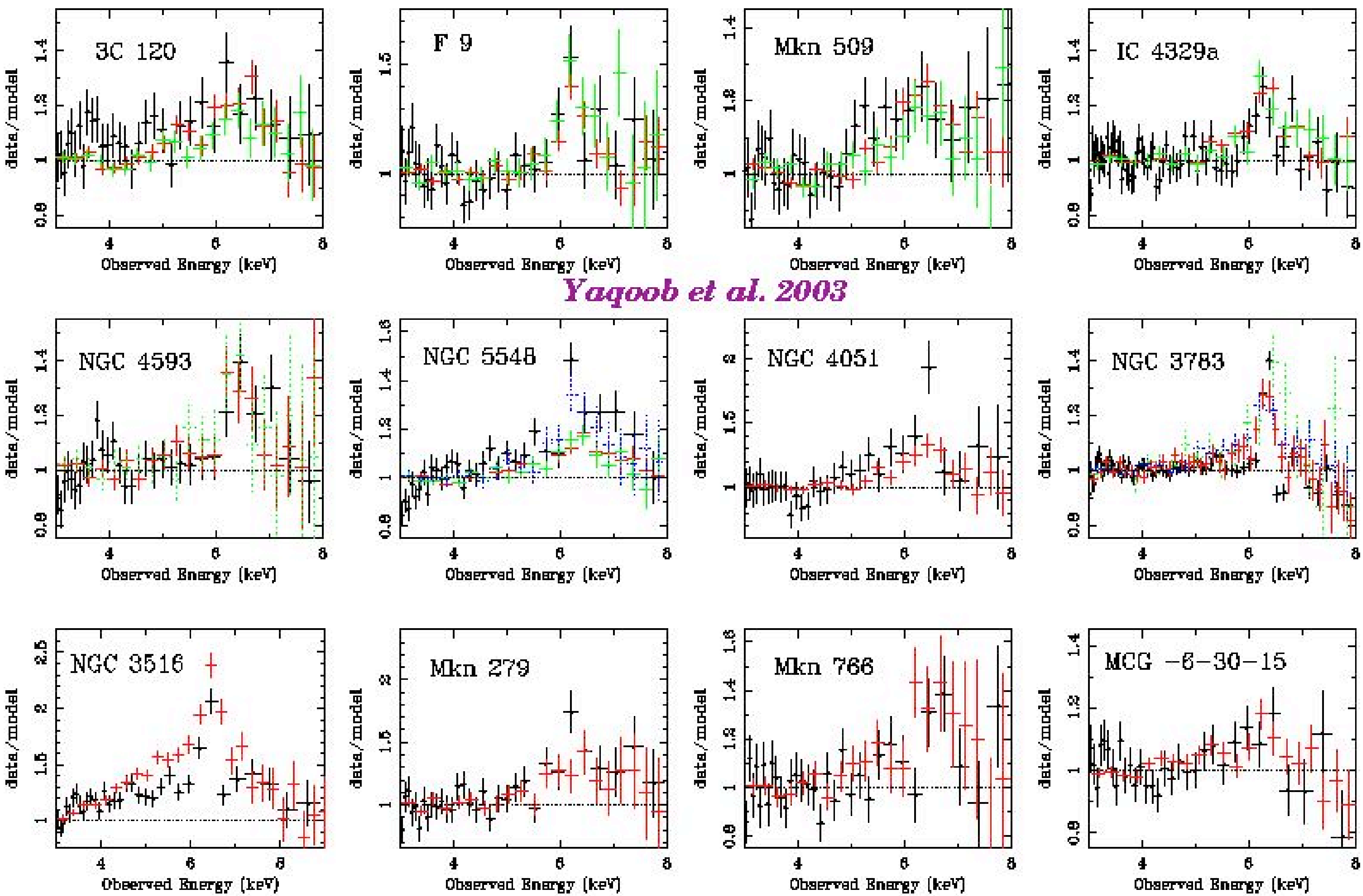
HETG sample of 15 Sy 1 galaxies. Yaqoob & Padmanabhan 2004.



At least 8/15 have a broad line. Core resolved in 3/15.

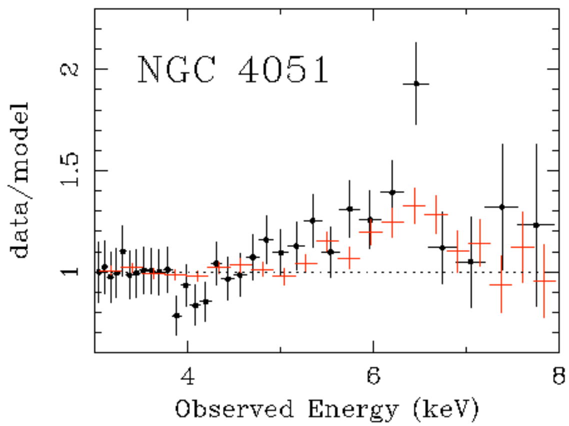
Mean FWHM: 2380 +/- 760 km/s



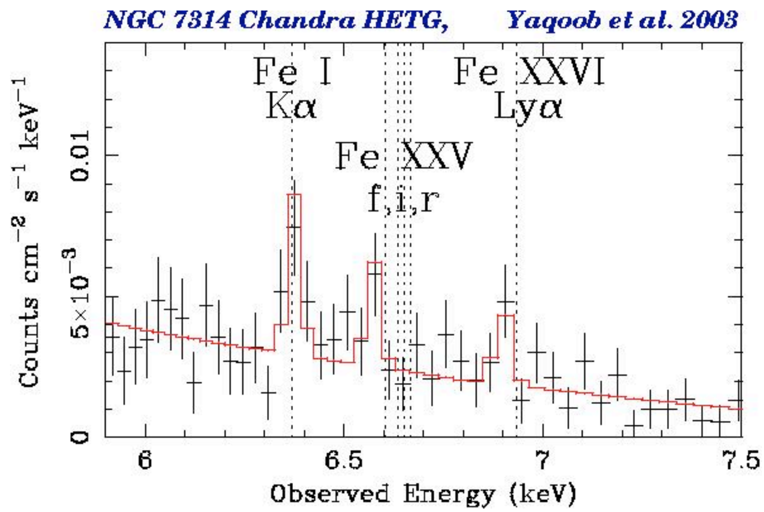


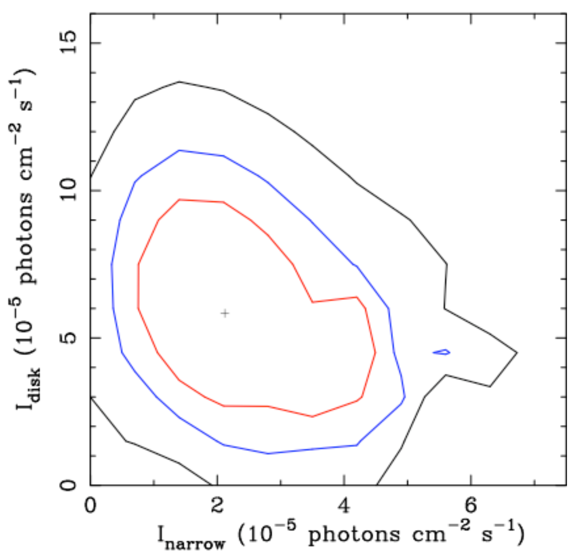
Chandra HEG (BLACK) vs. ASCA S0+S1 (COLORED)

Deconvolution of the Fe K emission line from the accretion disk & distant matter is difficult even with Chandra HETG & has only been done for a few cases. Some Fe K line profiles show complexity due to lines from highly ionized Fe, which are becoming increasingly common (e.g. see Bianchi et al. 2004).

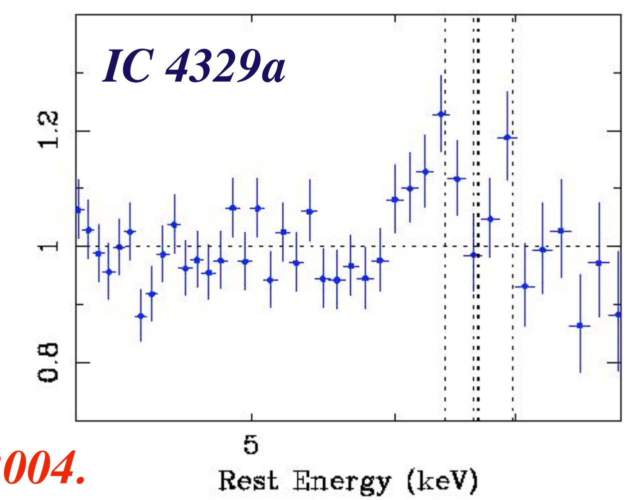


NGC 4051:
Black: Chandra HETG
Red: Non-simultaneous ASCA.



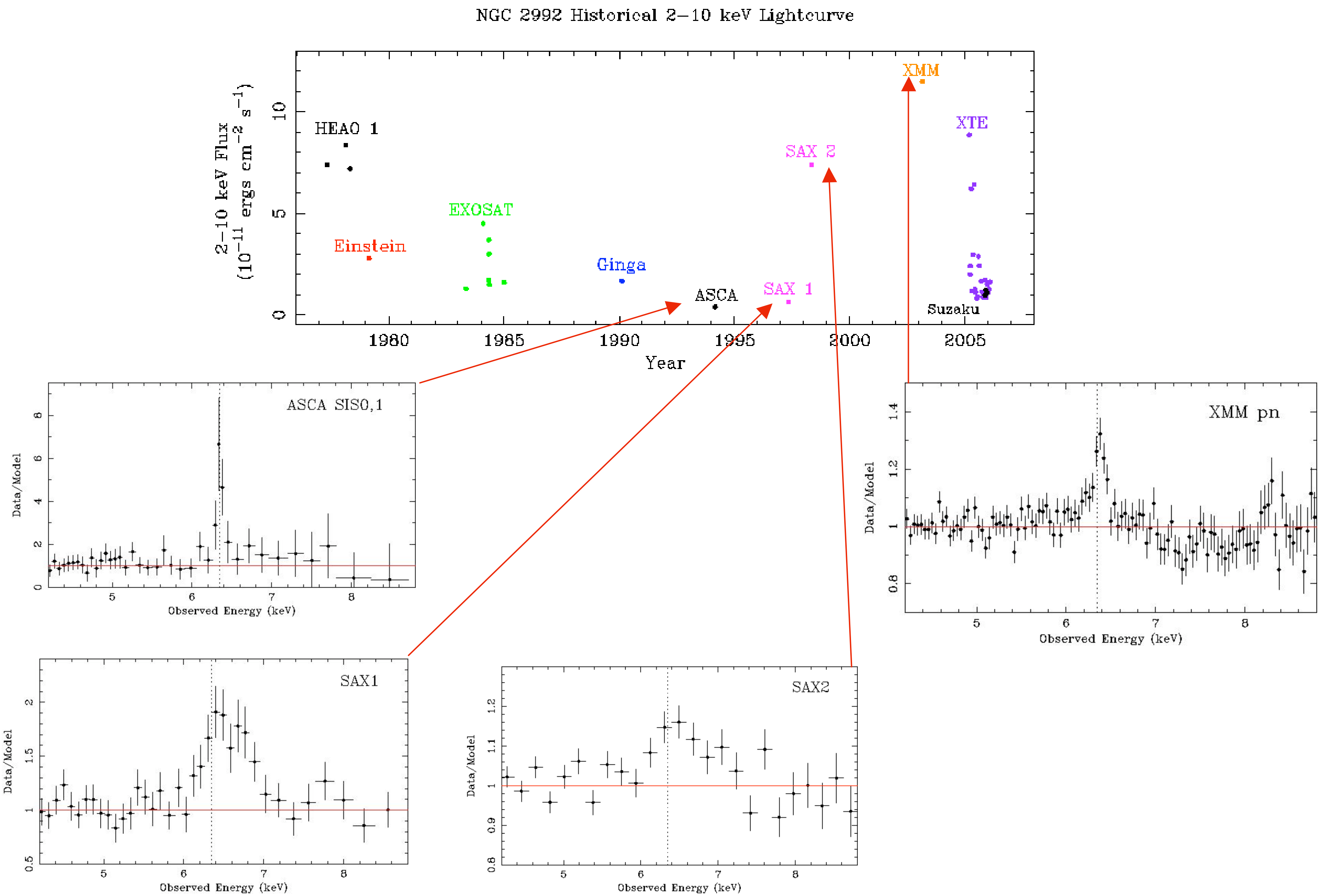


Left: NGC 4051 Disk Fe-K line intensity vs. narrow distant-matter line intensity from HETG data.



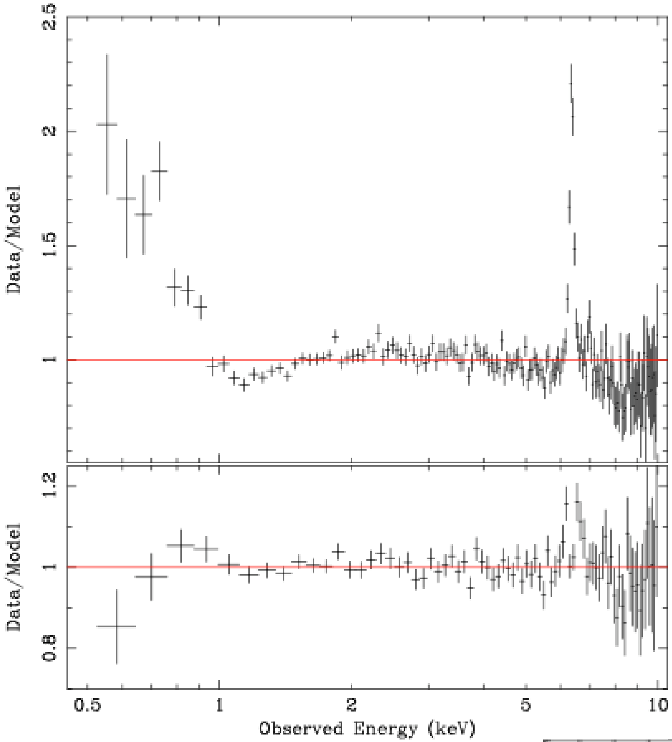
Right: IC 4329a Fe K complex: Fe Lya? McKernan & Yaqoob 2004.

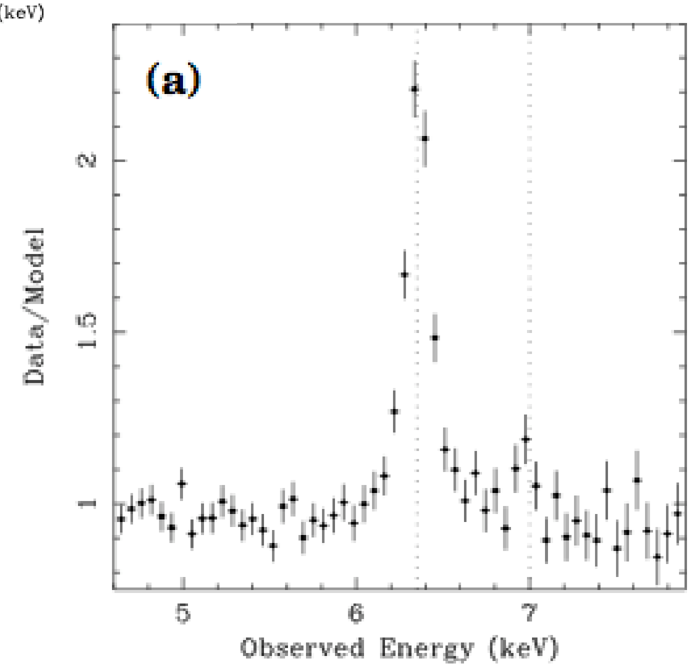
NGC 2992: An SBH Accretion Disk Laboratory

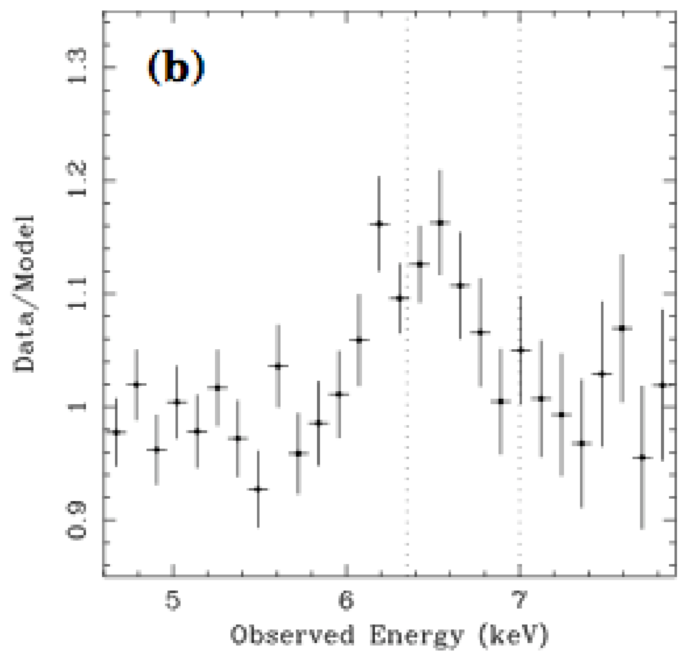


Suzaku XIS data for NGC 2992

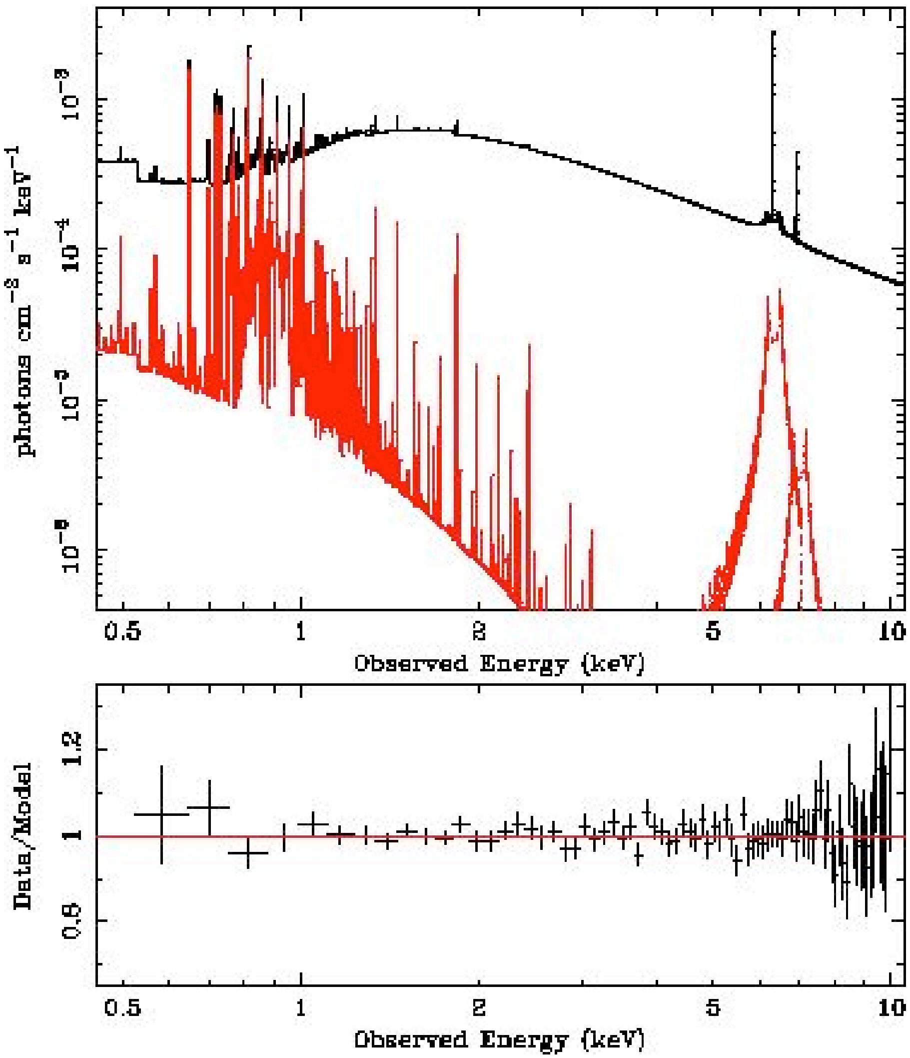
Summed XIS data for 3 observations in Nov-Dec 2005. Left: absorbed power-law plus scattering models. Below: (a) Fe K line profile; (b) Narrow lines removed showing a broad Fe K line profile.





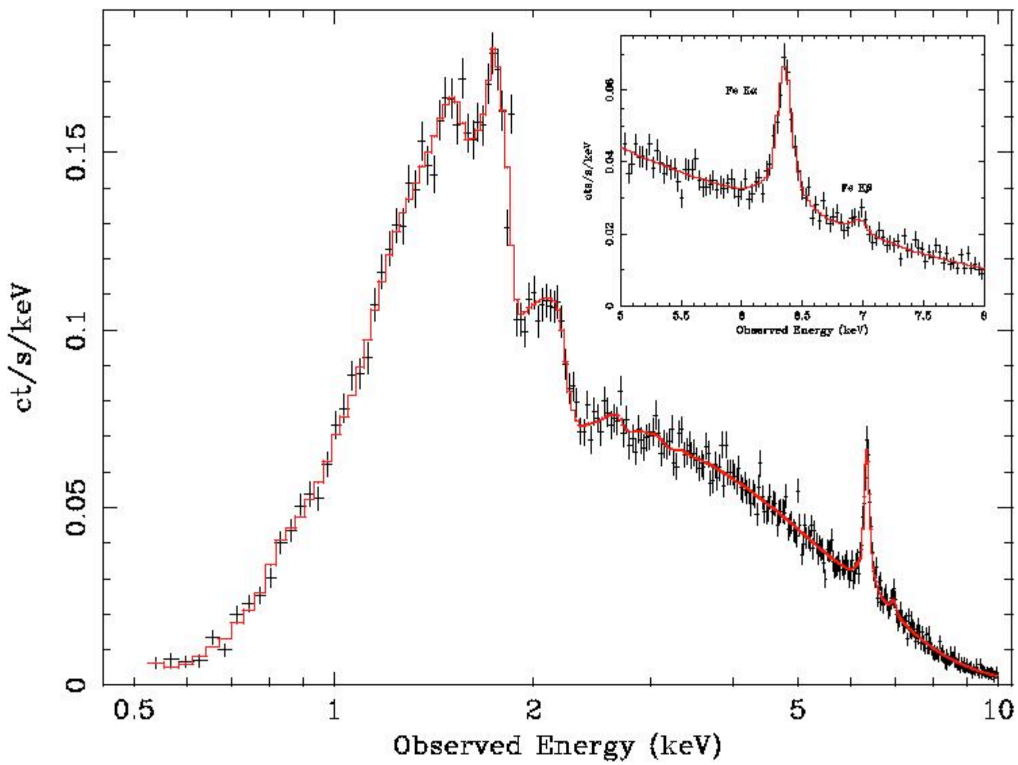


NGC 2992 *Suzaku* Data: Baseline Model

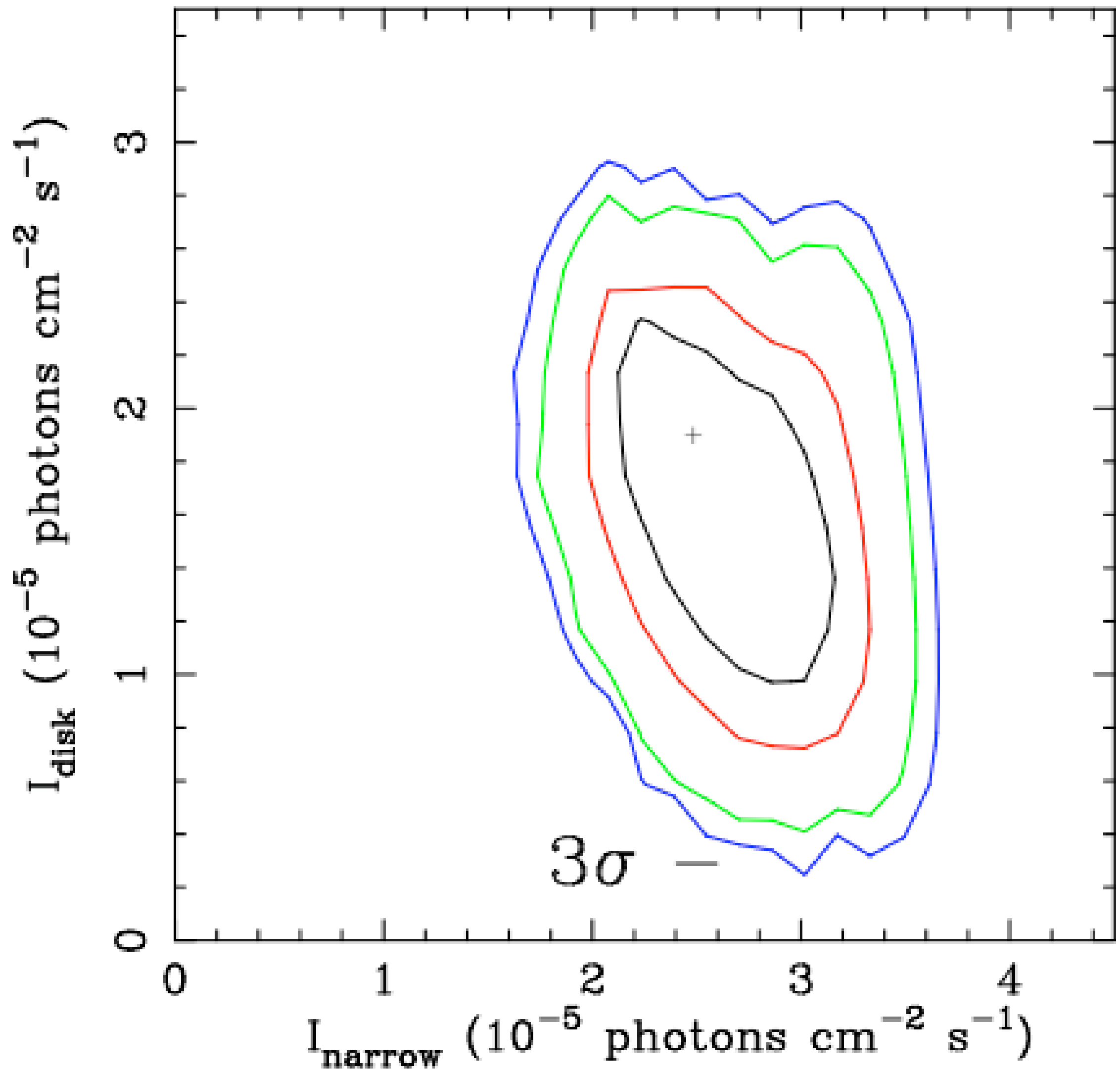


Disk Line θ > 31 deg.
Compton-thin: lg(NH) ~ 22

Details in PASJ Suzaku special issue (Nov. 2006) paper.

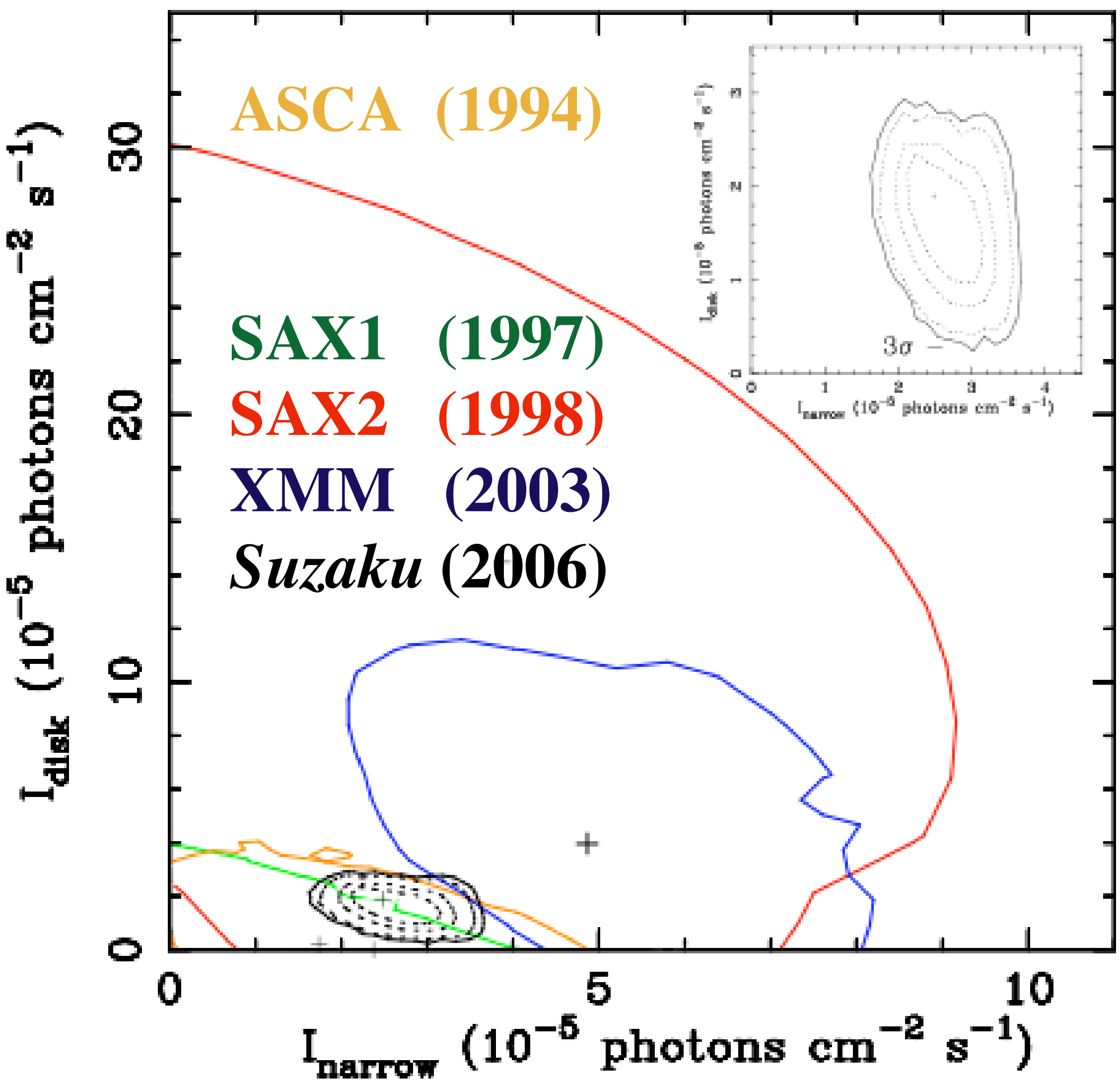


Suzaku XIS CCDs deconvolve the disk & distant-matter Fe K lines in NGC 2992 for the first time! Thus far this has only been possible in a few AGN.



Moreover, NGC 2992 was in a LOW STATE!

NGC 2992: Comparison with attempts at the Fe K line complex deconvolution from previous data.

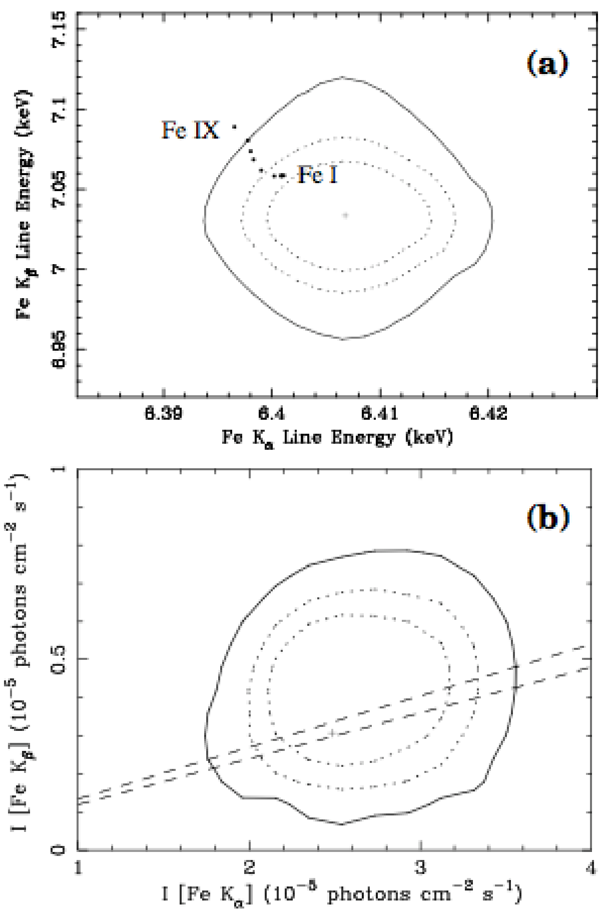


Precision measurement of the ionization state of Fe for the distant matter line.

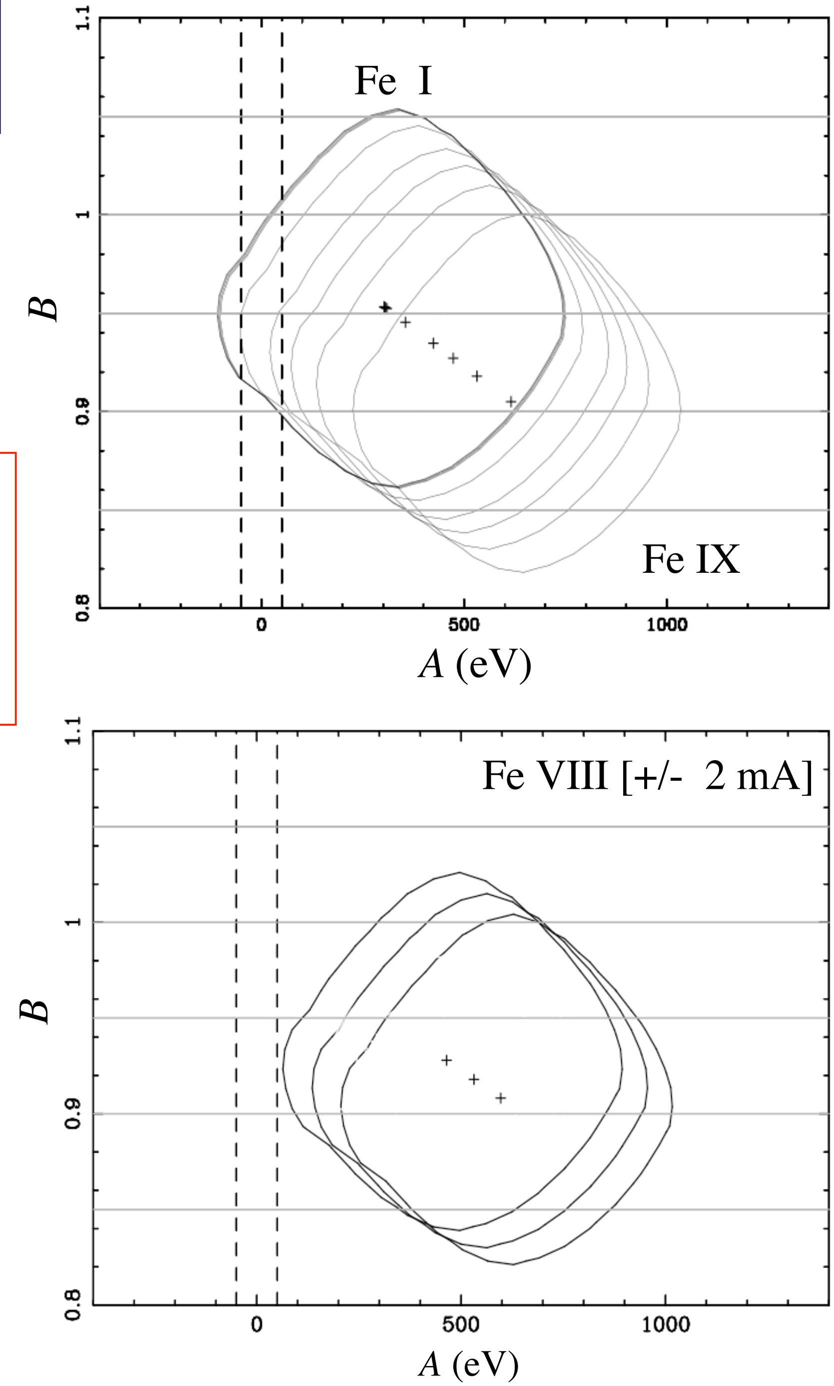
$$E_{i,\mathrm{Fe\ K}\alpha}\ (\mathrm{observed}) = A + B \times E_{i,\mathrm{Fe\ K}\alpha}\ (\mathrm{true})$$

and

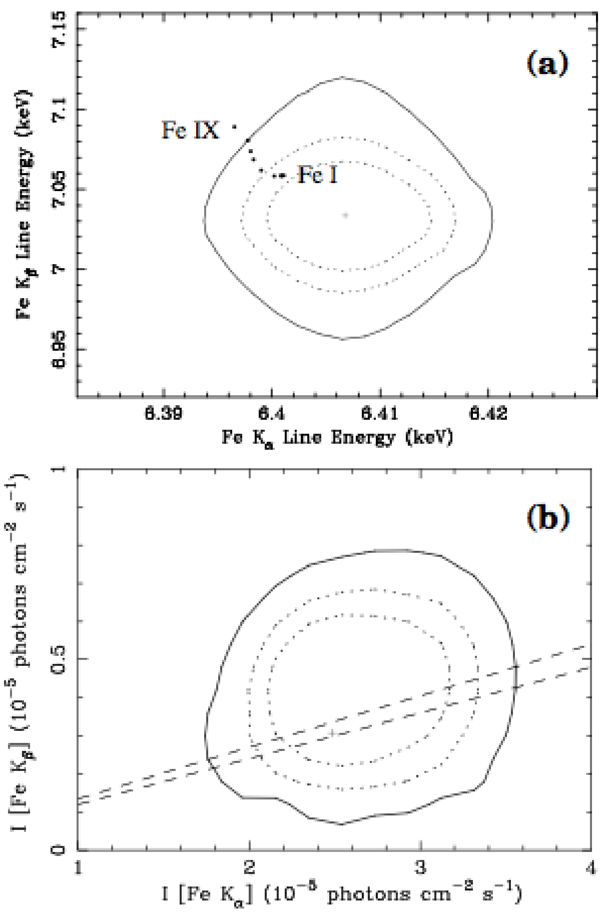
$$E_{i,\mathrm{Fe\ K}\beta}\ (\mathrm{observed}) = A + B \times E_{i,\mathrm{Fe\ K}\beta}\ (\mathrm{true}),$$



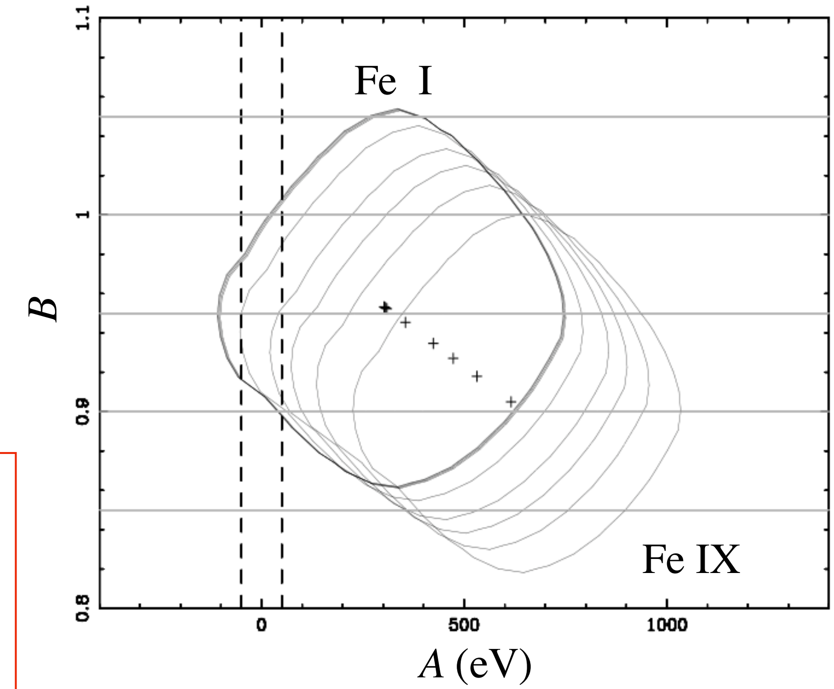
NGC 2992 Suzaku: distant-matter ionization state.

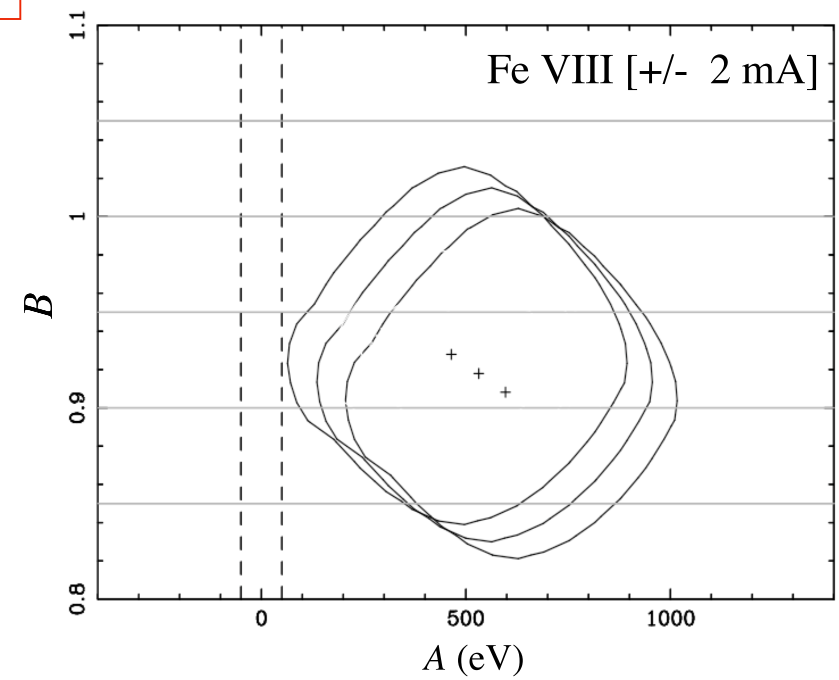


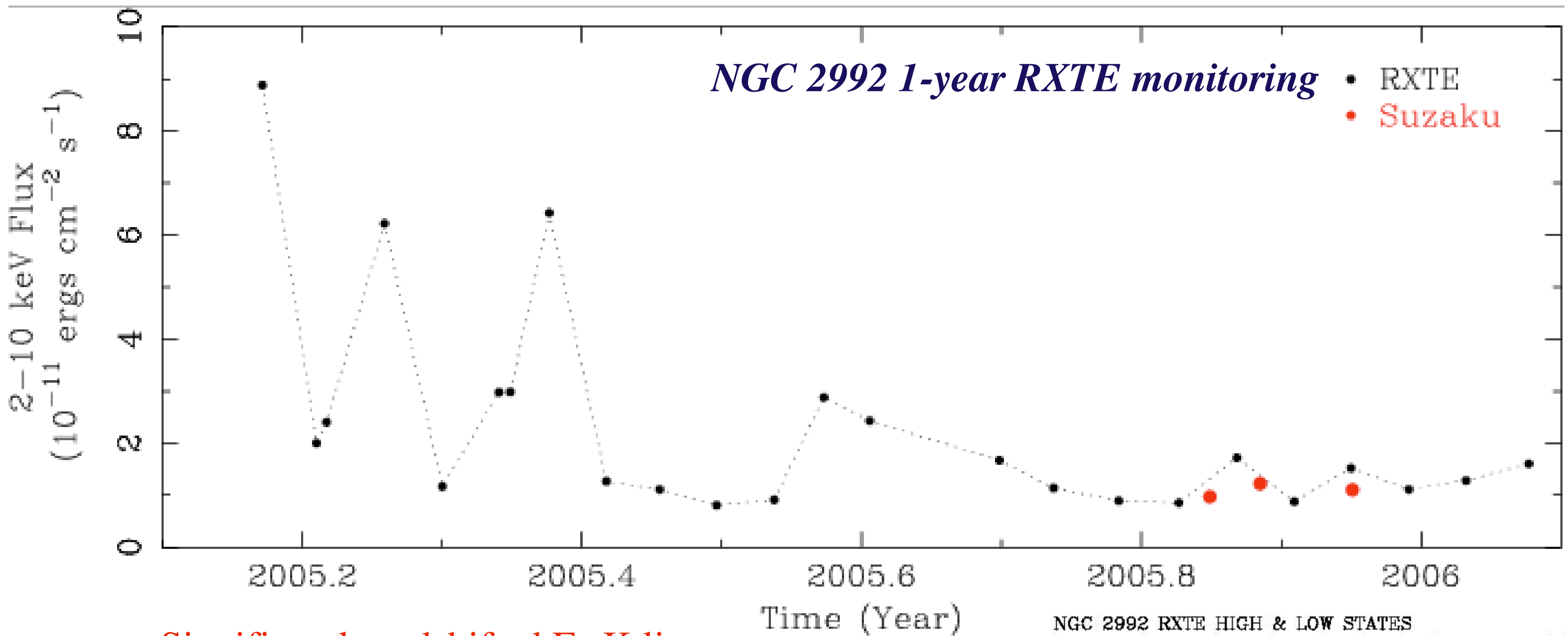
Unprecedented precision in constraining the ionization state of Fe responsible for the narrow XIS Fe K line due to the redundant information provided by the high SNR Fe Kβ line. States higher than Fe VII are ruled out after conservatively accounting for instrumental and theoretical uncertainties.



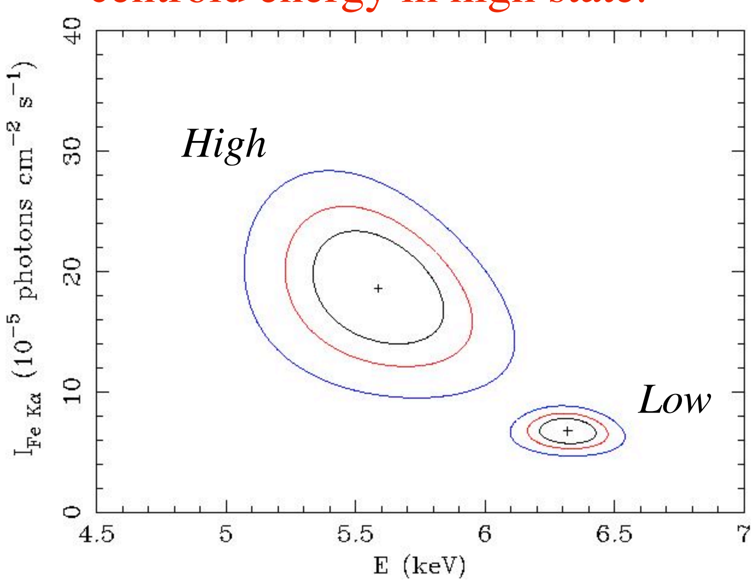
NGC 2992 Suzaku: distant-matter ionization state.

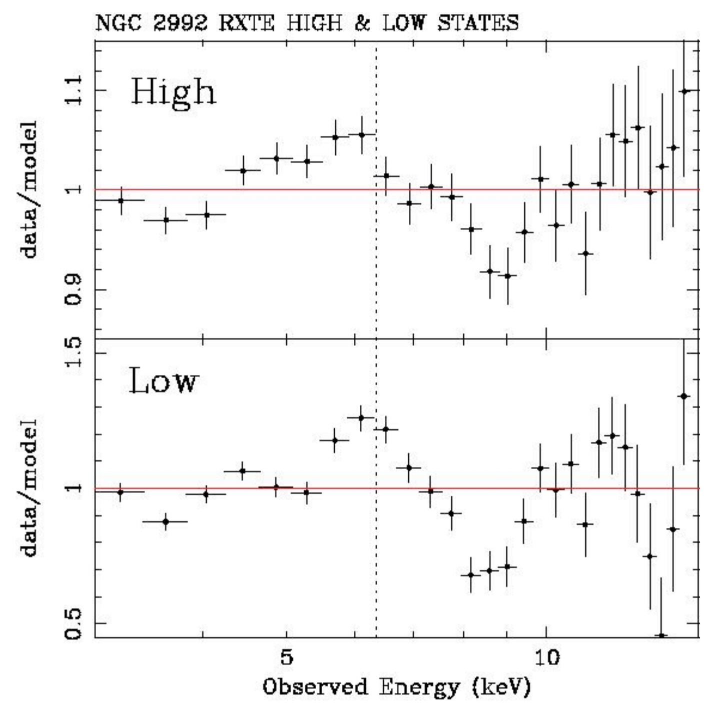




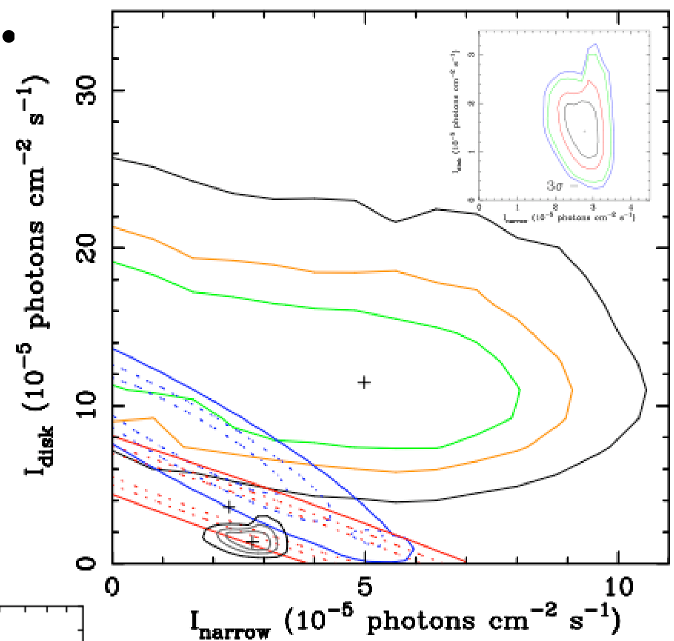


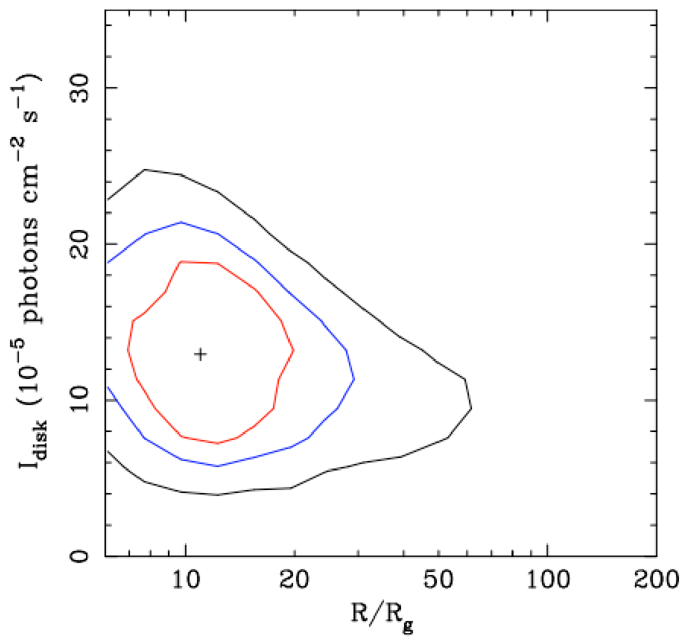
Significantly redshifted Fe K line centroid energy in high state.

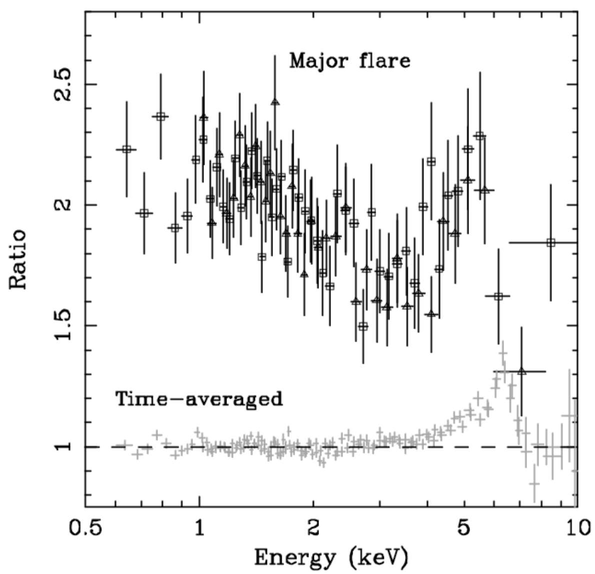




Implication of RXTE Fe K line variability in NGC 2992: violent activity of the continuum restricted to the inner accretion disk.

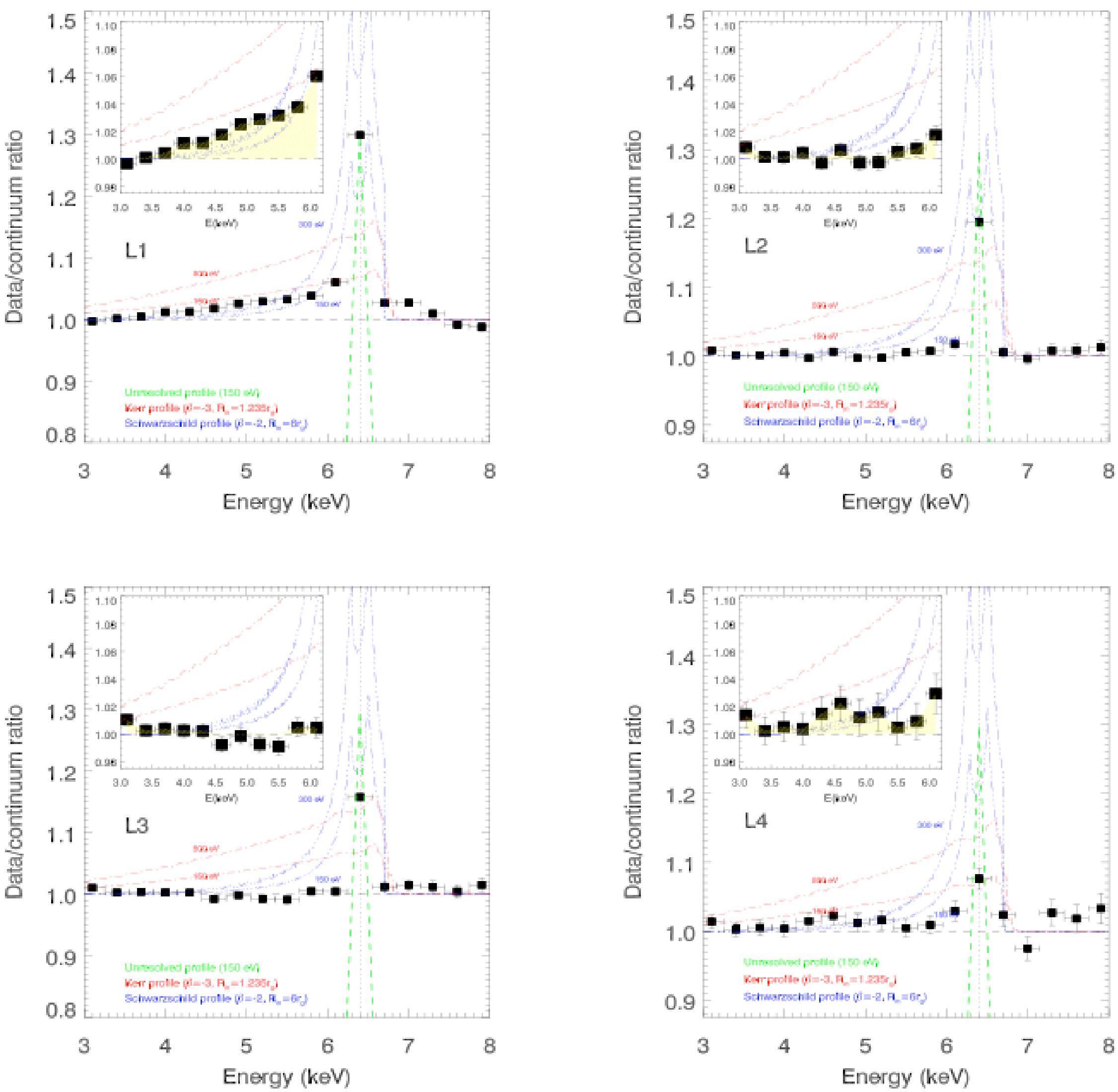






Similar behavior was once seen by ASCA in MCG -6-30-15 (Iwasawa et al. 1999).

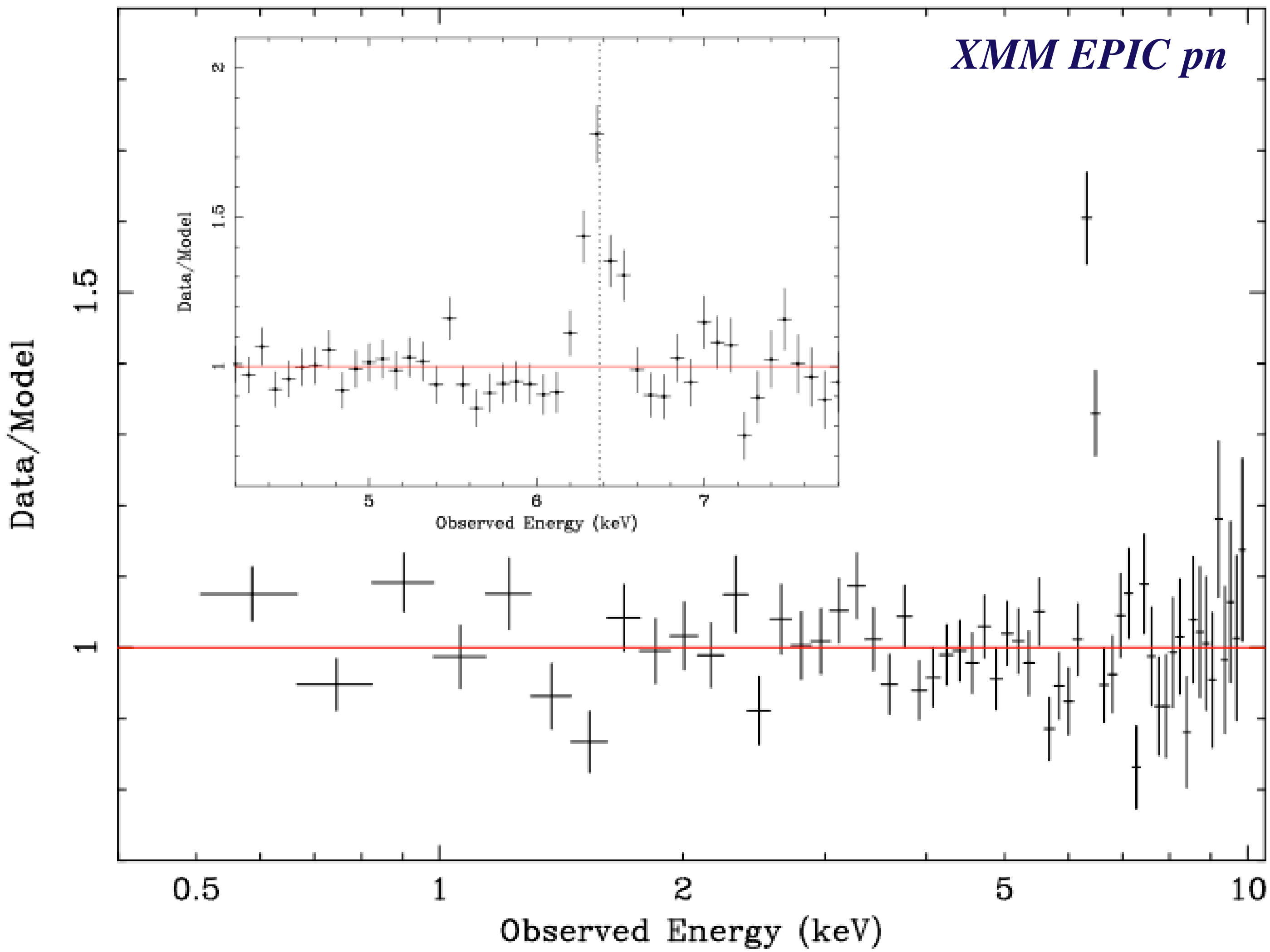
How Common is the Broad Fe K Line?



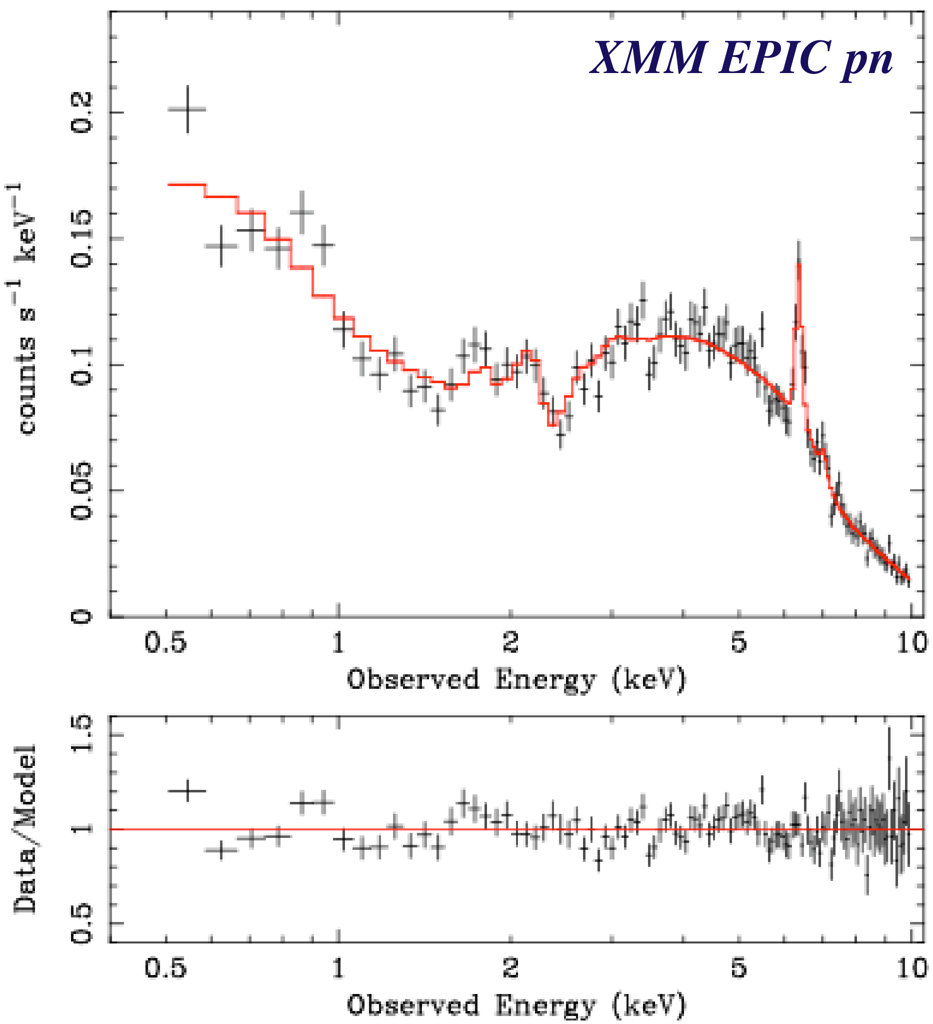
- Guainazzi et al. (2006; G06) study & several other sample studies (mostly XMM) find the broad line apparently absent; Dewangan et al. 2002, Perola et al. 2002, Page et al. 2004, Jimenez-Bailon et al. 2005.
- Summed profiles from G06 in 4 Lx bins - broad line strongest in lowest Lx bin.

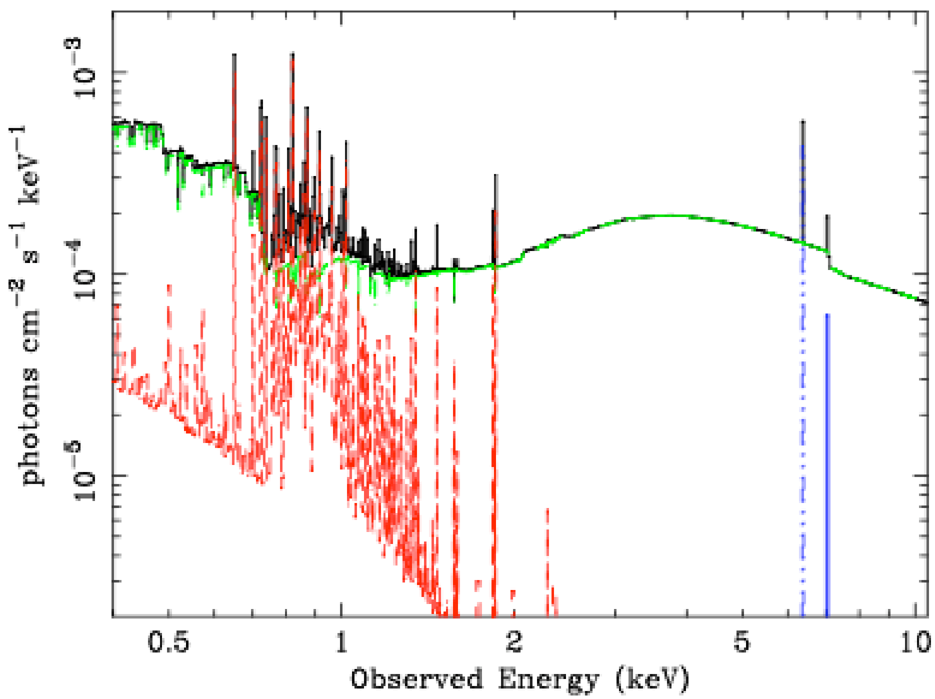
  lgLx: [<43], [43-43.7], [43.7-44.2],[>44.2].
- Upper limits on non-detections are very model-dependent, as is the fraction with detections (~25-50%?)
- What fraction of sources have unresolved narrow-line complexes like NGC 7314? Need higher resolution.

NGC 3227: Robust Example with no Relativistic Line Detection



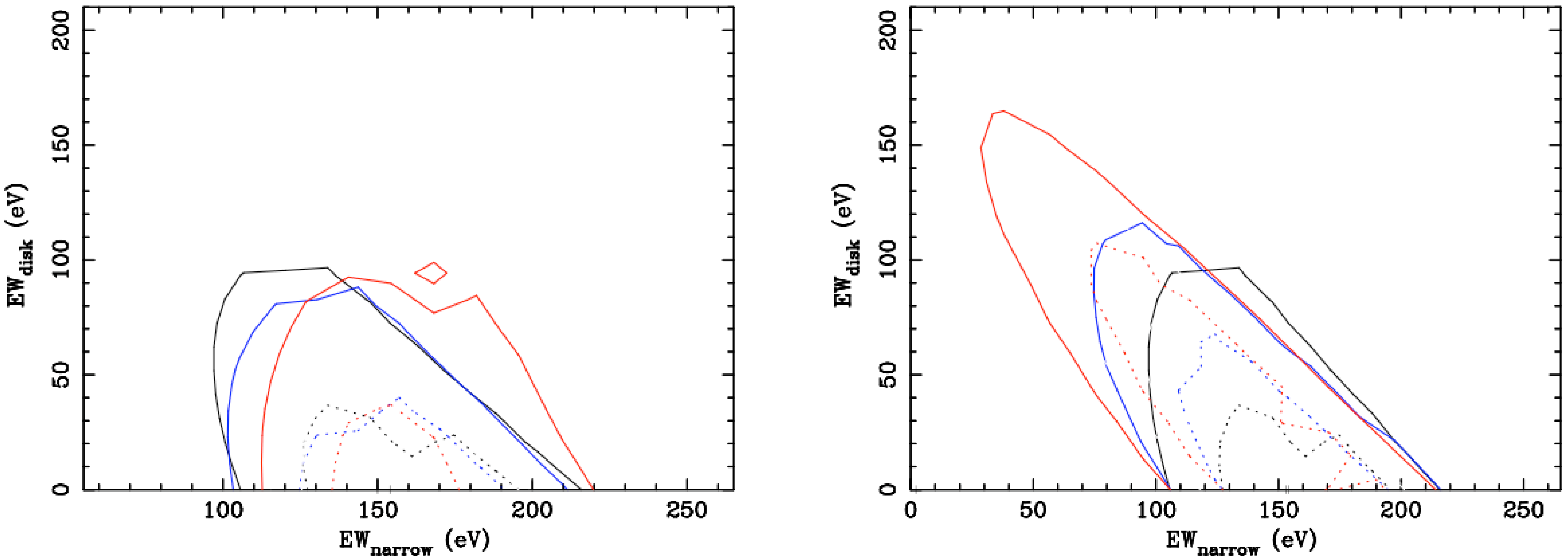
NGC 3227: Complex Fit with no Relativistic Line





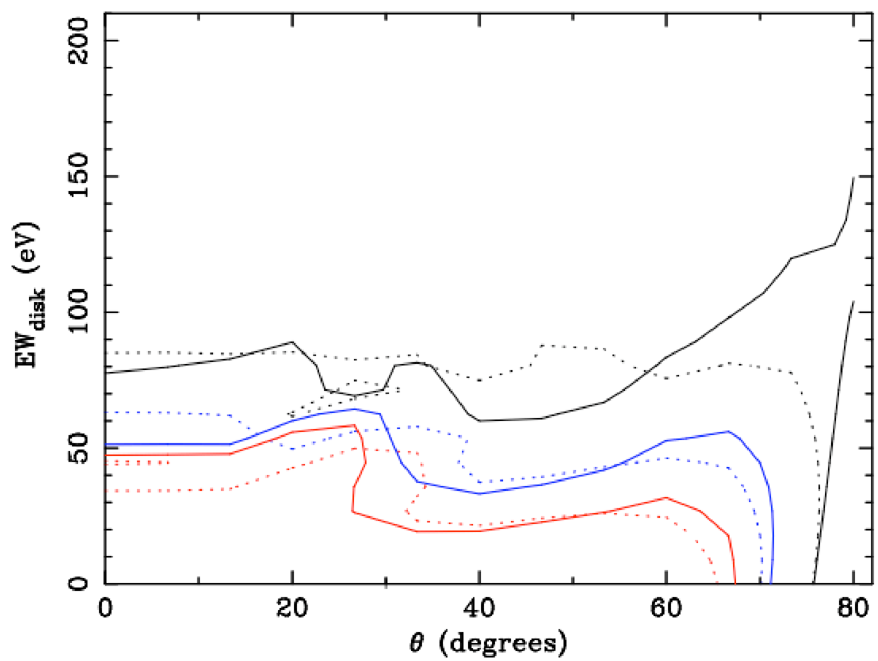
The continuum luminosity is LOW at ~ 3 x 10^{41} erg/s.

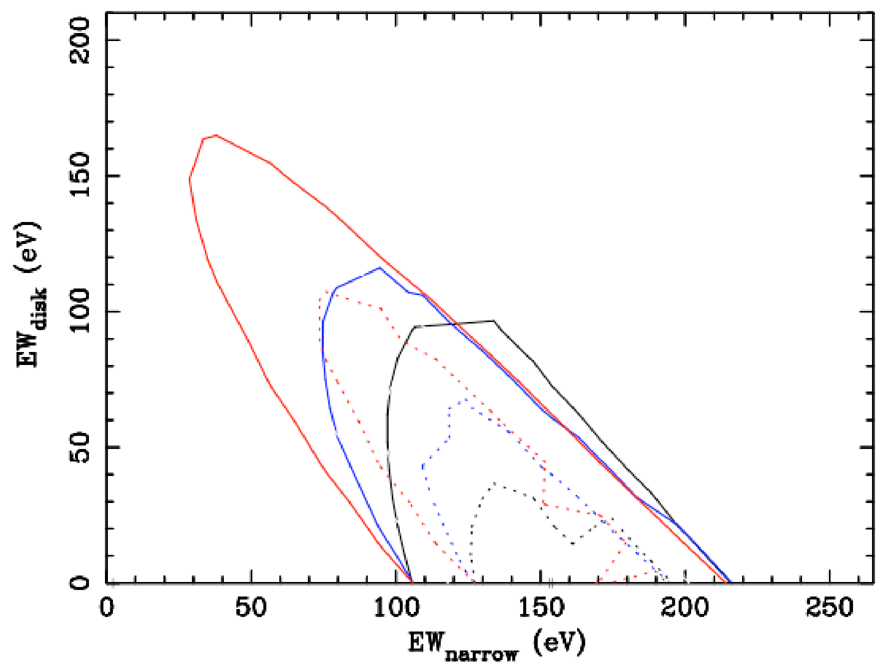
NGC 3227: Relativistic Line EW versus Distant-Matter Line Confidence Regions



- *Contours are 99% confidence (dotted: 68%). Baseline model: emissivity ~R^{-q} with q=2.0, Rin=6Rg, Rout=400Rg.*
- *Left: a/M = 0, 30 degrees (black); a/M=max, 30 degrees (blue); a/M=max, 60 degrees (red).*
- *Right: ALL a/M = 0, 30 degrees; Baseline model (black); Rin=100Rg (blue); q=0.5 (red).*

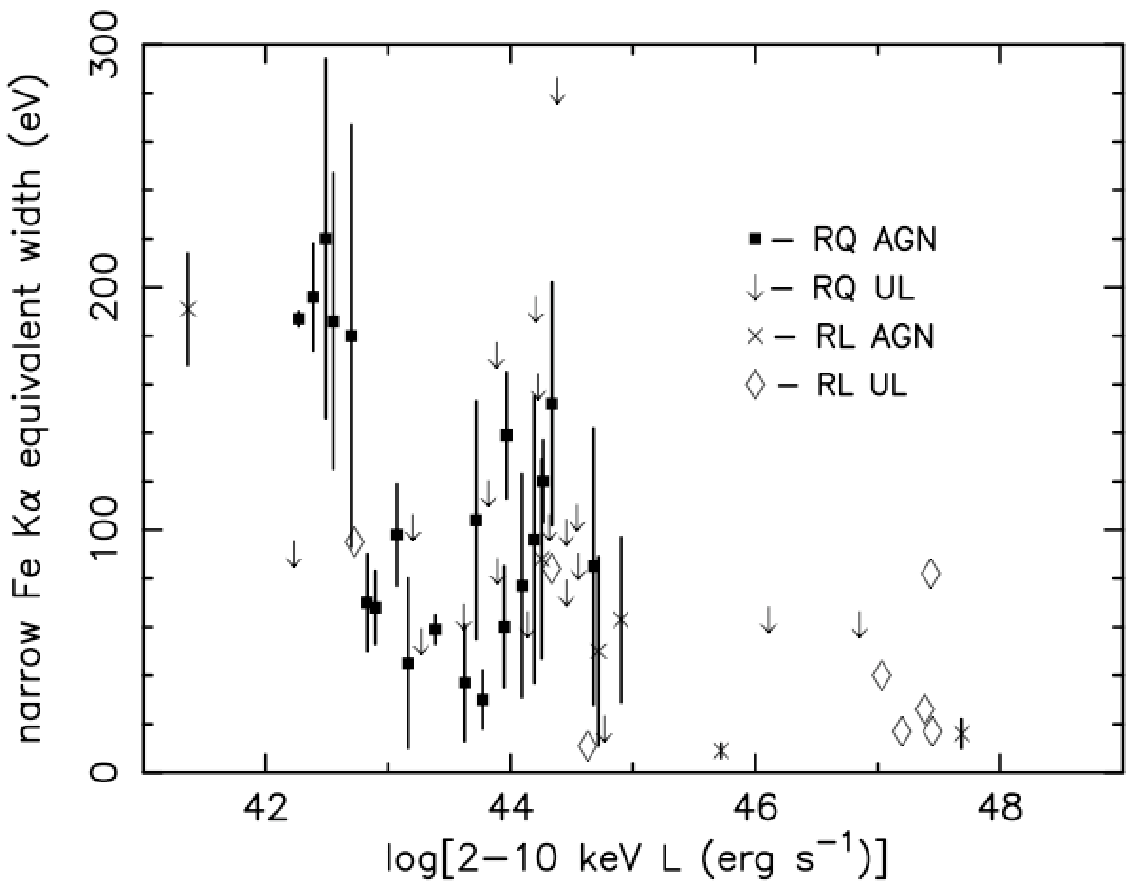
NGC 3227: Relativistic Line EW and Disk Inclincation Angle Confidence Regions





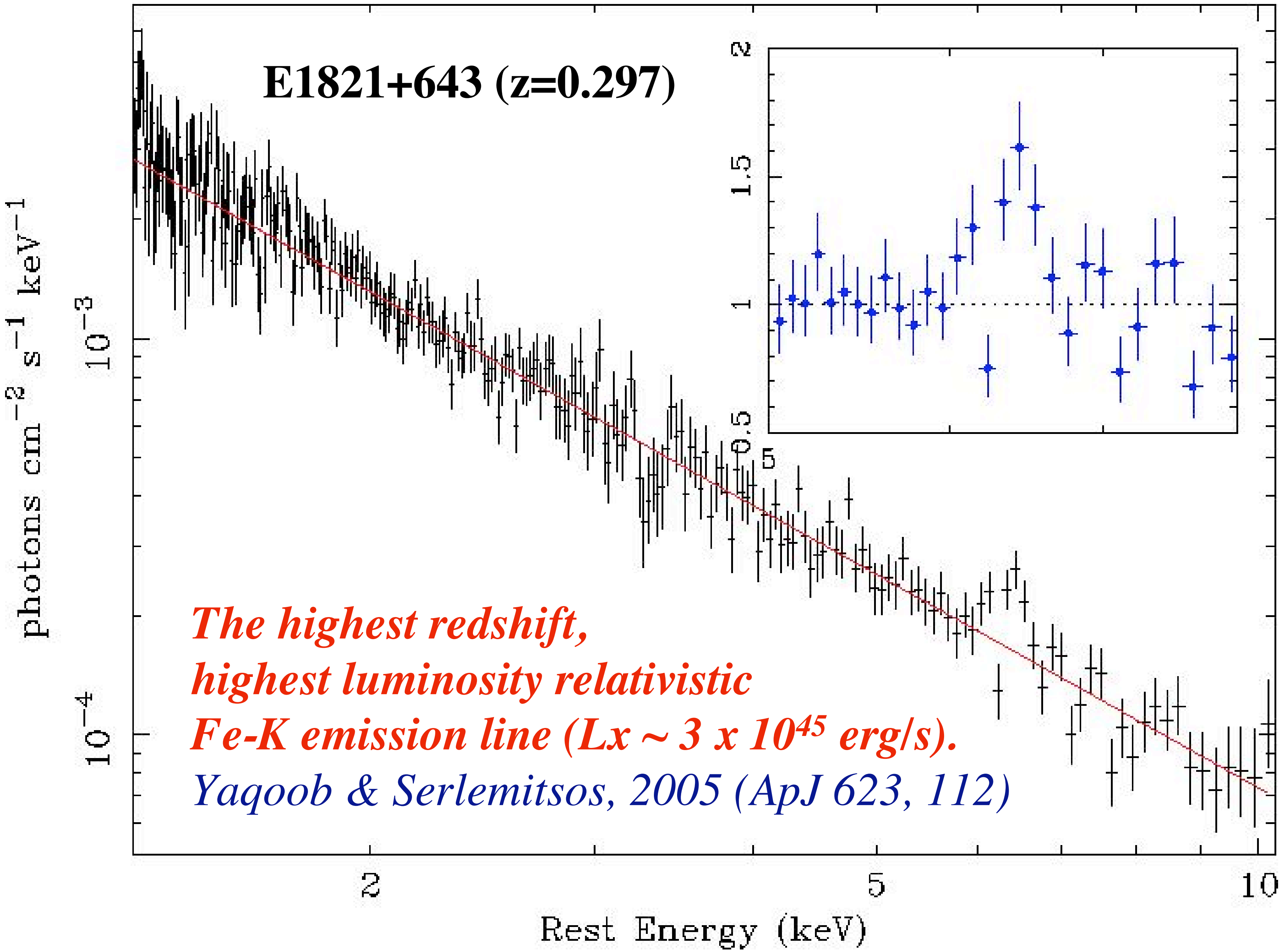
- *Same baseline parameters as before; Narrow Fe K line intensity, intrinisc width, and centroid energy FREE.*
- *Left: 68%, 90%, 99% confidence contours; DASHED: a/M=0, SOLID: a/M = max.*
- *Right: ALL a/M = 0, 30 degrees; Baseline model (black); Rin=100Rg (blue); q=0.5 (red).*

Does Fe K Line Emission Vanish in High-Luminosity AGN (X-ray Baldwin Effect)?

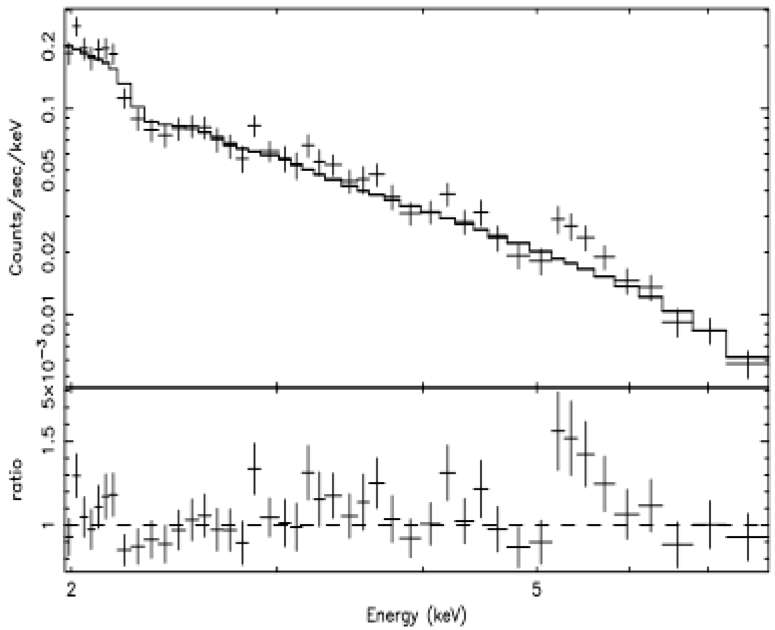


Plot from Page et al. 2004

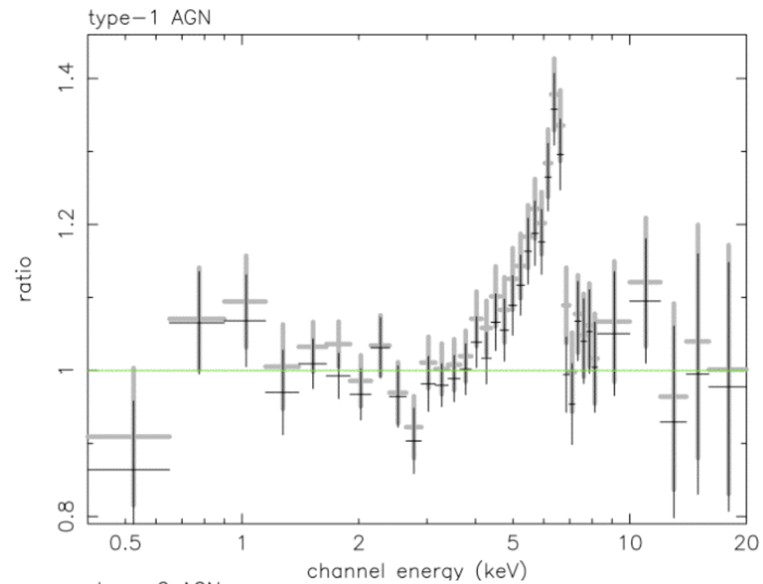
- Many reports of XBE; Iwasawa & Taniguchi 1993; Nandra et al. 1997; Reeves et al. 2000; Dewangan et al. 2002; Page et al. 2004 etc.
- Sample compositions are arbitrary.
- High Lx sources are rarer and usually RL.
- Effect of continuum variability with no line response in single sources?
- Separation of broad & narrow components?
- Important counter examples exist!…

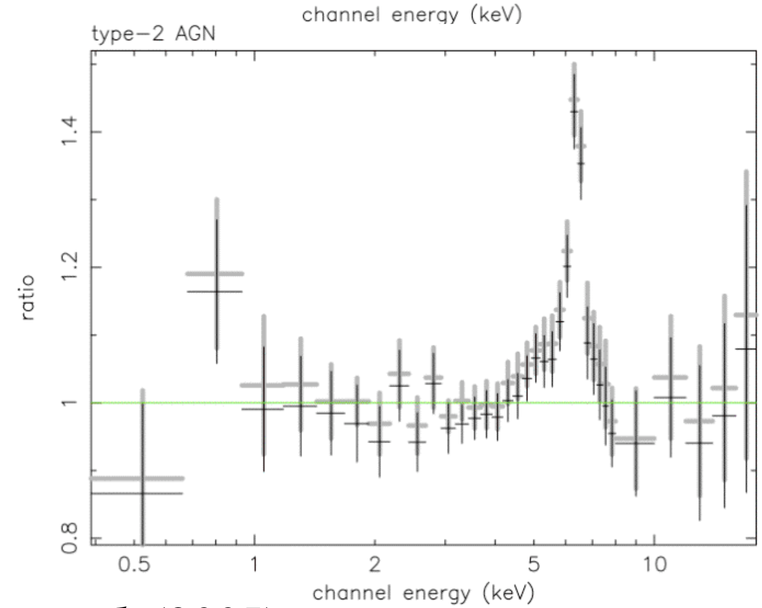

E1821+643 (z=0.297)
photons cm^{-2} s^{-1} keV^{-1}
10^{-3}
10^{-4}
2
5
10
Rest Energy (keV)
2
1.5
1
0.5
5
The highest redshift,
highest luminosity relativistic
Fe-K emission line (Lx ~ 3 x 10^{45} erg/s).
Yaqoob & Serlemitsos, 2005 (ApJ 623, 112)

More High Luminosity/High Redshift Broad Fe K Lines



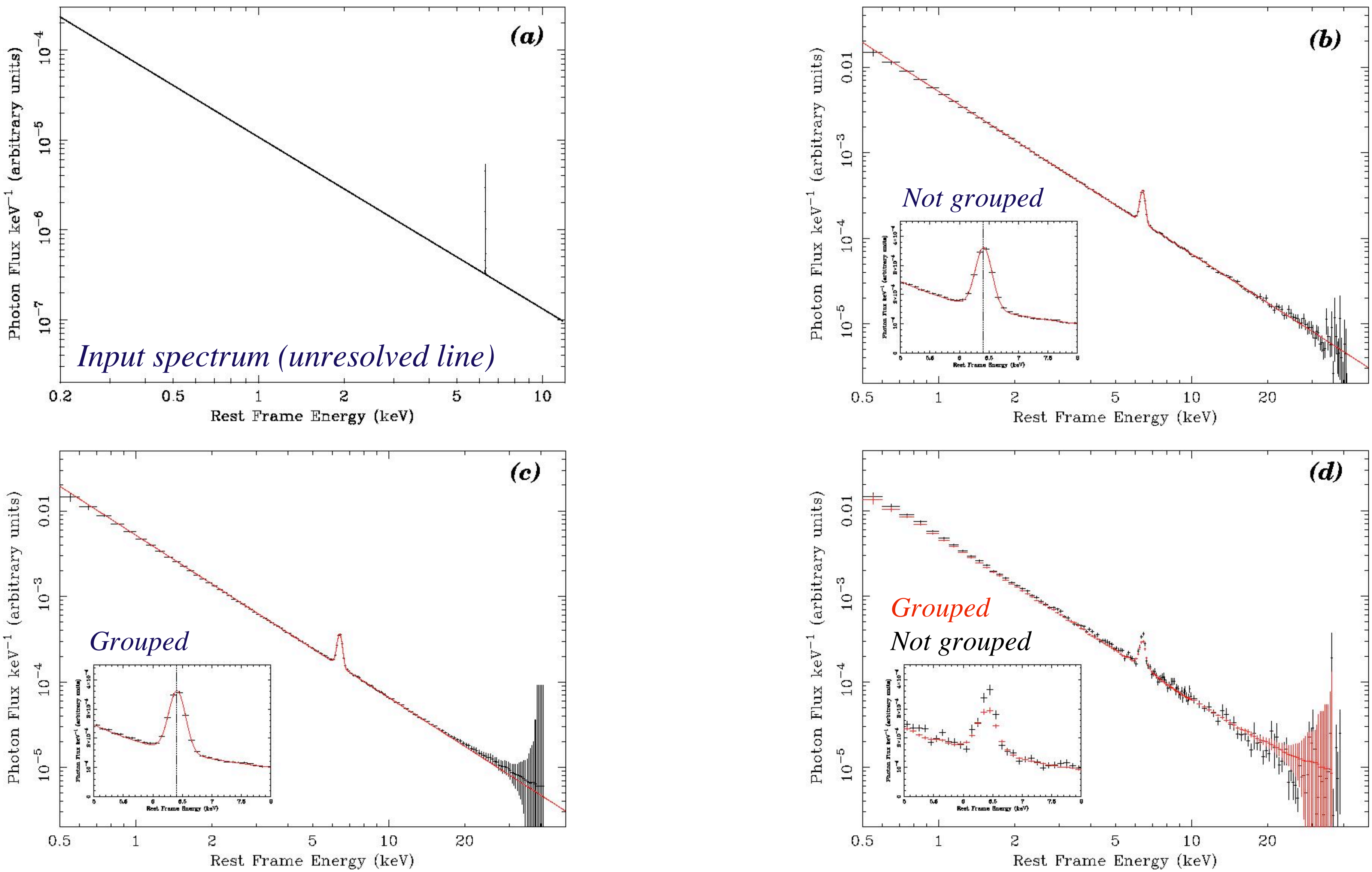
Q0056-363, z = 0.162, Lx ~ 2 x 10^{44} erg/s (Matt et al. 2005). EW ~150-300 eV, FWHM ~ 30,000 km/s.



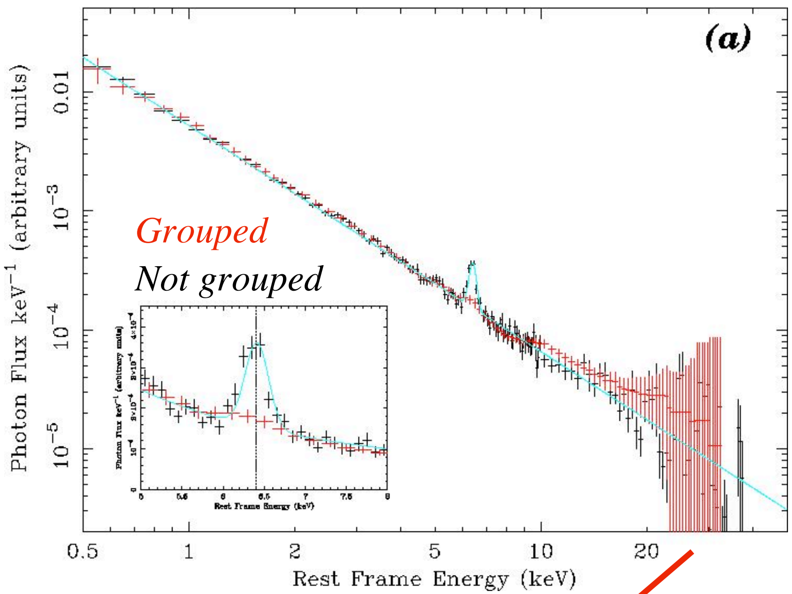


Co-added spectra from AGN in an XMM deep field (Lockman Hole) with z ~ 0-4.5 (mean ~2 for type 1 AGN, ~0.7 for type 2). From Streblyanska et al. (2005).

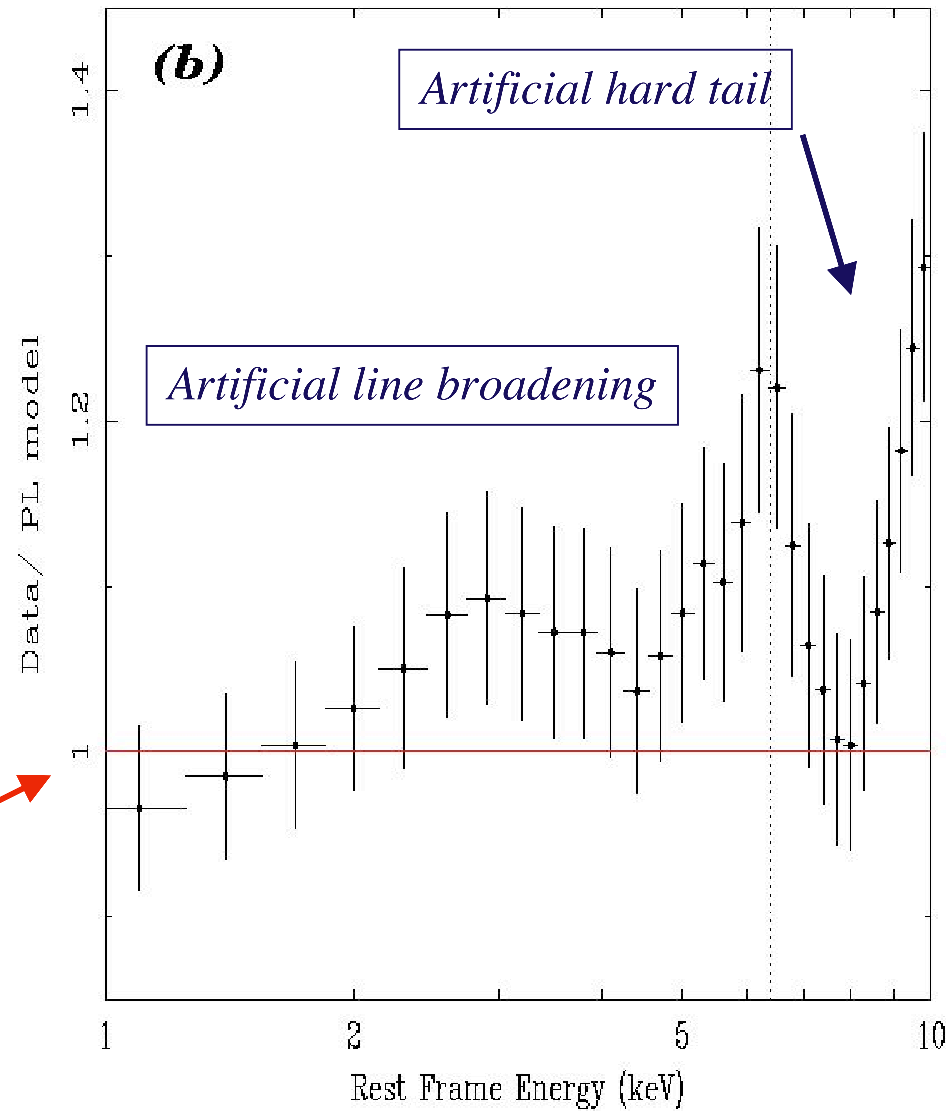
XMM simulations to test accuracy of standard procedures for co-adding X-ray spectra of weak, background-limited sources with a distribution in redshift.



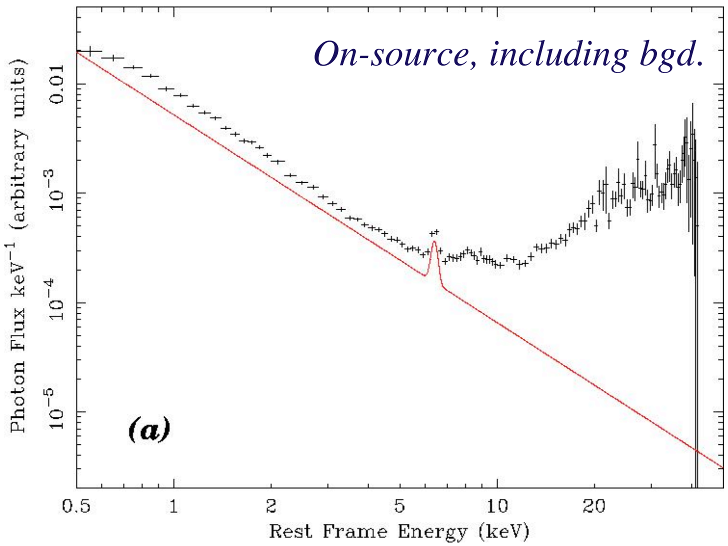
Spectral Distortion in Conventional Method for Co-adding X-ray Spectra



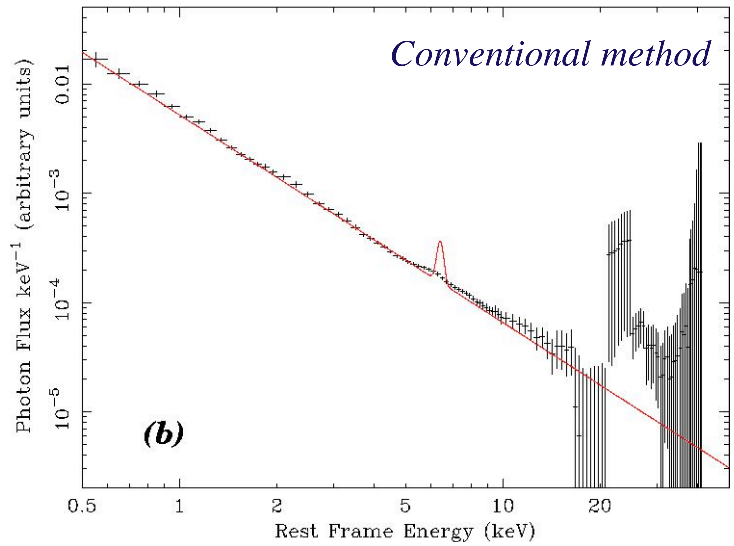
Average spectrum made from grouped individual spectra: ratio to a power law

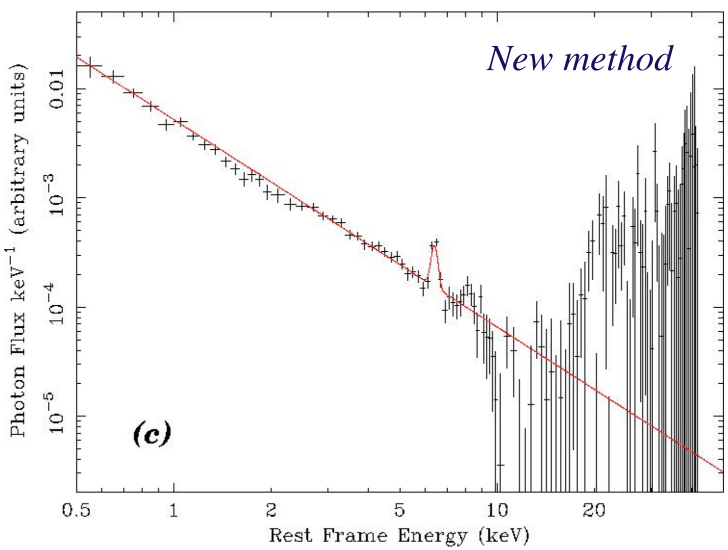


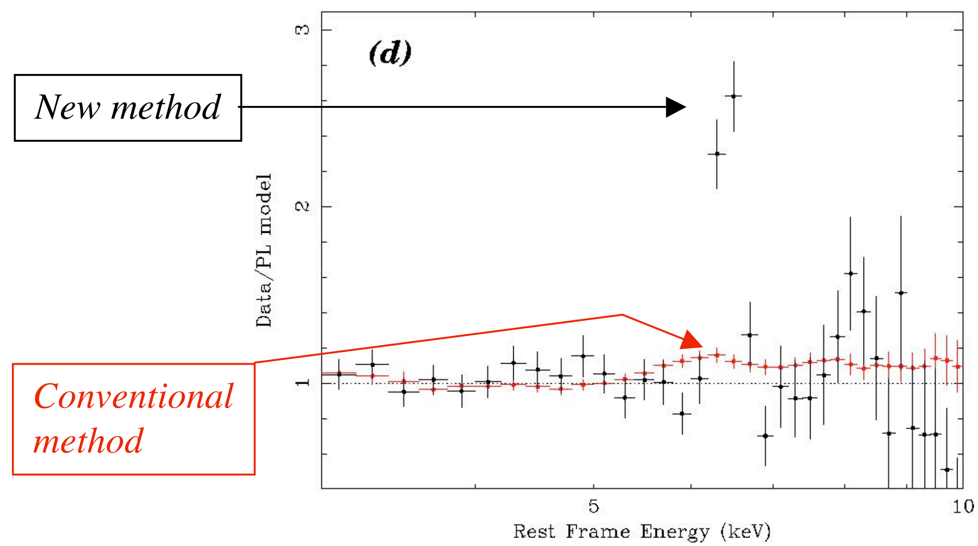
Improved Method of Co-adding Background-Limited Spectra with a Range in Redshift

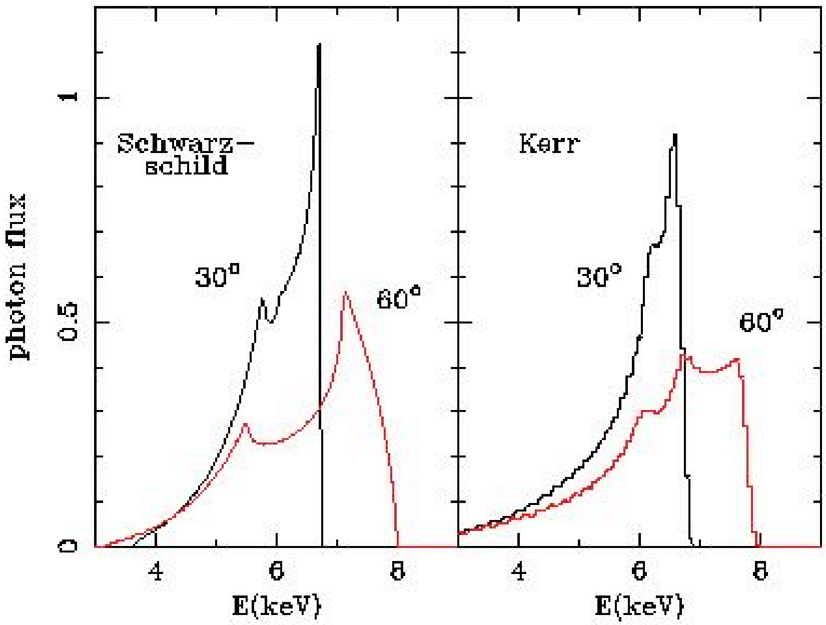


More details in IAUS 230, 461.









Comparison of Relativistic Line Profiles: Can we measure spin?

Inner Radius: 6 Rg (a=0), 1.24 Rg (a=0.9982)

Outer Radius: 400 Rg

Radial emissivity index, q=2.5 [R^{-q}]

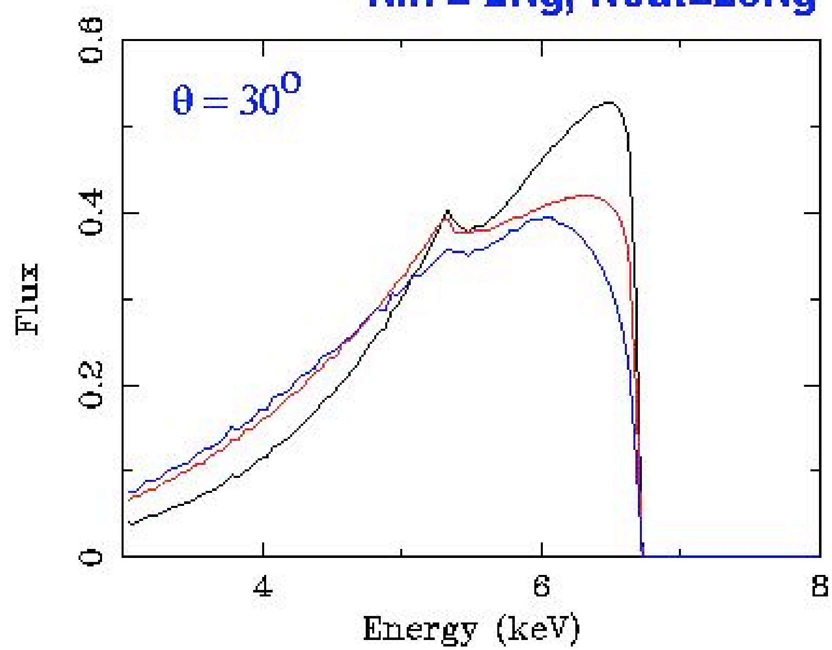
Can we distinguish between a=0 & a~1?

Black: a=0, q=3

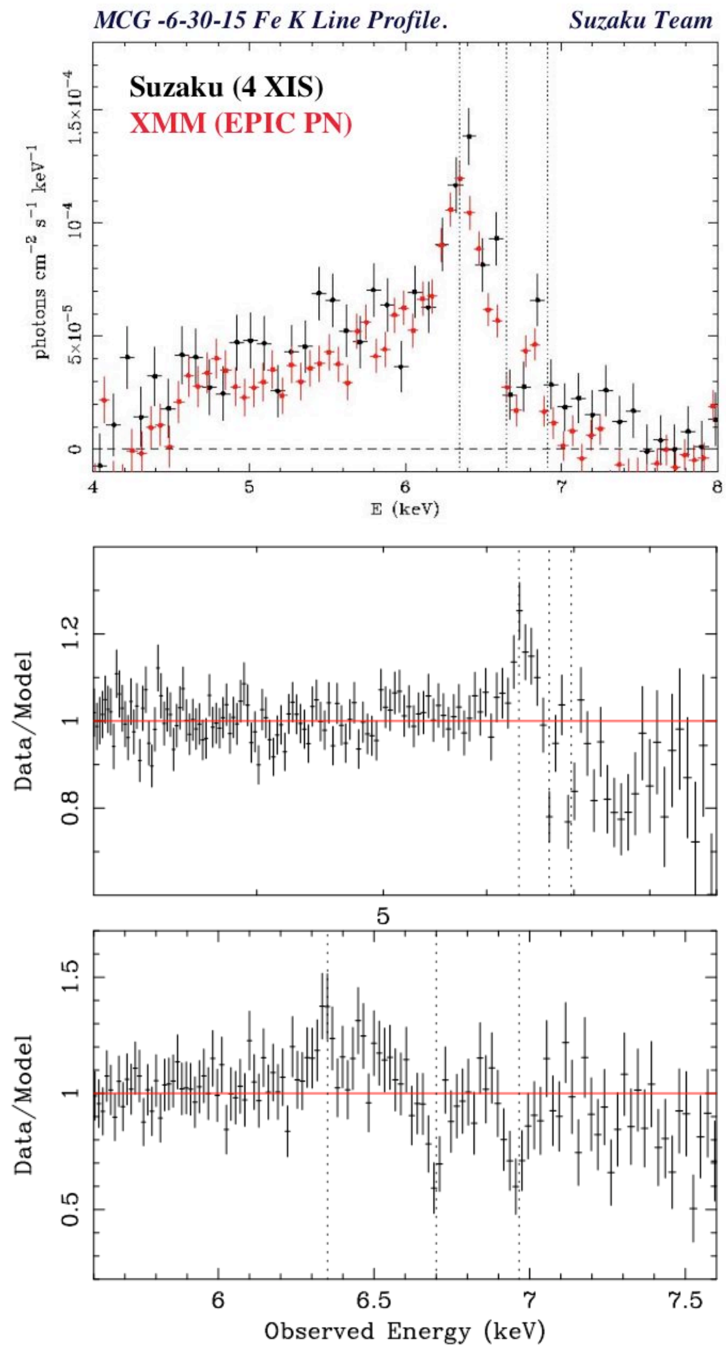
Red: a=0.9982, q=3

Blue: a=0, q=4

Rin = 2Rg, Rout=20Rg



Profiles calculated using Dovciak, Karas, Yaqoob (2003) model

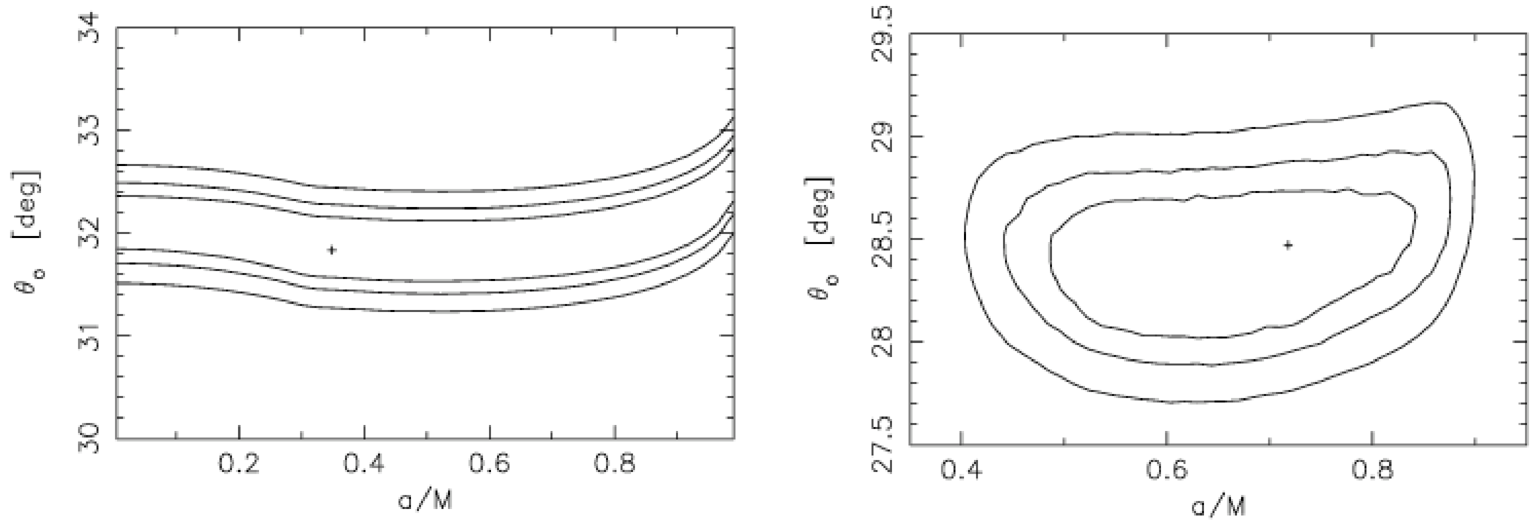


Fe K (& reflection continuum) variability needed to break the degeneracy…but clear & simple variability has not been observed. Although the lack of variability has been explained in terms of light-bending in strong gravity (Miniutti & Fabian 2004), it makes the future prospects of reverberation mapping of the disk even more challenging.

Left: Chandra HETG ~500 ks spectrum of MCG -6-30-15: high-resolution view of the complexity in the Fe K profile (see also Young et al. [2005]). NOTE: Absorption lines could be Fe XXV & Fe XXVI EITHER at z=0 OR outflow in the AGN with V~cz ~ 2325 km/s.

Black Hole Angular Momentum

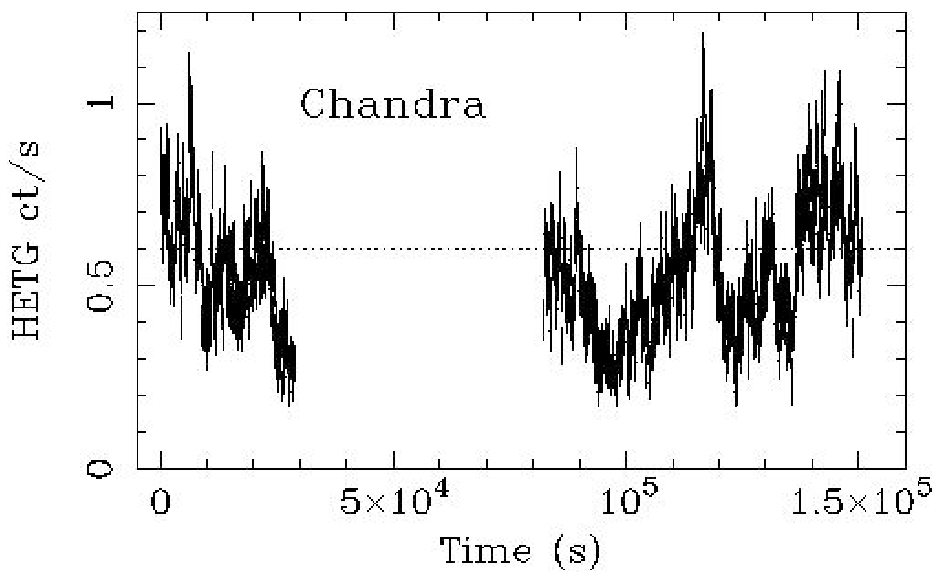
Black Holes have NO HAIR (only 3 measurable parameters): Mass, Spin Charge. -> Very important to measure spin but it has never been done without making some unproved assumptions.



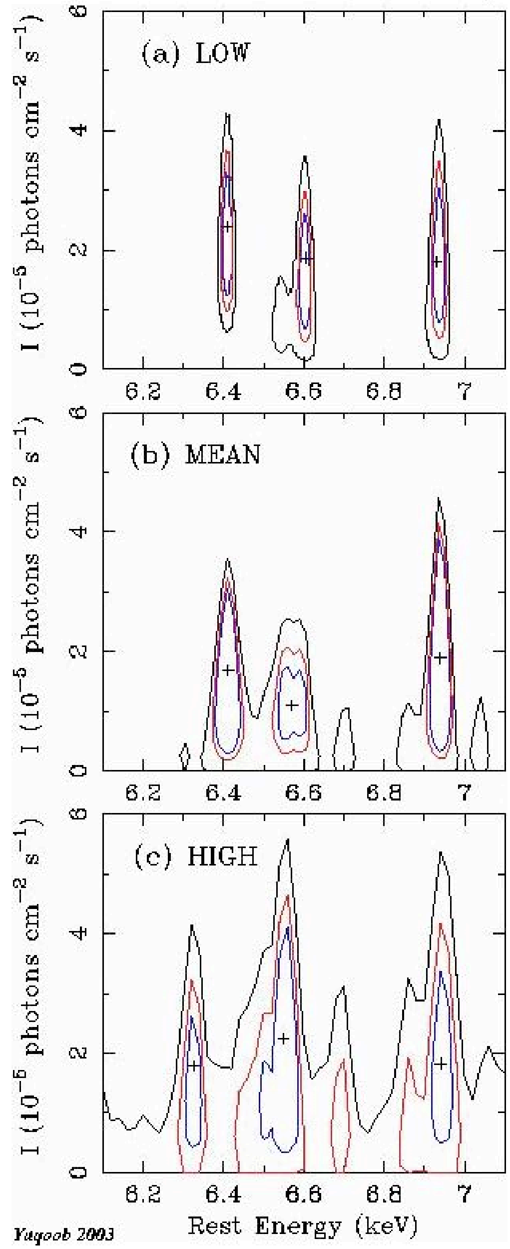
Dovciak, Karas, & Yaqoob 2004; a/M free parameter in models fitted to highest s/n (300 ks, XMM) MCG -6-30-15 broad Fe K line data available. So far a/M remains unconstrained (e.g. above contours from two different model assumptions give very different a/M). Beckwith & Done (2004) models also available to fit a/M in xspec. The measurement of a/M is a "holy grail" in the observational study of black holes & accretion (a/M ~1 accretion is ~6 times more efficient than a/M ~0).

Fe K line variability IS observed in some cases, but the data are sparse. However, the prospect of constraining the black-hole parameters with future instrumentation, independent of the unknown spatial distribution of the line emissivity on the disk is promising. Mkn 766? (Miller et al. 2006).

NGC 7314: Yaqoob et al. 2003



NGC 7314 – Rapid Variability of Fe –K Emission Complex



How to Measure Black-Hole Spin

Extremities (peaks) due to hotspot, $E_{\rm min}$ and $E_{\rm max}$, are a function of only:

- radius, r
- black-hole spin, a
- disk inclination angle, $\theta_{\rm obs}$
- rest energy, E_0, of the Fe Kα line (between 6.4–6.97 keV).

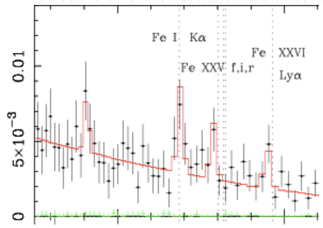
i.e.

$$E_{\rm min} = f(r, a, \theta, E_0) \tag{3}$$

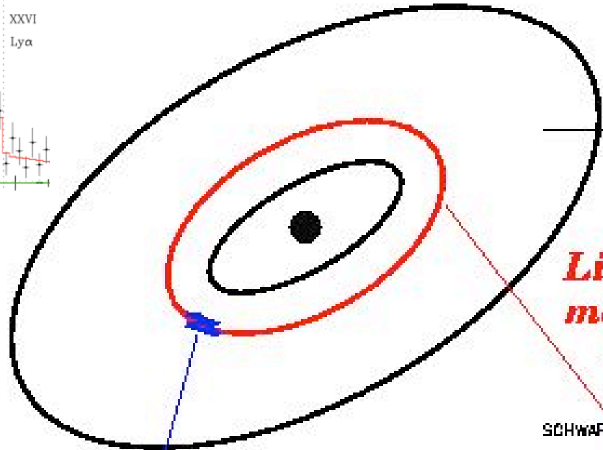
$$E_{\rm max} = g(r, a, \theta, E_0) \tag{4}$$

Measure $E_{\rm min}$, $E_{\rm max}$, $\theta_{\rm obs}$ from time-averaged profile; E_0 is 6.4–6.97 keV (or constrain from time-averaged profile); hence constrain r and a.

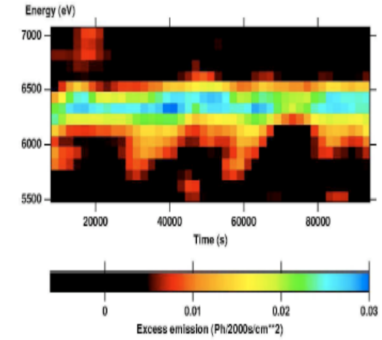
Constellation-X Simulations



NGC 7314: Yaqoob et al. 2003.



NGC 3516: Iwasawa et al. 2004

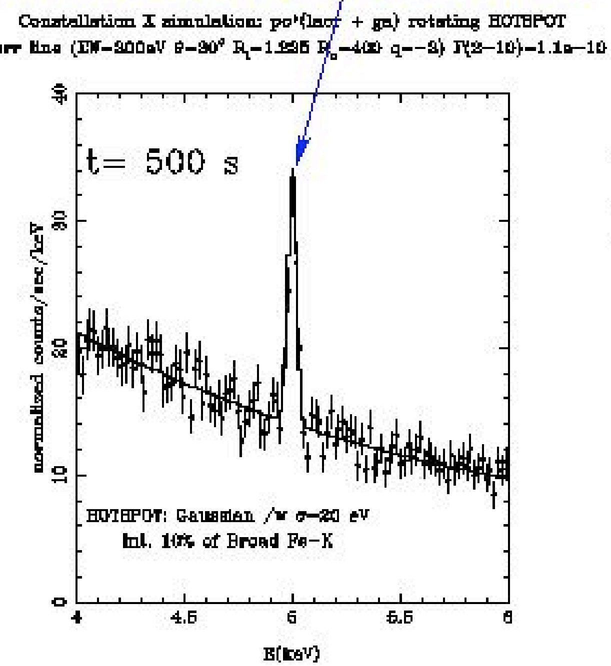


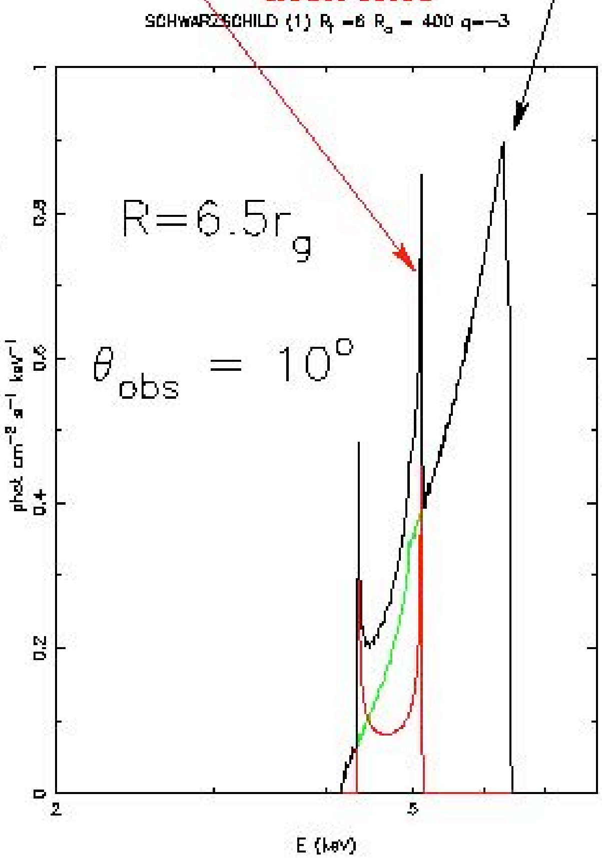
Line profile averaged over disk & time

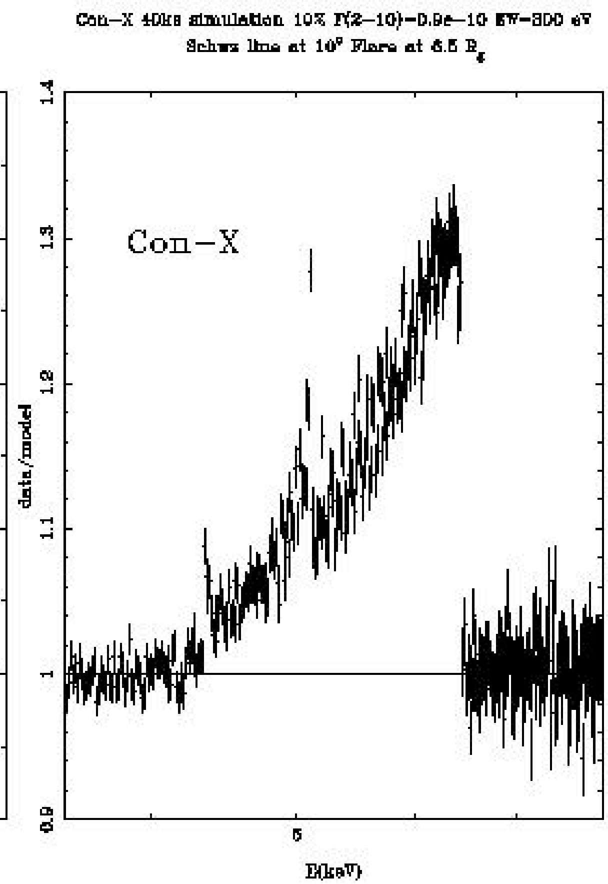
Line from annulus modulation of time-averaged disk line

Con-X 40 ks simulation

At high time resolution: measure hotspot -> BH mass







Yaqoob 2000-2003

Summary

- *Occurrence of relativistic Fe K lines in AGN consistency with theoretical expectations remains controversial due to model-dependence, especially for non-detections.*
- **Separation of relativistic and distant-matter Fe K lines challenging. Case of NGC 2992 - strong narrow line helps to constrain the broad line.**
- *Genuine non-detections of broad line (e.g. NGC 3227) do not necessarily rule out presence of a broad line and may still be consistent with theory.*
- **The broad Fe K emission line in the high-luminosity (L[2-10 keV] ~ 3 x 1045 erg/s), high z (0.297) quasar kills the "X-ray Baldwin Effect".**

  - So does Q0056-363.
- *Are broad Fe K lines common at high redshift? Standard methods for co-adding weak, background-limited spectra over a range of redshifts can introduce artificially broadening.*
- **BH angular momentum cannot be constrained from time-averaged Fe K line profiles (even in MCG -6-30-15) due to unknown spatial distribution of disk line emissivity.** *Need to combine time-averaged information with localized hotspot measurements to constrain a/M, independent of emissivity.*