The Origins, Applications and Mysteries of the Fluorescent Iron Line

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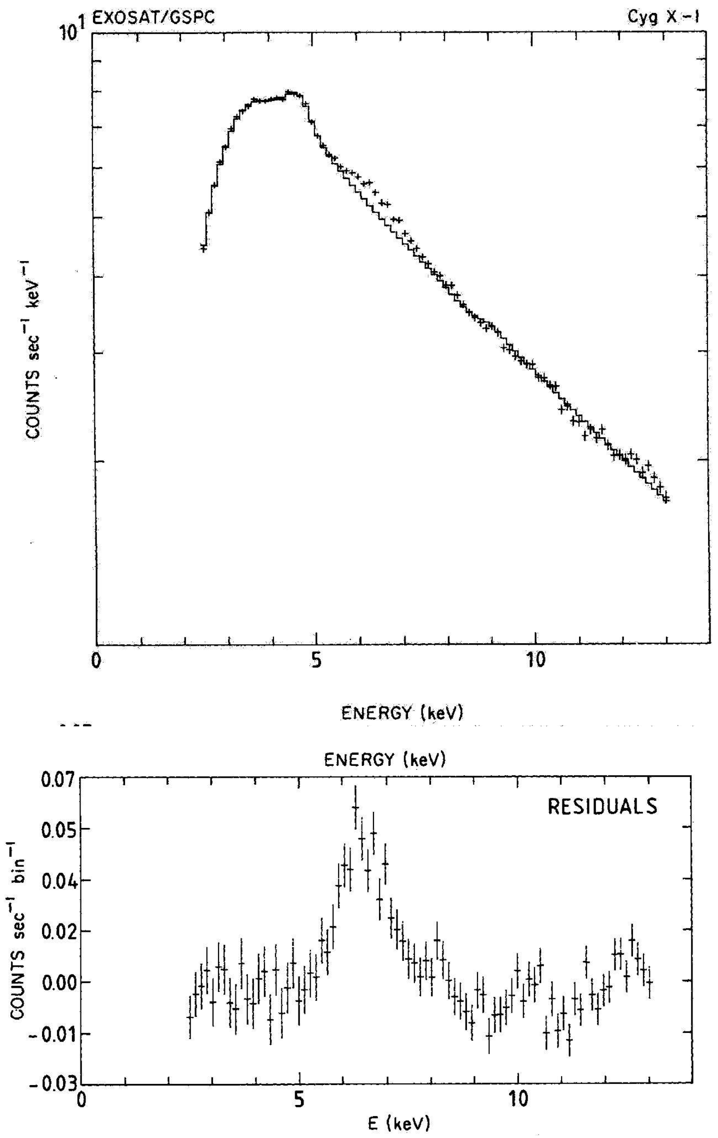
Outline

- Who? When? How? (history)
- What? (fluorescence)
- Where? (origins, disk models)
- Why? (spacetime/disk probing, reverberation)
- Wassup? (problems...)
- Really? (resolutions...)
- Won't he ever stop talking? (conclusions...)

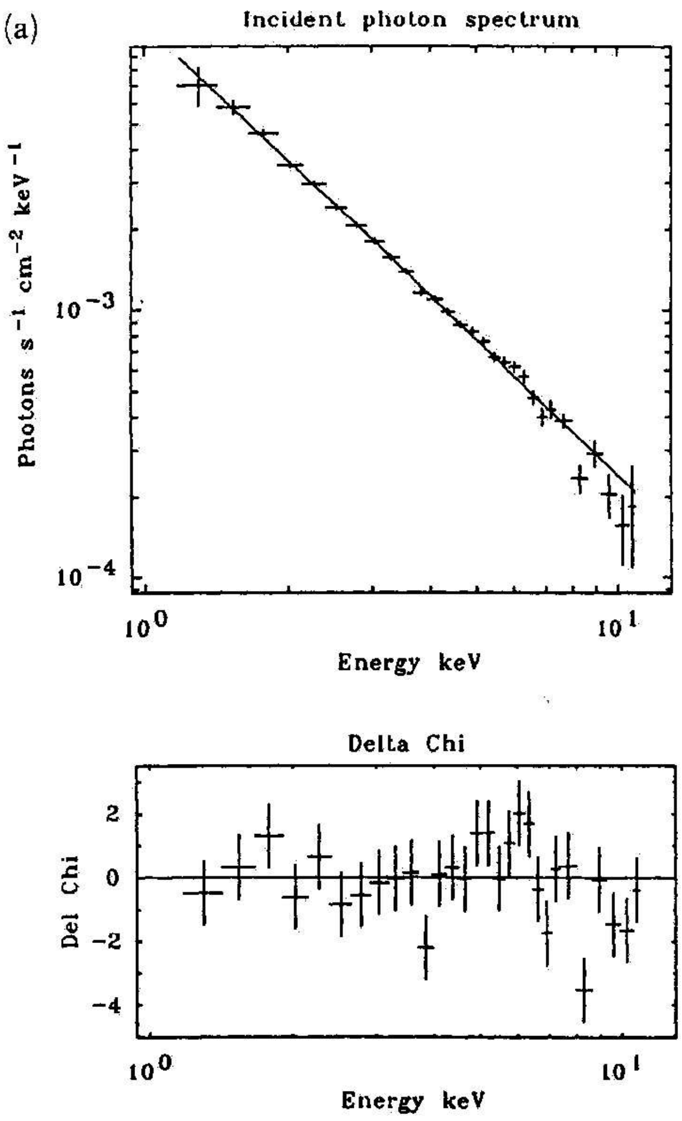
First Broad Iron Line



Cyg X-1

- Obs. by Barr, White, Page (1985) w/ EXOSAT
- Peak at $6.2\mathrm{keV}$
- EW $\sim 120\mathrm{keV}$
- Variability $\sim t_{\mathrm{orb}}$
- Interpreted by Fabian et al. (1989)

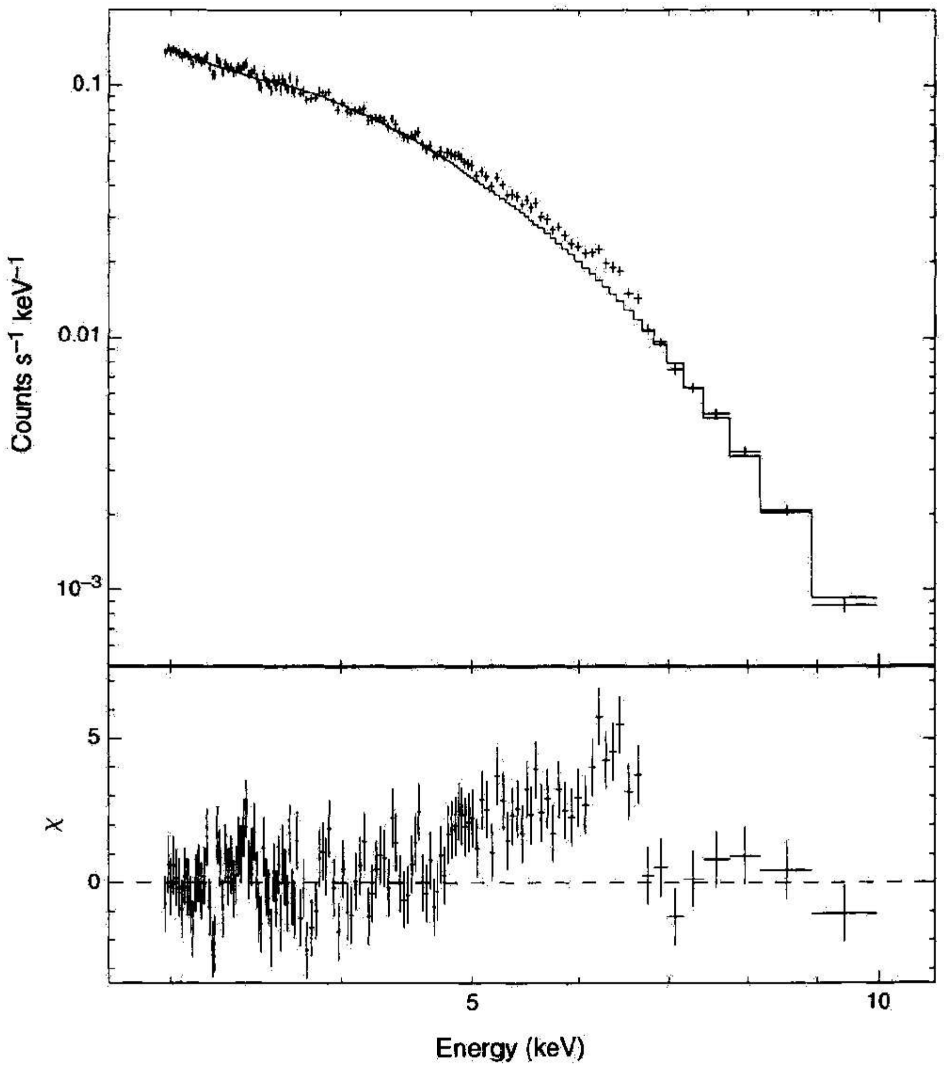
First Broad Iron Line from AGN



MCG-6-30-15

- Seyfert Type-1
- Nandra, Pounds, Stewart, Fabian, Rees (1989)
- 2-day EXOSAT observation
- Not interpreted as relativistic broadening

ASCA Revolution



MCG-6-30-15

- Tanaka et al. (1995)
- ASCA 4-day observation
- Beginning of detailed matching to models

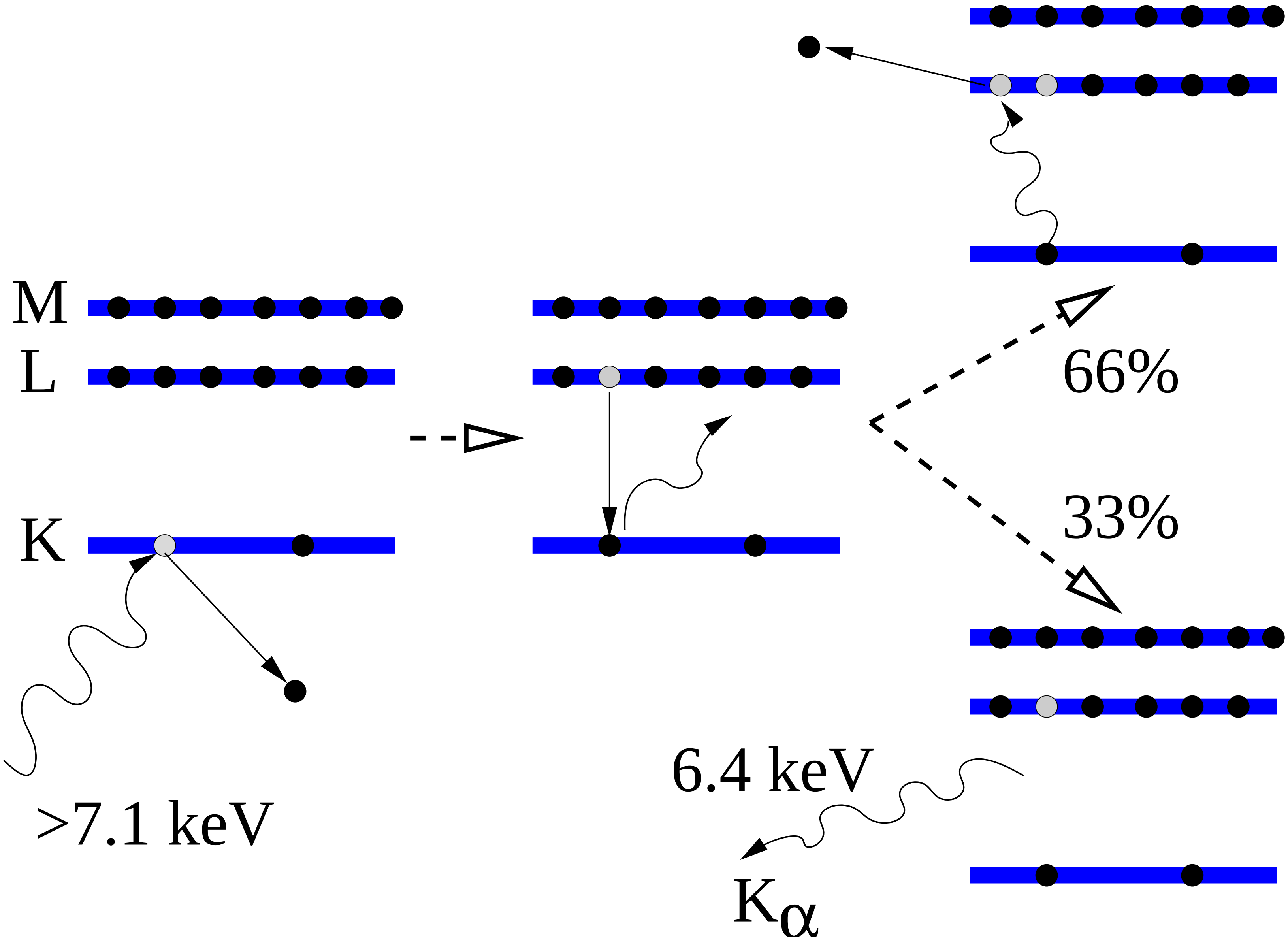
X-ray Observatories

Table 1
Observatories and instruments that have been important for studies of X-ray reflection from black hole sources

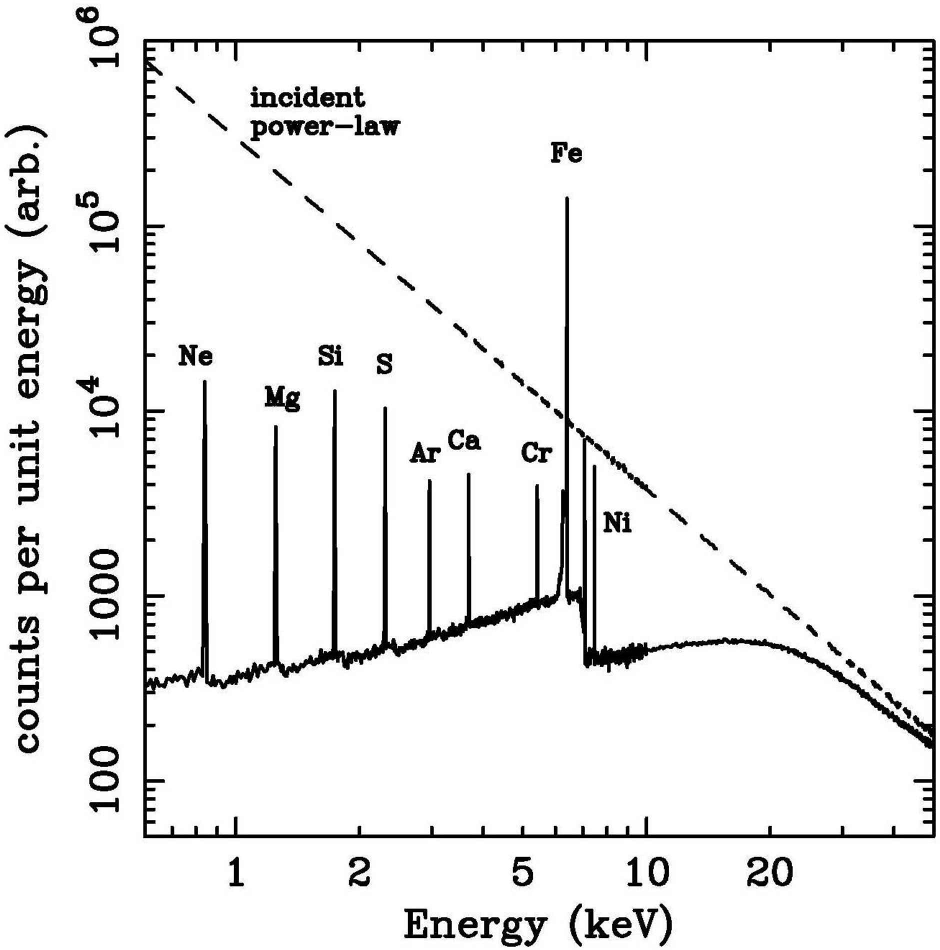
Observatory (lifetime)	Instrument	Area (cm^2)	Band pass (keV)	Resolution ($E/\Delta E$ at 6 keV)
EXOSAT (ESA)	GS	100	2–20	10
May 1983–April 1986	ME	1600	1–50	10
Ginga (Japan)	LAC	4000	1.5–37	10
February 1987–November 1991				
ASCA (Japan+NASA)	GIS	2×50 @ 1 keV	0.8–11	10
February 1993–March 2001	SIS	2×100 @ 6 keV	0.5–10	50
RXTE (NASA)	PCA	6500	2–60	10
December 1995–present	HEXTE	2×800	15–250	—
BeppoSAX (IT+NL)	LECS	22 @ 0.28 keV	0.1–10	8
April 1996–April 2002	MECS	150 @ 6 keV	1.3–10	8
	PDS	600 @ 80 keV	15–300	—
Chandra (NASA)	ACIS	340 @ 1 keV	0.2–10	50
July 1999–present	HETG	59 @ 1 keV	0.4–10	200
XMM-Newton (ESA)	EPIC-MOS	2×920 @ 1 keV	0.2–12	50
December 1999–present	EPIC-PN	1220 @ 1 keV	0.2–12	50

[Reynolds & Nowak (2003)]

$K\alpha$ **Fluorescence**



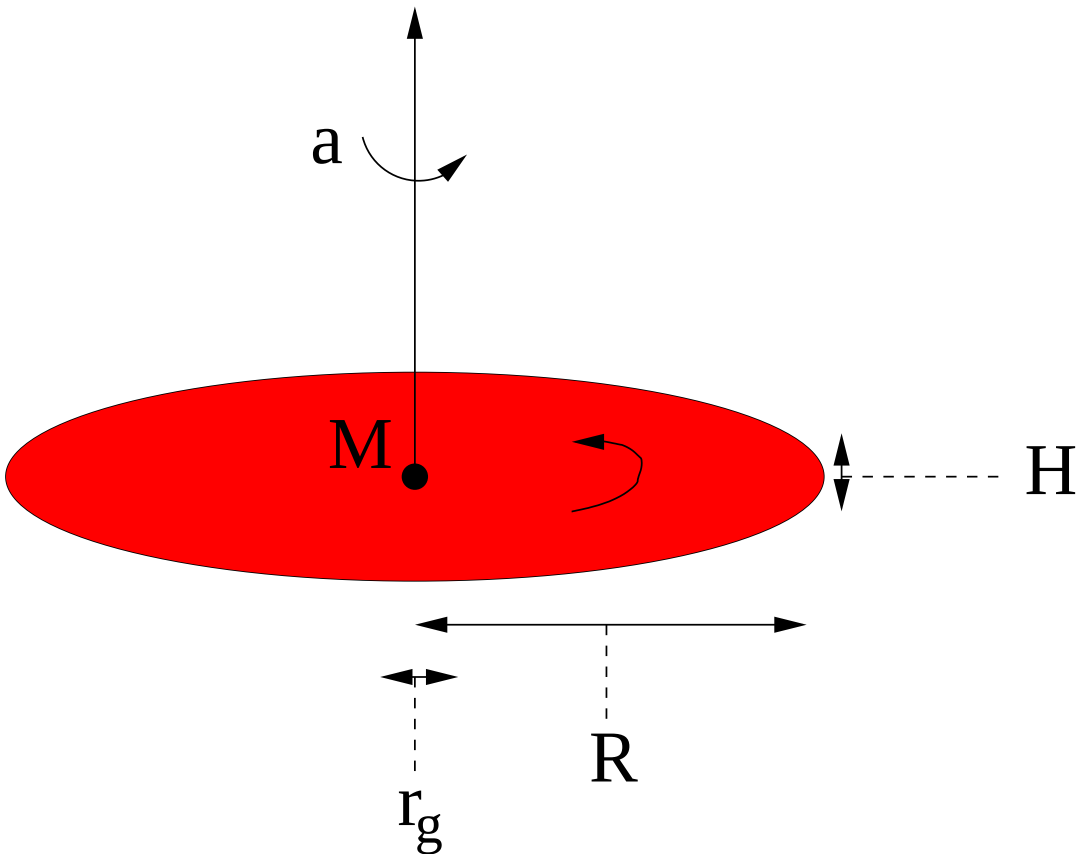
X-ray Reflection Spectrum



[Reynolds, Ph.D. Thesis (1996)]

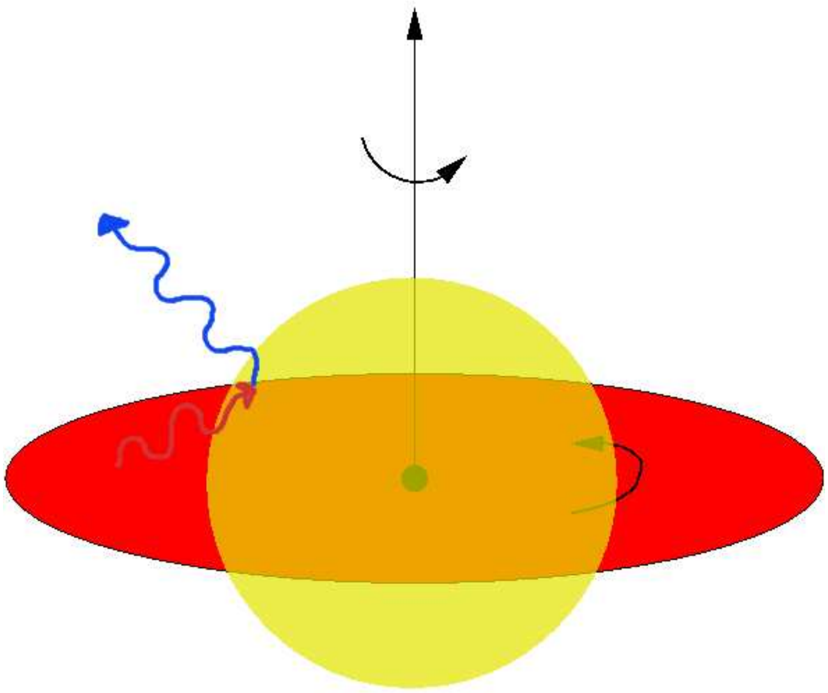
- Incident Flux: $F_N \propto E^{-\Gamma}$ (where $\Gamma = 2$ here);
- Cosmic Abundances: H+, He++, neutral metals;
- $K\alpha = 6.4 - 6.7$ keV ($\mathrm{Fe_I}$ to $\mathrm{Fe_{XXV}}$);
- $K\beta = 7.1$ keV ($\mathrm{Fe_I}$);
- Abs.Edge $= 7.1 - 7.8$ keV ($\mathrm{Fe_I}$ to $\mathrm{Fe_{XXV}}$);

Accretion Disk Models



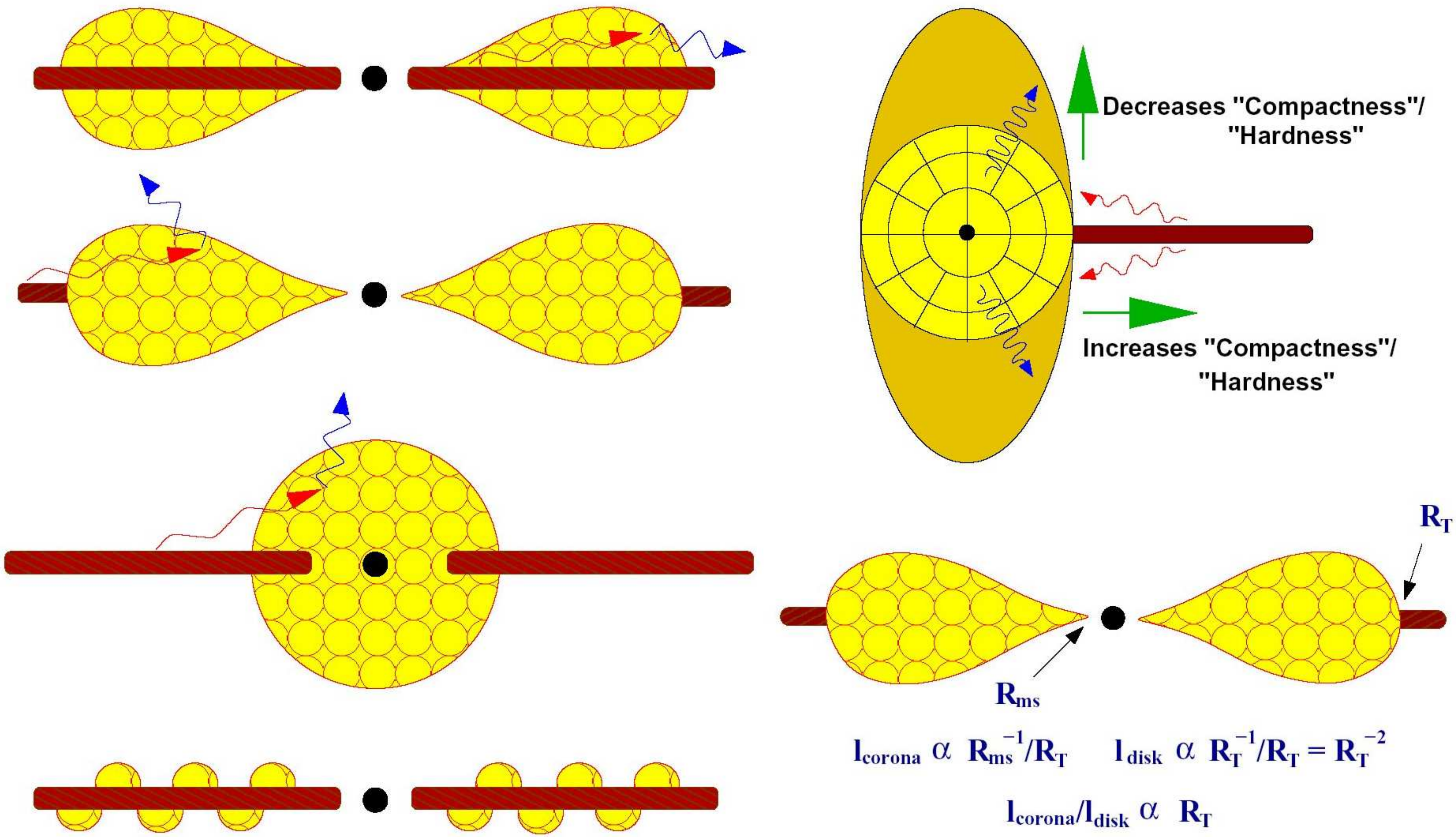
- $r_g/c = GM/c^3 \sim t_{\rm dyn} \sim \alpha\, t_{\rm therm} \sim \alpha\,(H/R)^2\, t_{\rm visc}$
- $t_{\rm dyn} = 310 \left[a + (r/r_g)^{3/2}\right] \frac{M}{10^7 M_\odot}$ sec.
- $T \propto M^{1/4} \quad , \quad L = \eta \dot{M} c^2$

Accretion Disk Models



- Thermal, black-body spectrum from disk;
- Inverse Compton (IC) scattering up-scatters thermal γ's into power-law X-ray;
- X-rays $\rightarrow K\alpha$ in disk;
- IC cut-off at $E \gtrsim 100\mathrm{keV}$ when $E_\gamma \simeq E_{e^-} \Rightarrow T_{\mathrm{corona}}$
- IC cools corona

Corona Models

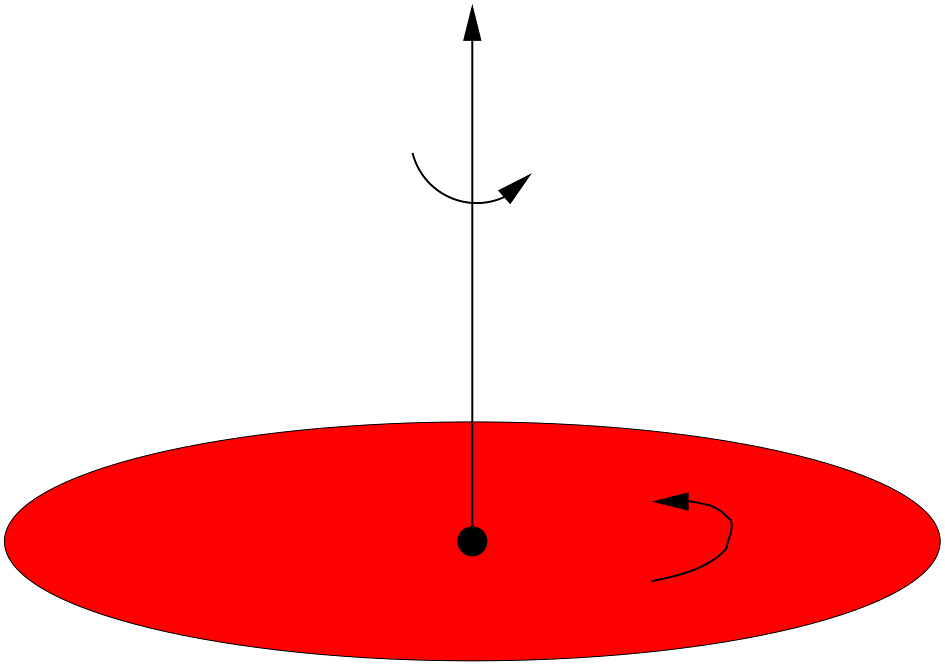


[Nowak astro-ph/0207624]

Types of Accretors

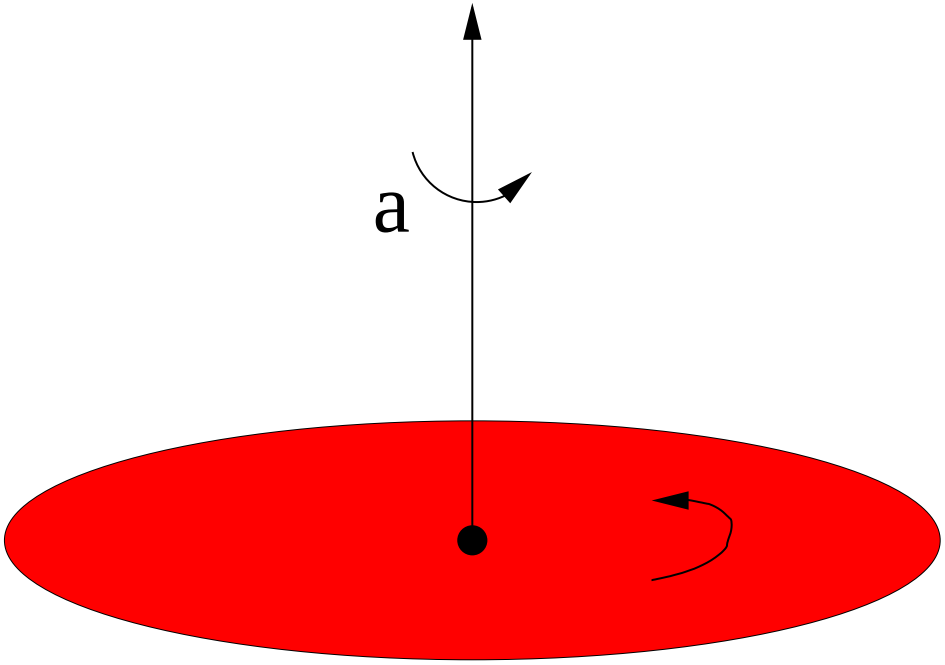
	AGN	GBHC's
$\mathbf{M} =$	$10^6 - 10^9 M_\odot$	$1 - 100 M_\odot$
$T \propto M^{-1/4} \sim$	$10^5 - 10^6 K$	$10^7 K$
Spectra	Opt./UV BB + P-L tail	X-ray BB + P-L tail
$t_{\rm dyn} \sim$	minutes to hours	$t_{\rm dyn} =$ milliseconds
$t_{\rm obs} \sim 1{\rm ks} \sim$	$t_{\rm therm}$	$t_{\rm visc}$

Numerical Models for Fitting



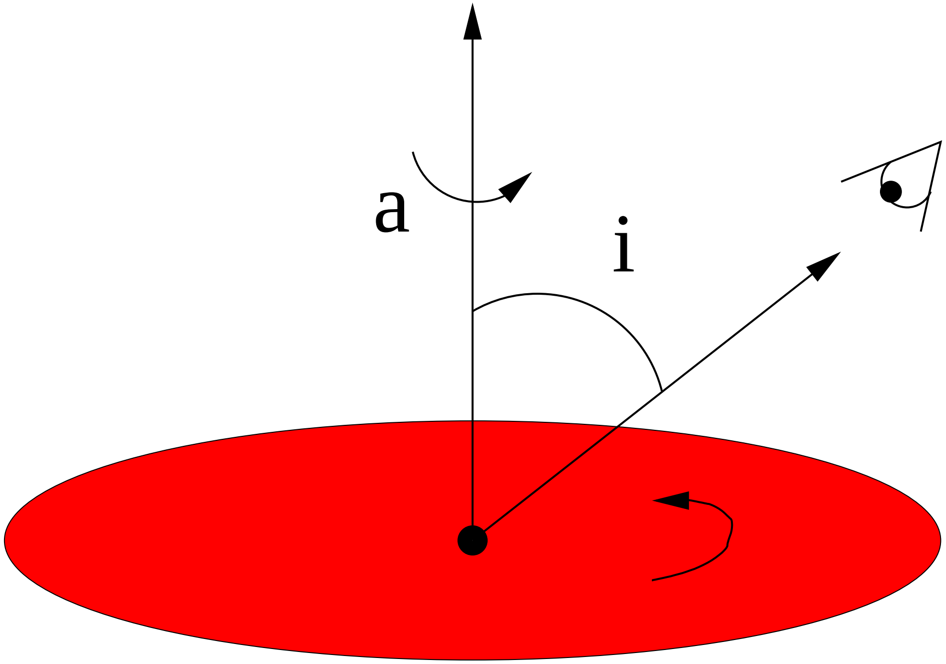
- Thin disk,
  cosmic abundances...

Numerical Models for Fitting



- Thin disk,
  cosmic abundances...
- BH spin: $0 < a \leq 0.998$

Numerical Models for Fitting



- Thin disk,
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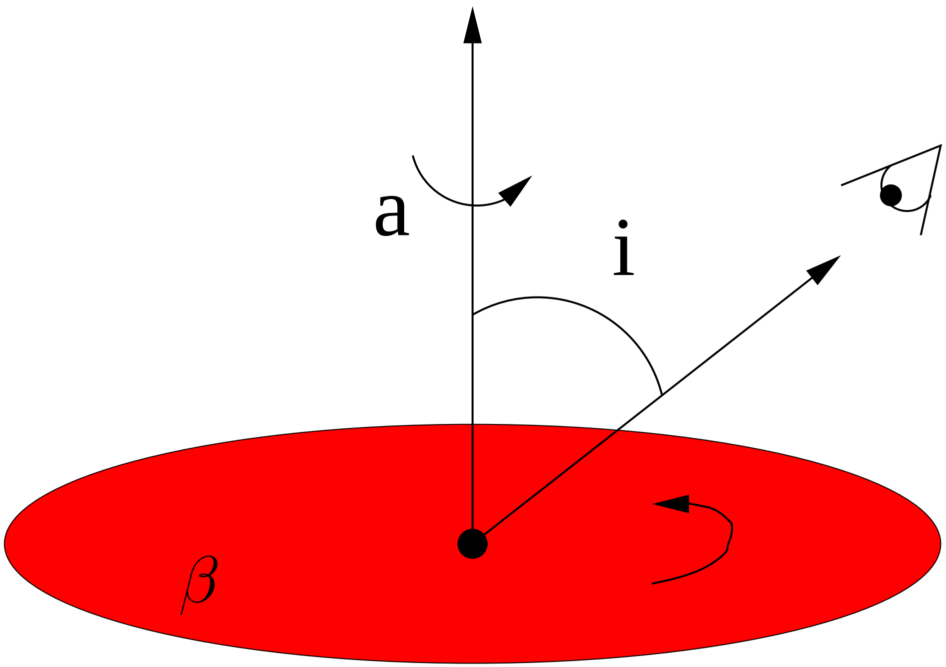
- BH spin: $0 < a \leq 0.998$
- Inclination angle: i

Numerical Models for Fitting



- Thin disk,
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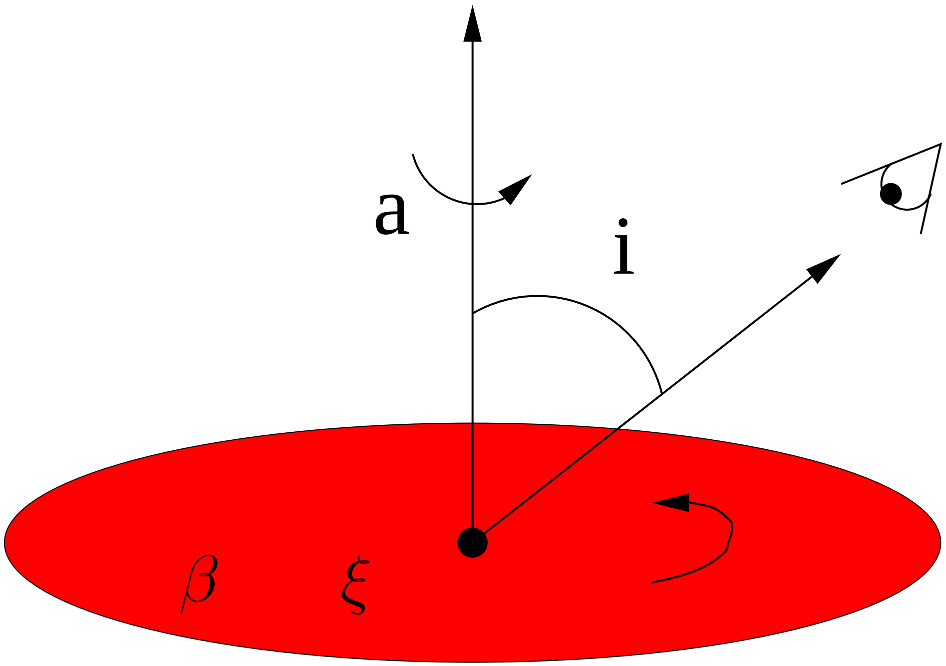
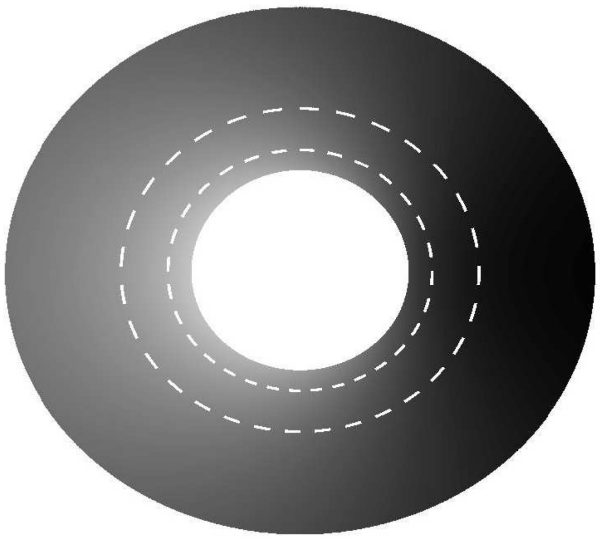
- Inclination angle: i
- Emissivity (β): $I_e \propto {r_e}^{-\beta}$

Numerical Models for Fitting

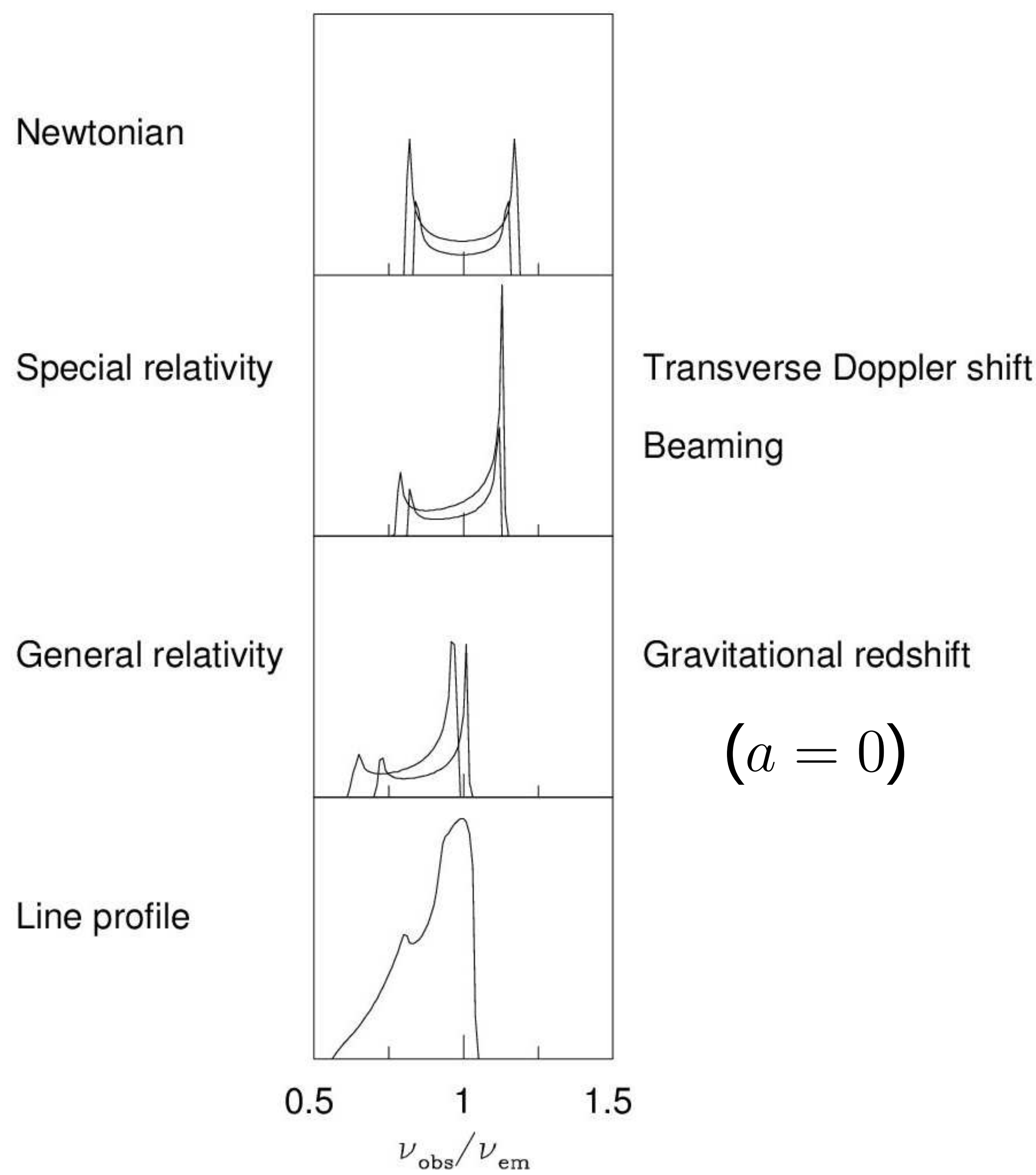


- Thin disk,
  cosmic abundances...
- BH spin: $0 < a \leq 0.998$
- Inclination angle: i
- Emissivity (β): $I_e \propto {r_e}^{-\beta}$
- Ionization Parameter ξ

Relativistic Effects

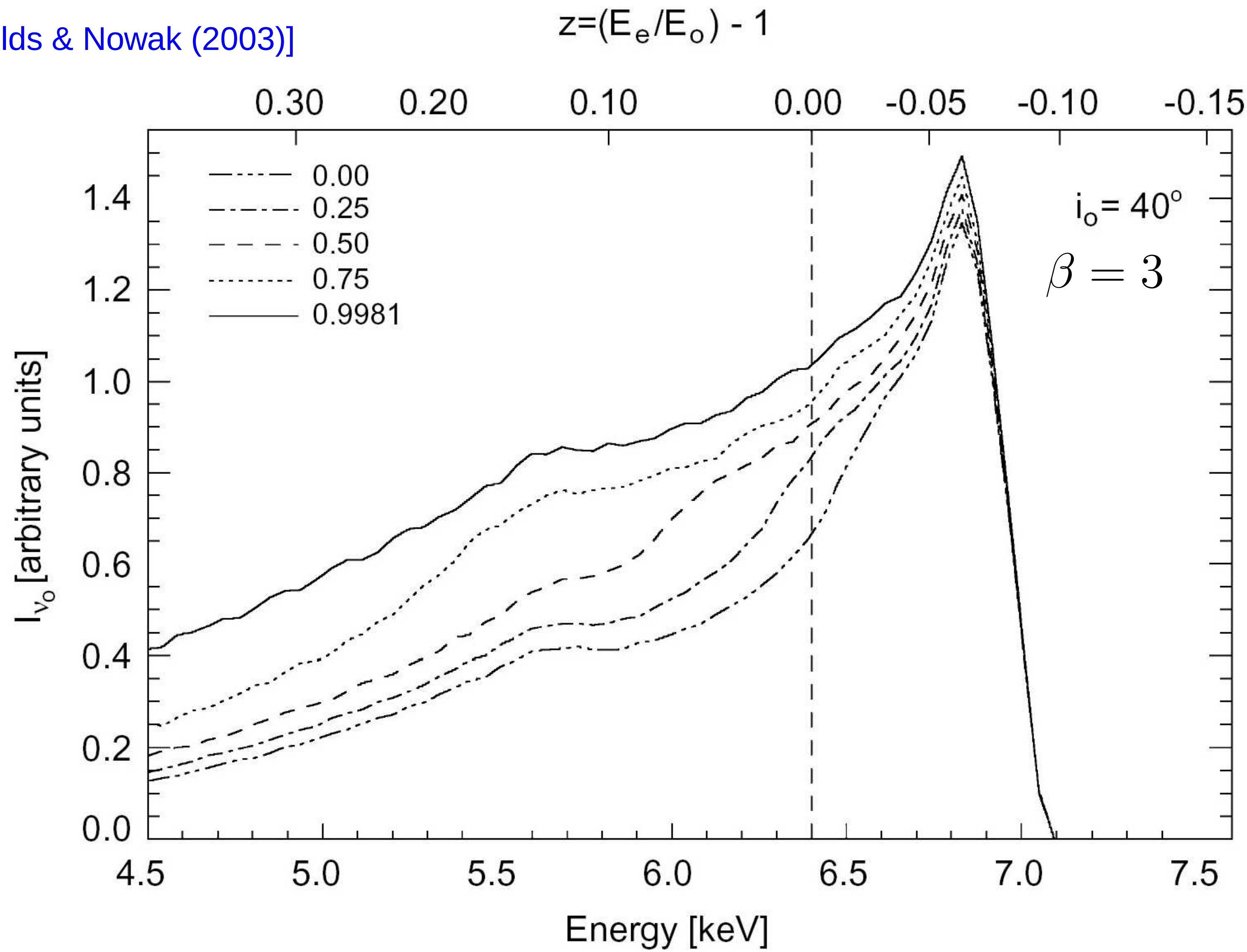


[Fabian, Iwasawa, Reynolds, Young (2000)]



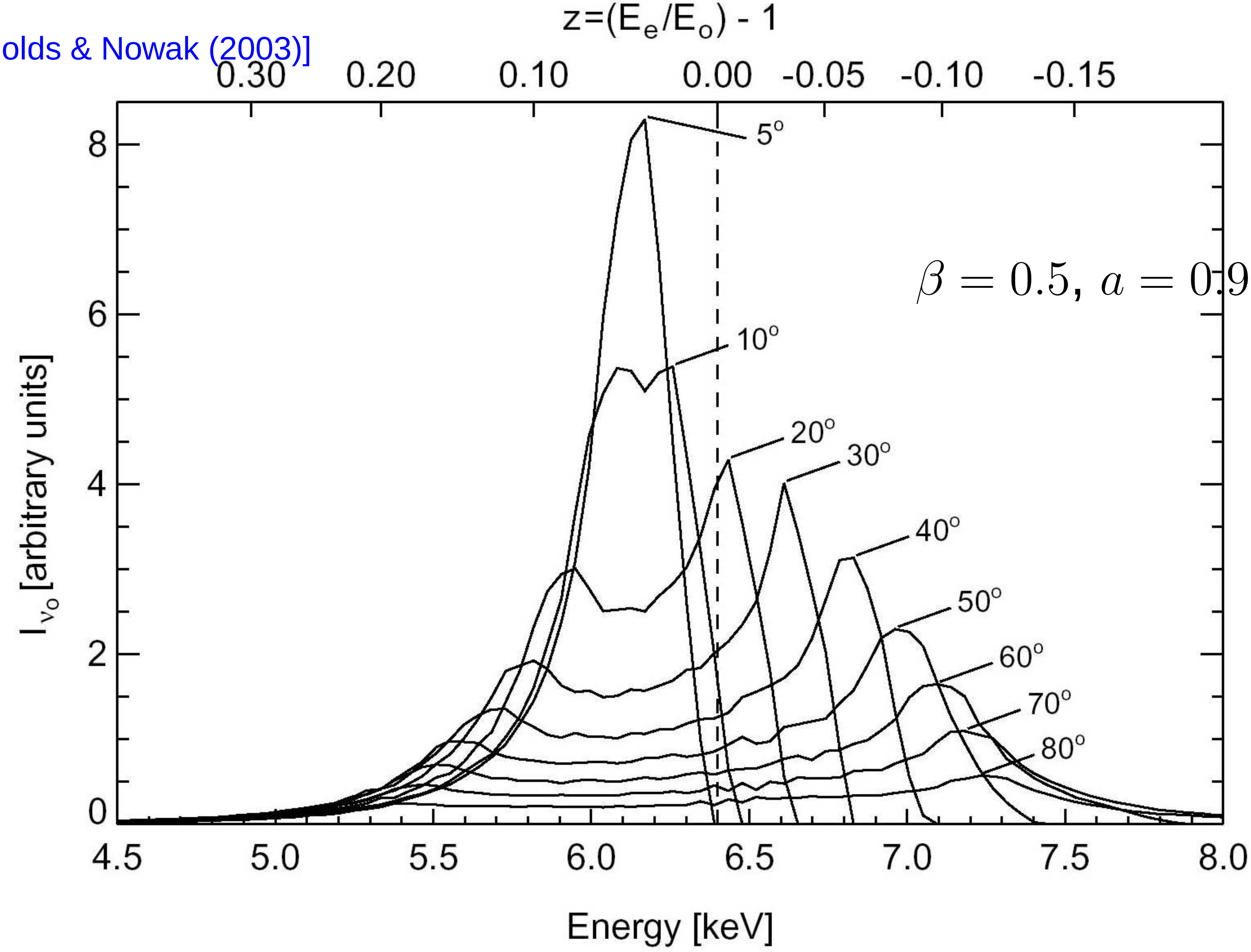
Dependence on BH Spin

[Reynolds & Nowak (2003)]



Dependence on Inclination

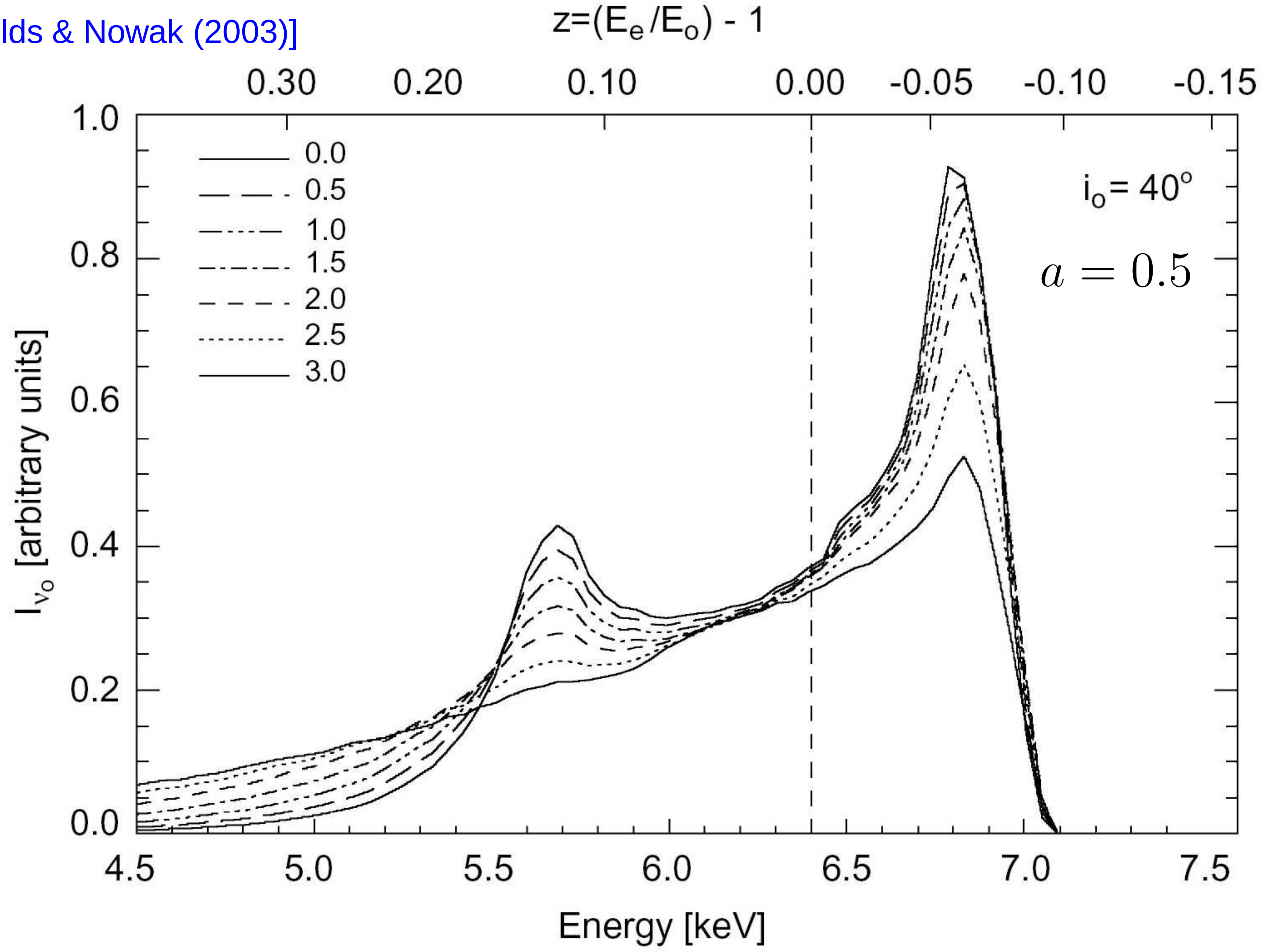
[Reynolds & Nowak (2003)]



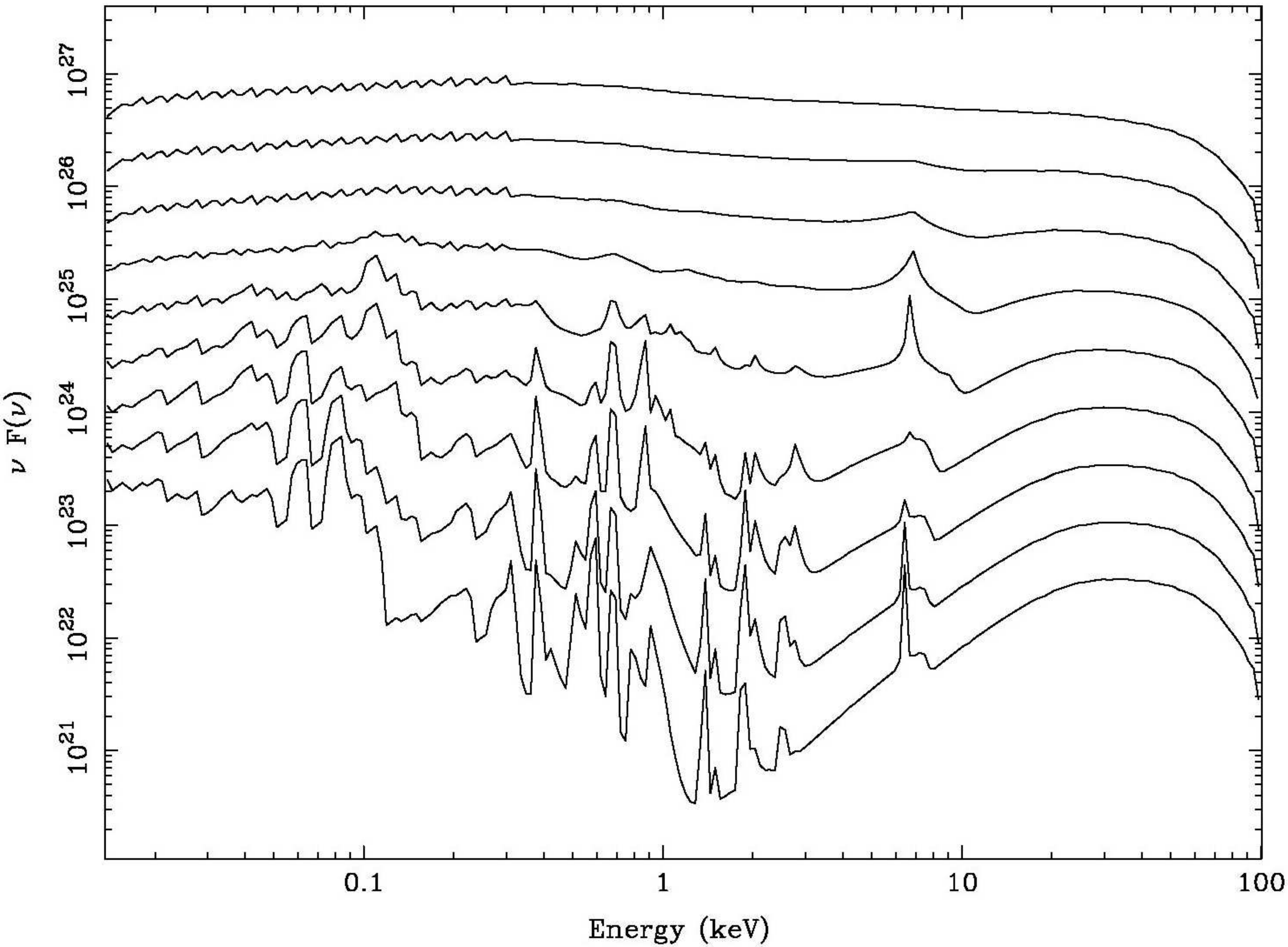
$\beta = 0.5$, $a = 0.998$

Dependence on Emissivity

[Reynolds & Nowak (2003)]



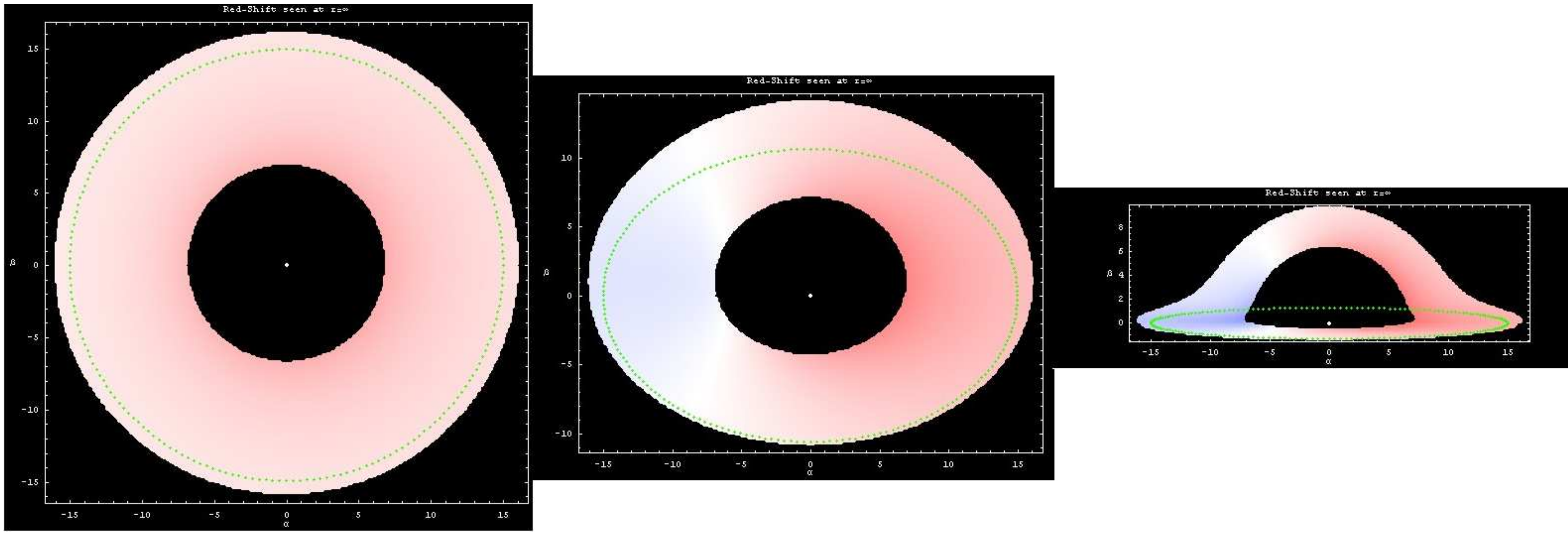
Dependence on Ionization



from [Reynolds & Nowak (2003)], calculated by [Ballantyne et al. (2001)]

Appearance of Disk's Temperature

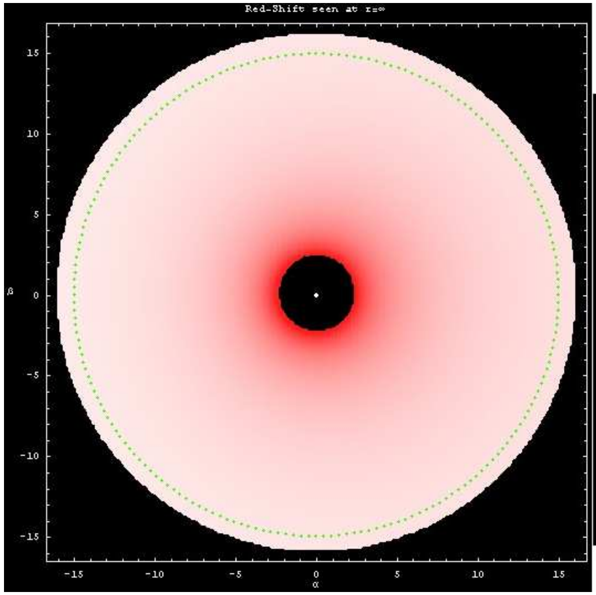
a = 0.01

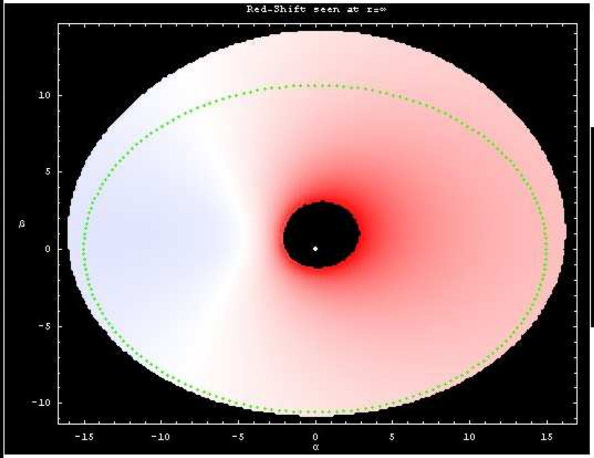


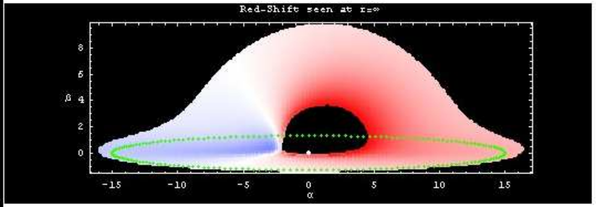
$i = 85°$ $i = 45°$ $i = 5°$

Appearance of Disk’s Temperature

$$\mathbf{a = 0.998}$$



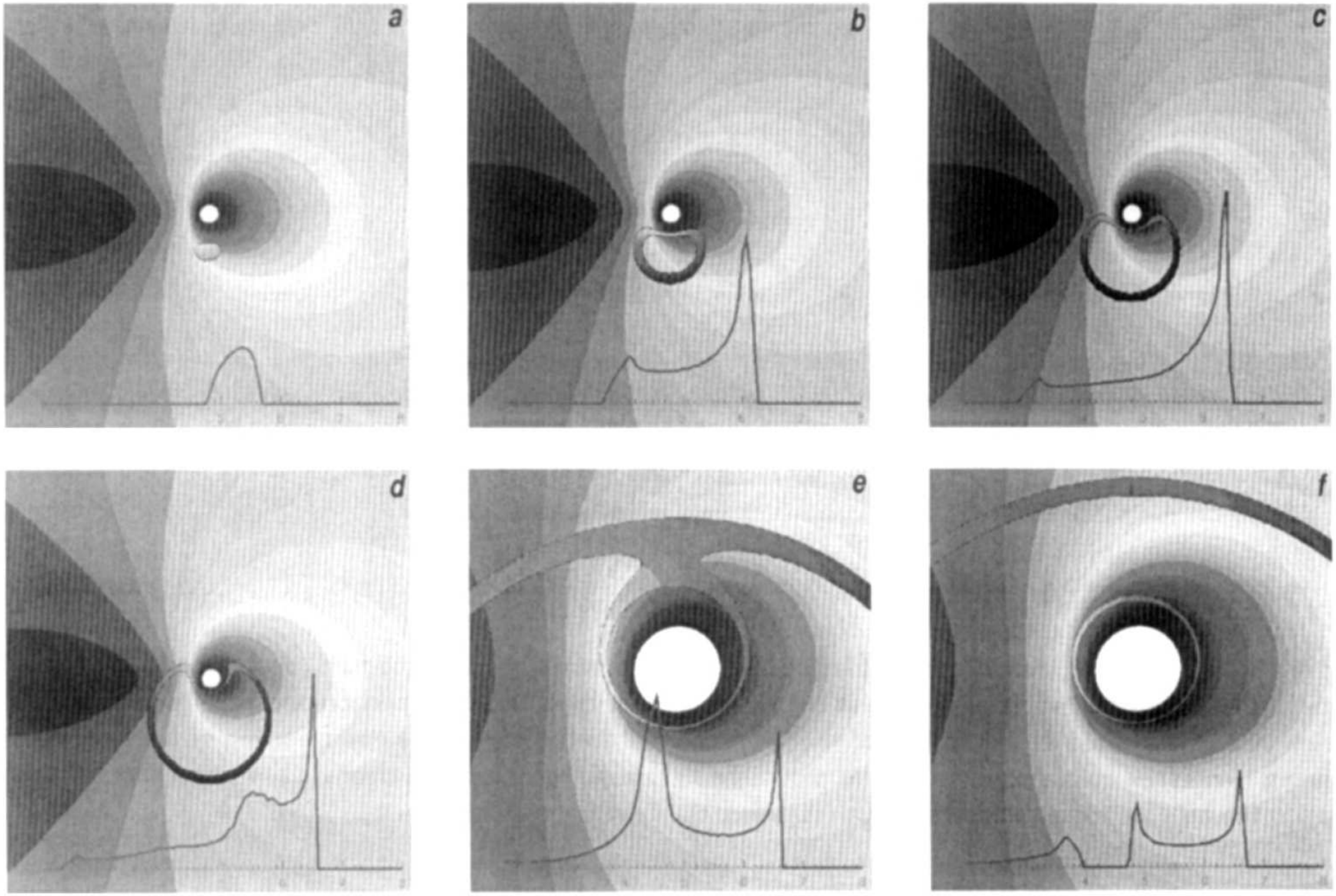




$i = 85°$ $i = 45°$ $i = 5°$

Reverberation

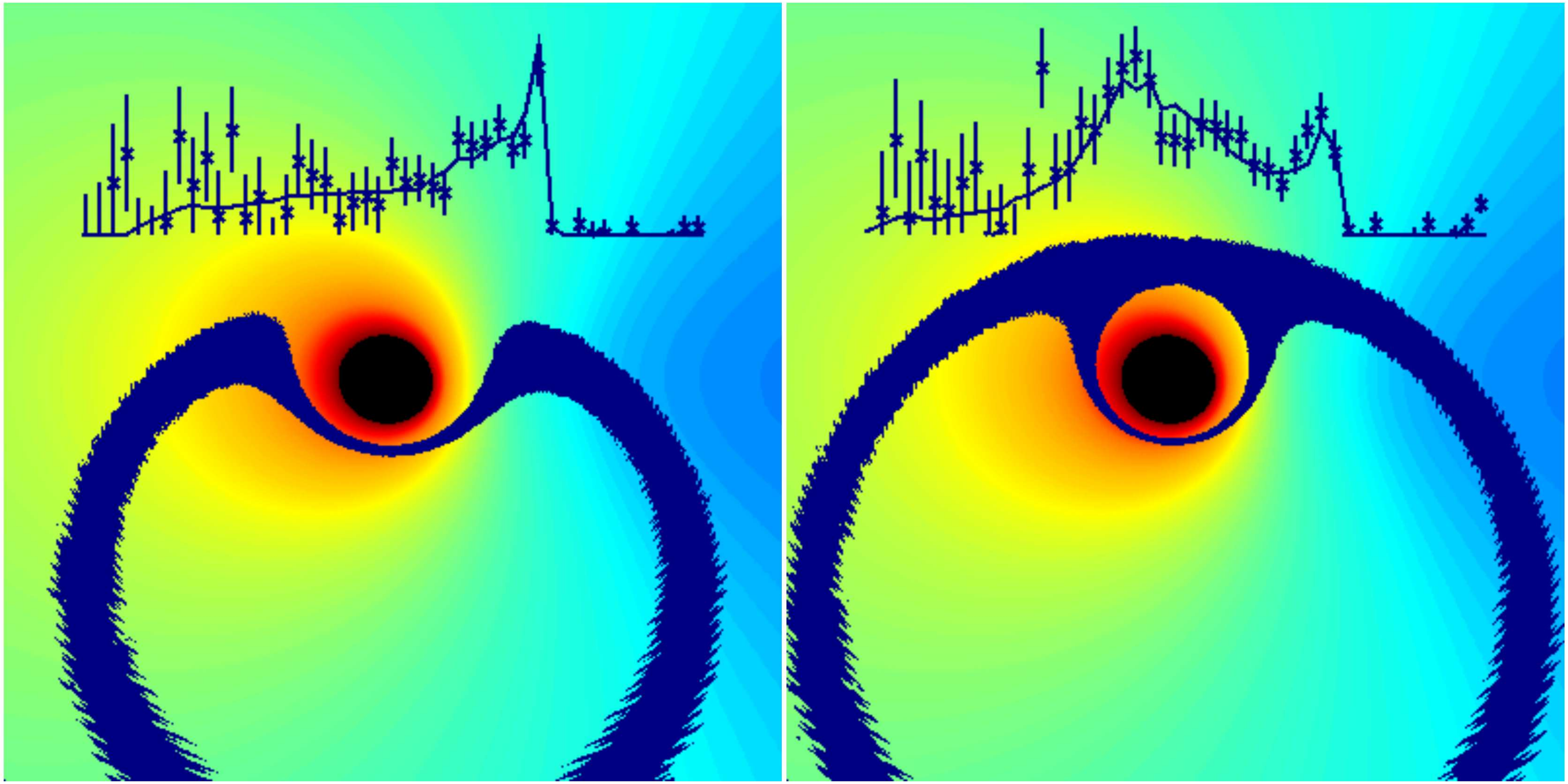
$$a = 0.998\ ,\ i = 30^{\circ}\ ,\ h_{\rm flare} = 7.5 r_g$$



[Reynolds et al. (1999)], [Young & Reynolds (2000)], [Young (2003)]

Reverberation

$$a = 0.998 \text{ , } i = 30^\circ \text{ , } h_{flare} = 10r_g$$

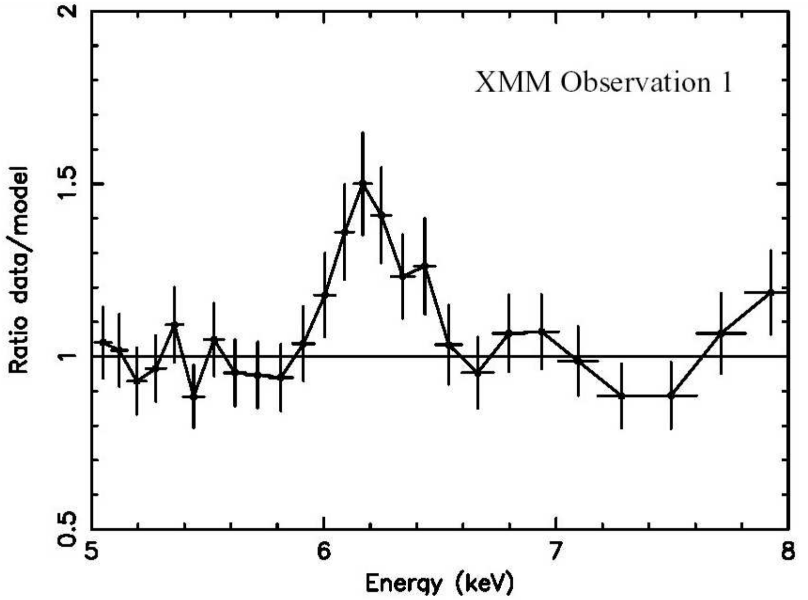


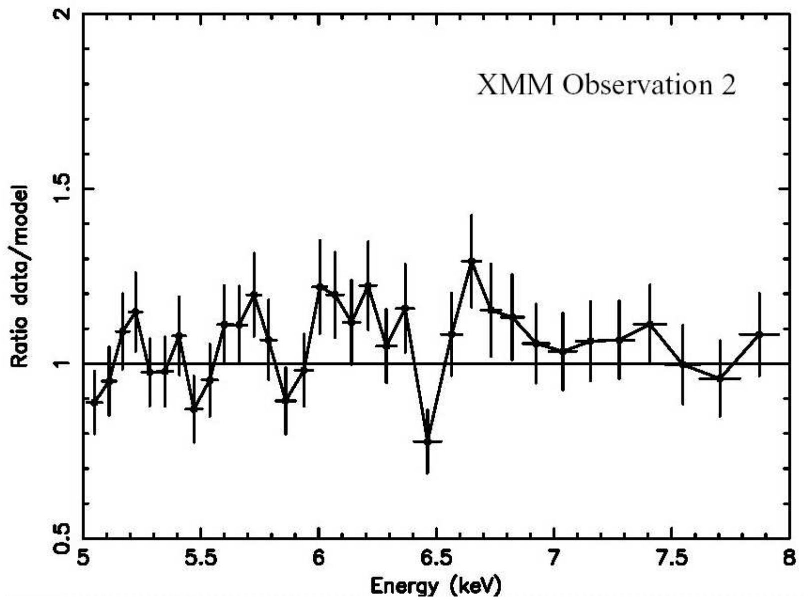
[Reynolds http://constellation.gsfc.nasa.gov]

Variability Problem

- $F_{K\alpha}$ varies without $F_{\rm cont}$ variation
  - Mrk 841, Seyfert-1, $t_{\rm var} \sim 10{\rm hours}$, [Petrucci et al. (2002)]
- $F_{\rm cont}$ varies without $F_{K\alpha}$
  - MCG-6-30-15, Seyfert-1, [Vaughan & Fabian (2004)]
- $F_{K\alpha}$ varies *with* $F_{\rm cont}$ (kinda):
  - IRAS 18325-5926, Seyfert-2, highly-ionized disk, [Iwasawa et al. (2004)]
- No long-term ${\rm EW}/F_{\rm cont}$ correlation:
  - Sampling of 7 Seyfert-1 AGN, [Markowitz, Edelson, Vaughan (2003)]
  - Short-term (30 days) and Long-term (1000 days) RXTE obs.'s
  - Correlations between Γ and $F_{\rm cont}$

$F_{K\alpha}$ Variation

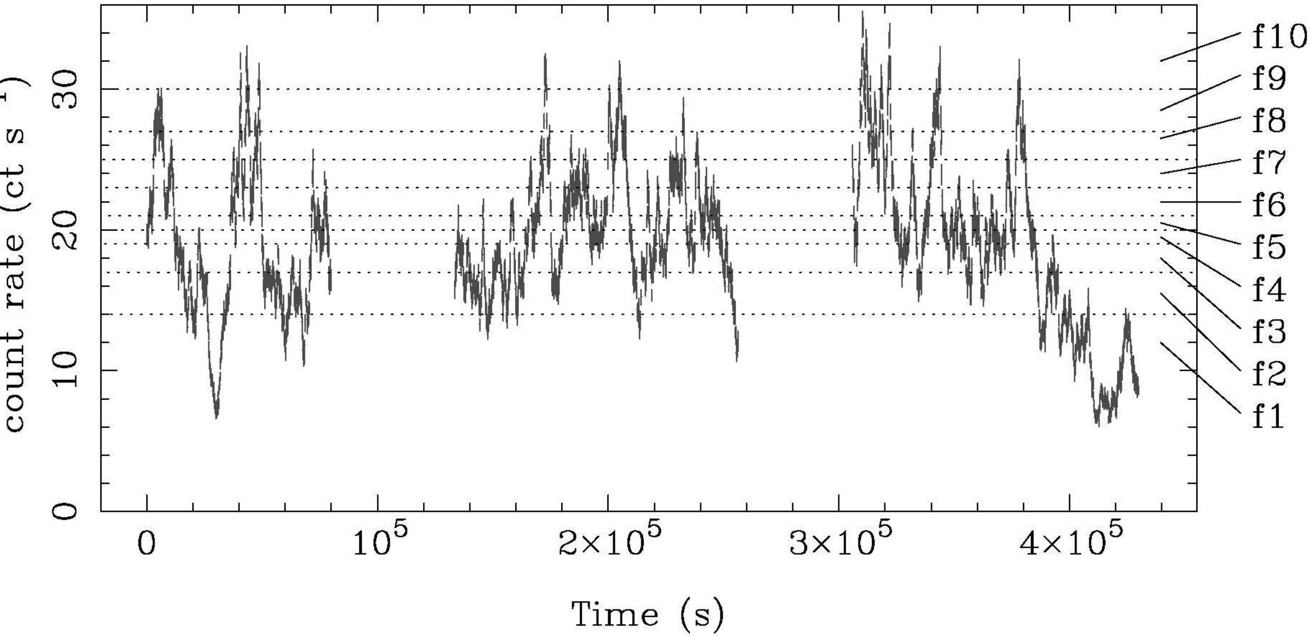


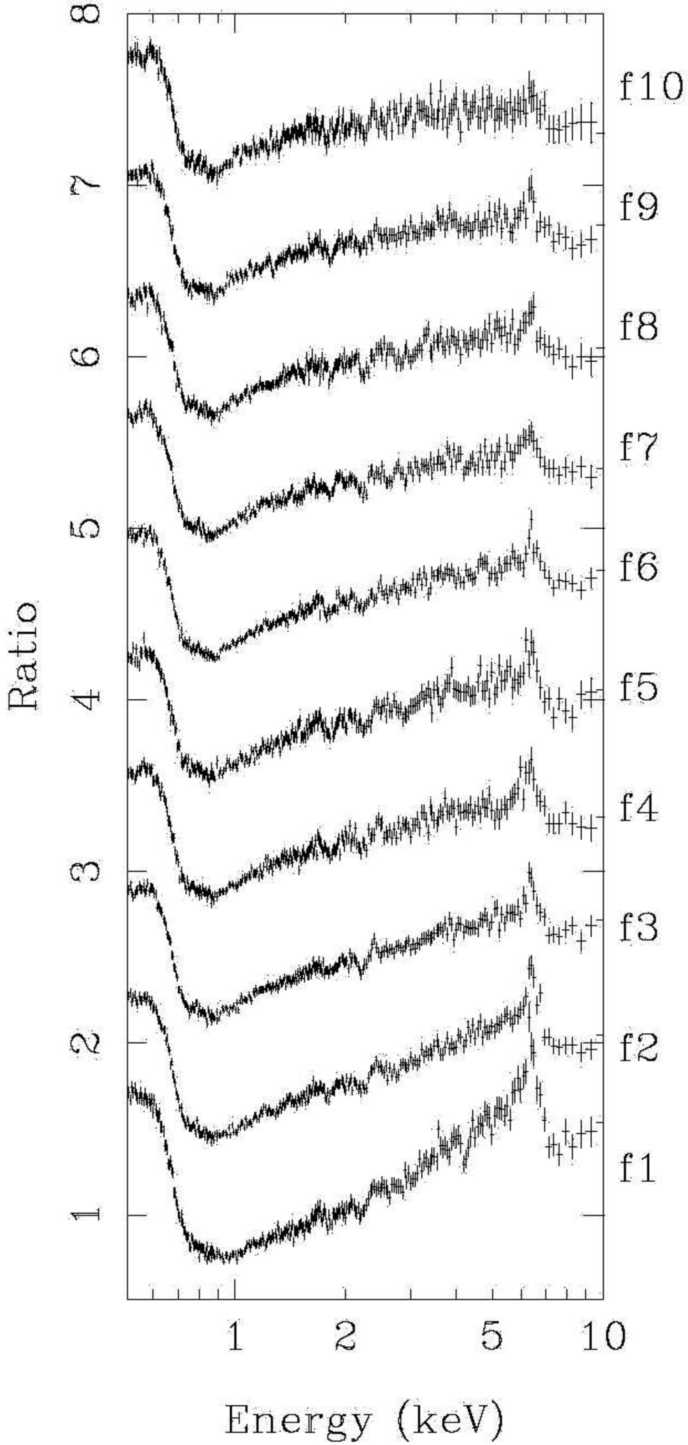


Mrk 841, Seyfert-1

[Petrucci et al. (2002)]

F_{cont} Variation





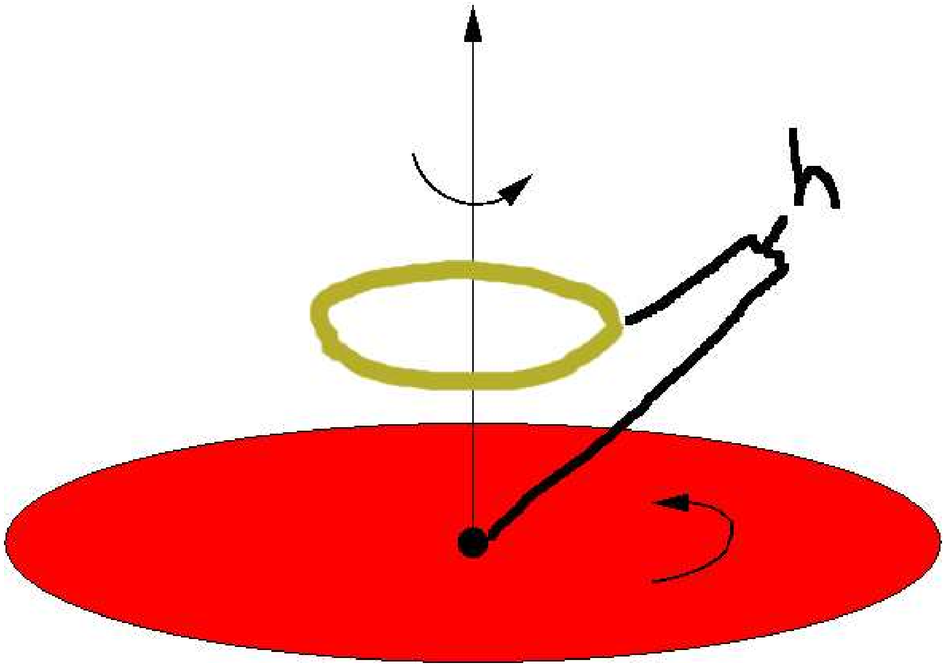
MCG-6-30-15, Seyfert-1

[Vaughan & Fabian (2004)]

Variation Resolutions: Disk Properties

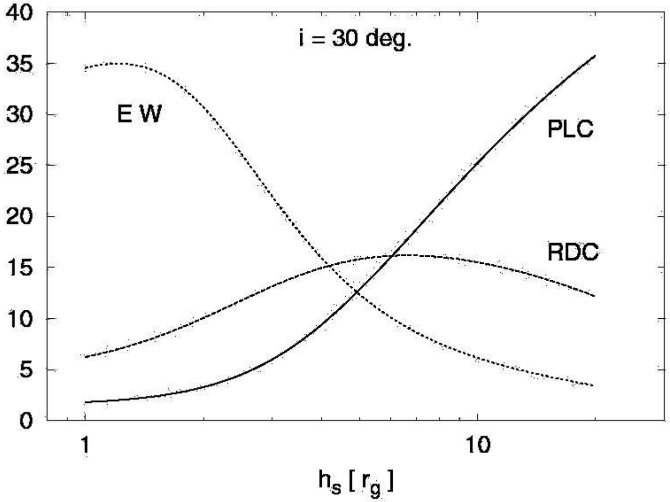
- $F_{K\alpha}$ diminished in Radio-loud AGN
- Anti-correlation with increasing ionization effects [Ballantyne et al. (2002)];
- Photon Bubble Instability, [Gammie (1998)], [Ballantyne et al. (2004)]
  - varying density structure $\sim t_{\rm dyn}$;
  - can explain Mrk 841 variability;
- Disk asymmetries $\rightarrow$ modulations from orbit w/o modulating source
  - Spiral density/ionization profile [Karas et al. (2001), Hartnell & Blackman (2002)];
  - MHD Turbulence (non-rel., ZEUS, $a = 0$) [Armitage & Reynolds (2003)];
  - $F_{K\alpha}$ from material within ISCO [Reynolds & Begelman (1997)], [Reynolds et al. (2004)];
  - Ang. Mom. Transfer from material within ISCO [Gammie (1999)], [Reynolds et al. (2004)];

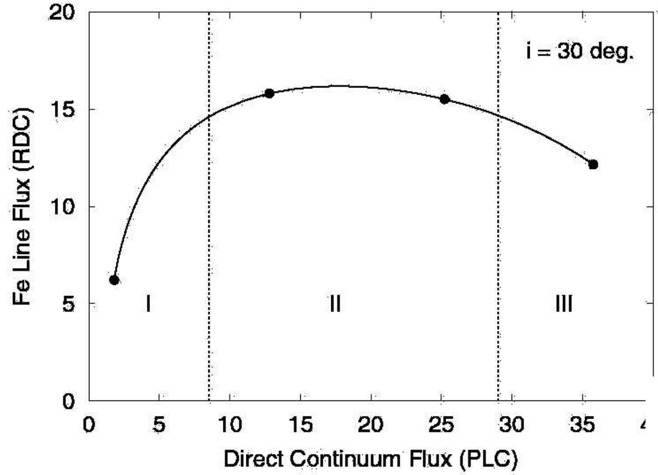
Variation Resolutions: Source Properties

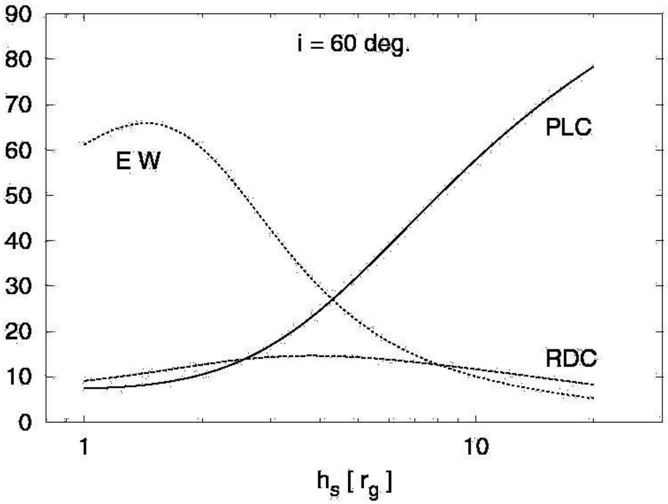


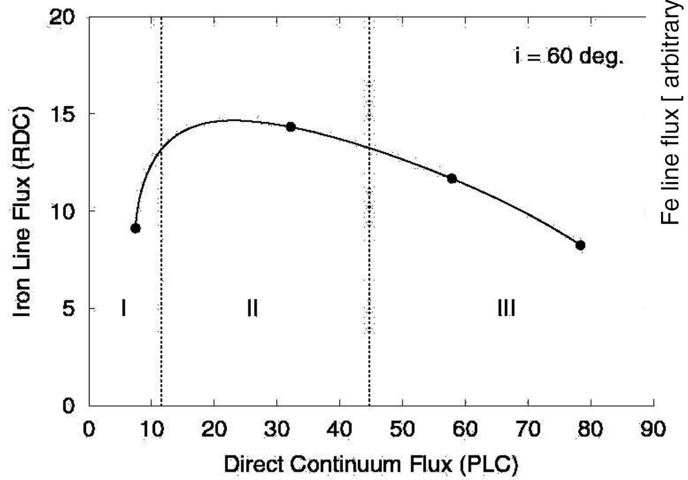
- [Miniutti & Fabian (2004)]
- Source asymmetry $\longrightarrow$ disk bias;
- Rel. effects magnify bias;
- $a = 0.998$

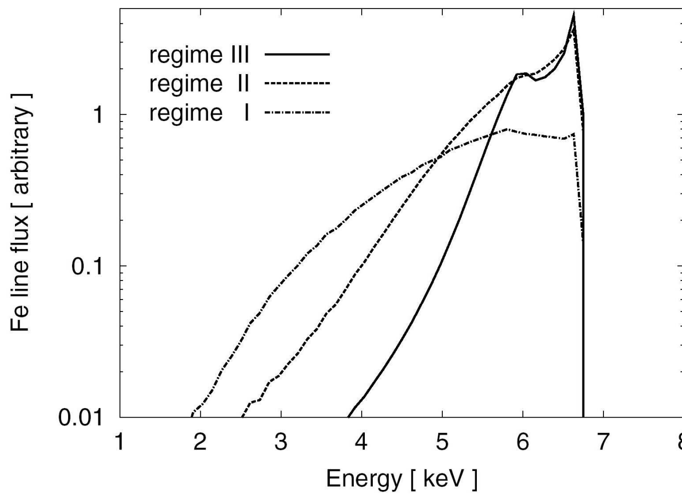
Variation Resolutions: Source Geometry



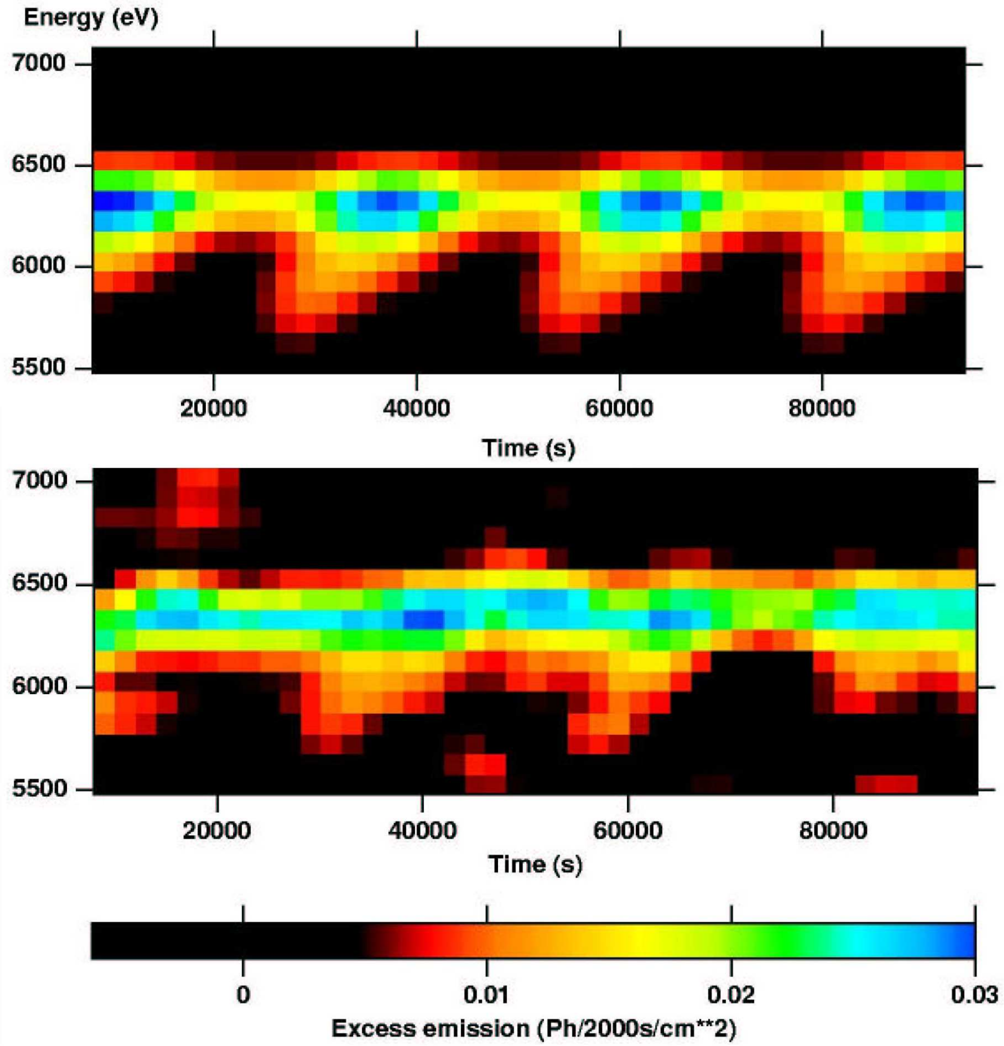








Variation Resolutions: Source Geometry



- [Iwasawa, Miniutti & Fabian (astro-ph/0409293)]
- Rotating point source, $r = 6r_g$, $h = 9r_g$, $i = 20°$, $a = 0.998$
- $M_{\rm sim} = 1 - 5 \times 10^7 M_\odot$
- $M_{\rm H\alpha} \simeq 1.68 \pm 0.33 \times 10^7 M_\odot$
- NGC 3516 Seyfert-1

Conclusions and the Future

- better spectroscopy + better models = real measurements
- more sophisticated models = more possibilities

- XEUS (ESA), Constellation-X (NASA), MAXIM
  - Measure iron-line for furthest known AGN
  - Resolve inner horizon
  - Greater time-resolved spectroscopy