Relativistic X-ray iron lines: a window on horizon scale astrophysics in accreting BH systems

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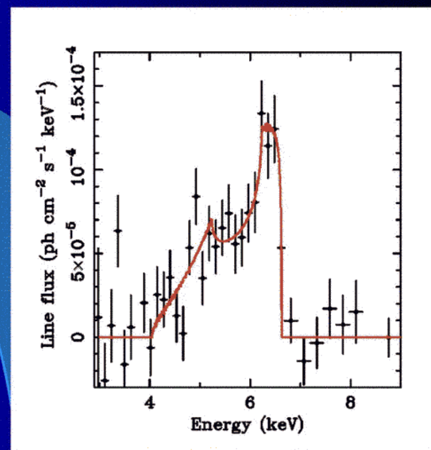

Tanaka et al. (1995)

Outline

- Introduction to X-ray reflection and relativistically broad iron emission lines.
- Robustness of the broad Fe line in MCG-6-30-15
  - Results from a 512ks Chandra grating observation
- Constraining black hole spin
  - Progress and roadblocks
- Constraining inner disk physics
  - Torqued disks and strong light bending

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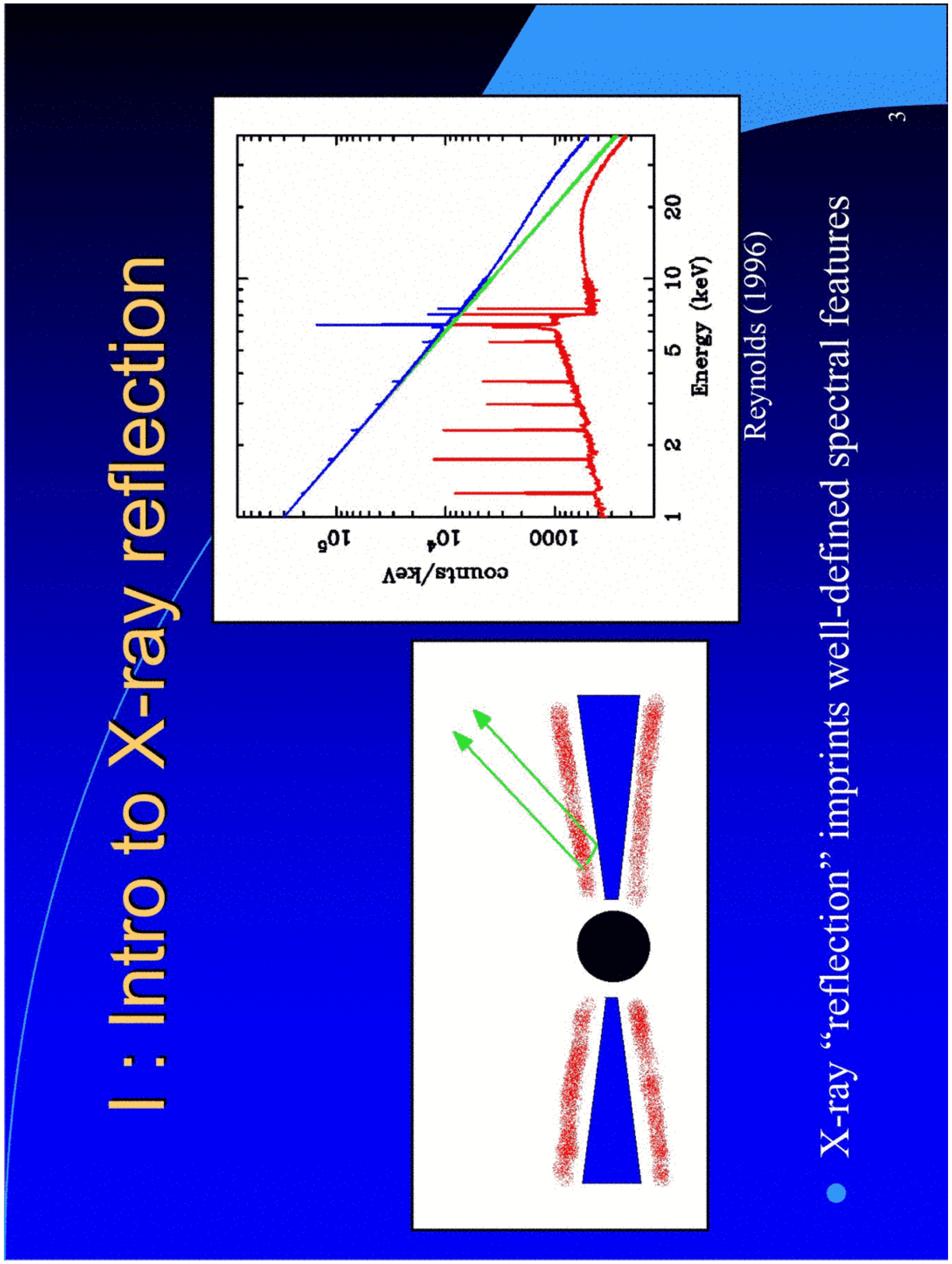
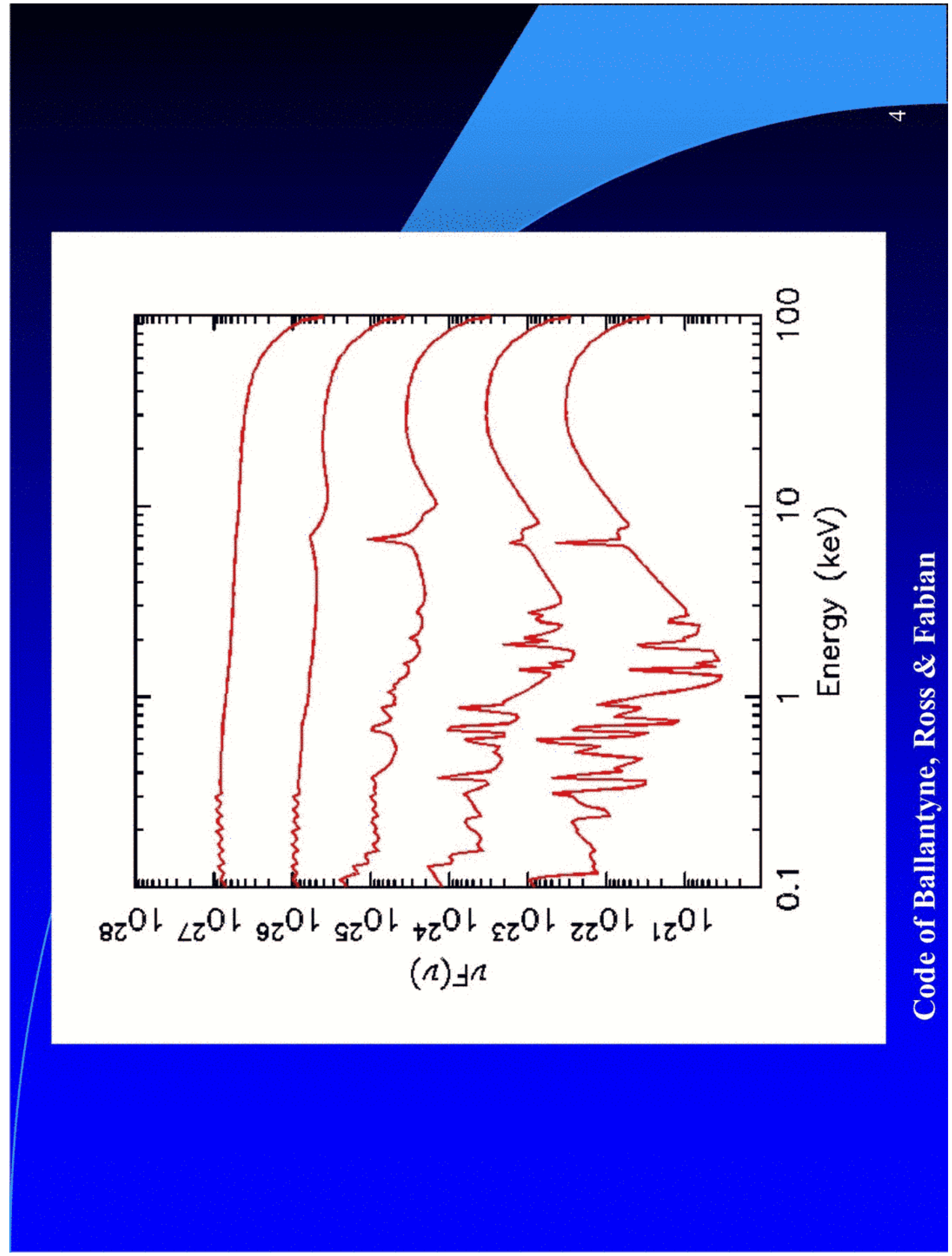
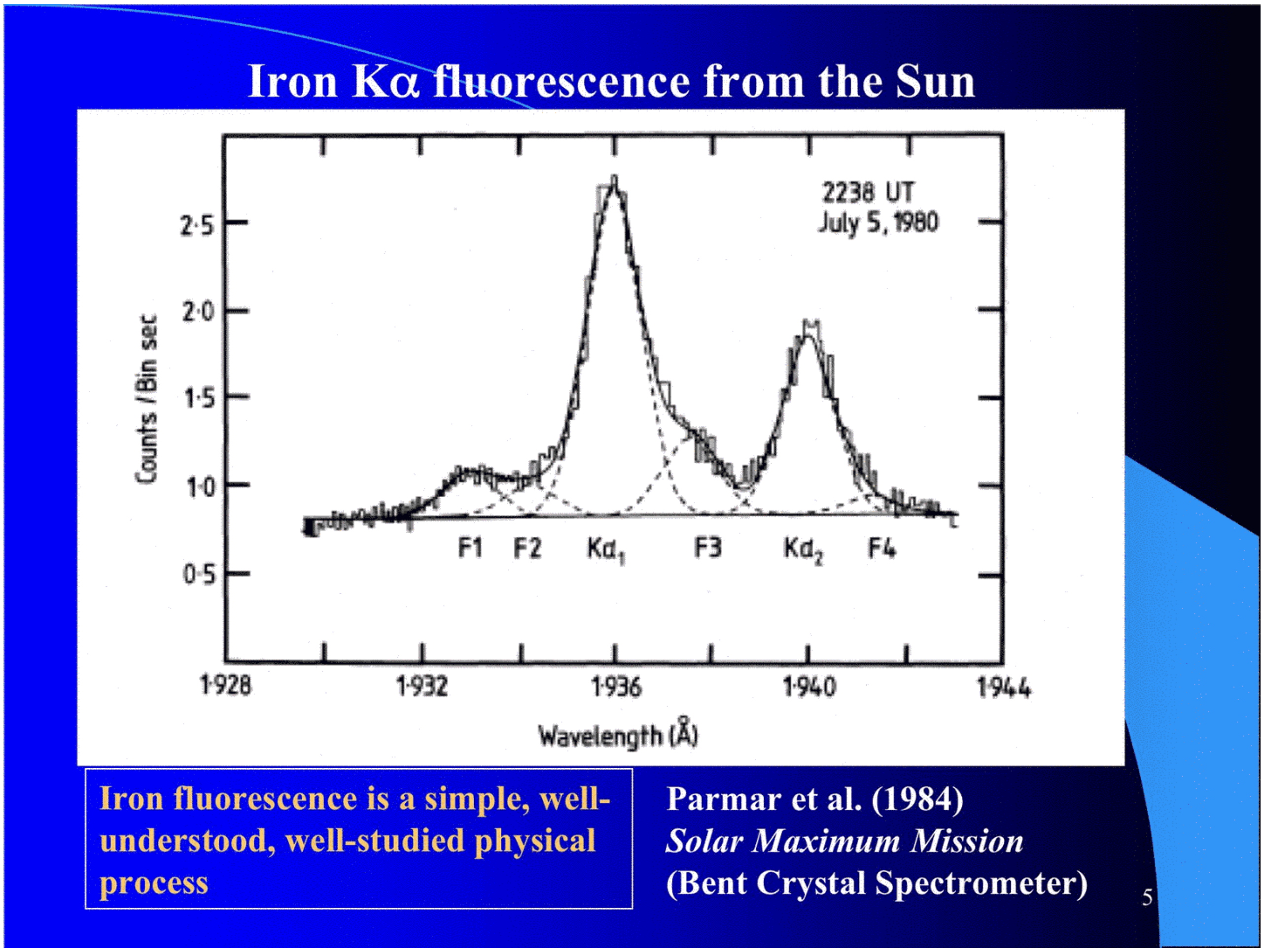
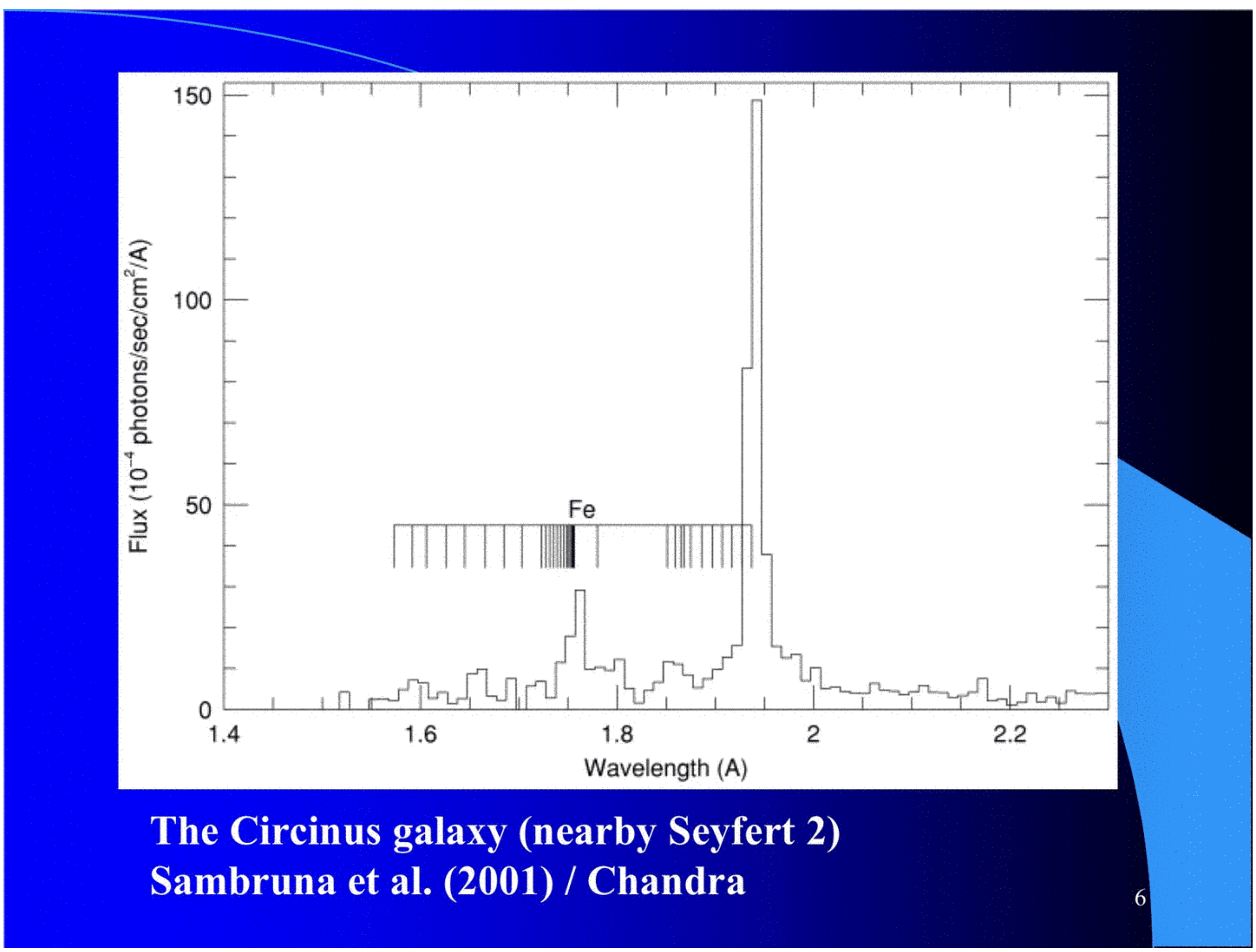
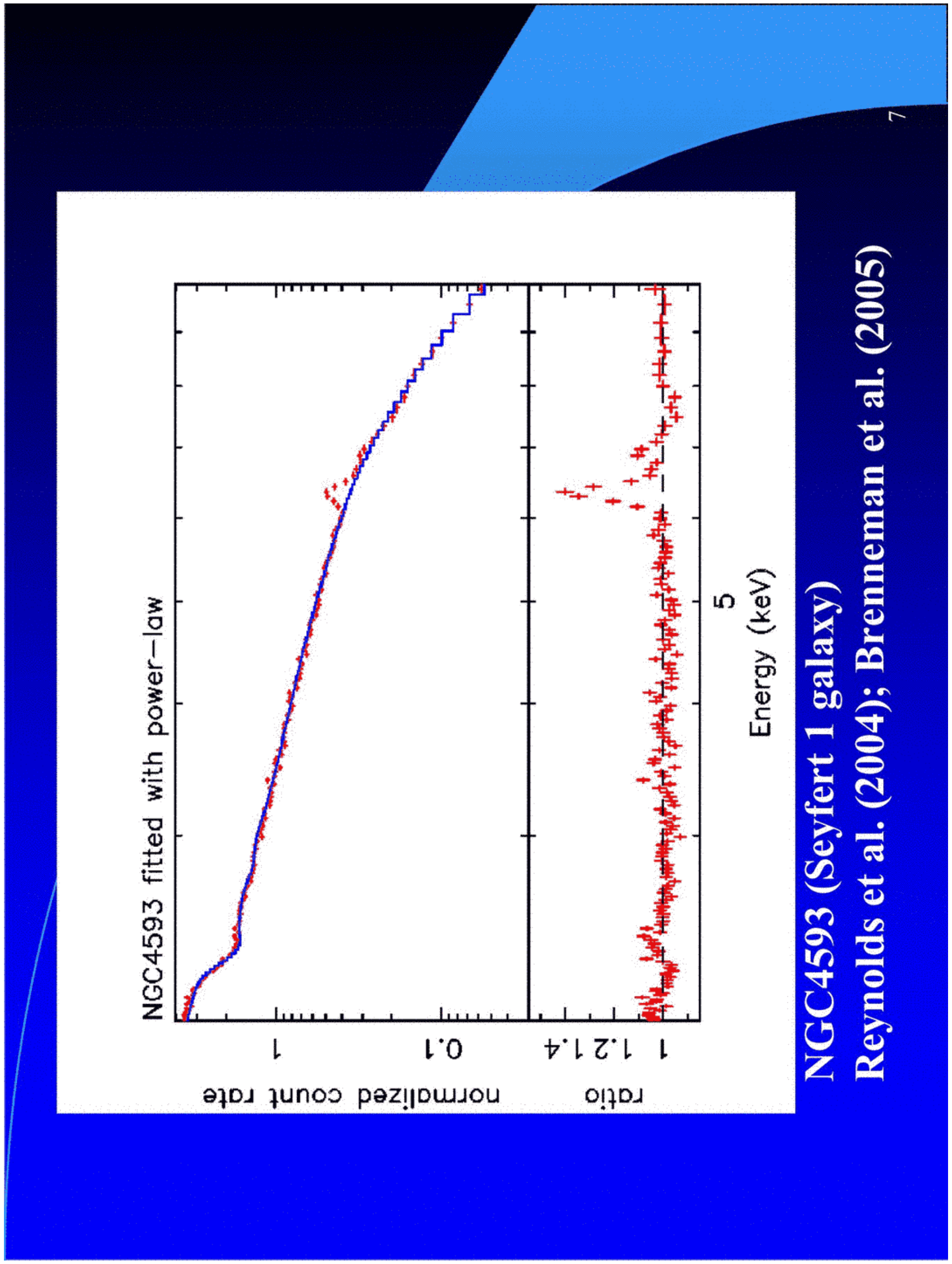
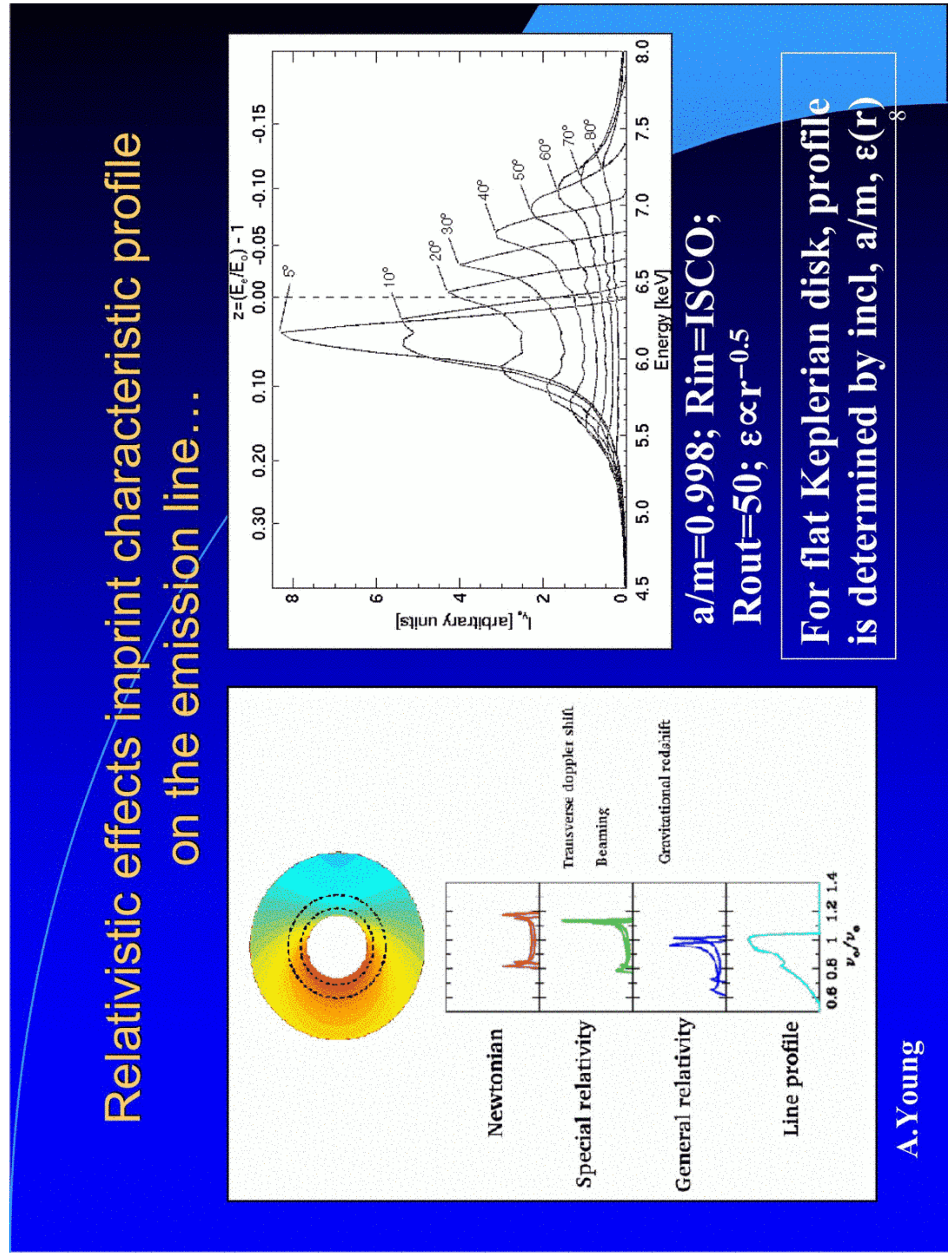

I : Intro to X-ray reflection
counts/keV
Energy (keV)
Reynolds (1996)
X-ray “reflection” imprints well-defined spectral features
3

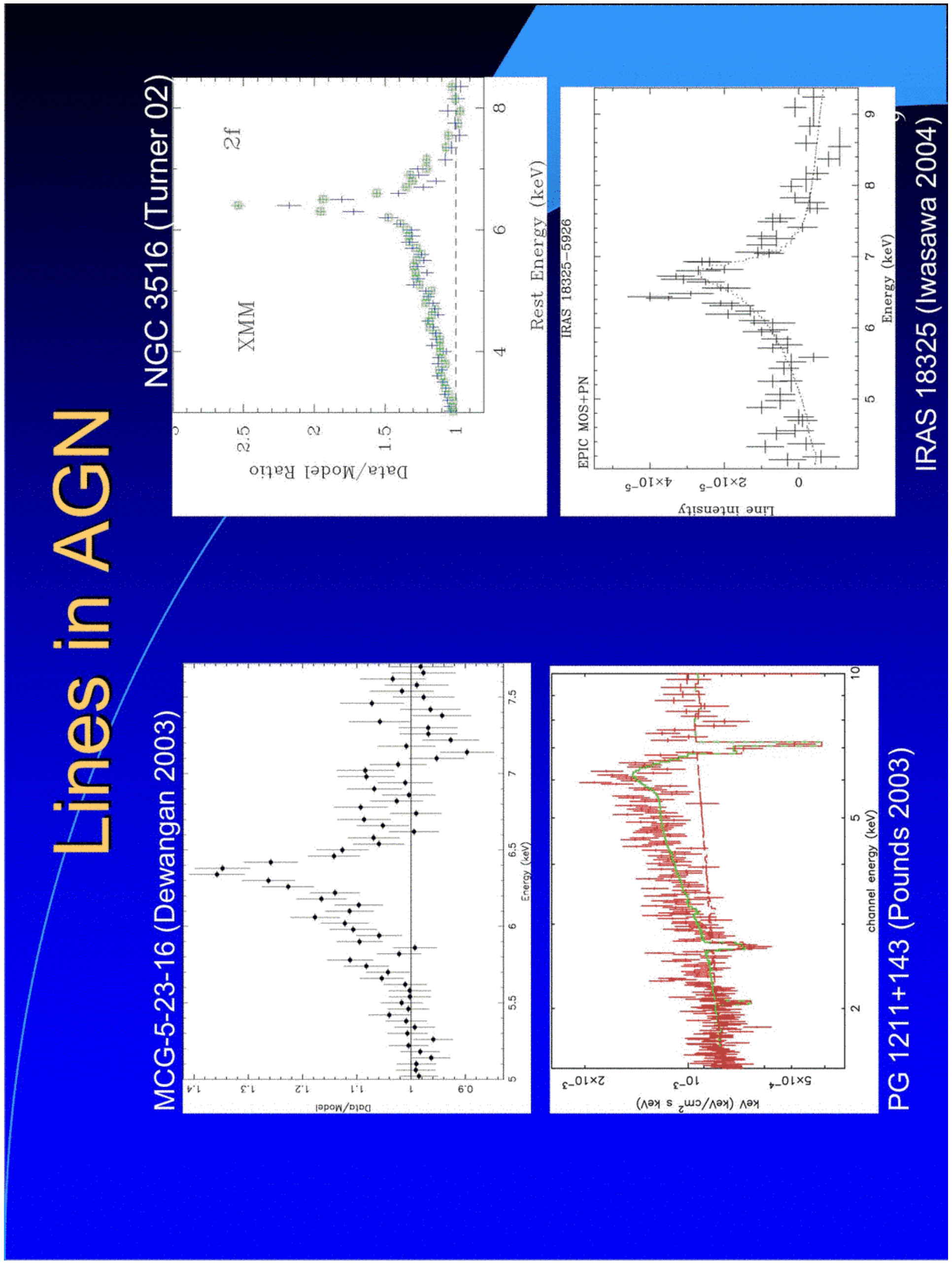

νF(ν)
Energy (keV)
Code of Ballantyne, Ross & Fabian
4

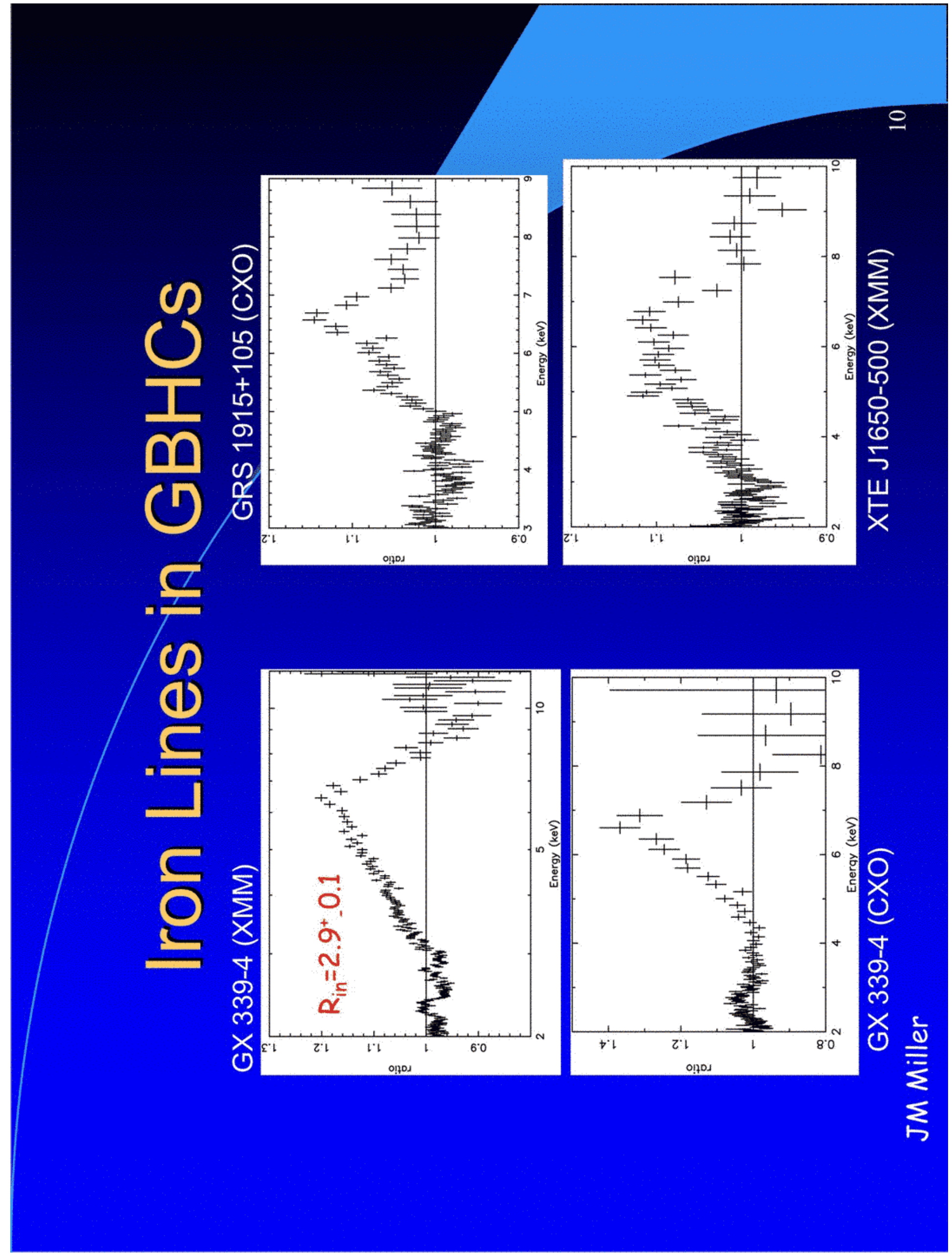

Iron Kα fluorescence from the Sun
2238 UT
July 5, 1980
Counts / Bin sec
2·5
2·0
1·5
1·0
0·5
1·928
1·932
1·936
1·940
1·944
Wavelength (Å)
F1 F2 Kα1 F3 Kα2 F4
Iron fluorescence is a simple, well-understood, well-studied physical process
Parmar et al. (1984)
Solar Maximum Mission
(Bent Crystal Spectrometer)
5


Flux (10^-4 photons/sec/cm^2/A)
150
100
50
0
1.4
1.6
1.8
2
2.2
Wavelength (A)
Fe
The Circinus galaxy (nearby Seyfert 2)
Sambruna et al. (2001) / Chandra
6


NGC4593 fitted with power-law
normalized count rate
ratio
Energy (keV)
NGC4593 (Seyfert 1 galaxy)
Reynolds et al. (2004); Brenneman et al. (2005)
7

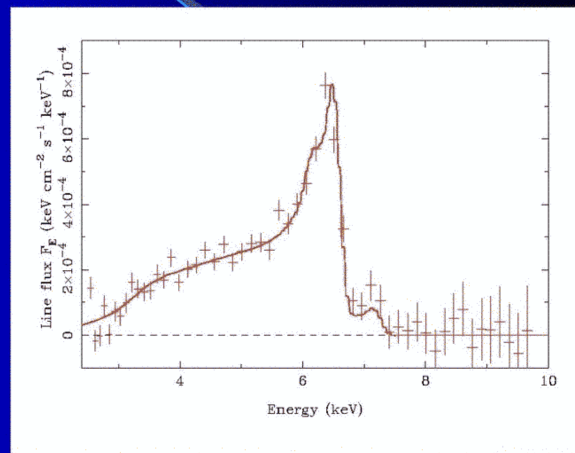

Relativistic effects imprint characteristic profile
on the emission line…
Newtonian
Special relativity
General relativity
Line profile
Transverse doppler shift
Beaming
Gravitational redshift
A.Young
Energy [keV]
a/m=0.998; Rin=ISCO;
Rout=50; ε∝r^-0.5
For flat Keplerian disk, profile
is determined by incl, a/m, ε(r)
8


Lines in AGN
NGC 3516 (Turner 02)
IRAS 18325 (Iwasawa 2004)
MCG-5-23-16 (Dewangan 2003)
PG 1211+143 (Pounds 2003)

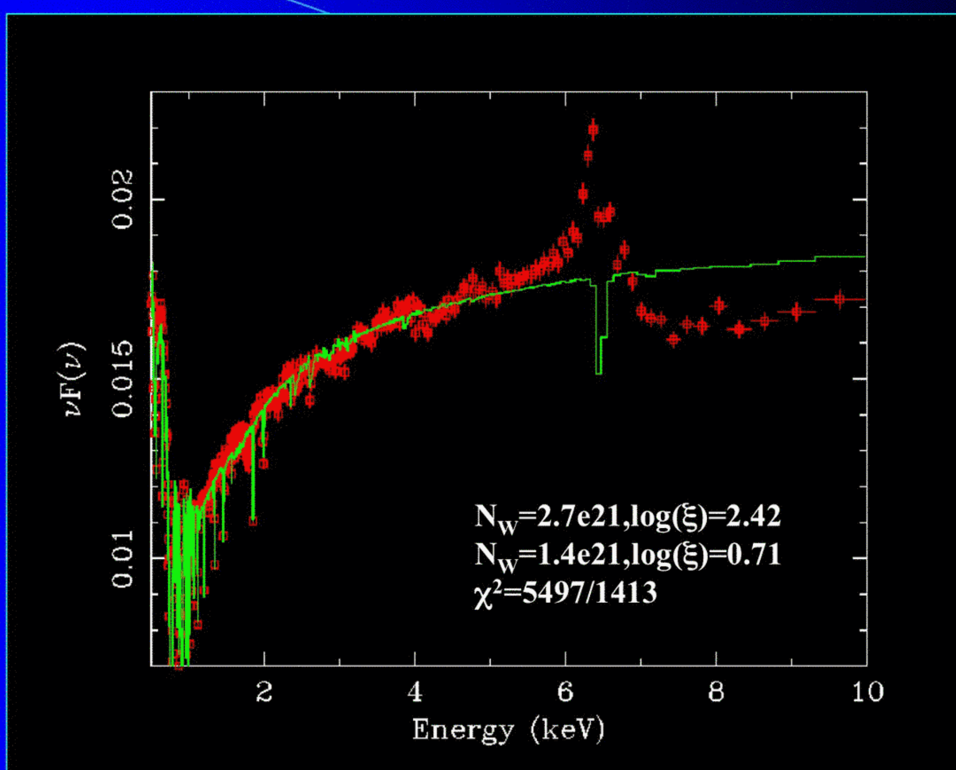

Iron Lines in GBHCs
GRS 1915+105 (CXO)
XTE J1650-500 (XMM)
GX 339-4 (XMM)
GX 339-4 (CXO)
JM Miller

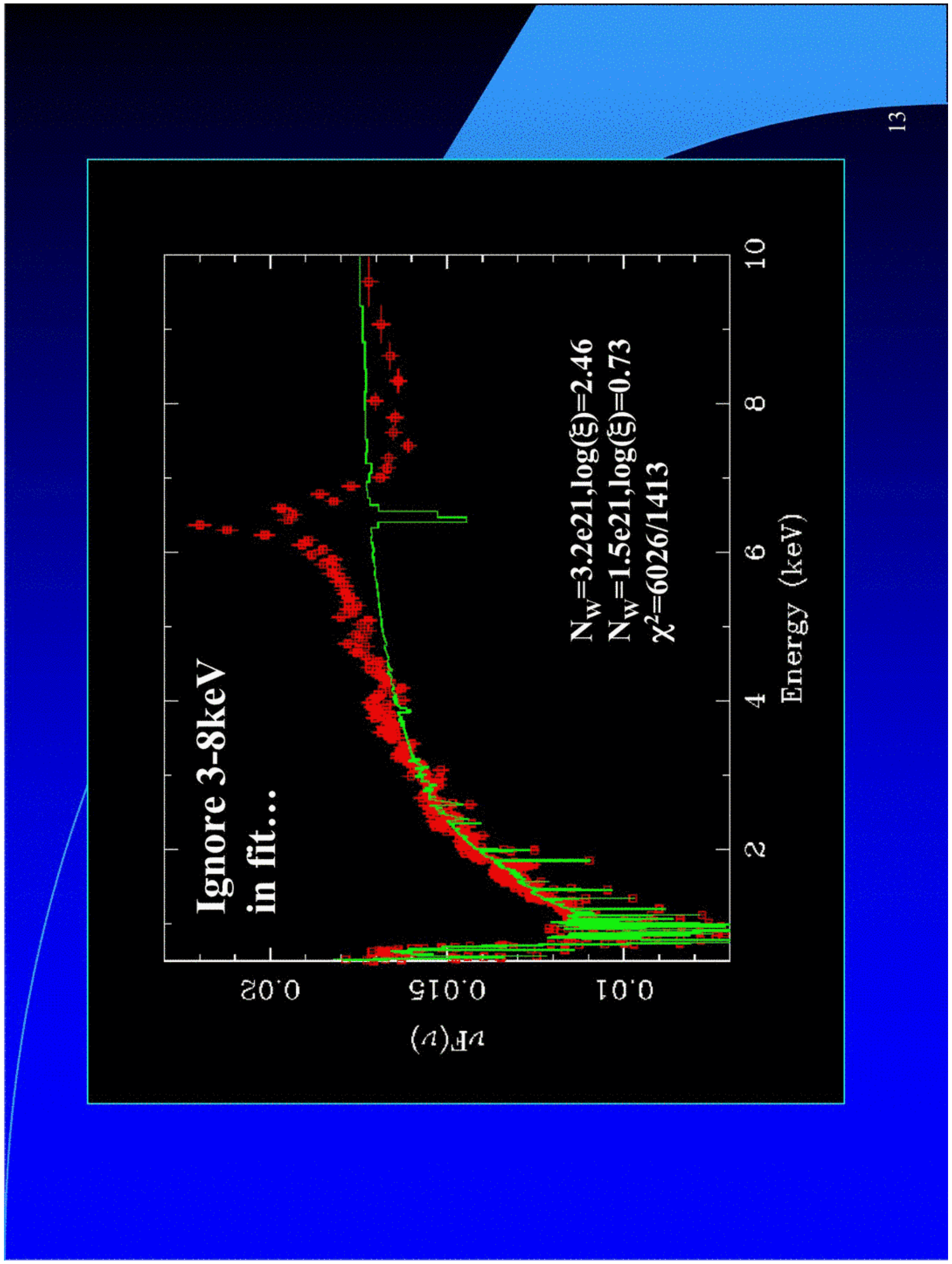
I : The line in MCG-6-30-15

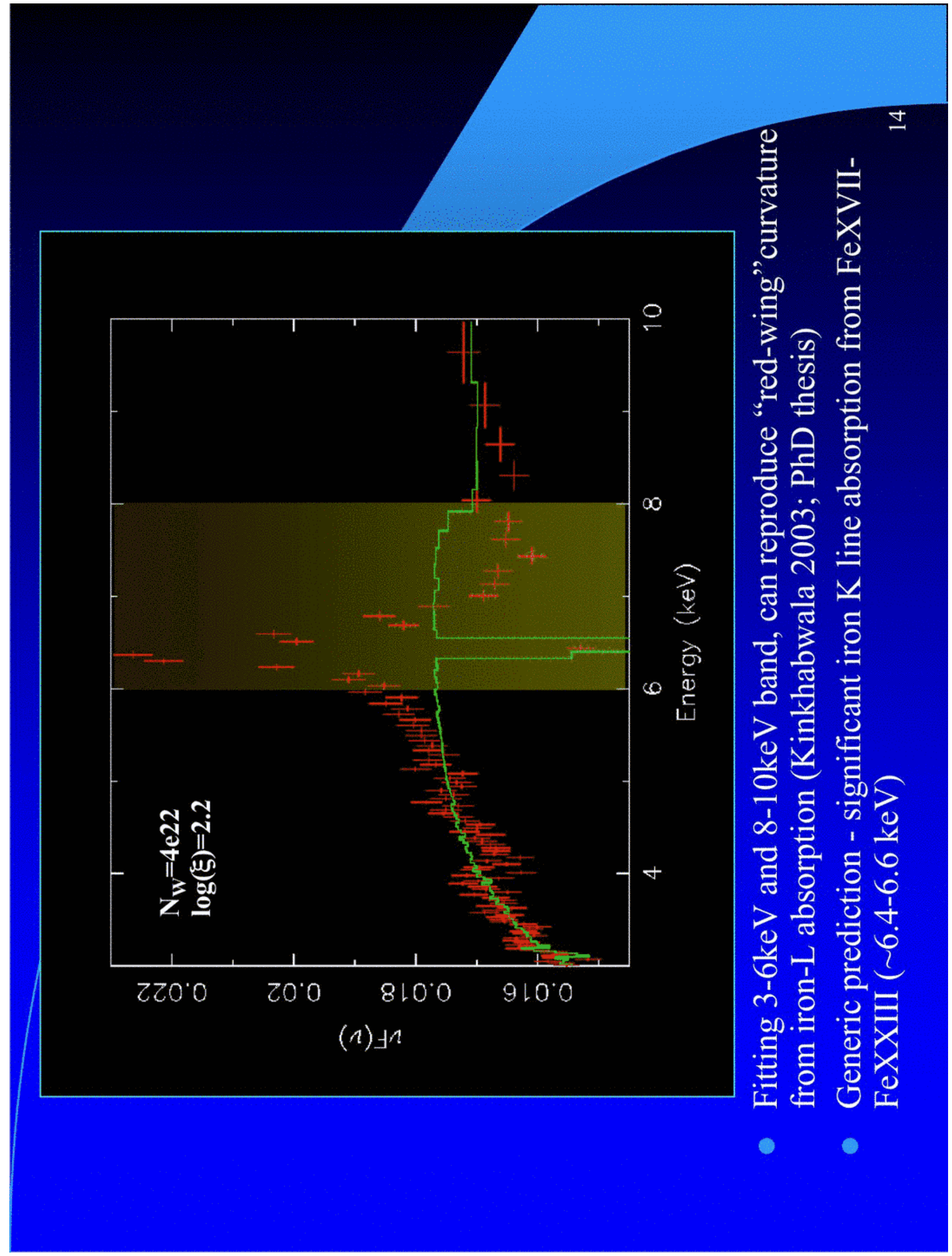
- Poster child broad iron line: Seyfert 1.2 galaxy MCG-6-30-15
- Subtract off continuum consisting of a photo-abaorbed power-law
- Line in the NORMAL state well described by…
  - Spin a=0.998
  - $\epsilon \propto r^{-5}$ from 1.23-6M
  - $\epsilon \propto r^{-2.5}$ beyond 6M
- **HOW ROBUST IS THE LINE?**

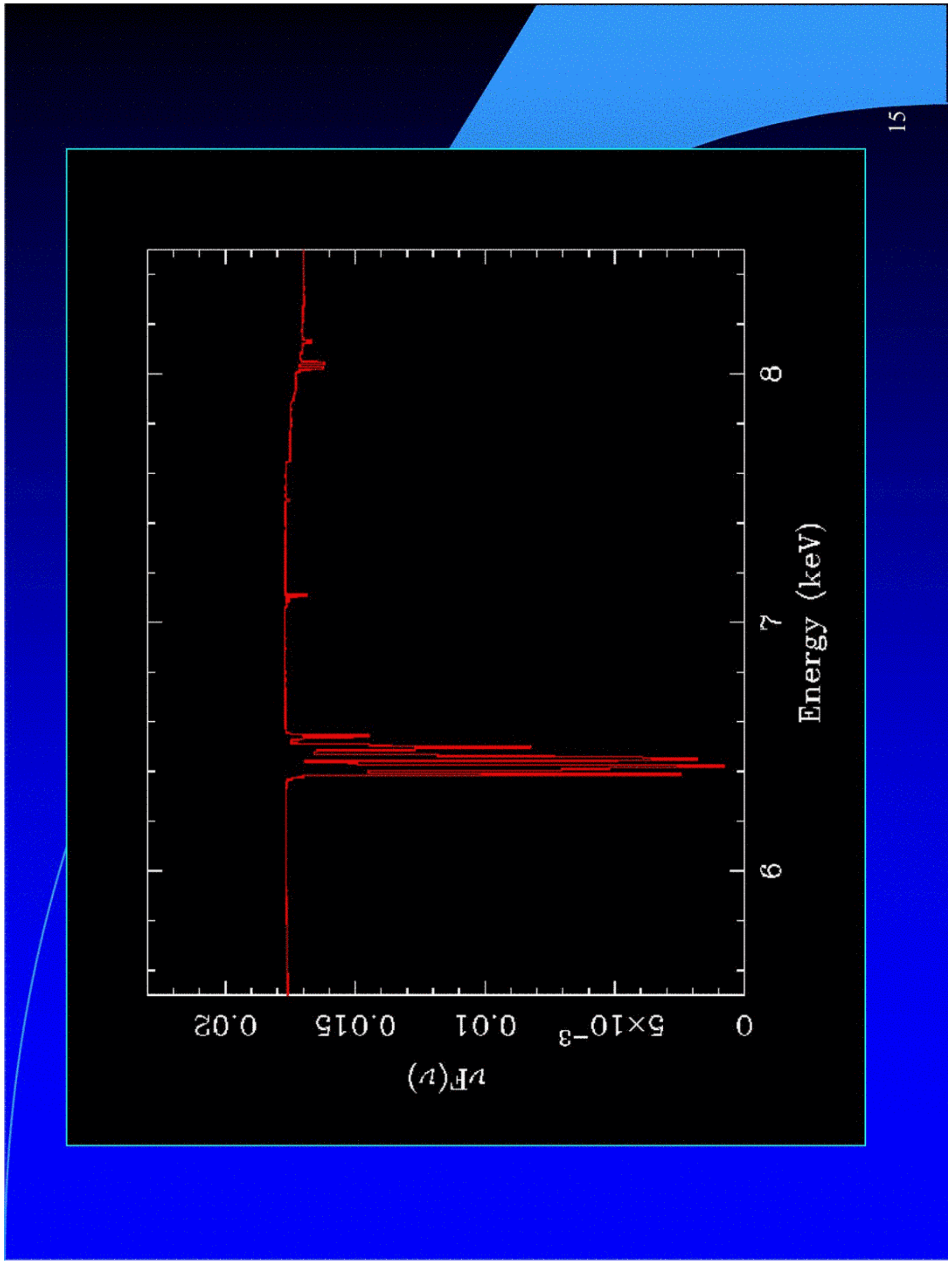


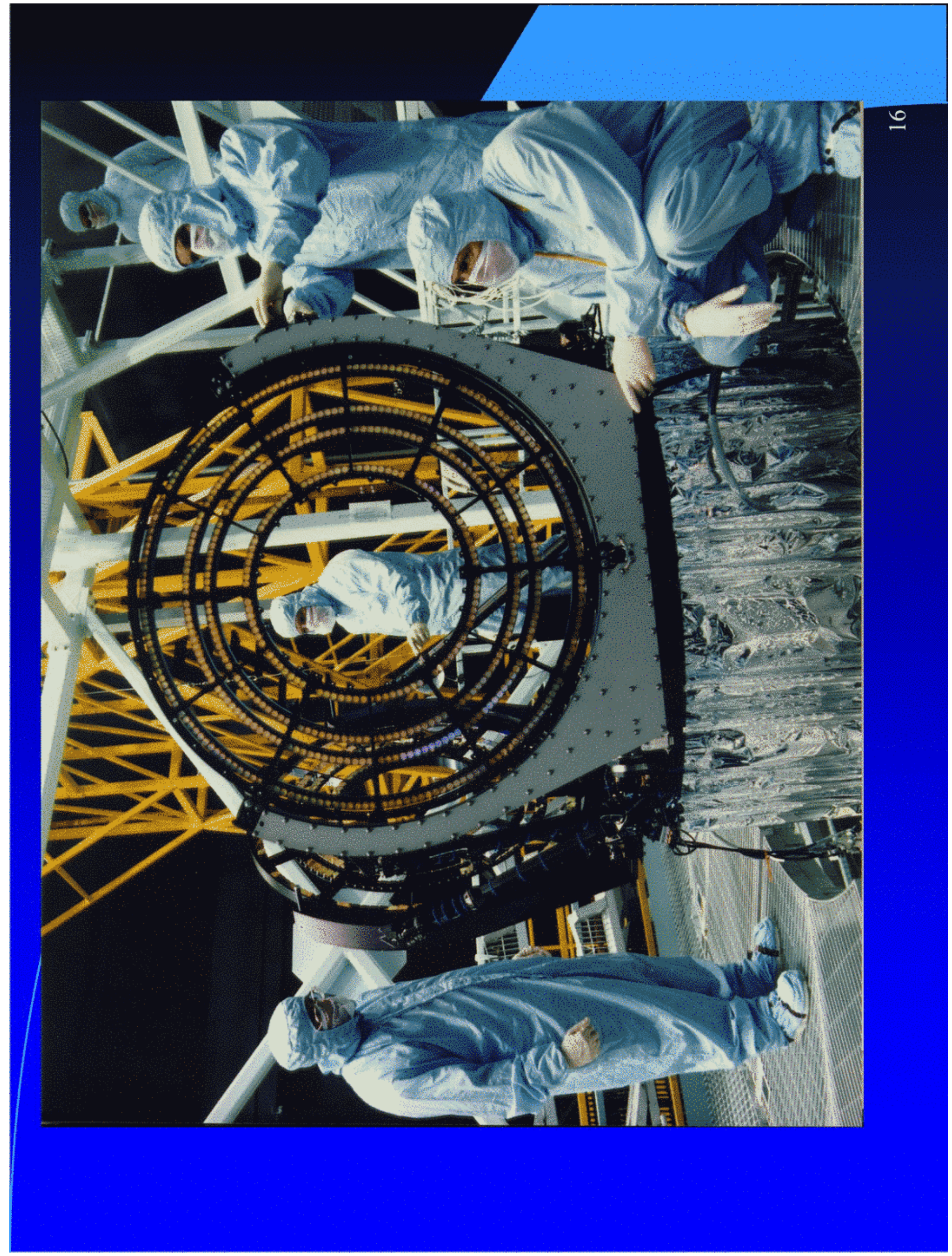
MCG-6-30-15 from XMM-Newton
Continuum subtracted
Fabian et al. (2002)

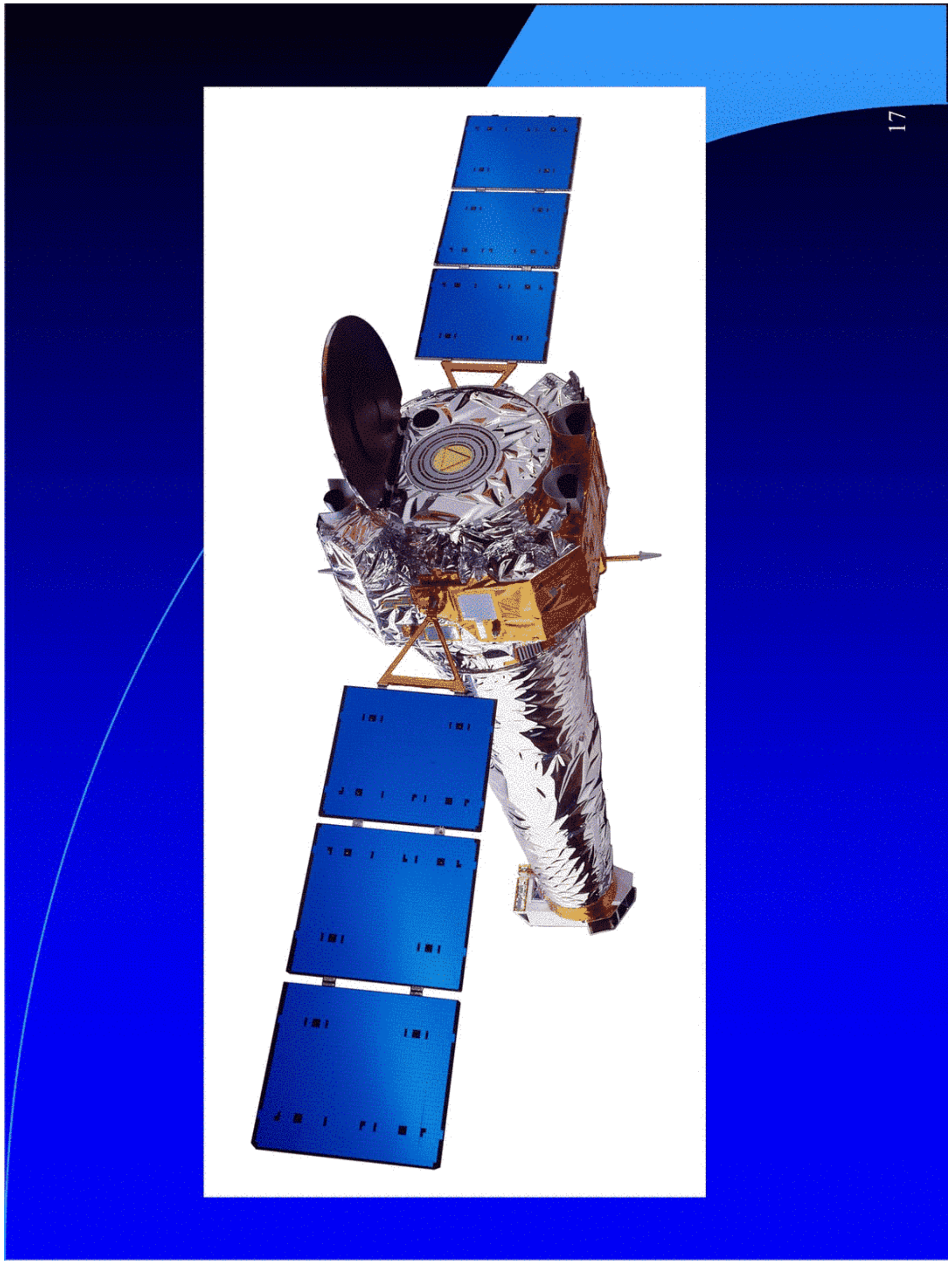


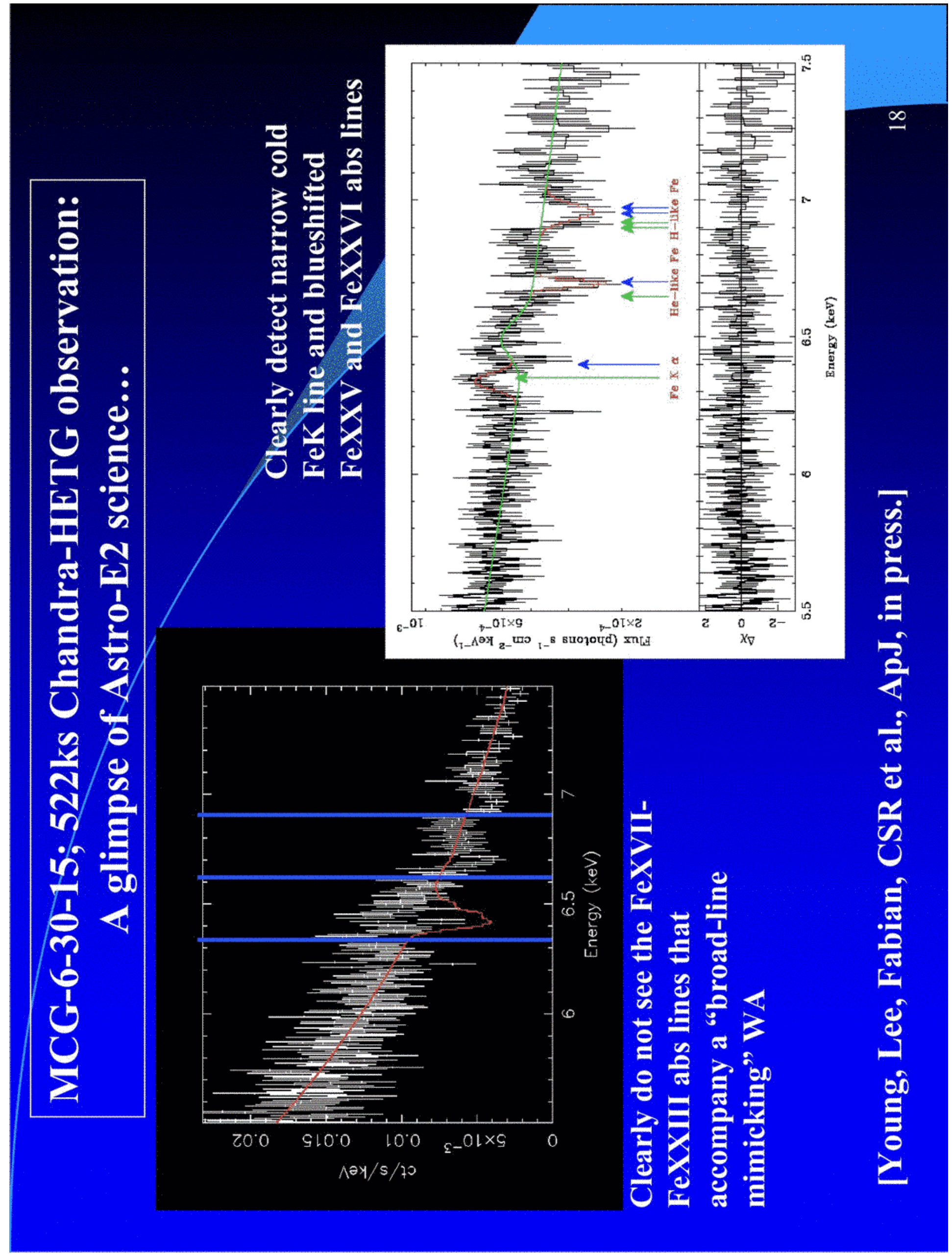

Ignore 3-8keV
in fit…
N_W=3.2e21,log(ξ)=2.46
N_W=1.5e21,log(ξ)=0.73
χ^2=6026/1413
Energy (keV)
νF(ν)
13


N_W=4e22
log(ξ)=2.2
Energy (keV)
νF(ν)
Fitting 3-6keV and 8-10keV band, can reproduce "red-wing" curvature from iron-L absorption (Kinkhabwala 2003; PhD thesis)
Generic prediction - significant iron K line absorption from FeXVII-FeXXIII (~6.4-6.6 keV)
14


15
Energy (keV)
6
7
8
νF(ν)
0
5×10^-3
0.01
0.015
0.02


16


17


MCG-6-30-15; 522ks Chandra-HETG observation:
A glimpse of Astro-E2 science…
Clearly detect narrow cold FeK line and blueshifted FeXXV and FeXXVI abs lines
Clearly do not see the FeXVII-FeXXIII abs lines that accompany a "broad-line mimicking" WA
[Young, Lee, Fabian, CSR et al., ApJ, in press.]
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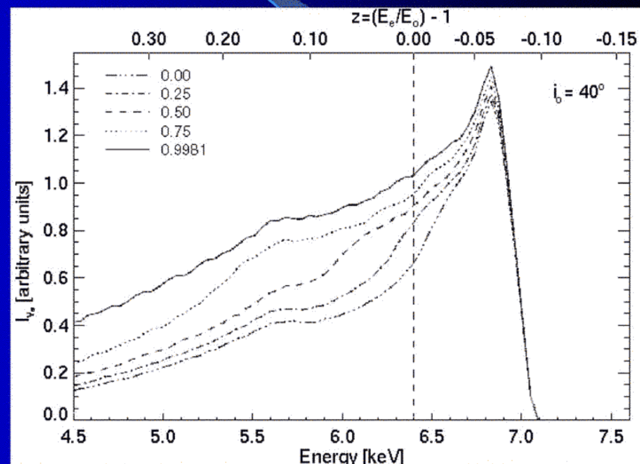
II : Black Hole Spin

- Spin affects line profile through…
  - Photon trajectories
  - **Disk structure**
- Principal effect…
  - ISCO lies at successively higher gravitational redshift for higher a/m



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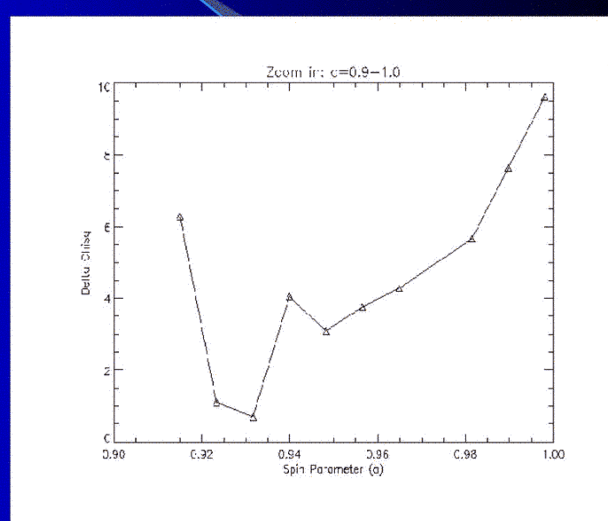
First step - assume no line emission within ISCO

- Obtain lower bound on a/m from maximum detected redshift.
- Fit sequence of line profiles to data with different a/m
- Formal result for MCG-6-30-15
  - a/m>0.91
  - (aside: rules out non-rotating boson stars)



L.Brenneman

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Major uncertainty: contribution from the plunge region

- You **can** get line emission from within ISCO!
- All you need is…
  - Optical depth $\tau_e>1$
    - Continuity $\Rightarrow$ $\tau_e>1$ for all radii if $L>0.1L_{Edd}$
  - Ionization parameter; $\xi\equiv 4\pi F/n<5000$
    - Uncertain, but $\xi<5000$ plausible some way into the plunge region (maybe down to 4.5M in Schwarzschild)
  - Illumination
    - Major uncertainty… vertically extended X-ray source or intrinsic dissipation within plunge flow?

Reynolds & Begelman (1997)

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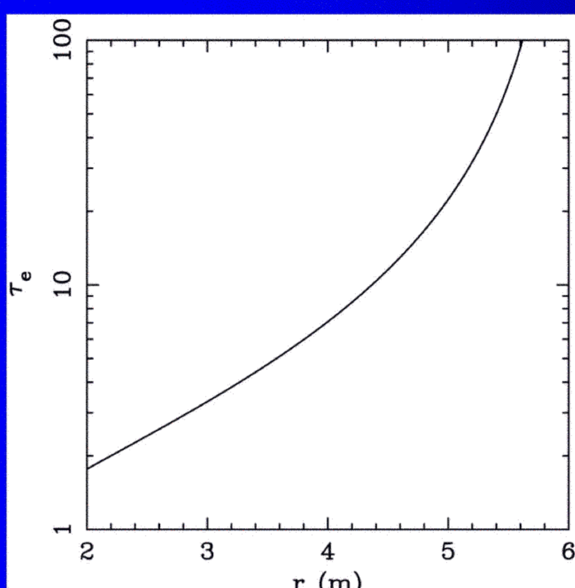
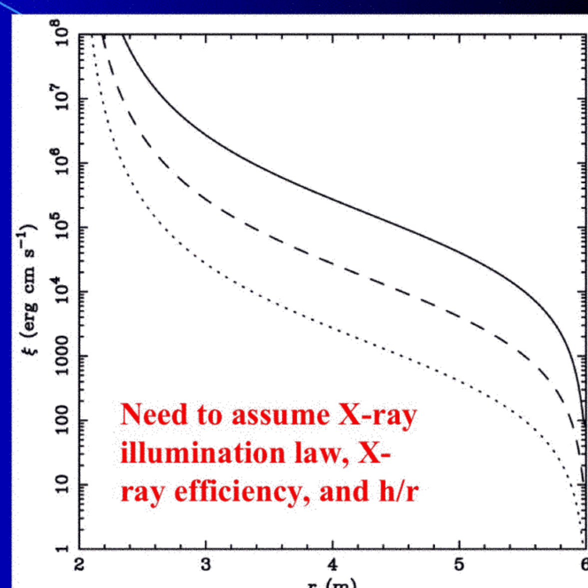
Schwarzschild geometry



OPTICAL DEPTH



IONIZATION

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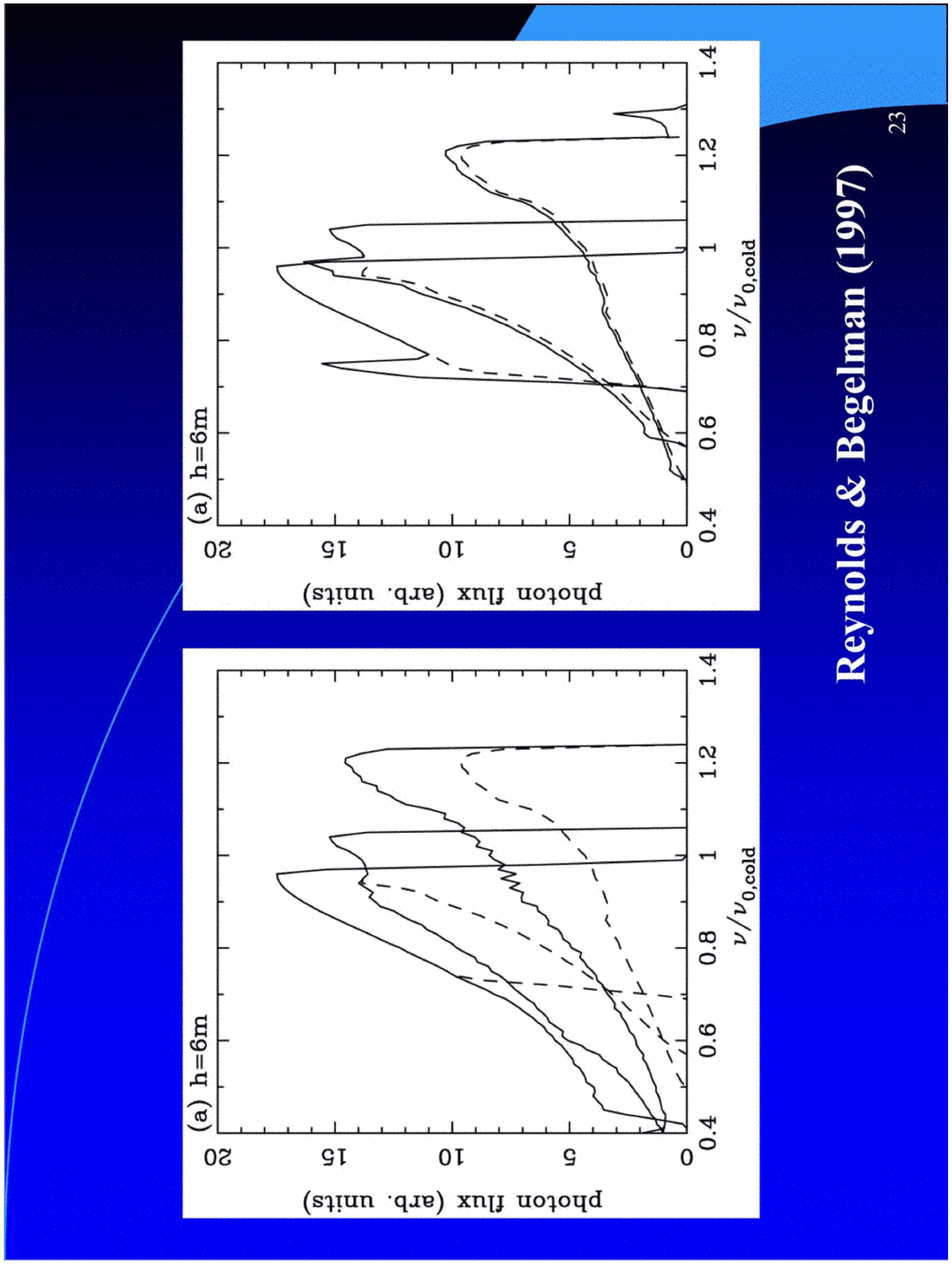
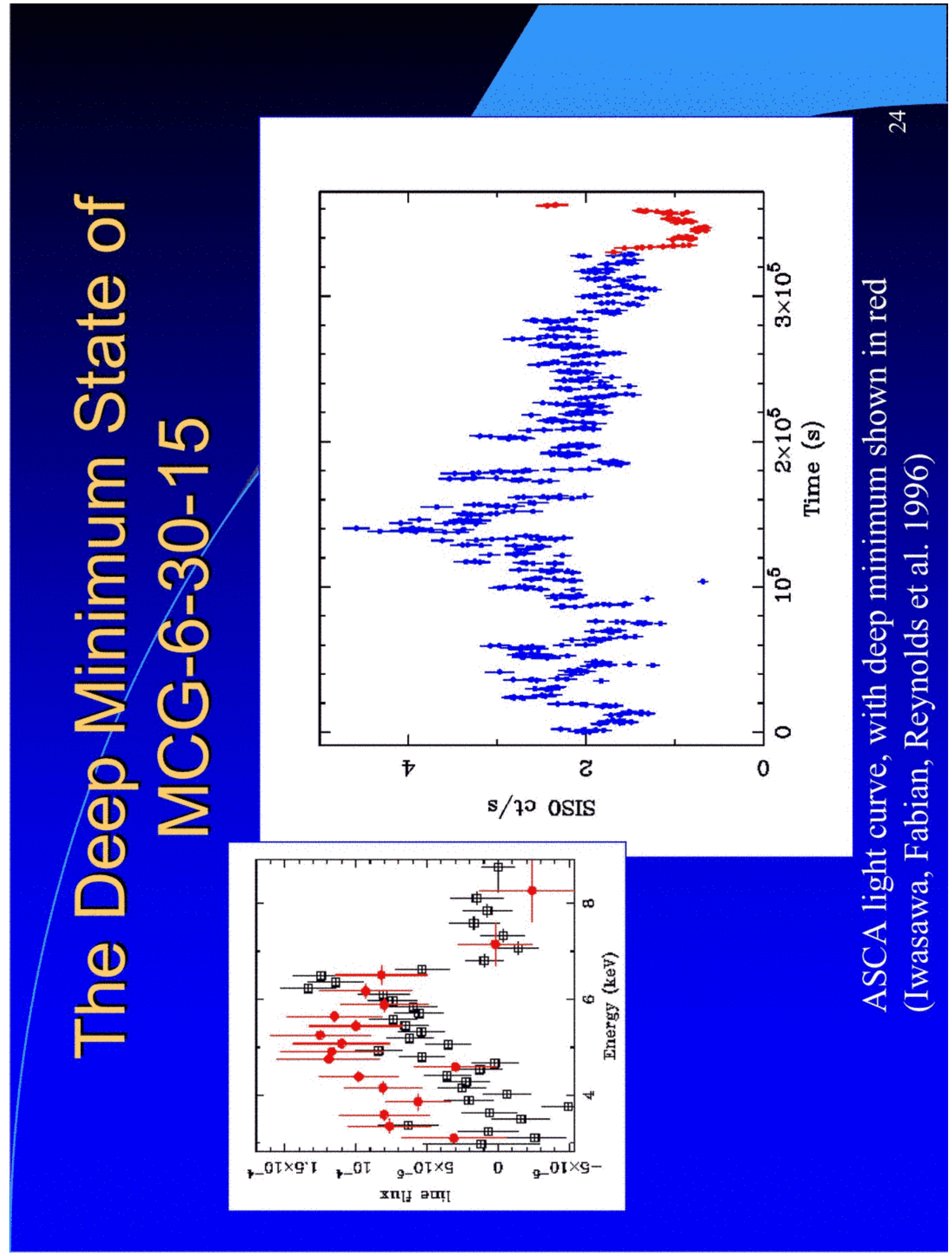
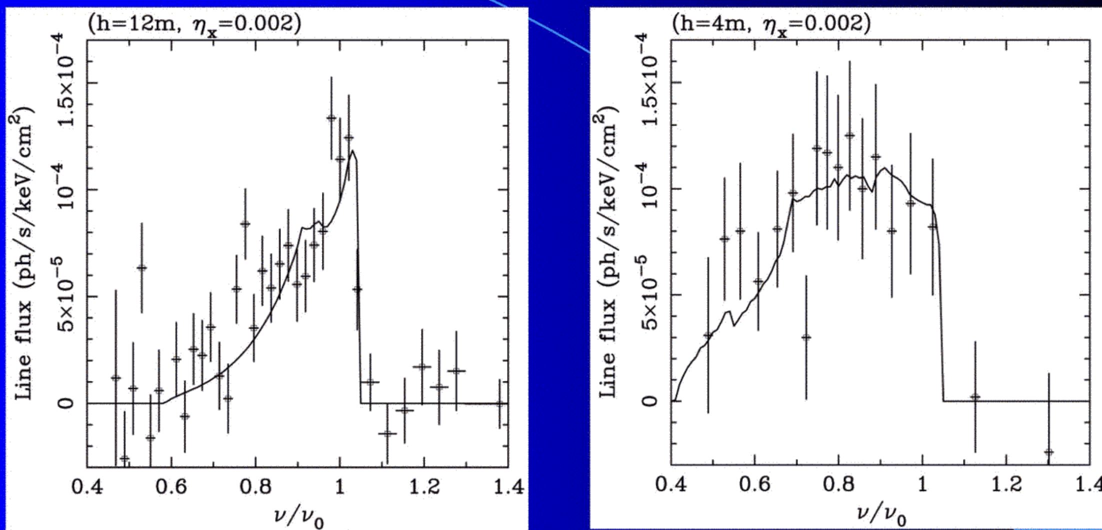

Reynolds & Begelman (1997)
23
(a) h=6m
photon flux (arb. units)
$\nu/\nu_{0,\mathrm{cold}}$
(a) h=6m
photon flux (arb. units)
$\nu/\nu_{0,\mathrm{cold}}$


The Deep Minimum State of MCG-6-30-15
24
SIS0 ct/s
Time (s)
line flux
Energy (keV)
ASCA light curve, with deep minimum shown in red
(Iwasawa, Fabian, Reynolds et al. 1996)

Application to ASCA data



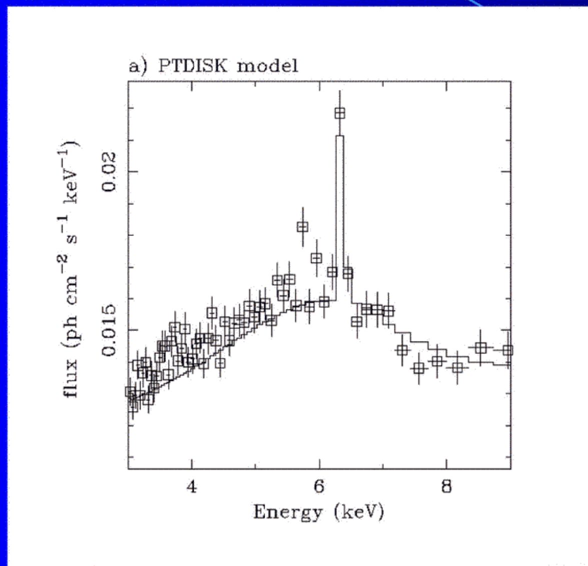
- Suppose X-ray source is some height h up symmetry axis
- Could explain change in continuum flux, and the iron line profile & strength just by changing height of source, for a/m=0!
- Relies on emission down to R~4.5M.

Reynolds & Begelman (1997)

Including emission within ISCO

- If we allow for reflection from any $r>r_{evt}$, one can produce an arbitrarily redshifted line even for a/m=0
- Has been suggested that this makes lines a bad diagnostic for BH spin (Dovciak et al. 2004)
  - Not true, but we must consider astrophysics of the plunge region.
- Case of MCG-6-30-15
  - a/m=0.0 fit ⇒ needs emission concentrated at r=3M
  - Simple model of plunge region (RB97) suggests this is not plausible… region would be fully ionized.
- **<u>Need a better model of the plunge region!!</u>**

III : Physics of the inner disk



Reynolds et al. (2004)

Assume that the X-ray reflection tracks dissipation in an underlying Novikov-Thorne disk… cannot produce observed redshifts.

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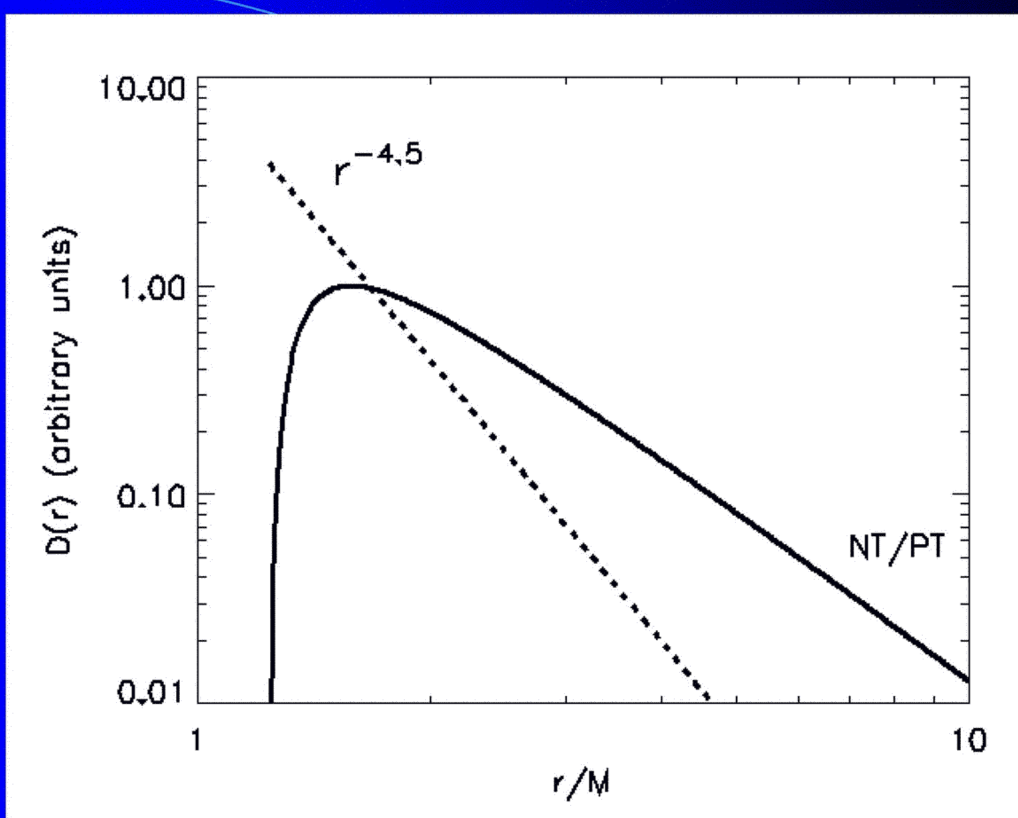

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Lines broader than predicted from NT disk

Disk is NT-like, but X-ray reflection does not track local dissipation (need light bending)

Fabian

Reflection tracks a dissipation that is much more centrally concentrated than NT law

CSR

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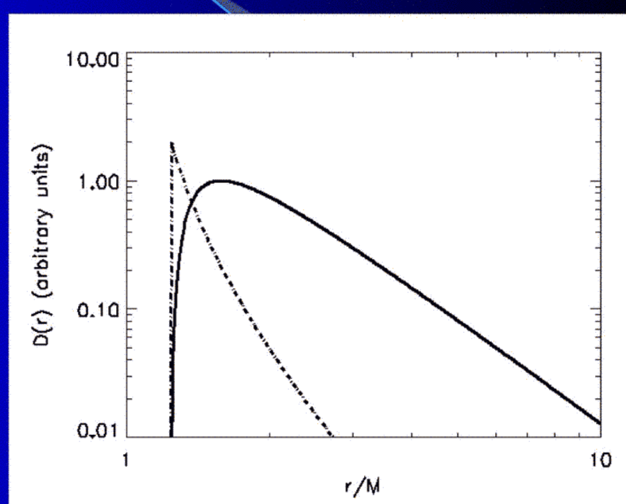
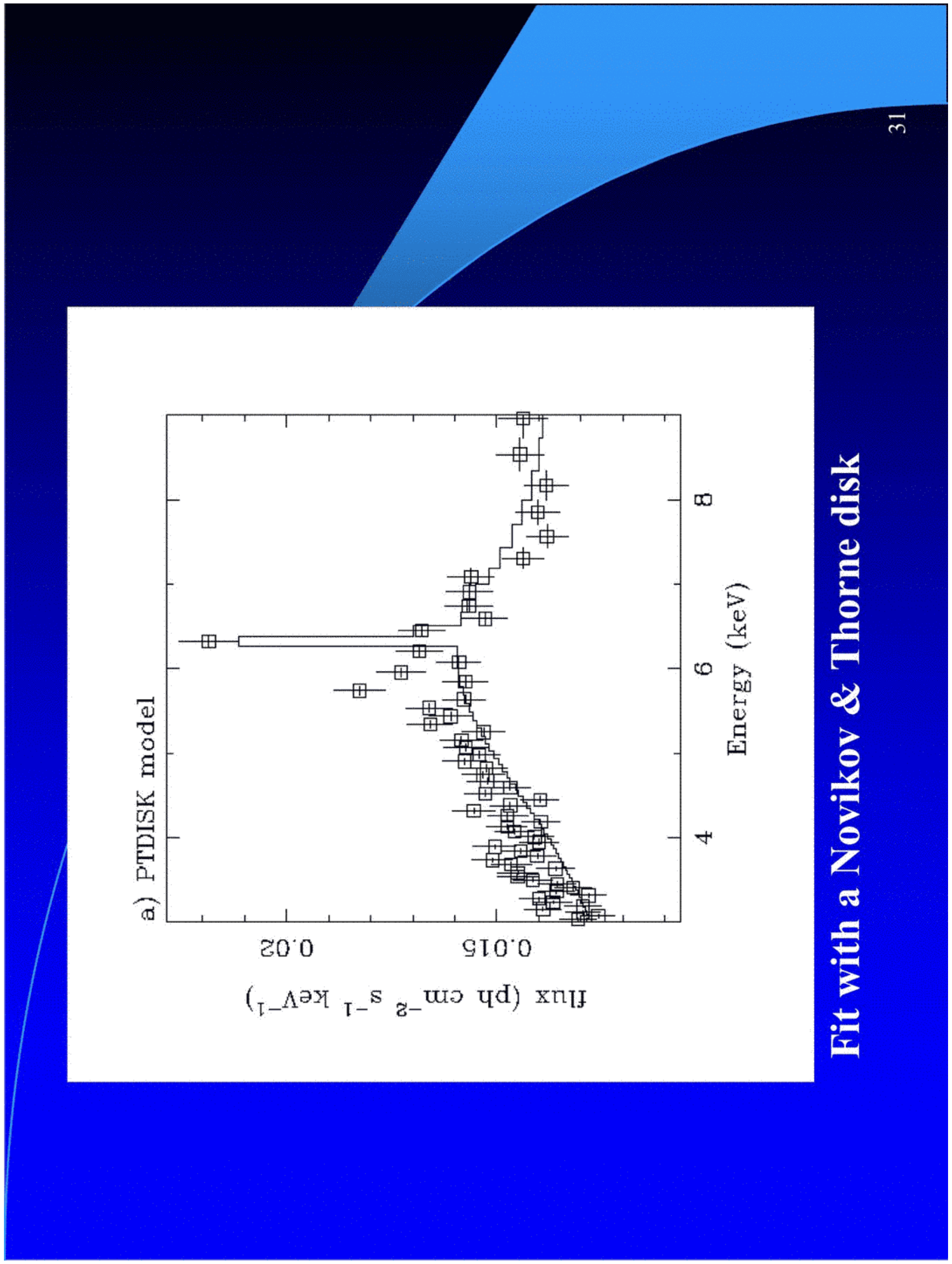
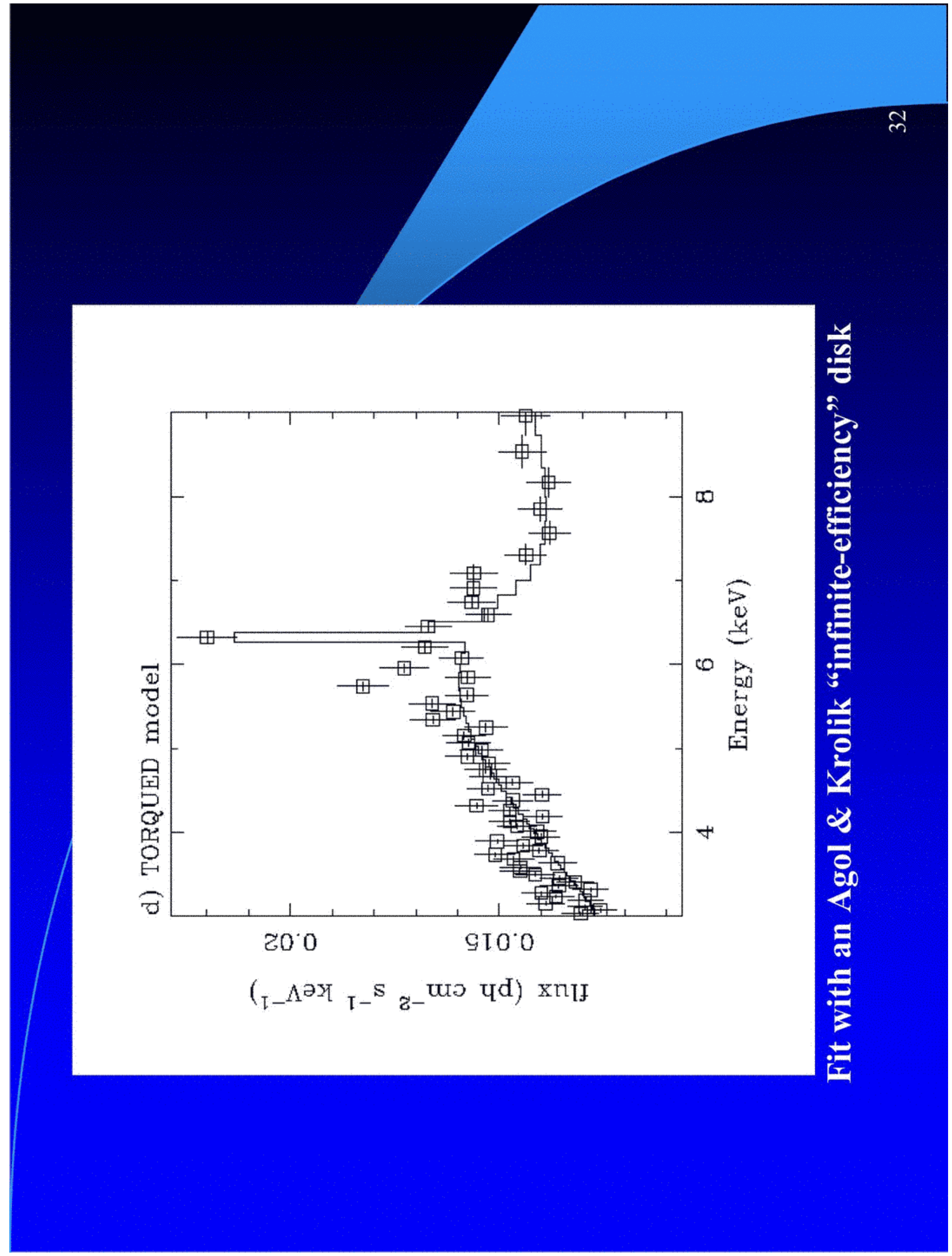
Extra dissipation in inner region?

- "Need extra power source near center of disk"
- Suppose inner edge of disk ($r=r_{ms}$) is subject to a torque…
  - Torque does work on disk.
  - Extra dissipation in disk associated with torque
- Examined for relativistic disk by Gammie (1999), Agol & Krolik (2000) and Li (2000)
- **But what about physics of plunge region?**

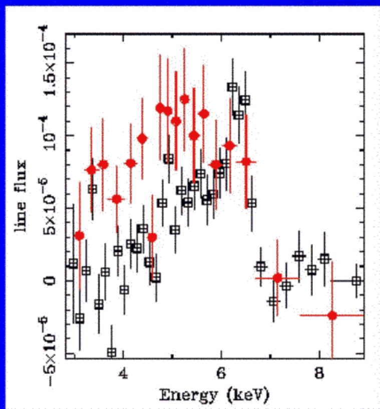


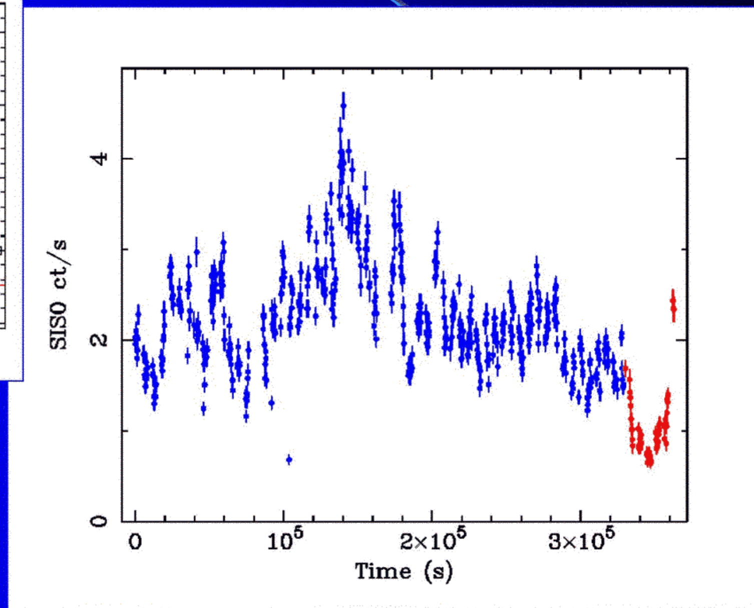
30


Fit with a Novikov & Thorne disk
a) PTDISK model
flux (ph cm^{-2} s^{-1} keV^{-1})
0.015
0.02
Energy (keV)
4
6
8
31


Fit with an Agol & Krolik "infinite-efficiency" disk
d) TORQUED model
flux (ph cm^{-2} s^{-1} keV^{-1})
0.015
0.02
Energy (keV)
4
6
8
32

The Deep Minimum State of MCG-6-30-15





ASCA light curve, with deep minimum shown
(Iwasawa, Fabian, Reynolds et al. 1996)

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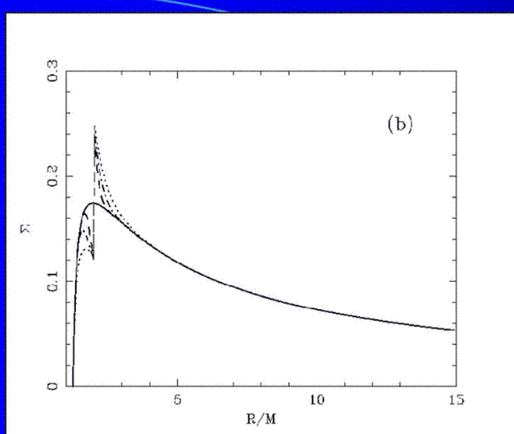

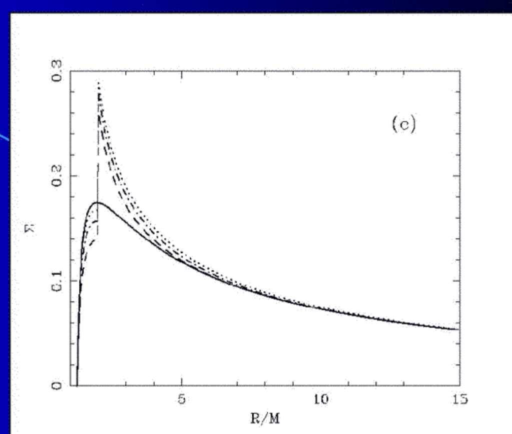

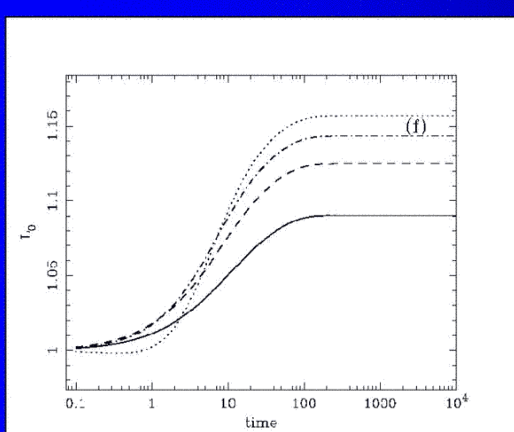

Response of disk to step-function torquing event… damming following by refilling of inner regions

Garofalo & Reynolds (2005)

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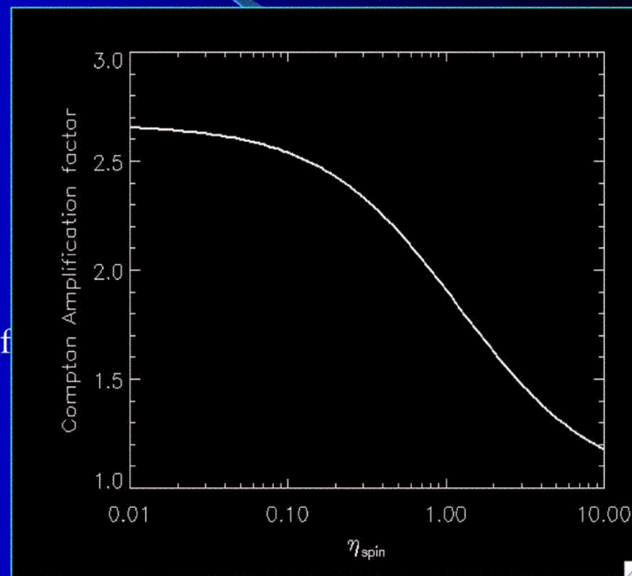
Sporadic torquing and the effect of Compton-cooling by Returning Radiation could give Deep Minimum

- Coronal suppression by Returning Radiation…
  - Corona suffers significant Compton cooling from other radii in disk (strong light bending)
  - Can significantly cool corona… reduce fraction of emission in 0.5-10keV band dramatically
  - May even completely collapse corona!



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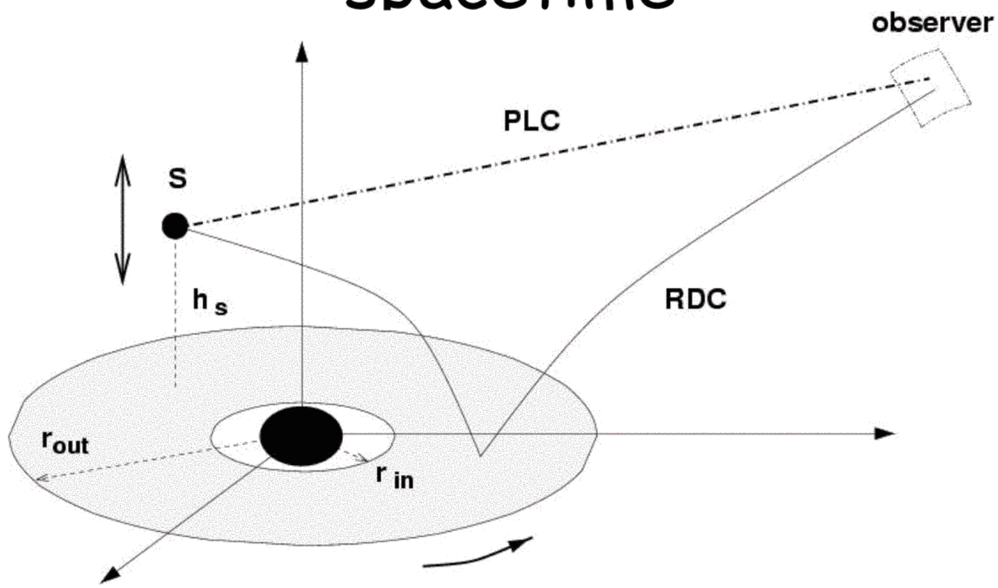
SLIDES COURTESY OF A. FABIAN

Light bending model in Kerr spacetime



Miniutti et al 03; Miniutti & Fabian 04; earlier work by Matt et al

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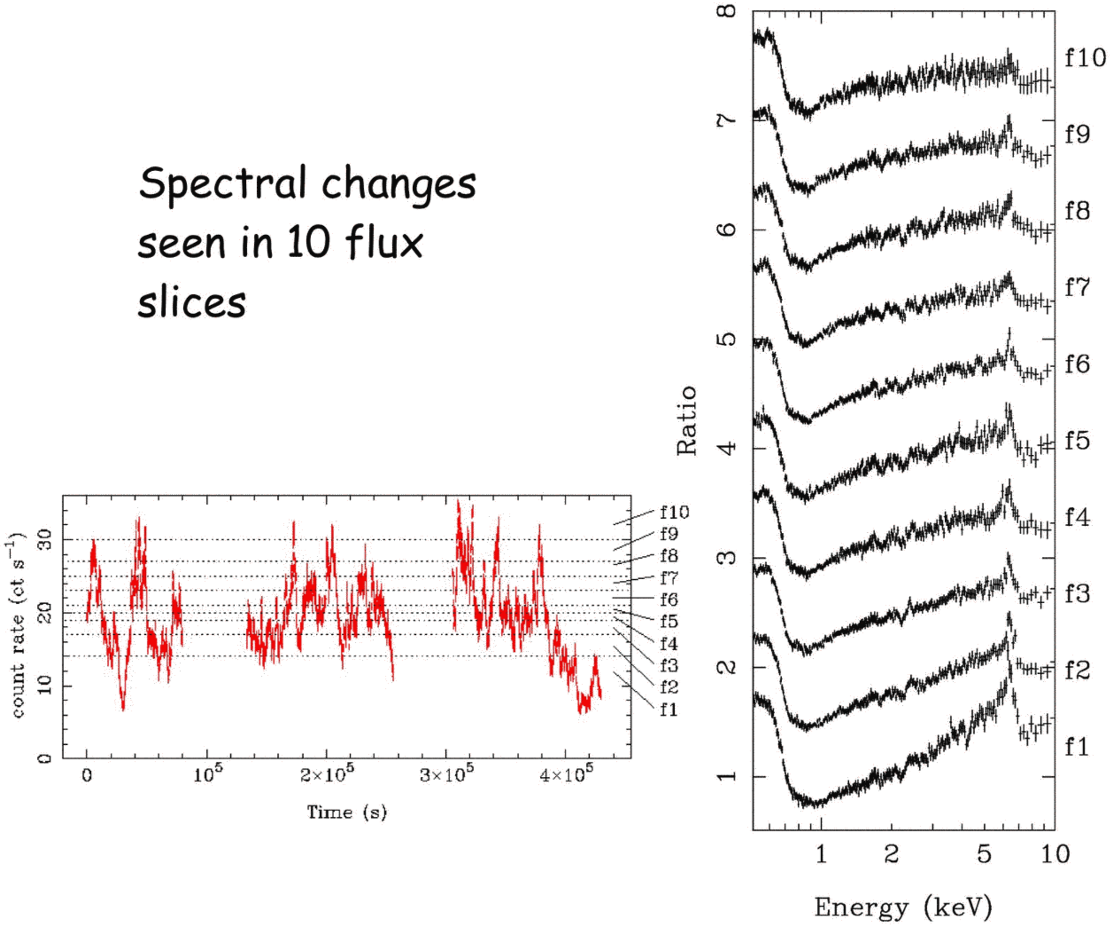
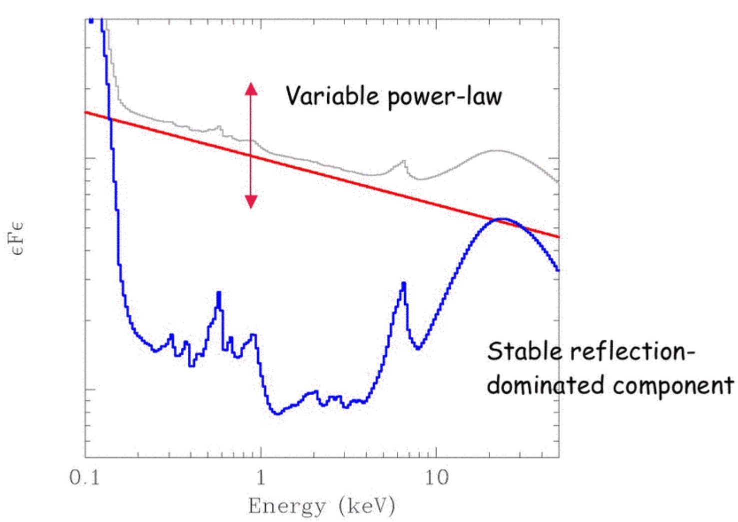
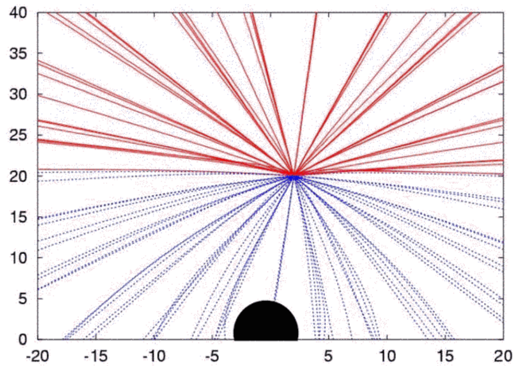
Spectral changes seen in 10 flux slices



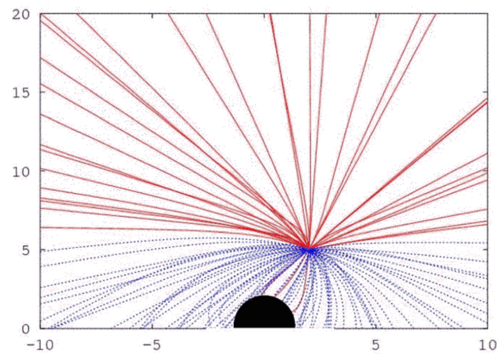
Schematic picture of the two-component model



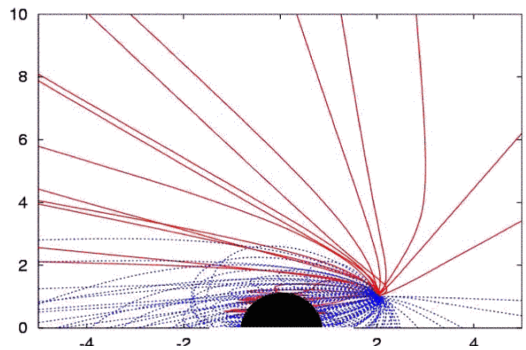


Primary source at h = 20 r_g
isotropy and R = 1

Red = escaping photons



Primary source at h = 5 r_g
anisotropy and R > 1



Primary source at h = 1 r_g
anisotropy and R >> 1

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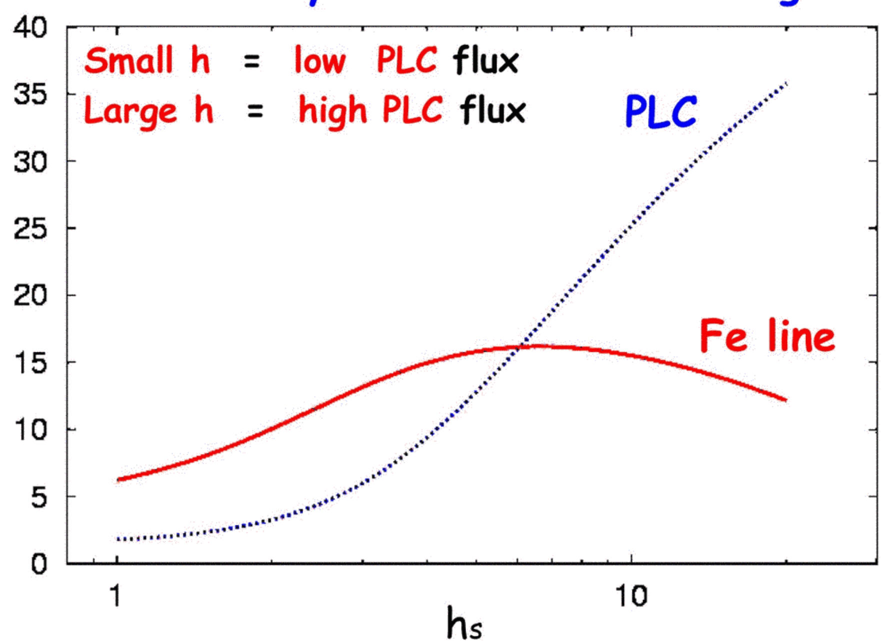
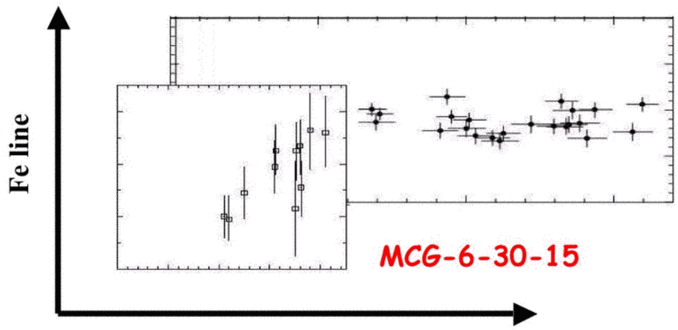
PLC and Fe line variability induced by light bending when an intrinsically constant source changes height

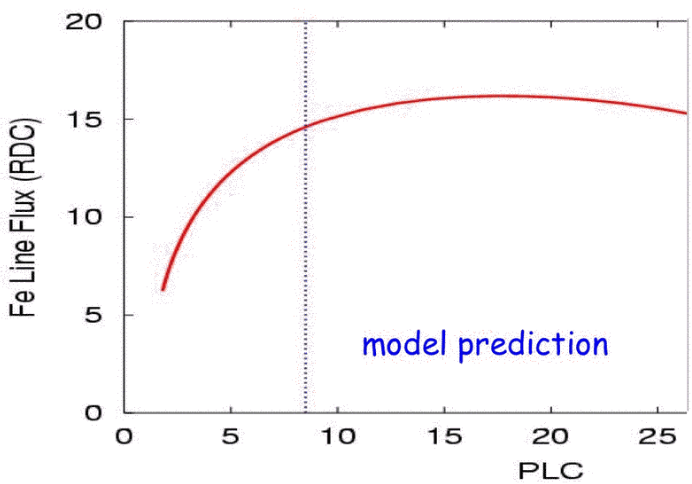


The Fe line varies with much smaller amplitude

40



Low flux results
from Reynolds et al



more details on the model:
GM et al, 2003, MNRAS 344 L22
GM & Fabian, 04
GM et al, 04

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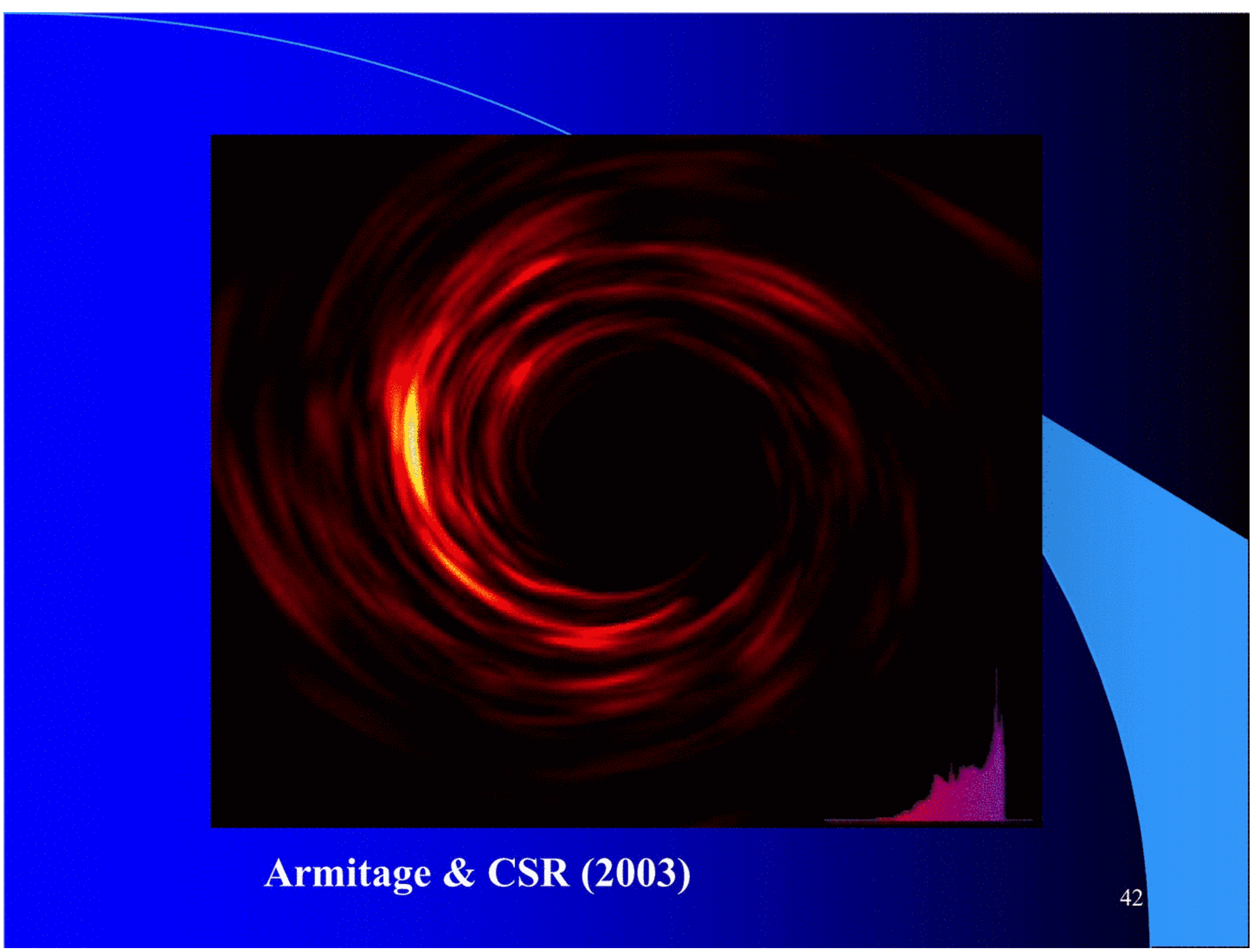

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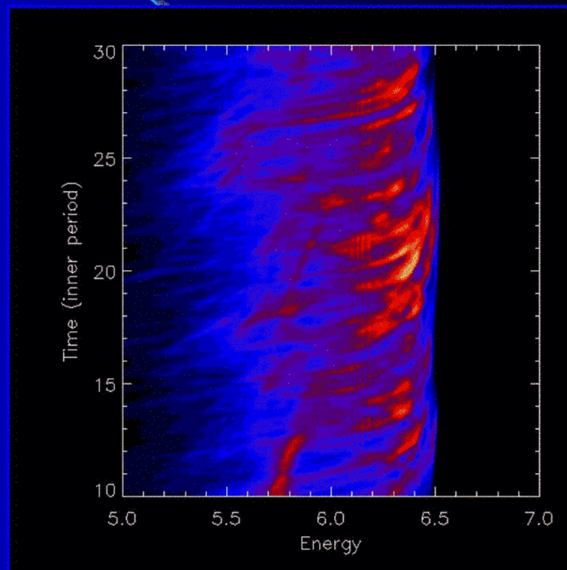
Iron line variability

- Con-X (XEUS) will allow detailed study of line variability
- See effects of non-axisymmetric structure orbiting in disk
  - Follow dynamics of individual "blobs" in disk
  - Quantitative test of orbital dynamics in strong gravity regime



Armitage & CSR (2003)

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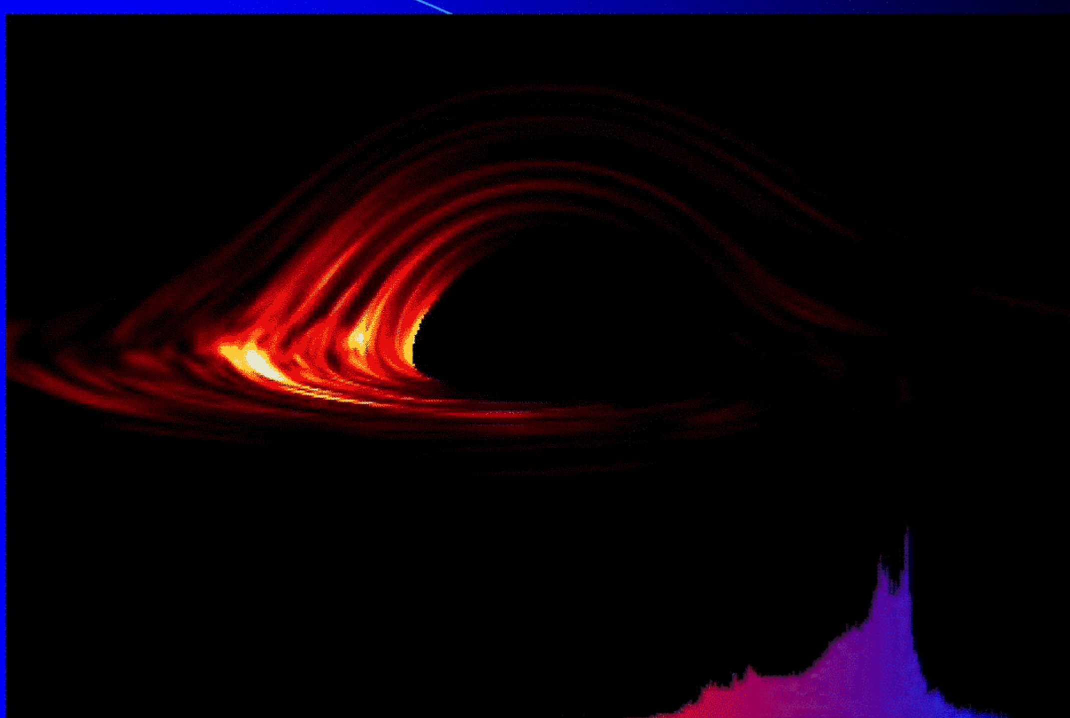
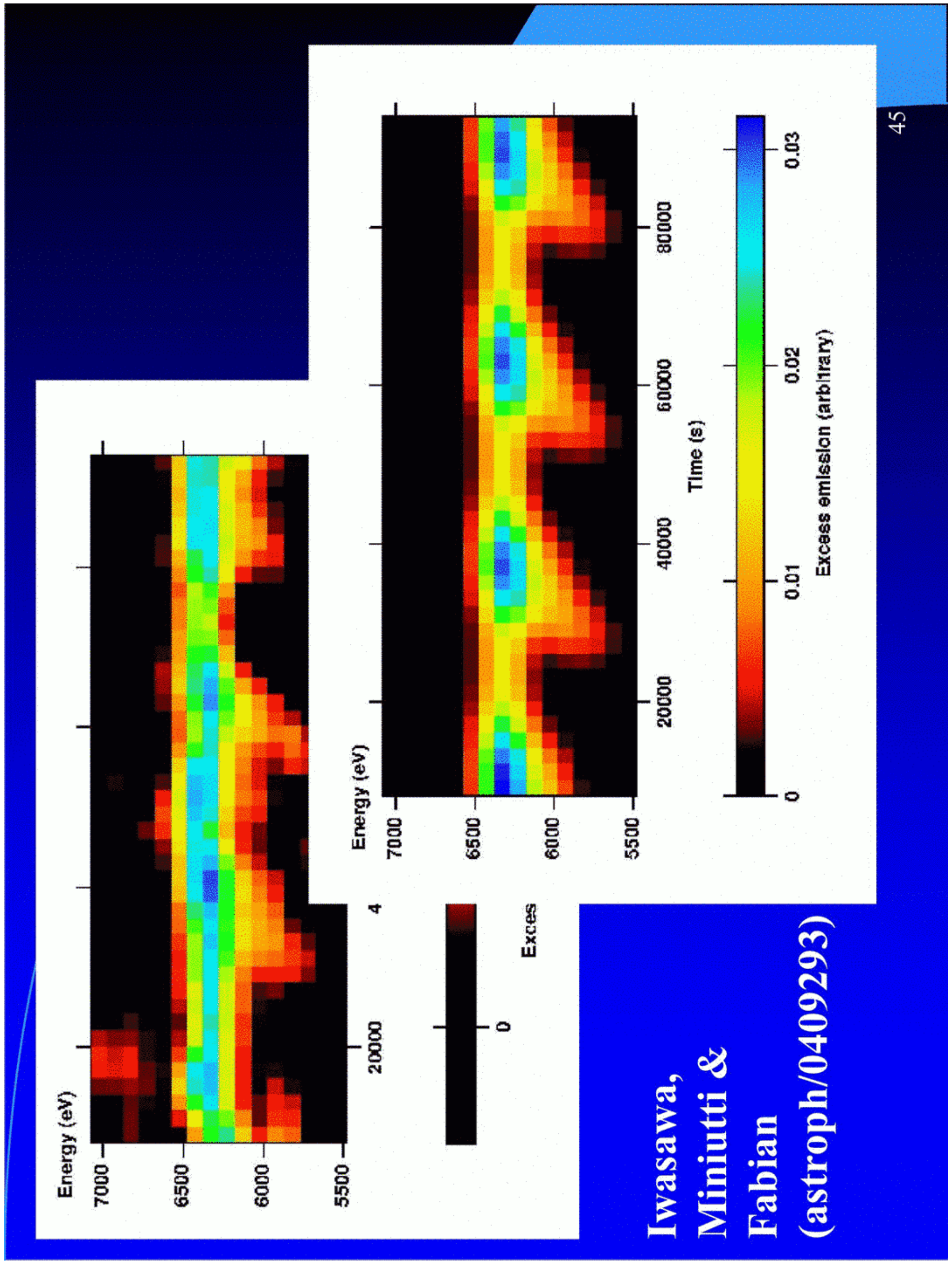
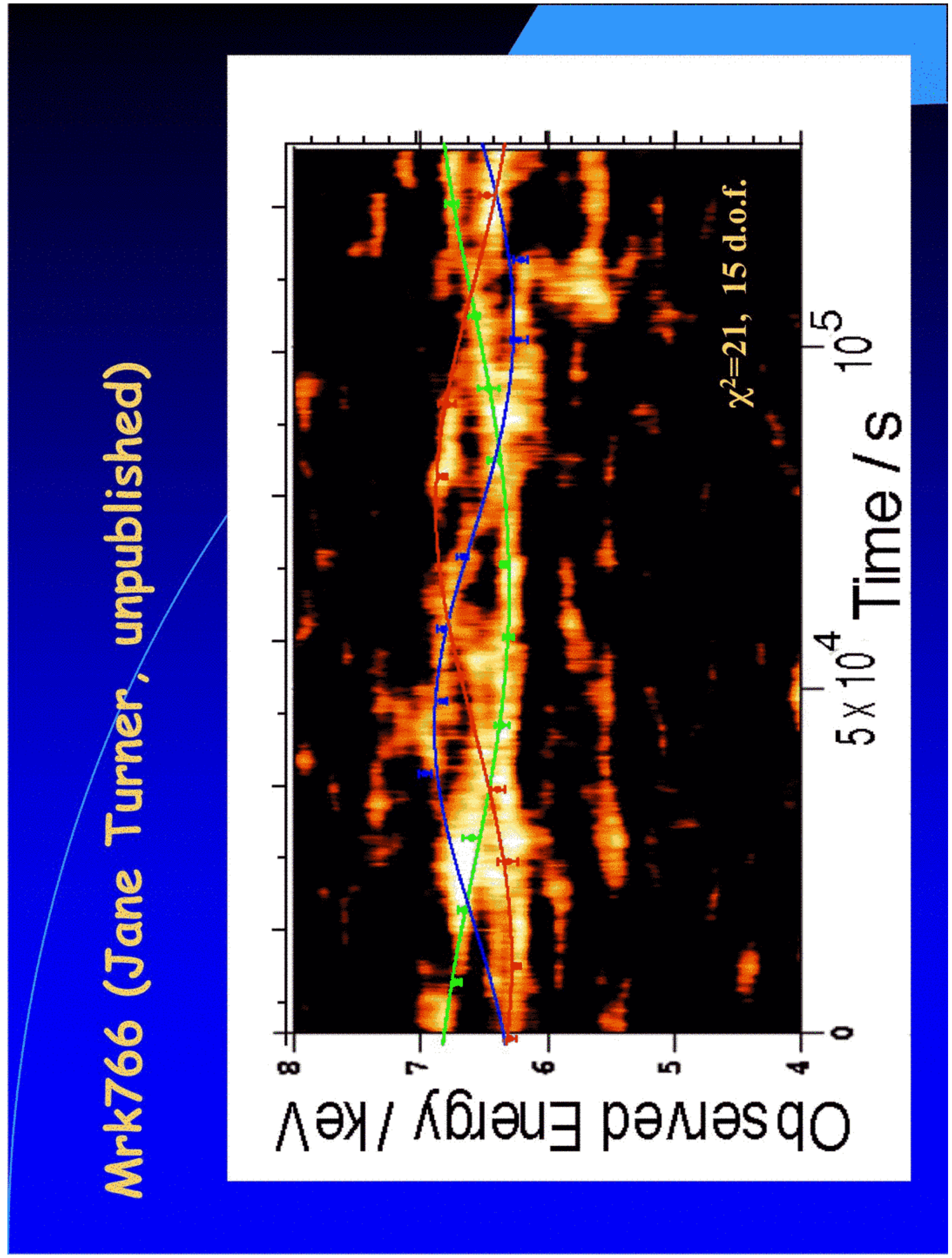


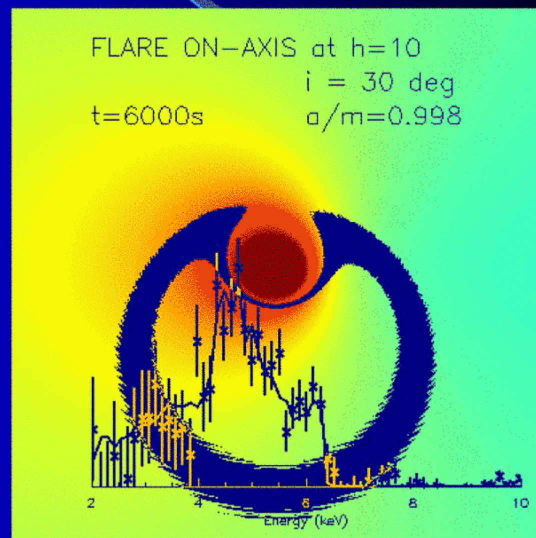
44


Iwasawa, Miniutti & Fabian (astroph/0409293)
Energy (eV)
Time (s)
Excess emission (arbitrary)
45


Mrk766 (Jane Turner, unpublished)
Observed Energy / keV
Time / s
χ2=21, 15 d.o.f.

Relativistic iron line reverberation…

- Reverberation
  - X-ray source displays dramatic flares
  - Flare produces "X-ray echo" that sweeps across accretion disk
  - Iron line profile will change as echo sweeps across disk
  - Needs high throughput spectroscopy – but probably within reach of Con-X



CSR et al. (1999)
Young & CSR (2000)

Summary

- There are robust examples of iron emission lines from the innermost regions of black hole disks
  - But fraction of sources showing line unclear…
- Line profiles are sensitive to BH spin
  - Can probably rule our Schwarzschild hole in MCG-6-30-15 and GX339-4
  - Constraints limited by models of plunge region…
- Probing astrophysics of innermost disk
  - Can rule out X-ray corona tracking simple NT disk
  - Good evidence for strong light bending (X-ray source base of jet, not corona?)
  - Can also confront modifications of NT disk.