X-ray signatures of strong gravity

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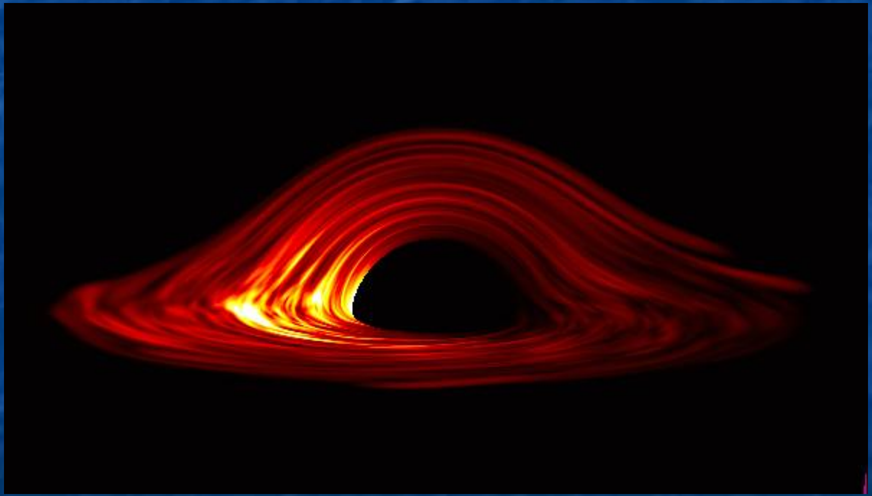


I : Outline

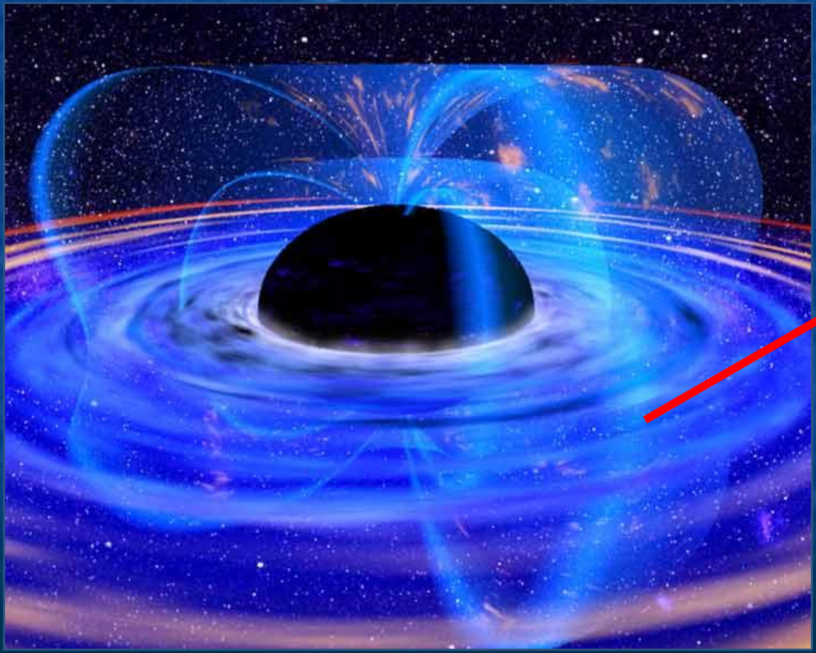
- X-ray emission as a probe of black holes & accretion
- Structure and physics of accretion disks
- Black hole spin and related astrophysics
- The future…

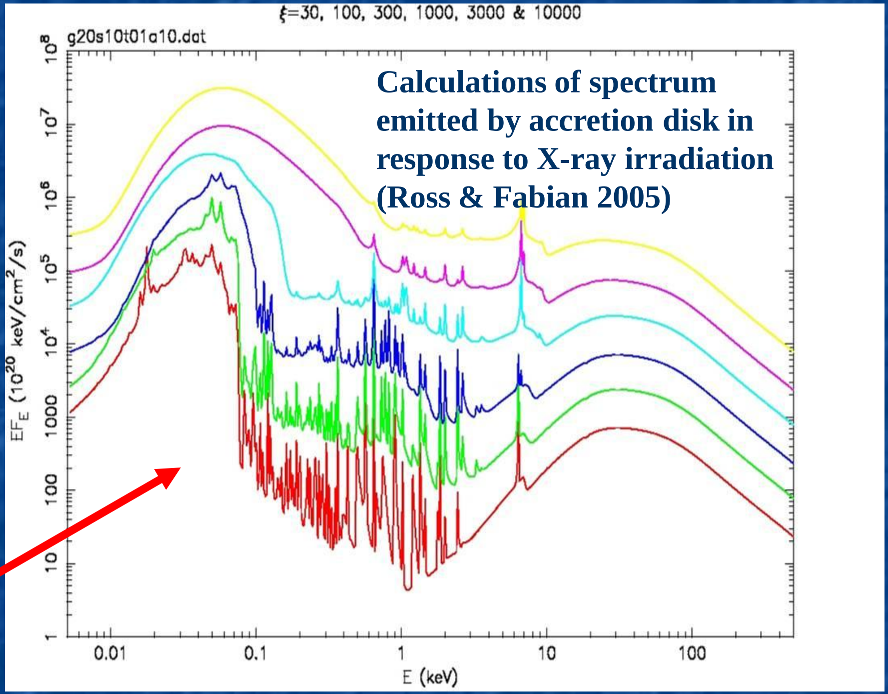
Collaborators:

- Laura Brenneman (GSFC)
- Andy Fabian (Cambridge)
- Cole Miller (UMd)
- Jon Miller (Michigan)
- Abdu Zoghi (Cambridge)

II : X-ray reflection spectroscopy

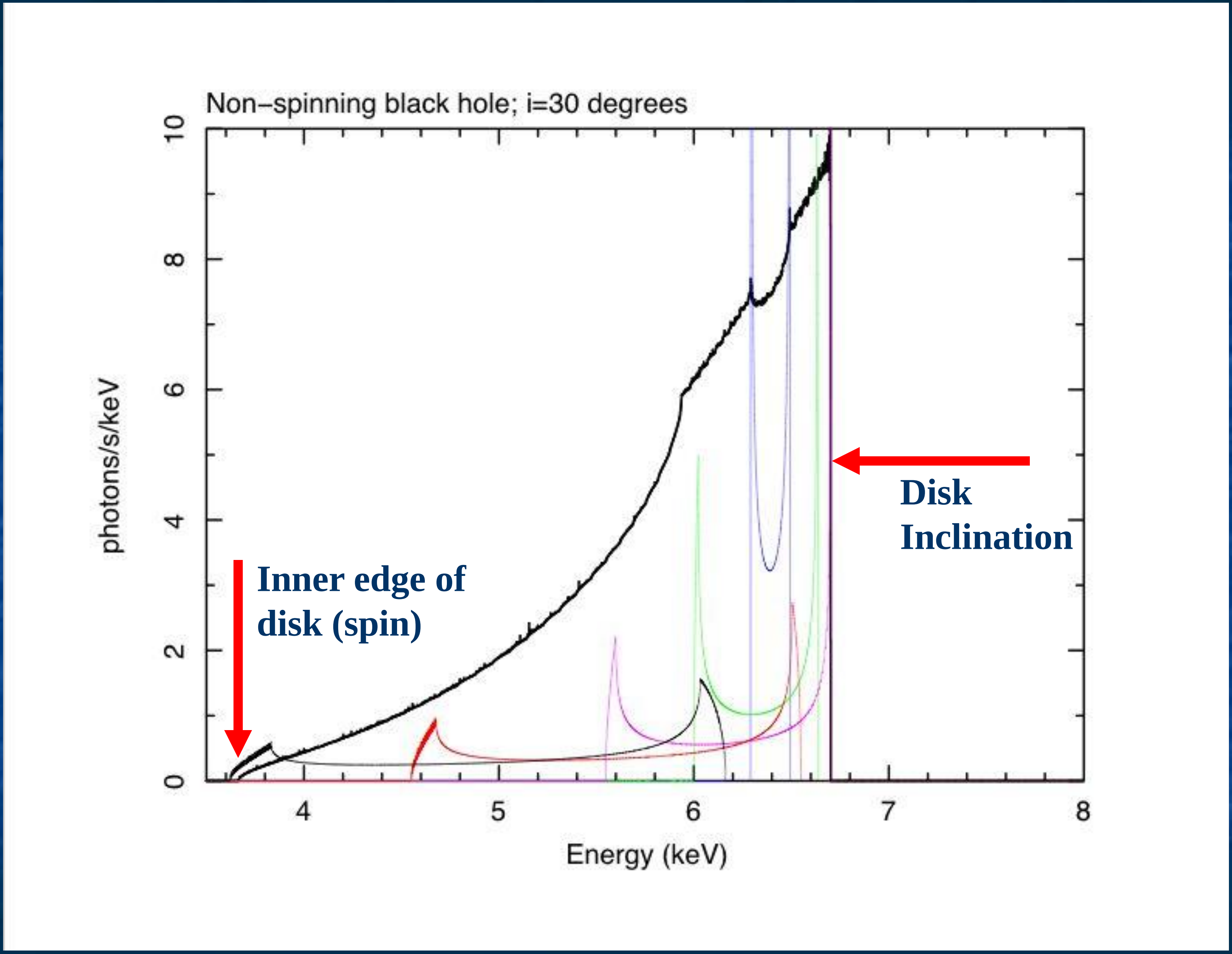
X-rays from corona/jet irradiate accretion disks… creates a backscattered spectrum rich in spectral features



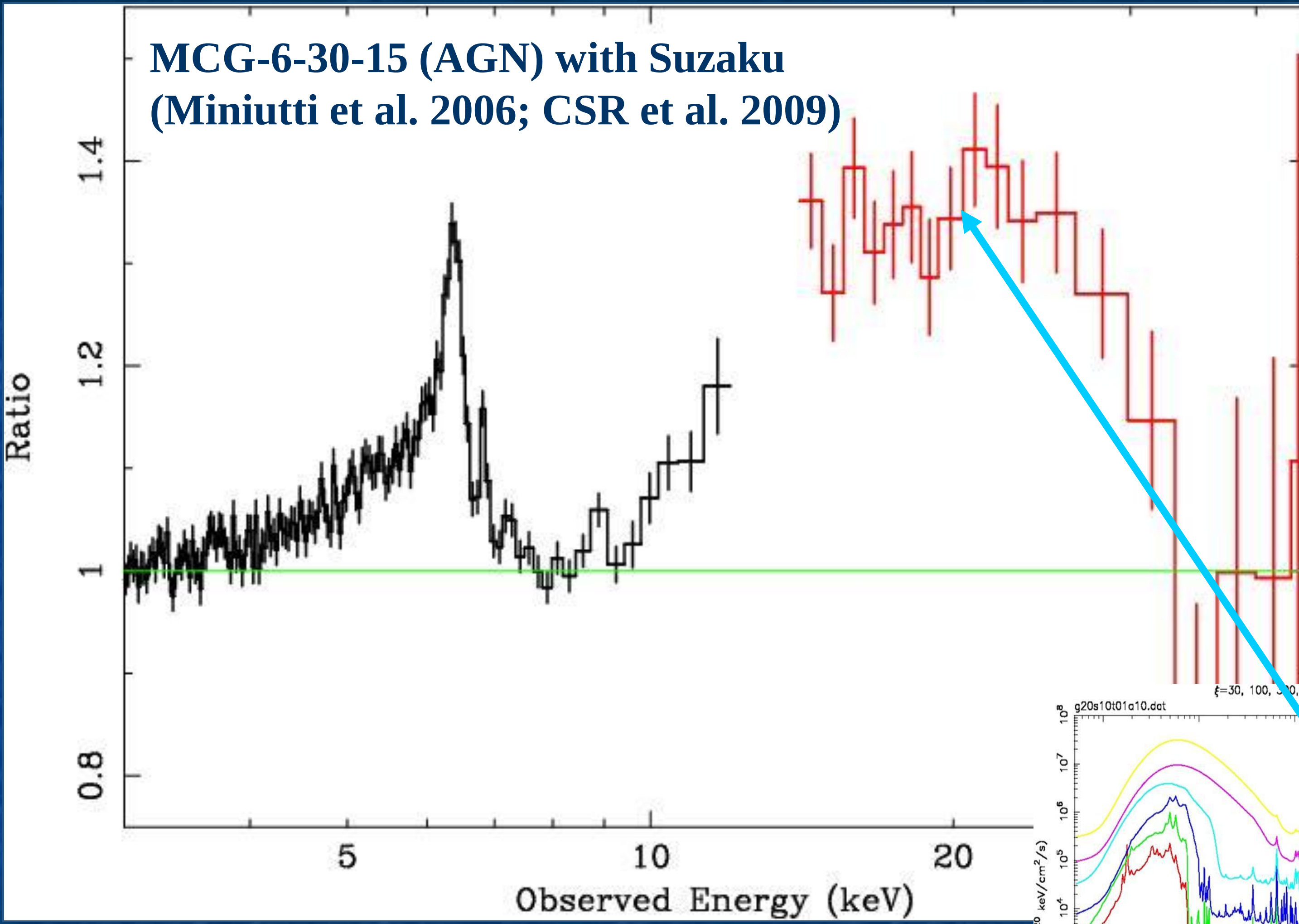


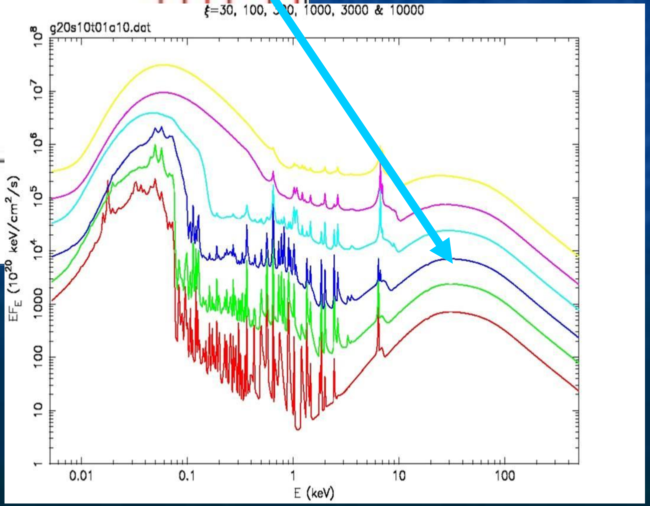
Calculations of spectrum emitted by accretion disk in response to X-ray irradiation (Ross & Fabian 2005)

Very similar fluorescence features seen from surface of Sun during X-ray bright solar flare

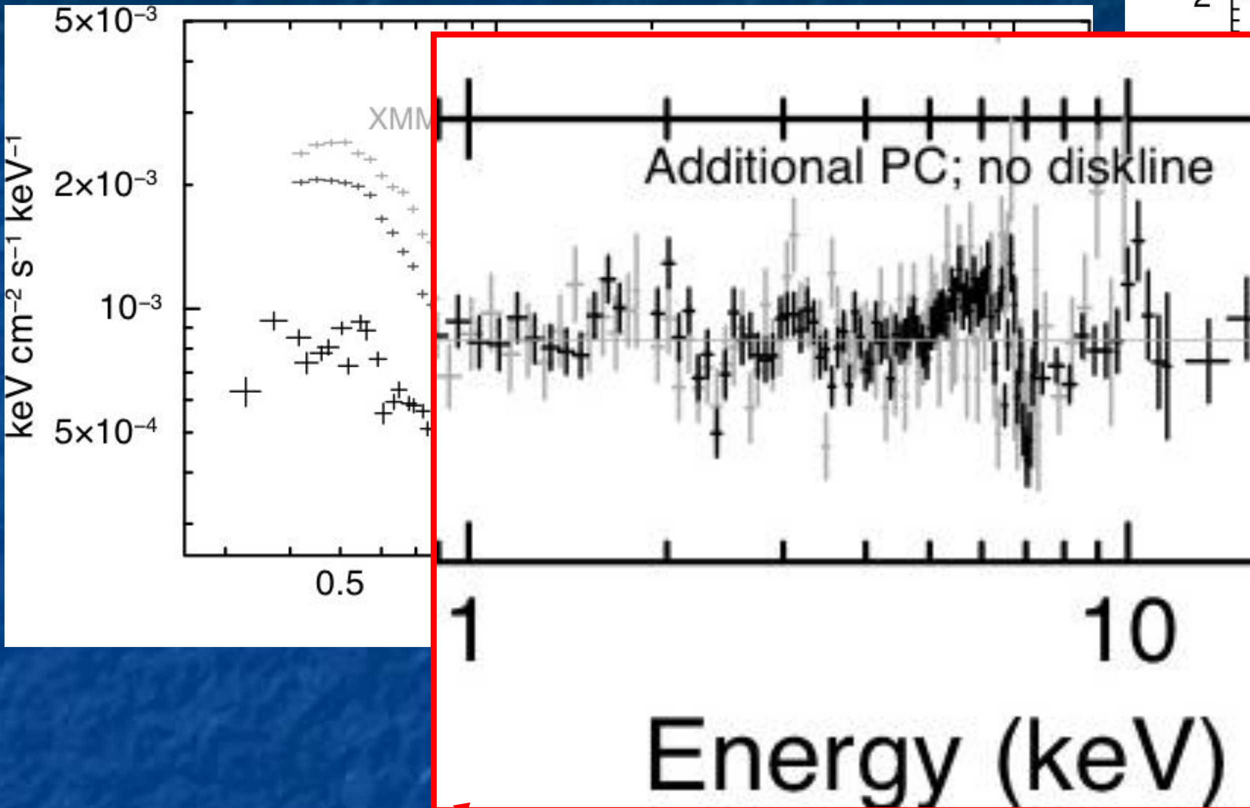

Non–spinning black hole; i=30 degrees
photons/s/keV
0
2
4
6
8
10
4
5
6
7
8
Energy (keV)
Inner edge of disk (spin)
Disk Inclination

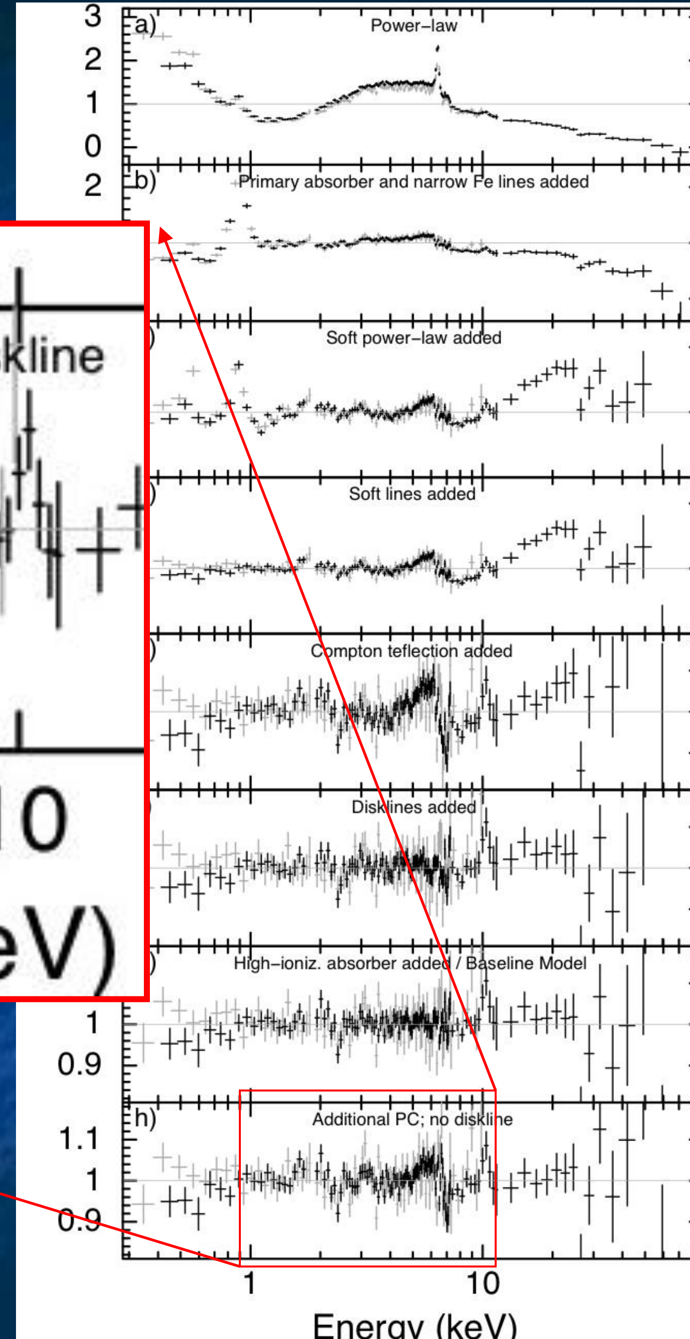
MCG-6-30-15 (AGN) with Suzaku
(Miniutti et al. 2006; CSR et al. 2009)





NGC 3516 (XMM and Suzaku)
(Markowitz et al. 2007)





Broad iron line still discernable, despite heavy and complex absorption; $r_{in}<5.5r_g$

III : Structure of the inner accretion disk

- Broad iron lines seen in >30-50% of luminous AGN and high/thermal state stellar-mass black holes
- Presence of broad iron lines has implications for the **geometric thickness** of the accretion disk…
  - Ionization parameter…

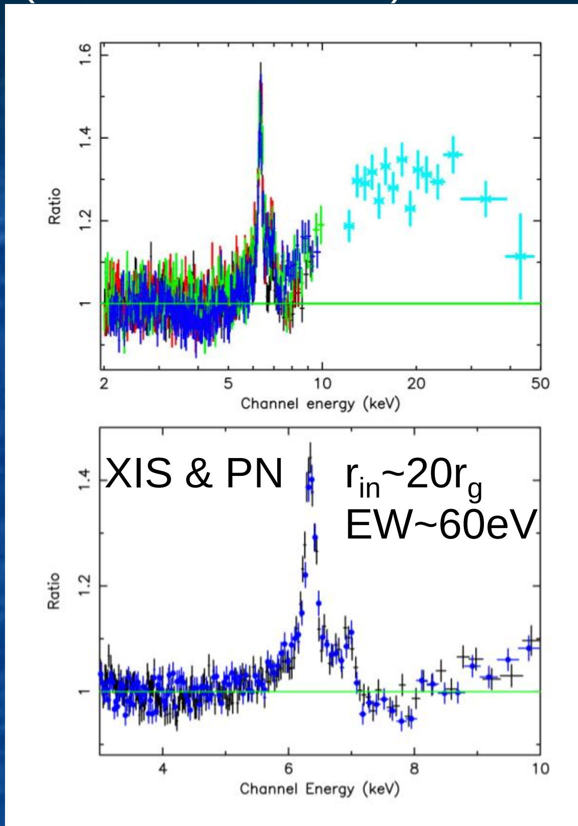
$$\xi = \frac{L}{nr^2} = \frac{L\sigma_T}{\tau g r}\left(\frac{h}{r}\right) \qquad g \equiv \frac{n_{\rm xph}}{\langle n \rangle}$$

  - Estimate τ from alpha-disk theory…

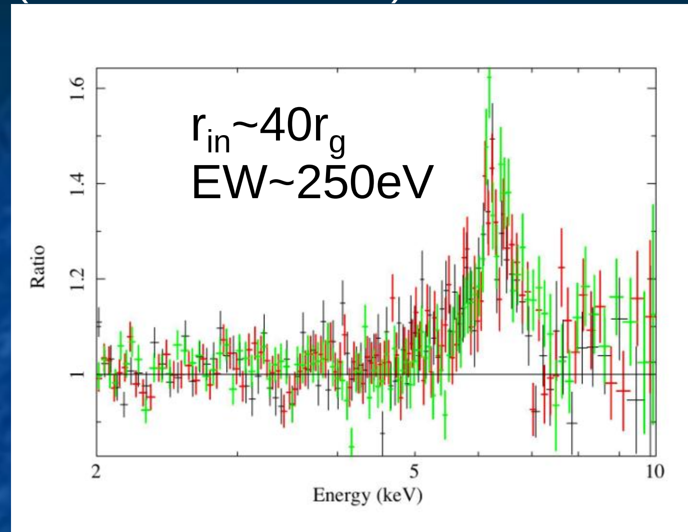
$$\frac{h}{r} \approx \frac{\xi}{m_p c^3} \cdot \frac{(r/r_g)^{5/2} g}{4\pi \dot{m}^2 f_{\rm ion} \alpha}$$

$$\frac{h}{r} \approx 0.04 \left(\frac{\xi}{300}\right)\left(\frac{r}{4r_g}\right)^{5/2}\left(\frac{\dot{m}}{0.1}\right)^{-2}\left(\frac{\alpha}{0.1}\right)^{-1}\left(\frac{f_{\rm ion}}{0.1}\right)^{-1} g$$

MCG-5-23-16 (100ks)
(Reeves et al. 2007)

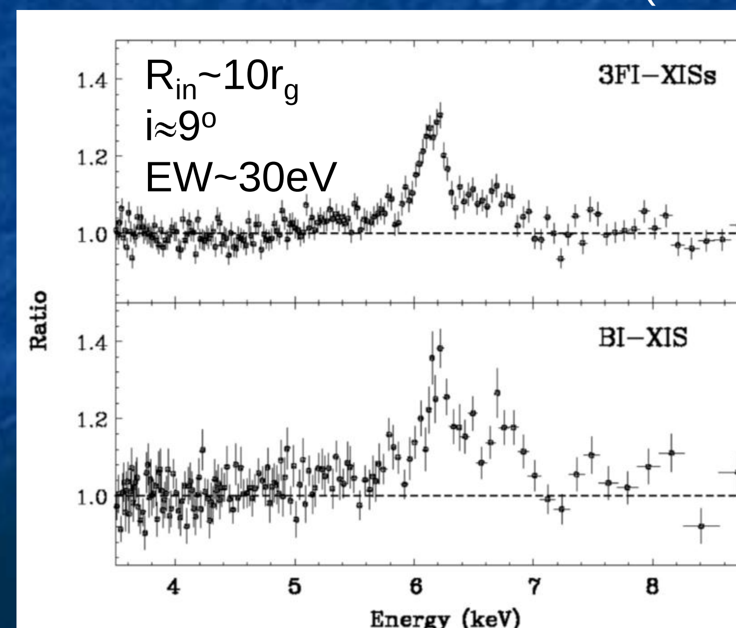


Mrk335 (151ks)
(Larsson et al. 2007)

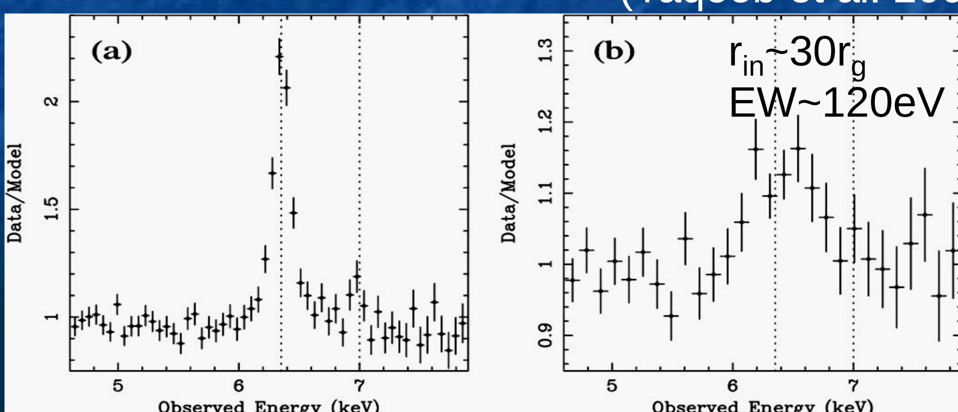


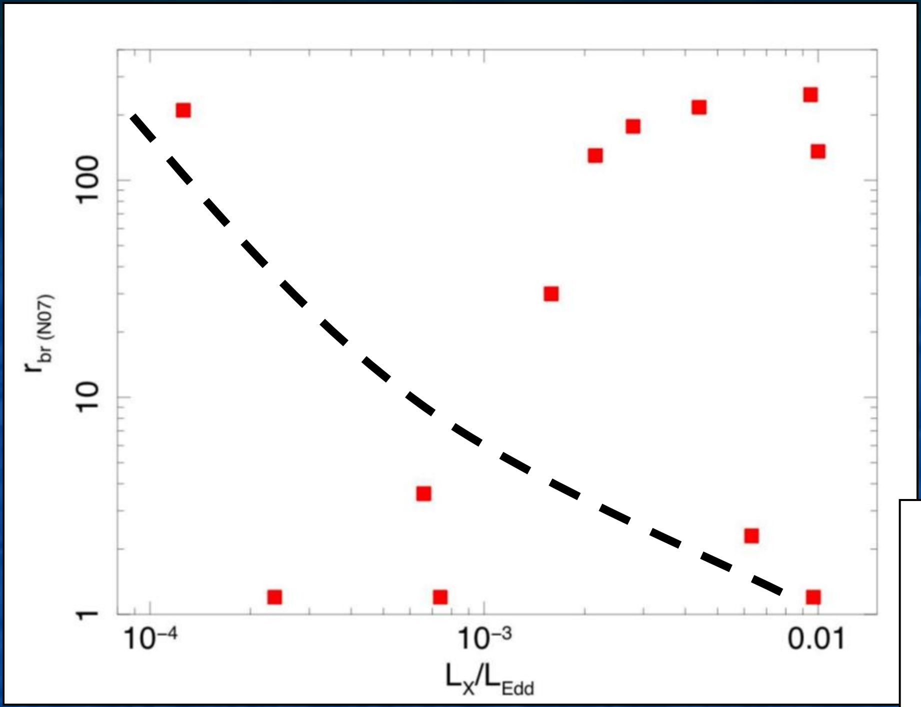
Many AGN seem to have truncated iron line emission regions…
ionized inner disk or transition to radiatively inefficient accretion flow (RIAF)?

3C120 (160ks)
Kataoka et al. (2007)

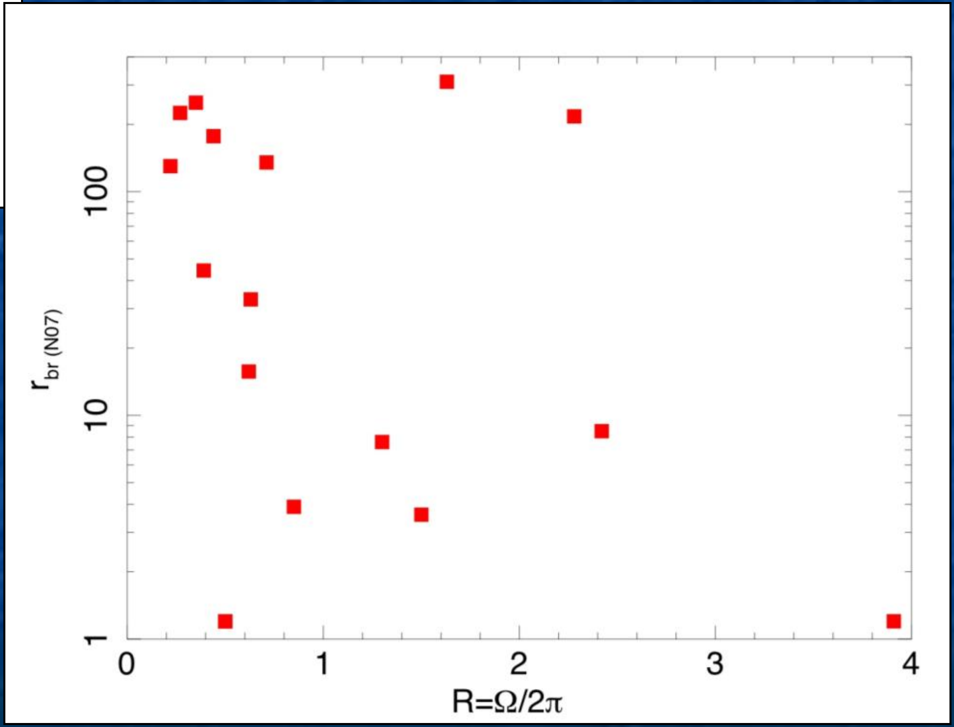


NGC2992
(Yaqoob et al. 2007)





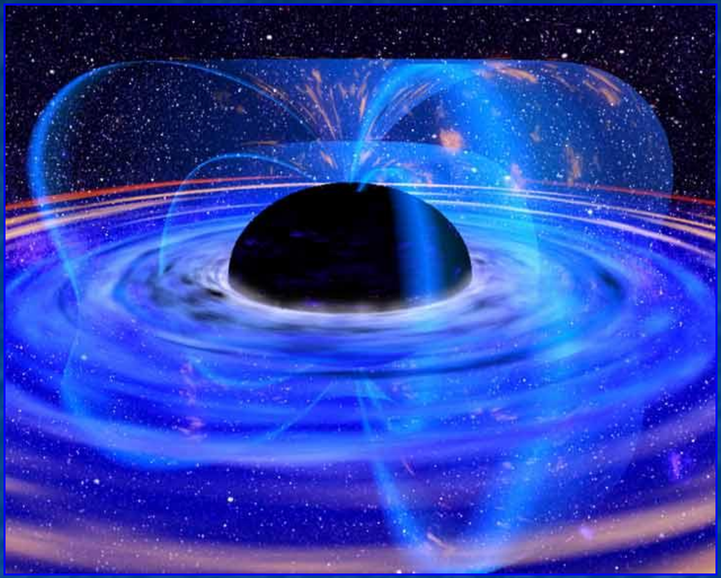
No clear correlation of size of reflecting disk with Eddington ratio… **contrary to predictions of RIAF-transition model**

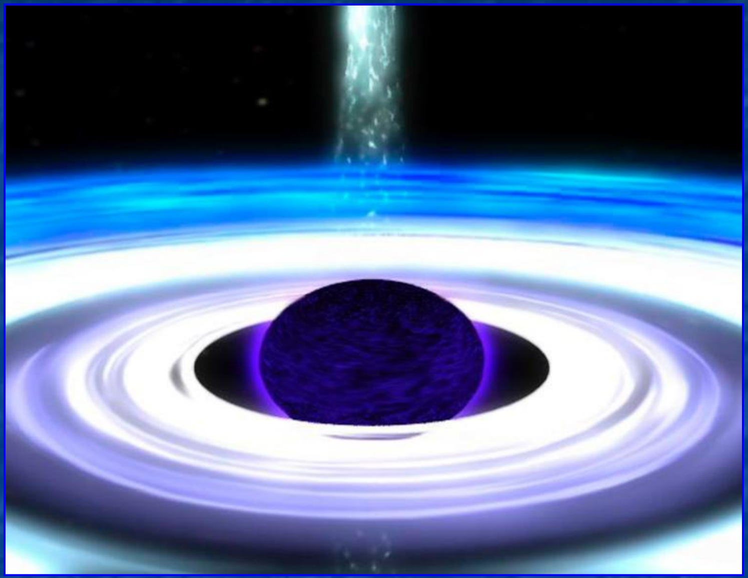


Large dispersions in apparent solid angle of reflecting disk as seen by X-ray source… possibly weak anti-correlation with size of disk. **Surprisingly large dispersion in geometry or anisotropy of X-ray emitting corona.**

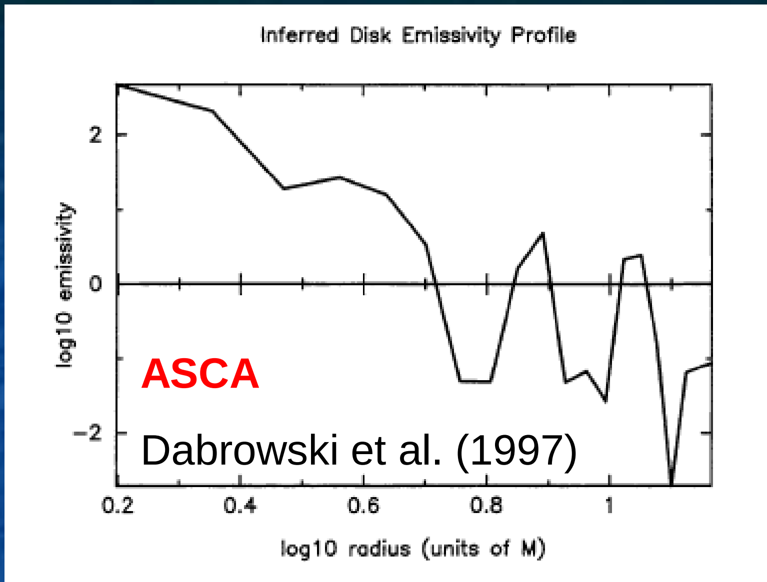
Data from Nandra et al. (2007) XMM sample

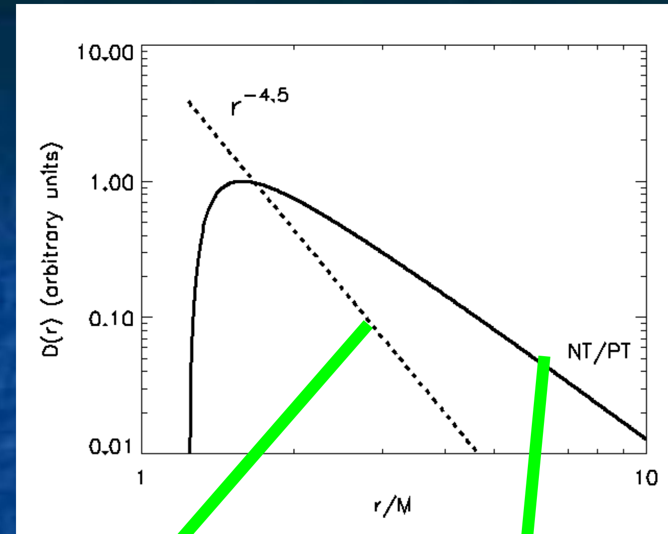
Where is the hard X-ray source?

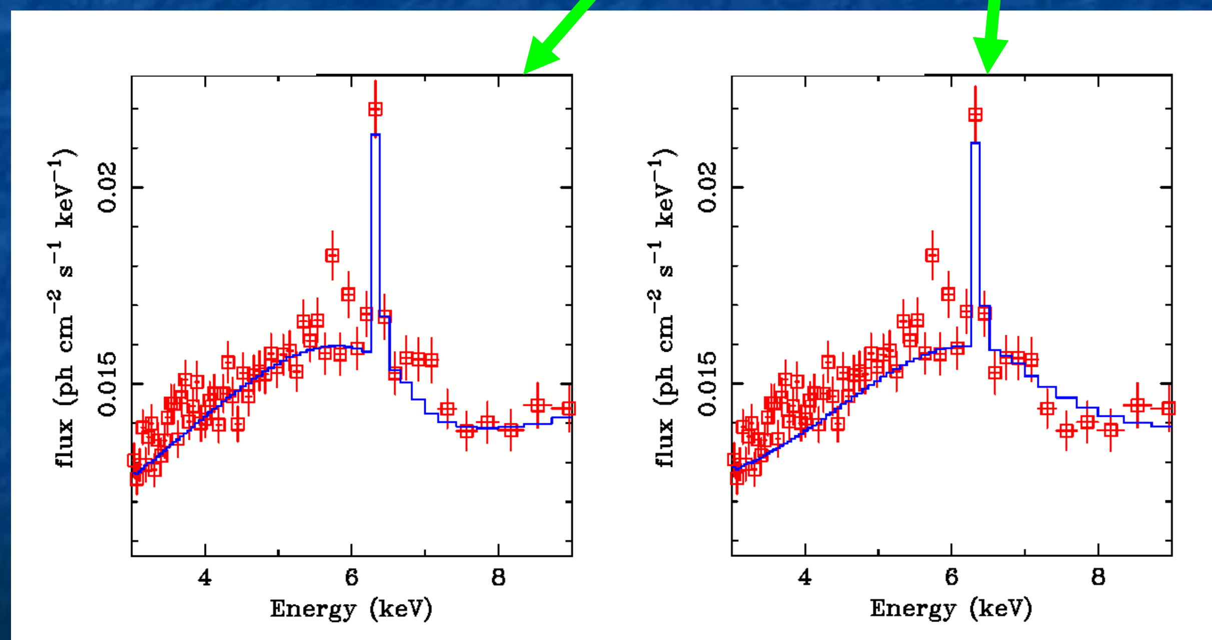




- Nature/geometry of hard X-ray source still very unclear… importance since this structure can process >20% of the total accretion energy
  - Corona energized (magnetically) by underlying disk?
  - Base of a jet (possibly powered by black hole spin)?
  - Either case… X-rays very likely produced by Comptonization

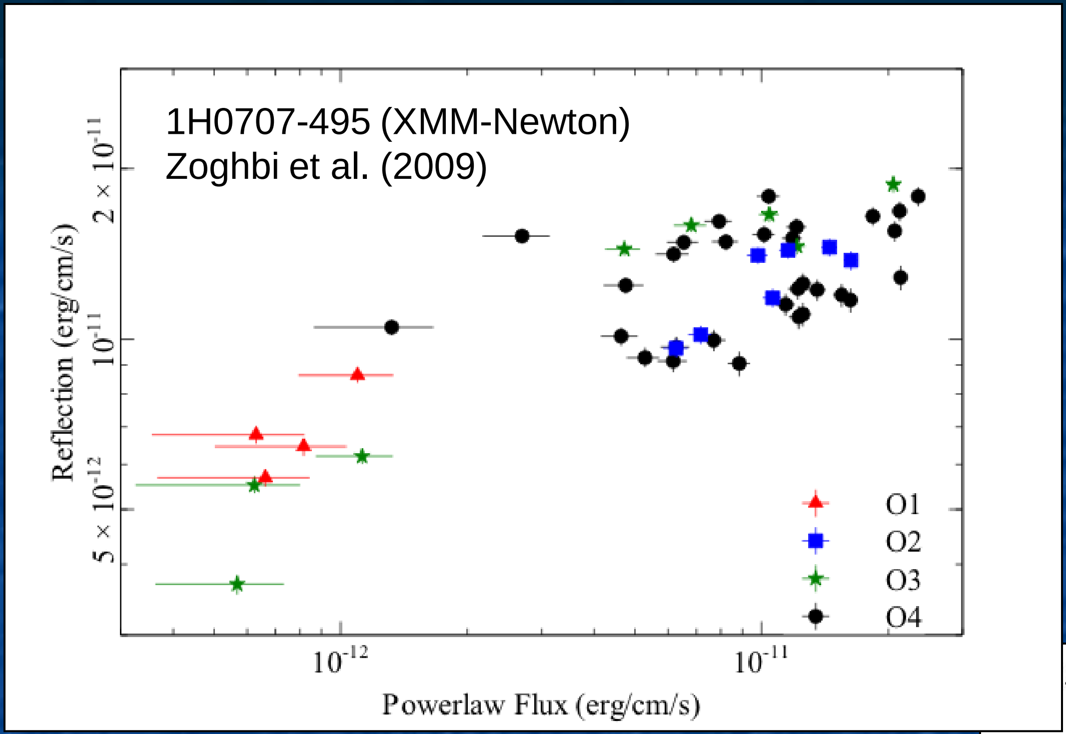






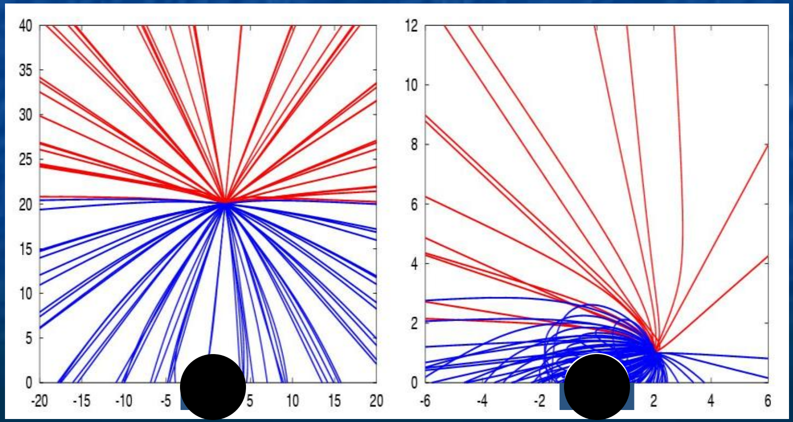
Irradiation clearly doesn’t follow “standard” Novikov-Thorne profile

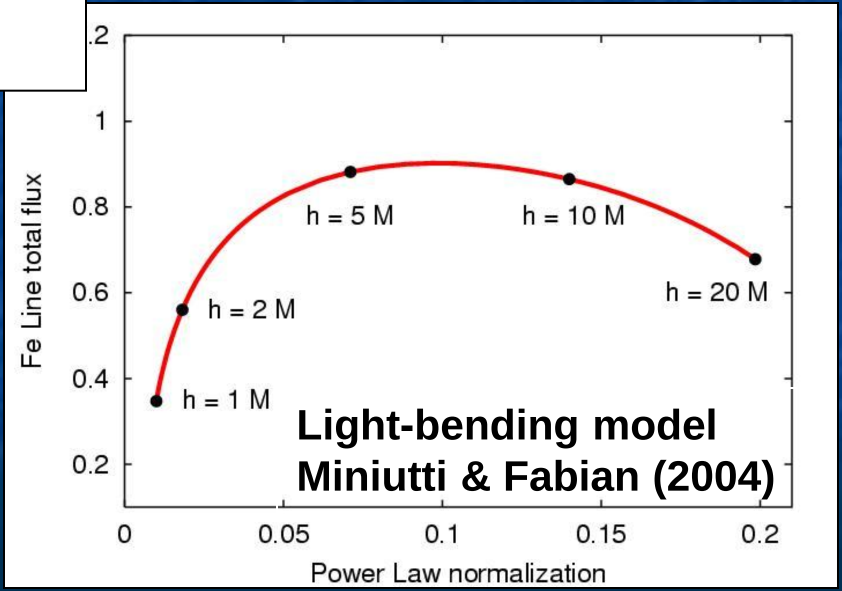
Wilms et al. (2001)
Fabian et al. (2002)
CSR et al. (2004)

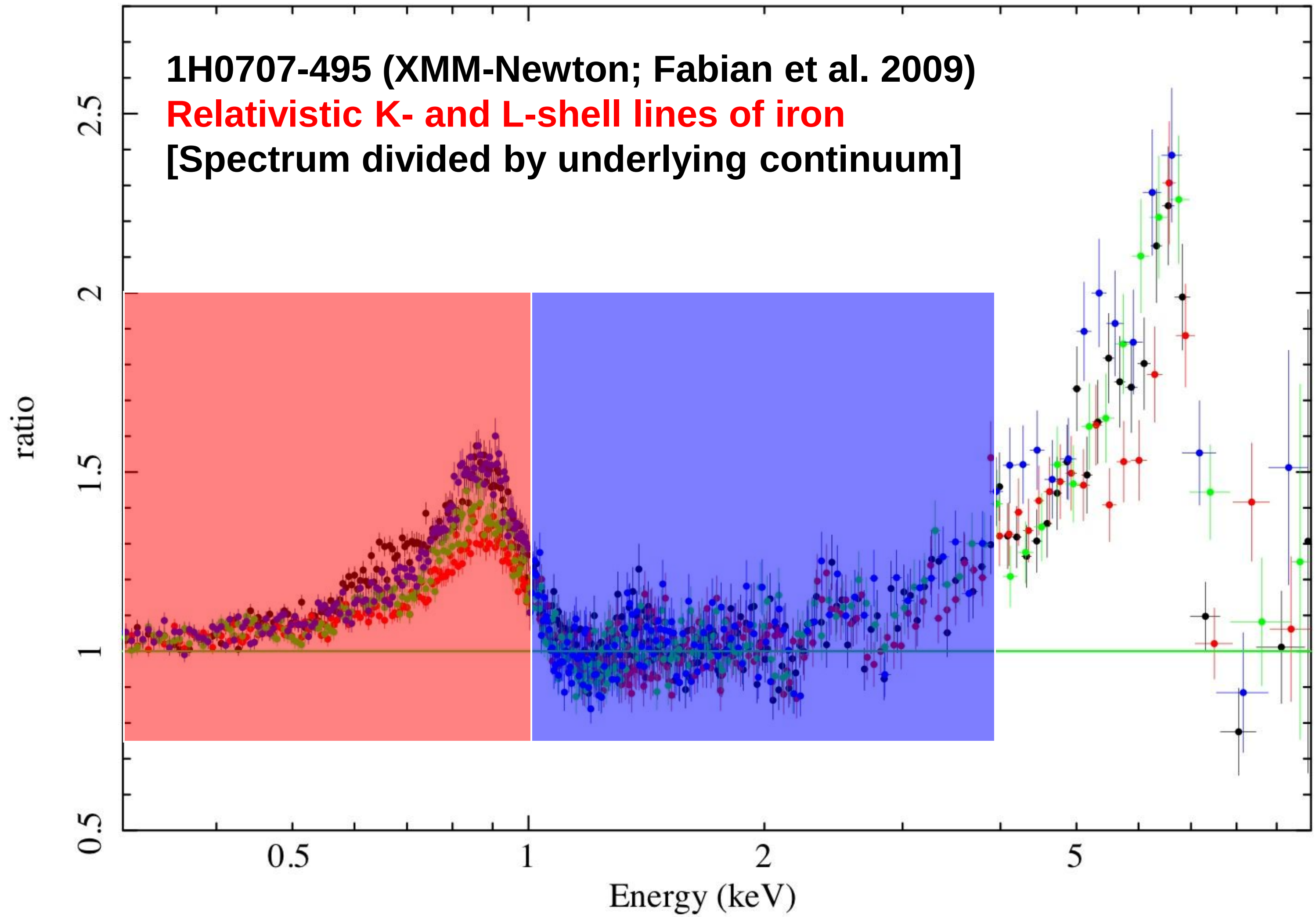


Reflection/iron line not simply proportional to observed continuum… naturally explained in model where primary source is close to spin axis, with a sporadically changing height

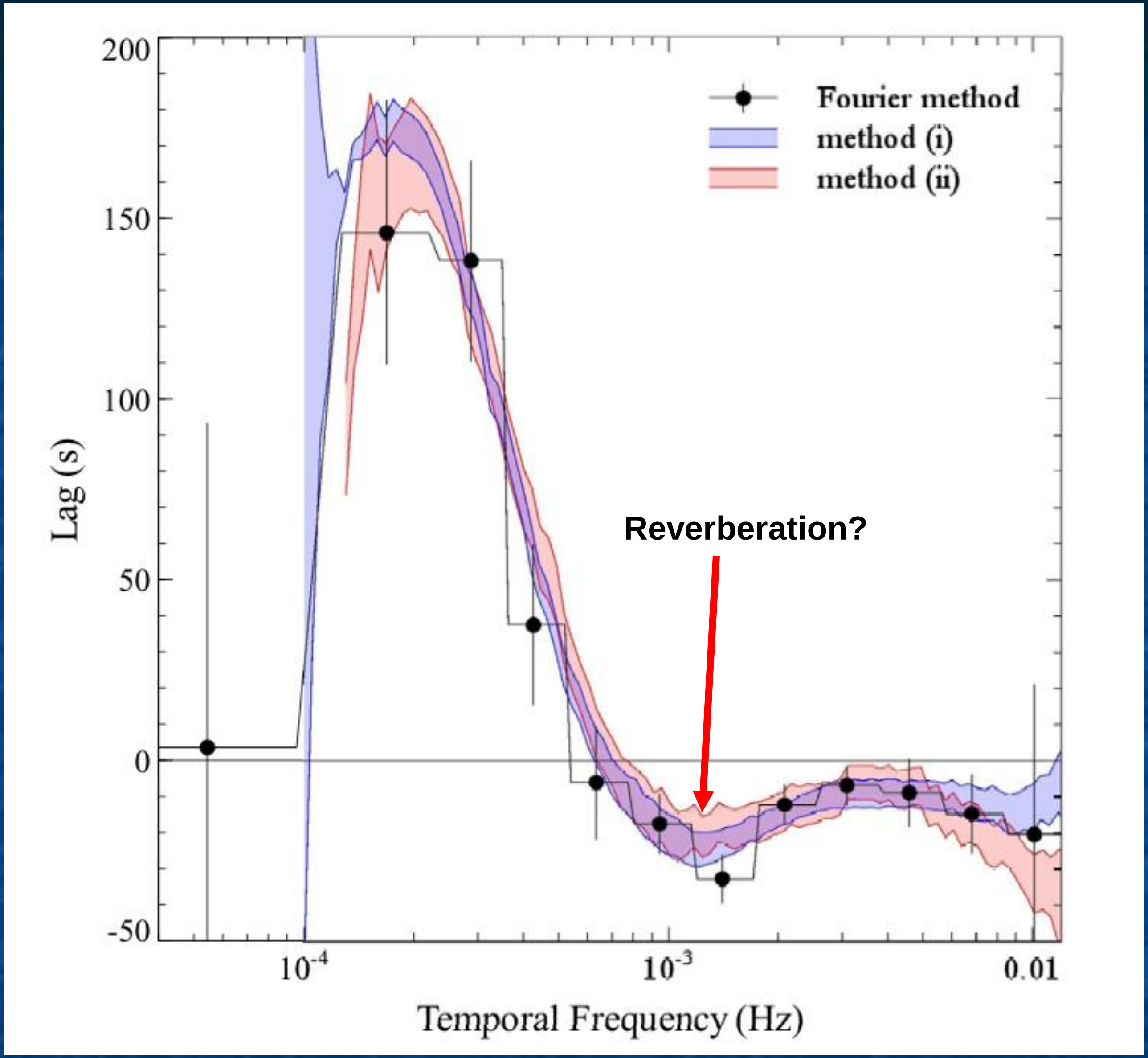
(Martocchia & Matt 1996; Reynolds & Begelman 1997; Miniutti & Fabian 2004)





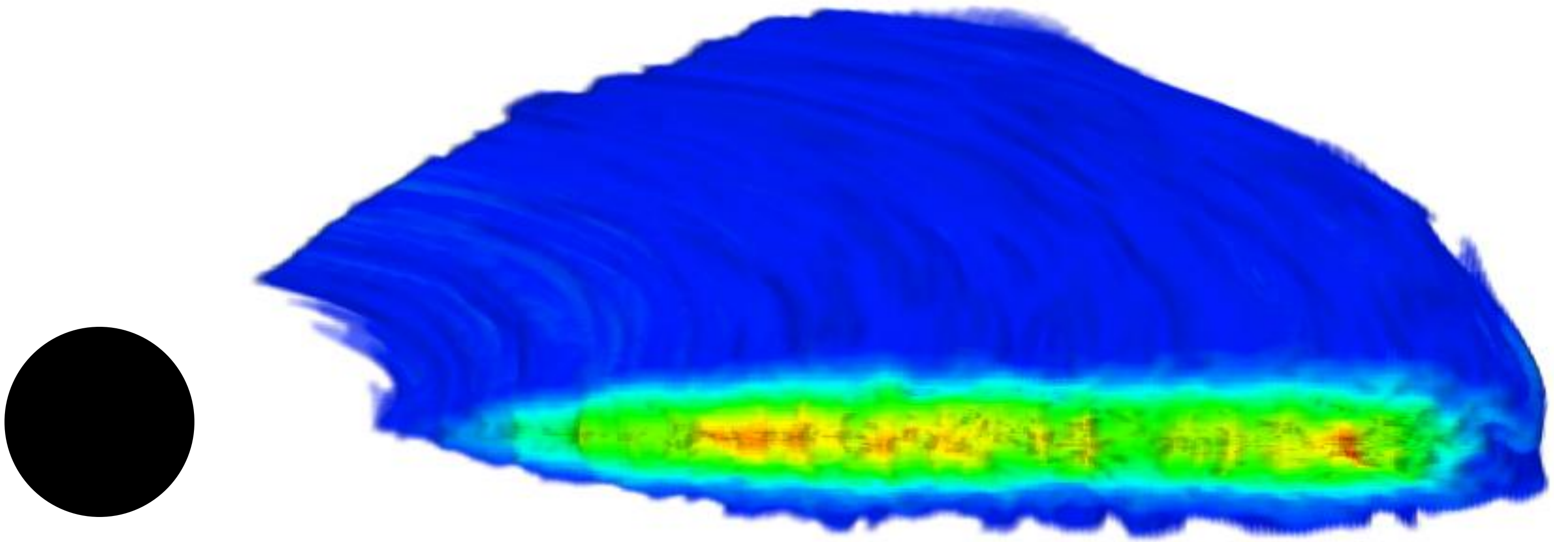


1H0707-495 (XMM-Newton; Fabian et al. 2009)
Relativistic K- and L-shell lines of iron
[Spectrum divided by underlying continuum]
ratio
0.5
1
1.5
2
2.5
0.5
1
2
5
Energy (keV)



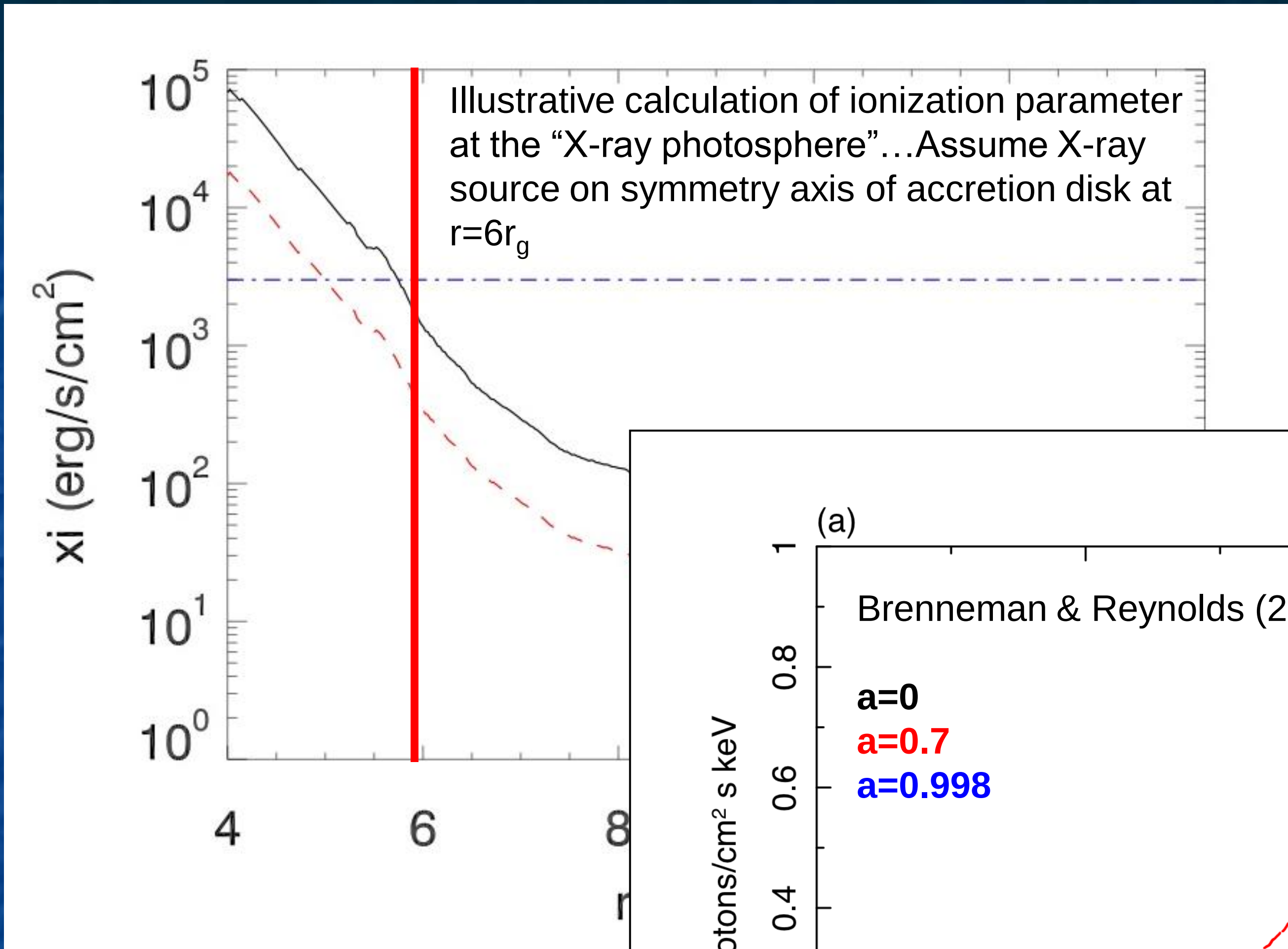
Zohgbi et al. (2009)

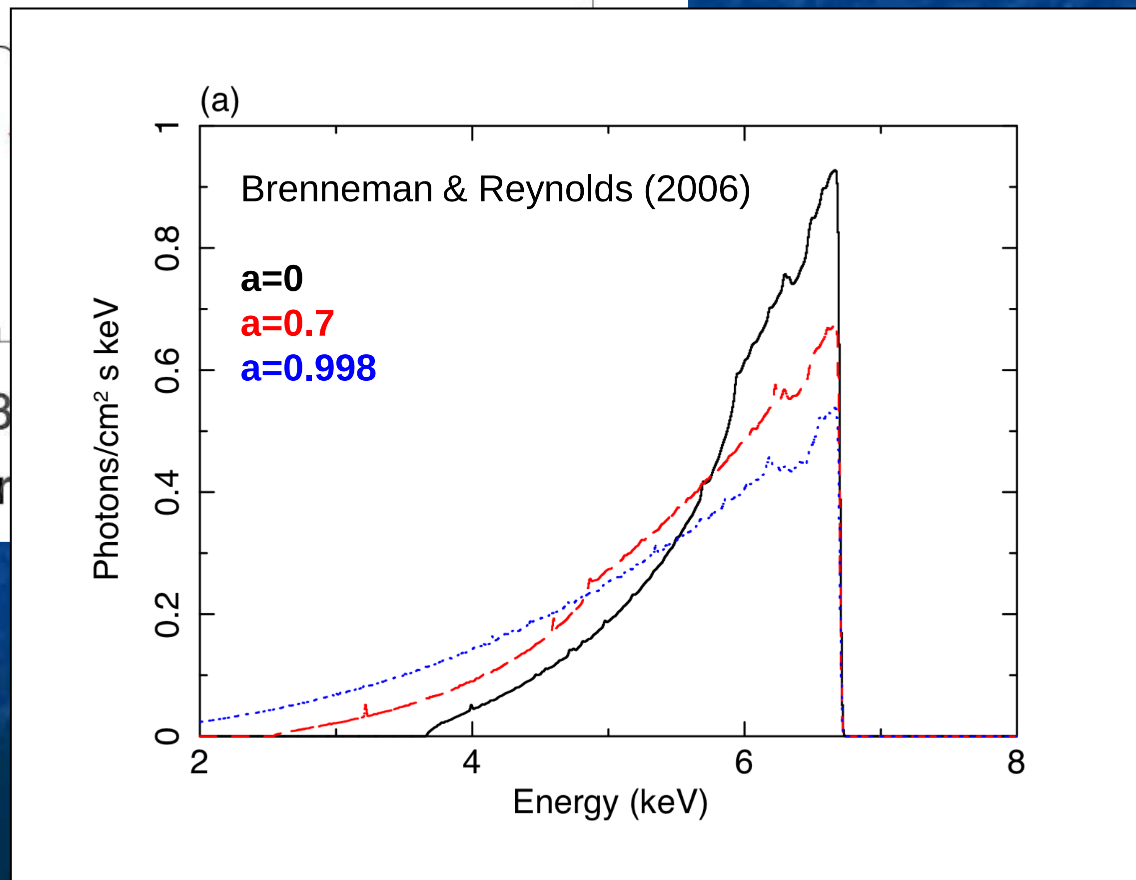
IV : Black hole Spin



3-D MHD simulation of 60^o wedge of disk
Pseudo-Newtonian potential
Performed using ZEUS-MP
Constant h ; h/r=0.05 at ISCO
Vertical resolution ~26 zones per scaleheight

CSR & Miller (2008)
CSR & Fabian (2008)


Illustrative calculation of ionization parameter at the "X-ray photosphere"…Assume X-ray source on symmetry axis of accretion disk at r=6r$_g$
xi (erg/s/cm^2)
10^5
10^4
10^3
10^2
10^1
10^0
4
6
8

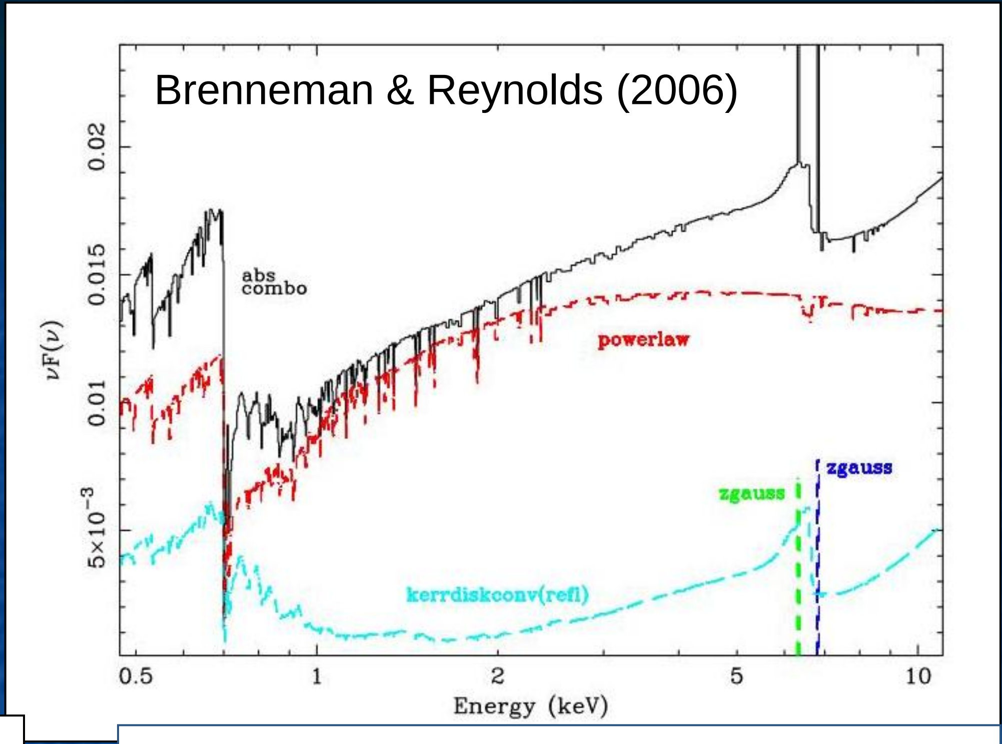

(a)
Brenneman & Reynolds (2006)
a=0
a=0.7
a=0.998
Photons/cm^2 s keV
0
0.2
0.4
0.6
0.8
1
2
4
6
8
Energy (keV)

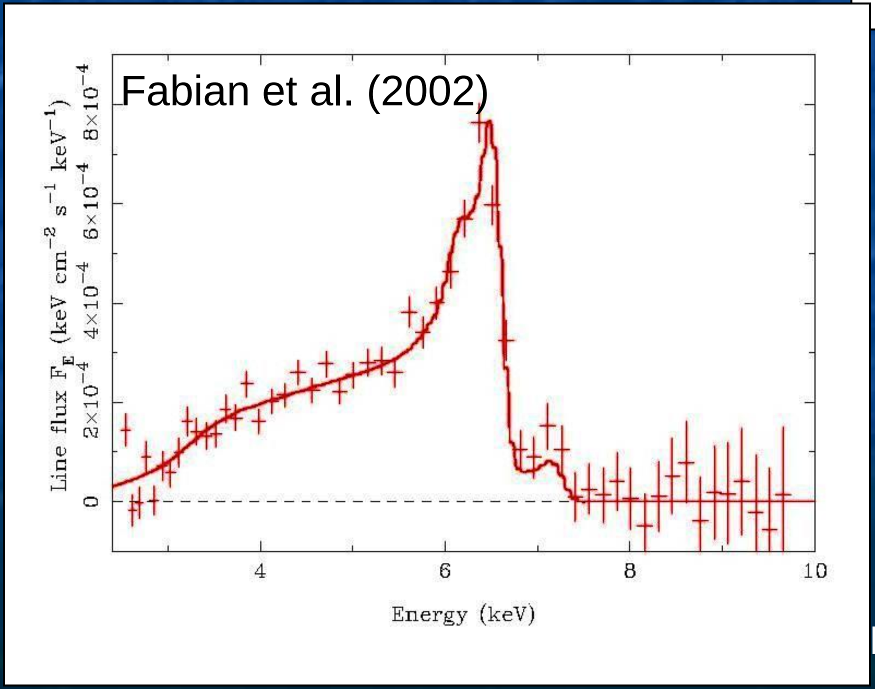
MCG-6-30-15

Strict Novikov-Thorne disk (ASCA DM-data) ⇒ a>0.94
(Dabrowski et al. 1997)

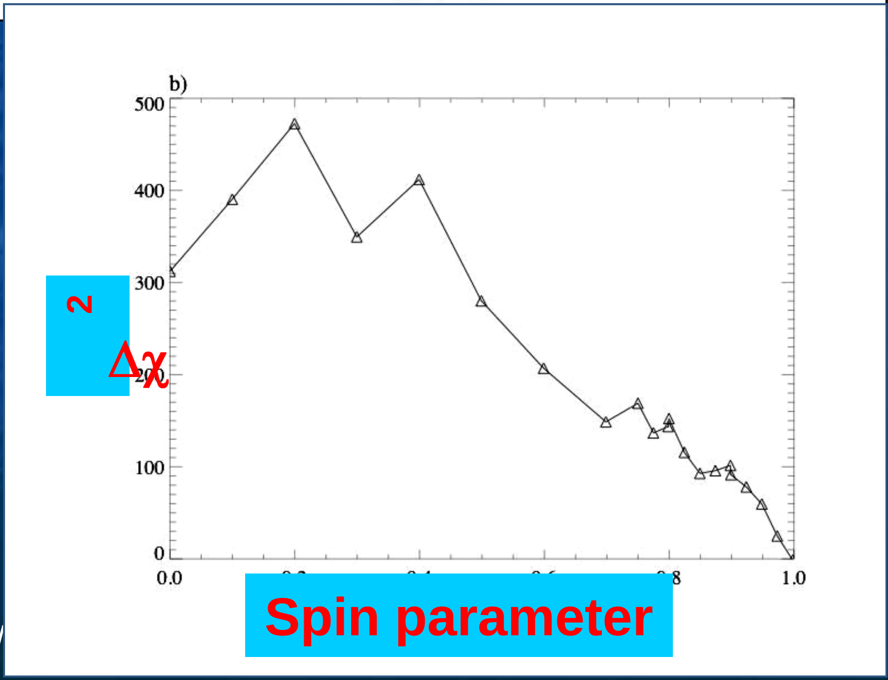
Emissivity truncated at ISCO (XMM data)⇒ a>0.987
(Brenneman & Reynolds 2006)

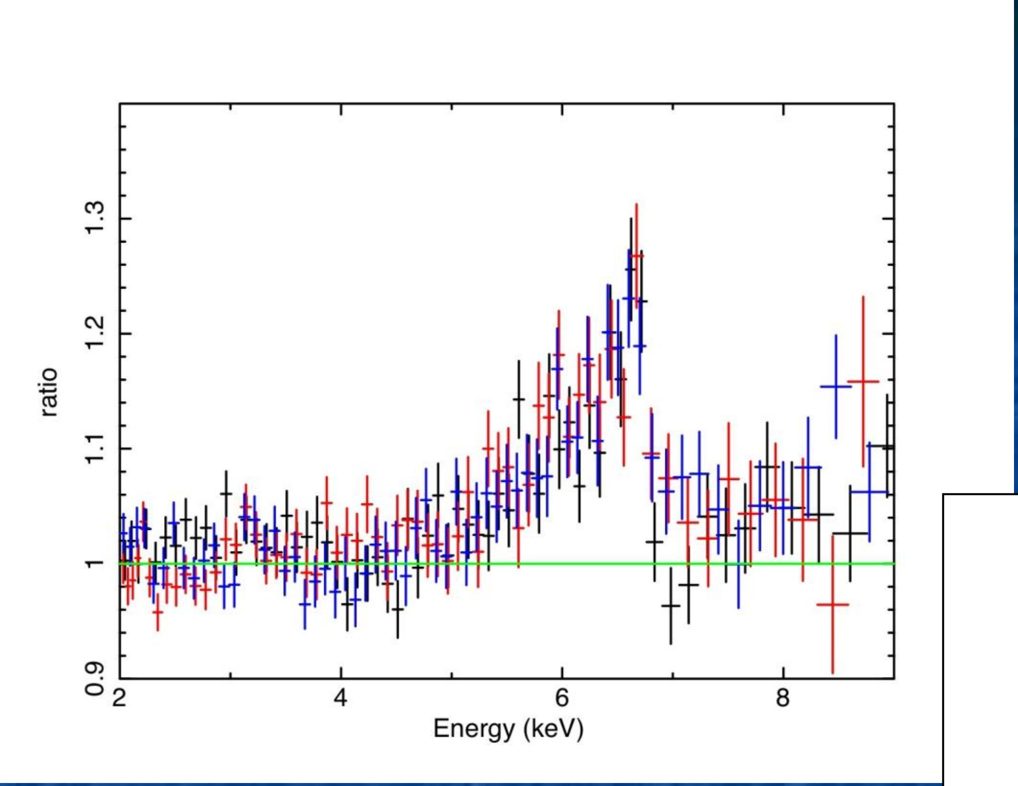
… including uncertain effects of ISCO emission ⇒ a>0.93
(Reynolds & Fabian 2008)



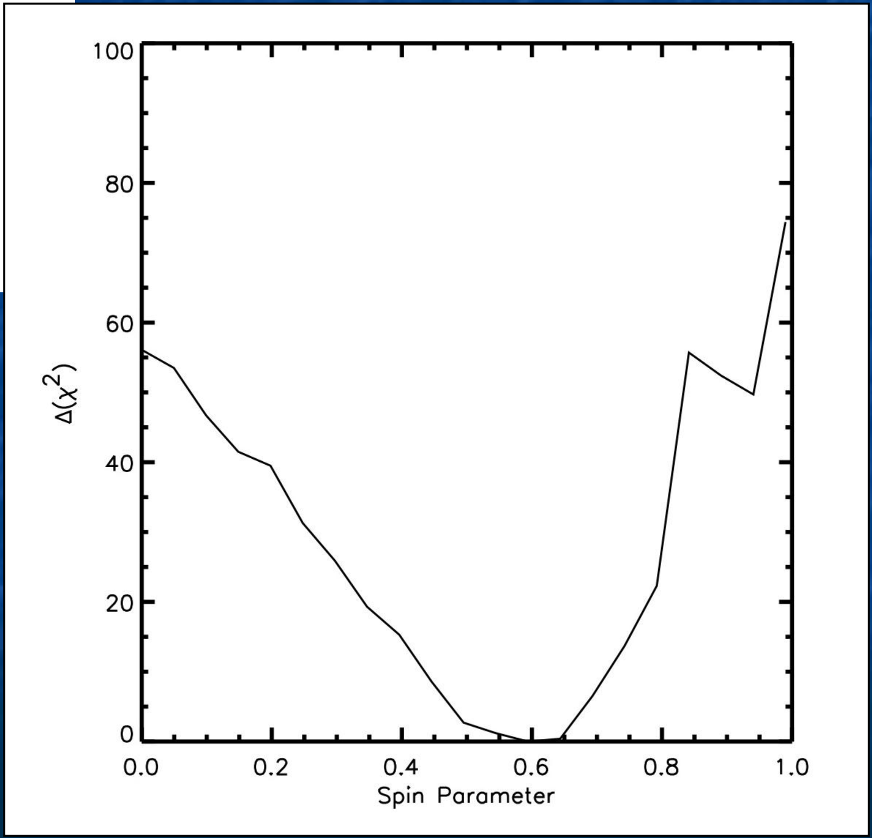


land w

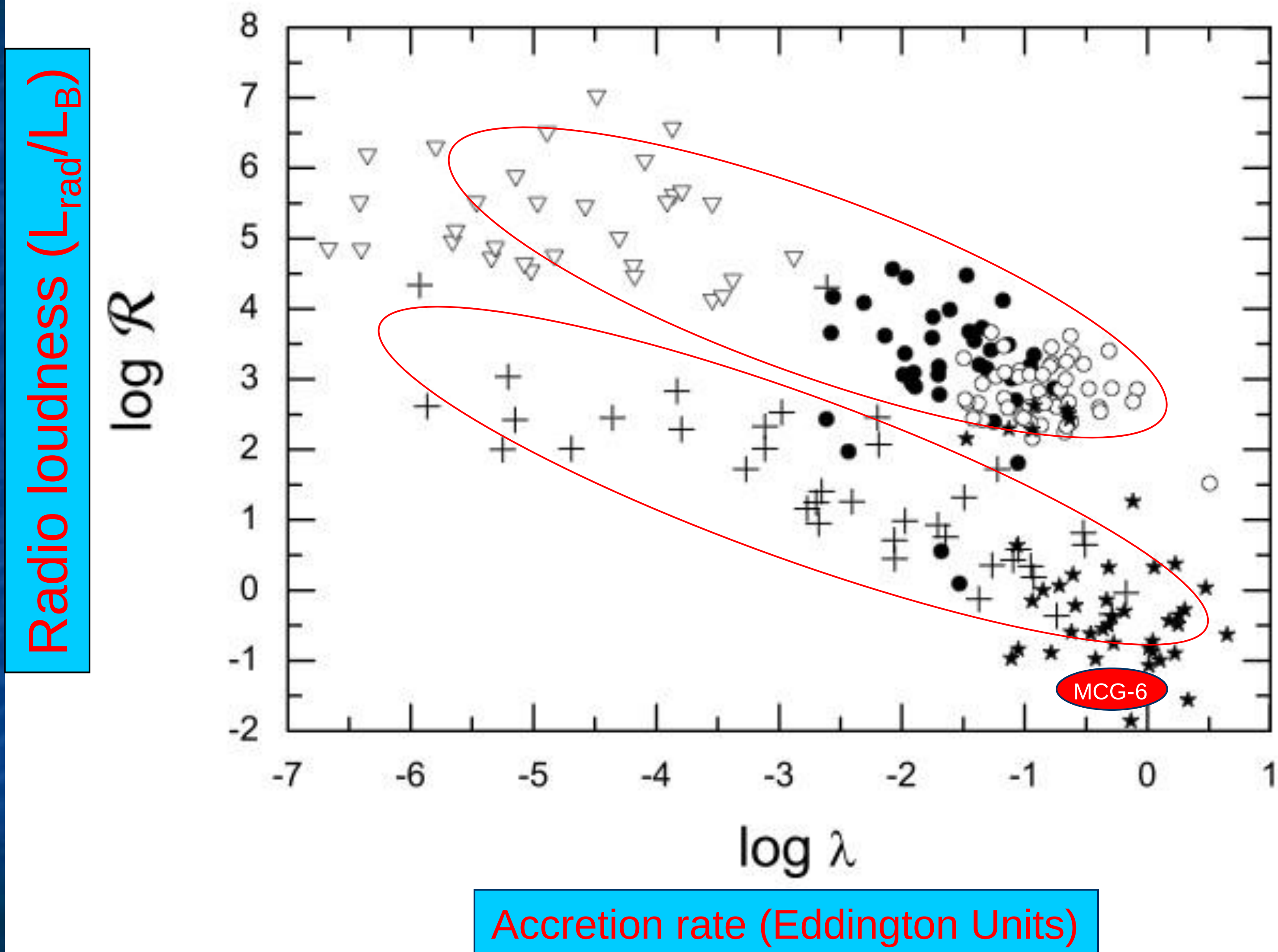




Fairall 9 (Suzaku)
Schmoll et al. (2009)

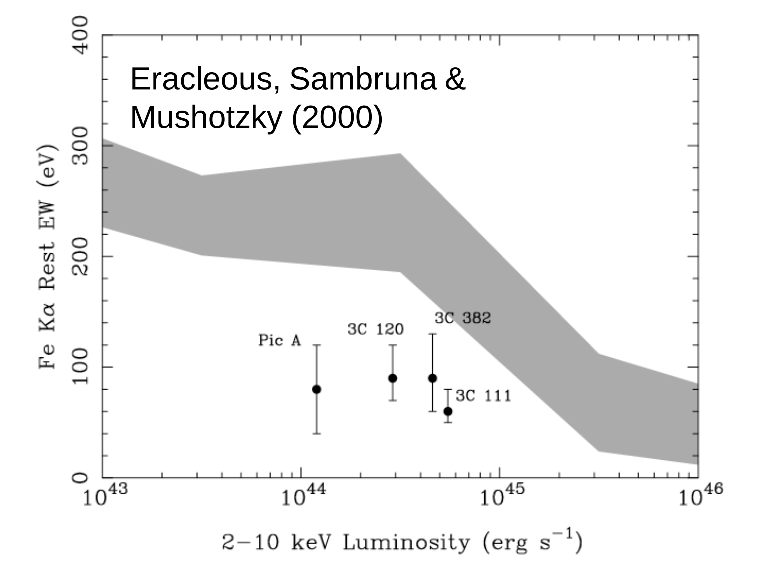


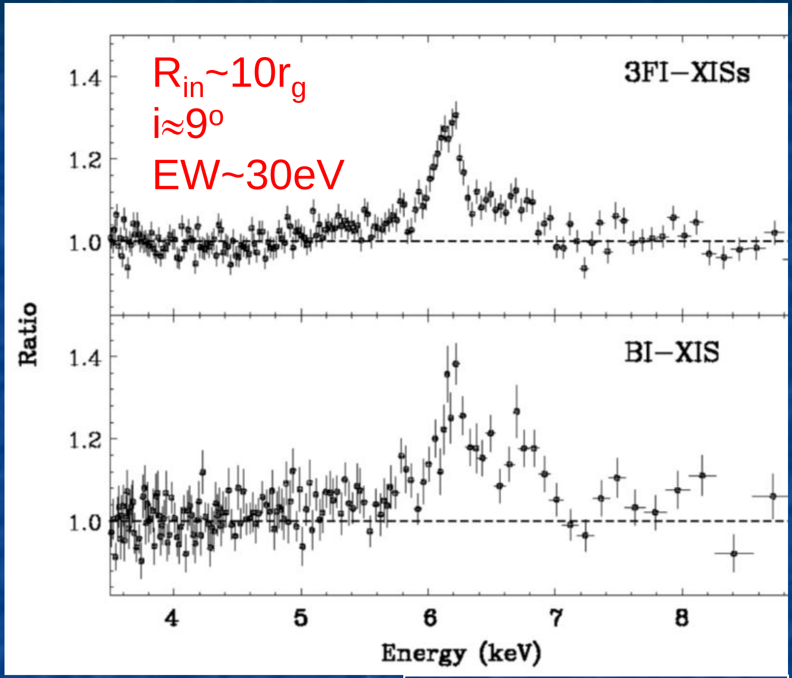
The radio-quiet/radio-loud dichotomy in AGN



Sikora et al. (2007)

Radio-loud AGN





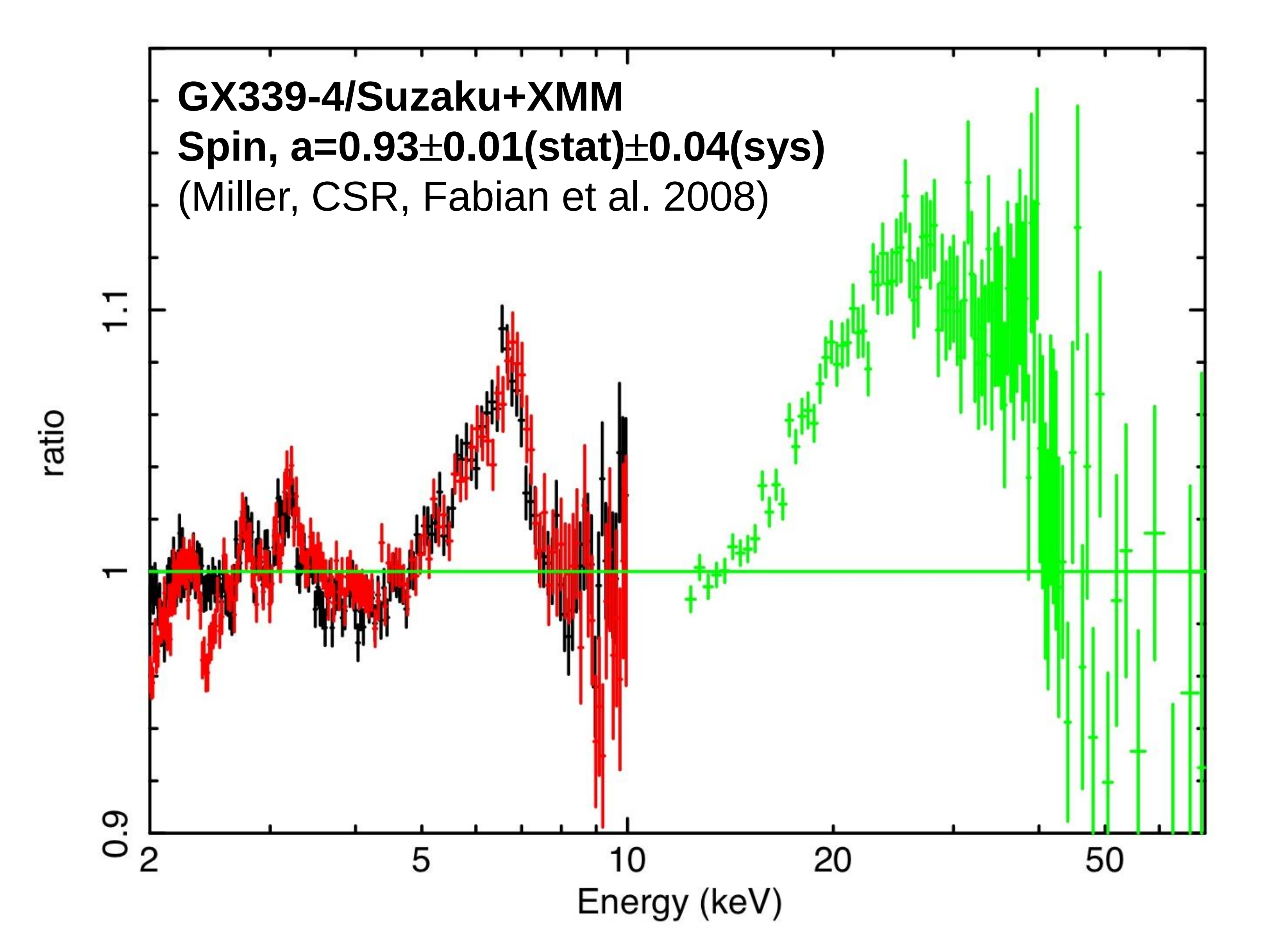
3C120 (Suzaku 160ks)
Kataoka et al. (2007)

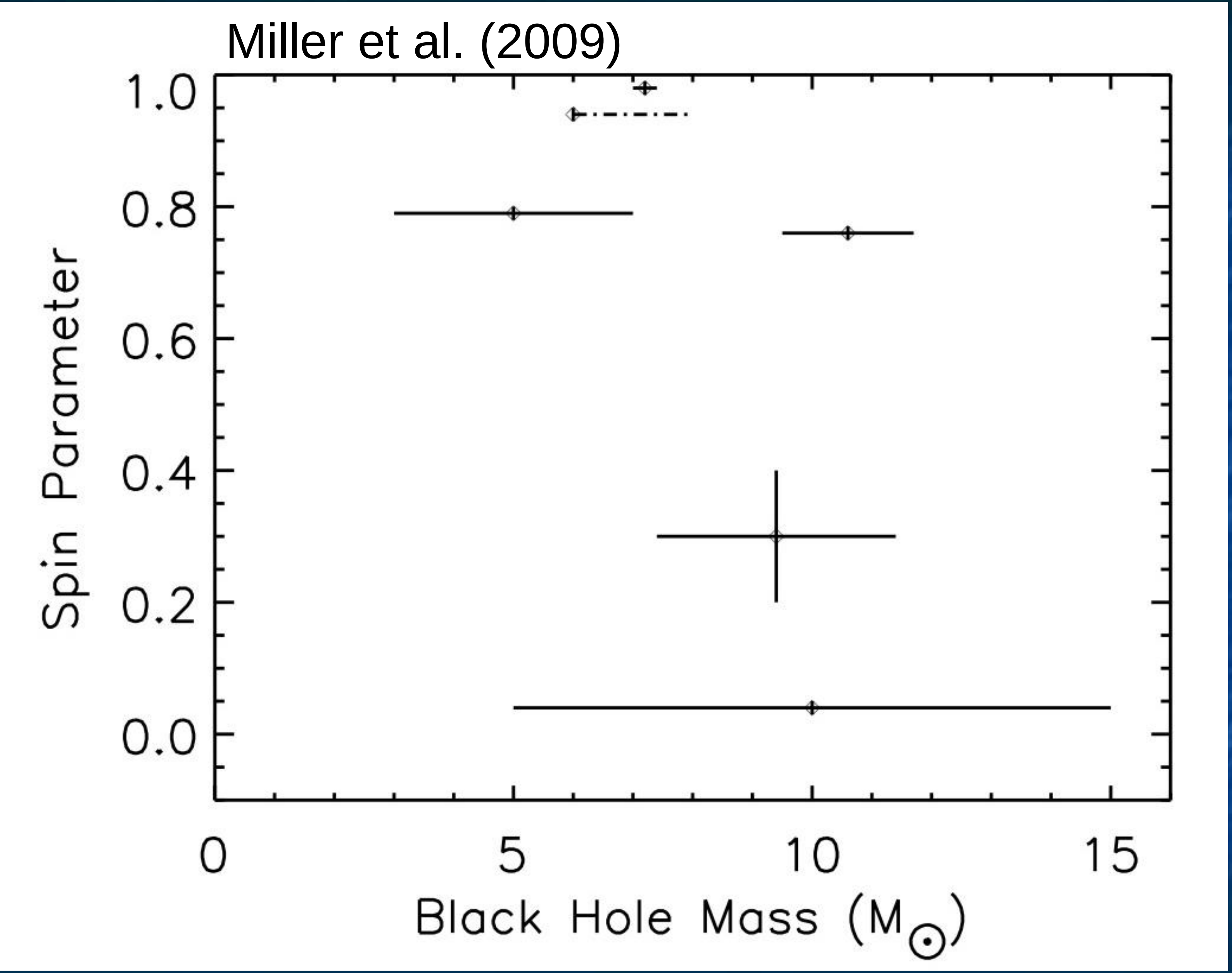
Weaker iron lines in radio-loud object;

- dilution by a beamed jet?
- inner disk is hot (lines do seem to be somewhat narrower)

Intriguing hypothesis (Garofalo 2009)

- powerful radio galaxies may be due to retrograde accretion onto rapidly rotating black hole
- jets are powered by BH spin; BZ effect enhanced by trapping of magnetic flux by the plunge region of the disk (Reynolds, Garofalo & Begelman 2009)


GX339-4/Suzaku+XMM
Spin, a=0.93±0.01(stat)±0.04(sys)
(Miller, CSR, Fabian et al. 2008)
ratio
0.9
1
1.1
2
5
10
20
50
Energy (keV)


Miller et al. (2009)
1.0
0.8
0.6
0.4
0.2
0.0
Spin Parameter
0
5
10
15
Black Hole Mass ($M_\odot$)

Conclusions

- X-rays are a powerful probe of the inner accretion flow and black hole
- Current data are already…
  - Constraining physical nature of accretion disk in immediate vicinity of black hole
  - Likely seeing effects of very strong light bending close to the black hole
  - Allowing measurements of black hole spin
- Tremendous future promise with deployment of GEMS (polarization), Astro-H (high-resolution spectroscopy), and IXO.