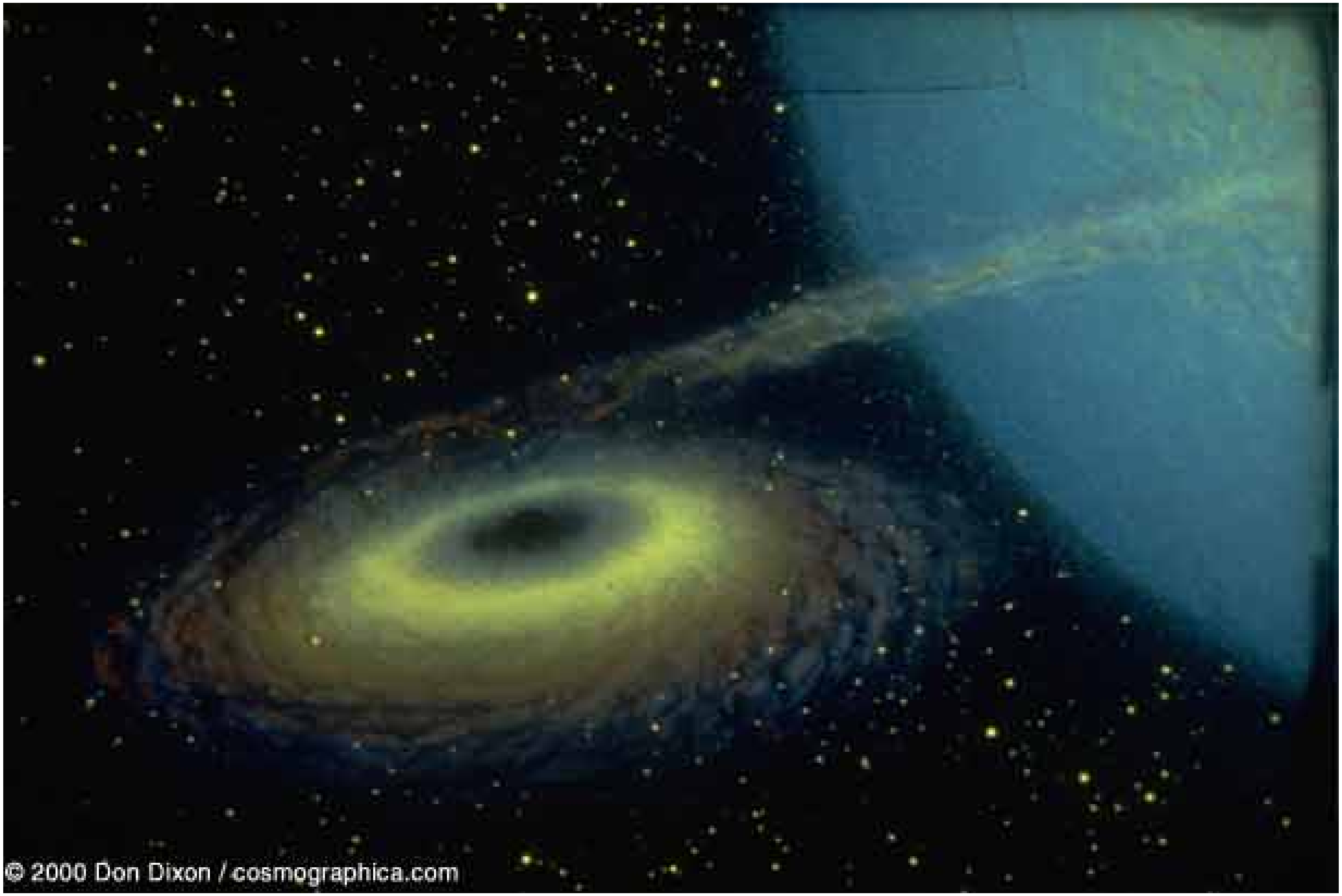
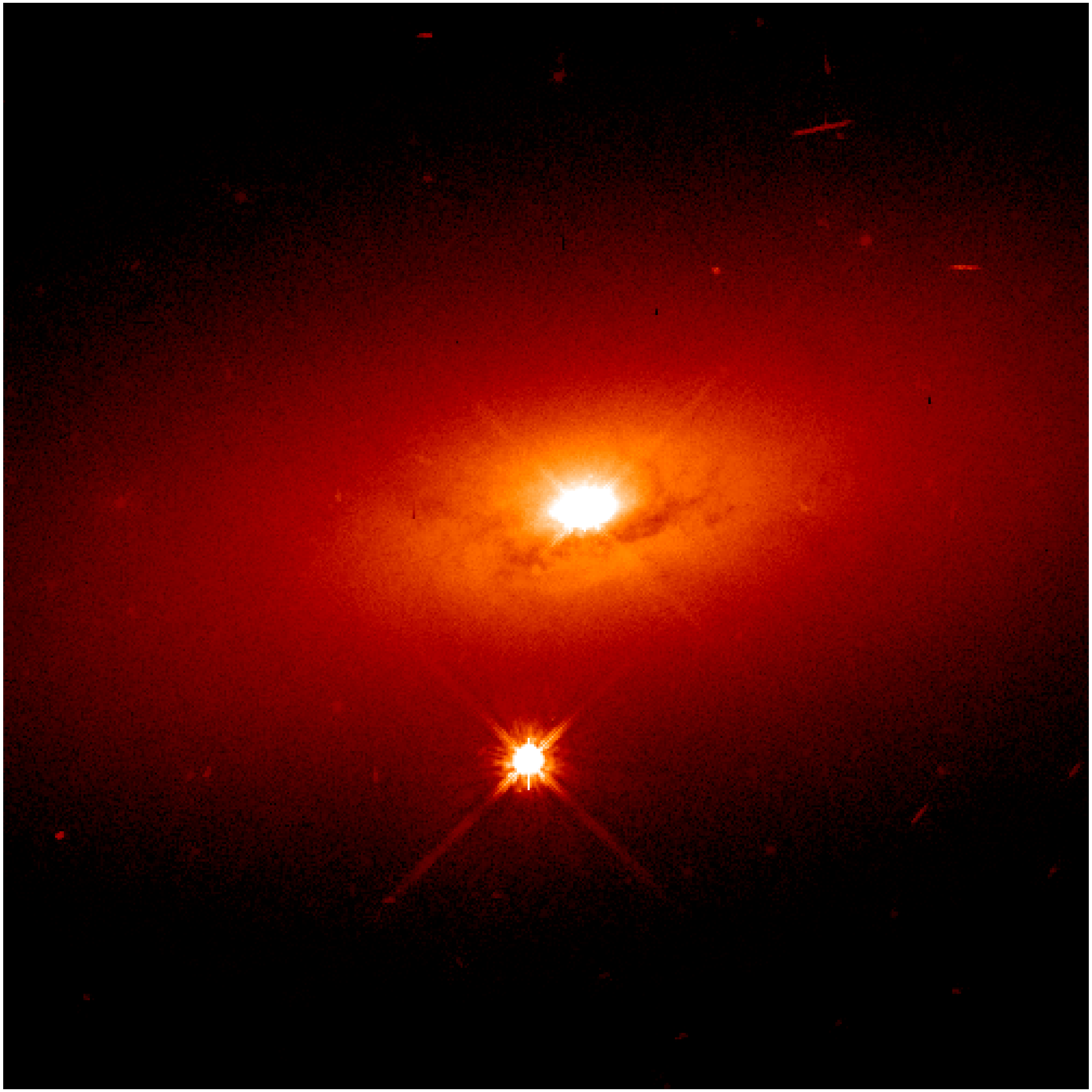
# Strong gravity and accreting black holes

- Finish how to get the masses of black holes
- The AGN Zoo
- Black Hole systems
  - The spectrum of accreting black holes
  - X-ray “reflection” from accretion disks
  - Strong gravity effects in the X-ray reflection spectrum

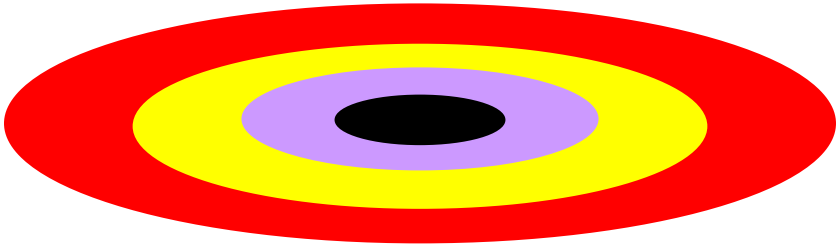
# Spectra of accreting black holes

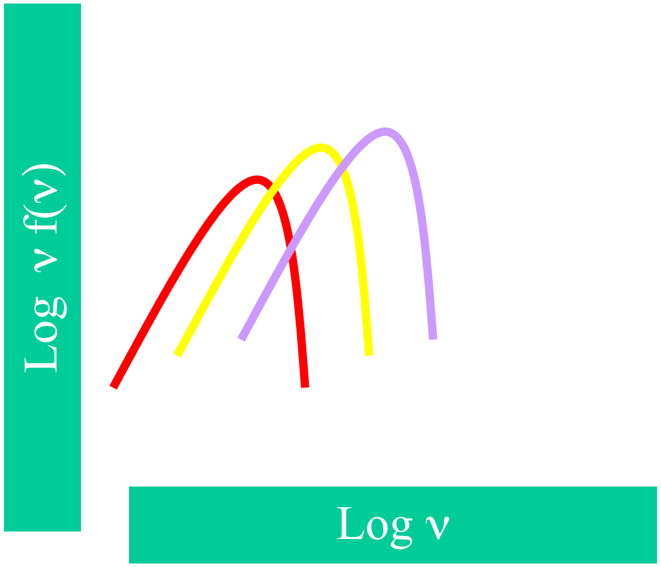




# Spectra of accretion flow: disc-
## C. Done

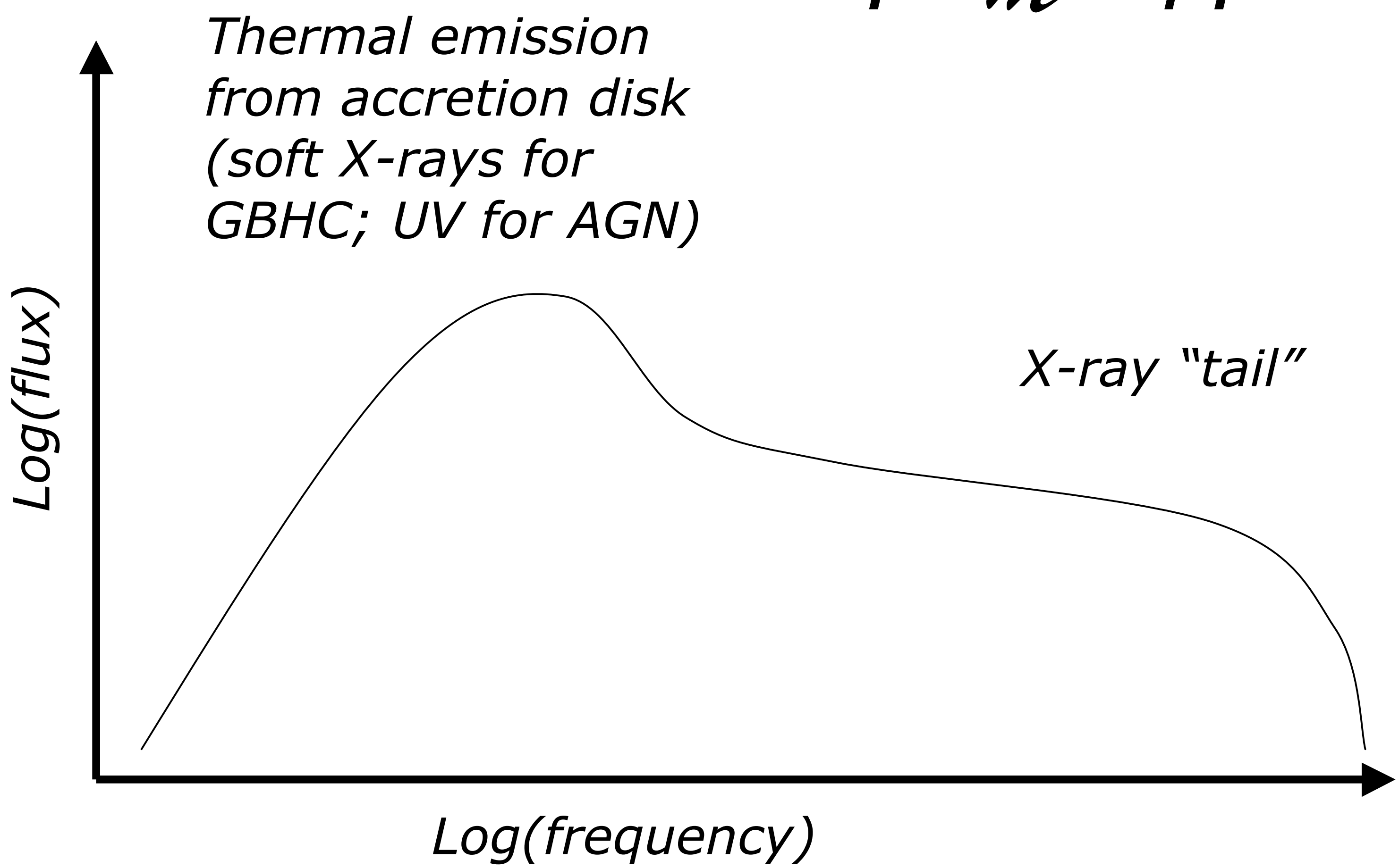
- Differential Keplerian rotation
- Viscosity : gravity → heat
- Thermal emission: $L = A\sigma T^4$
- Temperature increases inwards
- GR last stable orbit gives minimum radius $R_{ms}$
- a=0: $T_{max} = (M/M_{\odot})^{-1/4} (L/L_{Edd})^{1/4}$
  - 1 keV ($10^7$ K) for 10 $M_{\odot}$
  - 10 eV ($10^5$ K) for $10^8$ $M_{\odot}$
- a=0.998 $T_{max} \sim 2.2\ T_{max}$ (a=0)
- AGN: UV disc, ISM absorption, mass more uncertain. XRB…





# What Do Broad Band Spectra of Black Holes Look Like

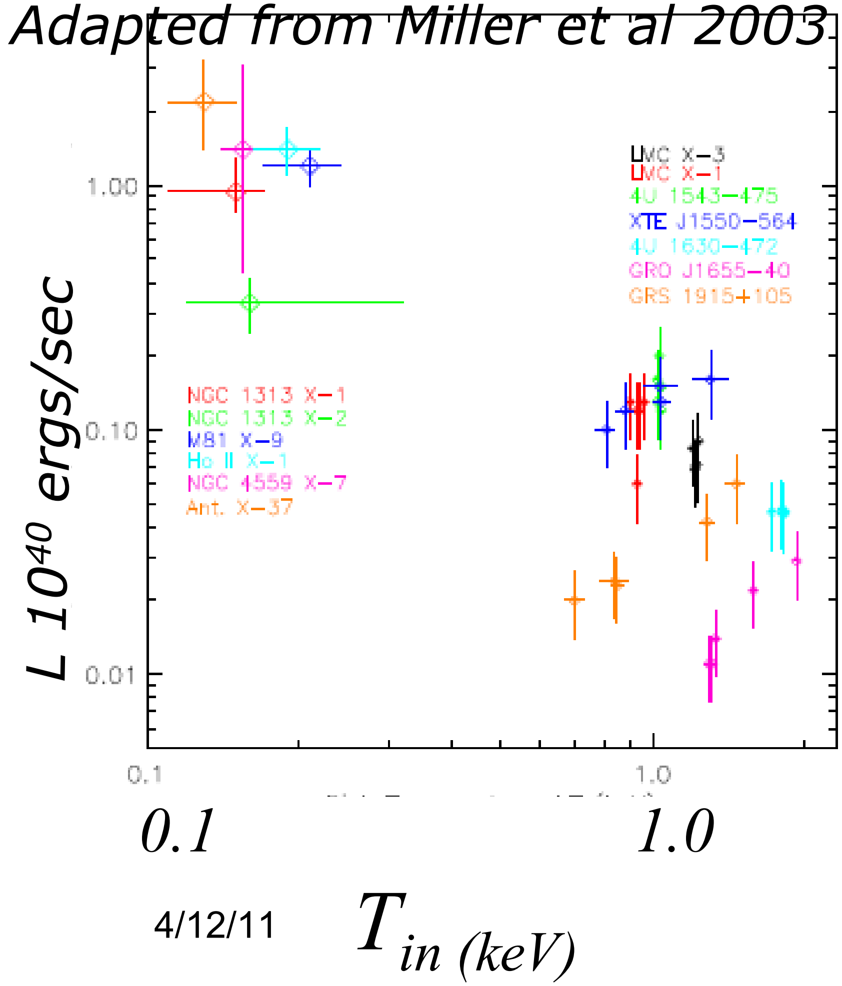
$$T \sim \mathscr{M}^{1/4} M^{-1/4}$$

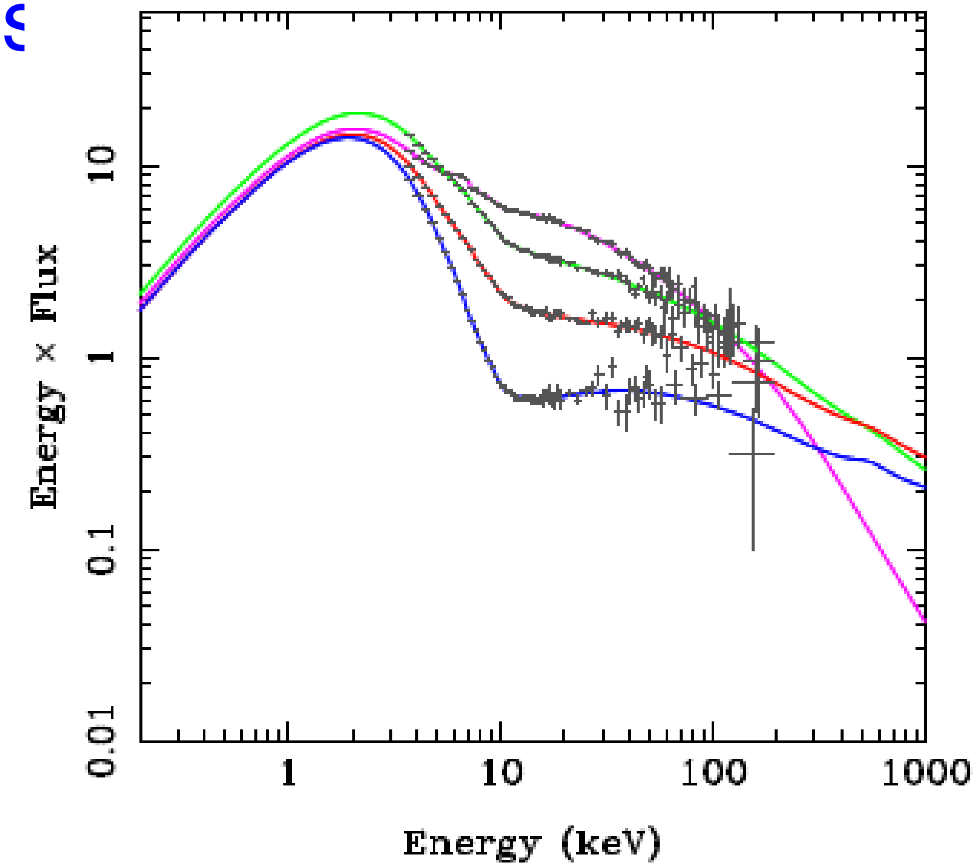


# Galactic Black Holes

- Relatively low mass and so the disk are 'hot'

*Adapted from Miller et al 2003*




L~ $7 \times 10^{38}$ ***f***$(M_{10})^2(T_{in})^4$ erg/s

Where $M_{10}$ is the mass in units of 10 $M_\odot$ and $T_{in}$ is in keV

***f* is a factor taking some physics into account**

# Derivation (See Rosswog and Bruggen sec 8.4)

- Derivation of previous eq
- $L=2\pi R_{in}^2 f(\cos i)^{-1}$; f is the flux from the surface of the disk, R is the radius
- Using the black body law

  $L=4\pi\sigma R^2 T_{in}^4$ $\sigma$ is the Stefan- Boltmann constant

In fitting the spectrum $T_{in}$ is directly observable

We can thus take the 2 equations to get the innermost radius

$R_{in}=\mathrm{sqrt}(L/4\pi\sigma T_{in}^4)$ and

$T_{in}\sim 3M_{10}^{-1/4}\mathrm{keV}$

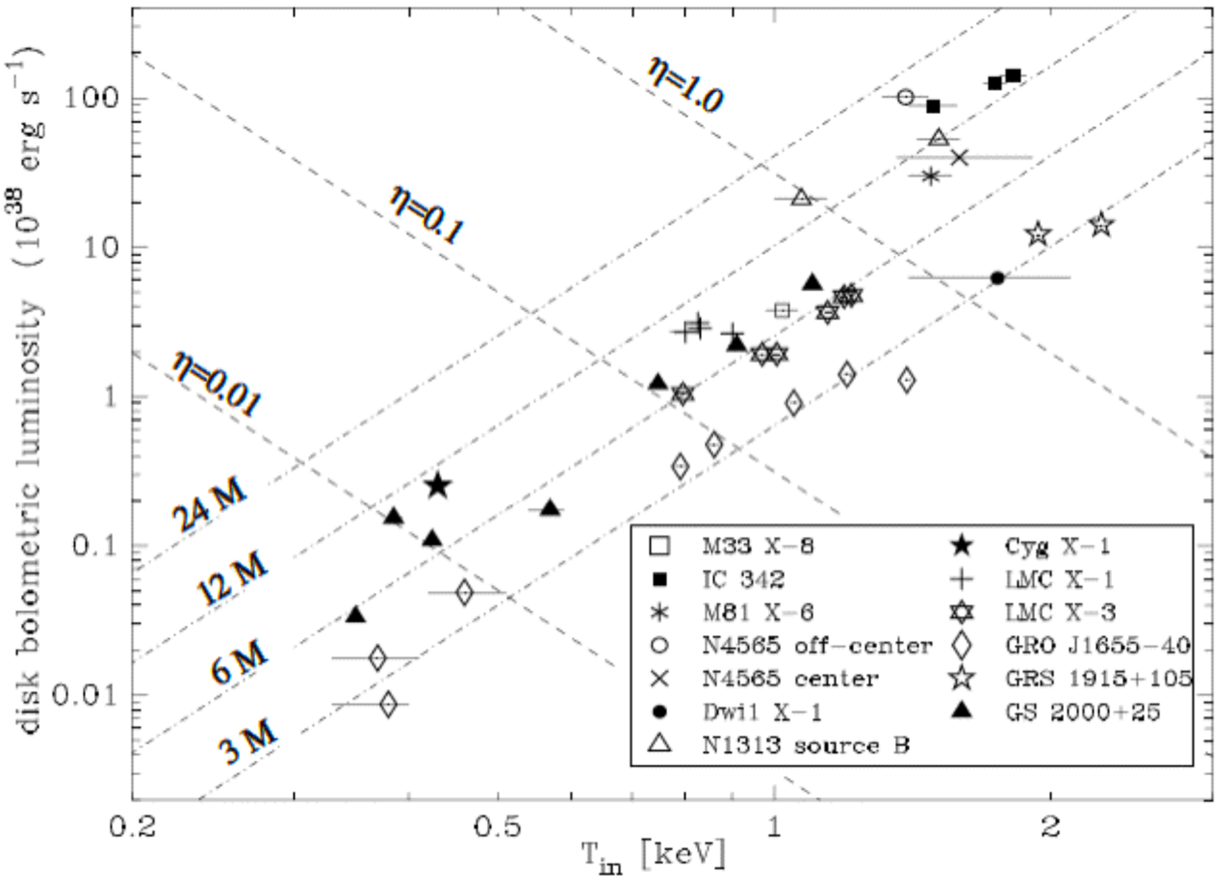
$T(r)=6.3\times10^5\, \mathcal{M}_{\mathcal{E}dd}^{1/4} M_8^{-1/4} (r/r_s)^{-3/4}$

($\mathcal{M}_{\mathcal{E}dd}$ *is the accretion rate in Eddington units,* $T=T_{in}$ for $r=r_s$)

# Real Objects

- Amazingly data for galactic black holes agrees with the simple theory

*Makishima et al 2000*




$$L_{\rm bol} = \eta L_{\rm E} \propto \eta M \ ,$$

# Todays Class

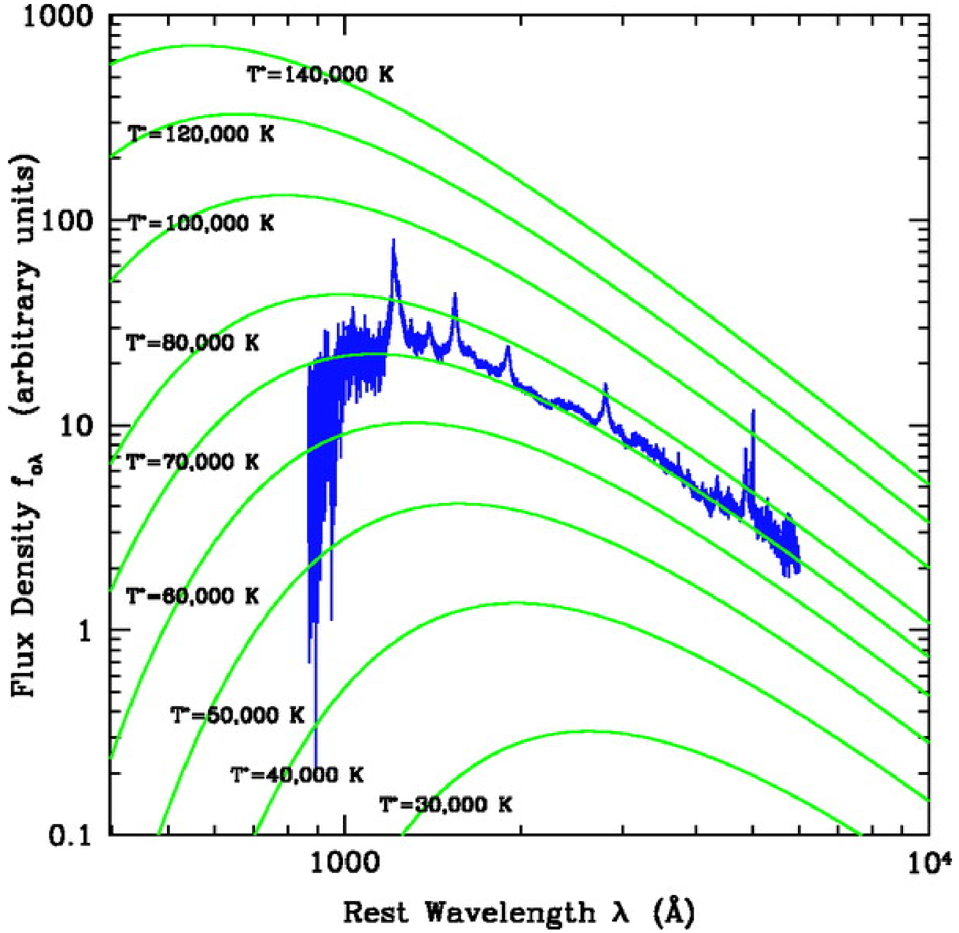
- Review of Accretion Disk fits to AGN spectra

- Broad band spectra are not so simple- what's there in addition to the accretion disk
  - the geometry of the innermost regions
  - brief review of Comptonization

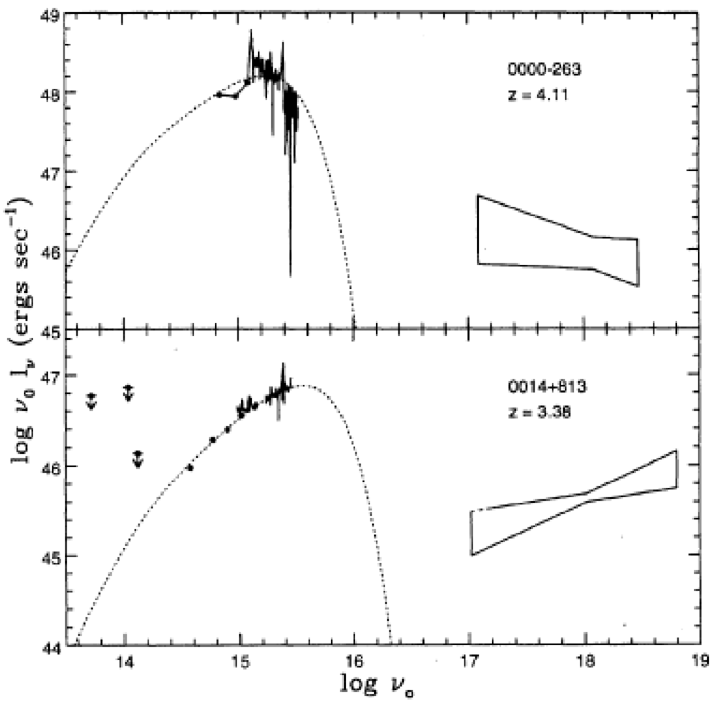
- Effects of 'reprocessing' - the disk 'sees' the hard x-ray radiation and there are measurable effects

# AGN

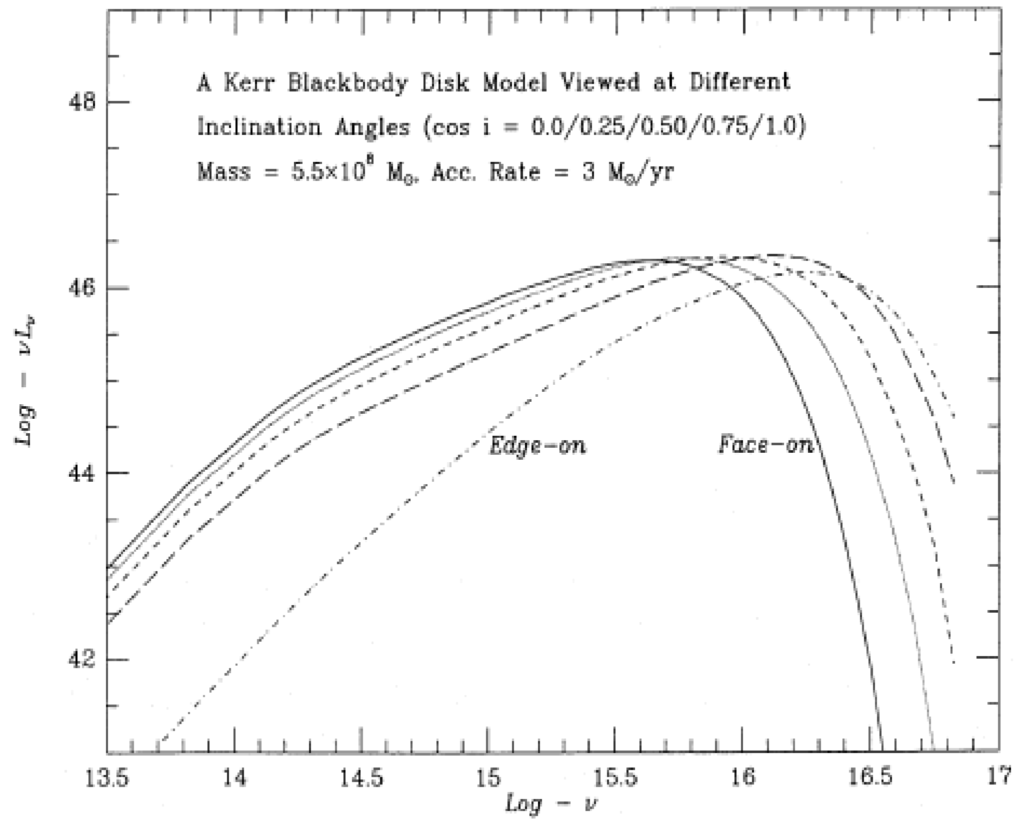
- AGN are very massive and so the predicted spectrum of the accretion disk is 'cool'
- $T \sim 8 \times 10^4$ k for a Eddington limited $M \sim 10^8 M_\odot$ black hole



- Can Fit AGN UV-optical data with accretion disk models

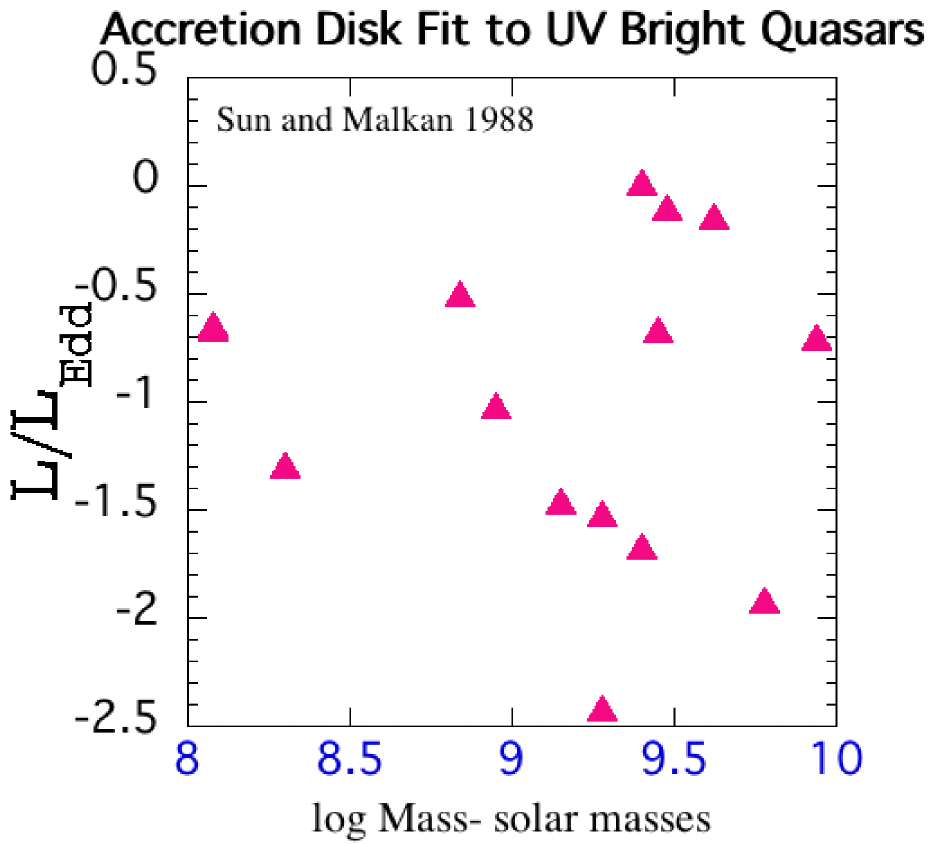



*Malkan and Sun 1989*

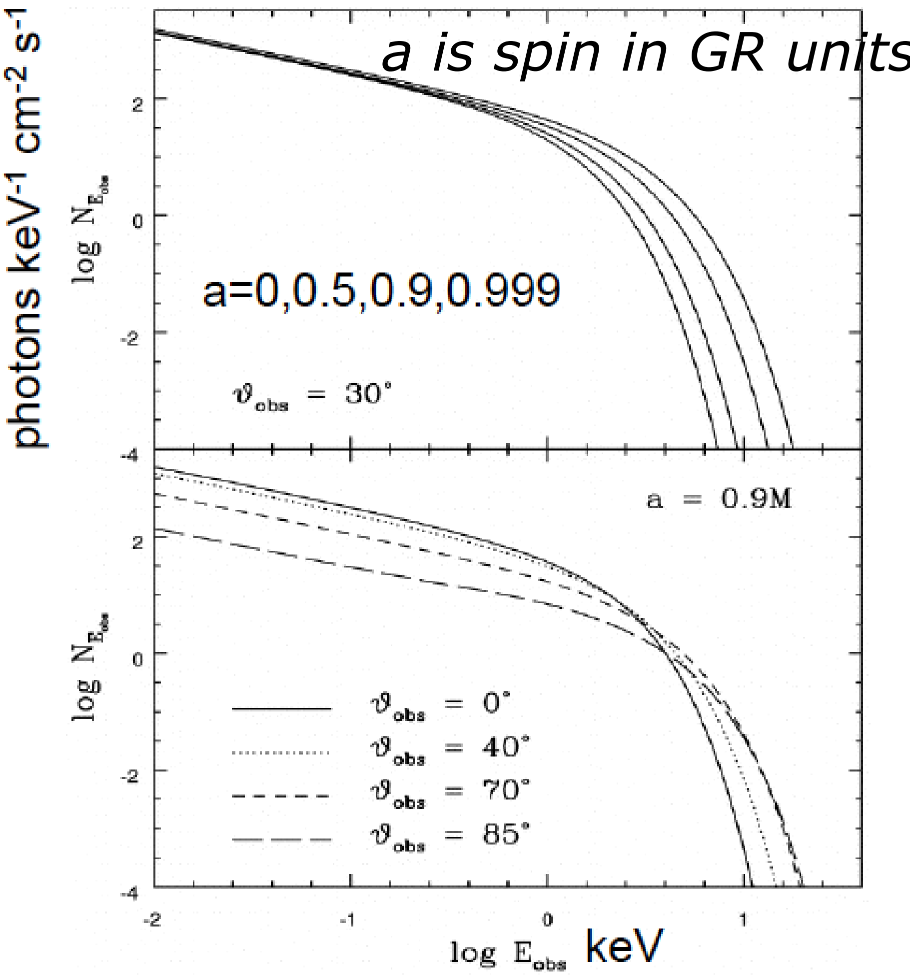


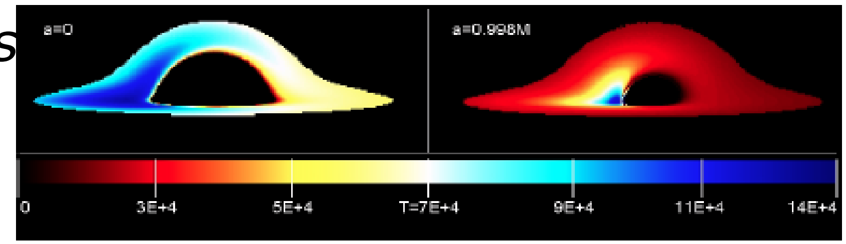
# Fitted Parameters for UV Disk Fits

- Results are 'reasonable' but not unique
- Now have independent mass estimates- results can be checked
- Find that values are not quite right- need more complex accretion disk models (surface is not BB relativistic effects)

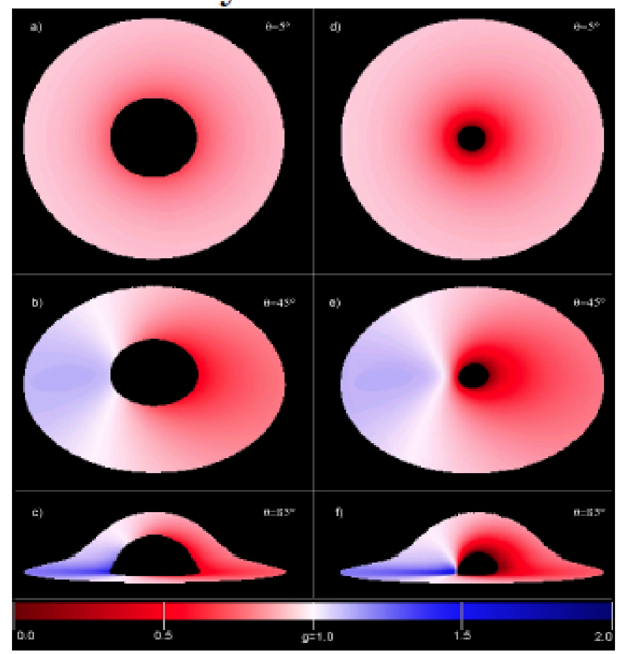


# Effects of Strong Gravity (Spin), Inclination Angle on Spectrum of Disk (Merloni 2010)



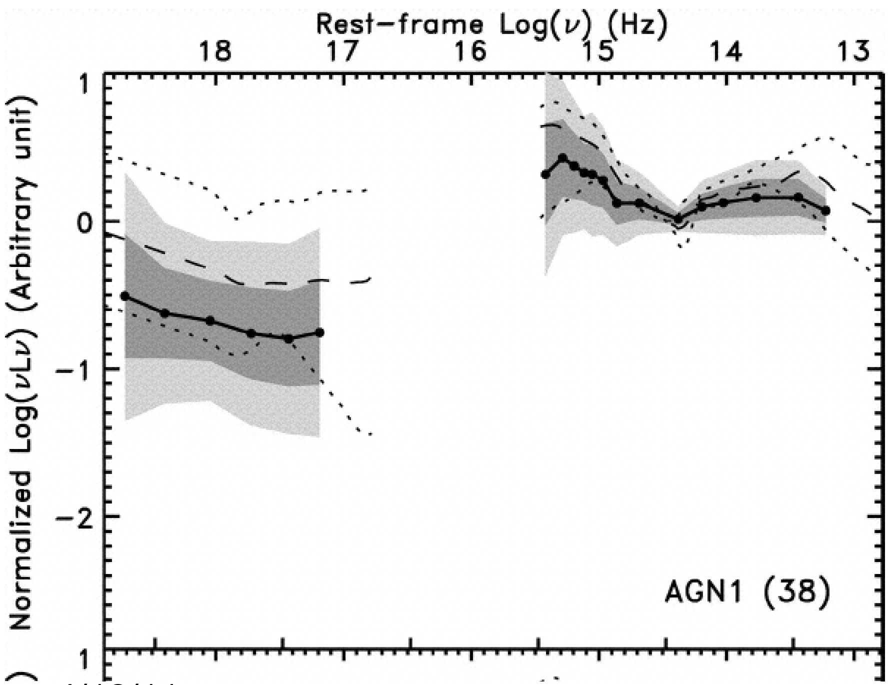

Courtesy of M. Calvani

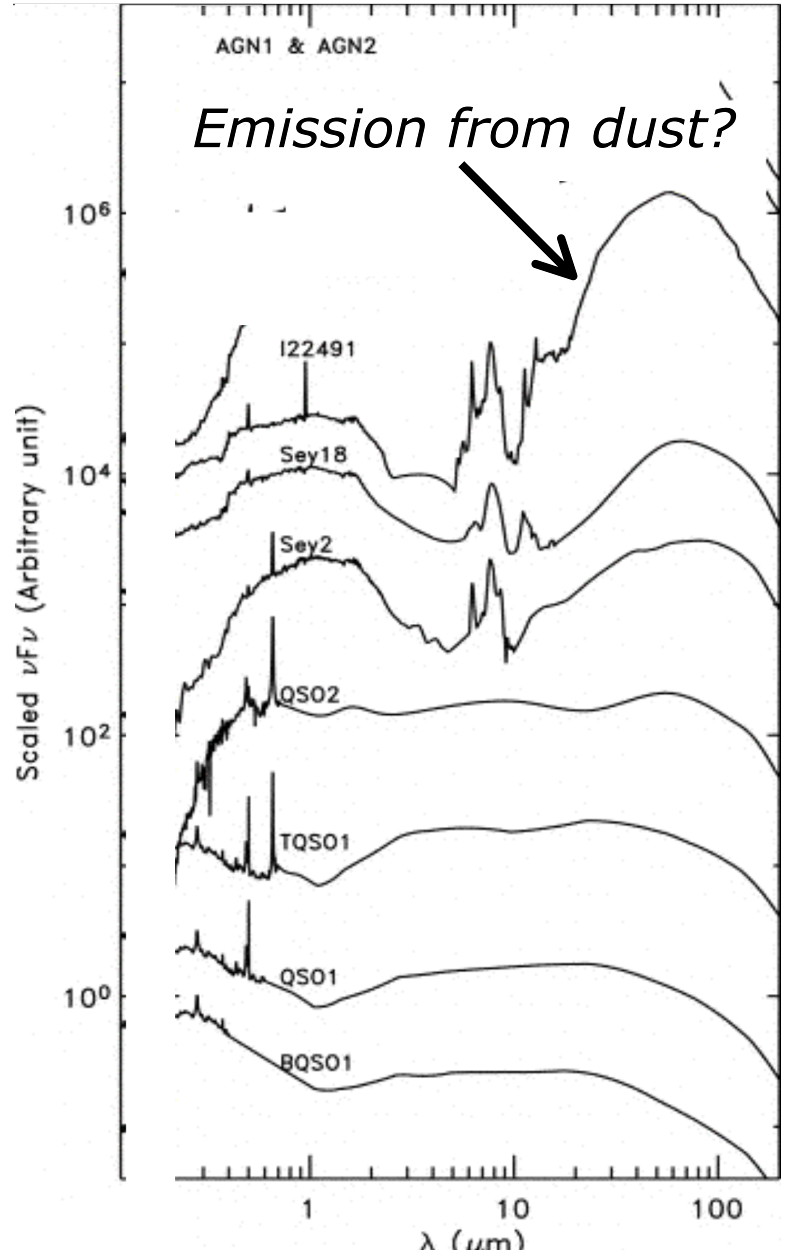


Zheng et al. 1997; Li et al. 2005; Shafee et al. 2006; McClintock et al. 2006; Nowak et al. 2008; Steiner et al. 2010; Kubota et al. 2010

# Life is Not So Simple

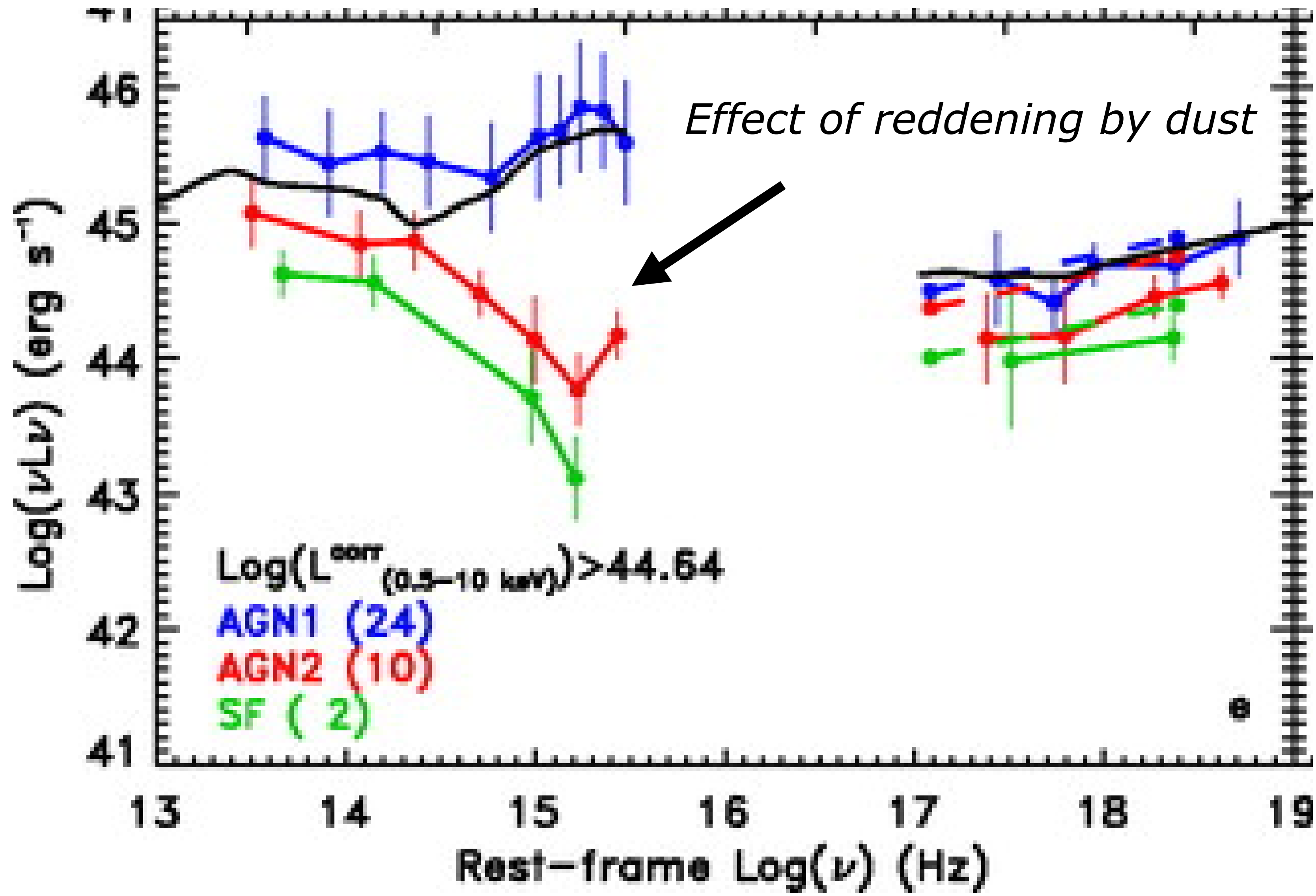
- The broad band spectra of both AGN and Galactic black holes have major deviations from disk spectra






*Adapted from Poletta et al 2007*

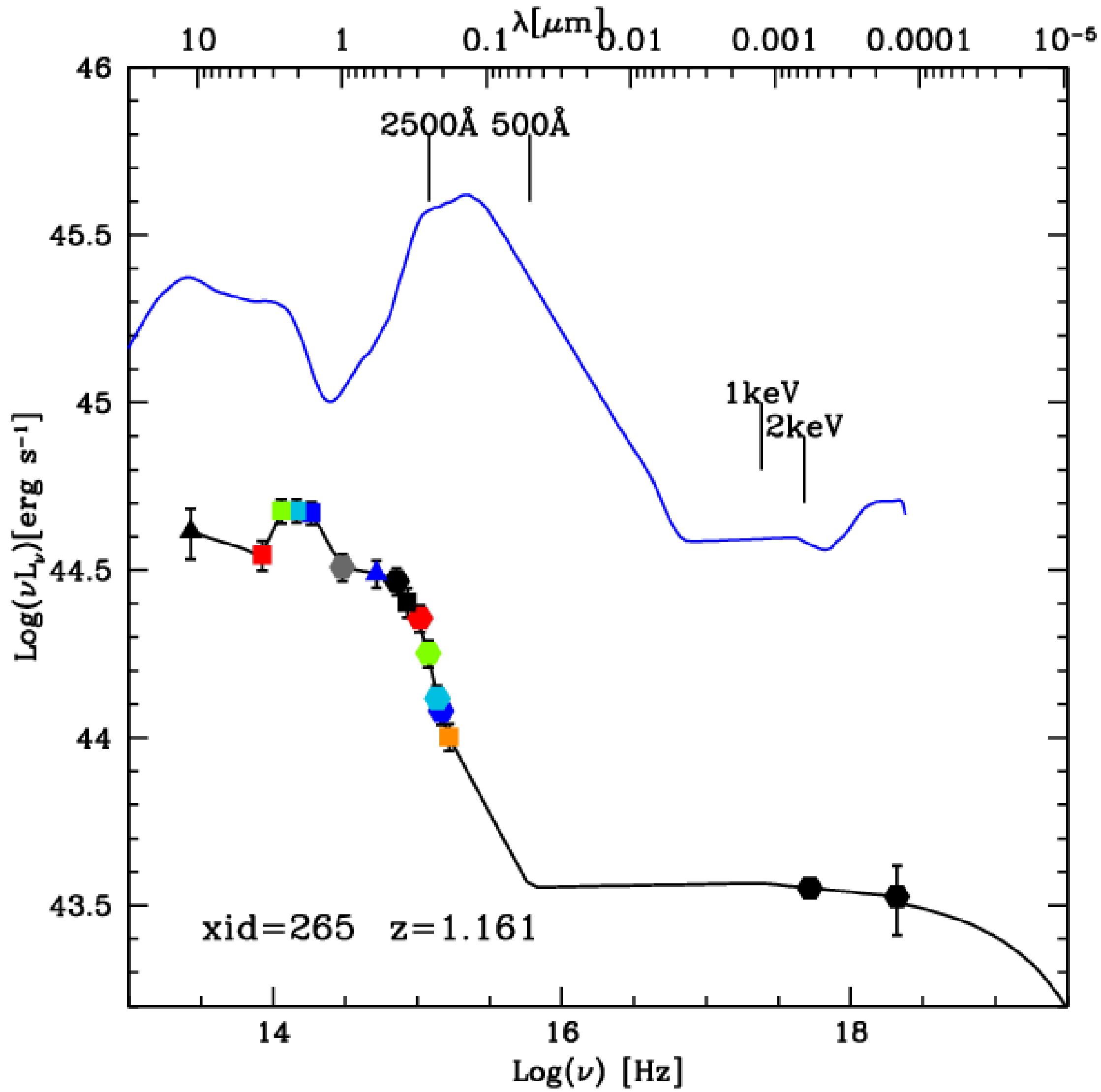



- Average Spectral Energy Distributions for 3 Classes of Objects Selected as X-ray Emitting AGN in a given x-ray luminosity bin (Polletta et al 2007)

# AGN

- A huge amount of work has gone into observing AGN across the entire electromagnetic spectrum
- There is a strong relationship between the optical-UV and the x-ray

*Brusa et al 2009*



# Effects of Dust Can Be Dominant

- Remember for the $M\sim10^8$ $T\sim5\times10^5$ K so 'roll over' is in the FUV
- $E_{max}\sim3kT\sim10^{16}$ hz
- The effects of dust (Reddening) go at $\lambda^{-2}$
- much bigger effects at shorter (UV) wavelengths- major effect on determination of temperature of accretion disk fits to quasars.

*average amount of reddening in the Milkyway at $b=50^0$*

*Massive thin accretion discs – III* 377

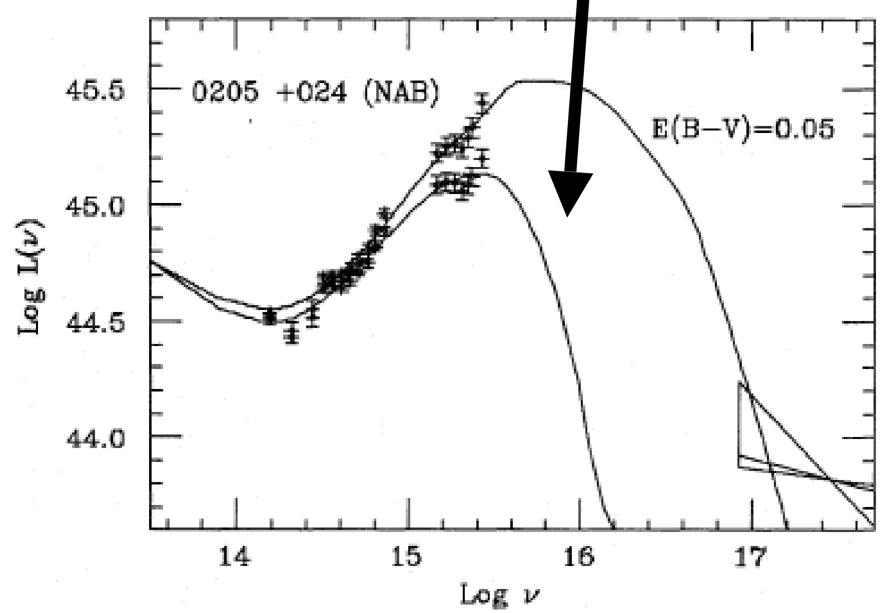
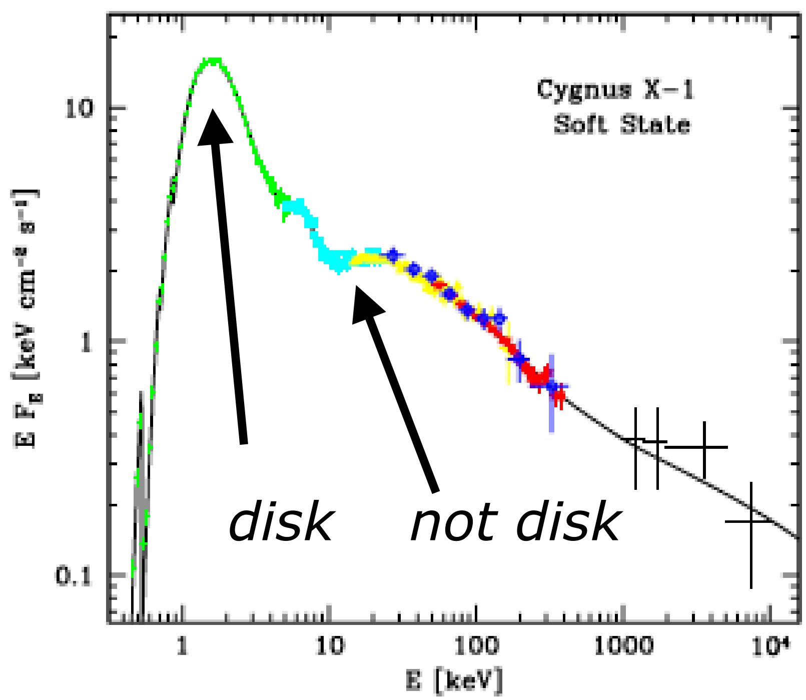
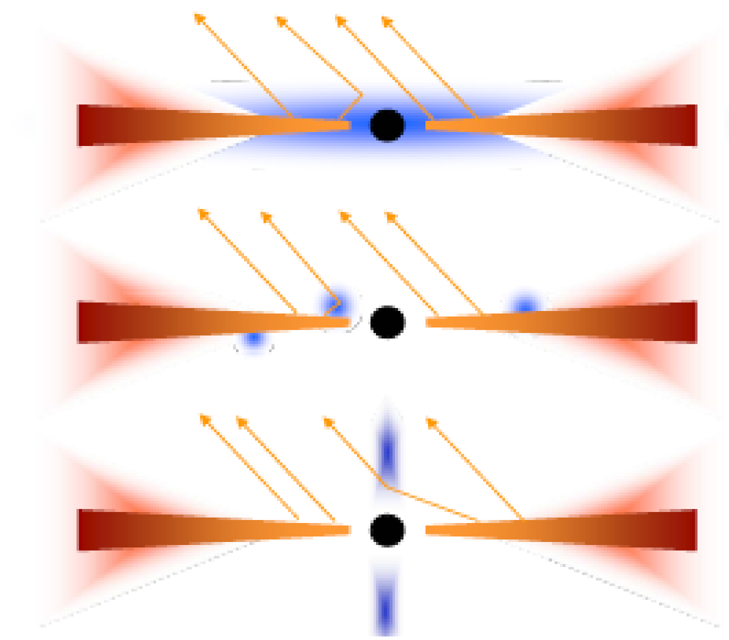



**Figure 6.** A fit for 0205+024 with and without a correction for internal reddening of $E(B-V)=0.05$. The best fit parameters are

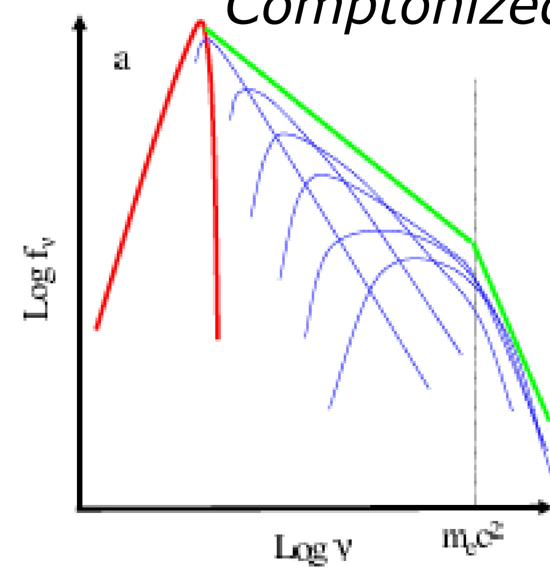
*Laor 1990*

# Real Data



*Comptonized spectra*




*Where do the high energy photons arise?*
*In both AGN and Black Hole binaries it is thought that this spectral component is due to Comptonization of a 'seed photon' population off of highly energetic electrons produced 'above' the disk*

# Comptonized Spectra

- The free parameter for the power law slope is y which controls the spectral slope
- However the smaller $\tau$ is larger T has to be to get the same slope - the 'bumpier' the spectra are
- spectrum steeps at high E (max T)
- y~1 is the usual case

- $y \sim 4kT/m_e c^2 (\max \tau, \tau^2)$
- slope $\alpha \sim -3/2+(9/4+y)^{1/2}$

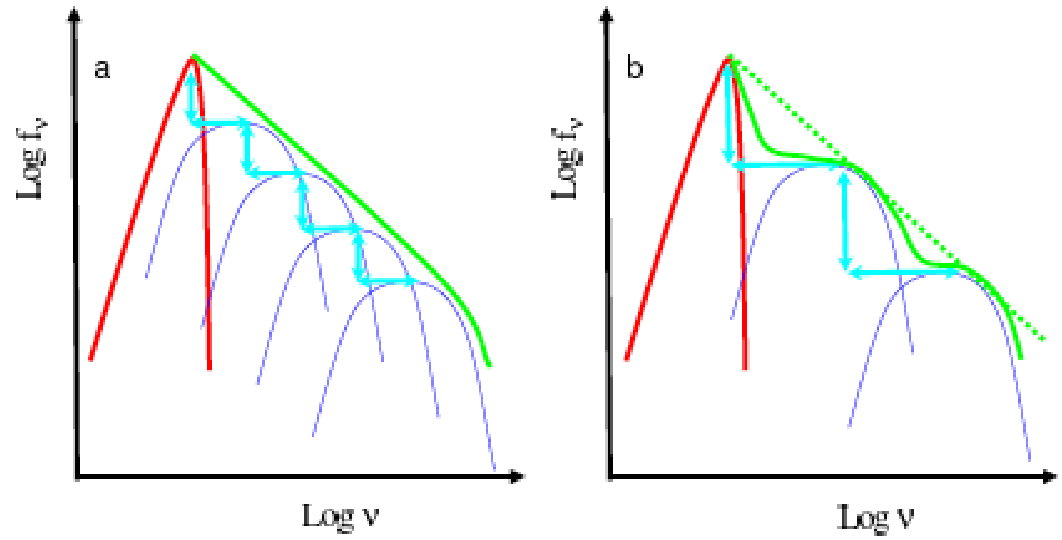
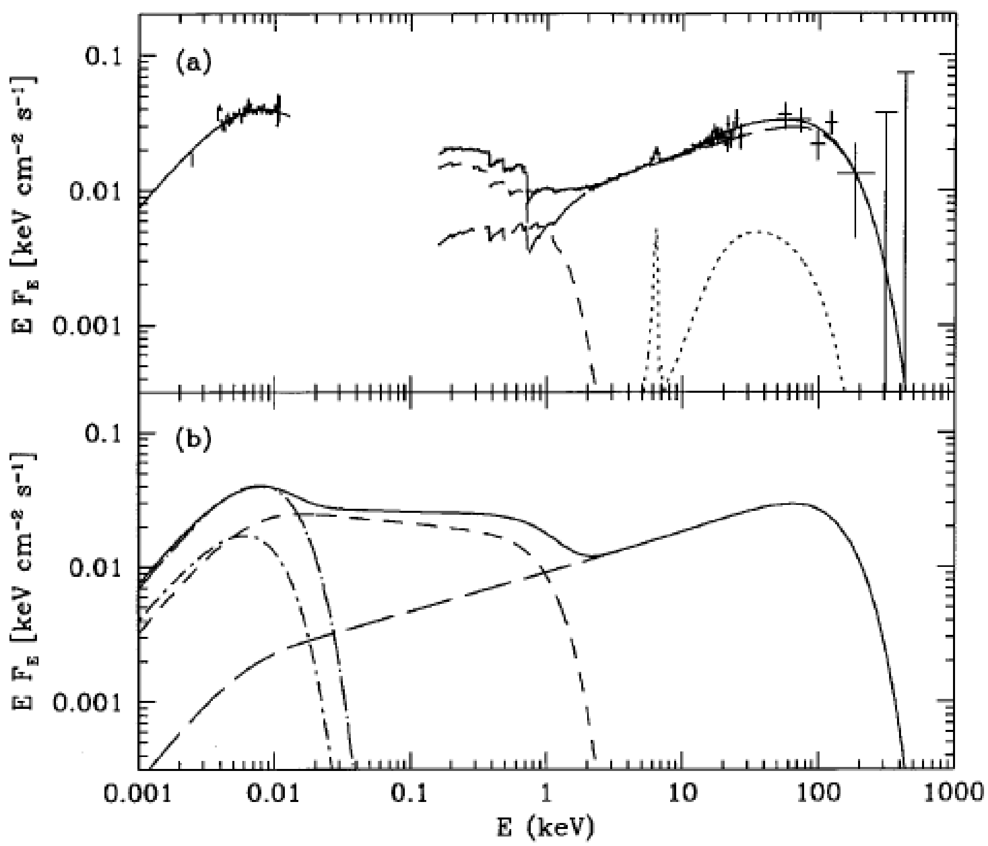


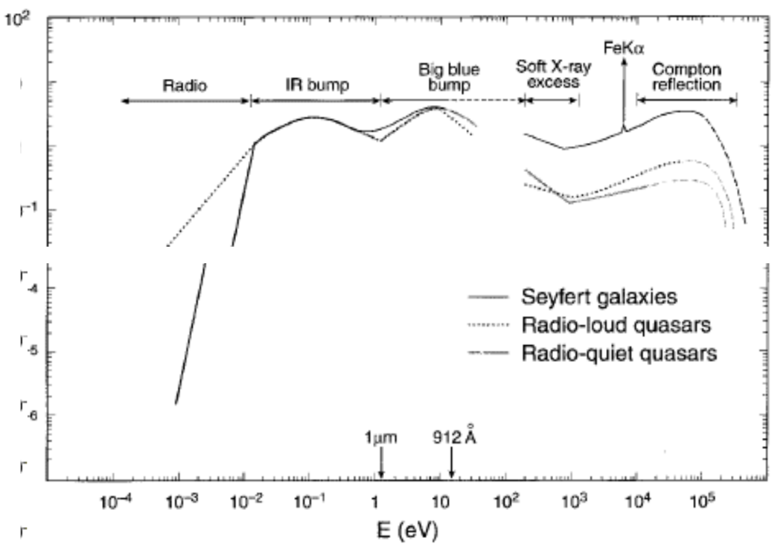

Figure 1.8 a) shows how the spectrum built up from repeated thermal Compton up scattering events for optically thin ($\tau \lesssim 1$) material. A fraction $\tau$ of the seed photons (red) are boosted in energy by $1 + 4\Theta$ and then these form the seed photons for the next scattering, so each scattering order (thin lines: blue in electronic version) is shifted down and to the right by the same factor, as indicated by the arrows (cyan), giving a power law (green solid line). b) shows that the same spectral index can be obtained by higher $\Theta$ and lower $\tau$ but the wider separation of the individual scattering orders result in a bumpy spectrum (green solid line) than a smooth power law (green dotted line).

*Done 2007*

# AGN

- 3 Broad bands of energy
- Disk dominates in optical-UV
- Comptonization in X-ray
- Reprocessed radiation in IR



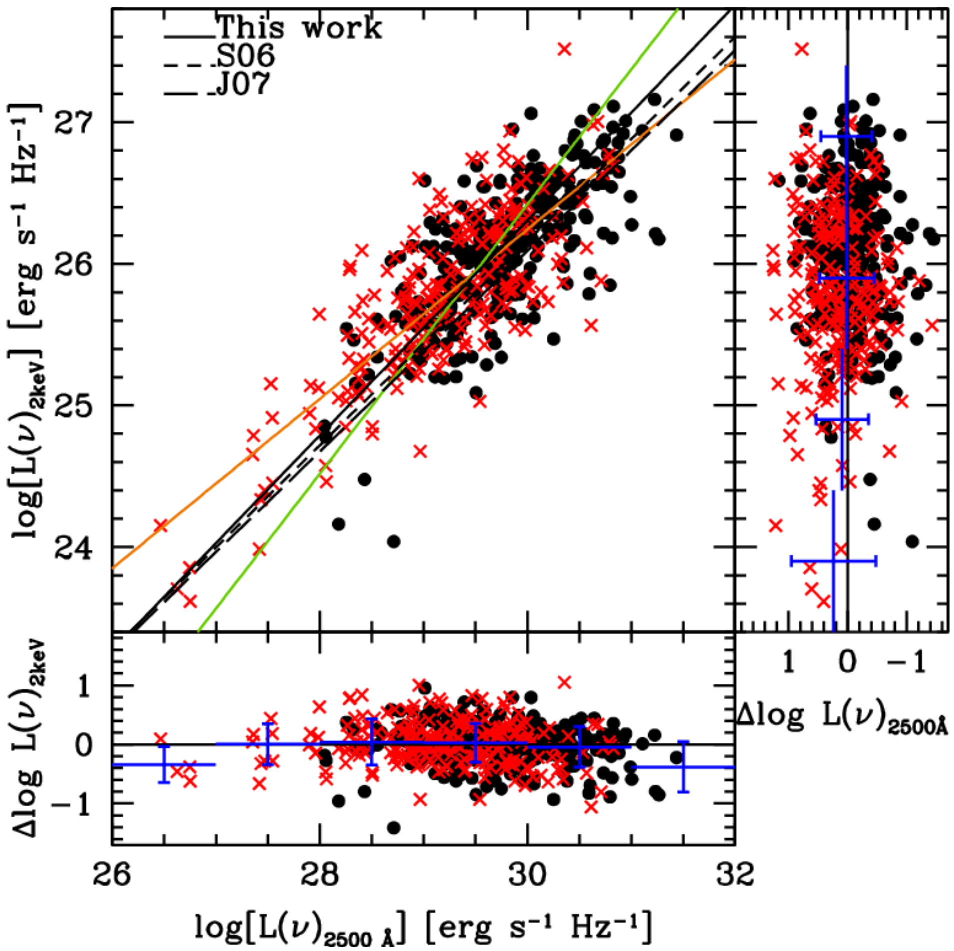

Magdziarz et al 1998

# More On BH Spectra

- Relationship of components
- Why do we think disk exists
- Geometry of central regions
- Reprocessing- how can we learn about the material in and around the black hole from spectral and temporal signatures in the spectra
- Spin and its influence

# X-ray to UV Relationship

- Over $10^3$ in luminosity the UV and x-ray track each in type I AGN
- Direct connection of disk emission to x-rays

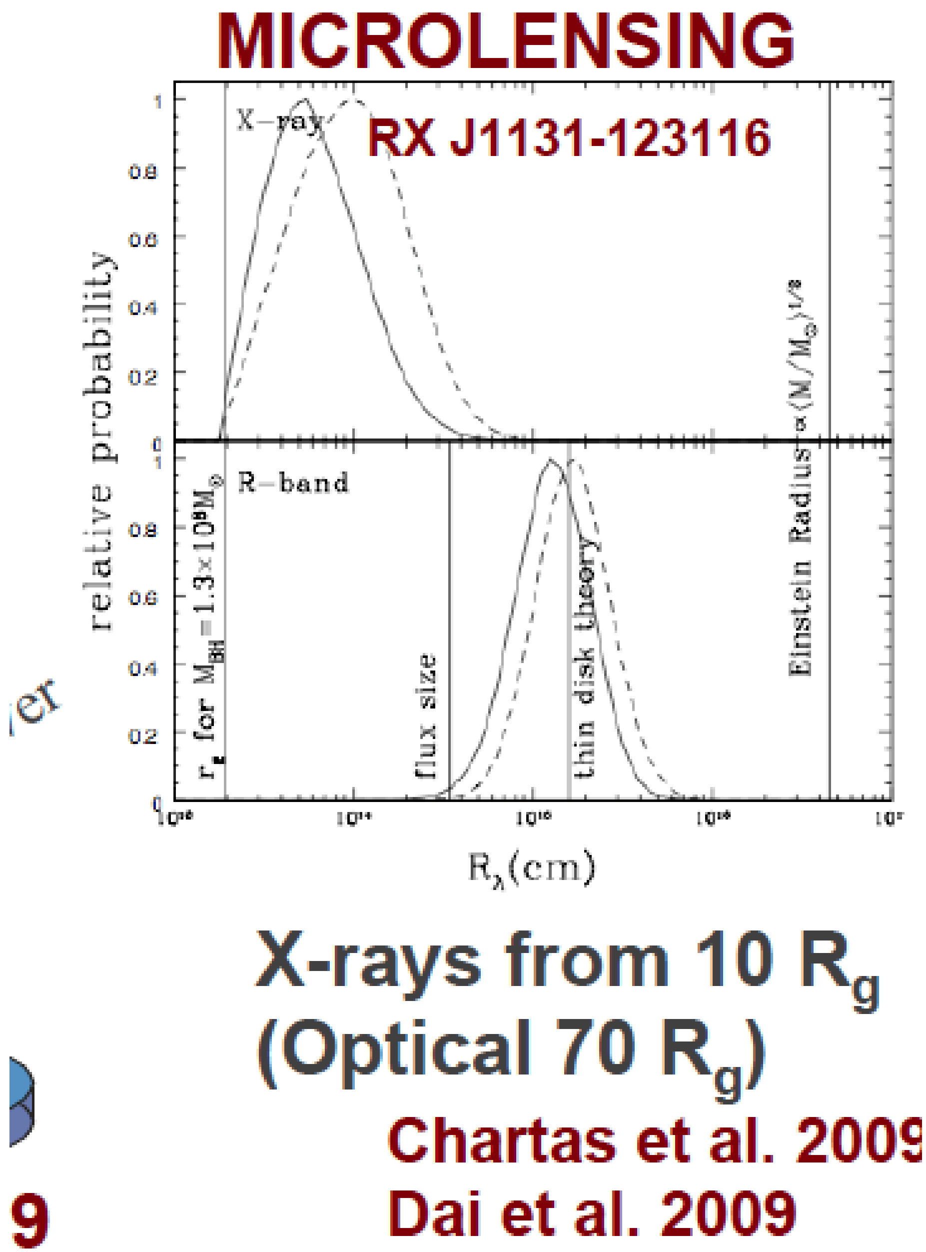





*Lusso et al 2010*

# How do we know that there really is a disk??

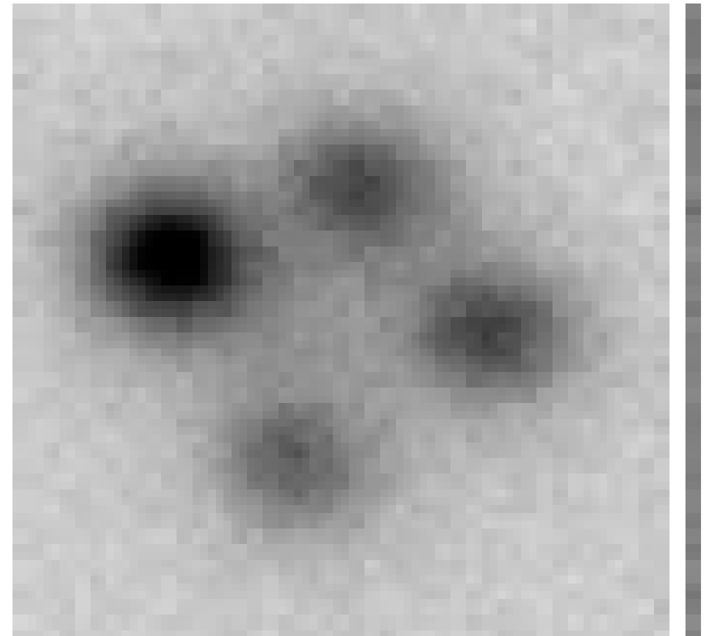
- Recent microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory- e.g. Microlensing perturbations to the flux ratios of gravitationally lensed quasar images can vary with wavelength because of the chromatic dependence of the sources apparent size.



# MicroLensing

- As we saw last time in a disk $T(r) \sim T_{max} r^{-3/4}$
- Writing it out in full
- $T_{eff}(r)=\{(3G^2 M_{BH}{}^2 m_p f_{Edd})/2c\sigma_{SB}\varepsilon r^3)\}^{1/4} (1-r_{in}/r)^{1/4}$
  - $f_{Edd}$ is the Eddington ratio , $M_{BH}$ is the BH mass,$s_{SB}$ the Stefan Boltzman constant , $\varepsilon$ is the relation between energy generation and $mc^2$
- Thus the disk emits most of its short wavelength light at small radii
- Integrating the disk temperature profile (Blackburne et al 2010) one gets that the half light radius as a function of size is
- $r_{1/2} \sim 1.7 \times 10^{16} cm (M_{BH}/10^9 M_\odot)^{2/3} ( f_{Edd}/\varepsilon)^{1/3} (\lambda/\mu)^{4/3}$
- In other words the effective size $\sim\lambda/^{4/3}$

- The size of the disk is in Einstein radius units which are converted to cgs units with a model of the grav potential of the lensing galaxy
- To compare to model disks, have to assume and $M_{BH}$, $f_{Edd}/\varepsilon$



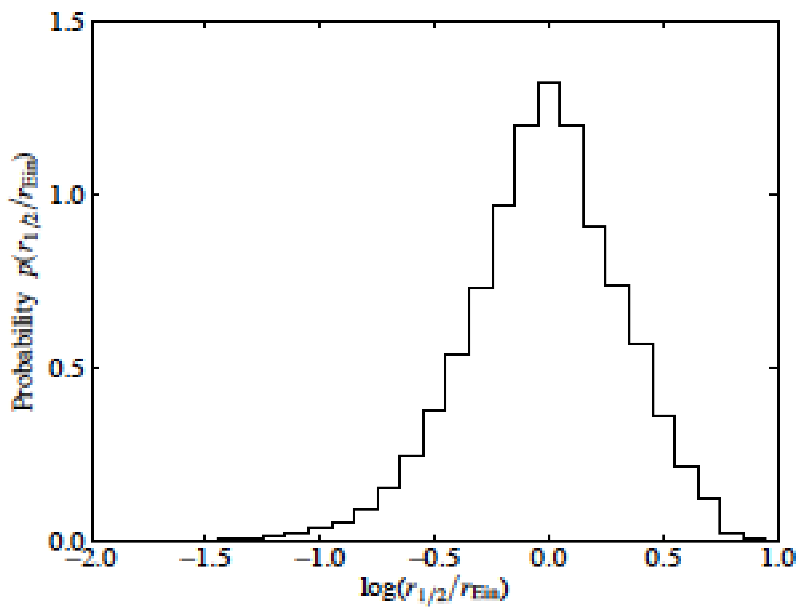
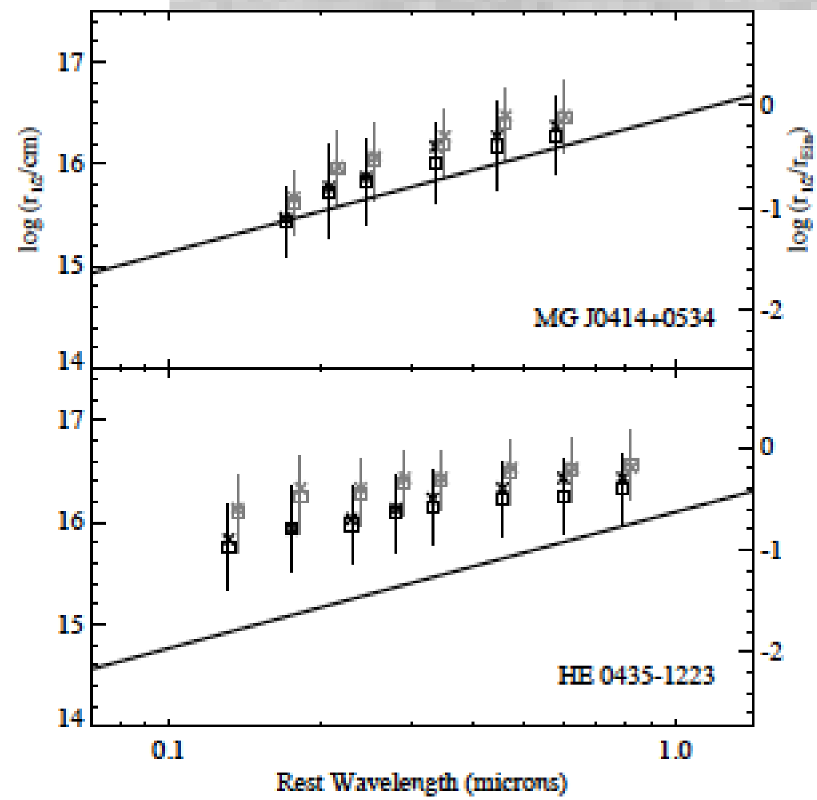
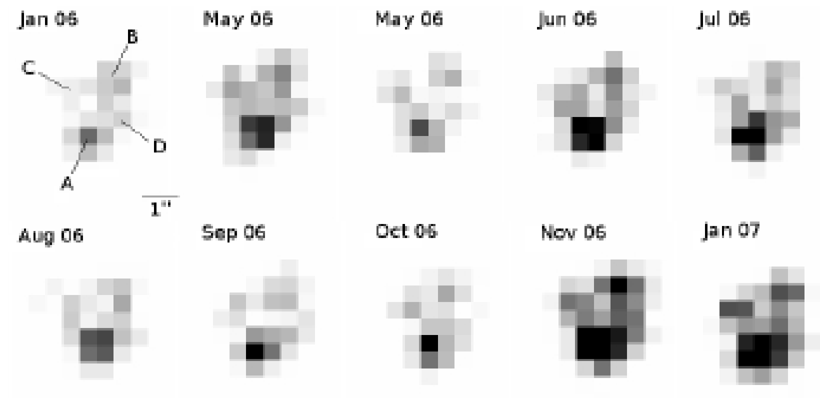


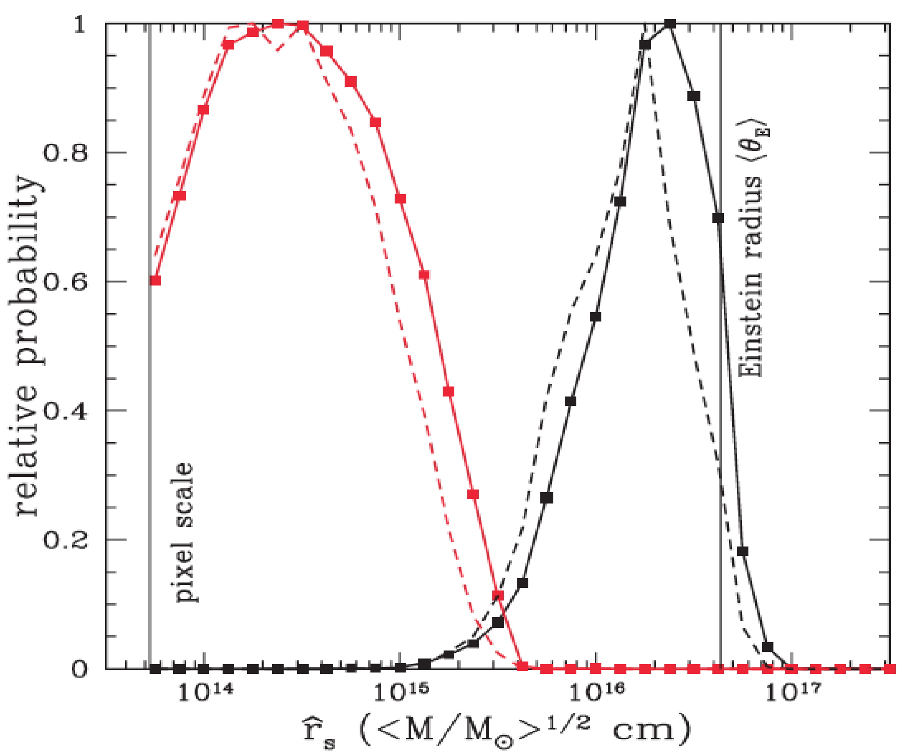

**Figure 5.** Posterior probability distribution for the size of PG 1115 in tl
$i'$ band, resulting from considering both $i'$-band and X-ray flux ratios. Tl

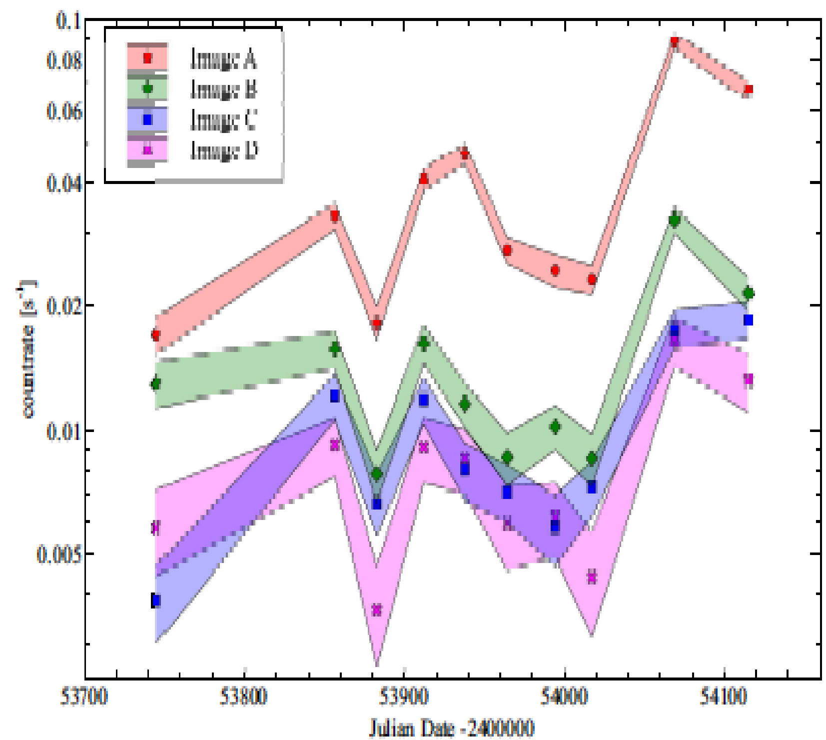


# X-ray MicroLensing Also

- Probability distribution of optical and x-ray source size (Zimmer et al 2010 , Chartas et al 2008)

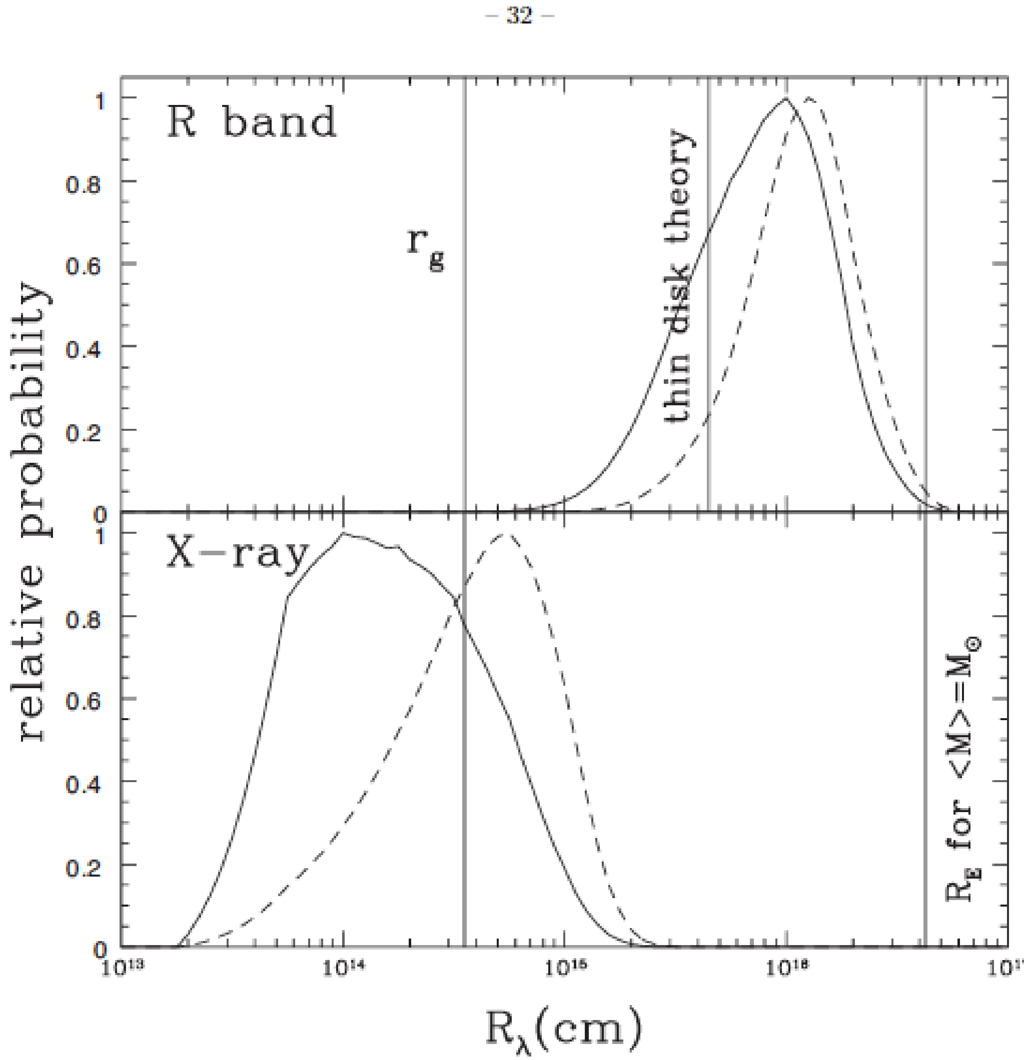


# Results are In Rough Agreement With Theory

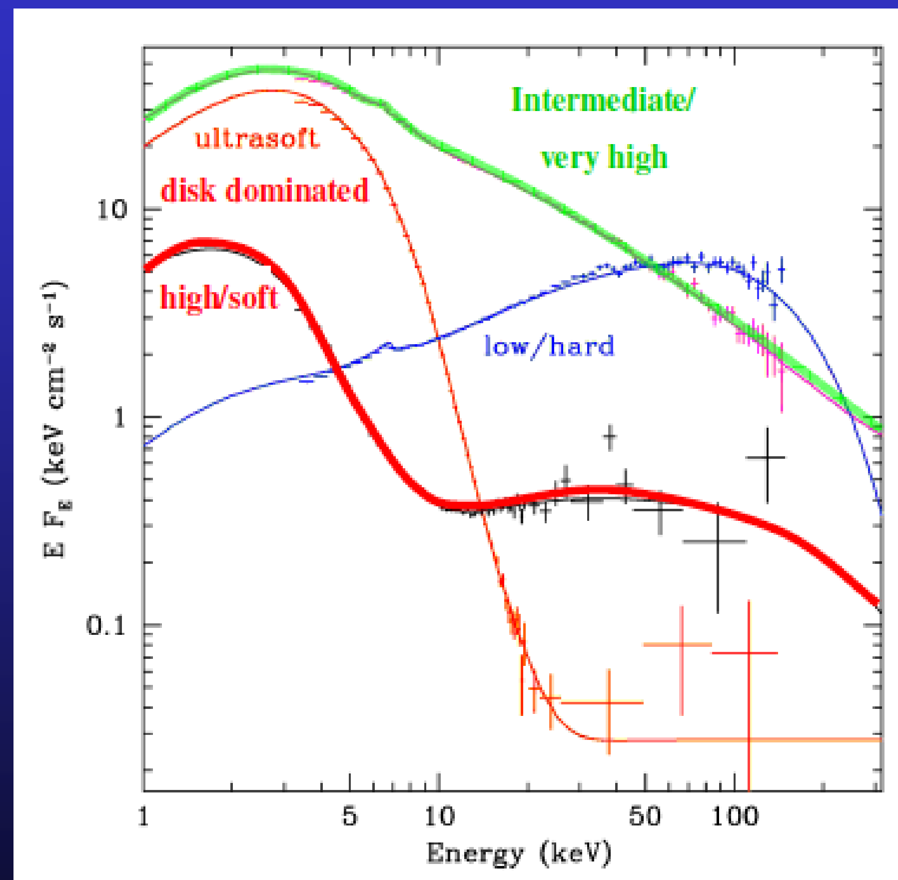
- Chartas 2008
- X-rays are emitting near the Schwarzschild radius
- Optical ~10x further out



# Spectral States of Black Hole Binaries

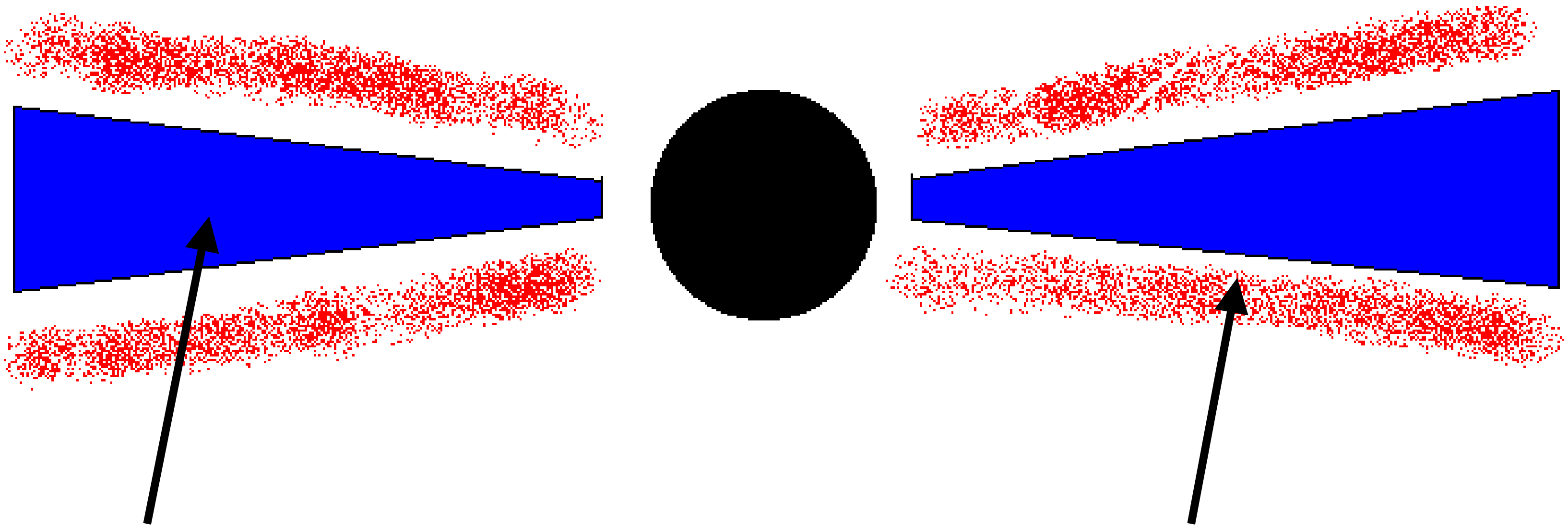
- thought to be due to changes in disk structure - not seen in AGN (yet)

- Dramatic changes in continuum – single object, different days
- Underlying pattern in all systems
- High $L/L_{Edd}$: soft spectrum, peaks at $kT_{max}$ often disc-like, plus tail
- Lower $L/L_{Edd}$: hard spectrum, peaks at high energies, not like a disc (McClintock & Remillard 2006)




Gierlinski & Done 2003

# Where do the Spectral Components Arise?

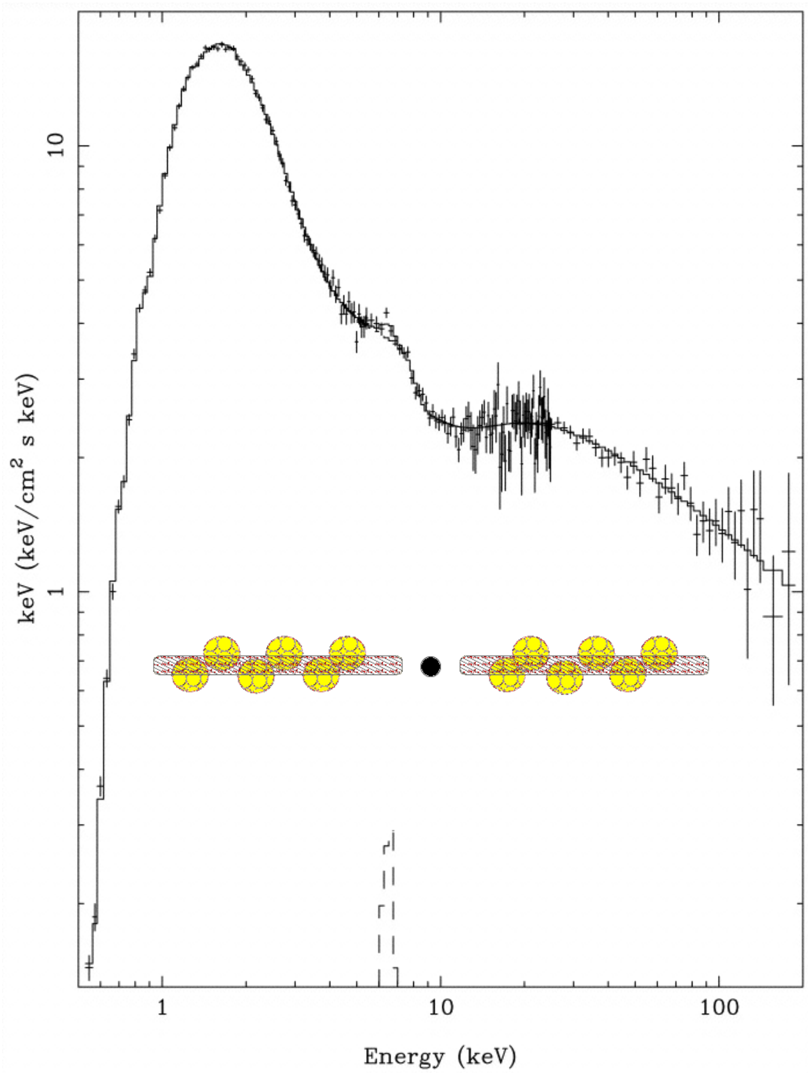


*Optically-thick part of the accretion disk emits thermal spectrum… black body radiation with*

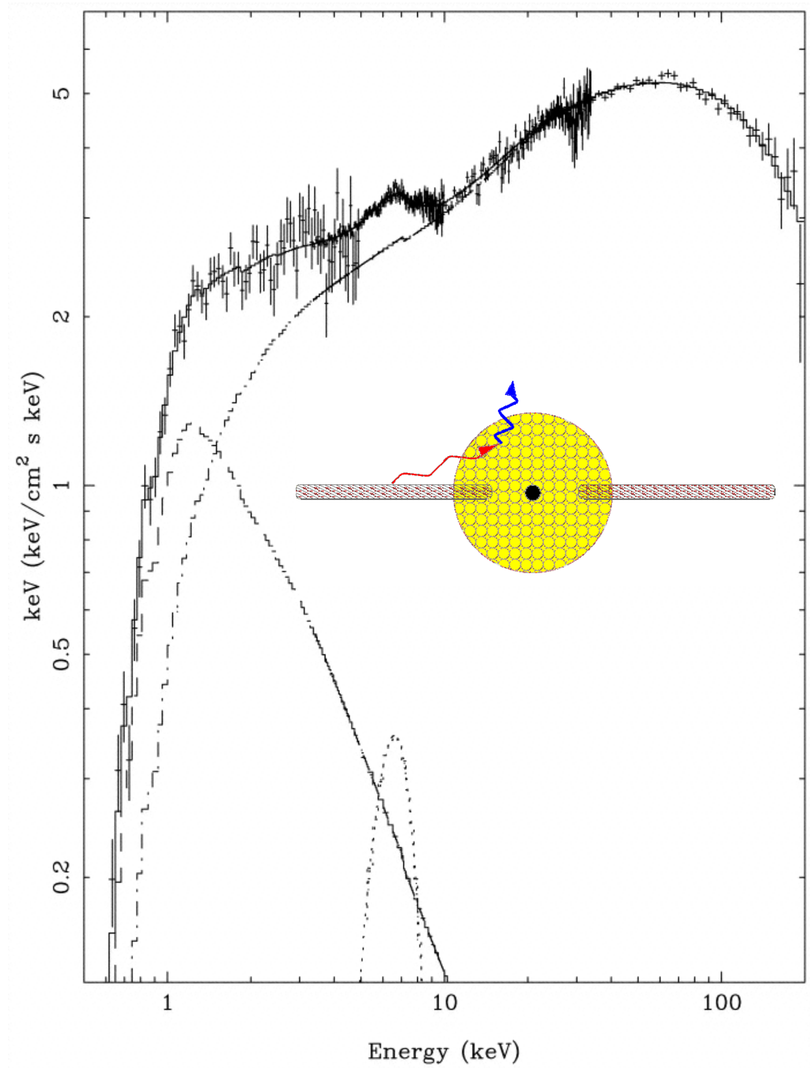
$$T = \left( \frac{3GM\dot{M}}{8\pi r^3 \sigma_{\rm SB}} \right)^{1/4}$$

*X-ray "tail" probably comes from a hot corona that sandwiches the disk… inverse Compton scattering of thermal disk emission by electrons with $T\sim10^9$K*

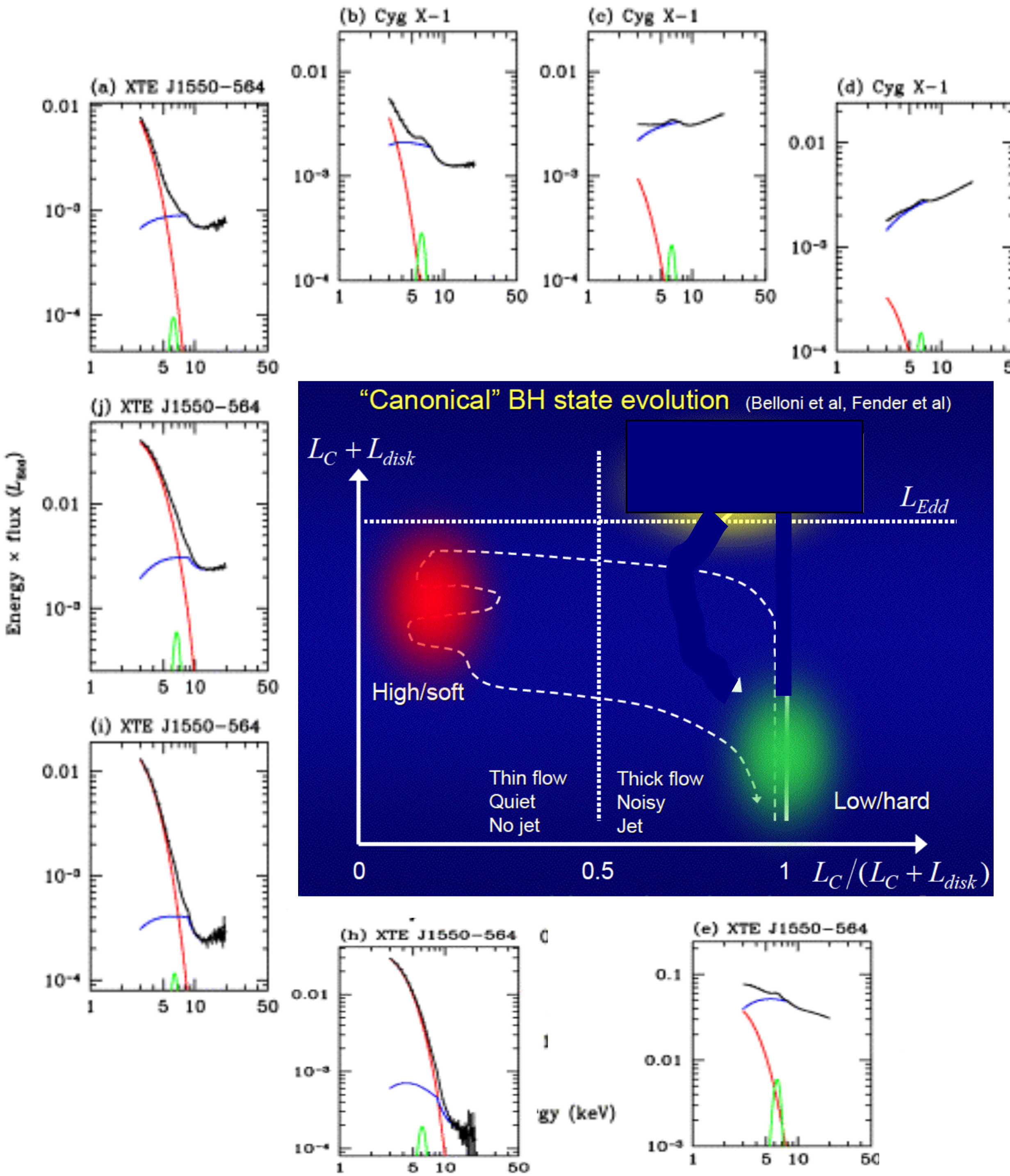
# Cygnus X-1 Spectral States and Ideas on Geometry




Soft (high) state; thermal disk emission + hard tail




Hard (low) state; hard X-ray spectrum, little/no thermal disk




*Wide Variety of Spectra in Galactic Accreting Black Holes- (Gierlinski and Done 2003)*

*Redline is accretion disk*

*Blue line is from Comptonization*

*The wide range in the ratio of the two is related to the Eddington ratio- states*

*At L→ $L_{Edd}$ Spectrum more disk dominated*

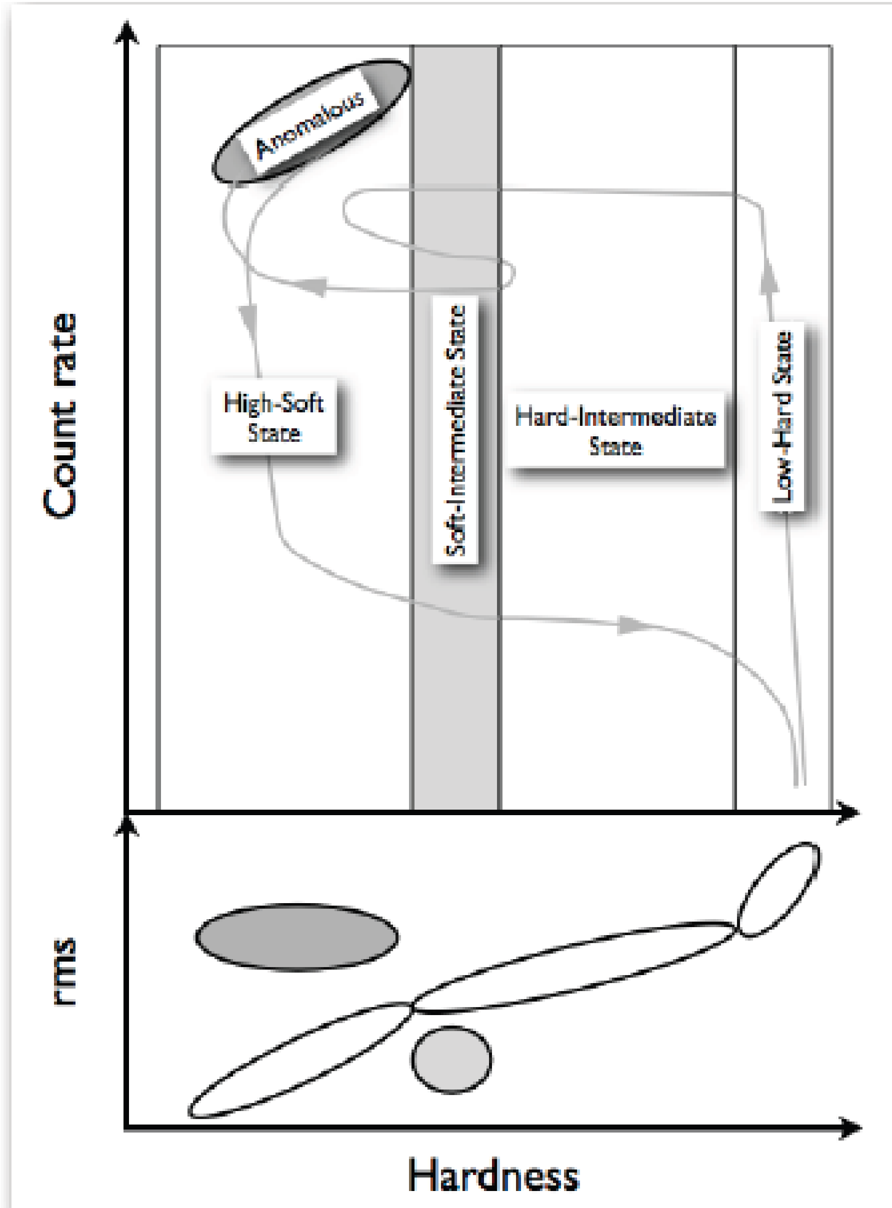
*In galactic black holes there is a pattern to the spectral/intensity changes*

*The high soft state is disk dominated*

*The low hard state is dominated by the x-ray power law*

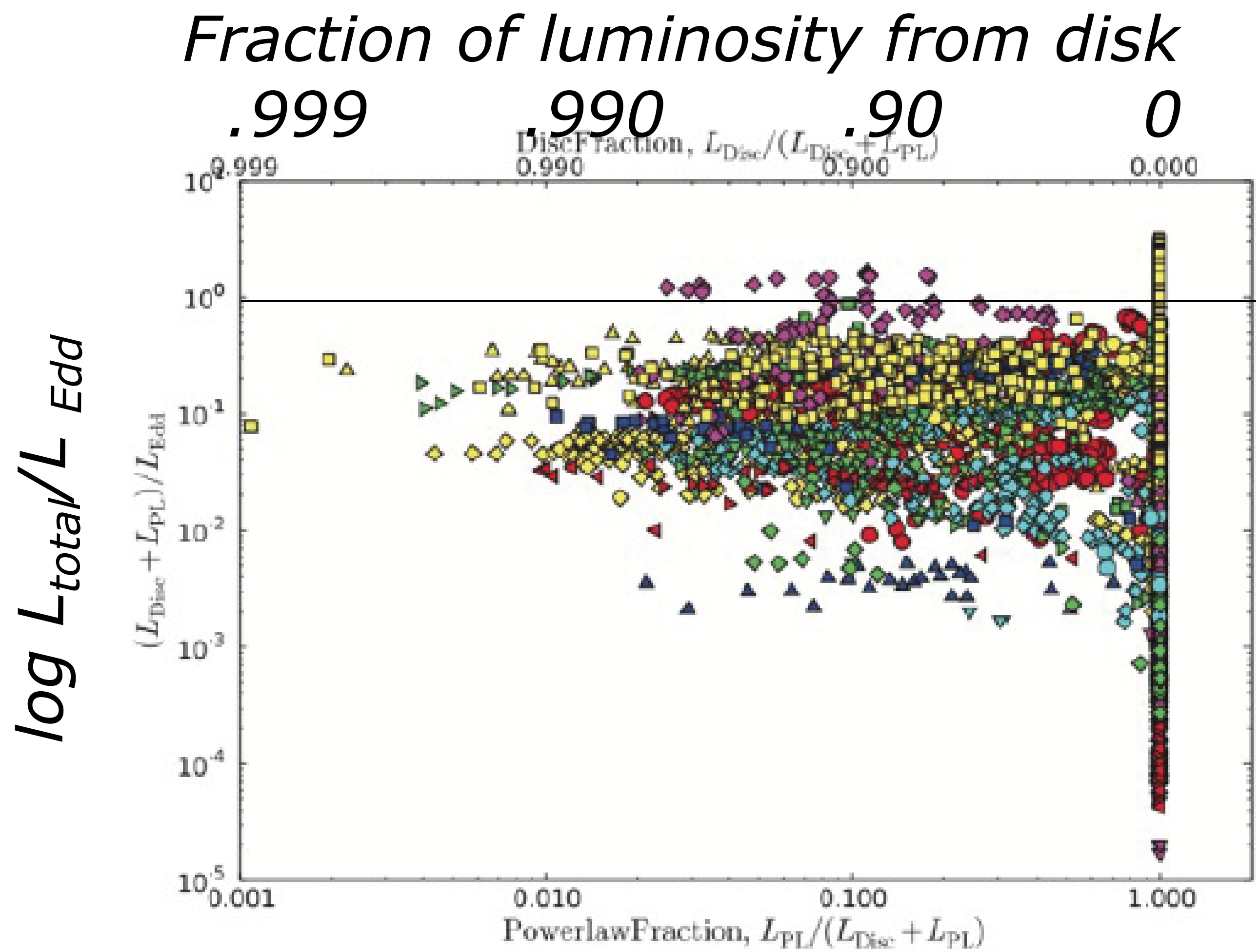
*The 'variability' - represented by the root mean square (RMS) variations is also related to the state*

*It is believed that these states are related to the geometry of the accretion flow*



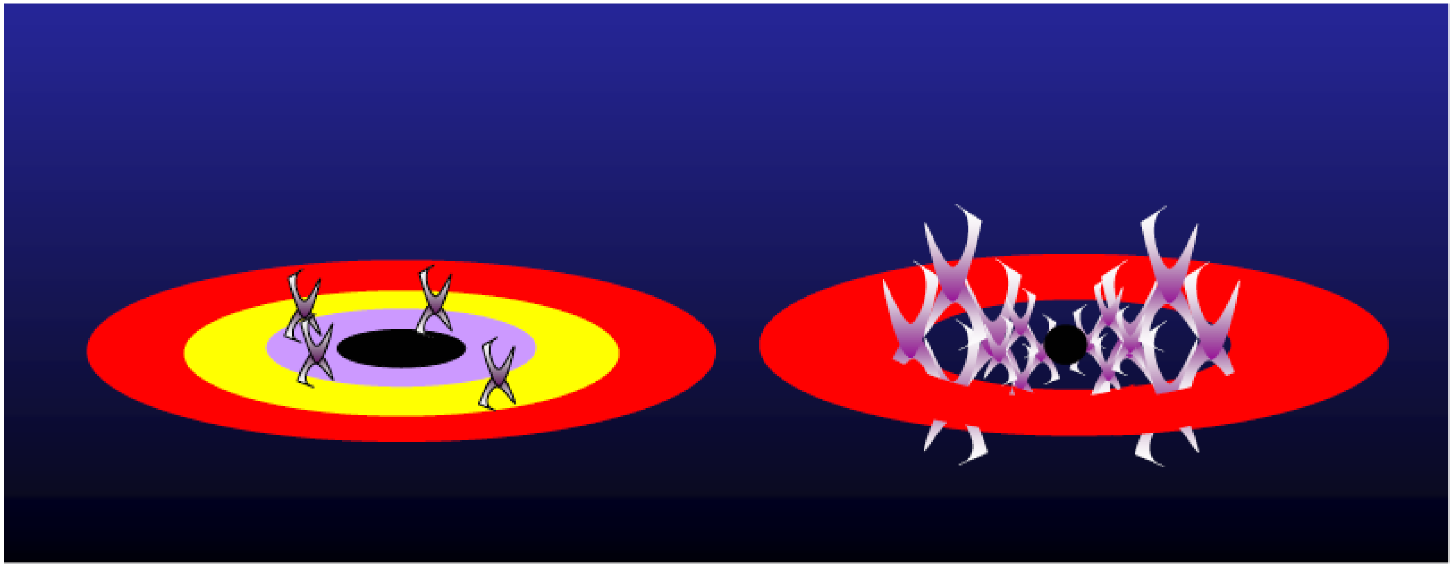

Belloni (2010)

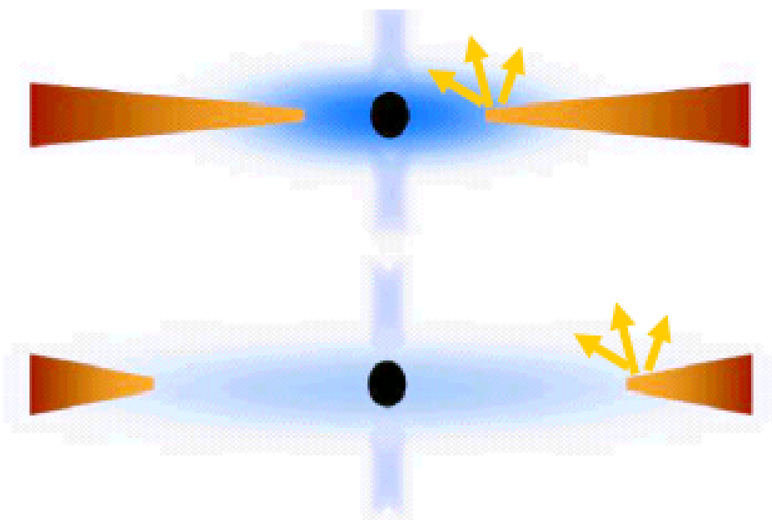
- Many (but not all) black hole binaries follow a similar track
- (each color is a different object)




*adapted from Belloni*

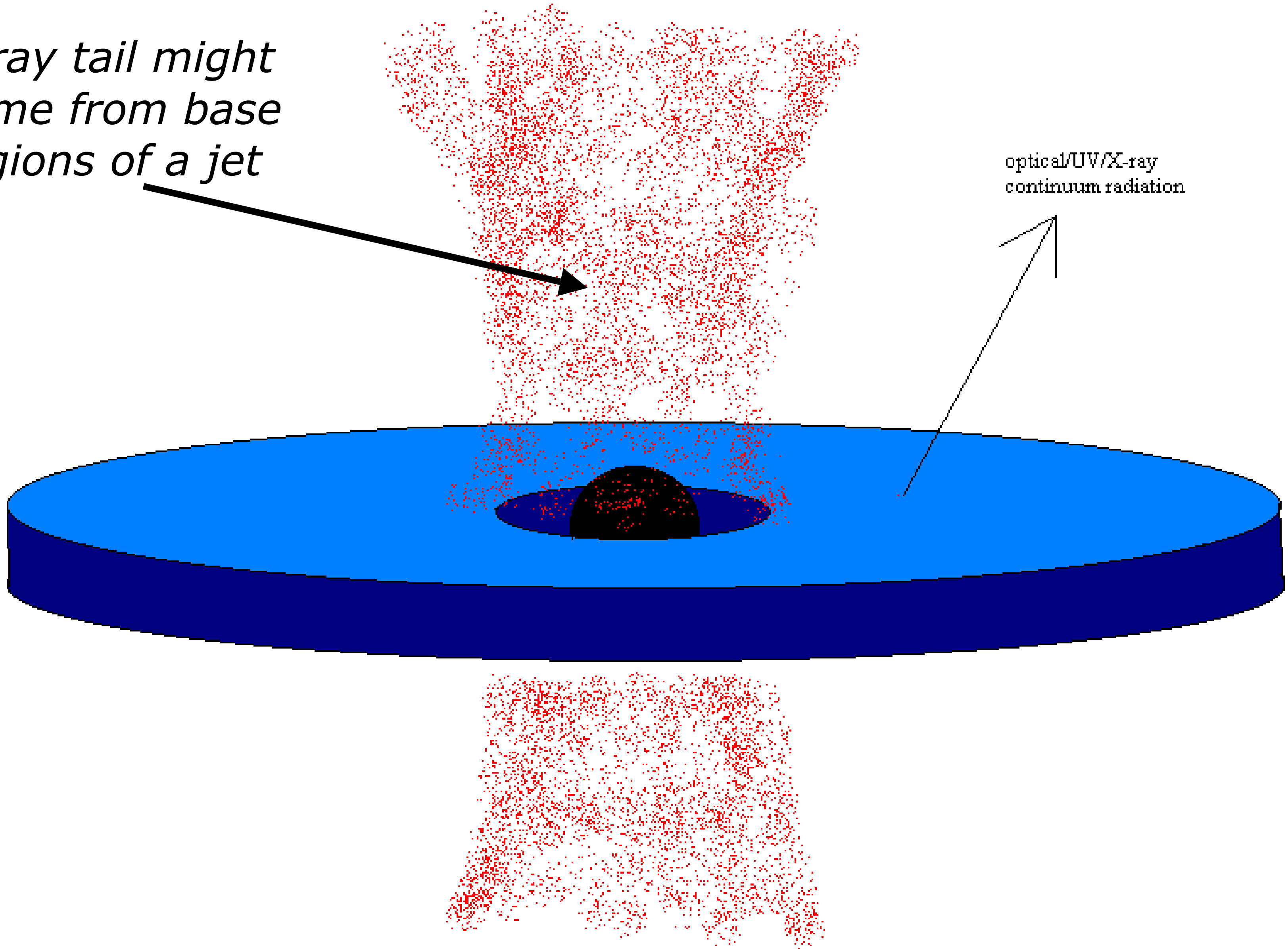
# Even More Possible Geometries





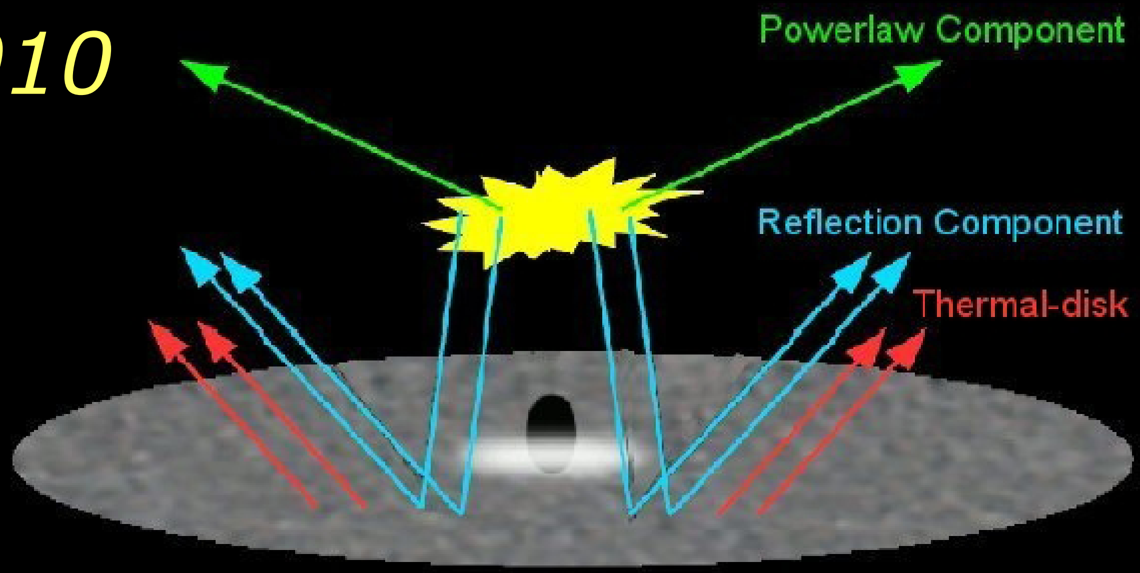
*From C. Done*

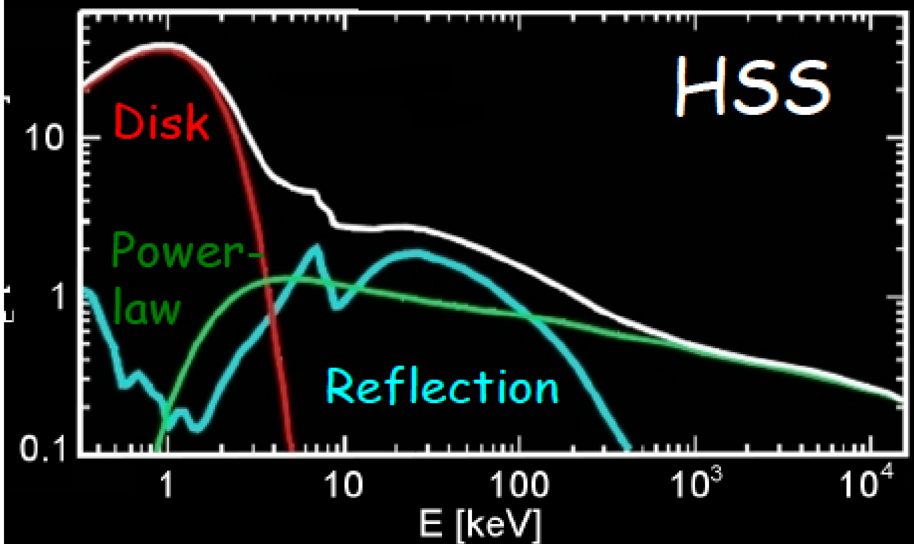
*X-ray tail might come from base regions of a jet*

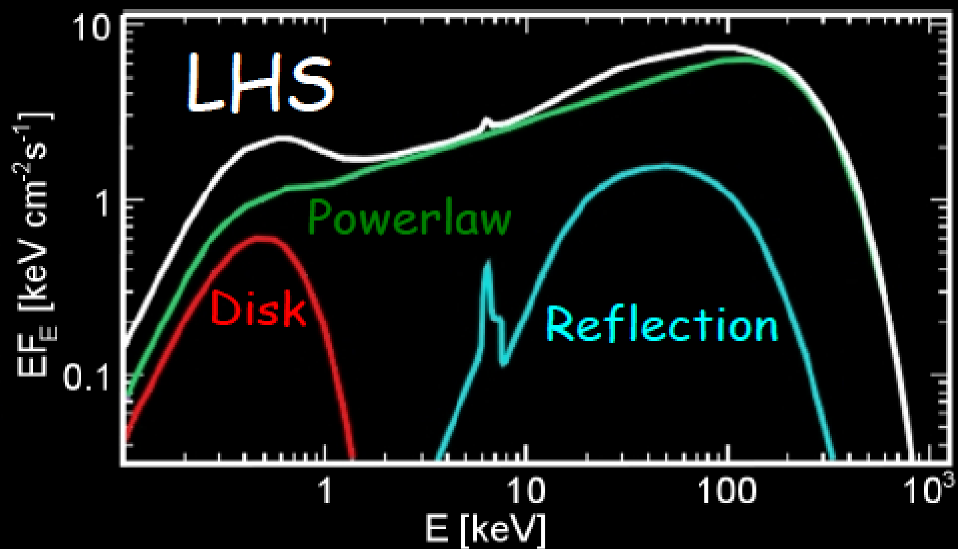


# Galactic Black Hole Binaries

*Reis 2010*



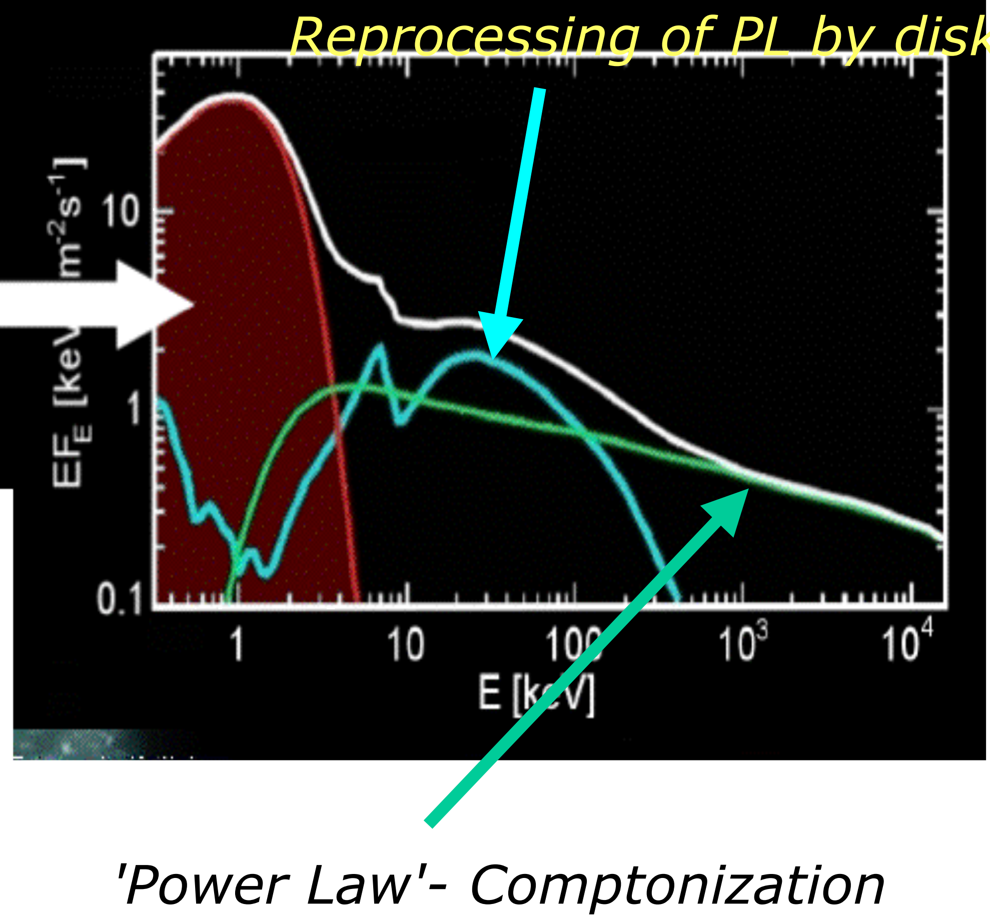



# Components in High State- R. Reis 2010

$$F_d = \frac{L_d cos(\theta)}{4\pi D^2}$$

$$L_d \simeq 4\pi R_{in}^2 \sigma T_{in}^4$$

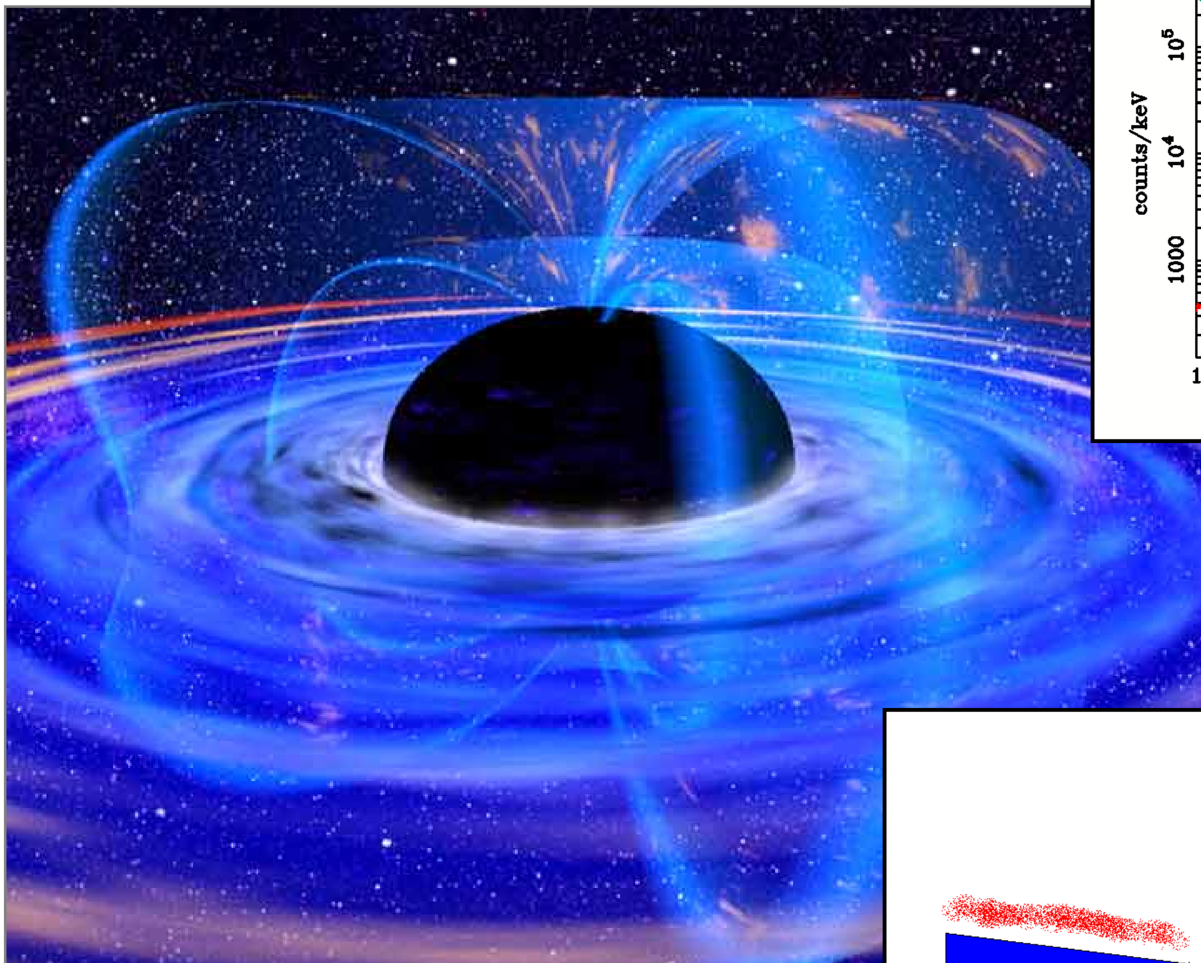


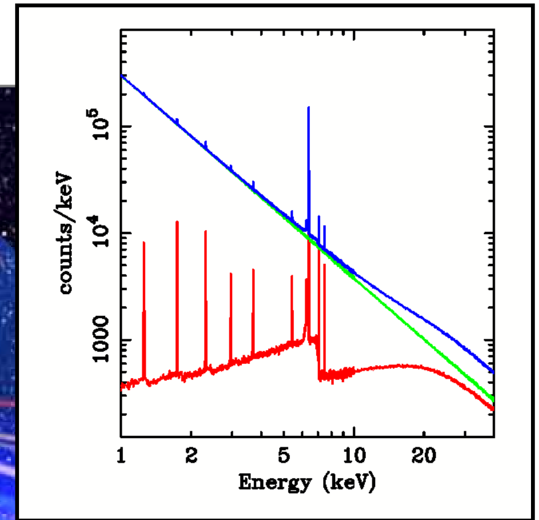
# Todays Lecture and ...

- Need your project titles on Thursday-------------
  ---------------------------------------

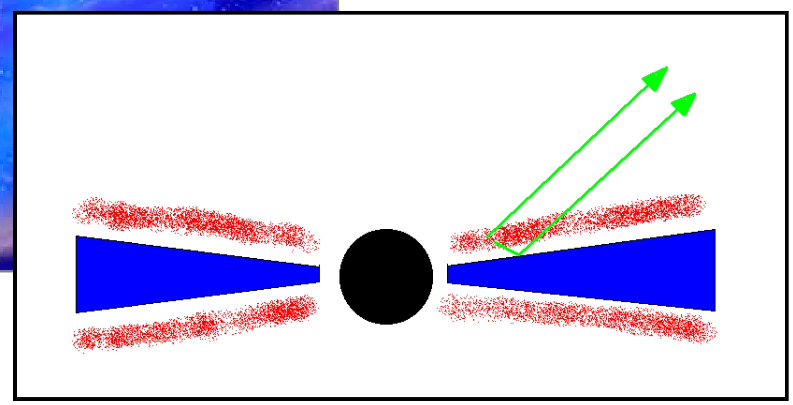
Reprocessing- how can we learn about the material in and around the black hole from spectral and temporal signatures in the spectra

Spin and its influence



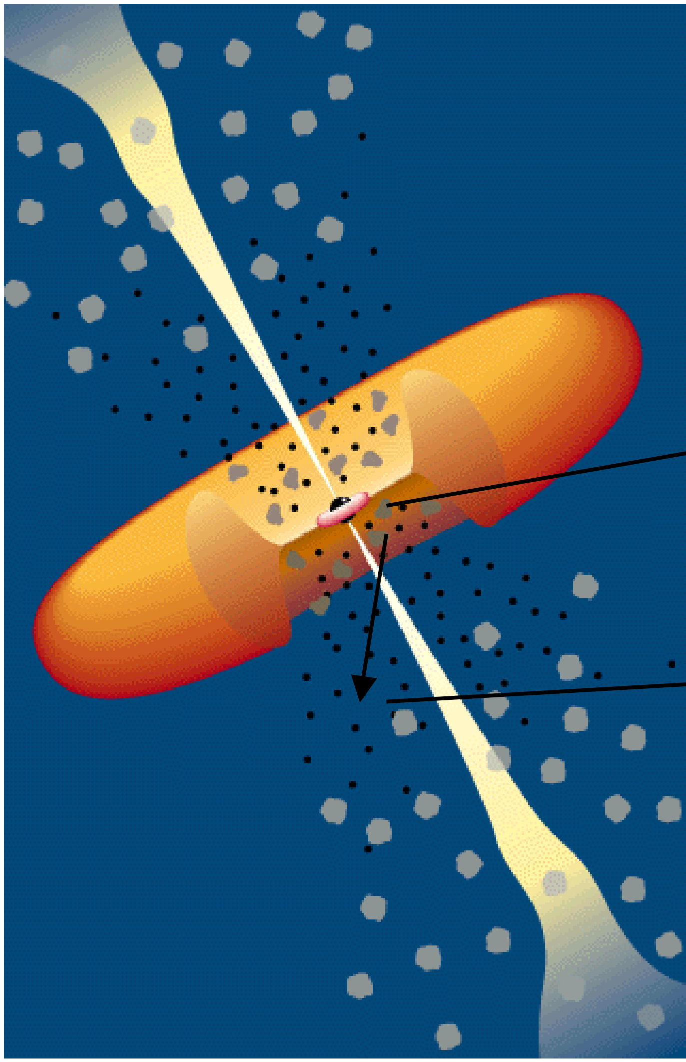


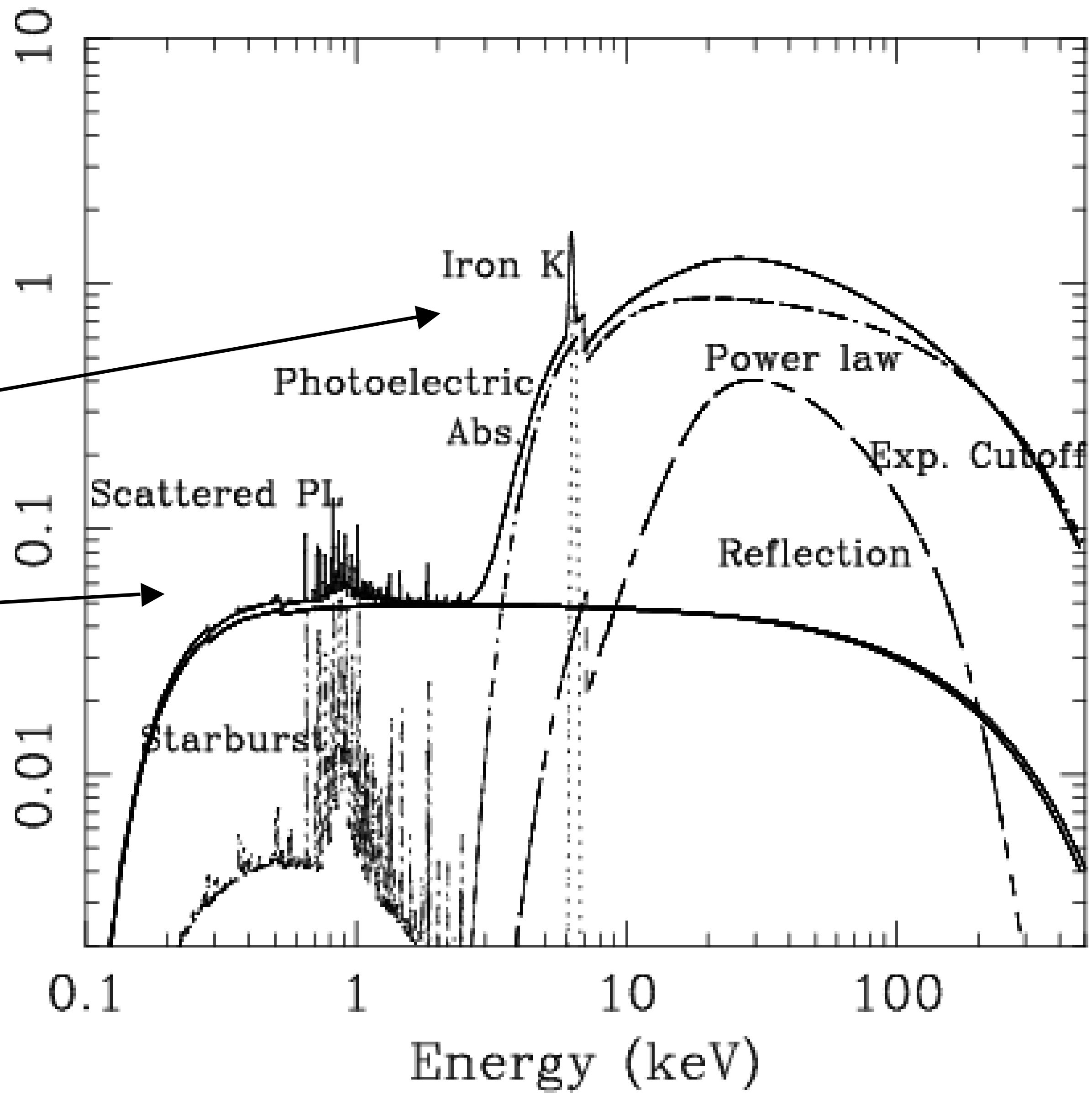

Reynolds (1996)



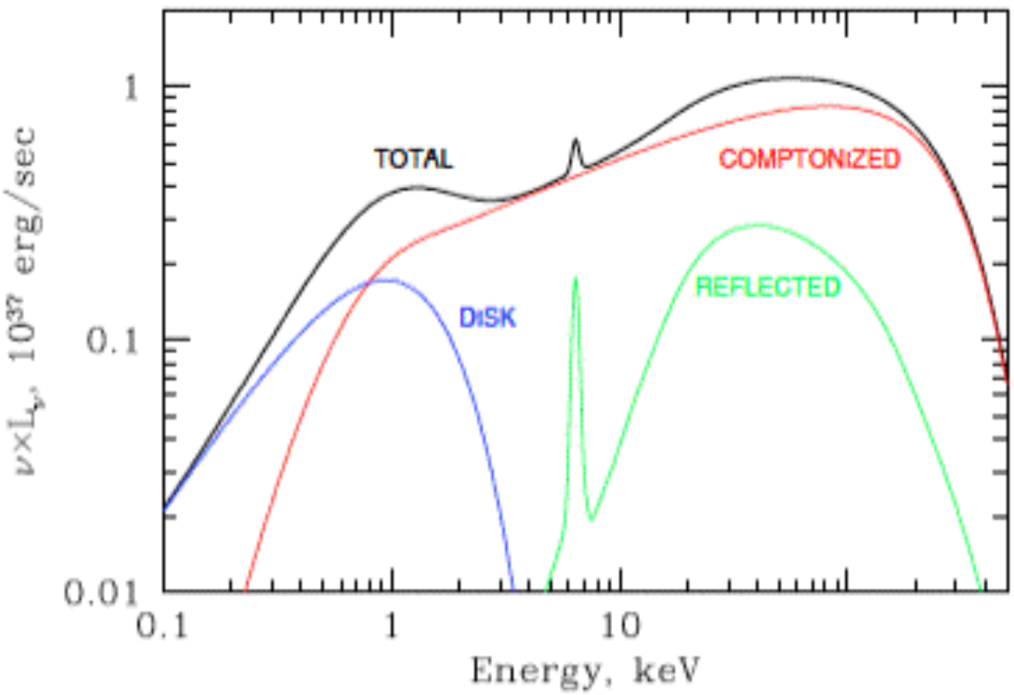
- X-ray “reflection” imprints well-defined features in the spectrum

■ .

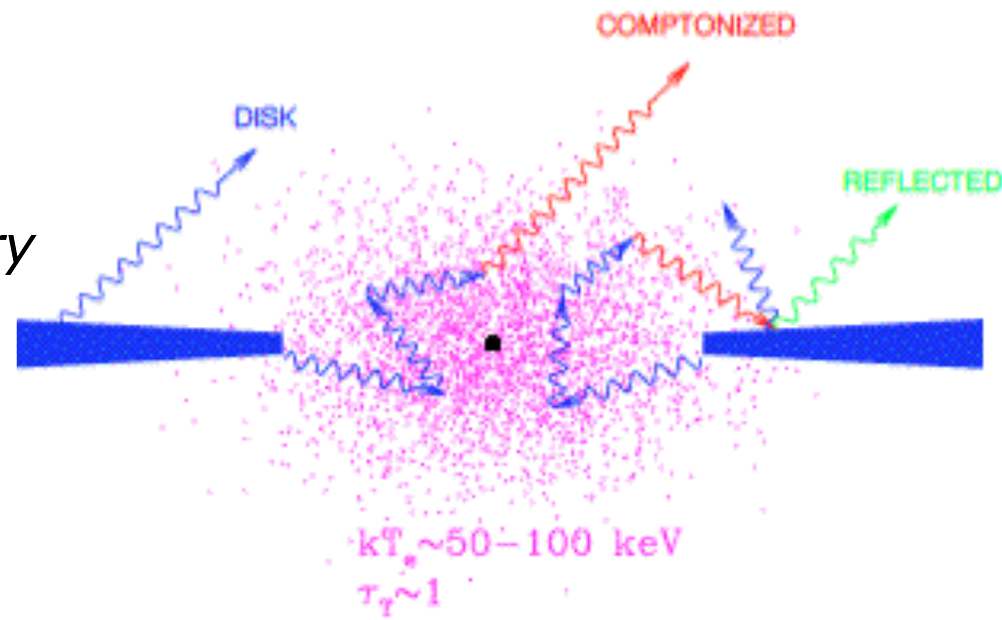



Iron K
Photoelectric
Abs.
Power law
Exp. Cutoff
Scattered PL
Reflection
Starburst
10
1
0.1
0.01
0.1
1
10
100
Energy (keV)

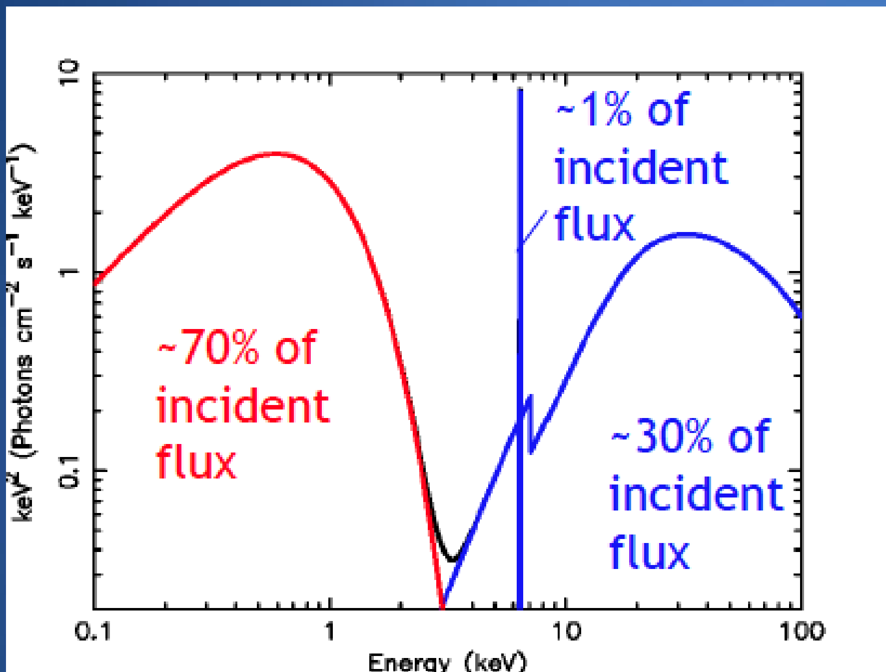
# *Connection Between Source Geometry and Spectra in an Black hole binary*



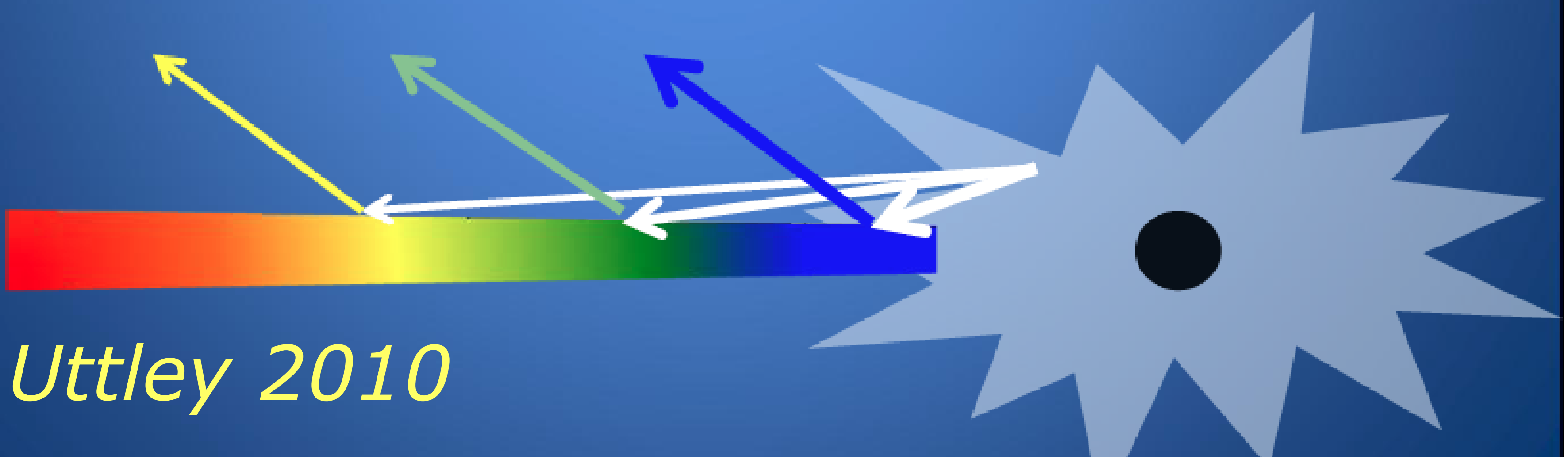

*An Alternative Geometry*



# Disc X-ray reverberation

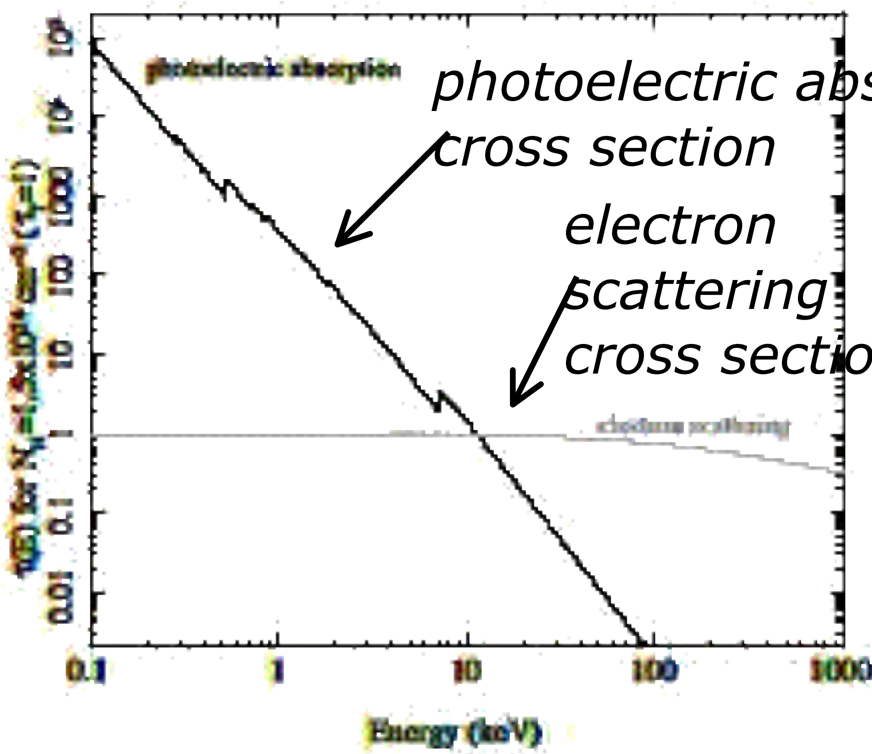


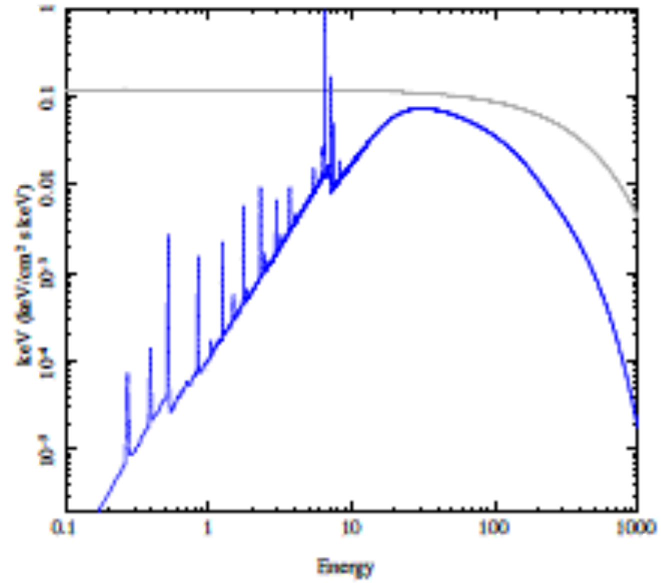

- ✧ X-rays from the continuum source (corona, jet base?) hit the disc
- ✧ Some are reflected (iron line and reflection continuum)
- ✧ The absorbed fraction is thermalised and re-emitted at the local disc temperature



*Uttley 2010*

# 'Reflection'- Reprocessing of Photons in the Disk

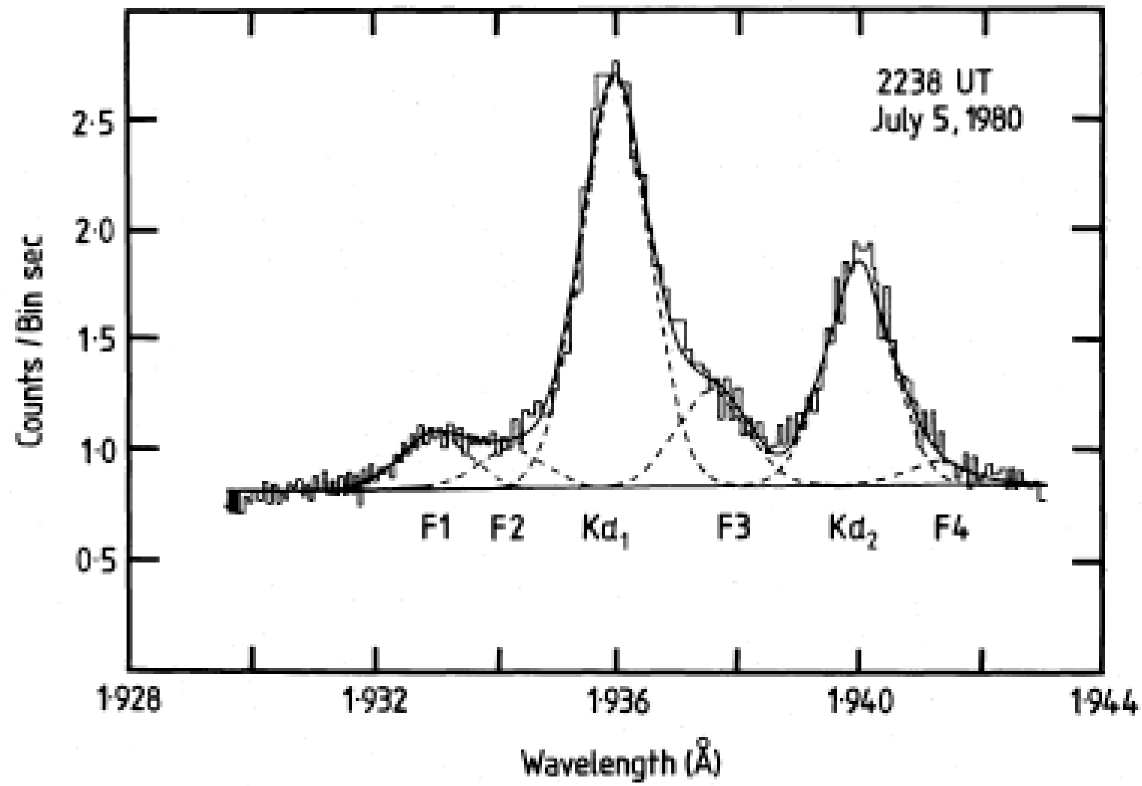


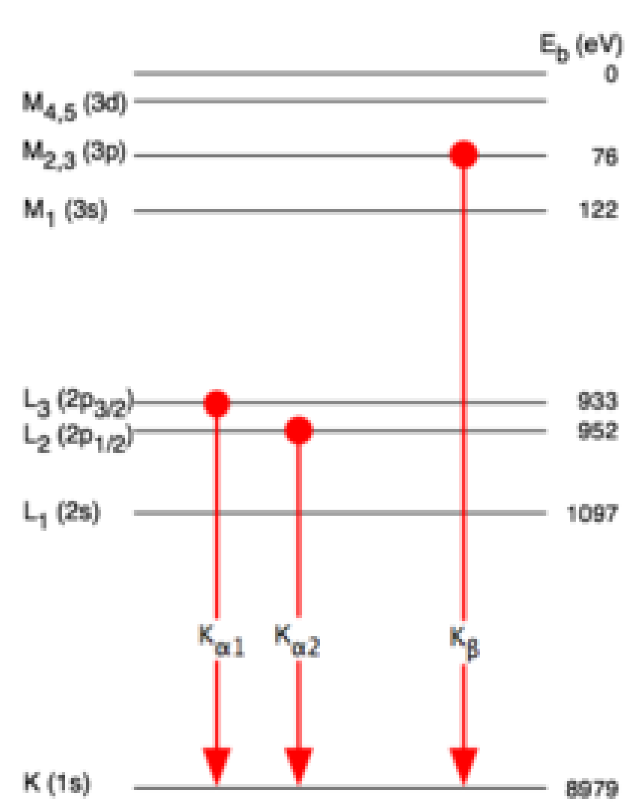




*Emission due to the two processes from a cold slab of thickness $\tau_{Thompson}$=1*

*The larger cross section at low energies of photoelectric absorption means that low E photons are absorbed not scattered and some are re-emitted as lines via fluorescence. Compton scattering reduces the energy of the high energy photons. The combination produces a characteristic peak in the spectrum.*

# Iron Kα fluorescence from the Sun




*energy levels for Cu*

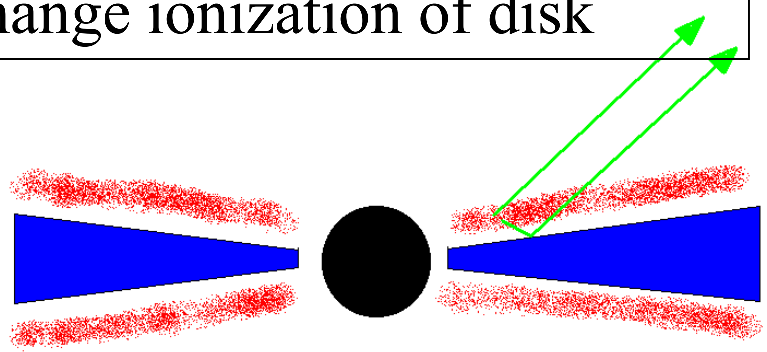
**Parmar et al. (1984)**
***Solar Maximum Mission***
**(Bent Crystal Spectrometer)**

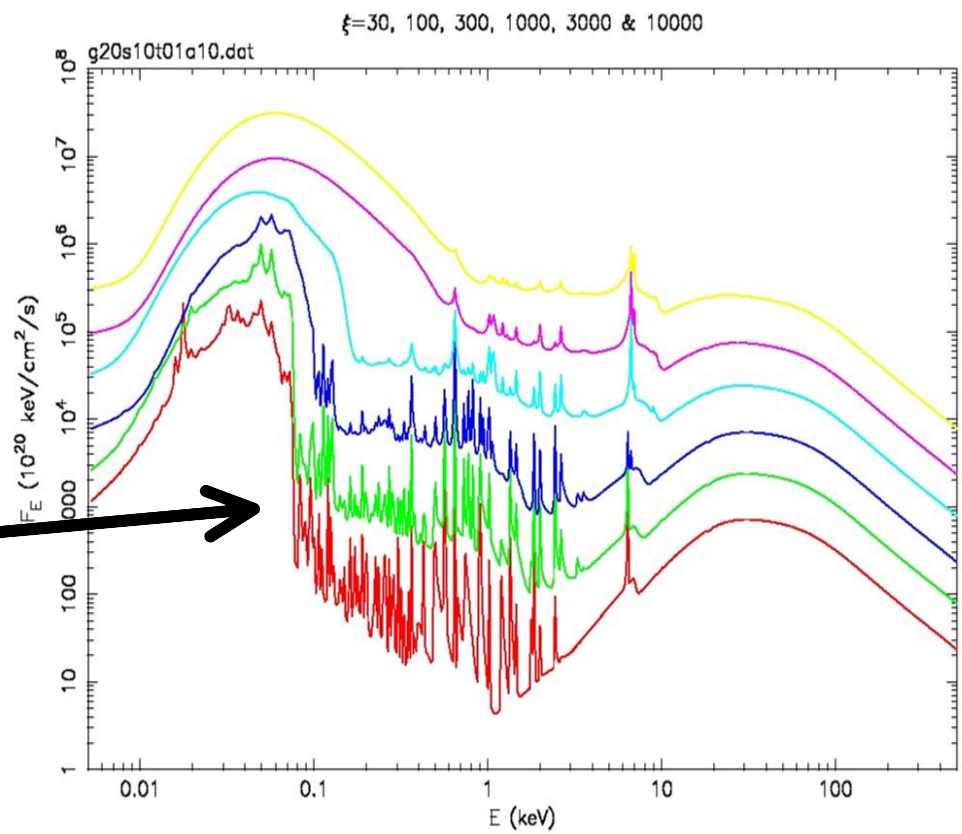
*With very high resolution there are 2 Fe K flourescent feature Kα1, Kα2*

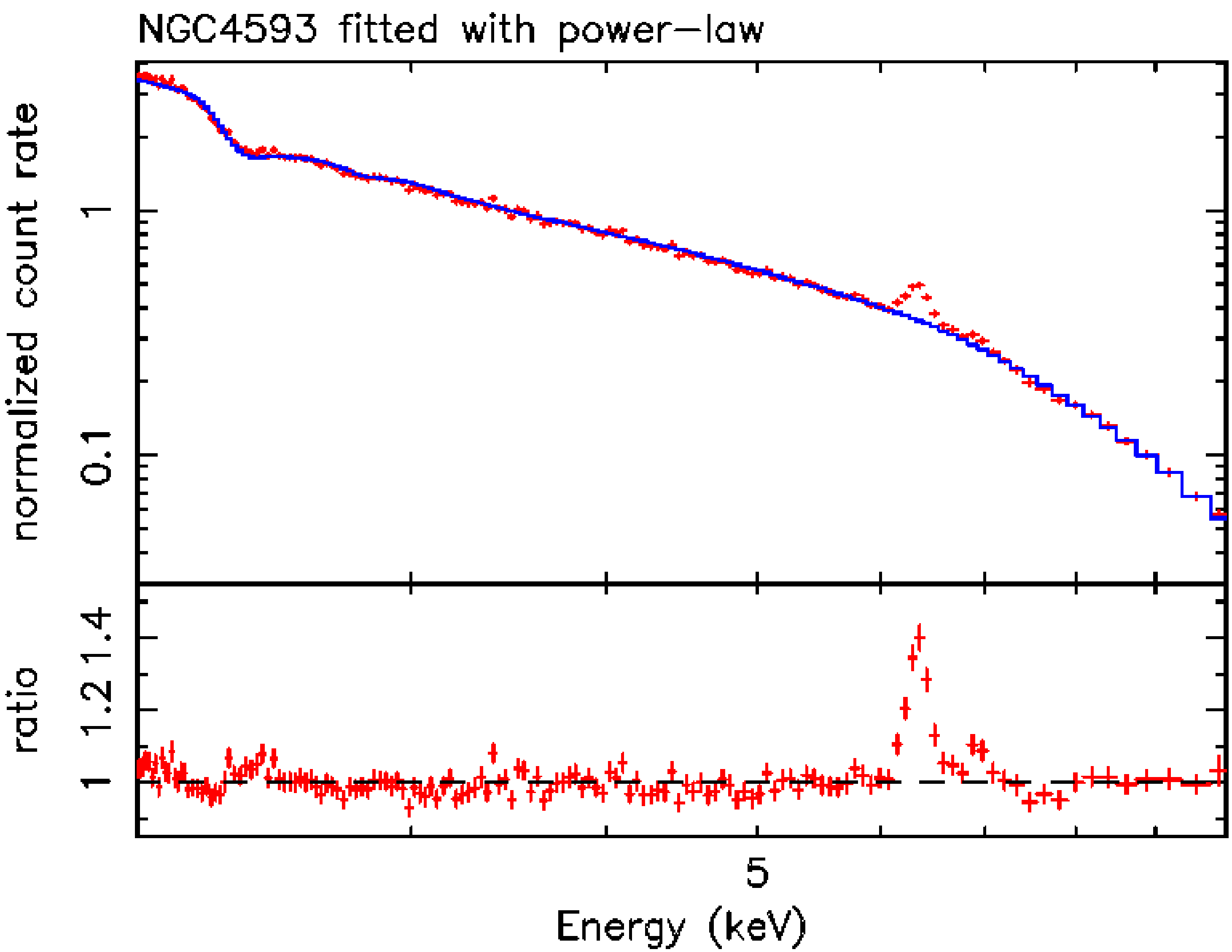
# X-ray reflection
# "Reflection' is Compton scattering

**Important consequence of corona**: underlying disk is irradiated by intense X-ray source… results in a characteristic spectrum being "reflected" from the disk surface layers

Different amounts of flux can change ionization of disk



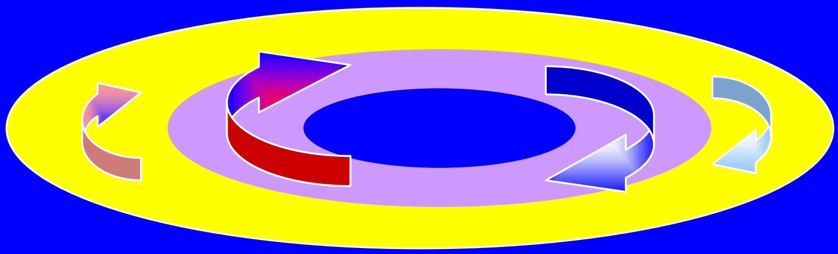





# NGC4593 (Active Galactic Nucleus; Seyfert 1)

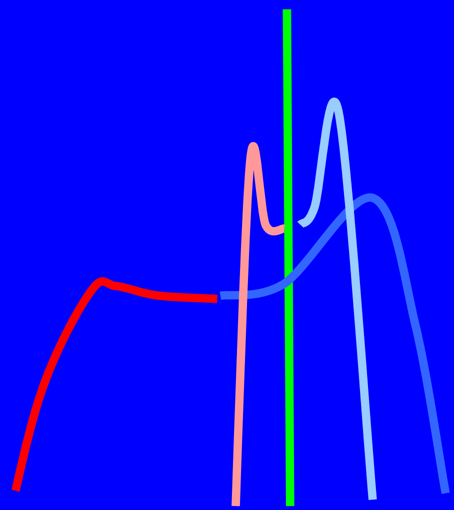
# Relativistic effects- C. Done

- Relativistic effects (special and general) affect all emission (Cunningham 1975)



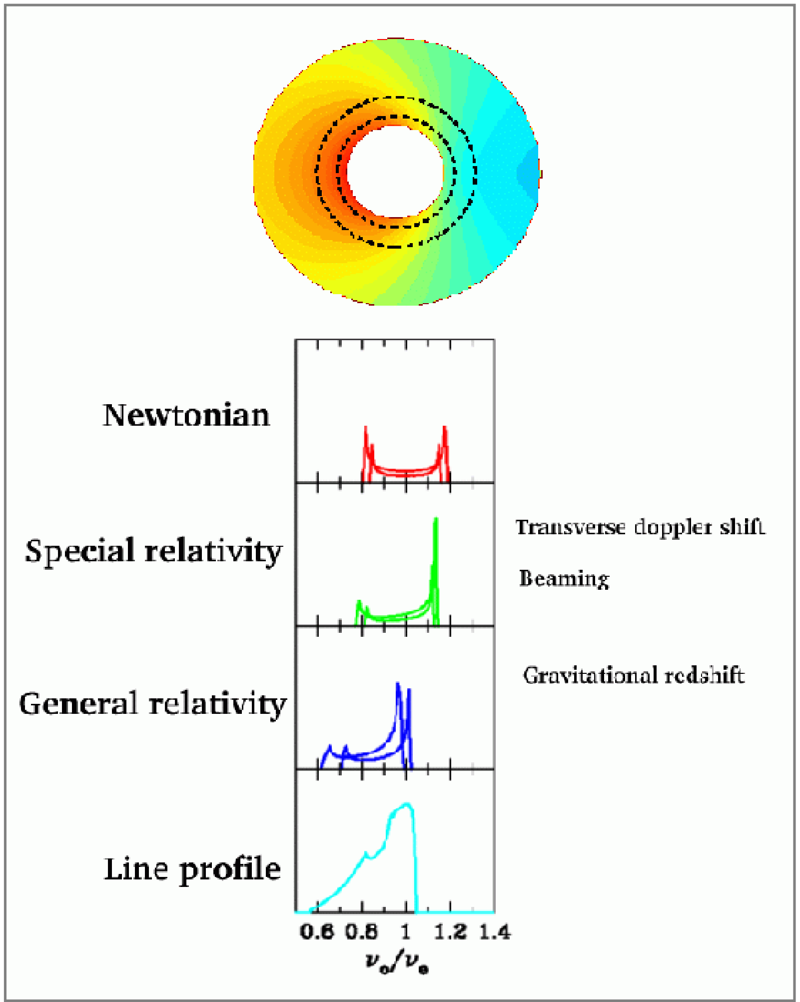
- Hard to easily spot on continuum components
- Fe K$\alpha$ line from irradiated disc – broad and skewed! (Fabian et al 1989)

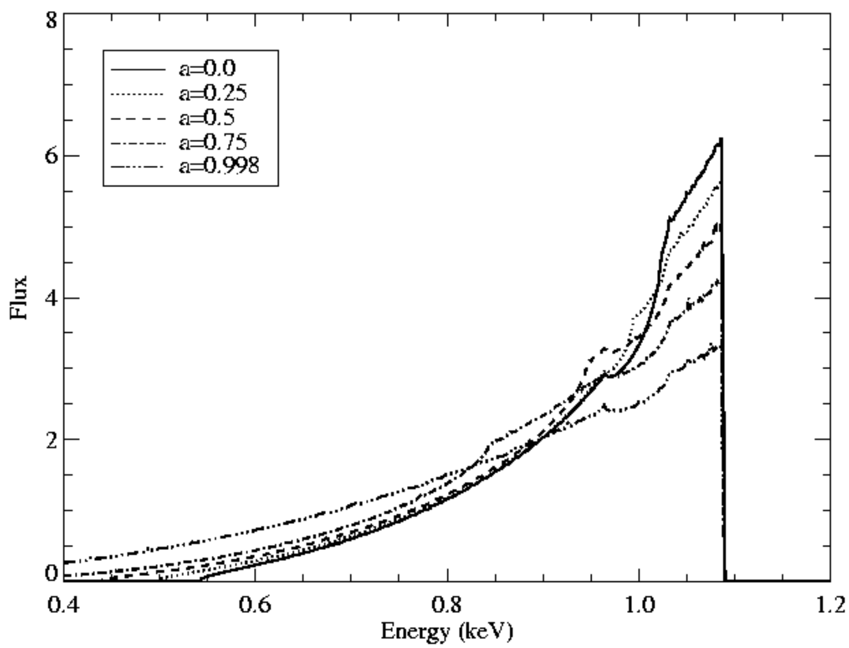
- Broadening gives an independent measure of Rin – so spin if ISO (Laor 1991)



- Models predict increasing width as go from low/hard to high/soft states

Relativistic effects imprint characteristic profile on the emission line…

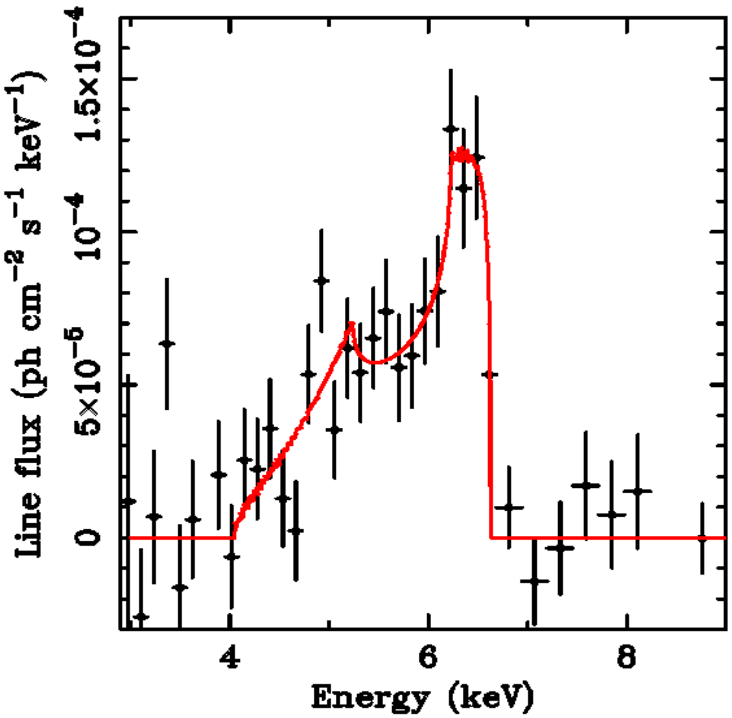



*Theoretical line profiles [Laura Brenneman]*

# Observations of relativistic emission lines

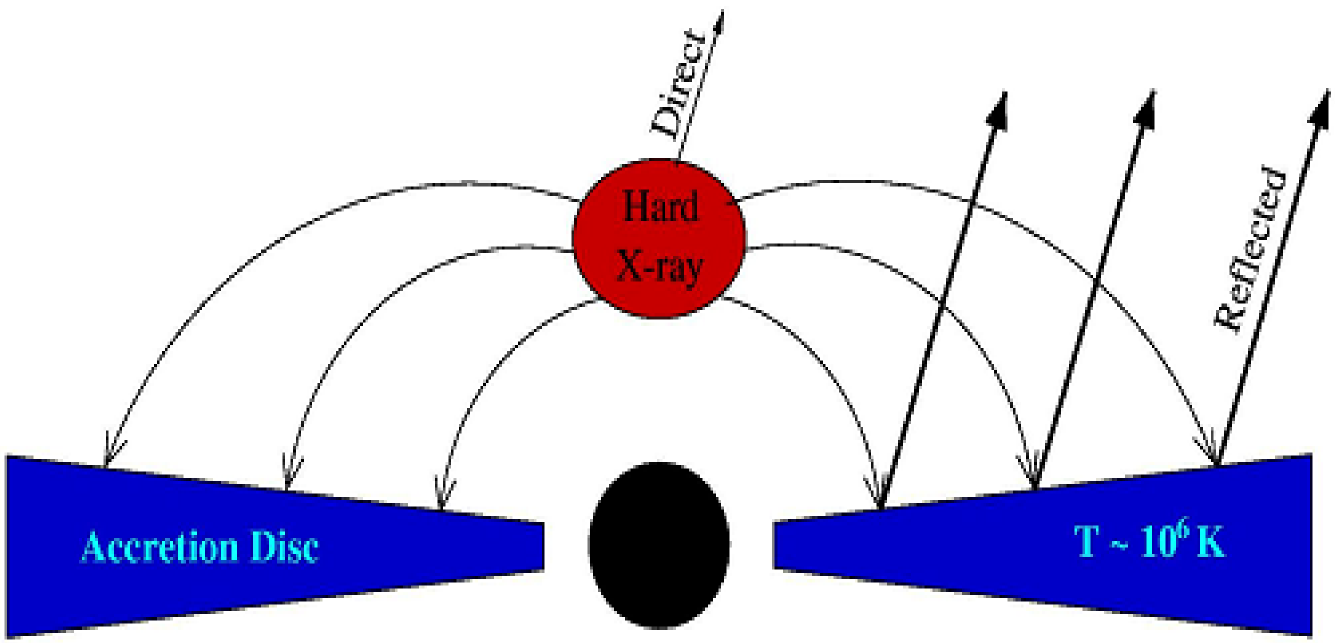
- First seen in 1994 with ASCA observatory
- 5 day observation of Seyfert-1 galaxy MCG-6-30-15
- Needed long observation to collect enough photons to form detailed spectrum



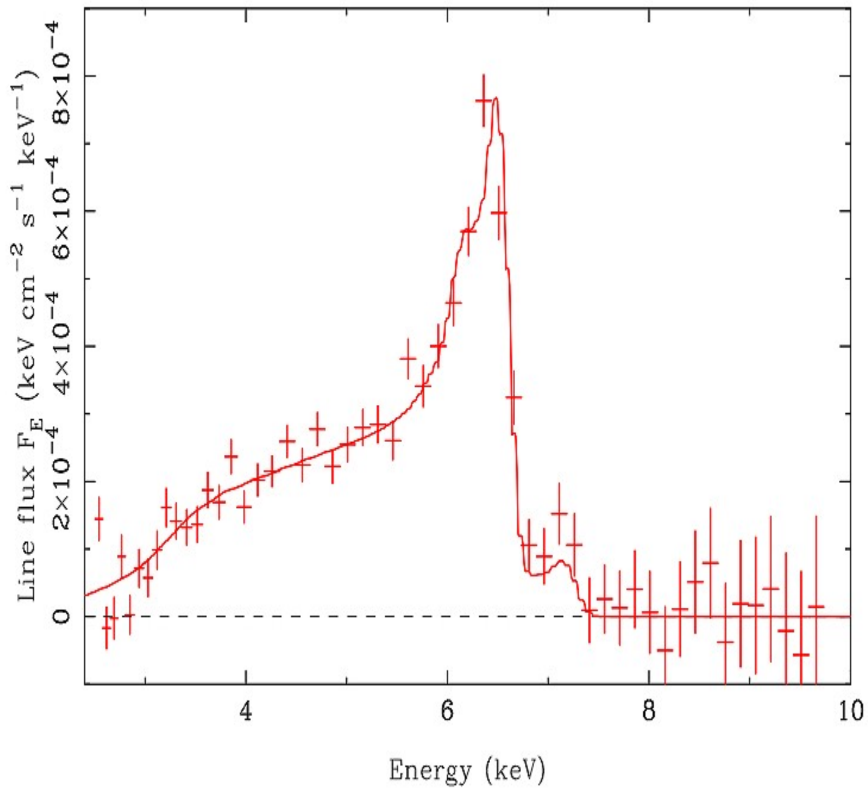

Power-law continuum subtracted
ASCA: Tanaka et al. (1995)

# Relativistic Effects

- Light rays are bent by strong gravity- making the geometry rather complicated
- Do not know 'where' x-ray source is - try to use data to figure it out

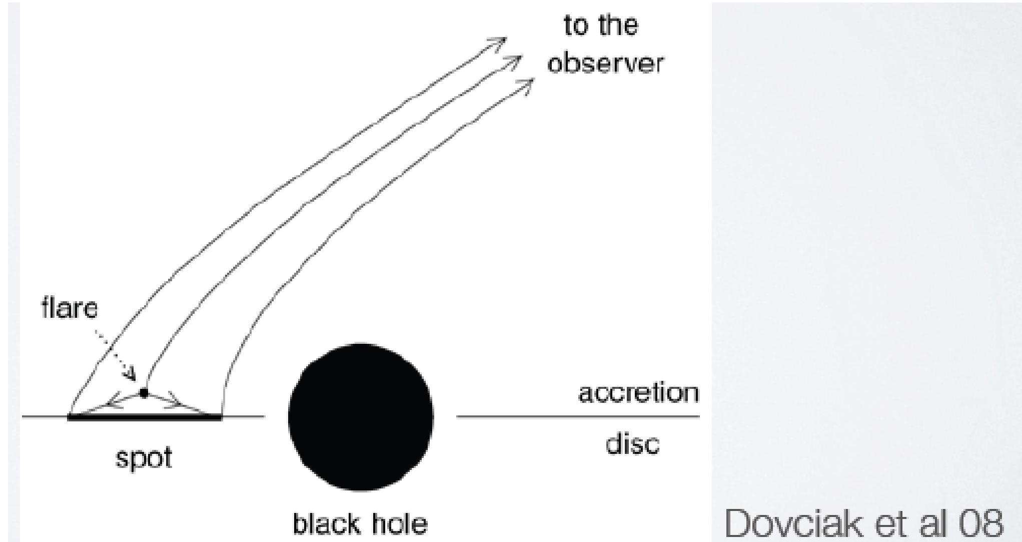


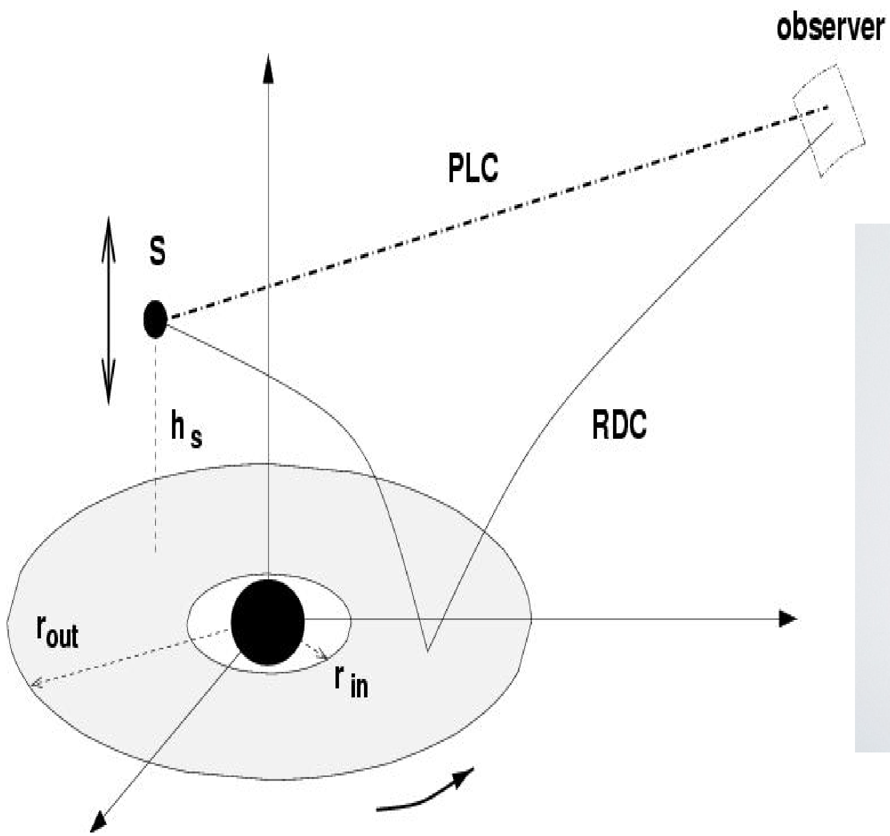
- Modern XMM-Newton observations
- Confirm relativistic line with extreme redshifts
- If no line emission from within ISCO, need to invoke spinning black hole to get strong enough redshifting

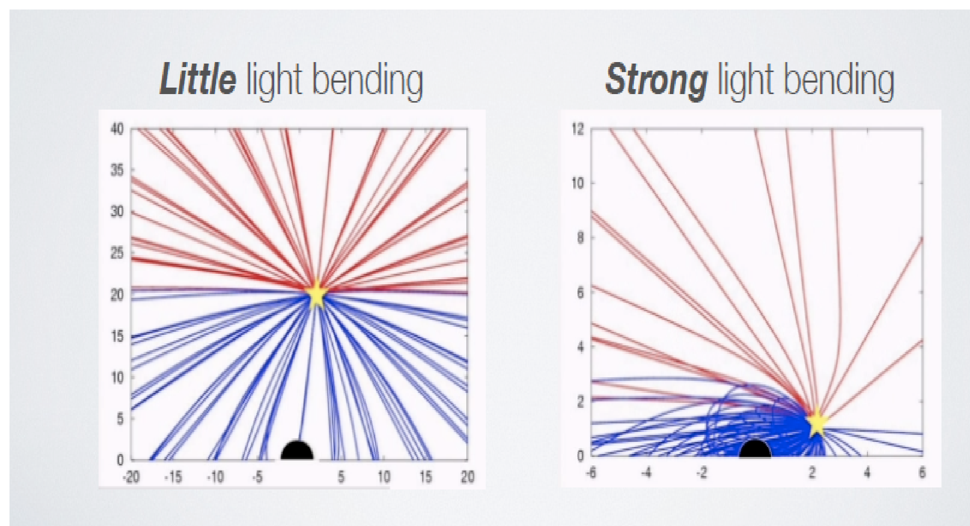



Power-law continuum subtracted
XMM: Fabian et al. (2002)

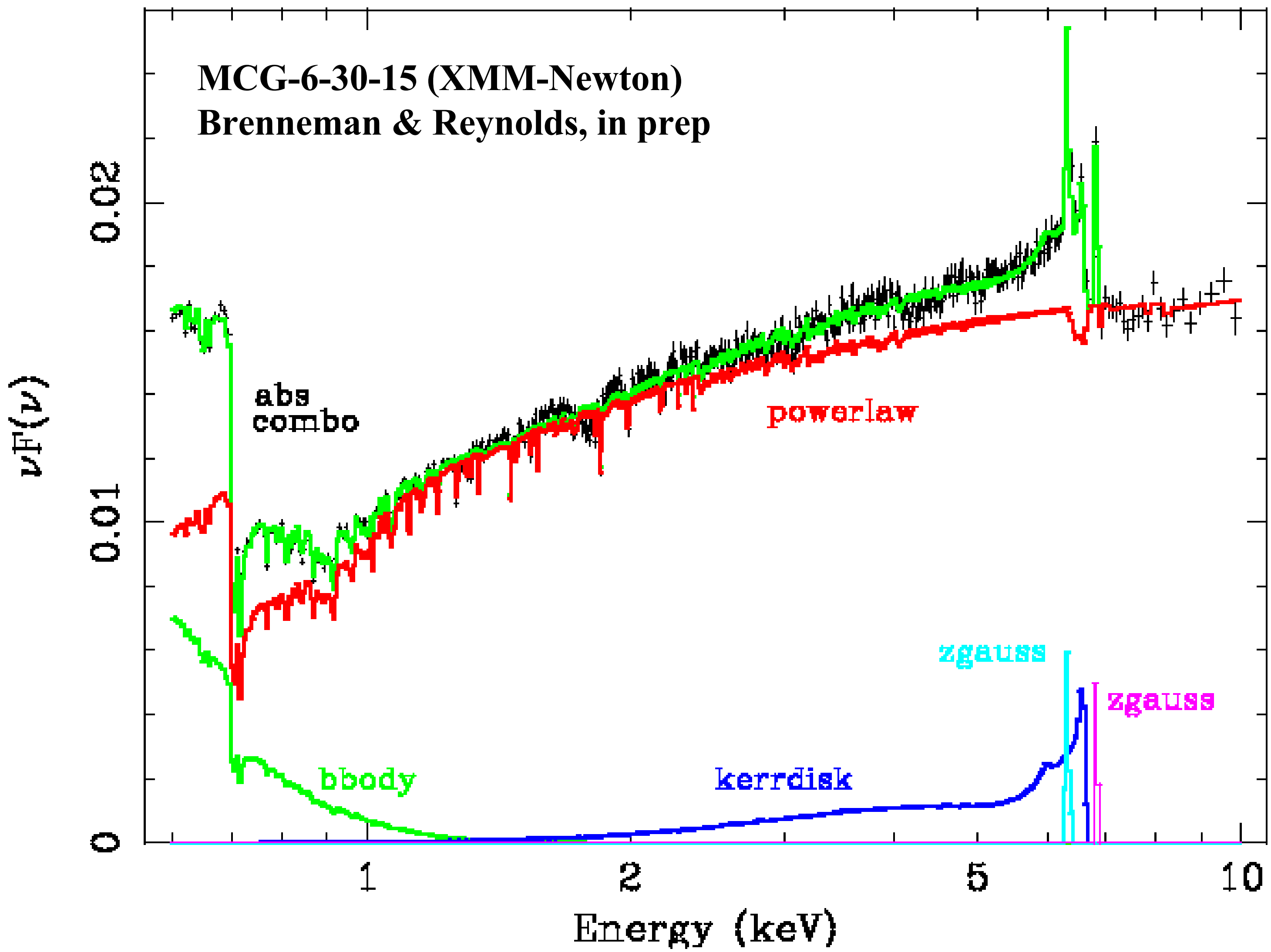
- if we only knew where the x-rays come from ($h_s \sim r_s$) from time variability arguments



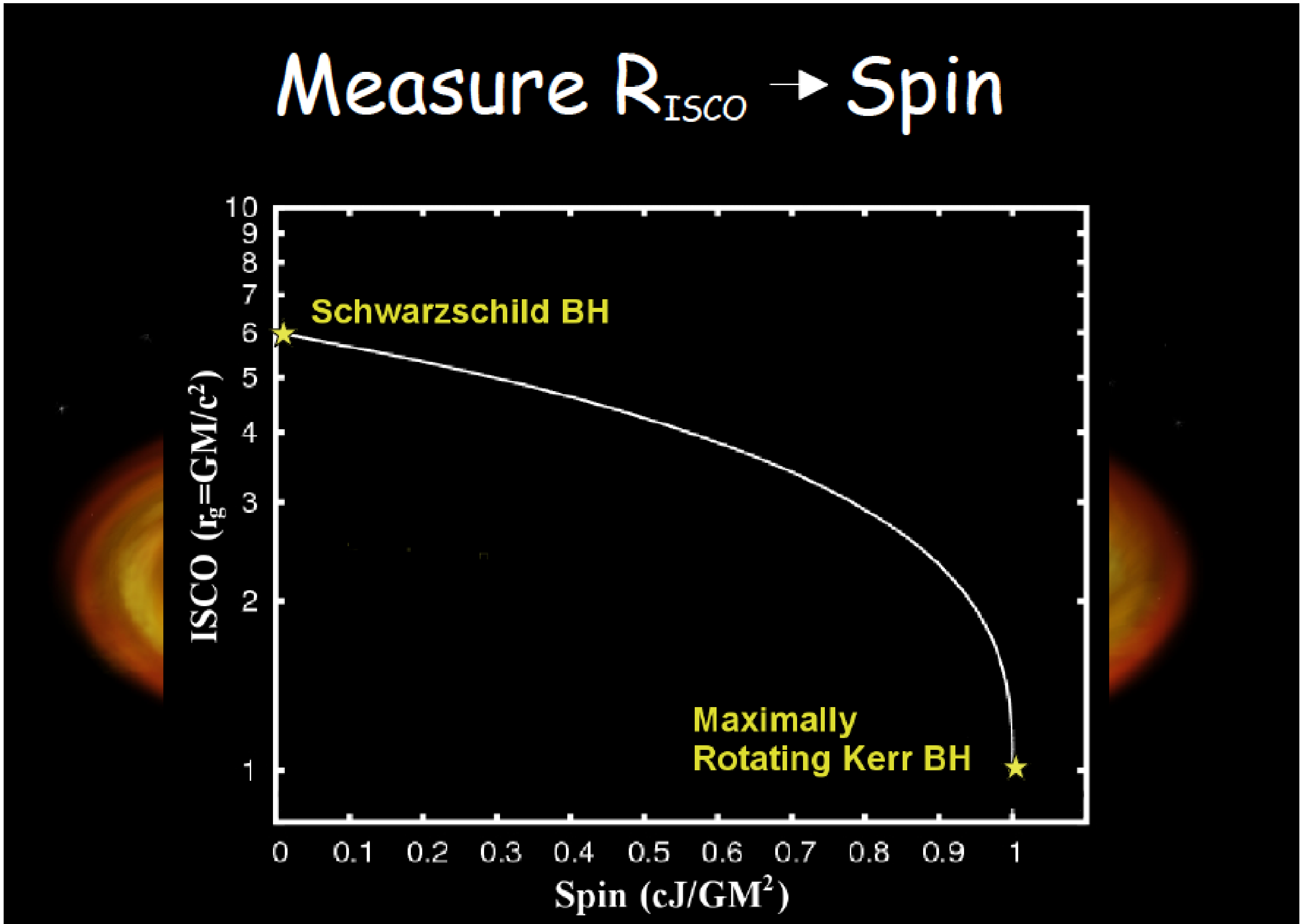



# Spectra are quite complex…



- Spin- is measured in units of $c/GM^2$



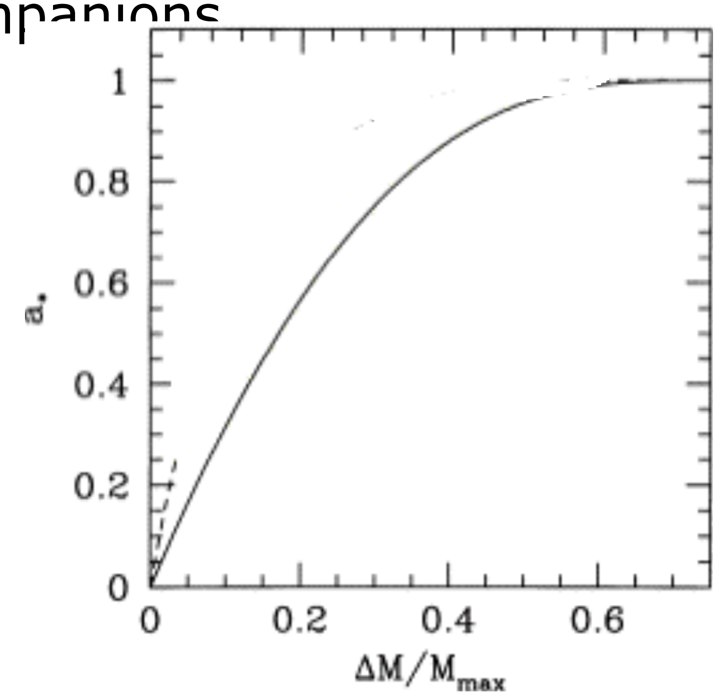

The radius of the innermost stable circular orbit depends on the spin. (Bardeen et al. 1972).

# Why Measure Spin

- BH has only 3 measurable properties Mass, spin, charge.
- Black hole spins affects
  - the efficiency of the accretion processes, hence the radiative output
  - how much energy is extractable from the hole itself
  - the retention of black holes in galaxies
  - gravitational wave signature
  - possible origin of jets.
- Origin of BH Spin
  - natal
  - history

# Spin

- For galactic black holes- not enough accretion to account for spin being due to accretion of angular momentum- need to accrete ~3/4 of the mass to spin it up to the maximal spin
- If accreting at the Eddington limit takes a very long time (~$10^8$ yrs)
  - too long for wind fed or Roche Lobe systems
  - too much mass for low mass companions
- Spin is natal



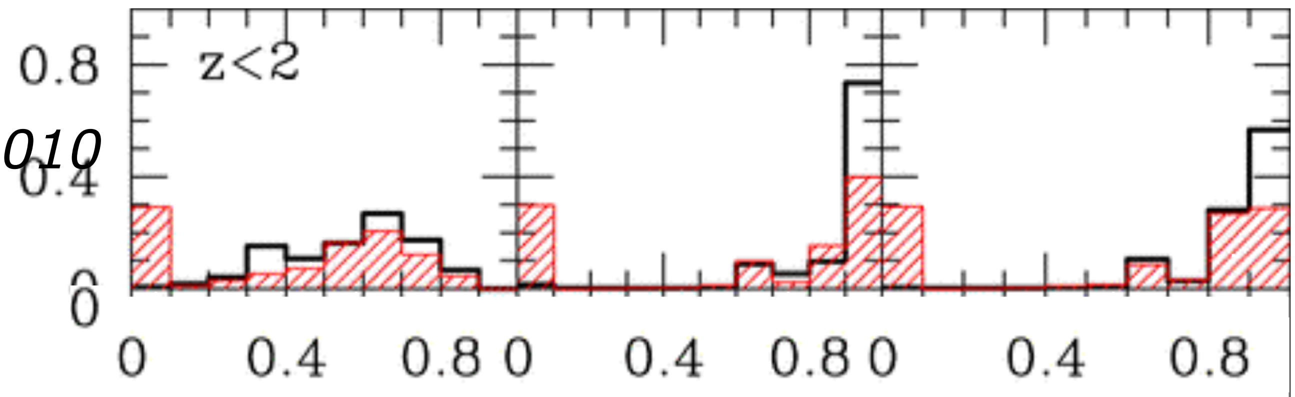
# Spin

- For supermassive black holes- If accreting at the Eddington limit (~$10^8$ $M_\odot$ accretes 0.25 $M_\odot$/yr) so takes $4\times10^8$ yrs to double its mass and spin up

- Spin can be due to accretion
- Requires 'organized' accretion of angular momemtum

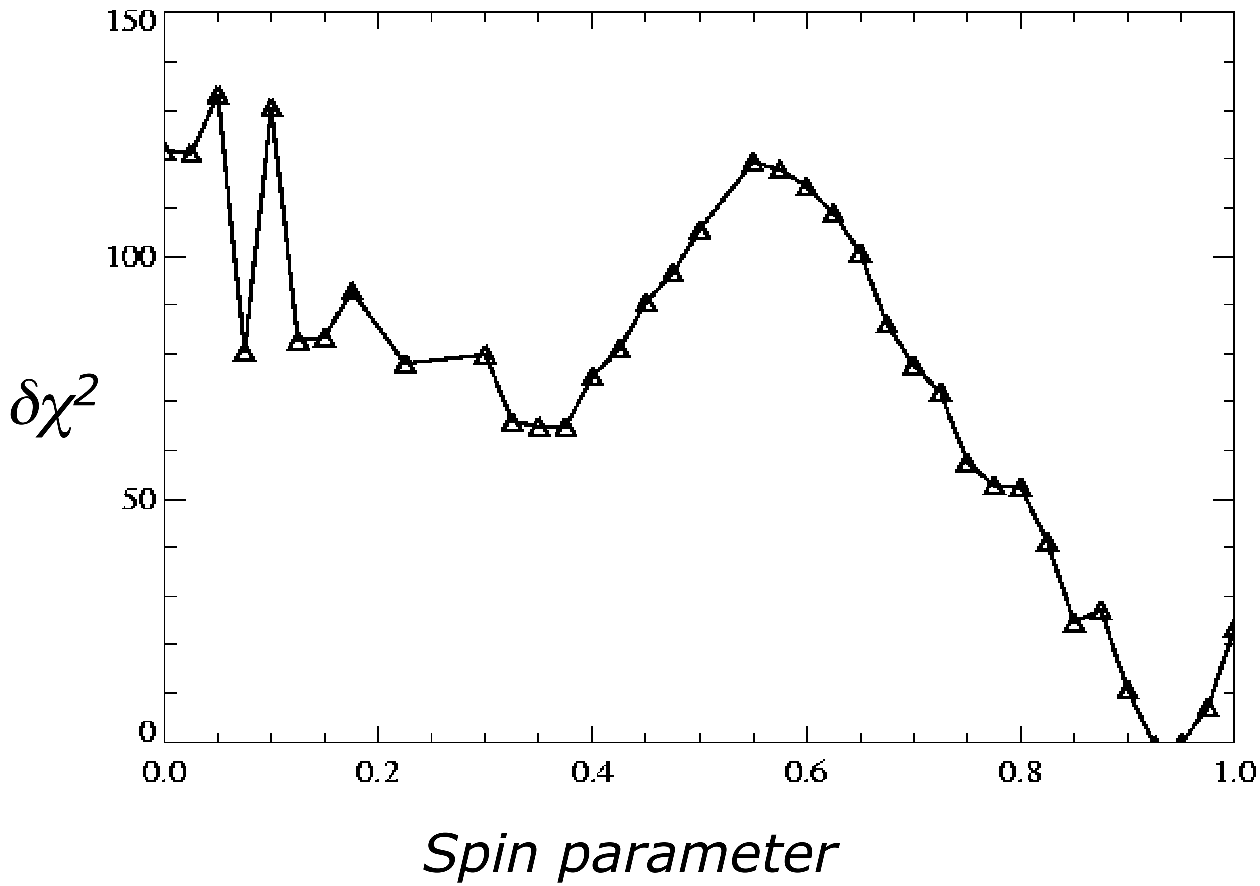
Alternatively spin could be due to mergers of black holes

*Volontieri et al 2010*




mergers only (left), mergers and prolonged accretion (center), and mergers and chaotic accretion

- Applied models to long (350ks) XMM dataset for MCG-6-30-15
  - Data strongly prefers rapidly spinning BH solution
  - a ~ 0.93



# Present knowledge of spin in Galactic Black Holes- R. Reis 2010