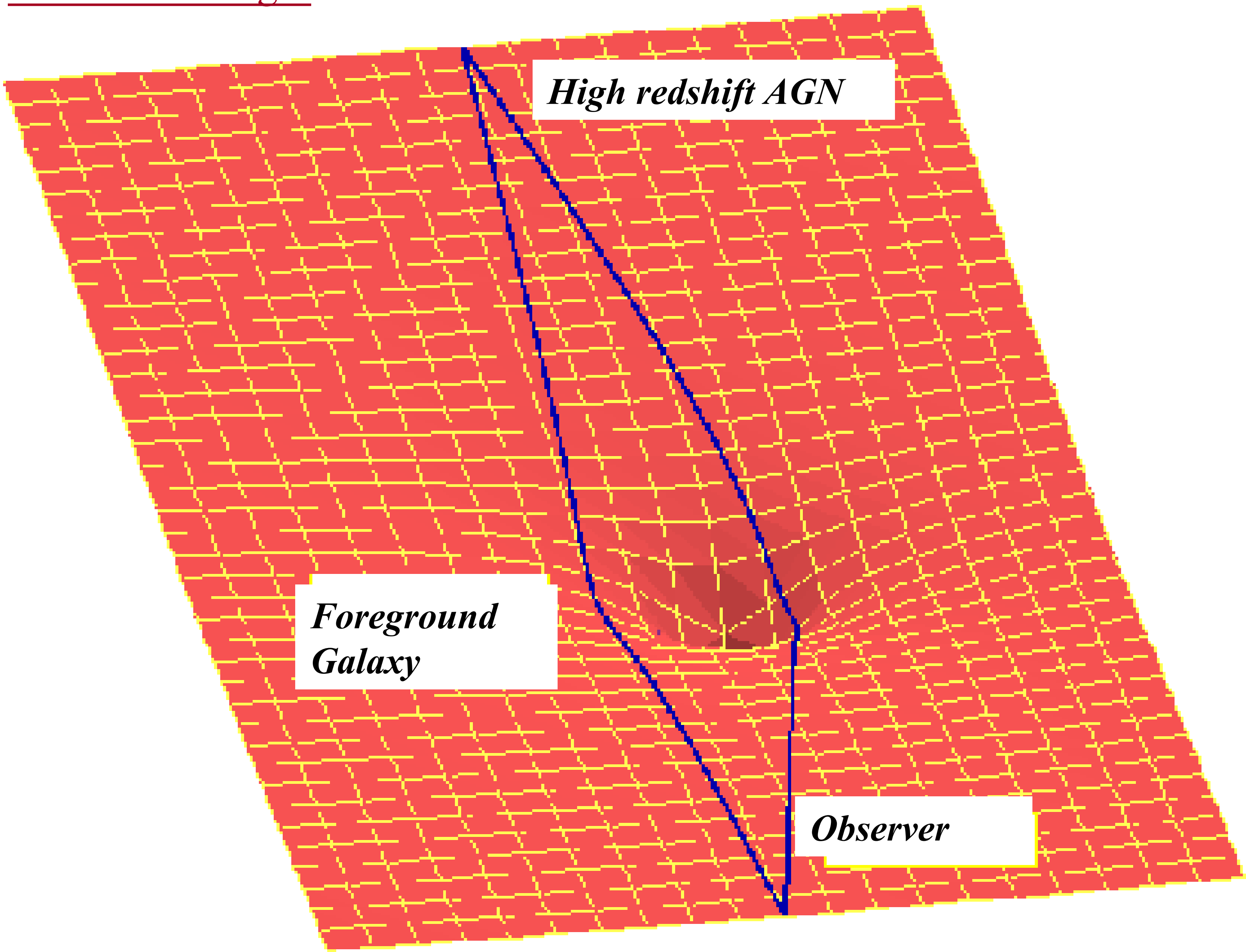
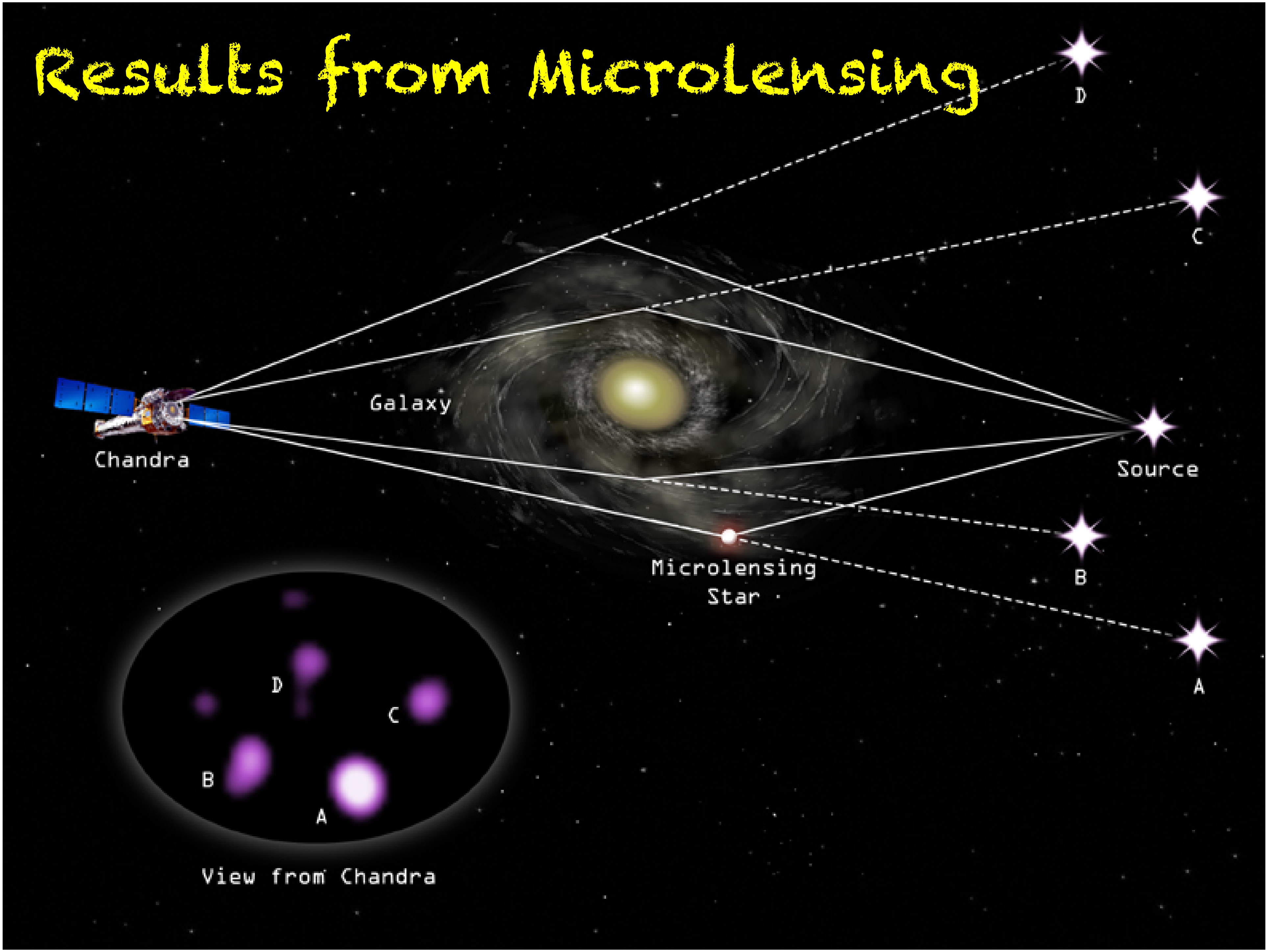
Gravitational Lensing - Einstein's General Relativity Theory
Mass Bends Light

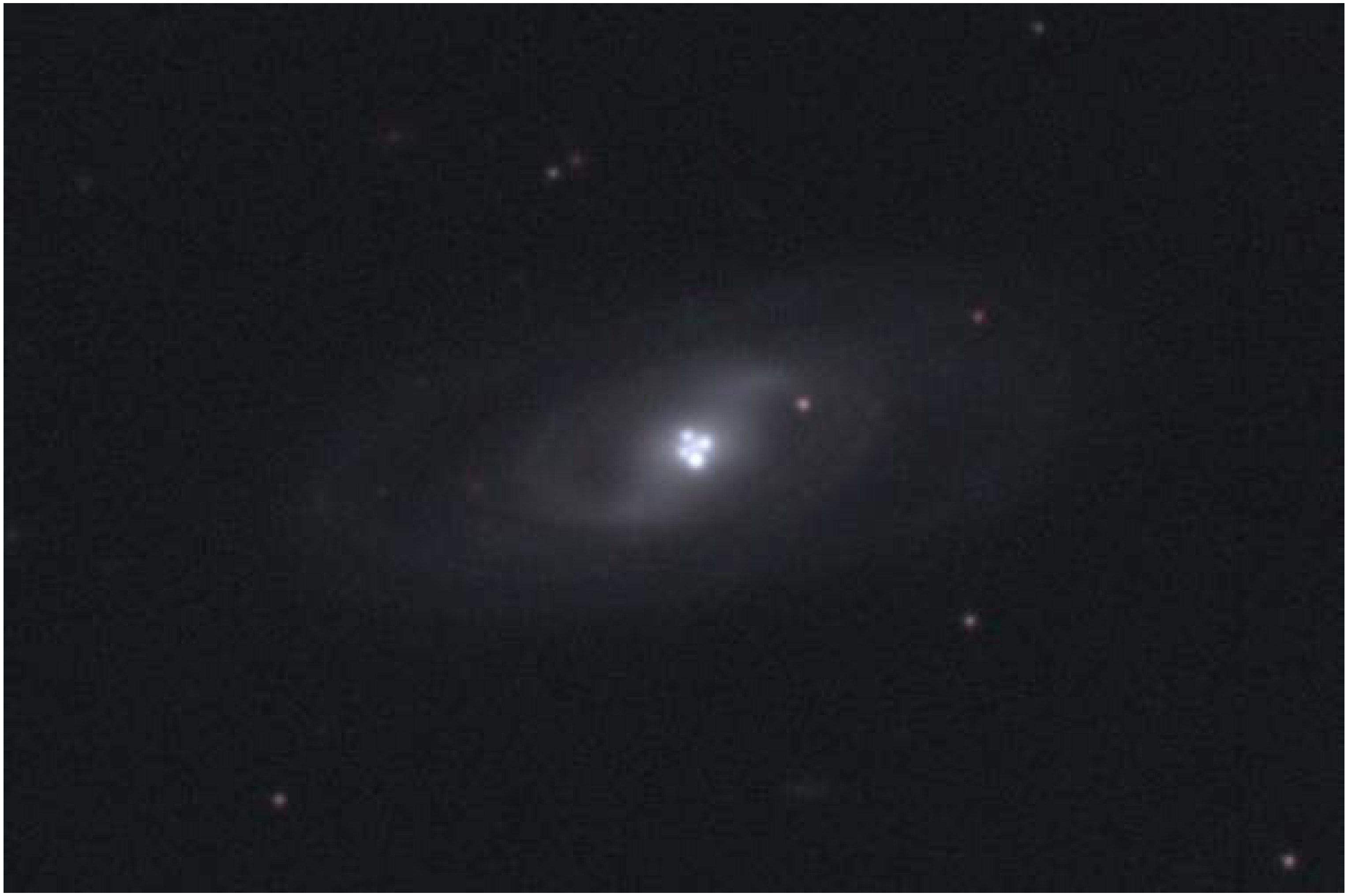


Credits: Peter Newbury

Results from Microlensing



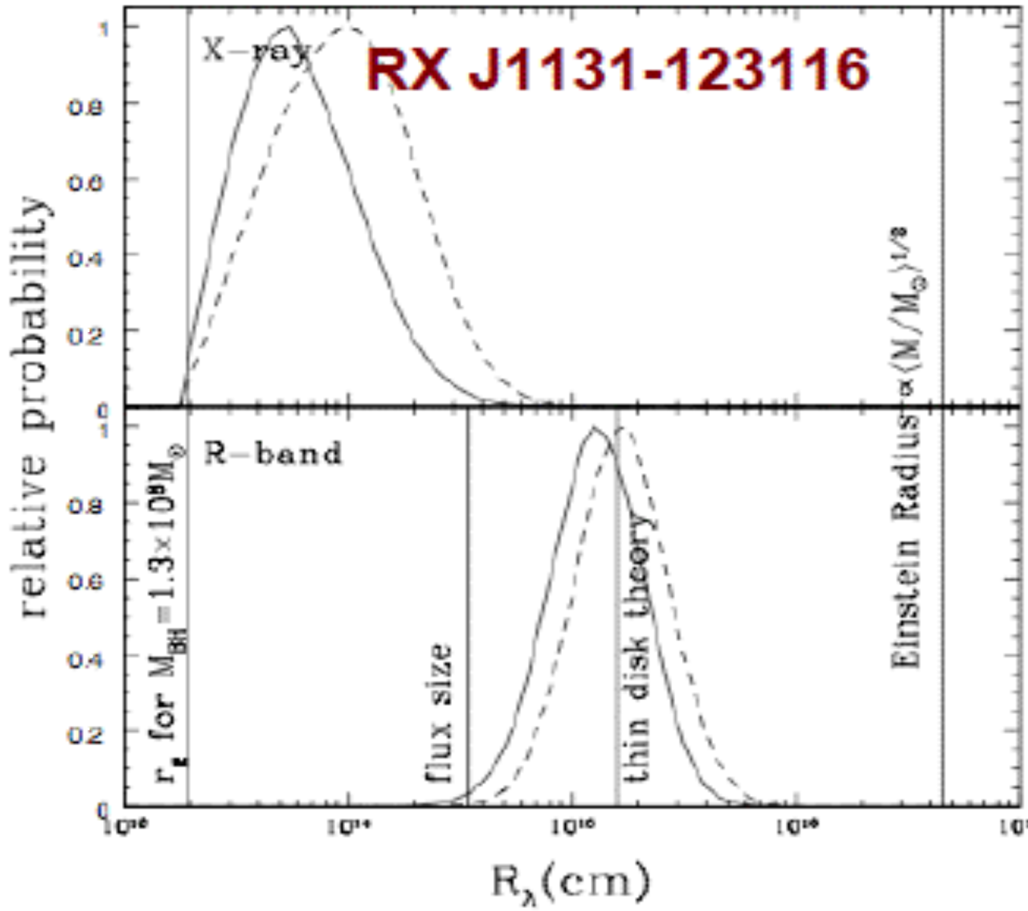
“The Einstein Cross”



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

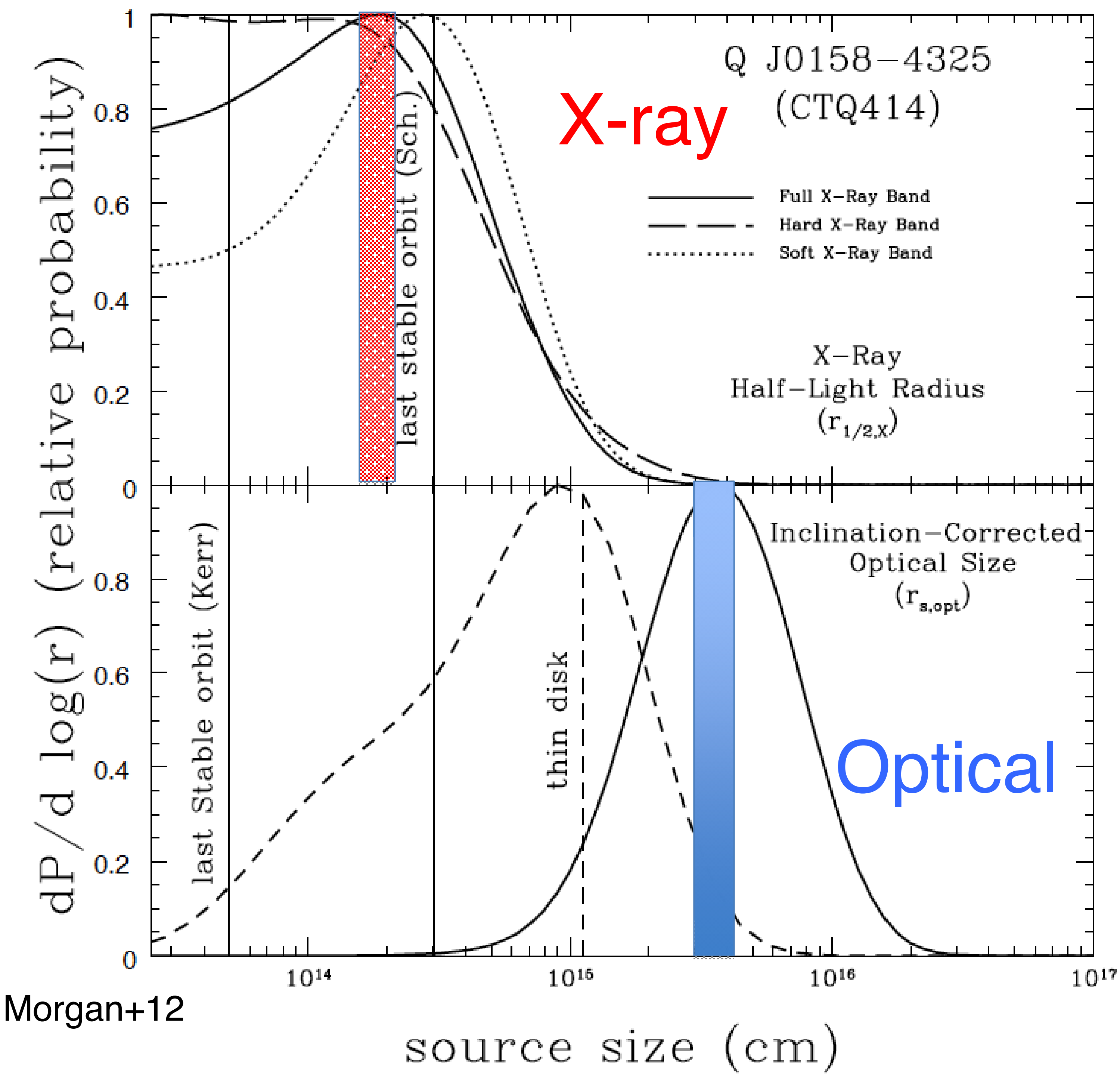
- microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory

MICROLENSING



X-rays from 10 R_g (Optical 70 R_g)

Chartas et al. 2009
Dai et al. 2009



Q J0158−4325
(CTQ414)
X-ray
Full X−Ray Band
Hard X−Ray Band
Soft X−Ray Band
last stable orbit (Sch.)
X−Ray
Half−Light Radius
($r_{1/2,X}$)
Inclination−Corrected
Optical Size
($r_{s,opt}$)
last Stable orbit (Kerr)
thin disk
Optical
dP/d log(r) (relative probability)
source size (cm)
0
0.2
0.4
0.6
0.8
1
10^{14}
10^{15}
10^{16}
10^{17}
Morgan+12

Lensing Data

- Constraint on disk size (probability vs size in light days) Jimenez-Vicente et al 2012

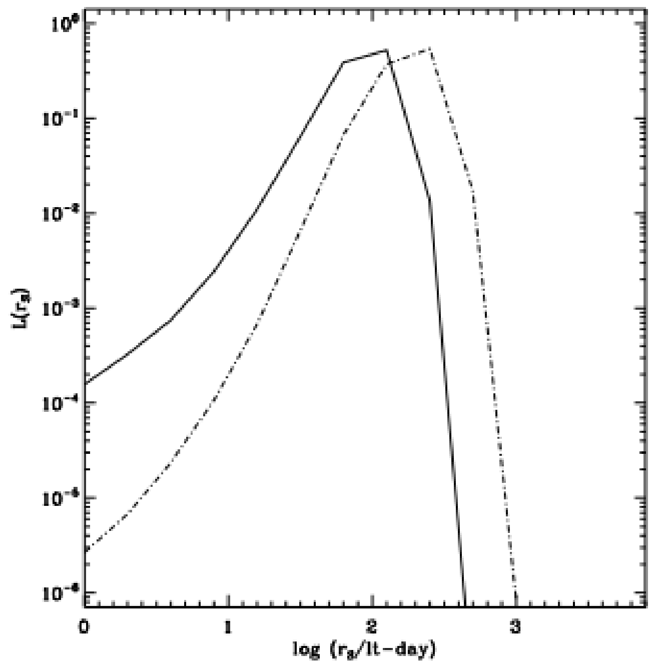
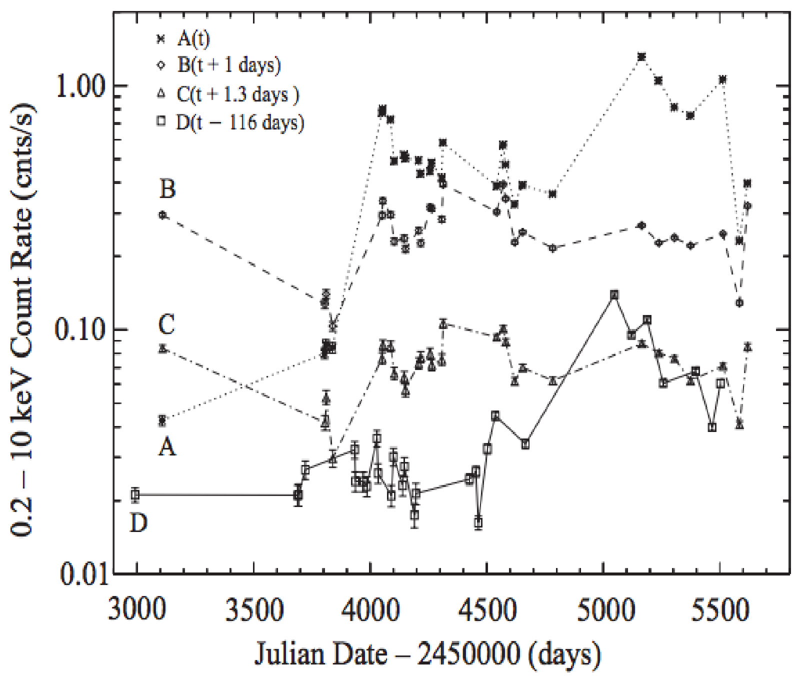
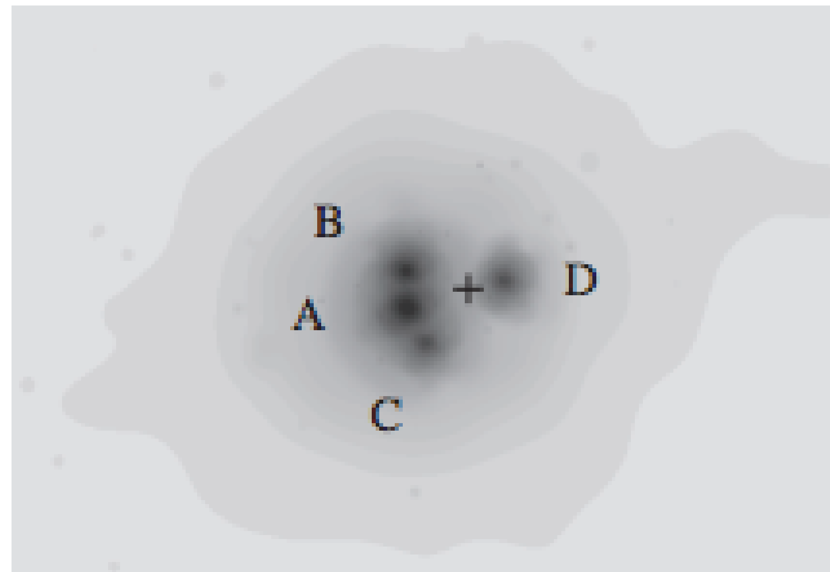
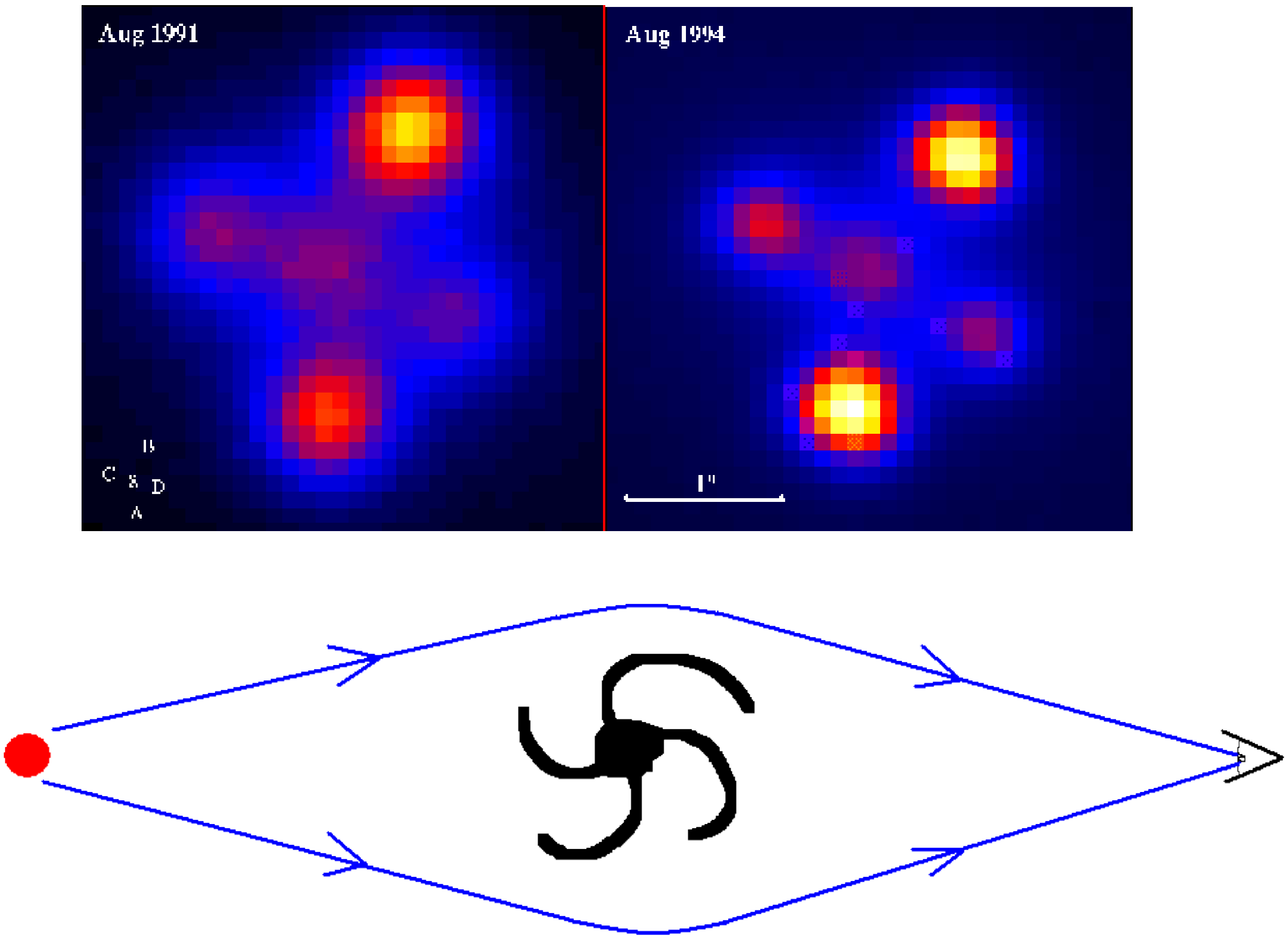


FIG. 2.— Likelihood functions for the size of the accretion disk $\log r_s$ for $\alpha = 0.05$ (continuous line) and $\alpha = 0.1$ (dashed line) in the full sample of quasars by MED09.





X-ray image of lensed quasar Chartas et al 2012


Aug 1991
Aug 1994
B
C
x
D
A
1"

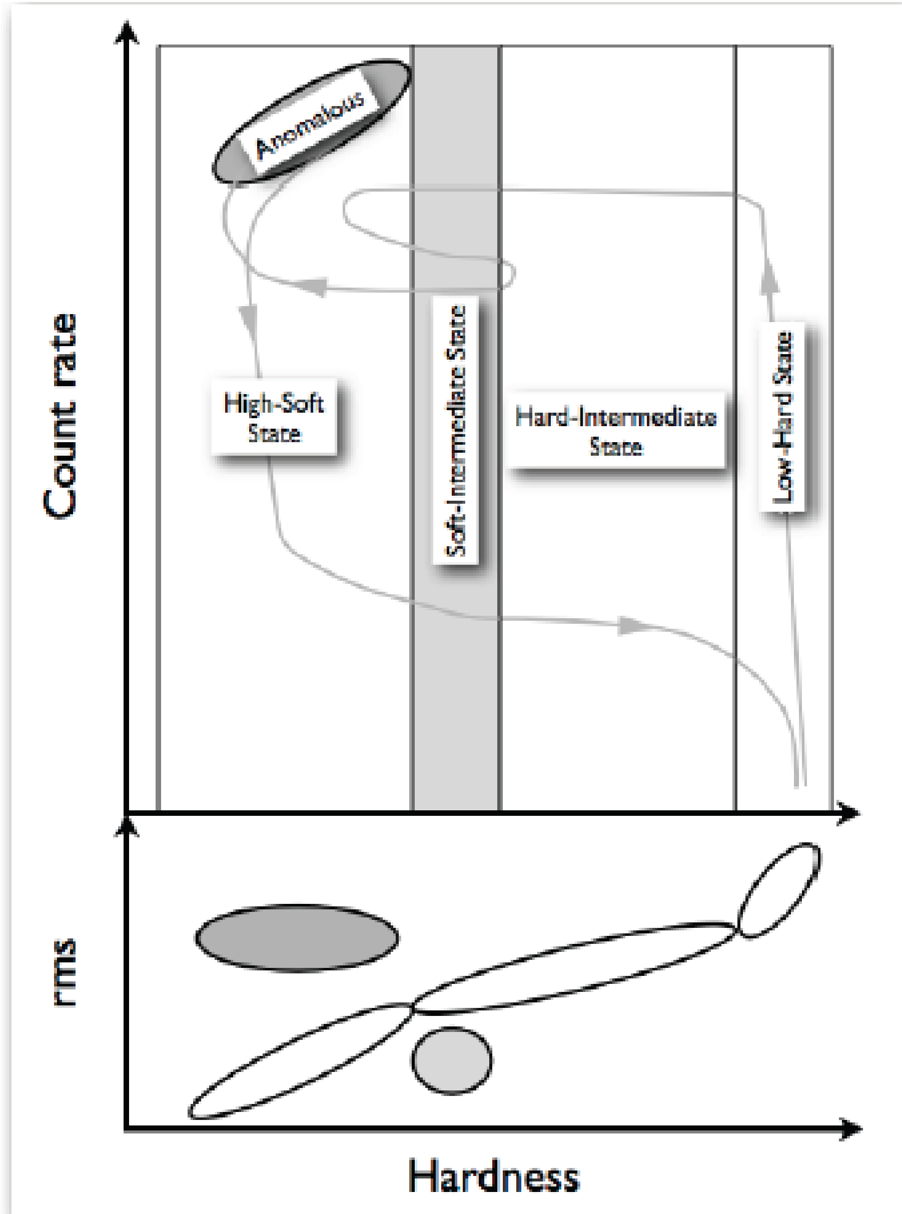
In galactic black holes there is a pattern to the spectral/intensity changes

The high soft state is disk dominated

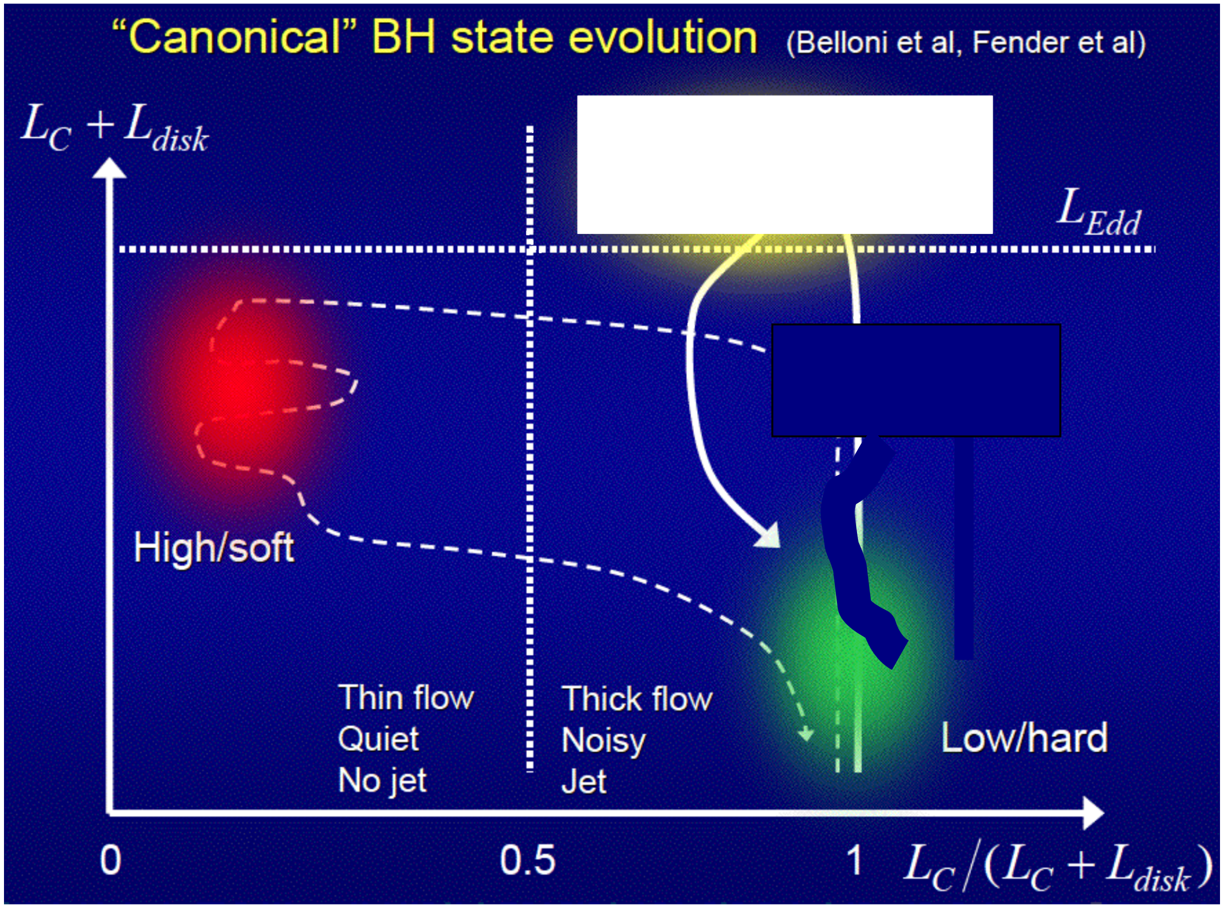
The low hard state is dominated by the x-ray power law

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)

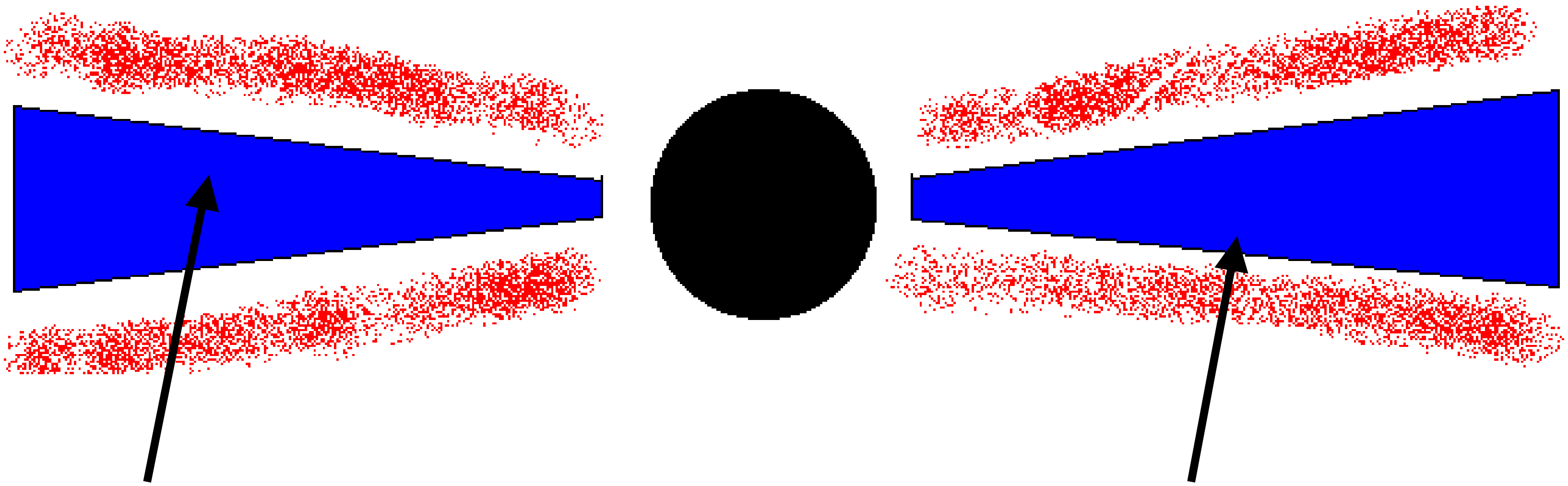


State transitions- (Gierlinski and Done 2003)

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

At L→ L_{Edd} Spectrum more disk dominated

Where do the Spectral Components Arise?



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

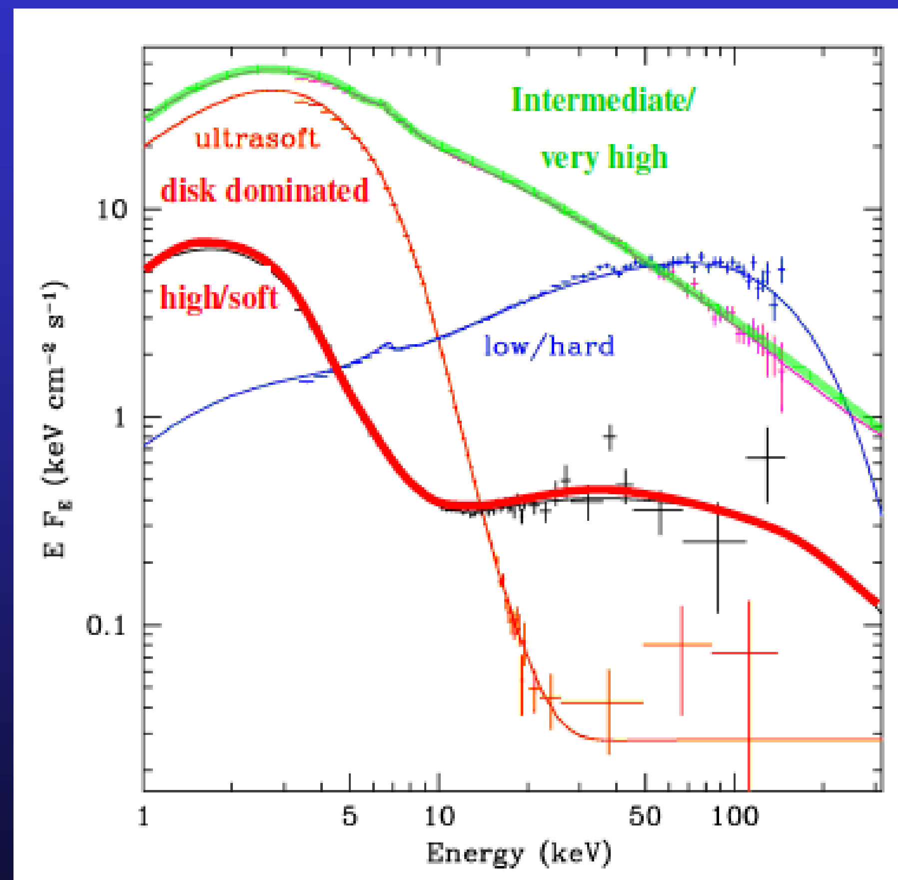
$$T = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_{\rm SB}} \right)^{1/4}$$

X-ray "tail" probably comes from a hot corona that sandwiches the disk… inverse Compton scattering of thermal disk emission by electrons with T~10^9K

Spectral States of Black Hole Binaries

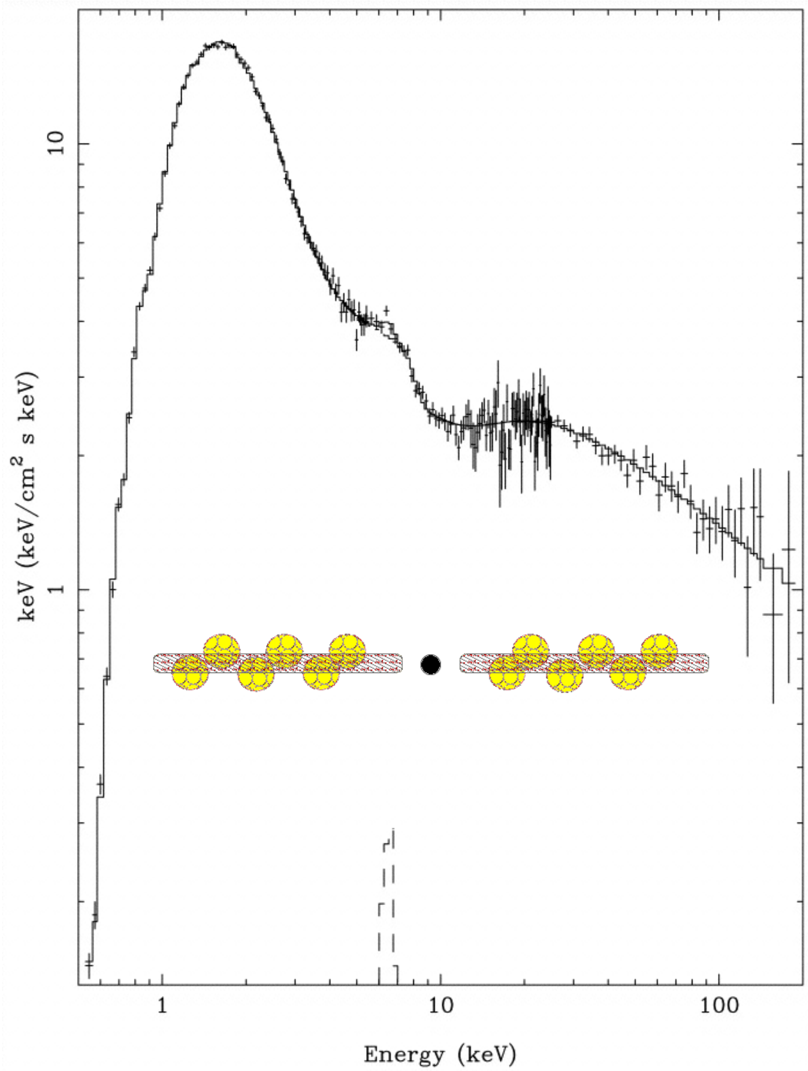
- thought to be due to changes in disk structure - not seen in AGN (yet)

- 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)

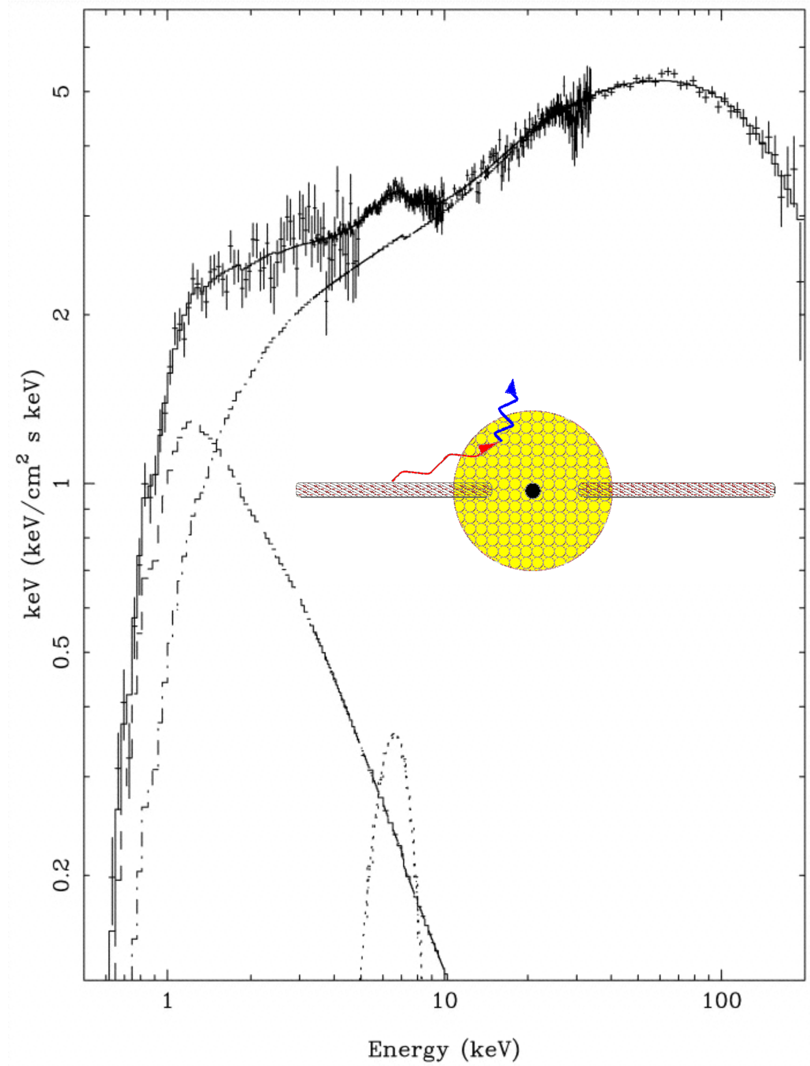


Gierlinski & Done 2003

Cygnus X-1 Spectral States and Ideas on Geometry

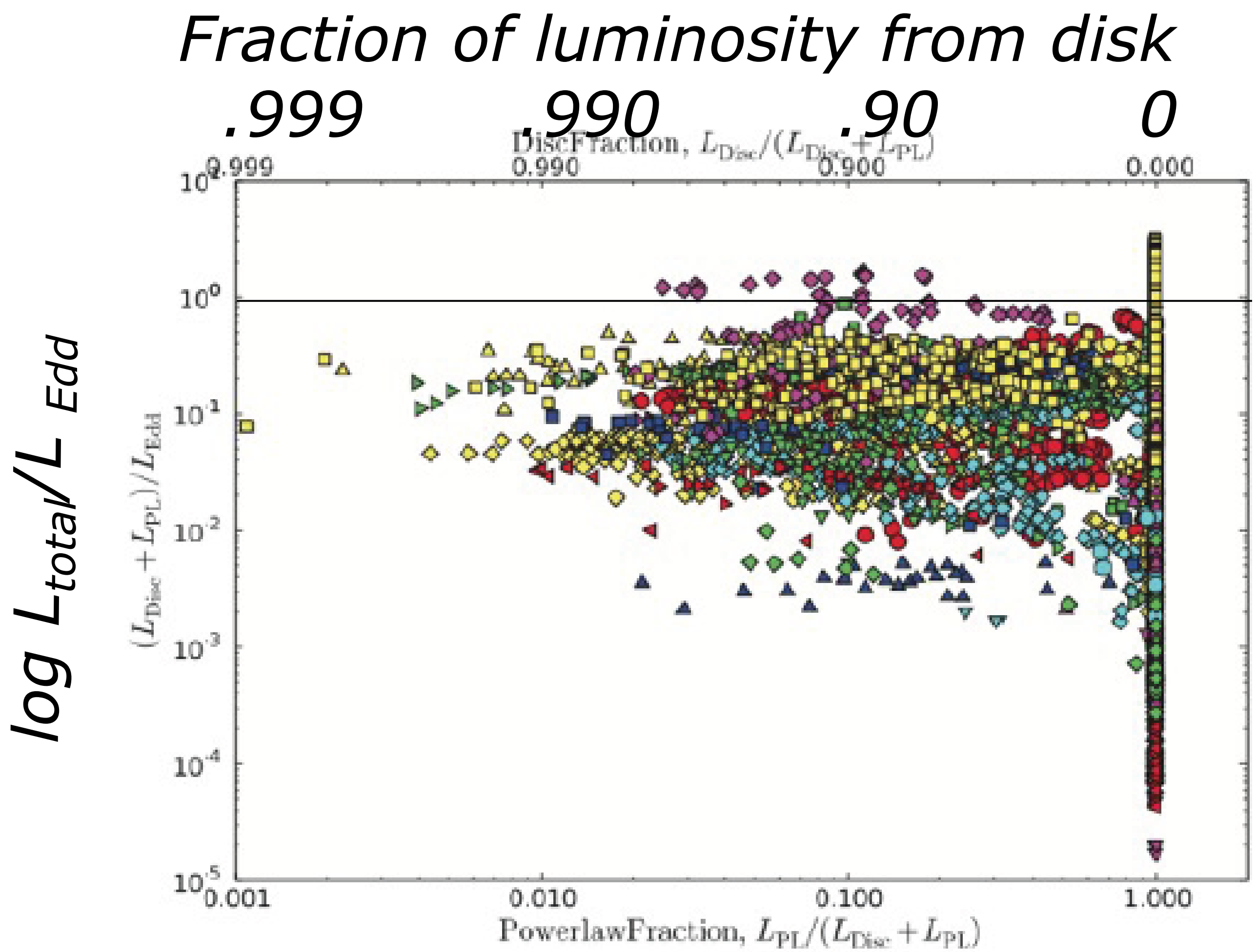


<u>Soft (high) state</u>; thermal disk emission + hard tail



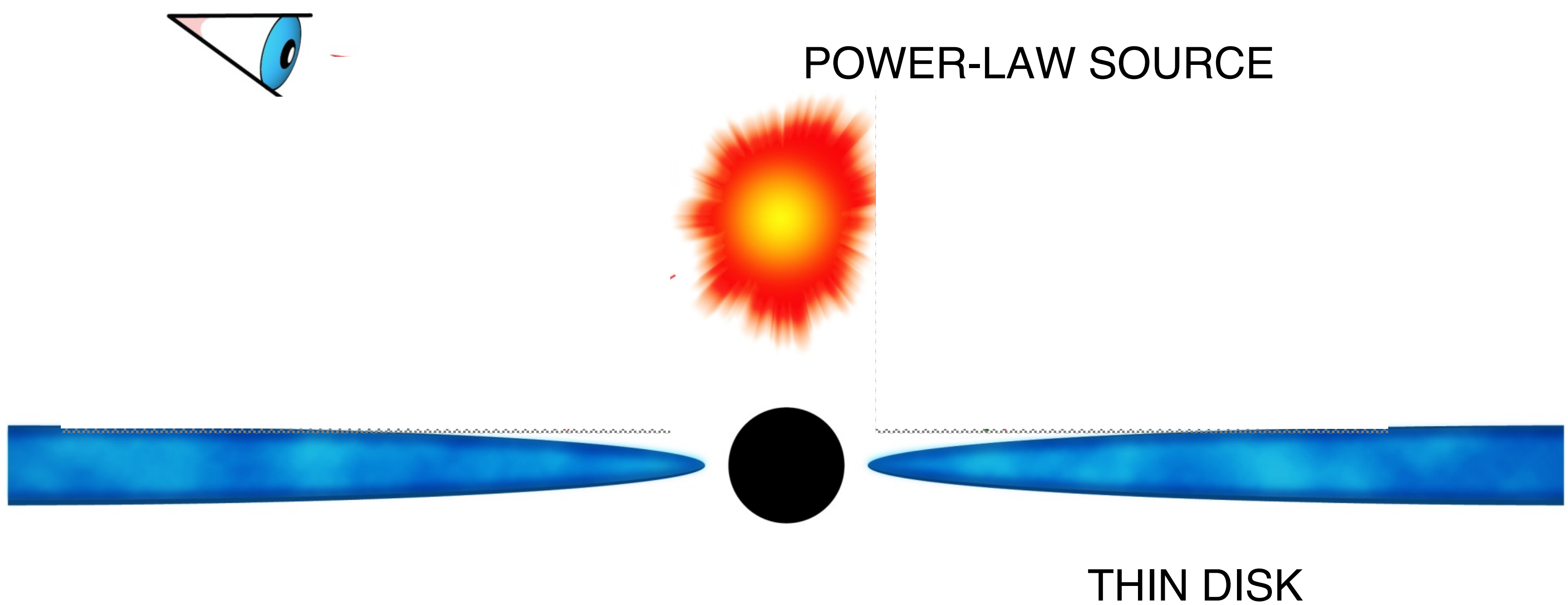
<u>Hard (low) state</u>; hard X-ray spectrum, little/no thermal disk

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



adapted from Belloni

STRONG GRAVITY - BLACK HOLES
HOW DO QUASARS WORK?

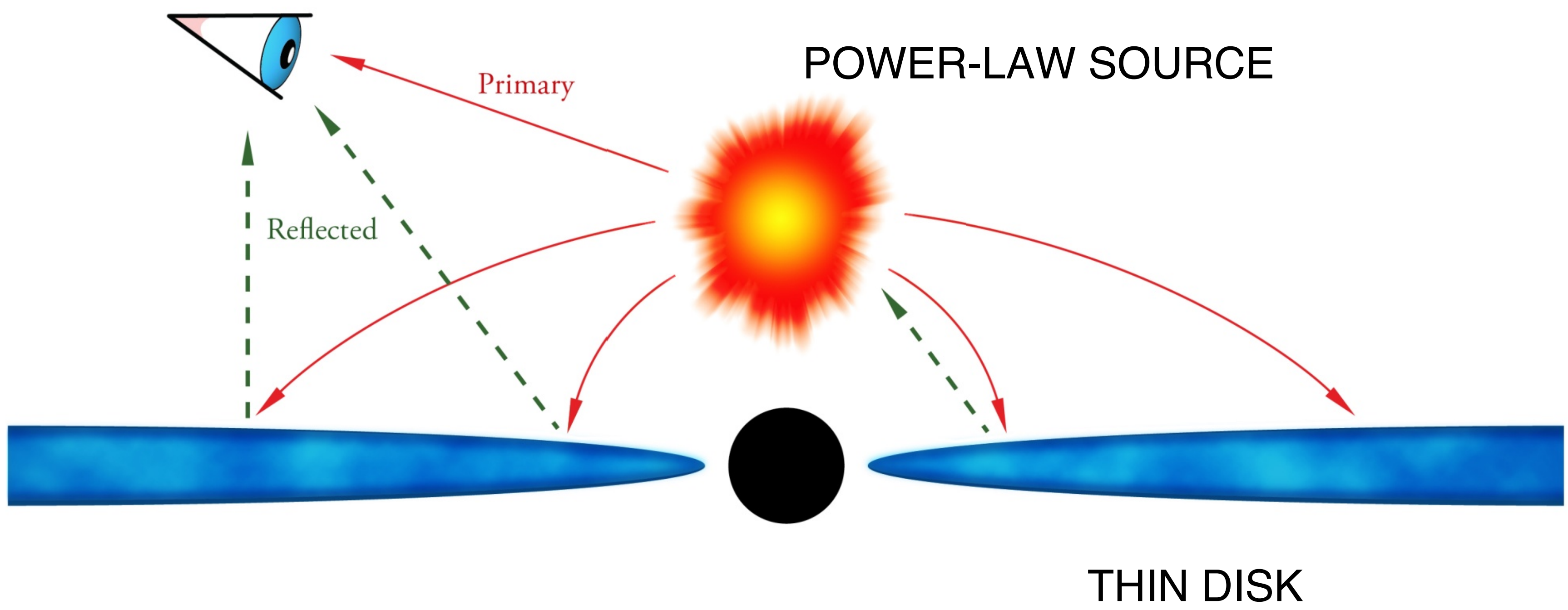


A. Fabian

Stellar mass – ULX – AGN – Quasar

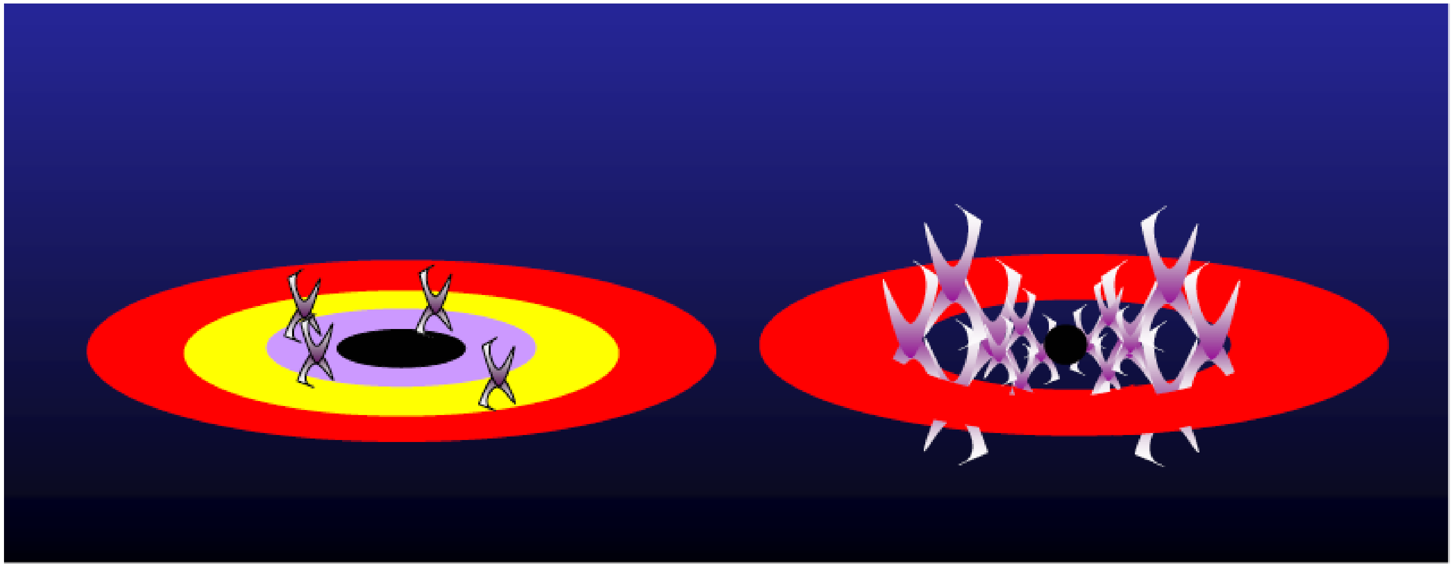
STRONG GRAVITY - BLACK HOLES

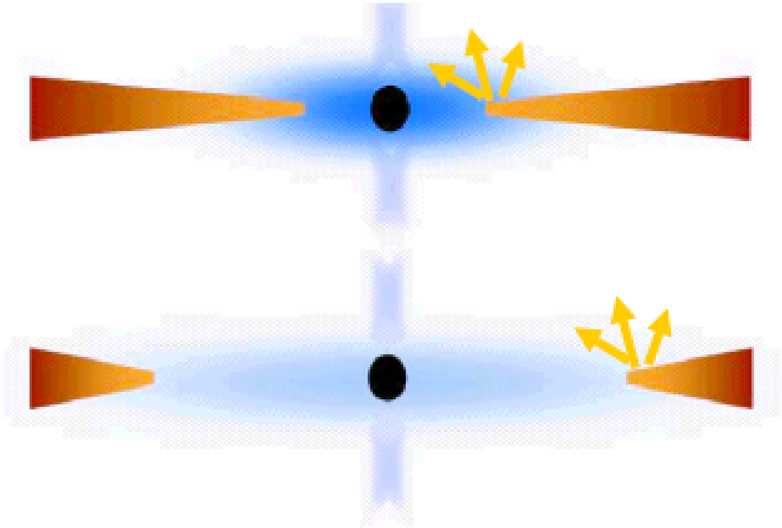
A. Fabian



Reflection, high velocities, gravitational redshift, light bending predicted

Even More Geometries

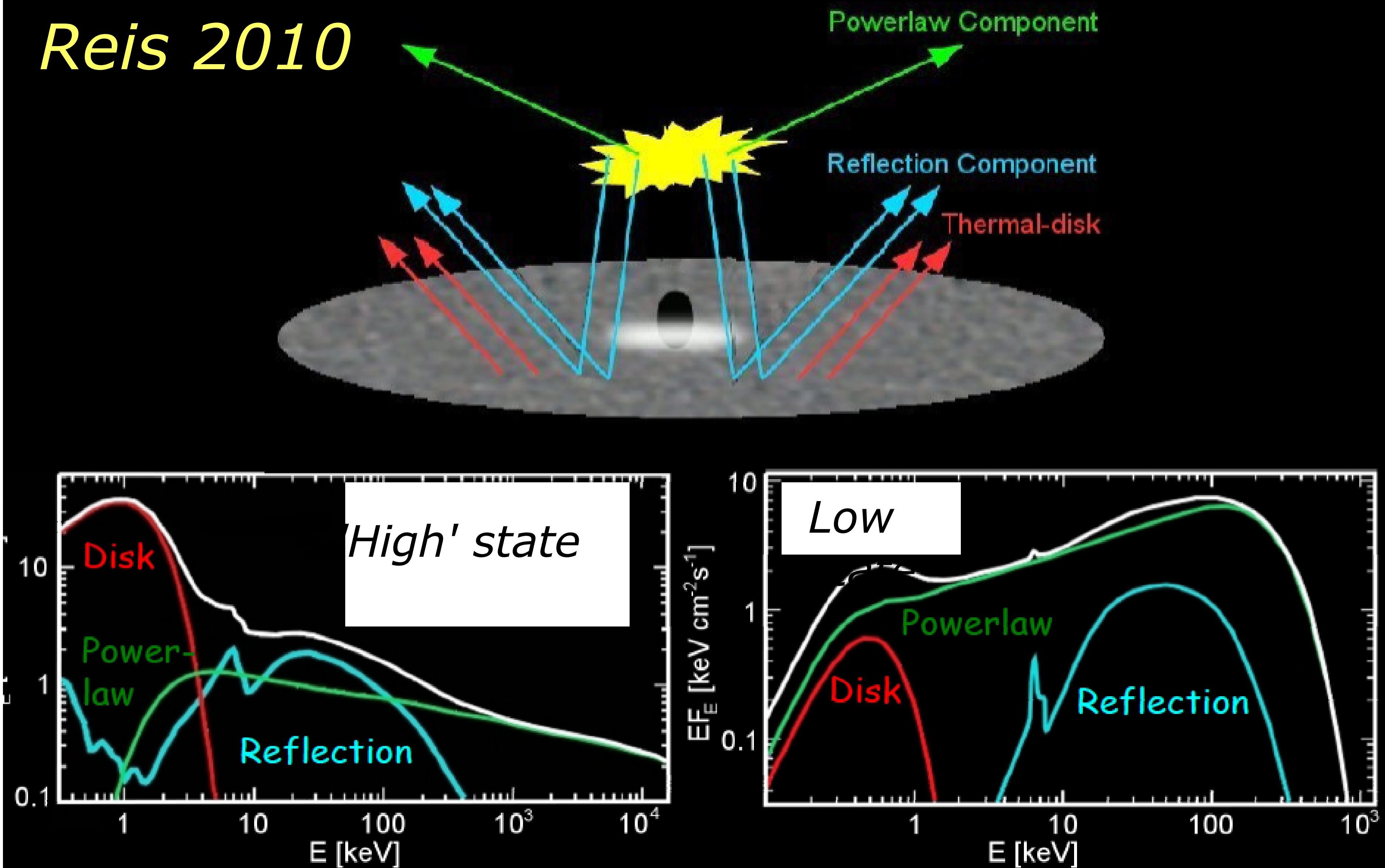




From C. Done

Galactic Black Hole Binaries

Reis 2010

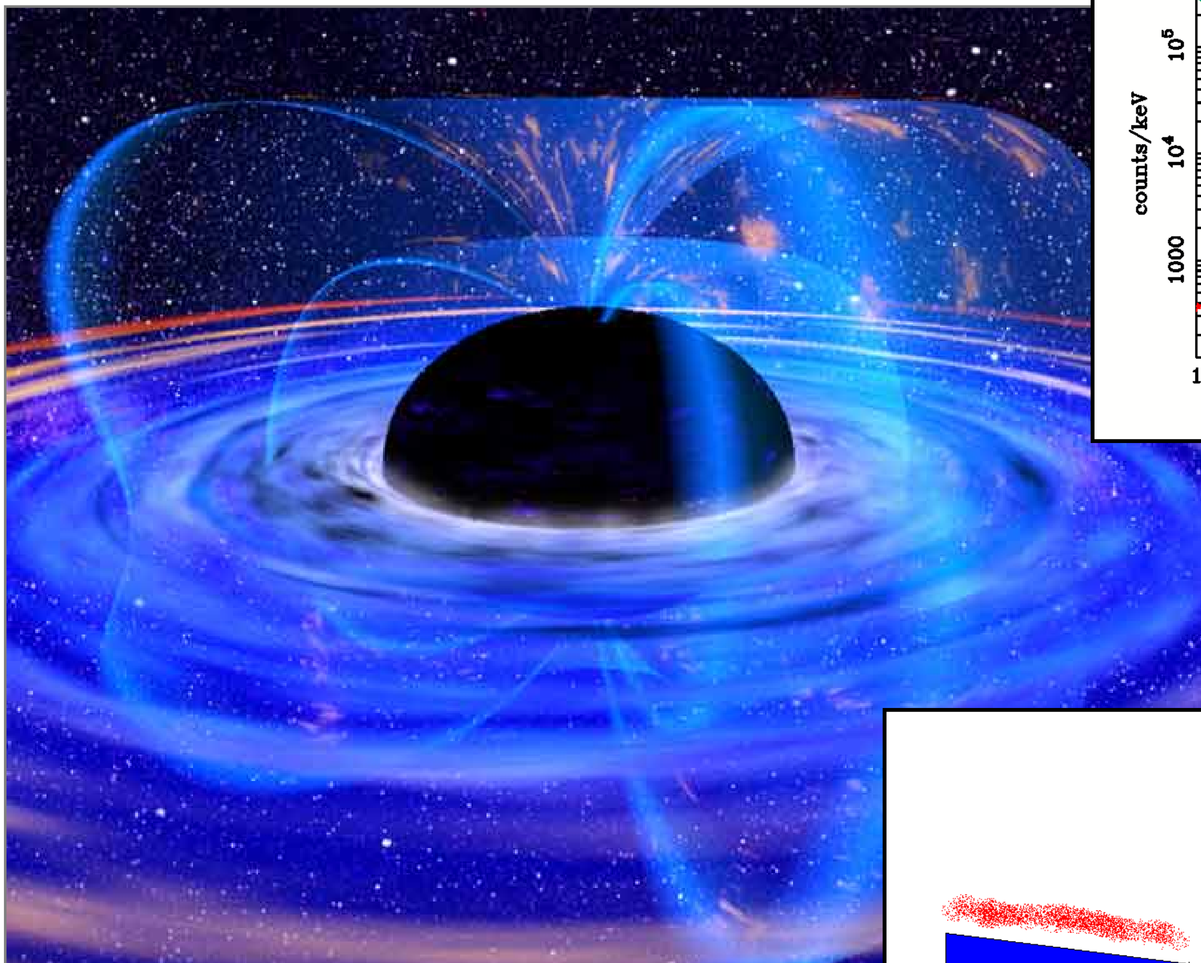


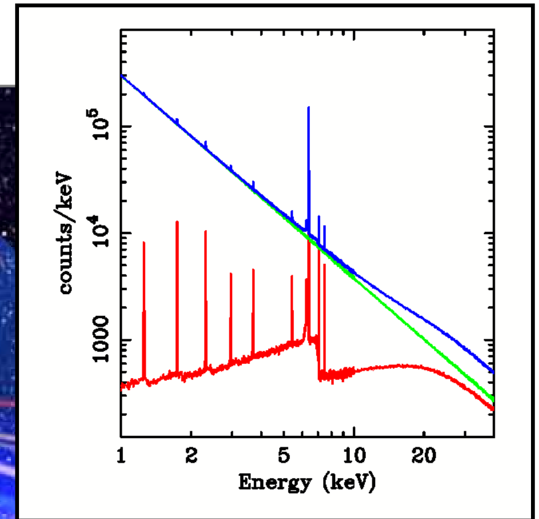
Next Topic- reprocessing

- Need your project titles SOON

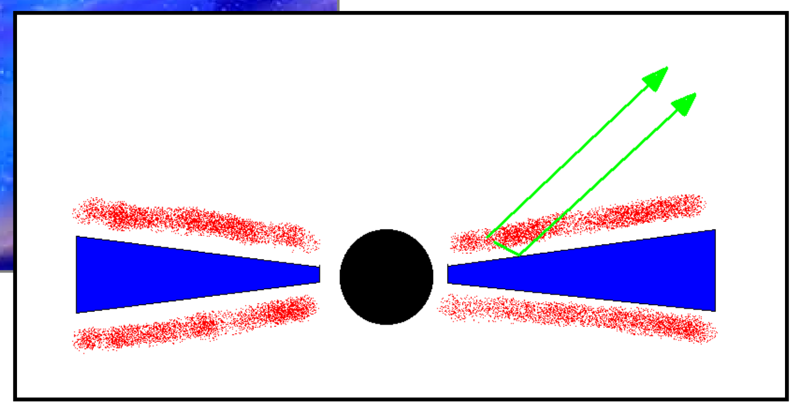
Reprocessing- how can we learn about the material in and around the black hole from spectral and temporal signatures in the spectra

Spin and its influence



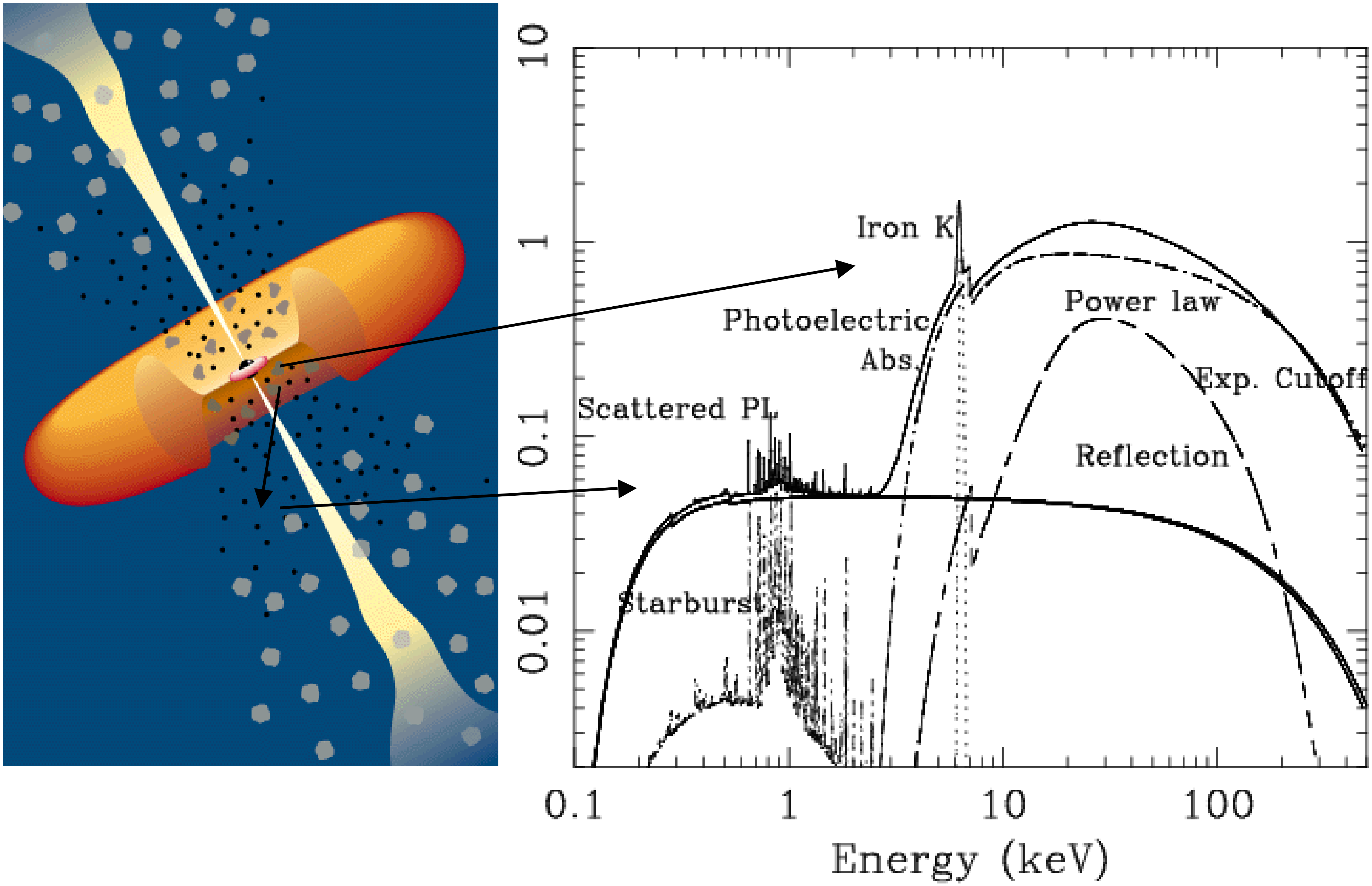


Reynolds (1996)

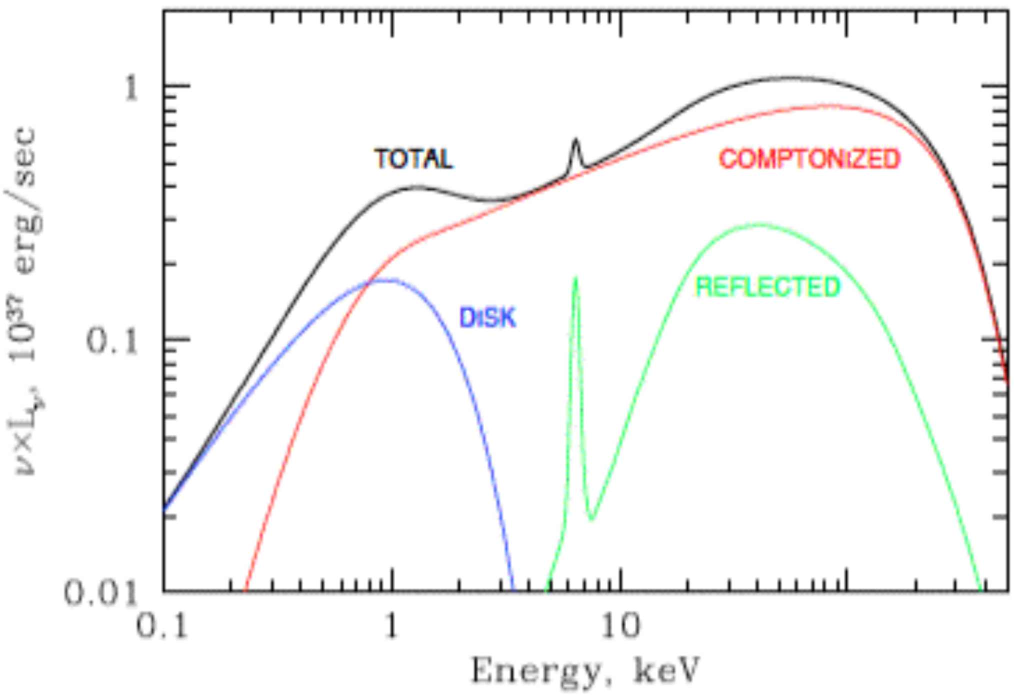


- X-ray “reflection” imprints well-defined features in the spectrum

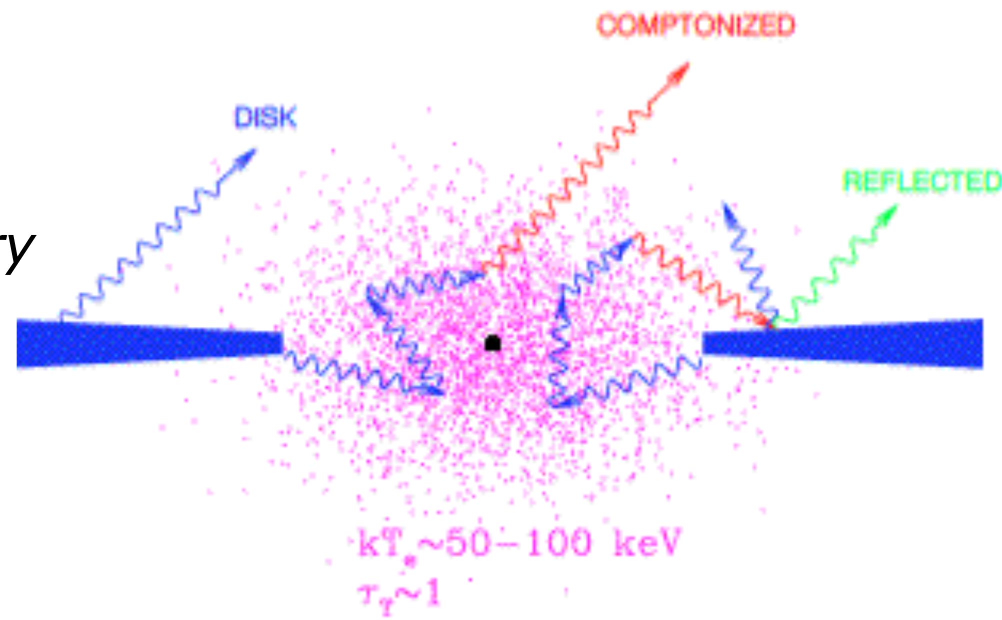
■ .


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)

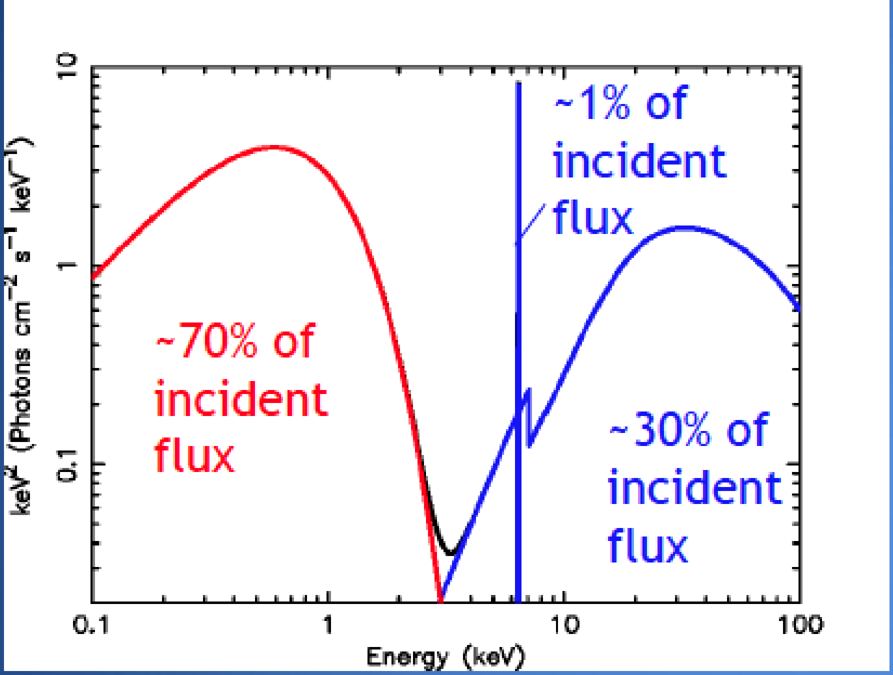
Connection Between Source Geometry and Spectra in an Black hole binary



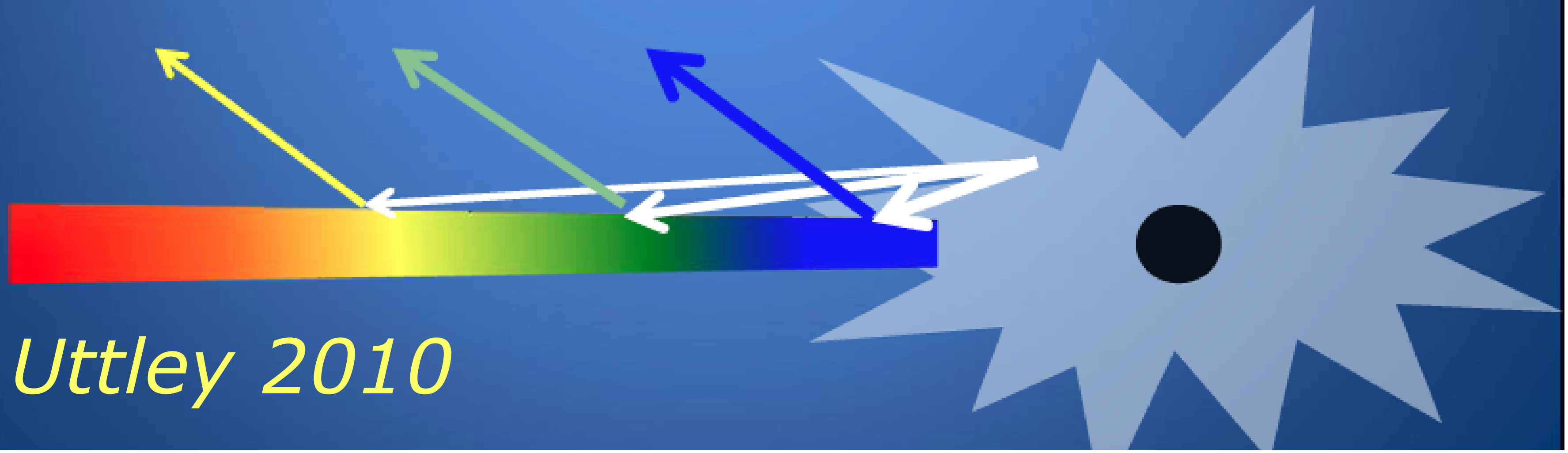
An Alternative Geometry



Disc X-ray reverberation

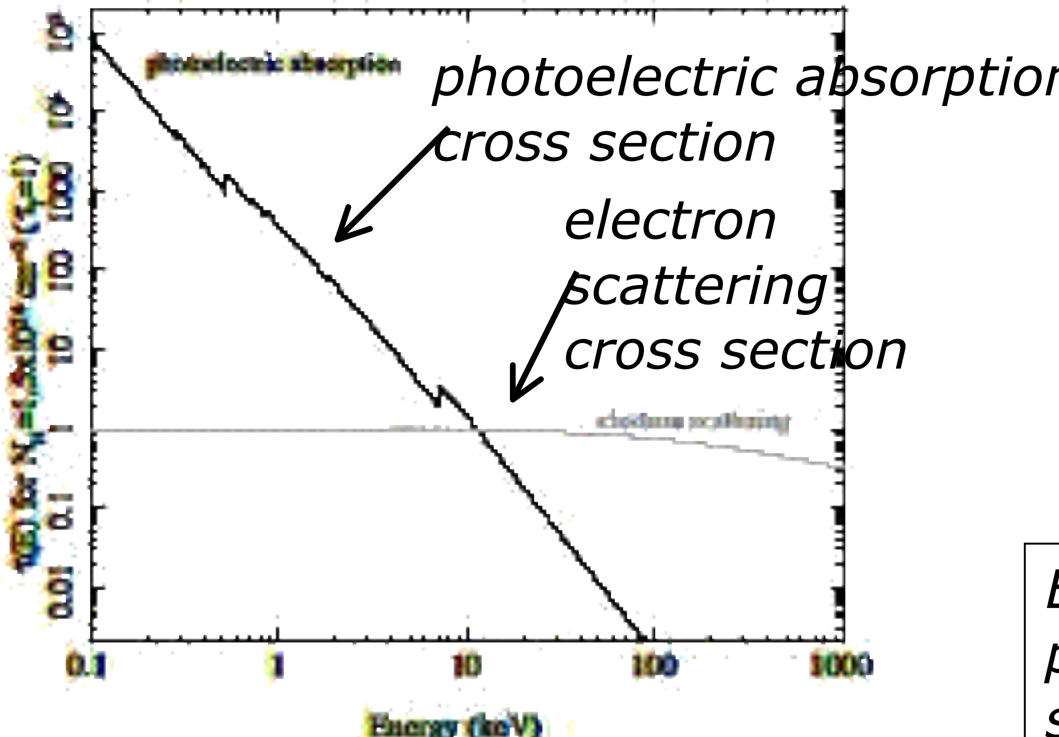


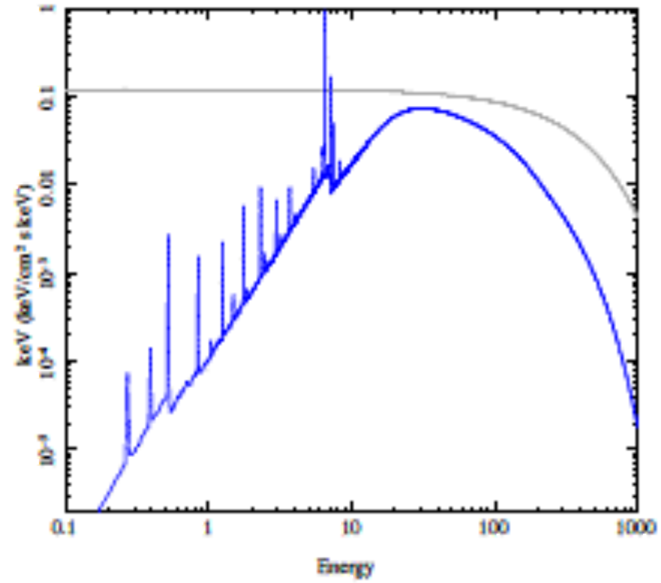
- ✧ X-rays from the continuum source (corona, jet base?) hit the disc
- ✧ Some are reflected (iron line and reflection continuum)
- ✧ The absorbed fraction is thermalised and re-emitted at the local disc temperature



Uttley 2010

'Reflection'- Reprocessing of Photons in the Disk

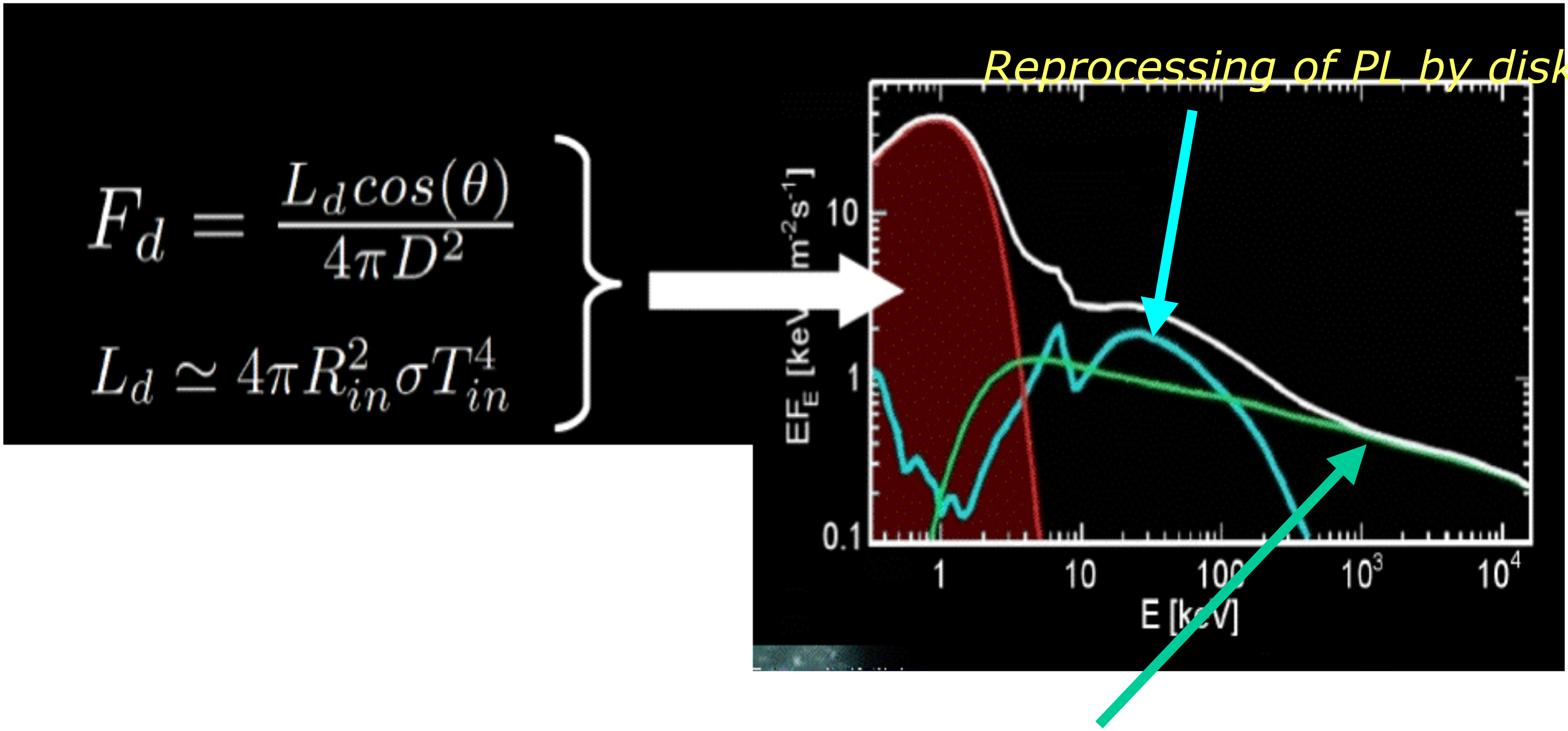




Emission due to the two processes from a cold slab of thickness $\tau_{Thompson}$=1

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.

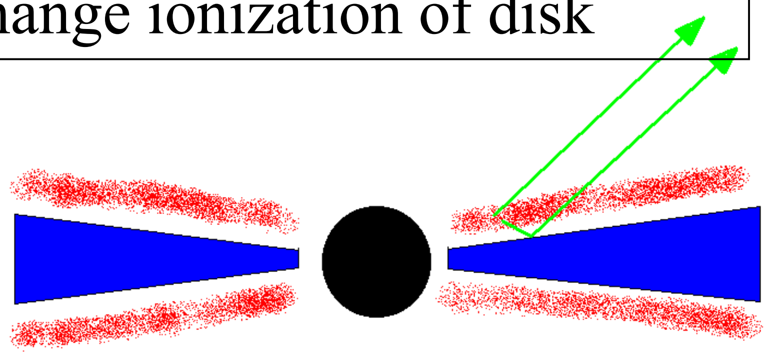
Components in High State- R. Reis 2010

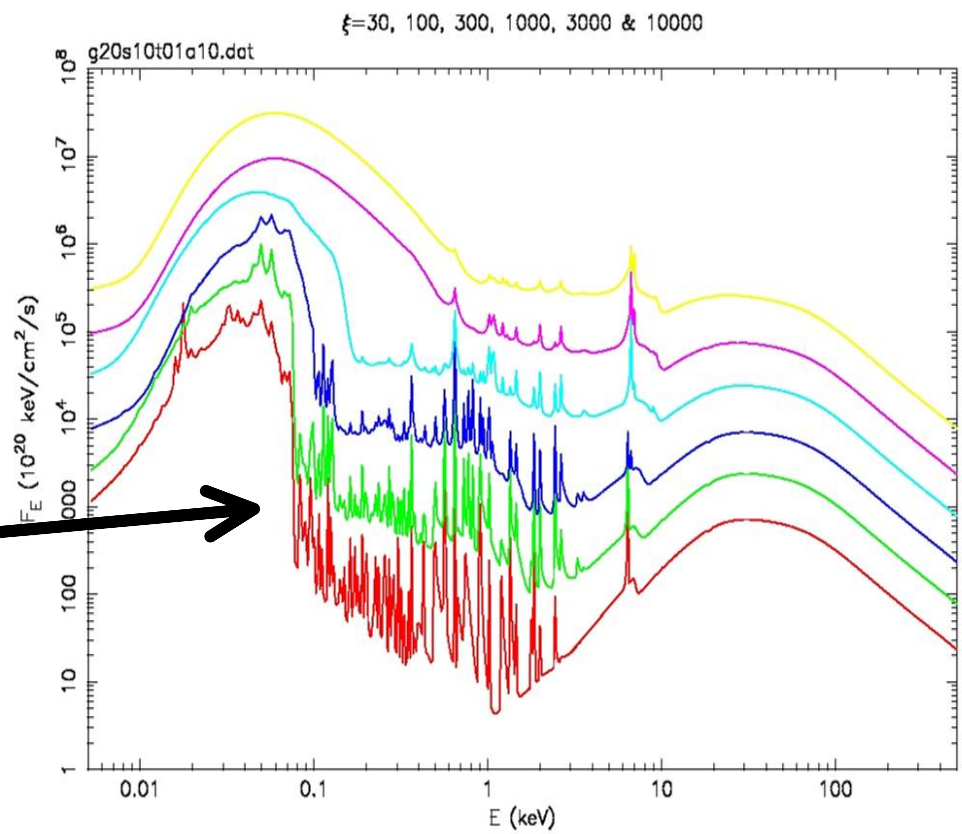


'Power Law'- Comptonization

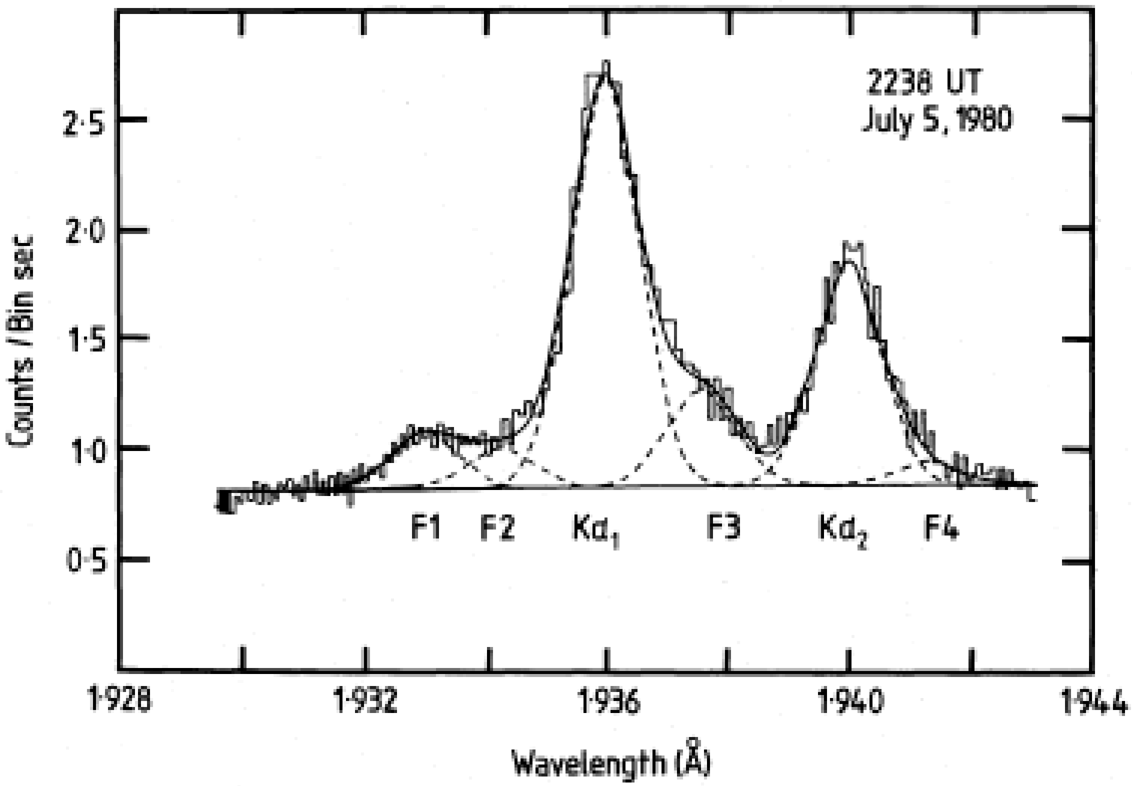
X-ray reflection
"Reflection' is Compton scattering

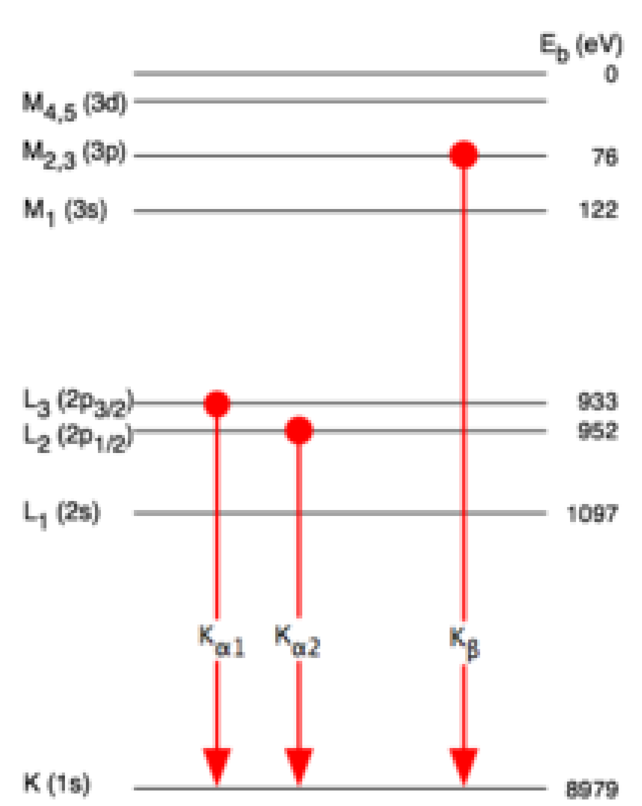
Important consequence of corona: underlying disk is irradiated by intense X-ray source… results in a characteristic spectrum being “reflected” from the disk surface layers
Different amounts of flux can change ionization of disk





Iron Kα fluorescence from the Sun

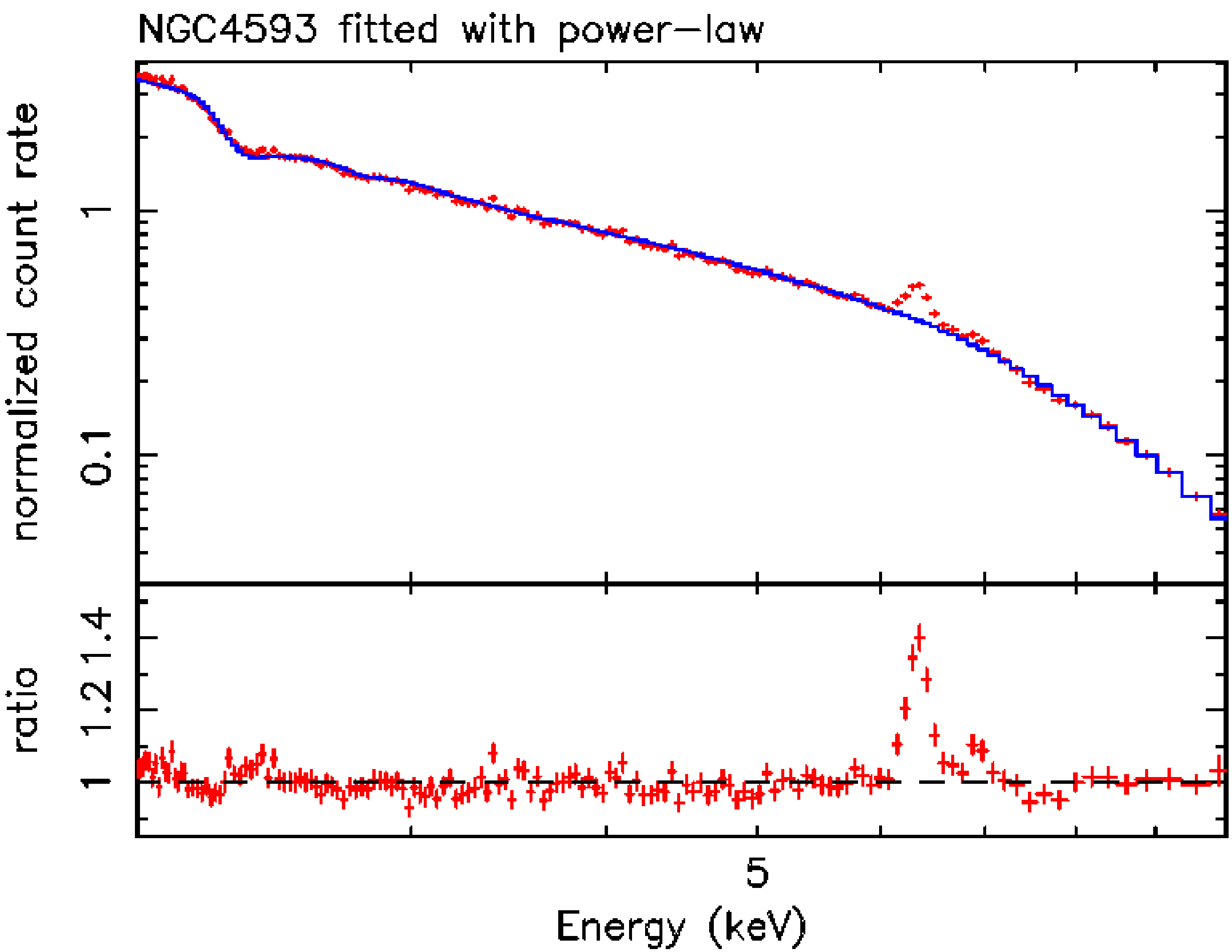




energy levels for Cu

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

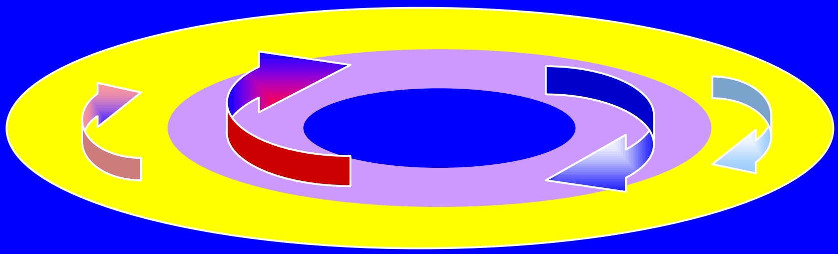
With very high resolution there are 2 Fe K flourescent feature Kα1, Kα2

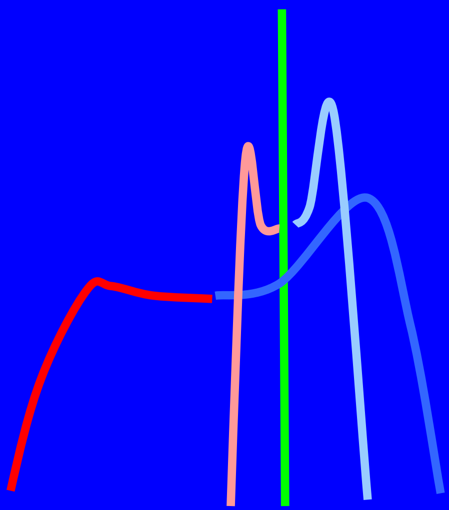


NGC4593 (Active Galactic Nucleus; Seyfert 1)

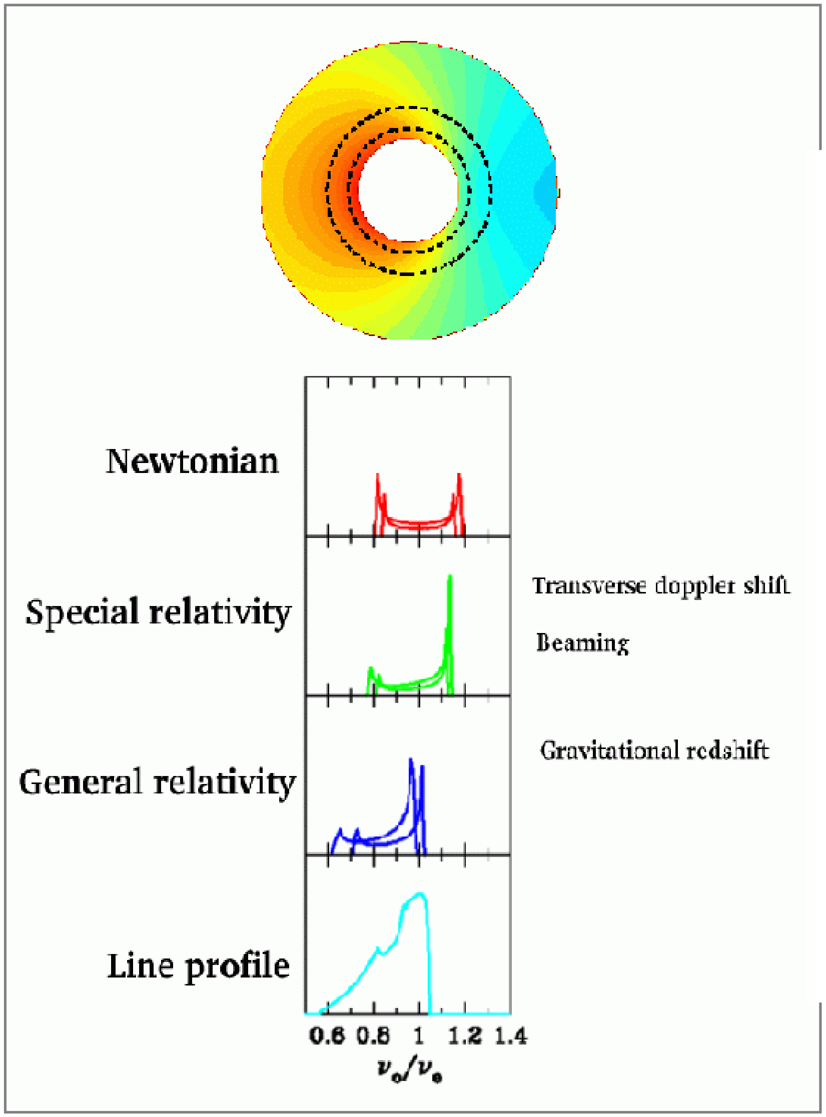
Relativistic effects- C. Done

- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe Kα line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of Rin – so spin if ISCO (Laor 1991)

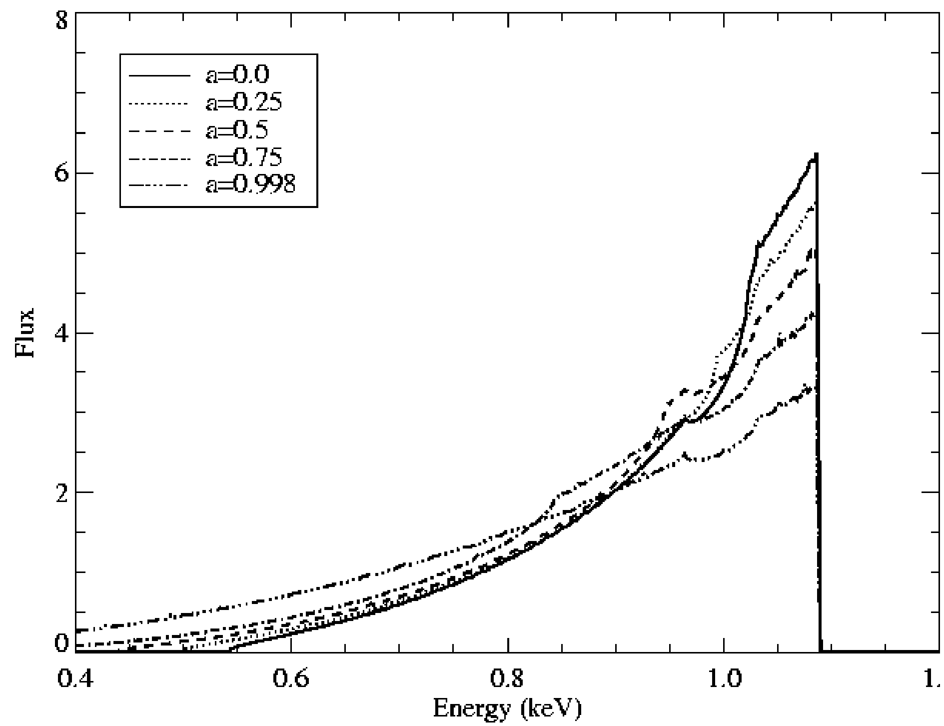




Relativistic effects imprint characteristic profile on the emission line…



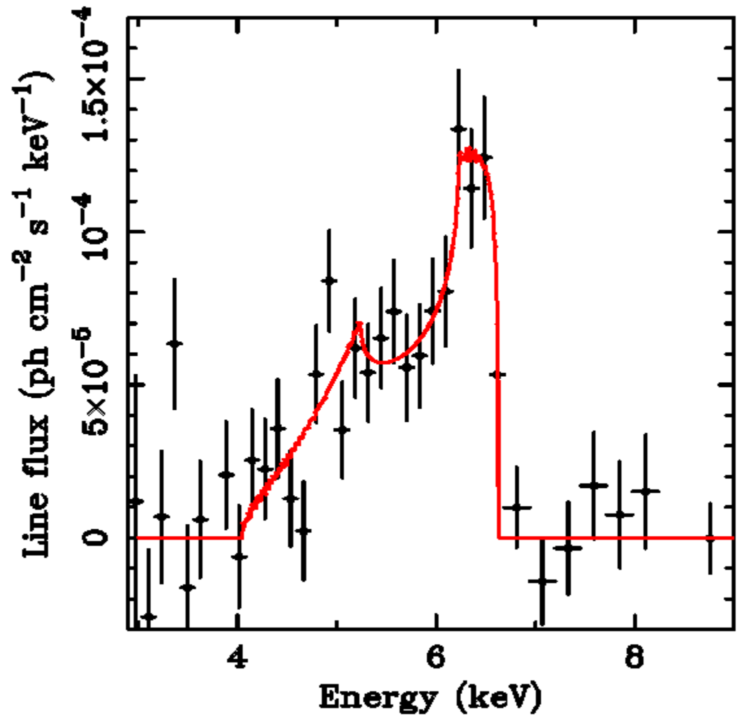
Andy Young



Theoretical line profiles [Laura Brenneman]

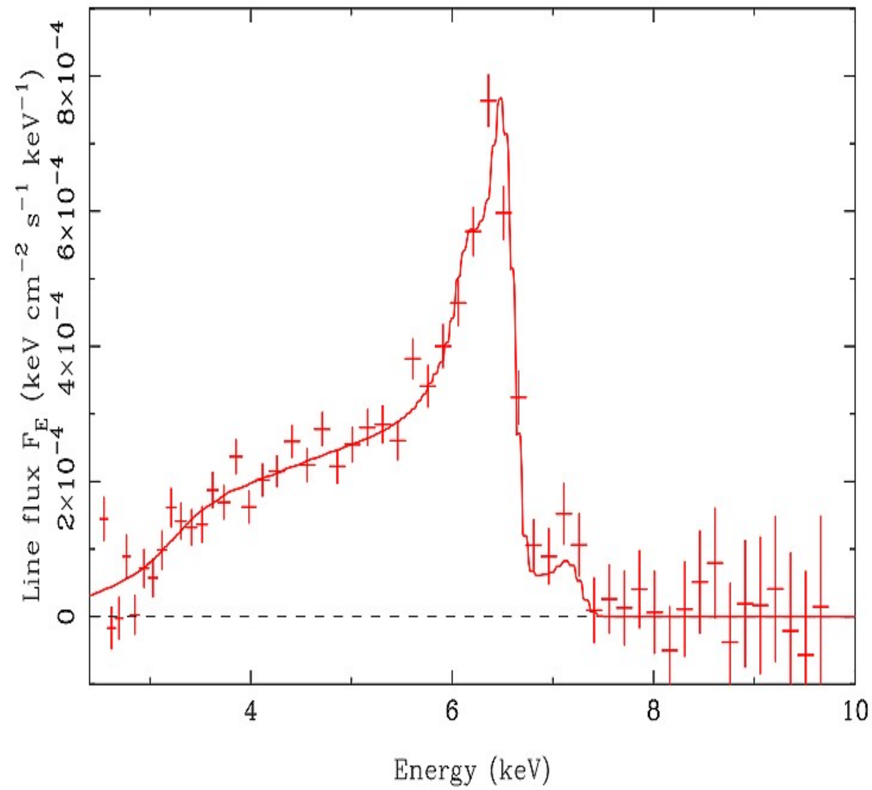
Observations of relativistic emission lines

- 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)

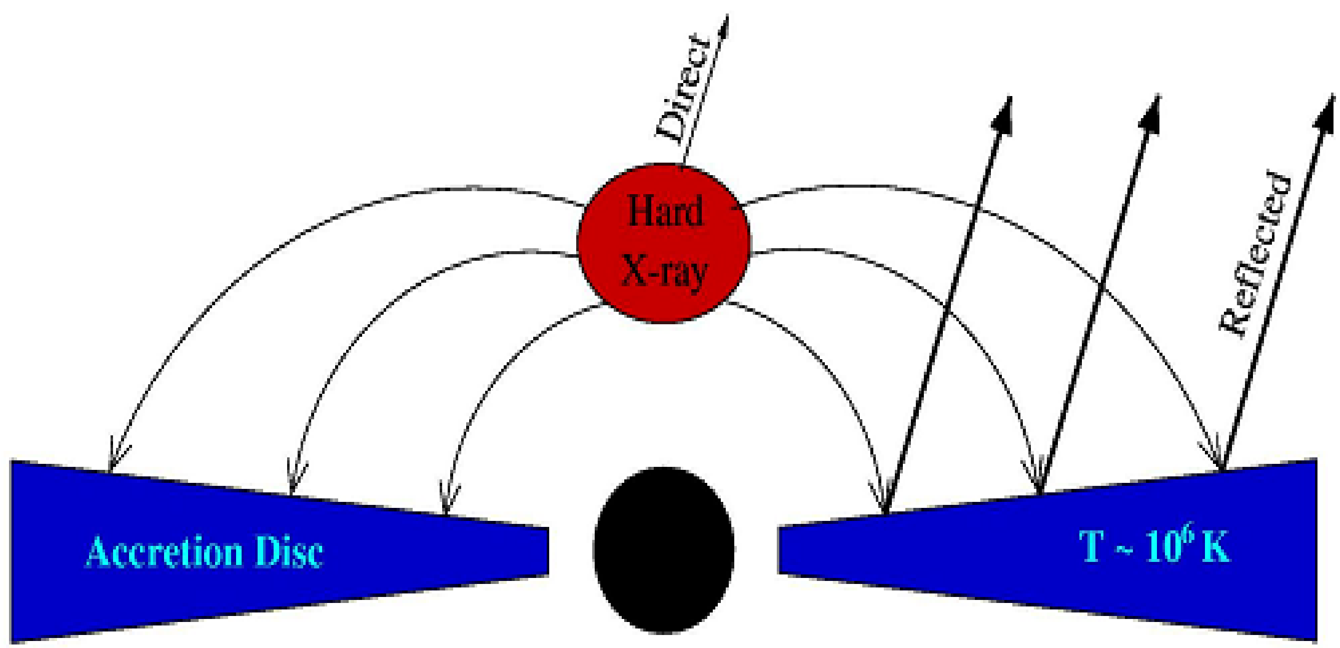
- Modern XMM-Newton observations
- Confirm relativistic line with extreme redshifts
- If no line emission from **within** ISCO, need to invoke spinning black hole to get strong enough redshifting



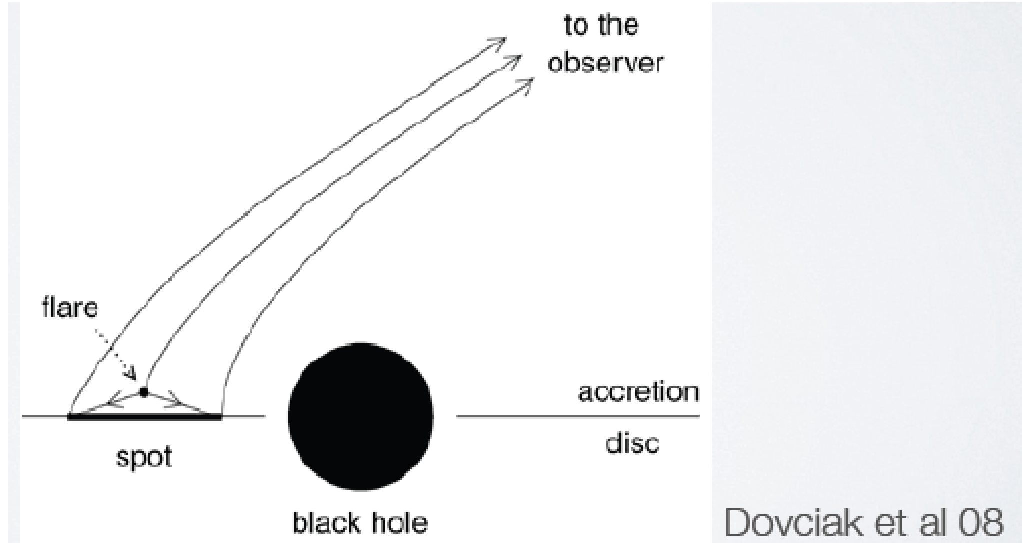
Power-law continuum subtracted
XMM: Fabian et al. (2002)

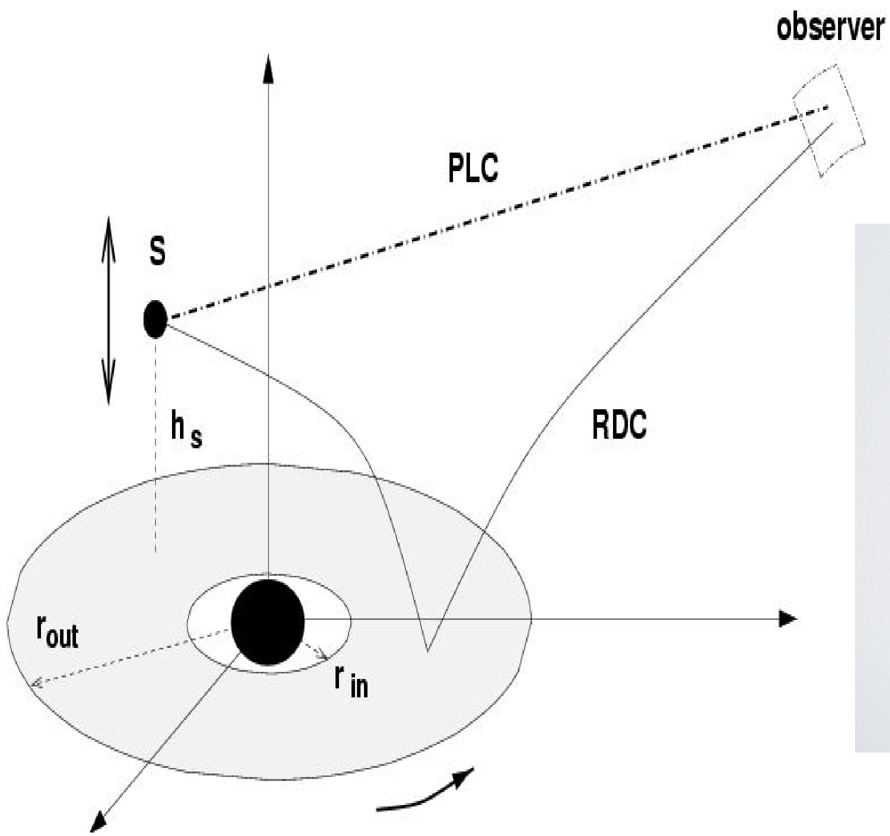
Relativistic Effects

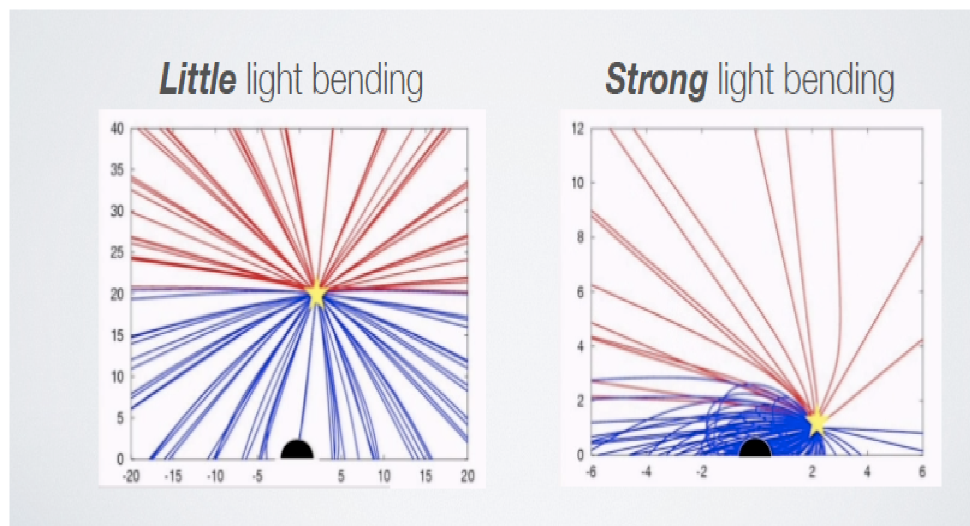
- Light rays are bent by strong gravity- making the geometry rather complicated
- Do not know 'where' x-ray source is - try to use data to figure it out



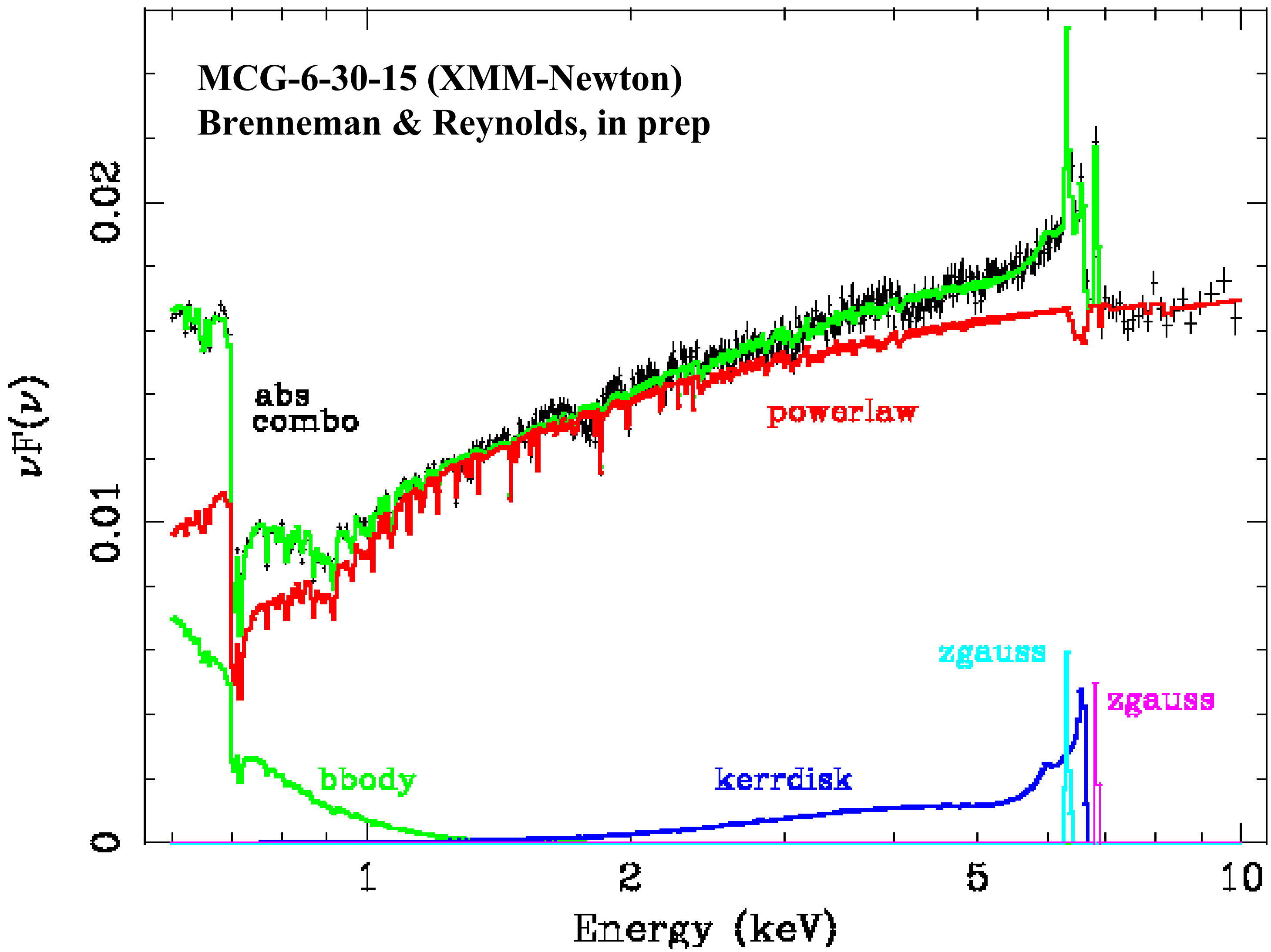
- if we only knew where the x-rays come from ($h_s \sim r_s$) from time variability arguments



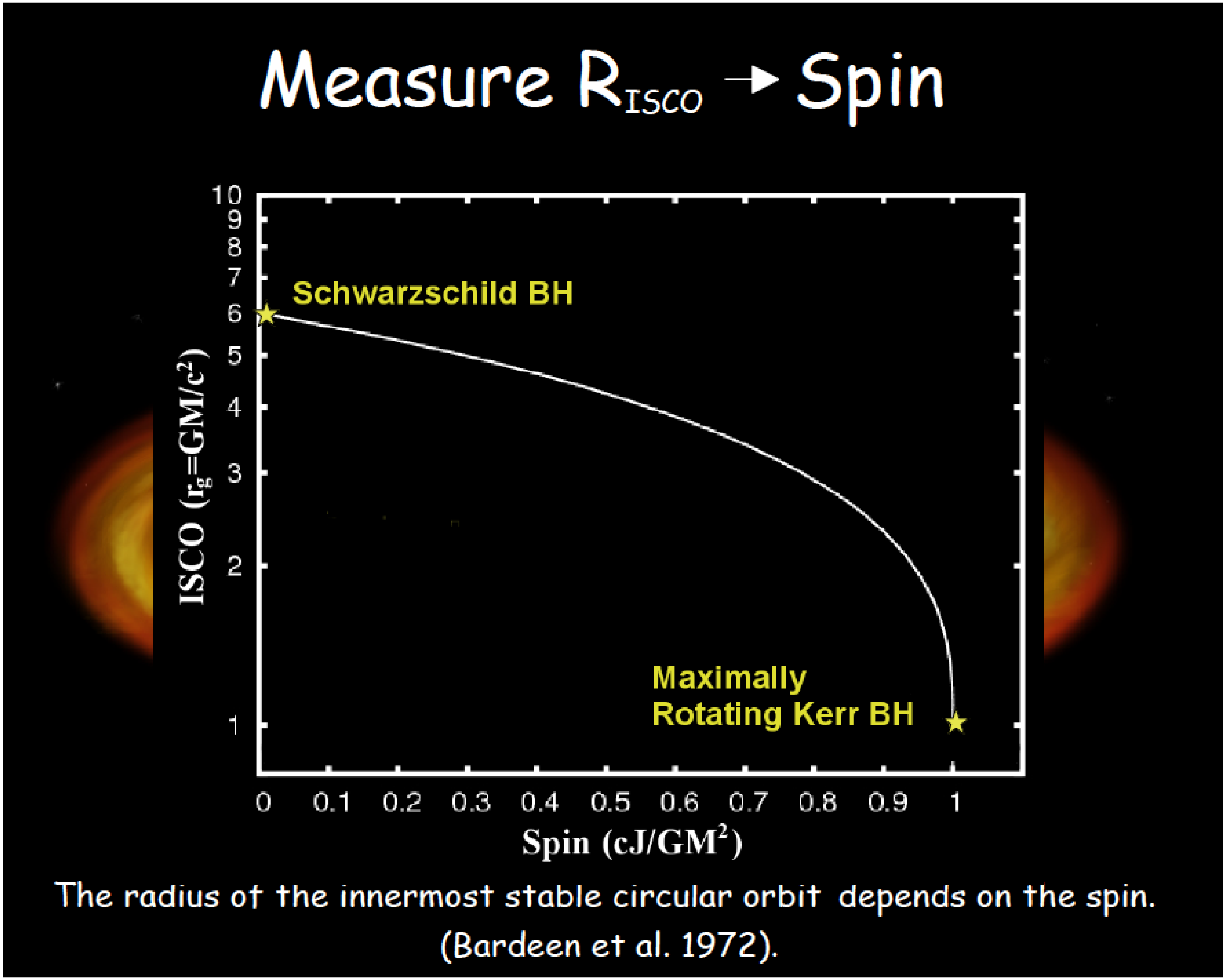




Spectra have lots of information…



- Spin- is measured in units of $a = cJ/GM^2$

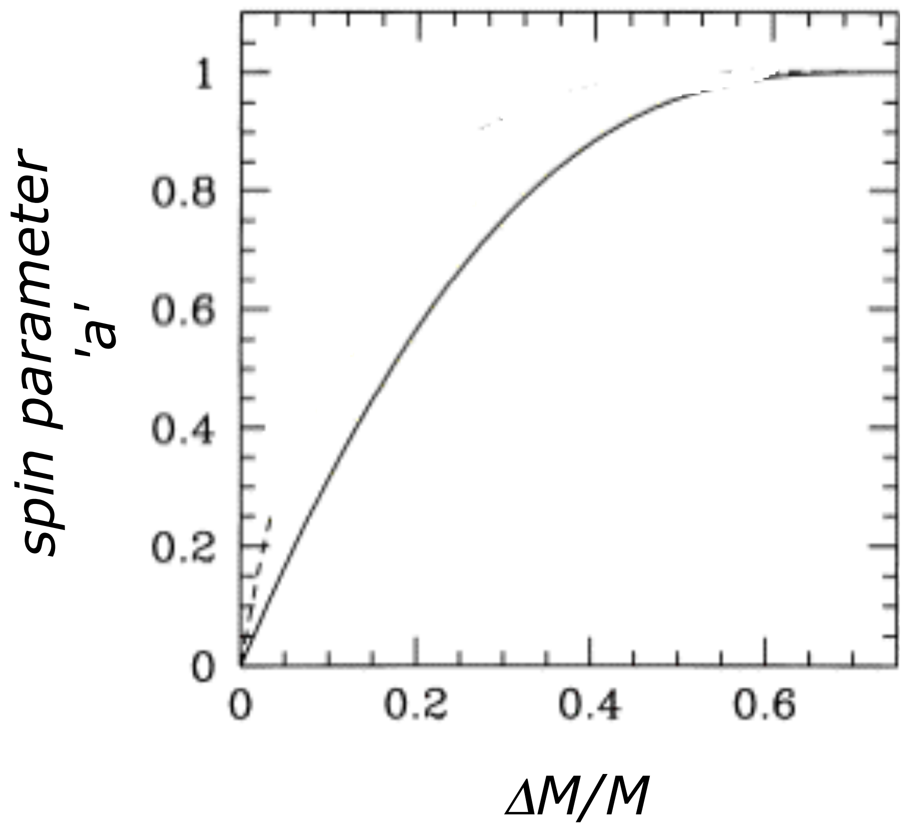


Why Measure Spin

- 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



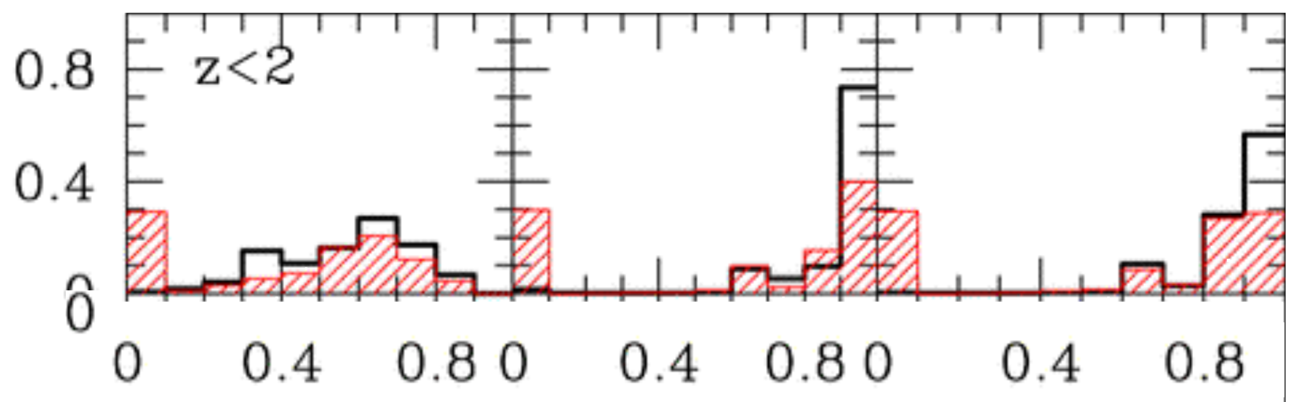
- If accreting at the Eddington limit takes a very long time (~10^8 yrs)
  - too long for wind fed or Roche Lobe systems
  - too much mass for low mass companions
- Spin is natal in galactic mass black holes

Spin

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

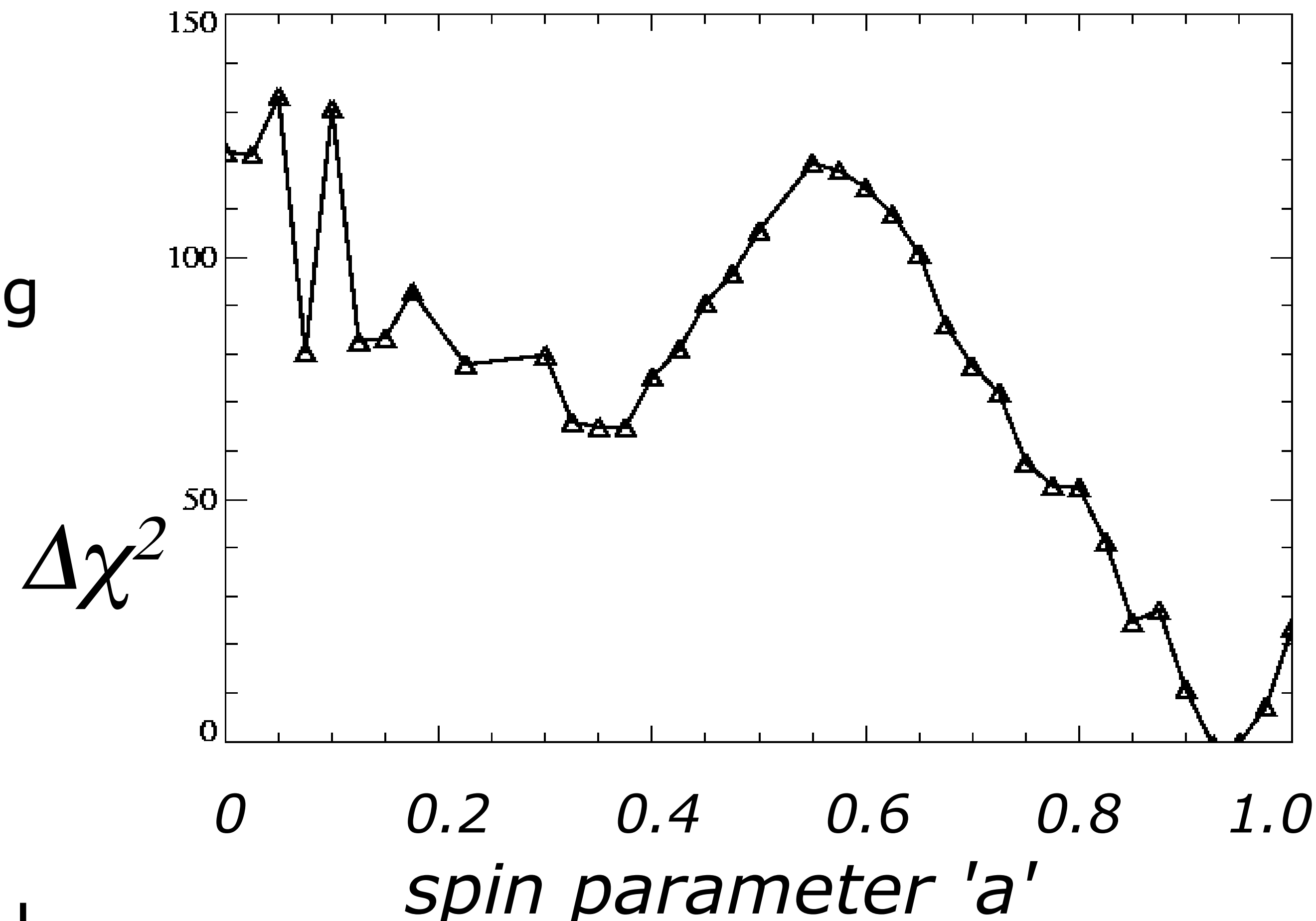
- Spin can be due to accretion
- Requires 'organized' accretion of angular momemtum

Alternatively spin could be due to mergers of black holes



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



L.Brenneman- is a measure of the probability- for 1 degree of freedom and Gaussian statistics =2.7 corresponds to 90% confidence

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