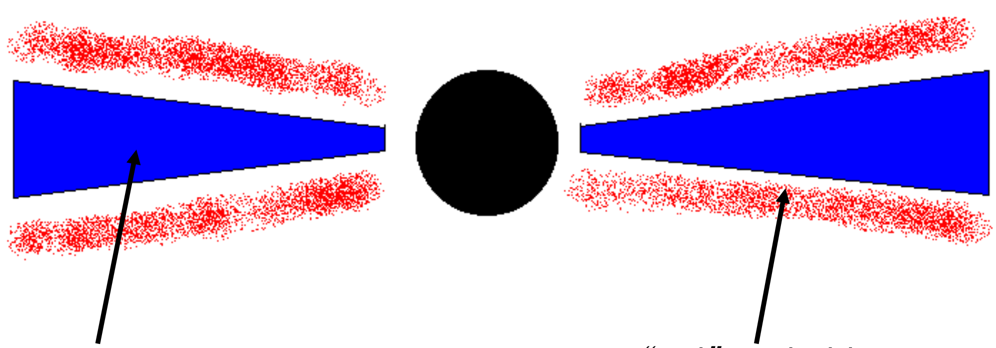
Today

- Comptonization and X-ray AGN Spectra
- X-ray Spectral Components and reprocessing
- Direct evidence for disks and small x-ray size from grav lensing
- Broad Fe K Lines and Spin

Where do the Spectral Components Arise?

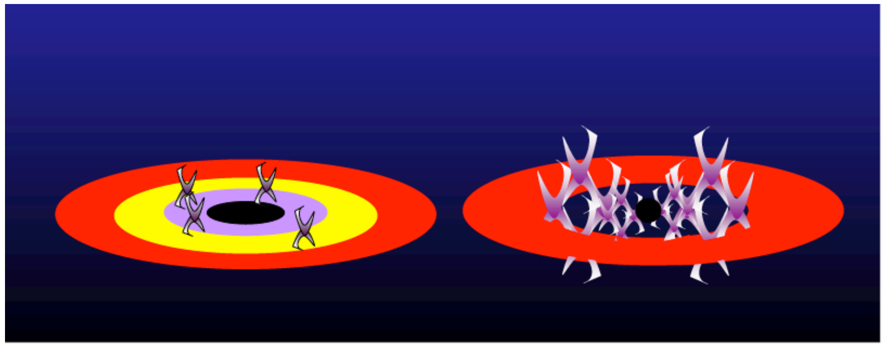


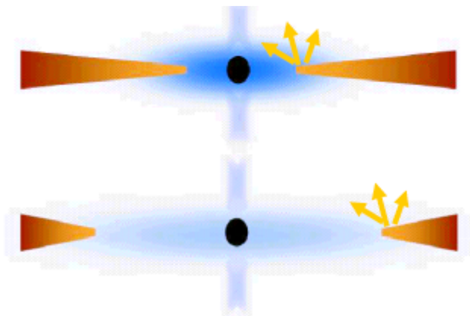
Optically-thick part of the accretion disk emits thermal spectrum… black body radiation with

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

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

Even More Possible Geometries





From C. Done

Comptonized Spectra Longair 9.4.1

- The free parameter for the power law slope is y which controls the spectral slope
- However the smaller τ is, the 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
- see **Unwrapping the X-ray Spectra of Active Galactic Nuclei** C. Reynolds **arXiv: 1510.07638**

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

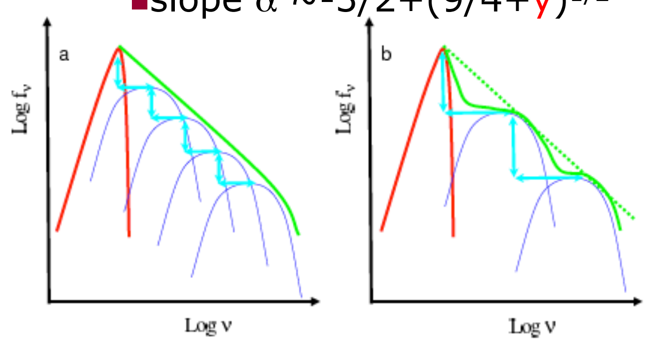
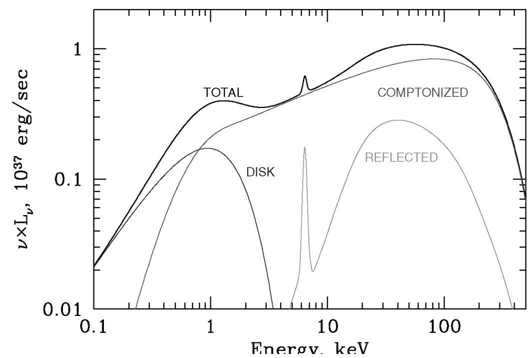


Figure 1.8 a) shows how the spectrum built up from repeated thermal Compton up scattering events for optically thin ($\tau \lesssim 1$) material. A fraction τ of the seed photons (red) are boosted in energy by $1 + 4\Theta$ and then these form the seed photons for the next scattering, so each scattering 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 Θ and lower τ 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

Thermal Comptonized Continuum

- The detailed solution is a bit messy (Zdziarski, Johnson & Magdziarz (1996) but for y>1 one forms a spectrum which can be approximated by a power law of slope G with a high energy cutoff related to the temperature of the hot electrons.
- power-law index of the photon count rate as a function of energy, $N(E) \propto E^{-\Gamma}$,



Typical slopes are ~-2 which gives τ_e~1 and y=3/4

$$\Gamma = \sqrt{\frac{9}{4} + \frac{3 m_e c^2}{kT_e \left[\left(\tau_e + \frac{3}{2} \right)^2 - \frac{9}{4} \right]}} - \frac{1}{2}.$$

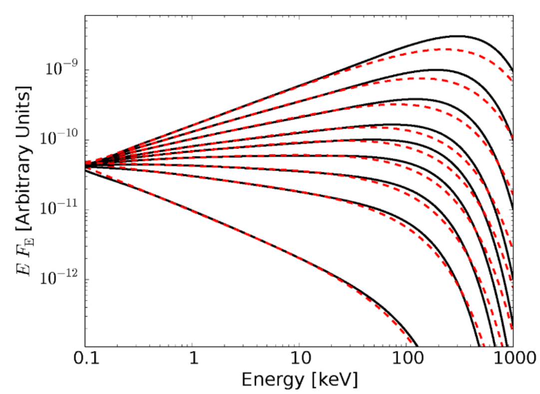
$y=4kT_e m_e c^2 \max(\tau_e, \tau_e^2)$ typical temperatures are 50-300 keV

Thermal Comptonized Spectra

- Typical slopes are ~-2
- which gives τ_e~1 and y=3/4

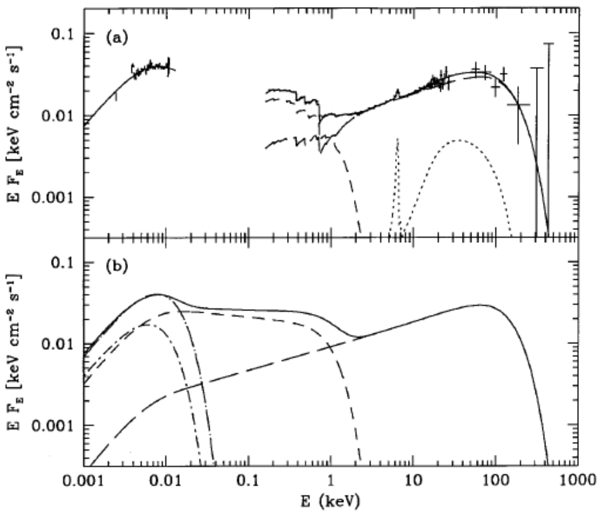
$y=4kT_e m_e c^2 \max(\tau_e, \tau^2_e)$

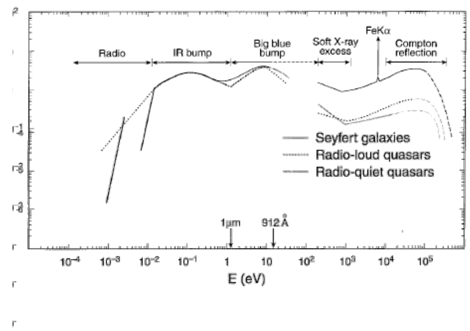
- typical temperatures are 50-300 keV



AGN- Summary of Spectral Components

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





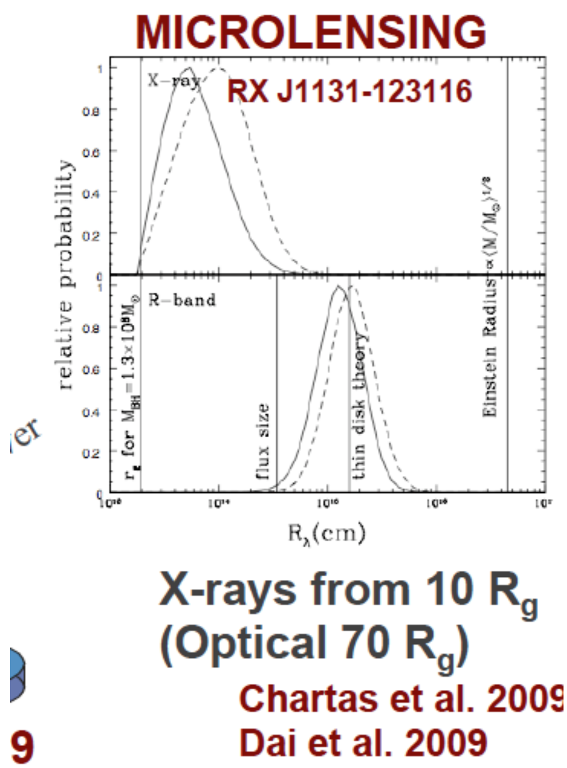
Magdziarz et al 1998

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

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

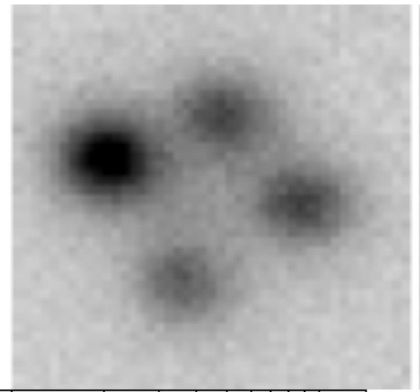
- Recent microlensing observations of a few QSOs have 'resolved' the x-ray and optical sources
- The optical source size and dependence of luminosity on wavelength are consistent with standard disk theory- e.g.
- Microlensing perturbations to the flux ratios of gravitationally lensed quasar images can 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
- $T_{eff}(r)=\{(3G^2M_{BH}^2 m_p f_{Edd})/2c\sigma_{SB}\varepsilon r^3)\}^{1/4}\ (1-r_{in}/r)^{1/4}$
  - f_{Edd} is the Eddington ratio , M_{BH} is the BH mass,s_{SB} the Stefan Boltzman constant , ε 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 <u>half light radius as a function of size is</u>
- $r_{1/2} \sim 1.7 \times 10^{16} cm (M_{BH}/10^9 M_\odot)^{2/3} (f_{Edd}/\varepsilon)^{1/3} (\lambda/\mu)^{4/3}$
- 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 M_{BH}, f_{Edd}/ε



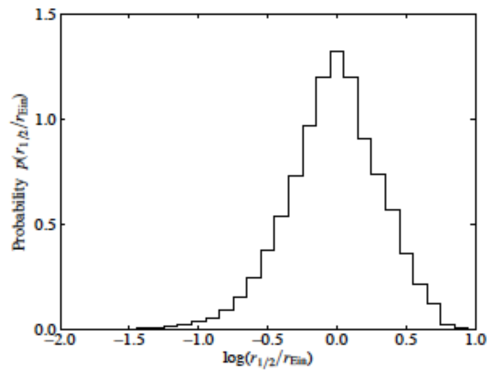
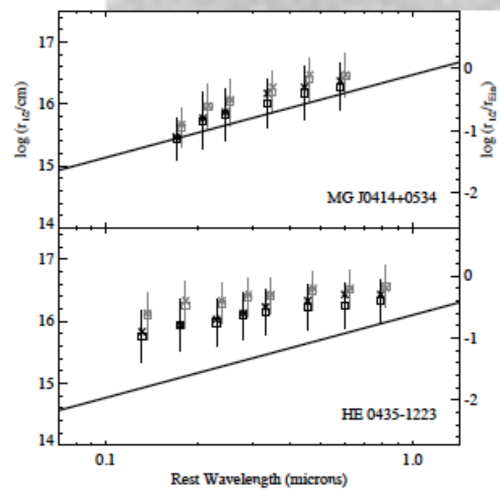
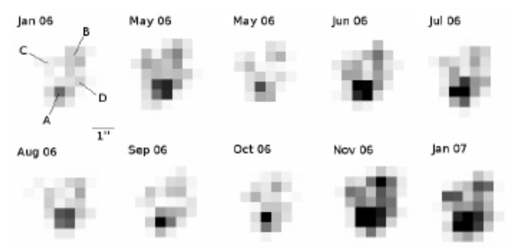


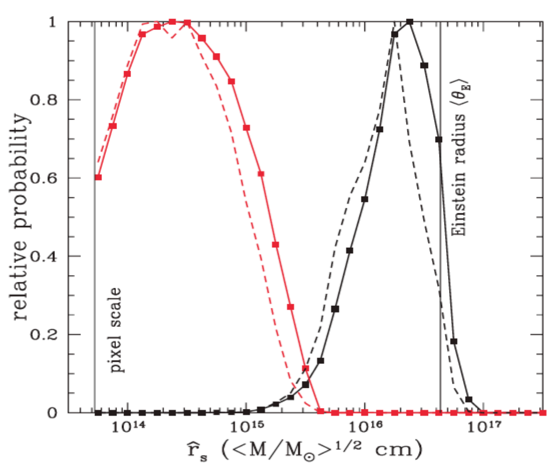
Figure 5. Posterior probability distribution for the size of PG 1115 in th
i' band, resulting from considering both i'-band and X-ray flux ratios. Th

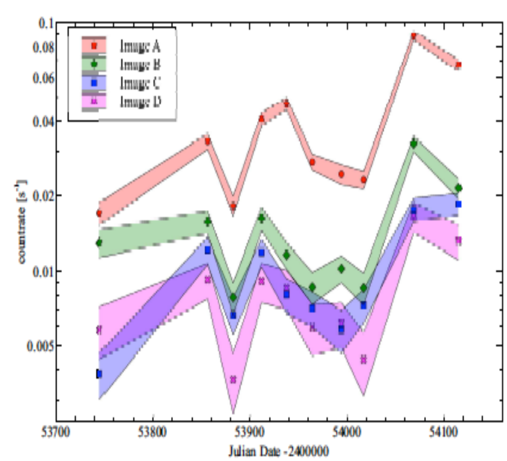


X-ray MicroLensing Also

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

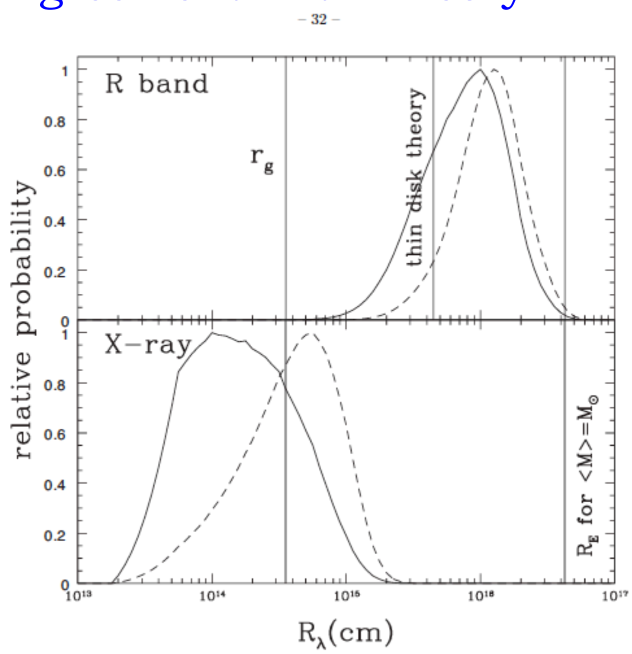






Results are In Rough Agreement With Theory

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



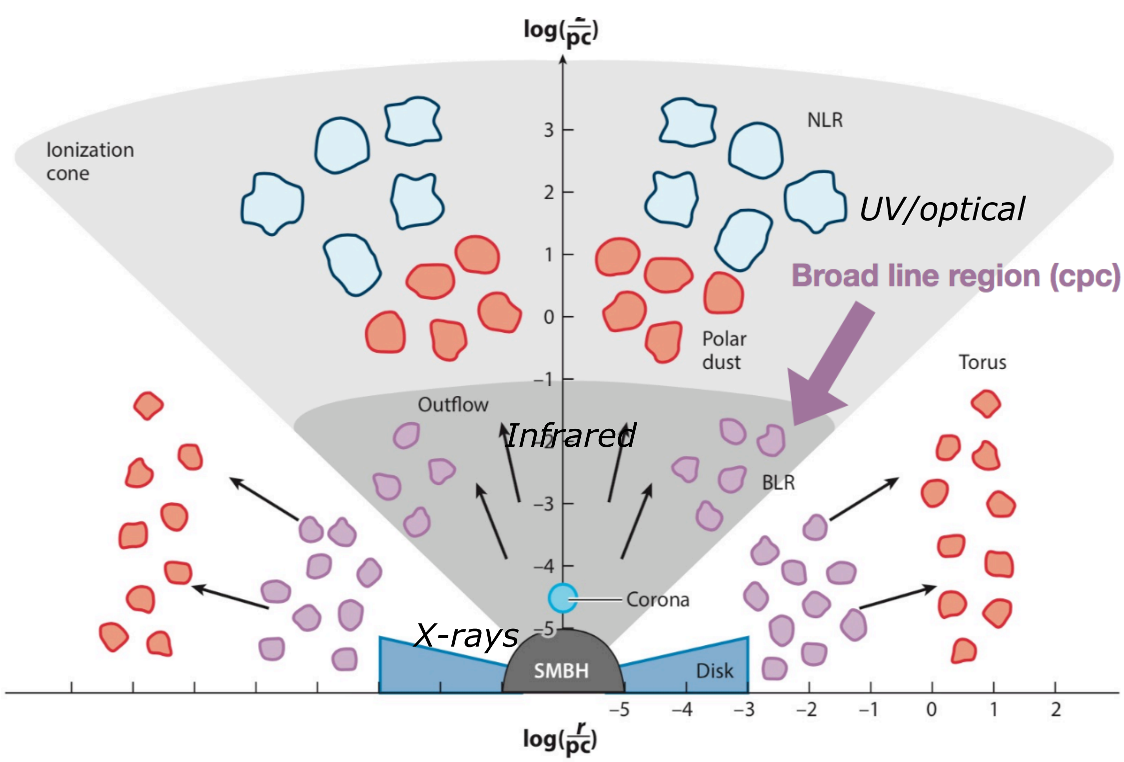
Chartas 2008

Next:

- 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

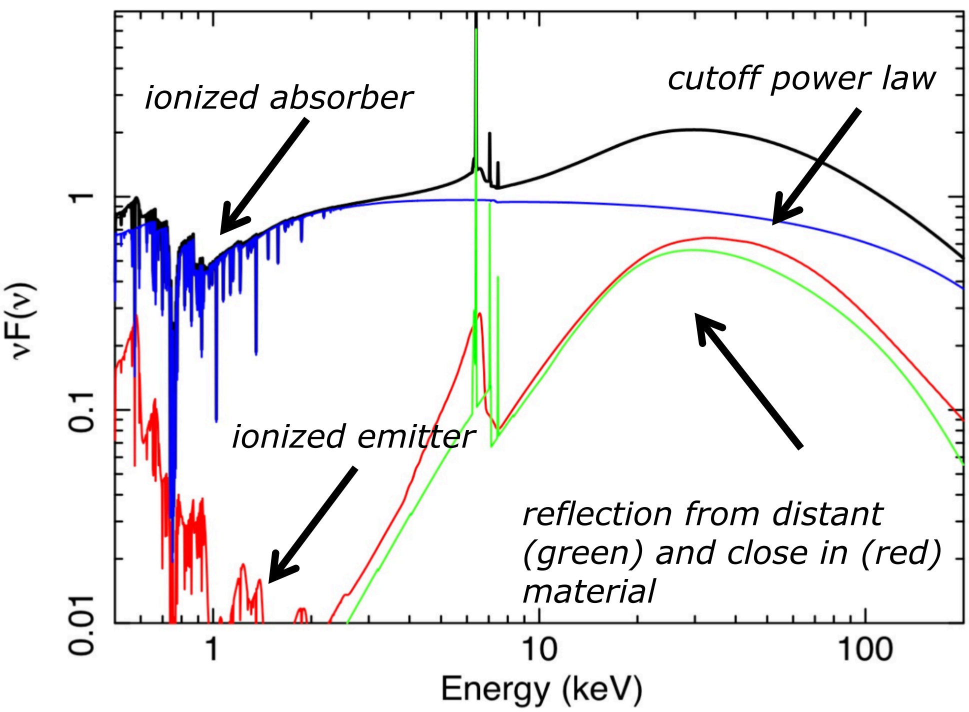
Basic Components of X-ray Spectra

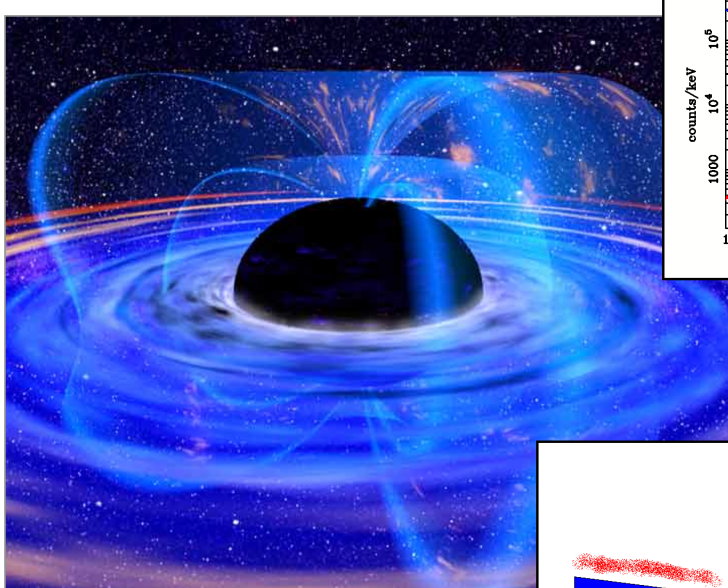
- X-ray spectra display standard components
  - Primary X-ray continuum (Γ~2 powerlaw with cuttoff at 50—300 keV)
  - Absorption (cold and photoionized gas along line-of-sight)
  - X-ray reflection from distant gas (torus of the unified scheme)
  - X-ray reflection from the inner accretion disk (strongly broadened)
  - Soft excess (origin unknown... maybe luke-warm Comptonization, or X-ray reflection from ionized accretion disk) (will not talk about)

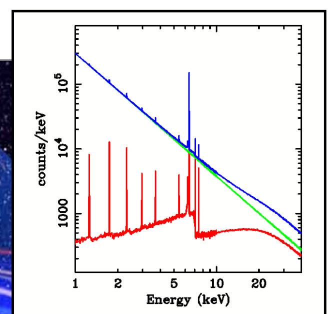


Ramos Almeida & Ricci (2017) Hickox and Alexander 2018

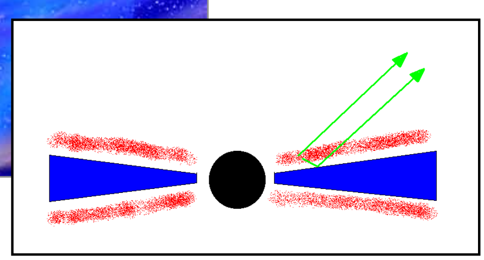
The multi-component X-ray spectrum of a typical RQ-AGN





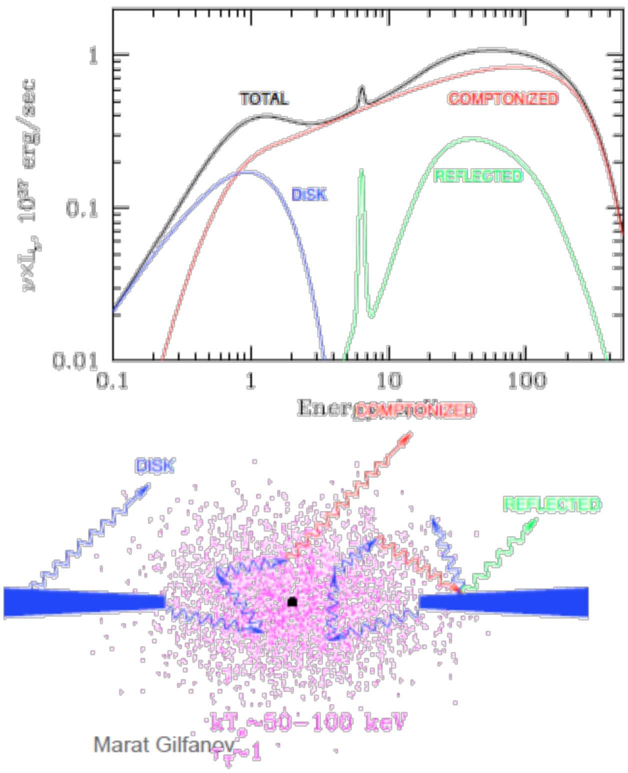


Reynolds (1996)



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

Connection Between Source Geometry and Spectra in an Black hole binary



'Reflection'- refers to reprocessing of the intrinsic x-ray 'power law' by material

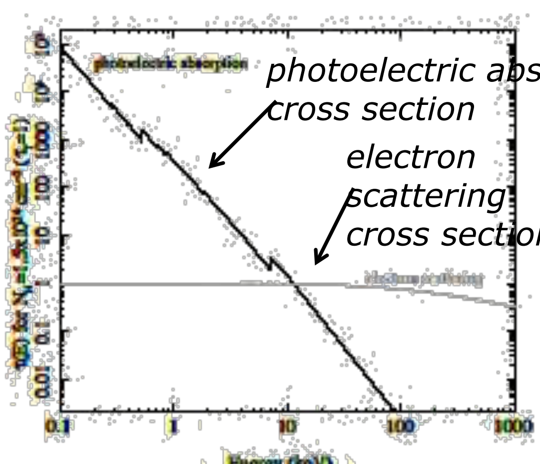
The nature of the reprocessing depends on the column density, ionization state, chemical composition, velocity structure and geometry of the 'reprocessor'

Main processes are Compton scattering, flourescent emission, photoelectric absorption

Marat Gilfanov

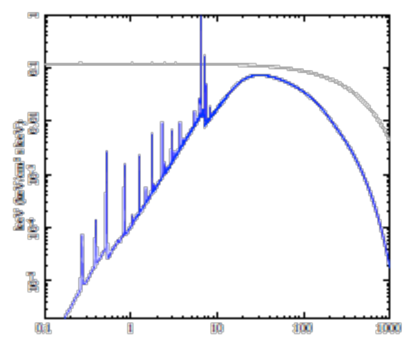
GRAVITAS, Garching, 26/10/2010

'Reflection'- Reprocessing of Photons in the Disk



photoelectric absorption cross section

electron scattering cross section



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.

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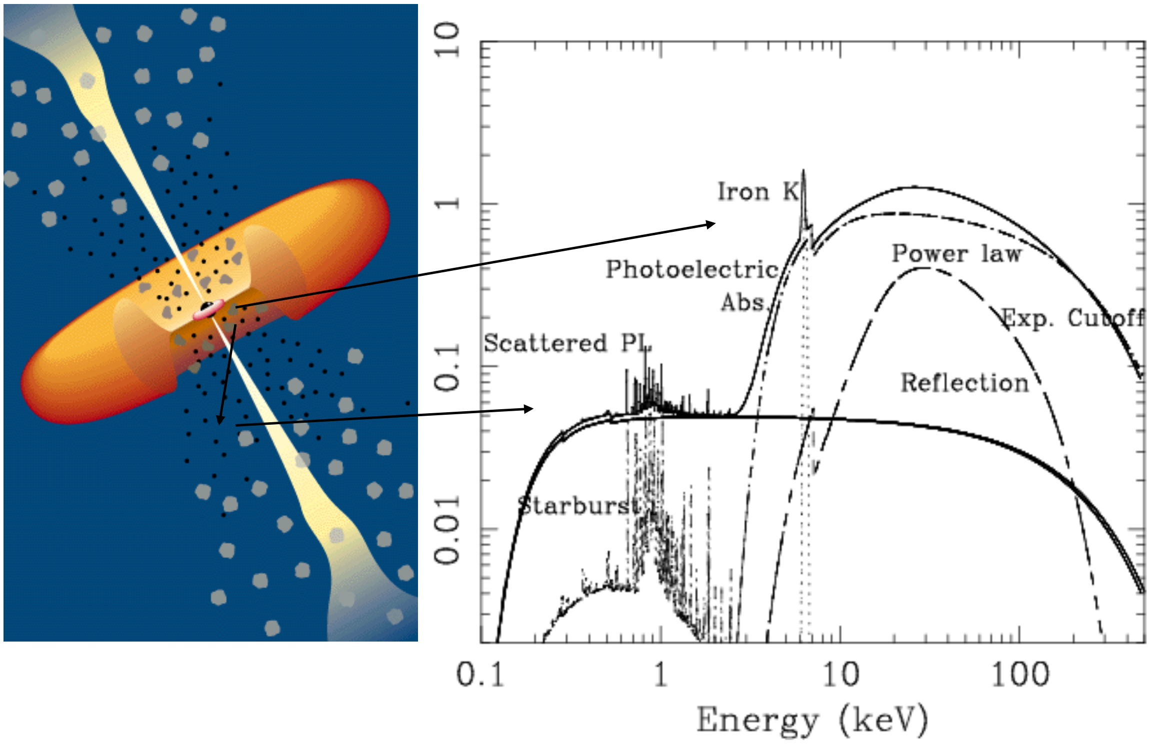
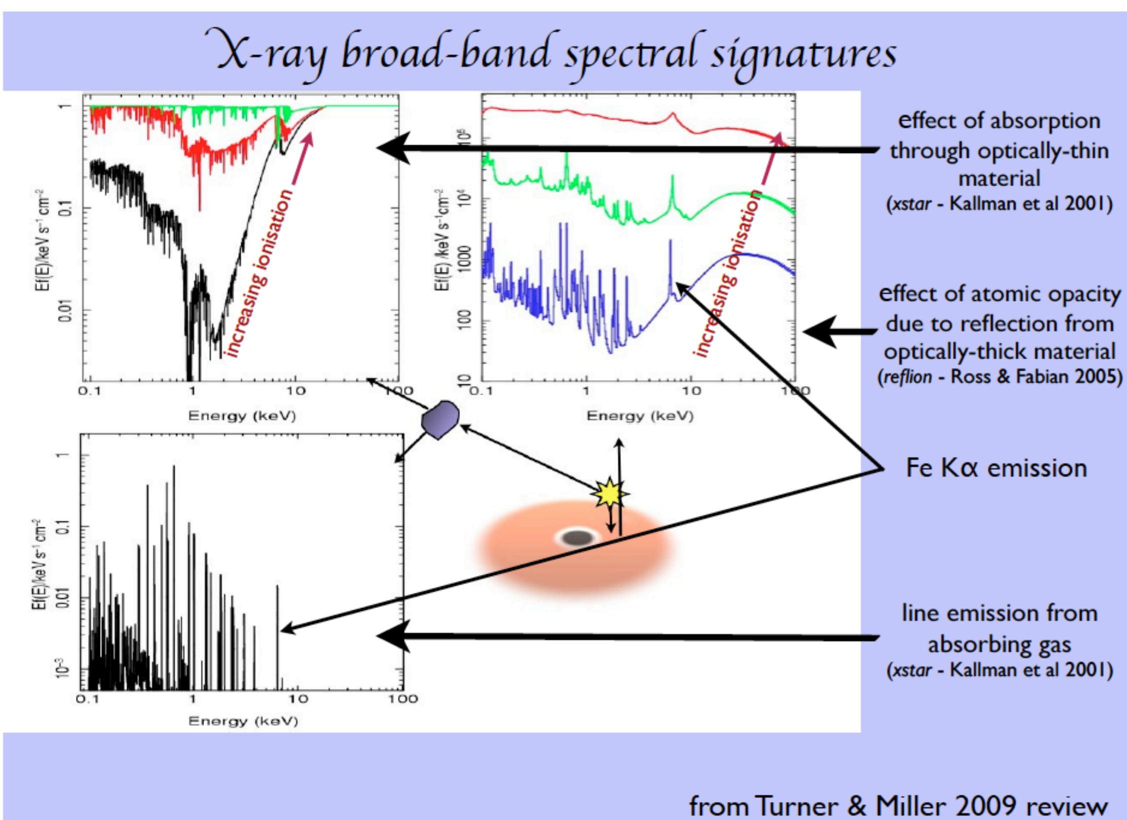
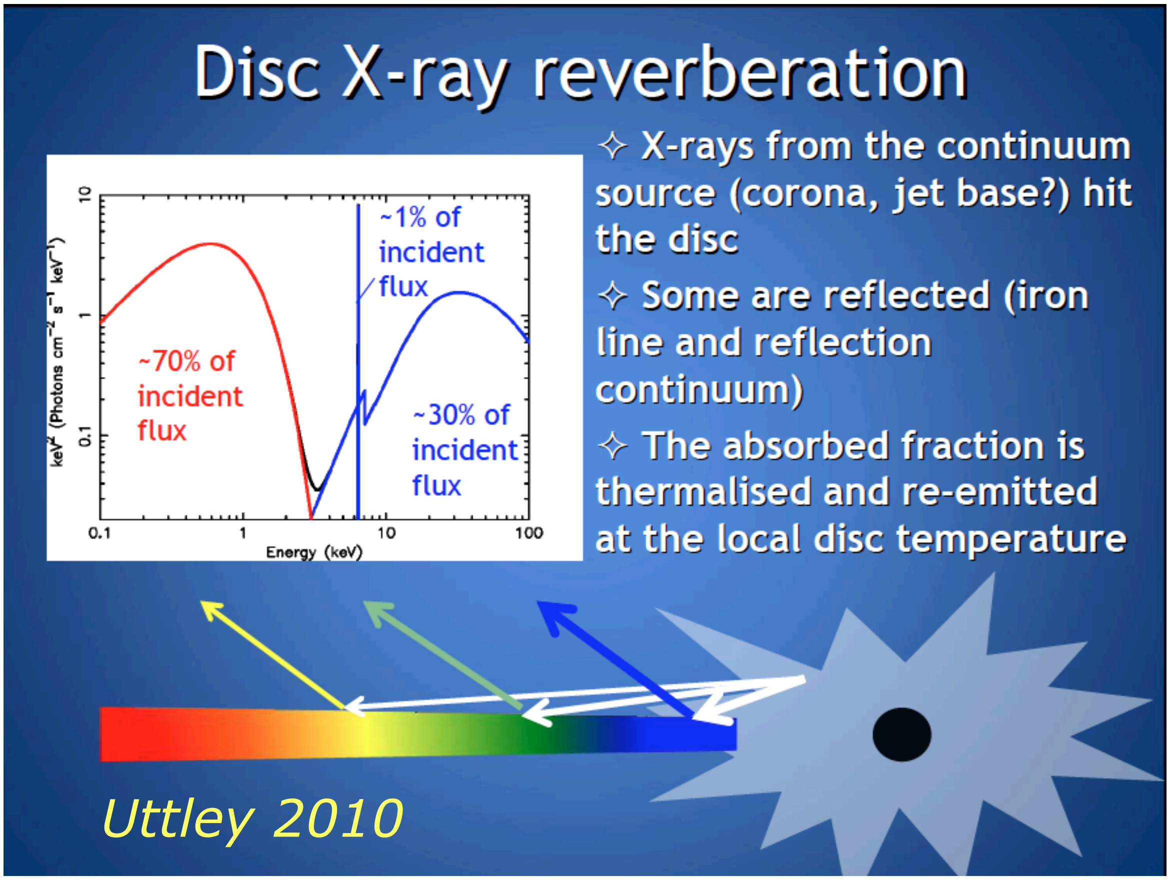
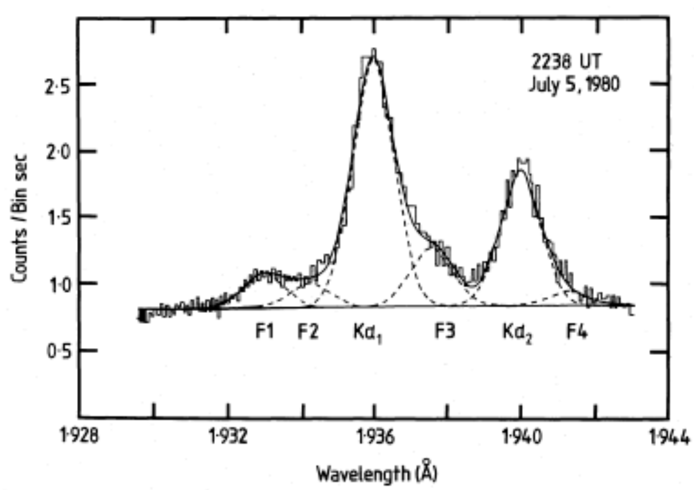
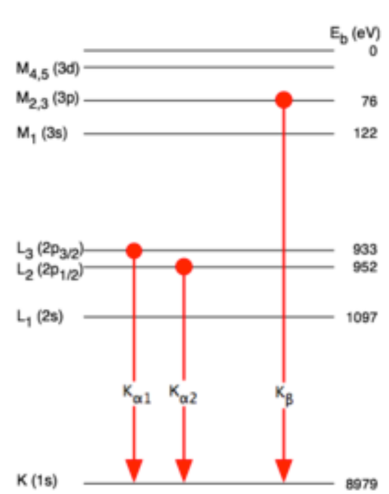

Iron K
Photoelectric Abs.
Power law
Exp. Cutoff
Scattered PL
Reflection
Starburst
0.01
0.1
1
10
0.1
1
10
100
Energy (keV)


X-ray broad-band spectral signatures
effect of absorption through optically-thin material
(xstar - Kallman et al 2001)
effect of atomic opacity due to reflection from optically-thick material
(reflion - Ross & Fabian 2005)
Fe Kα emission
line emission from absorbing gas
(xstar - Kallman et al 2001)
increasing ionisation
increasing ionisation
Ef(E)/keV s⁻¹ cm⁻²
Energy (keV)
from Turner & Miller 2009 review



Iron Kα fluorescence from the Sun





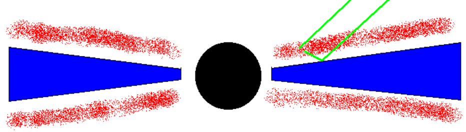
energy levels for Cu

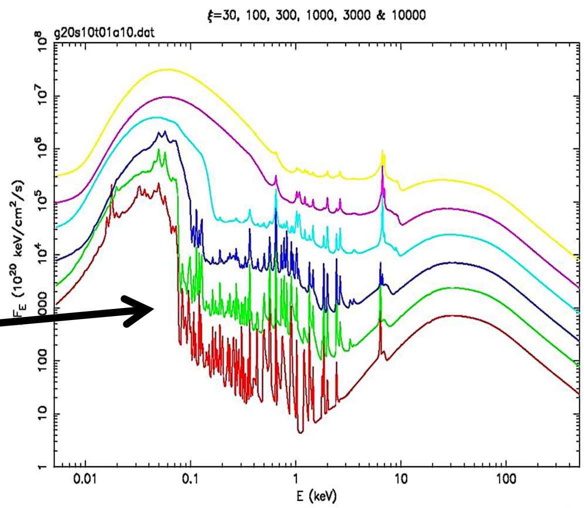
Parmar et al. (1984)
Solar Maximum Mission
(Bent Crystal Spectrometer)

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

A dominant component of "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

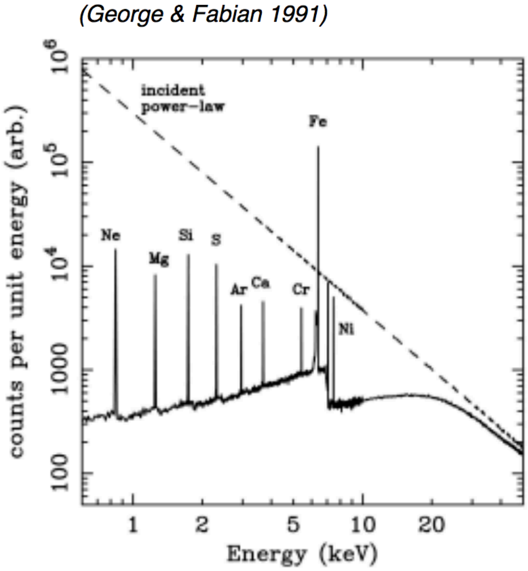




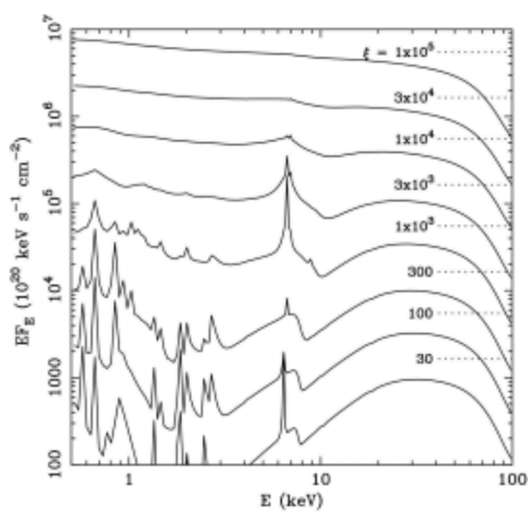
Reflection from material of different ionization state

Models of Disk Reprocessing

(George & Fabian 1991)



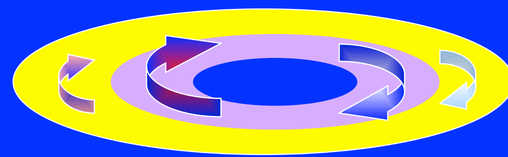
(Ross, Fabian, Young 1999)

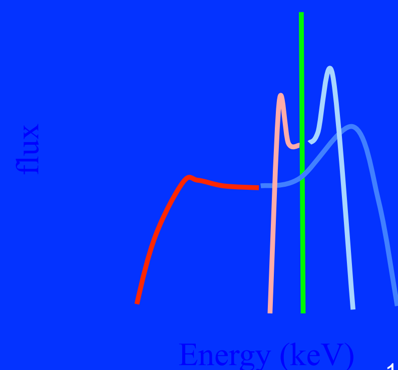


Varying the input radiation field

Relativistic effects- C. Done

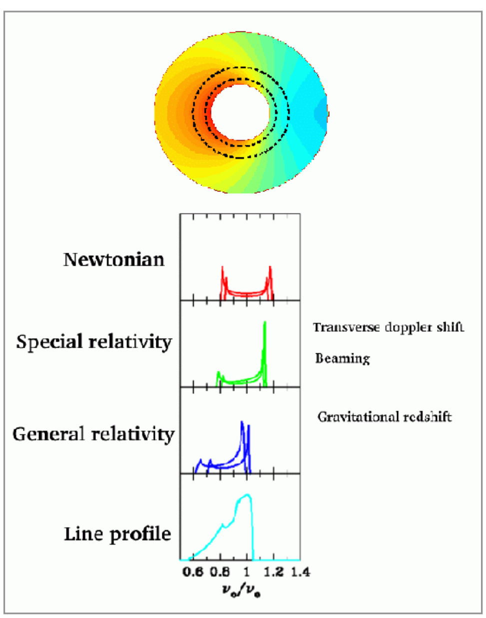
- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe Kα line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of Rin – so spin if ISO (Laor 1991)
- Models predict increasing width as go from low/hard to high/soft states



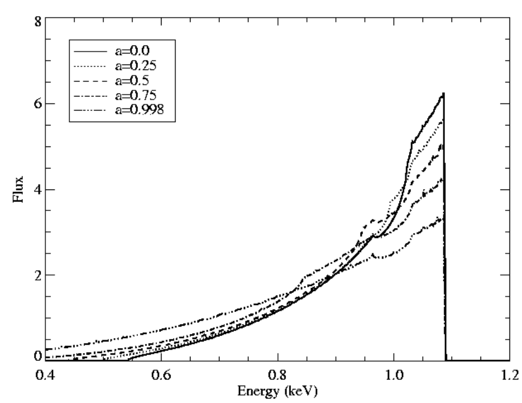


Fabian et al. 1989

Relativistic effects imprint characteristic profile on the emission line…



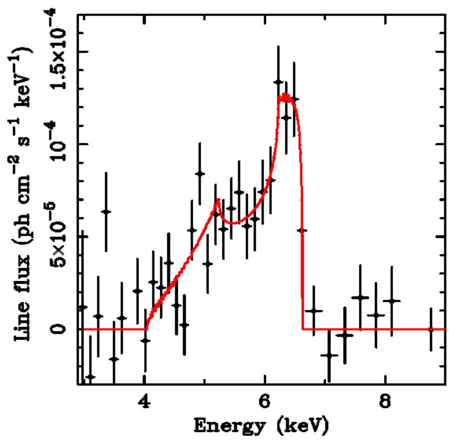
Andy Young



Theoretical line profiles [Laura Brenneman]

Observations of relativistic emission lines

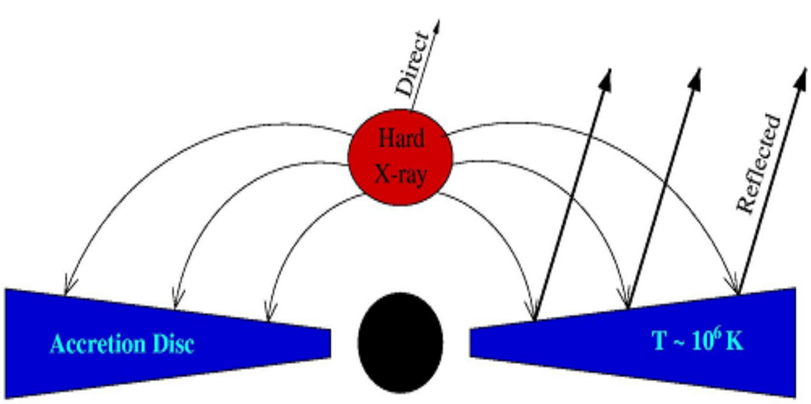
- First seen in 1994 with ASCA observatory
- 5 day observation of Seyfert-1 galaxy MCG-6-30-15
- Needed long observation to collect enough photons to form detailed spectrum



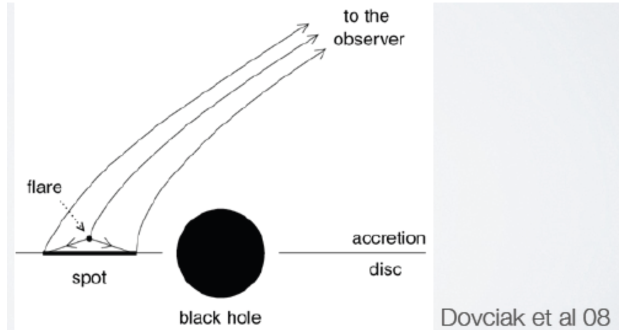
Power-law continuum subtracted
ASCA: Tanaka et al. (1995)

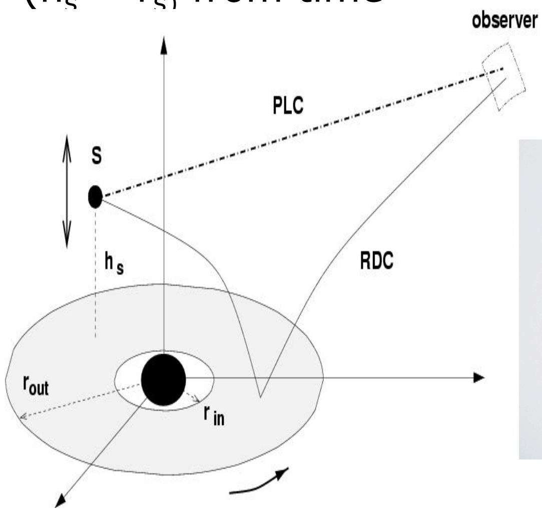
Relativistic Effects

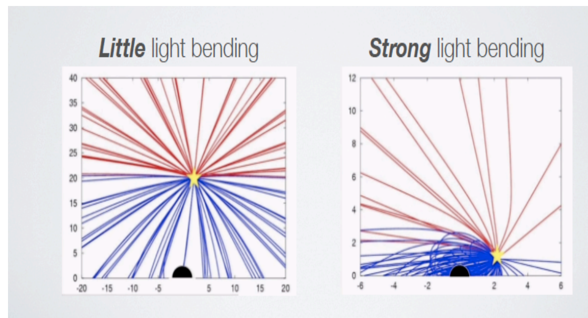
- Light rays are bent by strong gravity- making the geometry rather complicated
- Do not know 'where' x-ray source is - try to use data to figure it out – e.g. height above disk



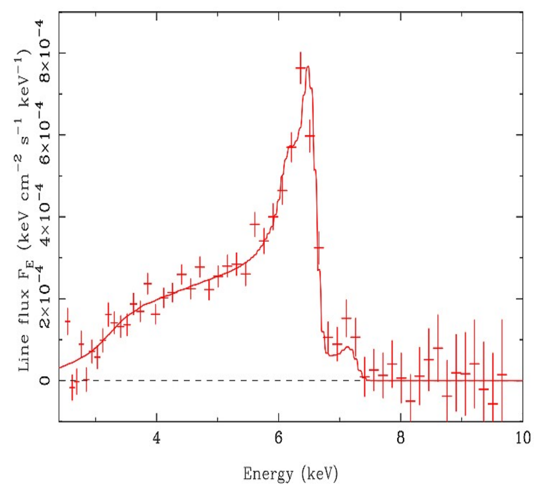
- Possible strong effect of light bending.
- if we only knew where the x-rays come from ($h_s \sim r_s$) from time





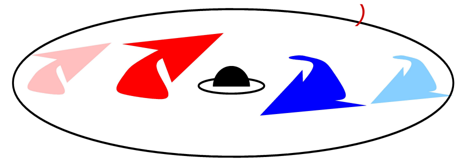


- Modern XMM-Newton observations
- Confirm relativistic line with extreme redshifts
- If no line emission from within ISCO, need to invoke spinning black hole to get strong enough redshifting
- Black holes must double their mass to change their spin. (Bardeen 70, Thorne 74)
- •Impossible in stellar binaries. Stellar-mass black hole spins are set in the creation event

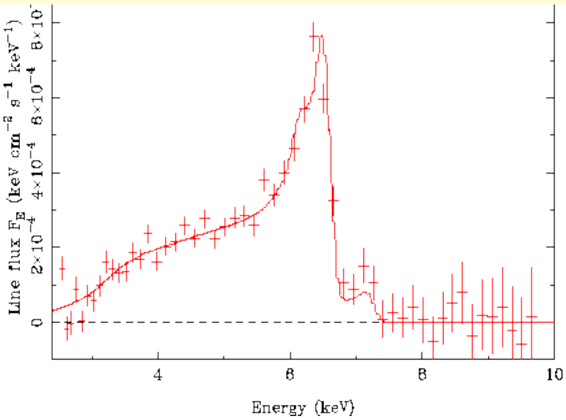


Power-law continuum subtracted
XMM: Fabian et al. (2002)

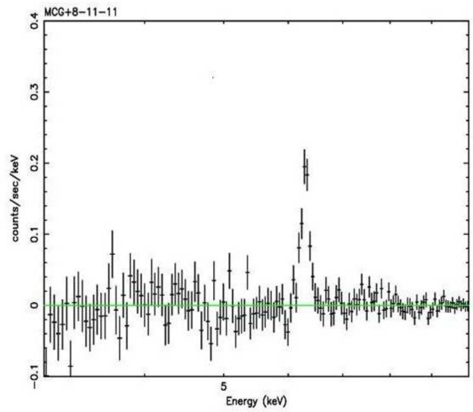
Relativistic lines



Relativistic lines are often observed, but not always
Line sensitive to emissivity profile, inclination, R(in), spin



MCG-6-30-15
(Fabian et al.



MCG-8-11-11
(Matt et al. 2006)

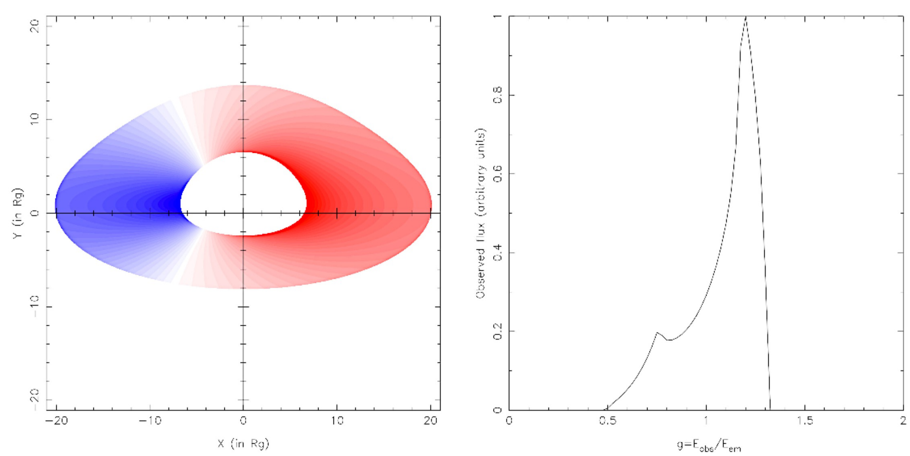
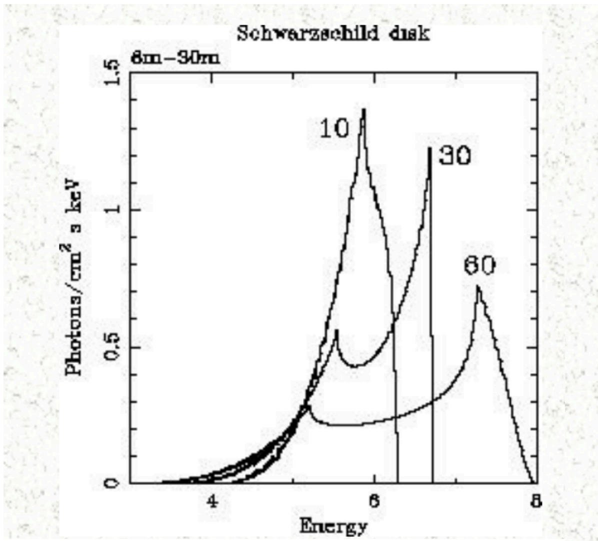
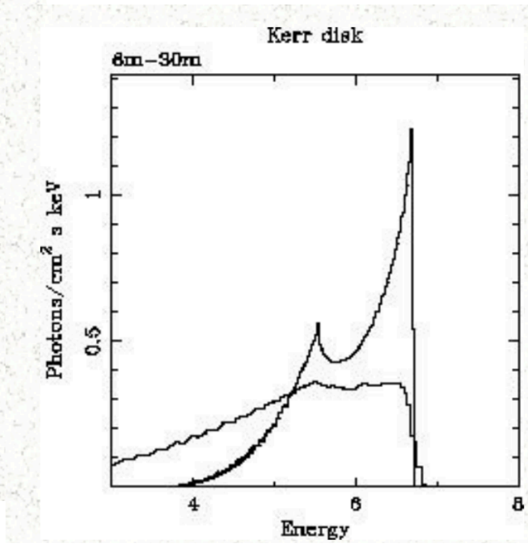


Fig. 3. The illustration of simulated an acretion disc (left) and the corresponding Fe Kα line profile (right). Parameters for simulation are $q = 2.5$, $i = 65$, $R_{in} = r_{ms}$, $R_{out} = 20$, $a = 0.05$, $nres = 5000$ and $nbin = 80$.



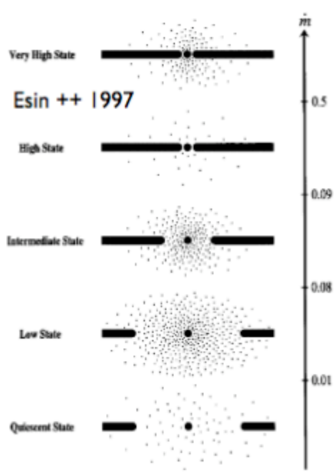


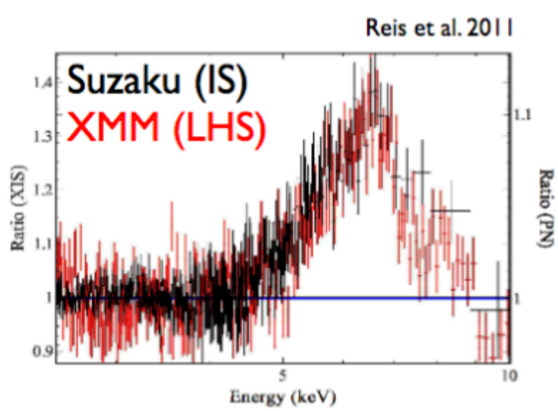
Effect of inclination
Schwarzschild
6 r_g (i.e. the radius of marginal stability) to 30 r_g.
inclination 10°, 30° and 60°.

Kerr vs Schwarzschild

BLACK HOLE BINARY

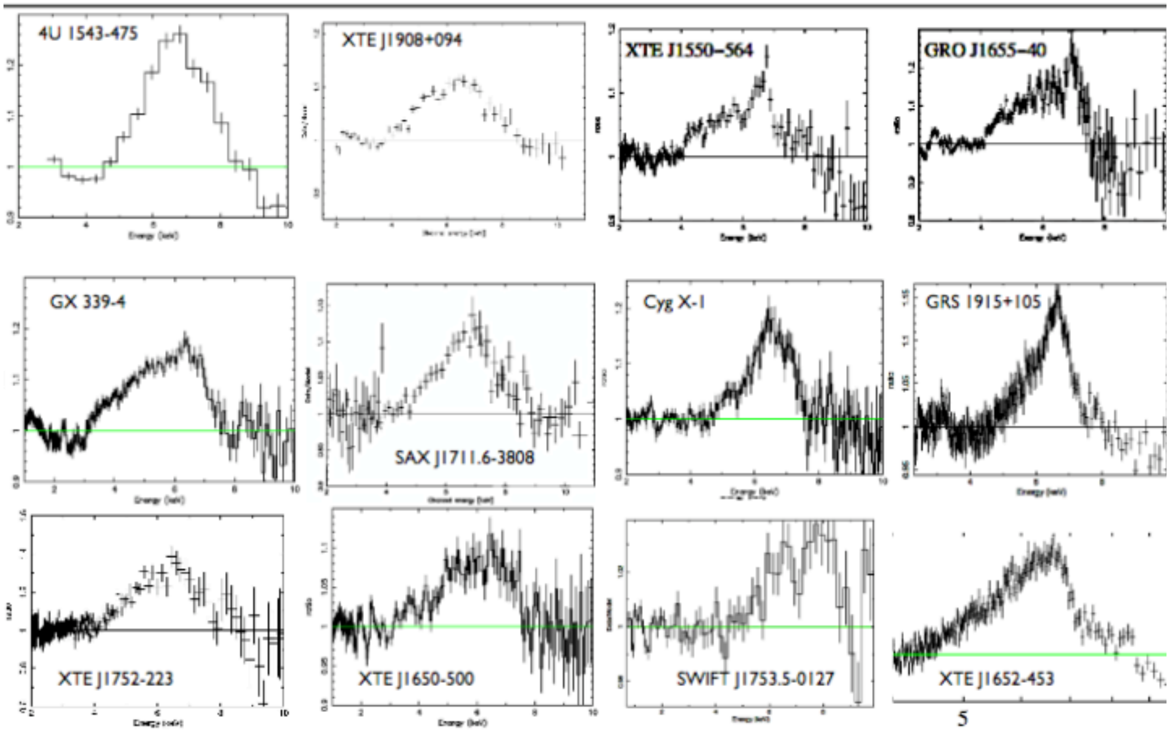
Spin in XTE J1752-223





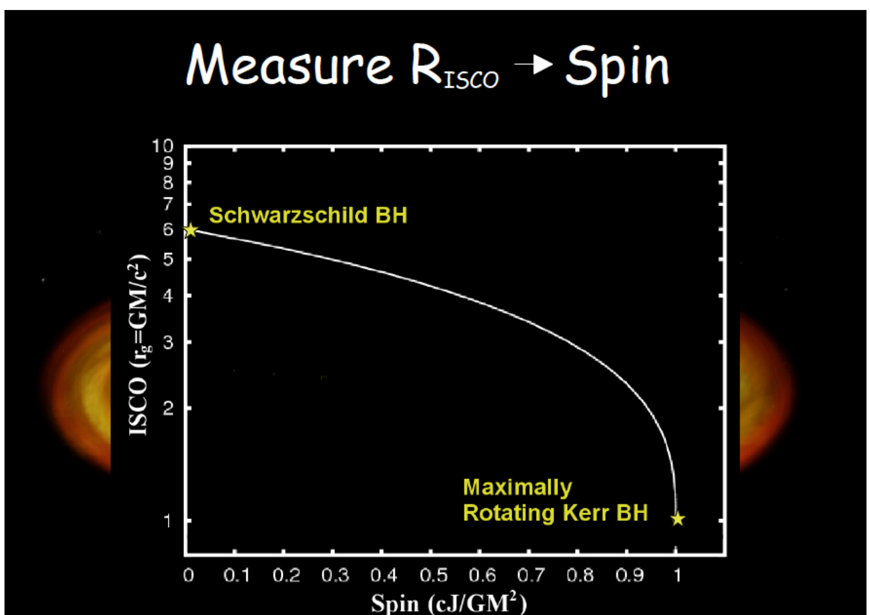
Intermediate State (Suzaku), low/hard state (XMM).
Blurred reflection fits: a/M = 0.52 +/- 0.11.
Strong implications for accretion flow models.

Black Hole Binaries

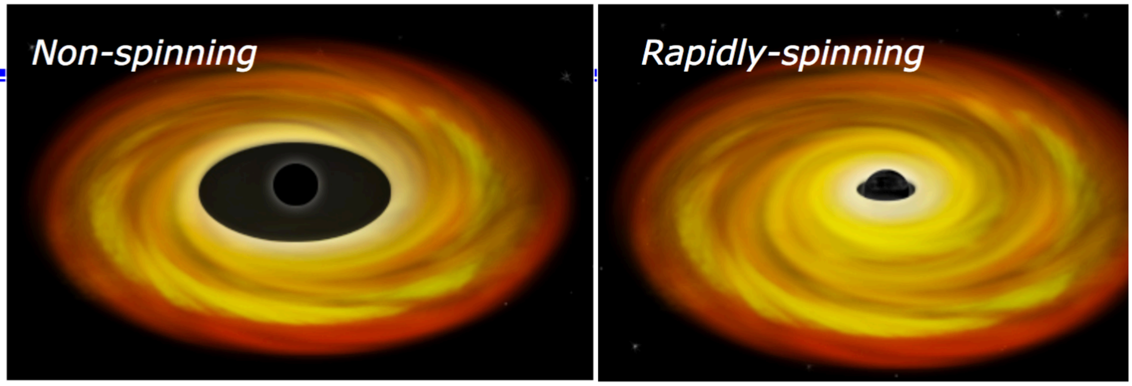


Reminder- Radius of ISCO depends on Spin

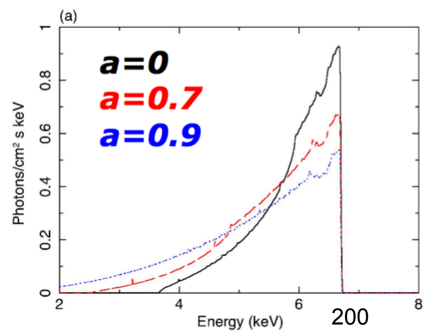
- Spin- is measured in units of c/GM2



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

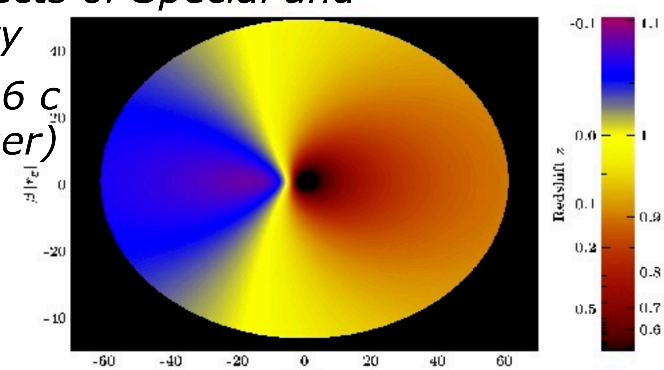


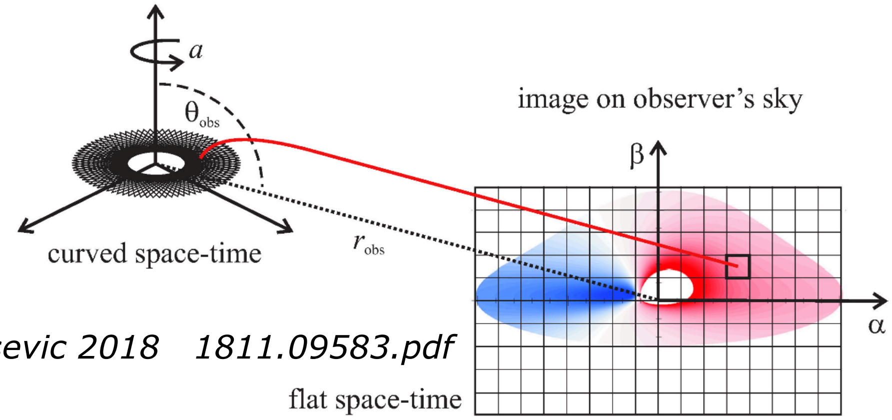
a=-1 -> r=9GM/c²
a=0 -> r=6GM/c²
a=1 -> r=GM/c²



Combing the Effects of Special and General Relativity

Notice the full range of 0.6 c in the velocities (T. Dauser)





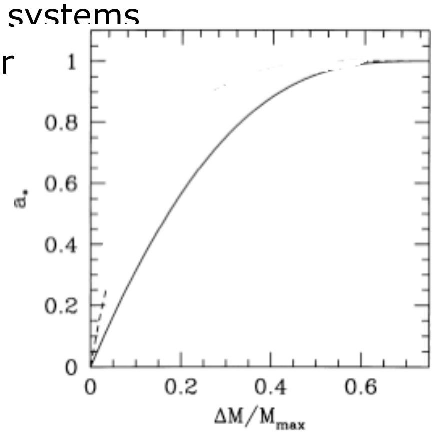
Milosevic 2018 1811.09583.pdf

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 (see graph- spin vs accreted mass)
- 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 compar
- **Spin is natal**

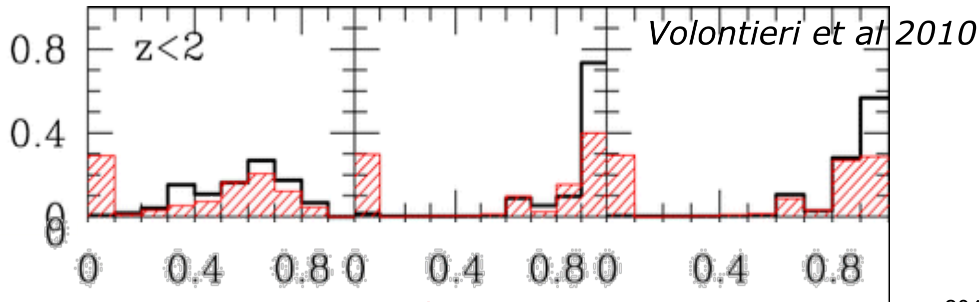


Spin

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

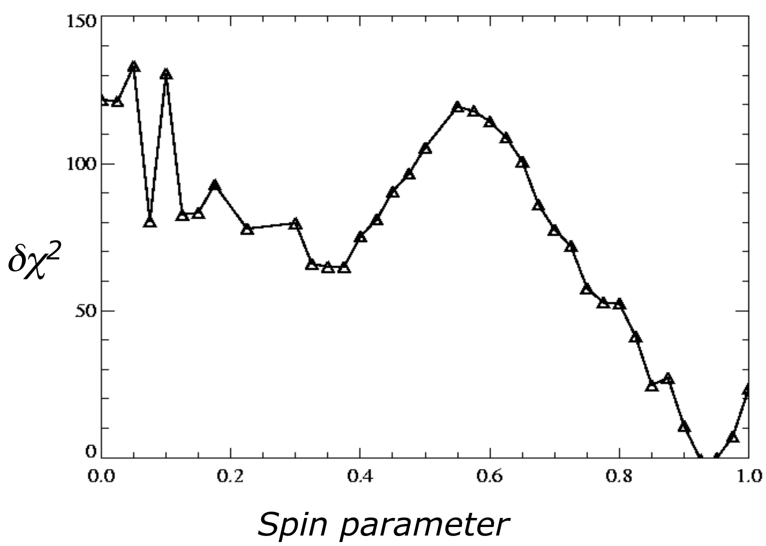
- Spin can be due to accretion
- Requires 'organized' accretion of angular momemtum

Alternatively spin could be due to **mergers** of black holes (Gravitational waves)



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



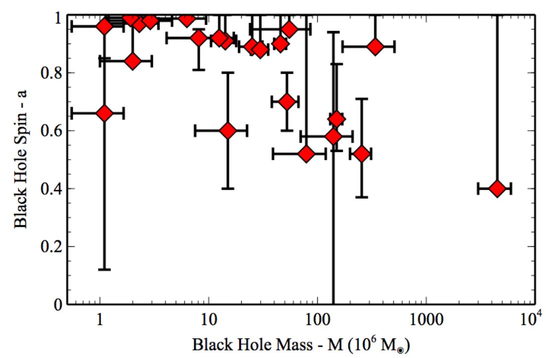
L.Brenneman

Constraints on Spin and Efficiency

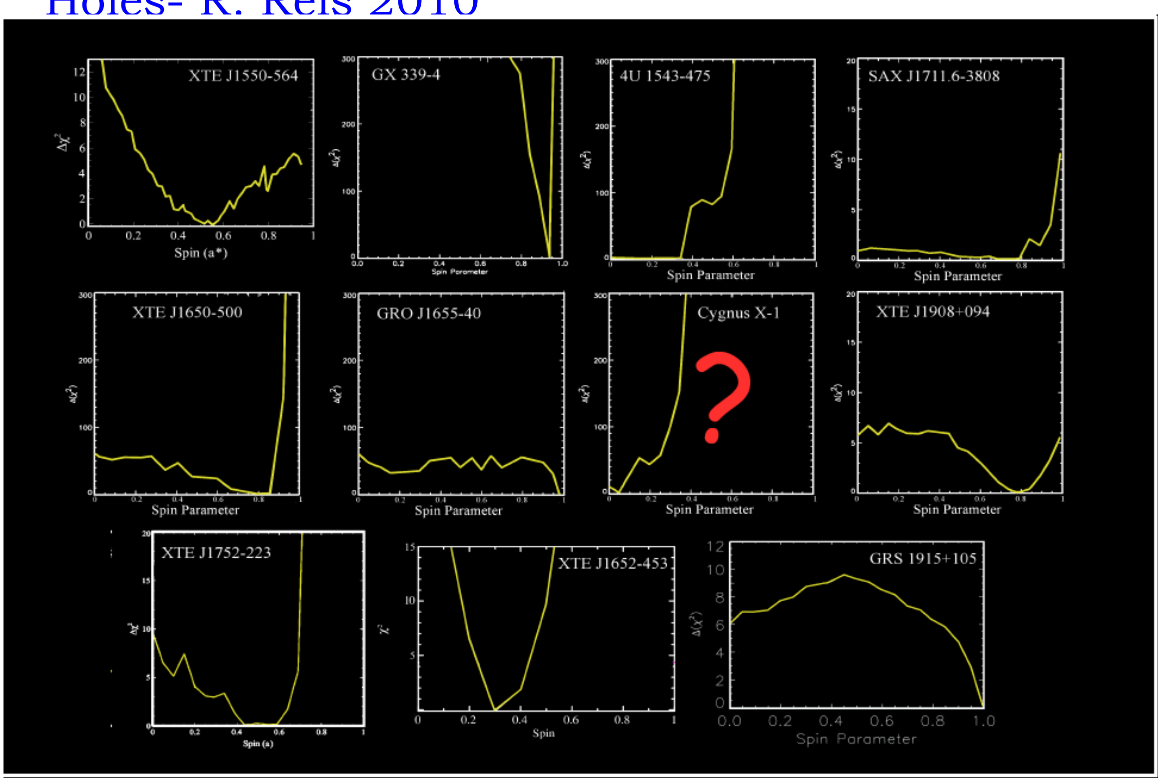
The present estimate of the BH mass density is ~ 3x10^{5}M⊙/Mpc^3 based on the correlation of BH mass and bulge velocity dispersion

- This is consistent with the integrated comoving energy density AGNs, if efficiency is ~10% and thus the average spin does not need to be large

- AGN spins from Fe K line fits tend to be large (Reynolds 2015)



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

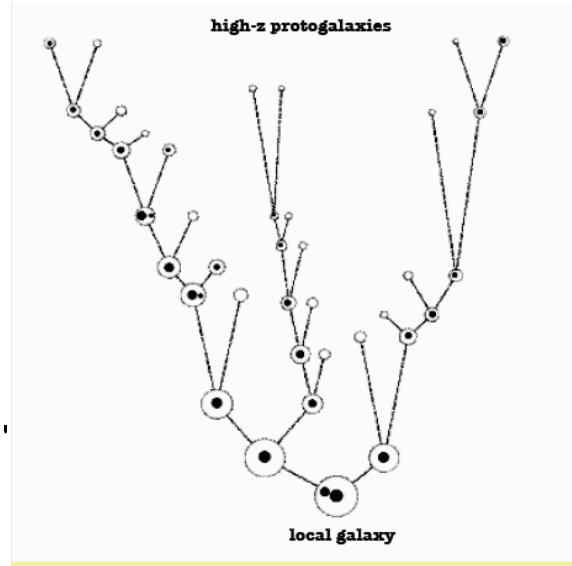


ASSEMBLY AND MERGING HISTORY OF SUPERMASSIVE BLACK HOLES IN HIERARCHICAL MODELS OF GALAXY FORMATION

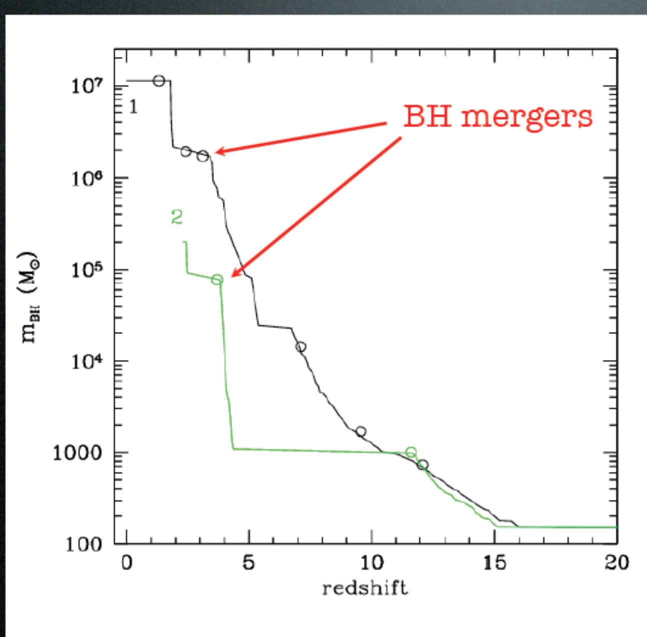
Volonteri, Haardt, & Madau

- Gravitational instability due to the non-uniform matter distribution caused matter to condense until small regions become gravitationally bound

- The first collapsing objects (halos) are small and merge later to form
- more massive systems: BOTTOM-UP/HIERARCHICAL
- Make Assumption that these 'small' objects host BHs and that as the galaxies merge the BHs also do
- When they merge they emit gravitational waves



Folding in mergers and accretion in a hierarchical model... *Volonteri 2008*



✔ MBH mergers are rare events, as they require a merger between two galaxies BOTH with a central MBH

✔ not ALL MBHs experience a merger in their lifetime, only ~40-50%

✔ mass growth dominated by accretion (cfr. Soltan's argument)