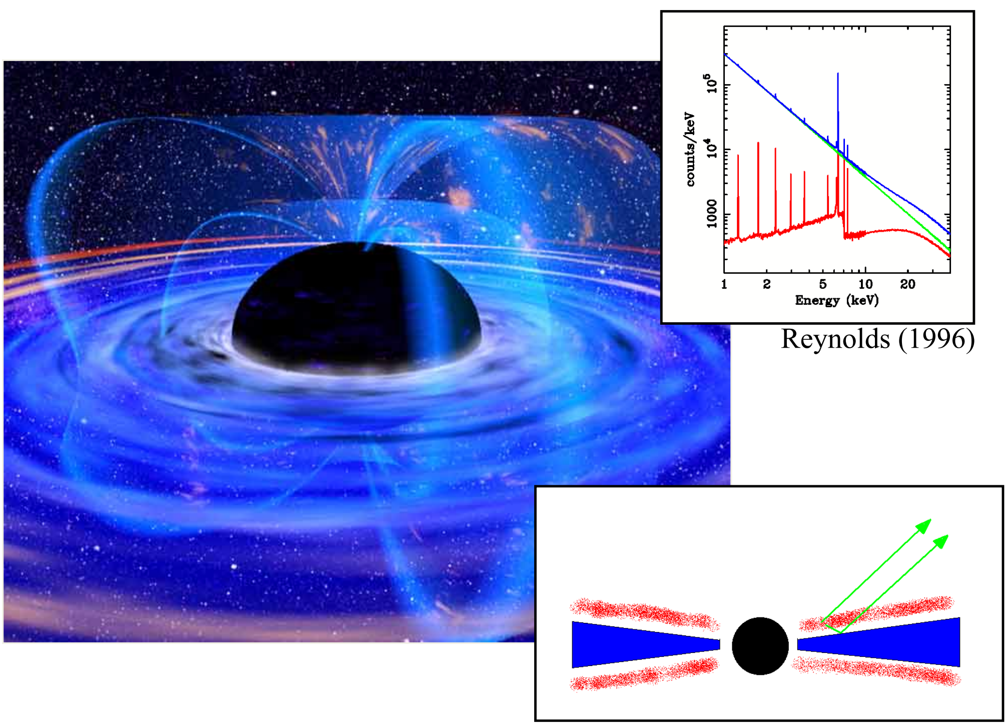
This Lecture

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

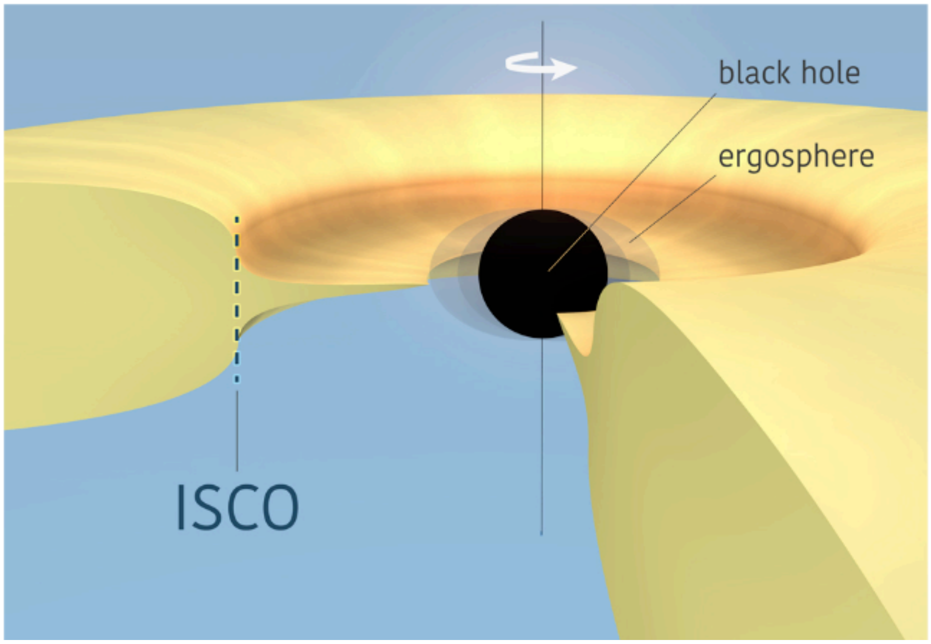
- Spin and its influence



Reynolds (1996)

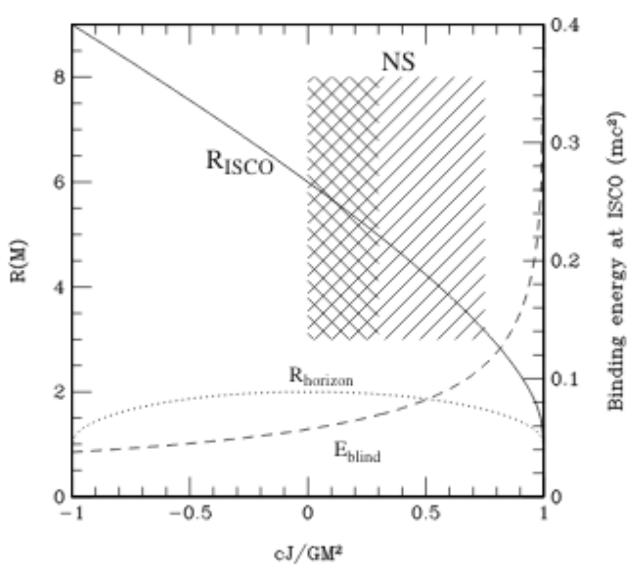
- X-ray “reflection” imprints well-defined features in the spectrum

What We Would Like to Probe



Reynolds 2019)

Dependance of Radius of ISCO on Spin

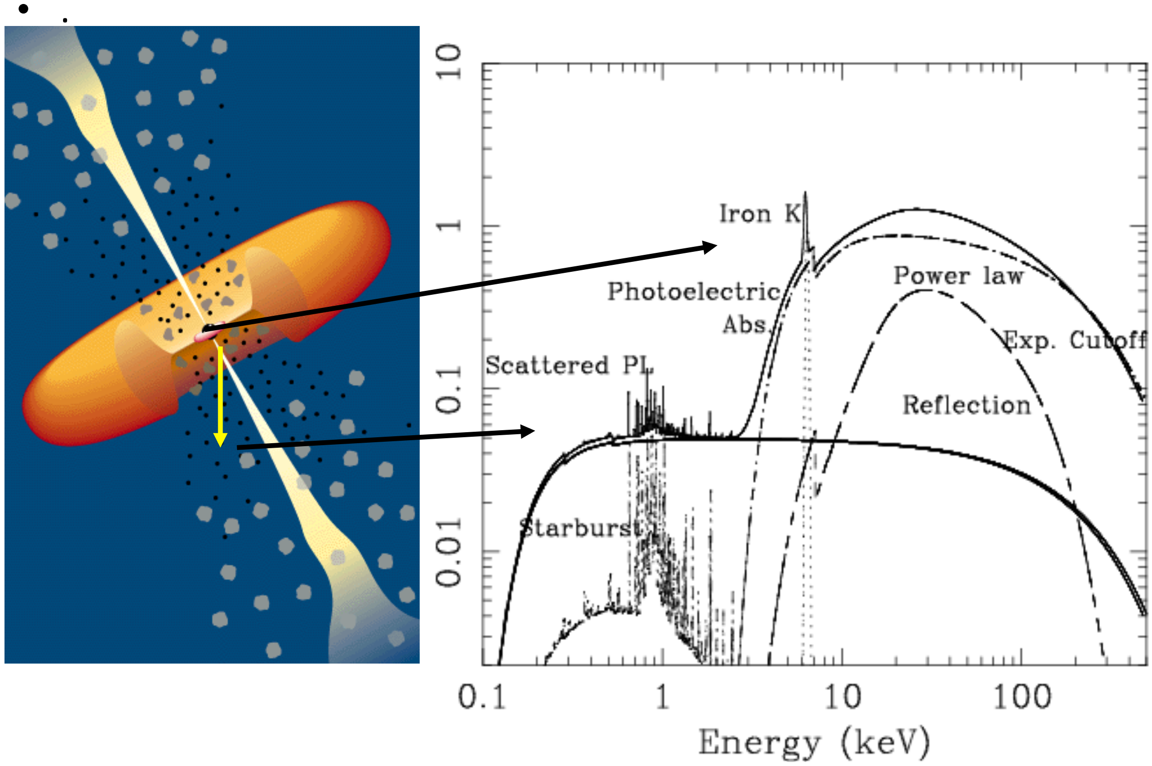


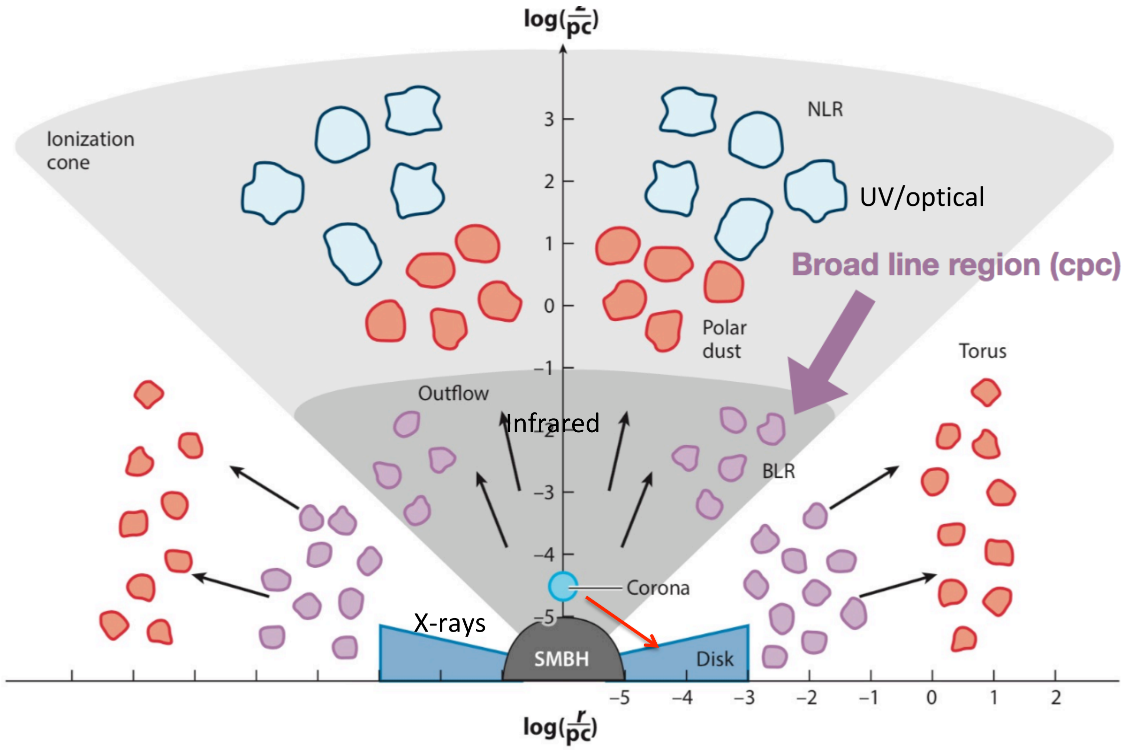
Basic Components of X-ray Spectra

- X-ray spectra display standard components
  - Primary X-ray continuum (Γ~2 powerlaw with cutoff at 50—300 keV) $dN/dE \sim E^{-\Gamma}$ photons/cm2/sec/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)

Relativistic X-ray Lines from the Inner Accretion Disks Around Black Holes J.M. Miller ARA&A 2007 45,441

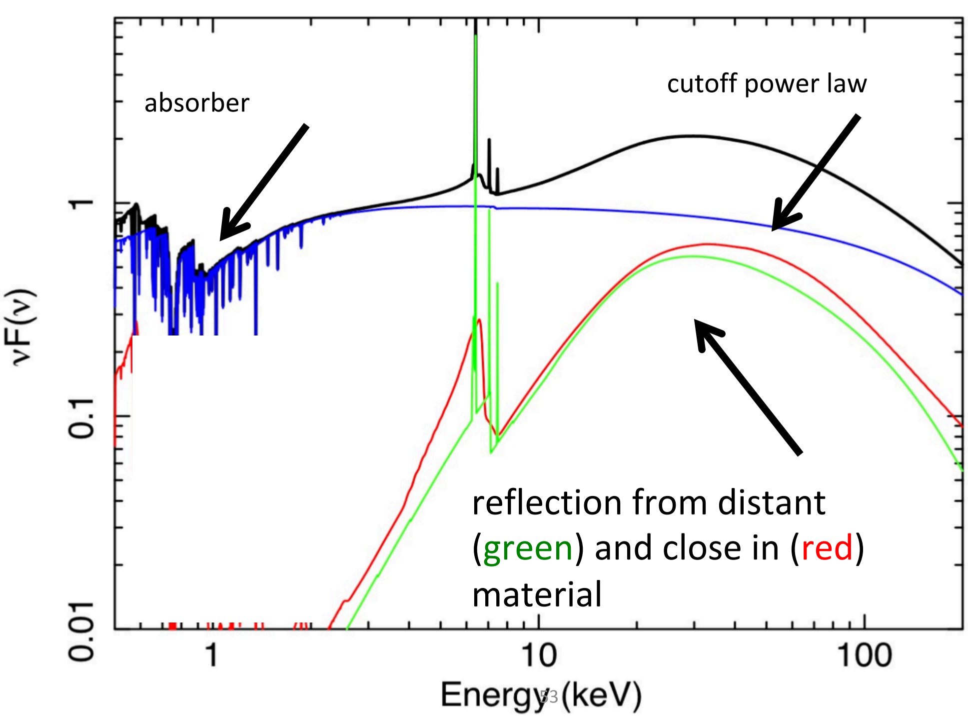
Basic Components of AGN X-ray Spectra



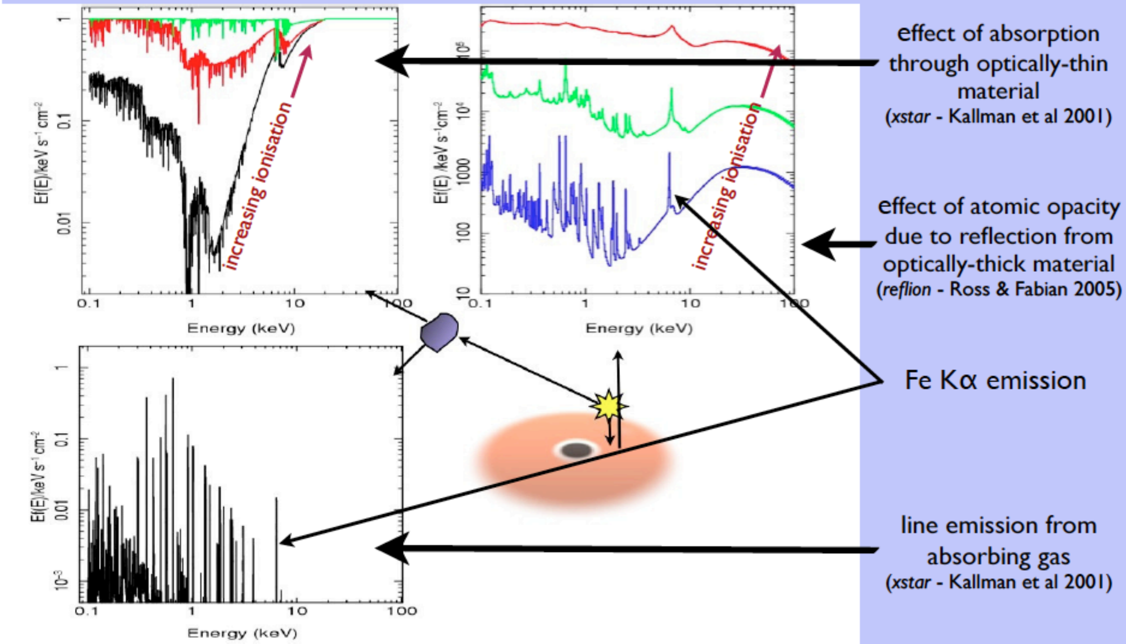


Ramos Almeida & Ricci (2017) Hickox and Alexander 2018

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



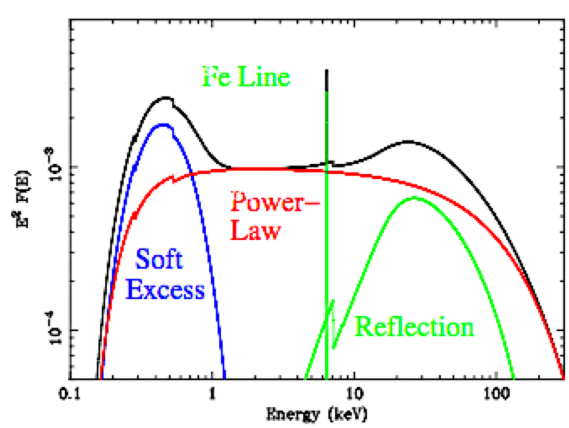
X-ray broad-band spectral signatures



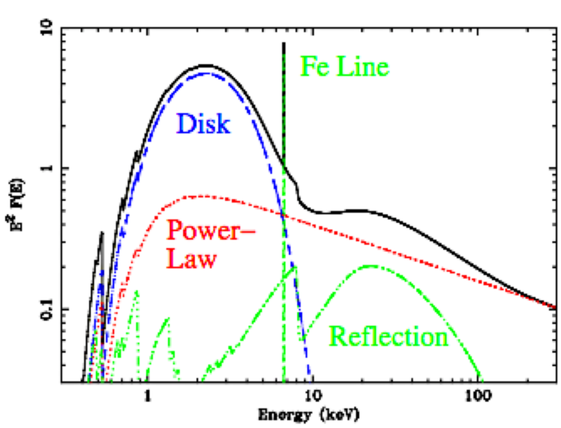
from Turner & Miller 2009 review

Black Hole X-ray Spectra

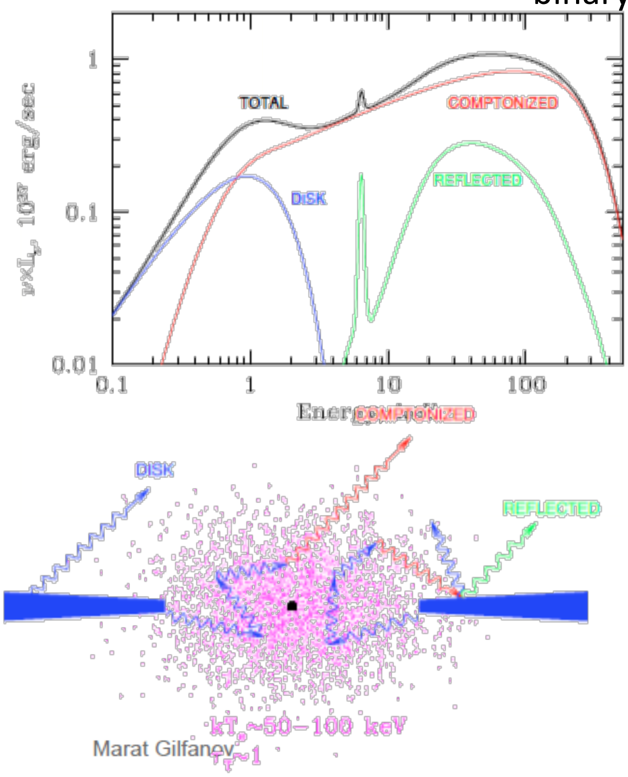
AGN



Stellar Mass Black Hole



Connection Between Source Geometry and Spectra in an Black hole binary



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

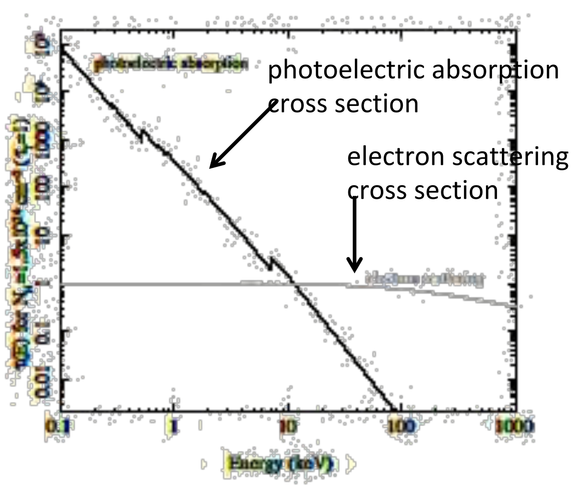
The nature of the reprocessing depends on the column density, ionization state, chemical composition, velocity structure and geometry of the 'reprocessor'

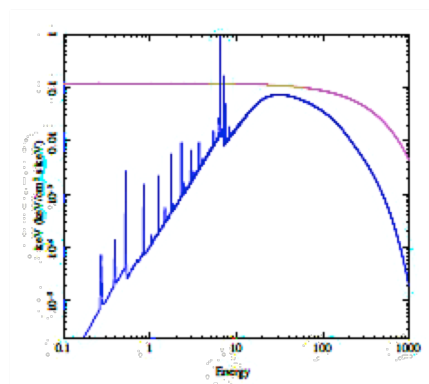
Main processes are Compton scattering, flourescent emission, photoelectric absorption

Marat Gilfanov

GRAVITAS, Garching, 26/10/2010

'Reflection'- Reprocessing of Photons in the Disk





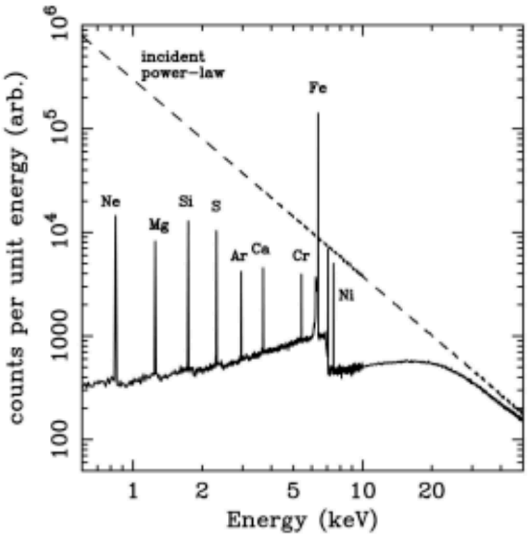
Emission due to the two processes from a cold slab of thickness $\tau_{Thompson}=1$

The larger cross section at low energies of photoelectric absorption means that low E photons <u>are absorbed not scattered</u> and <u>some are re-emitted as lines via fluorescence.</u>

Compton *scattering* reduces the energy of the high energy photons. **The combination produces a characteristic peak in the spectrum.**

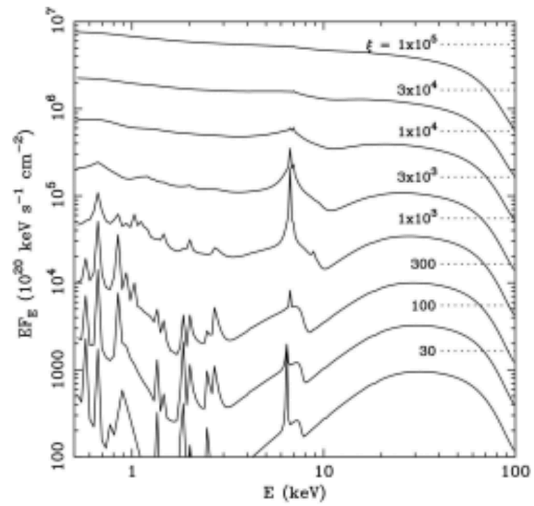
"Cold" Reprocessor

(George & Fabian 1991)



Ionized Reprocessors

(Ross, Fabian, Young 1999)

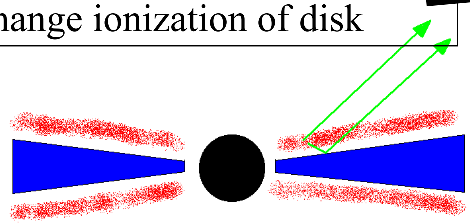


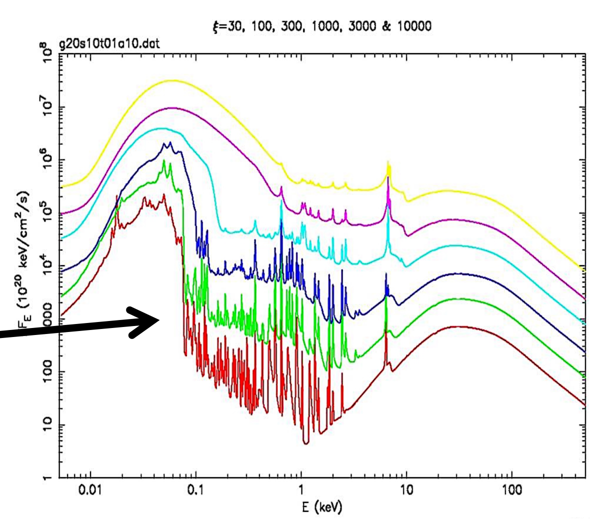
Varying the input radiation field

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

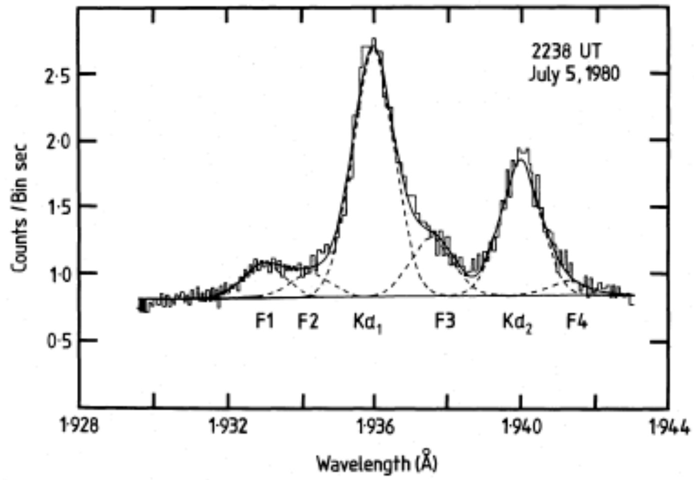
Different amounts of flux can change ionization of disk

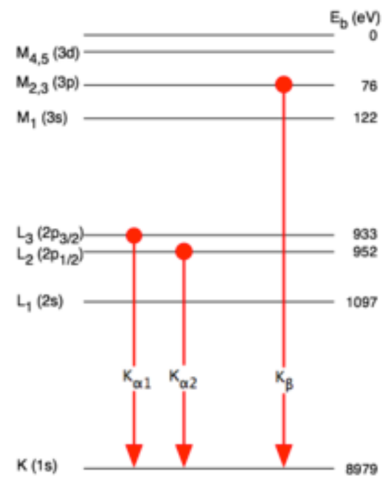




Reflection from material of different ionization state

Iron Kα fluorescence from the Sun





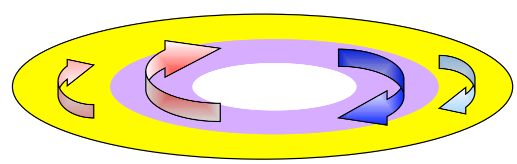
energy levels for Cu

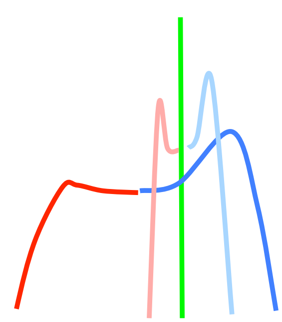
Parmar et al. (1984)
Solar Maximum Mission
(Bent Crystal Spectrometer)

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

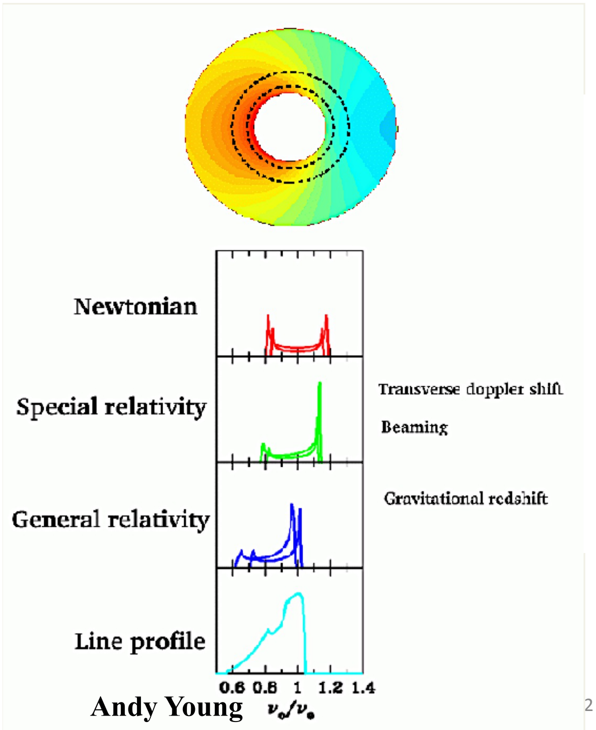
Relativistic effects- C. Done

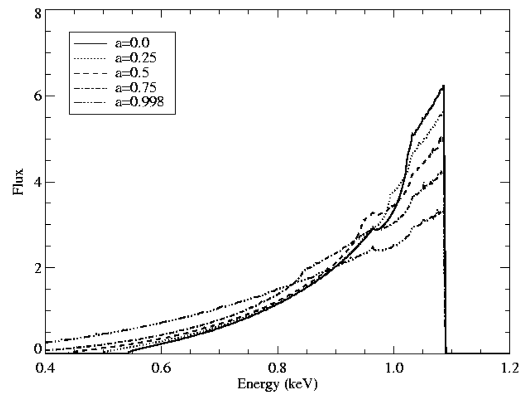
- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe Kα line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of R_{in} – so spin if ISO (Laor 1991)



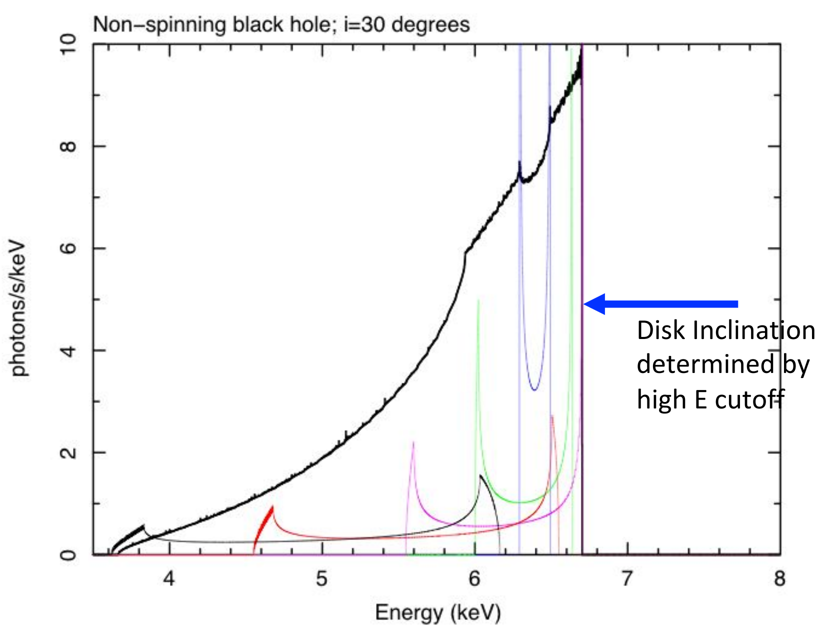


Relativistic effects imprint characteristic profile on the emission line…





Theoretical line profiles
[Laura Brenneman]

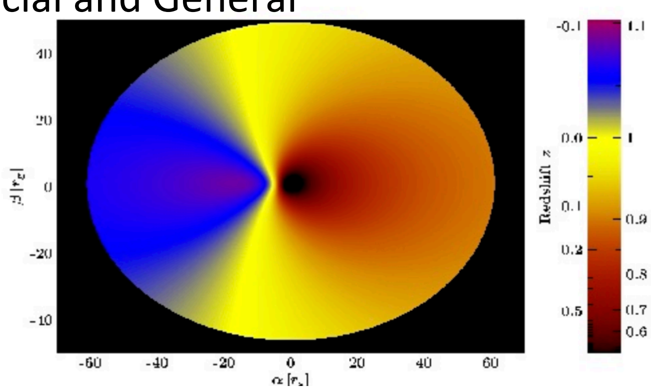


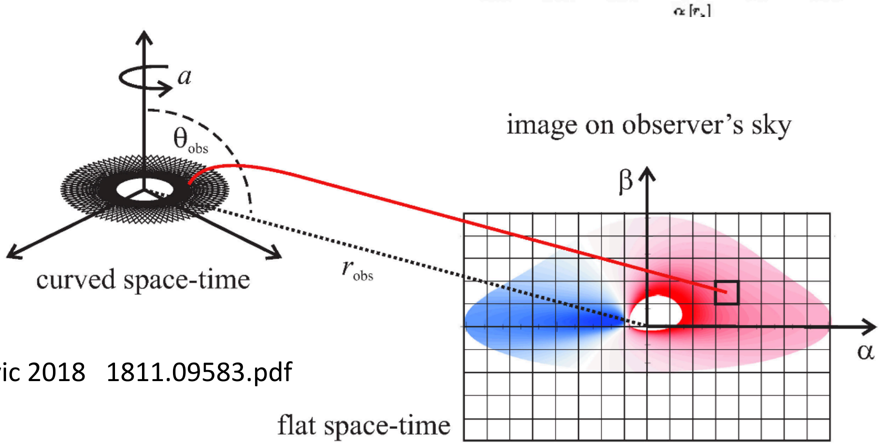
Fe K Line Shape

- Line profiles affected by
  - Doppler shift
  - Gravitational redshift
  - Other “astrophysics”… Compton broadening, blending of lines etc…
- Principal parameters in fitting data
  - Line energy
  - Disk inclination
  - Inner & Outer radii
  - Run of emissivity between inner and outer radii- e.g. where in the disk the line comes from

Combing the Effects of Special and General Relativity

Notice the full range of 0.6 c
 in the velocities- color bar is redshift
 (T. Dauser)





Milosevic 2018   1811.09583.pdf

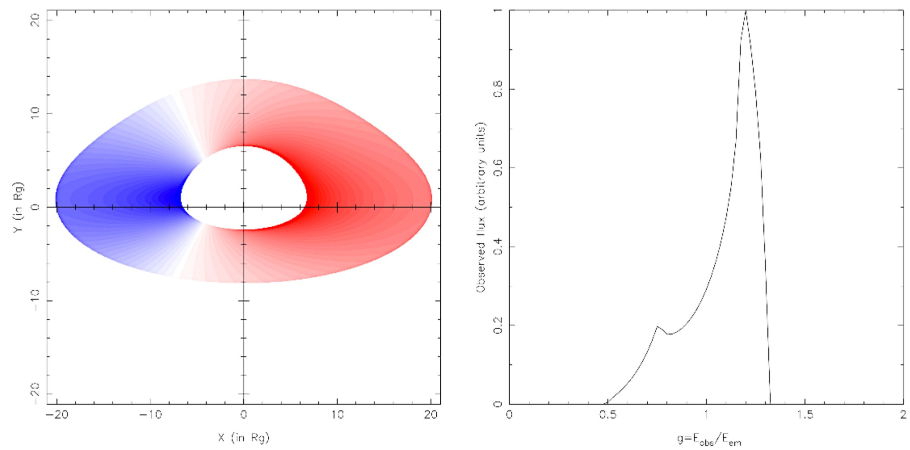
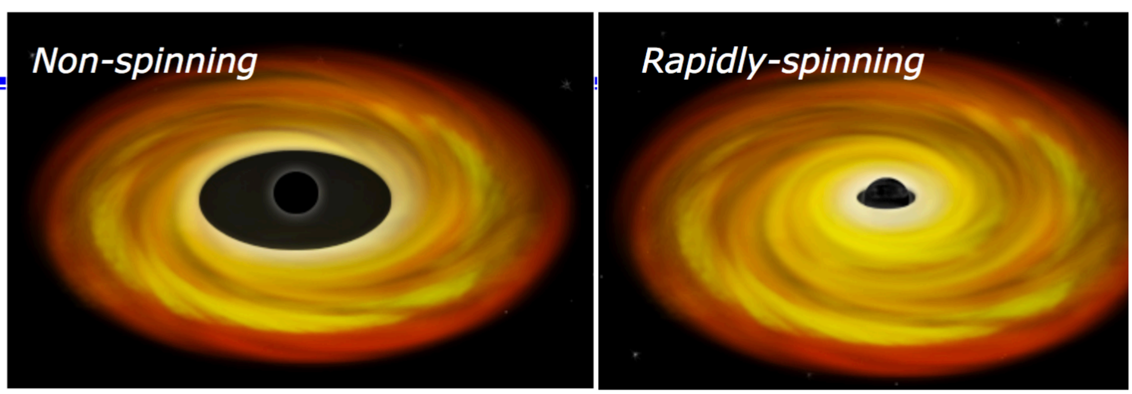
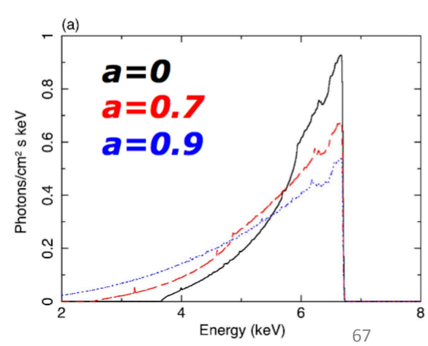


Fig. 3. The illustration of simulated an acretion disc (left) and the corresponding Fe Kα line profile (right). Parameters for simulation are $q = 2.5$, $i = 65$, $R_{in} = r_{ms}$, $R_{out} = 20$, $a = 0.05$, $nres = 5000$ and $nbin = 80$.

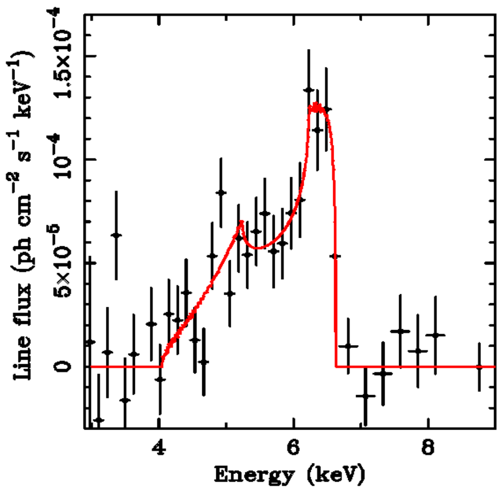


a=-1 -> r=9GM/c²
a=0 -> r=6GM/c²
a=1 -> r=GM/c²



Observations of relativistic emission lines

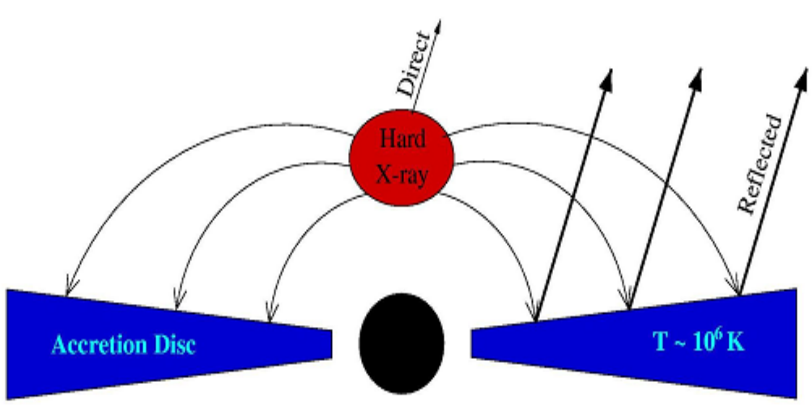
- First seen in 1994 with ASCA observatory
- 5 day observation of Seyfert-1 galaxy MCG-6-30-15
- Needed long observation to collect enough photons to form detailed spectrum

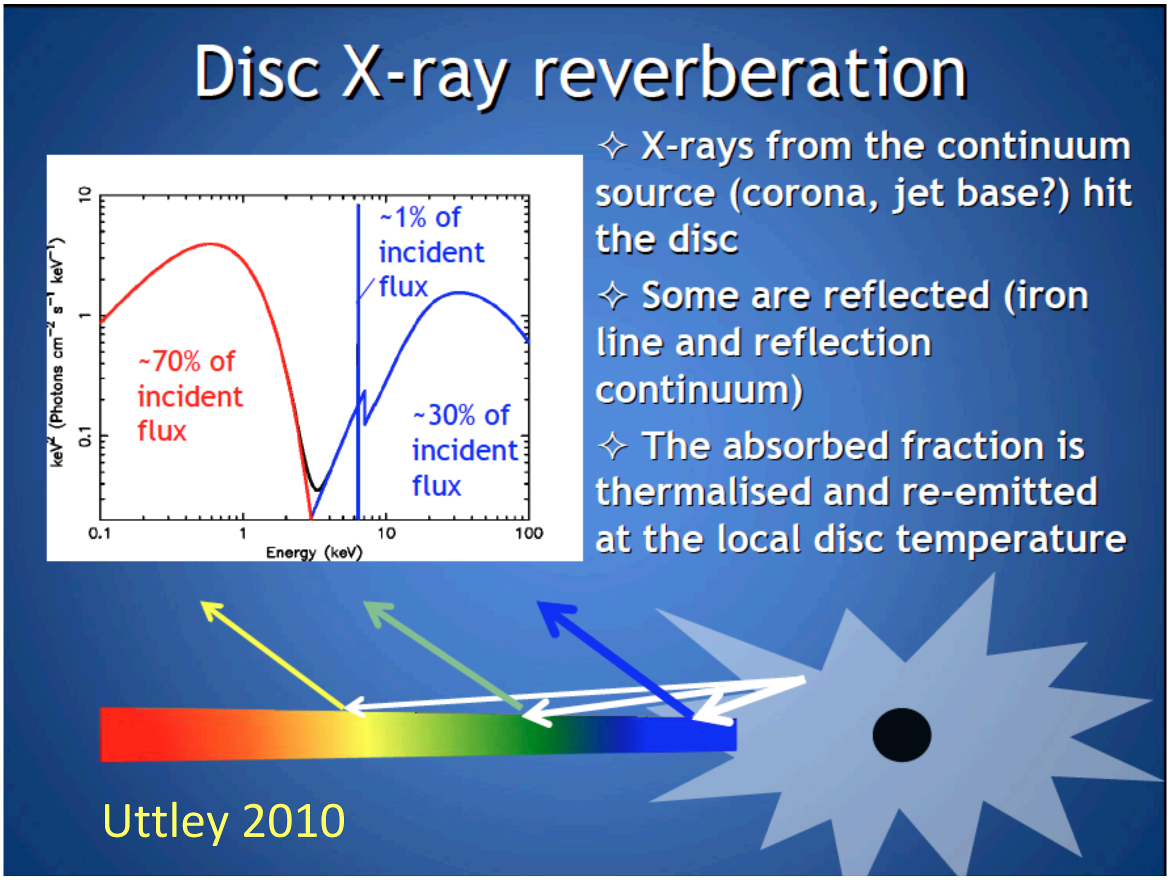


Power-law continuum subtracted
ASCA: Tanaka et al. (1995)

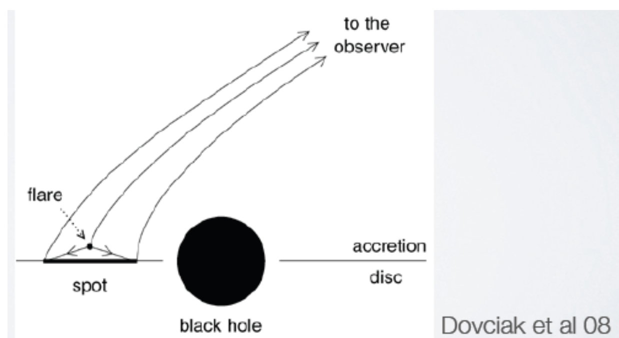
Relativistic Effects

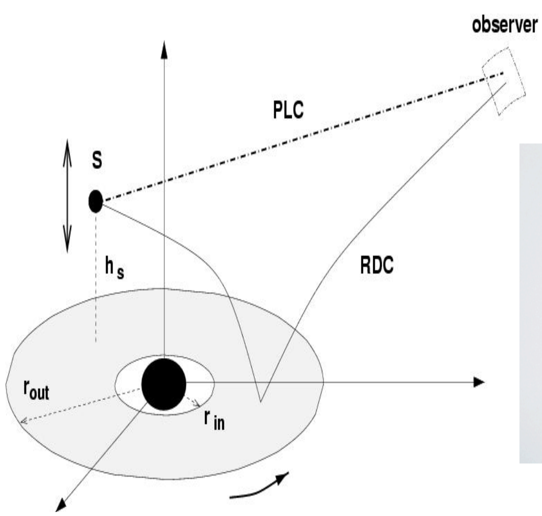
- Light rays are bent by strong gravity- making the geometry rather complicated
- Do not know 'where' x-ray source is - try to use data to figure it ou

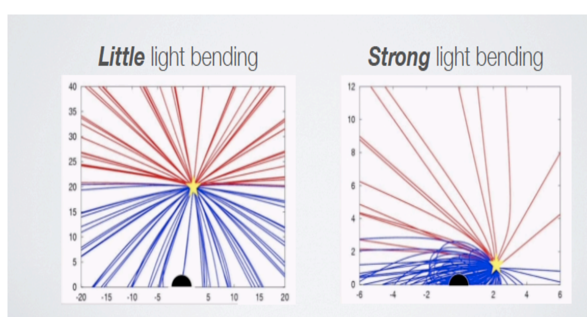




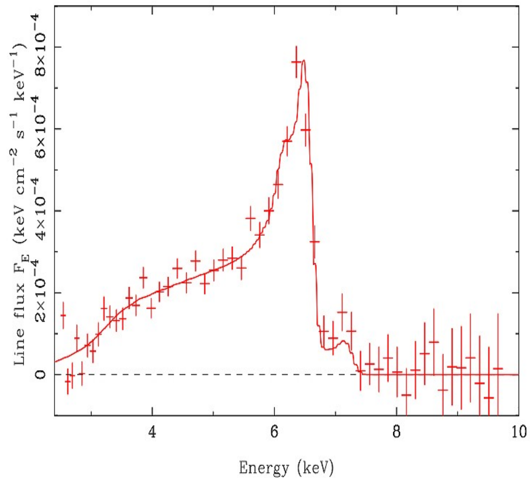
- Possible strong effect of light bending.
- if we only knew where the x-rays come from ($h_s \sim r_s$) from time variability arguments





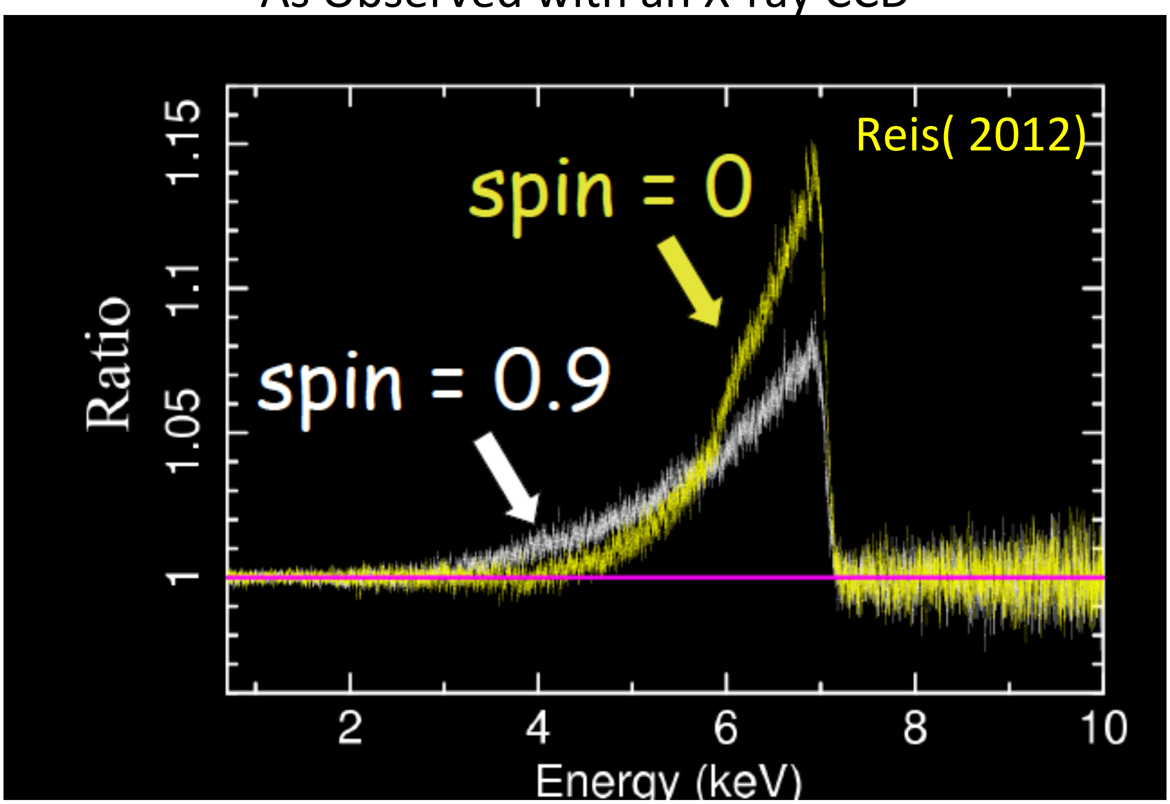


- Modern XMM-Newton observations
- Confirm relativistic line with extreme redshifts
- If no line emission from within ISCO, need to invoke spinning black hole to get strong enough redshifting
- Black holes must double their mass to change their spin. (Bardeen 70, Thorne 74)
- •Impossible in stellar binaries.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

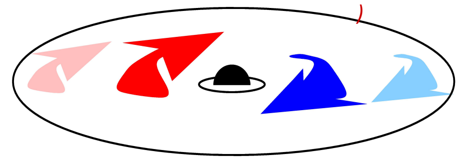


MCG-6-30-15 Power-law continuum subtracted
XMM: Fabian et al. (2002)

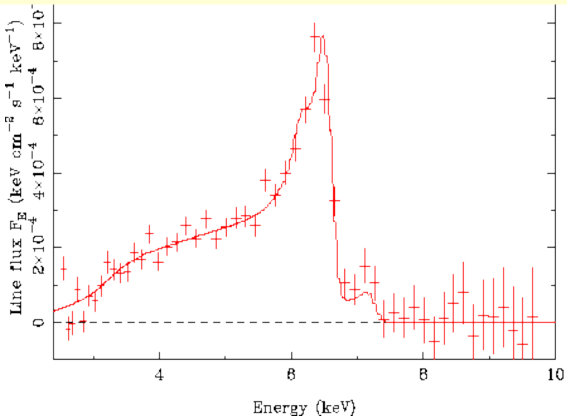
As Observed with an X-ray CCD



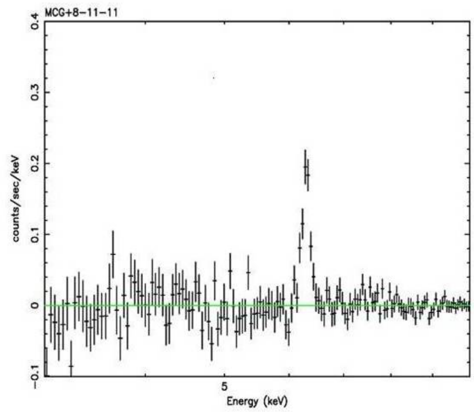
Relativistic lines



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

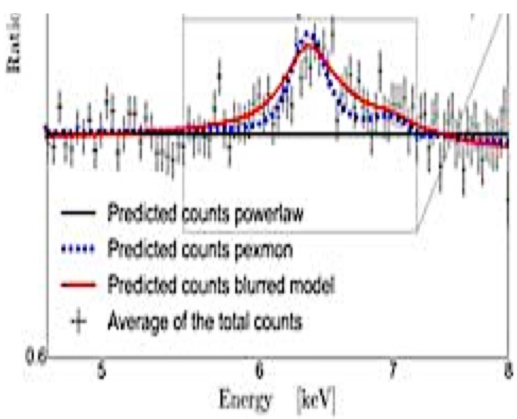


MCG-6-30-15
(Fabian et al. 2002)

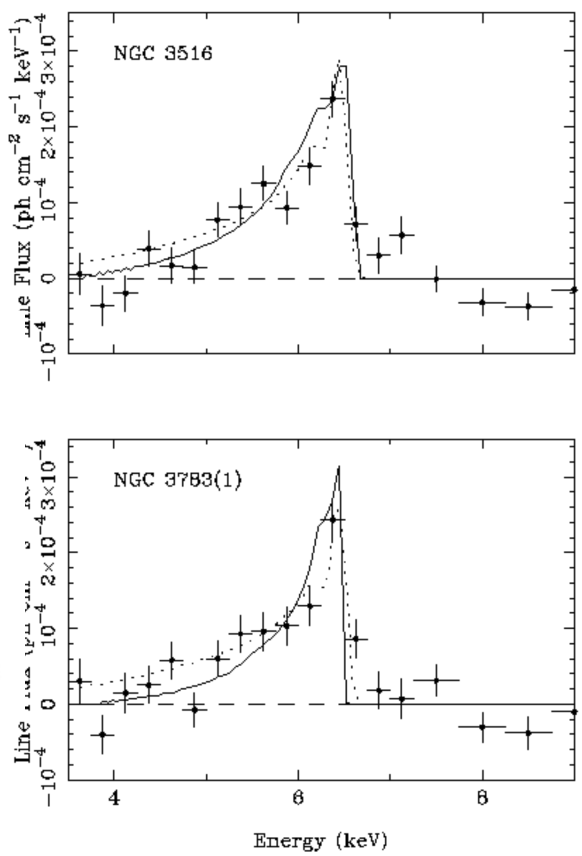


MCG-8-11-11
(Matt et al. 2006)

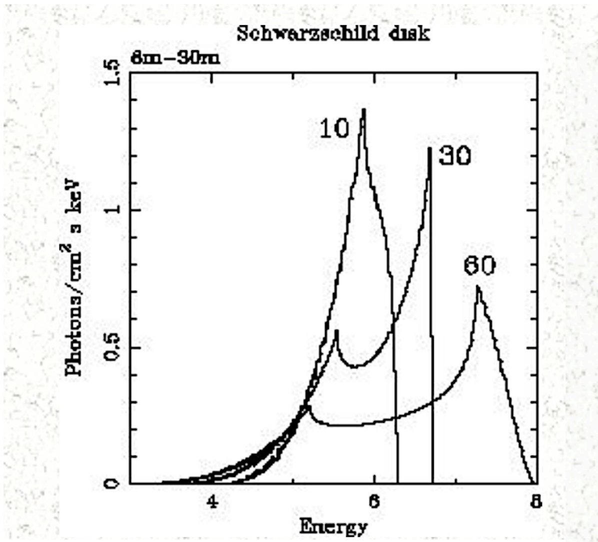
~25% of all AGN show
broad Fe K lines
strong function of signal
to noise

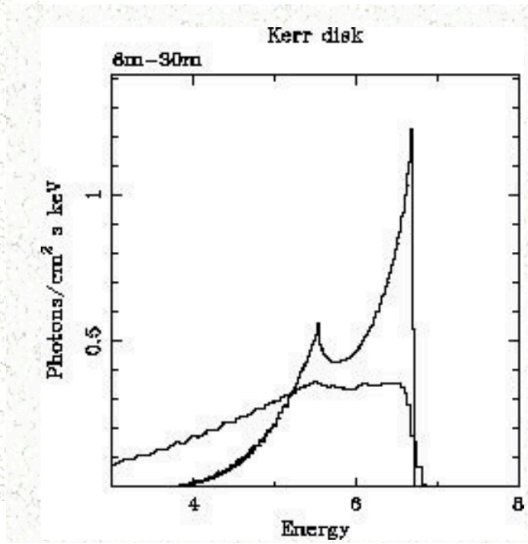


stacked 199 high z AGN



Effects of Inclination and Kerr vs Schwarschild



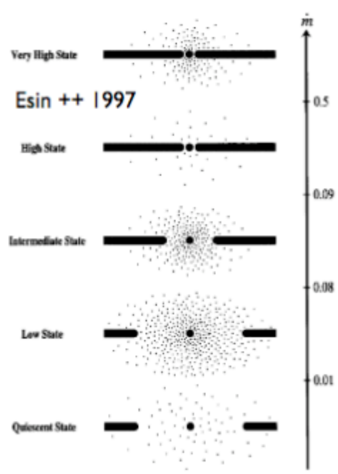


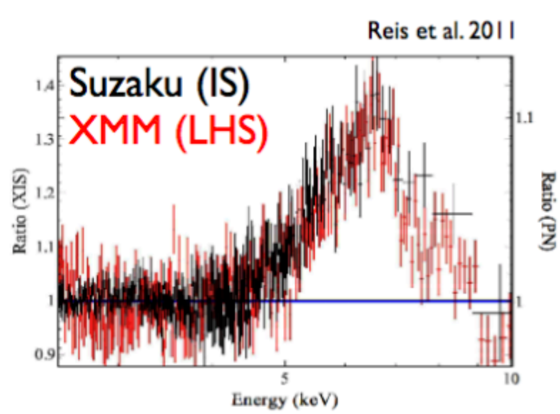
Effect of inclination Schwarzschild 6 r_g (i.e. the radius of marginal stability) to 30 r_g.
inclination 10°, 30° and 60°.

Kerr vs Schwarzschild

BLACK HOLE BINARY

Spin in XTE J1752-223





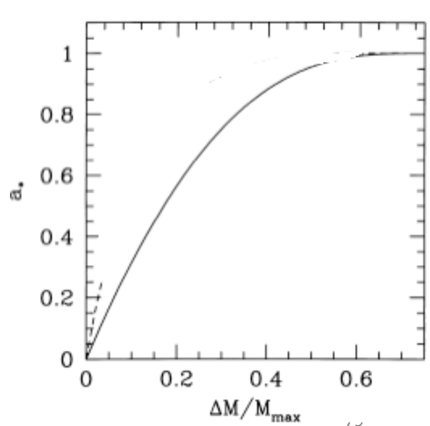
Intermediate State (Suzaku), low/hard state (XMM).
Blurred reflection fits: a/M = 0.52 +/- 0.11.
Strong implications for accretion flow models.

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 companions
- **Spin is natal**



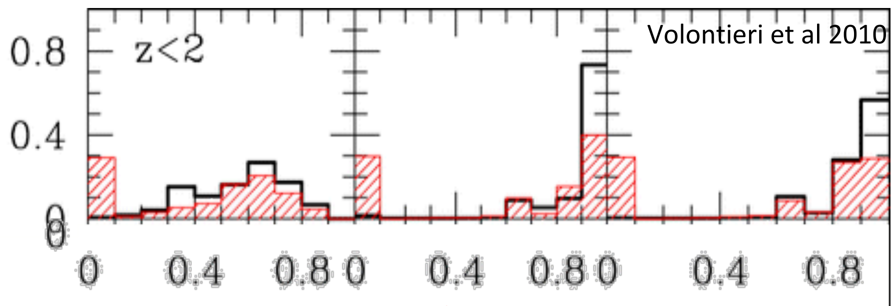
- See **The masses and spins of neutron stars and stellar-mass black holes Miller and Miller 2015** PhysicsReports 548 1

Spin

- For **supermassive black holes**- If accreting at the Eddington limit (~10^8 $M_\odot$ accretes 0.25 $M_\odot$/yr) so takes 4x10^8 yrs to double its mass and spin up

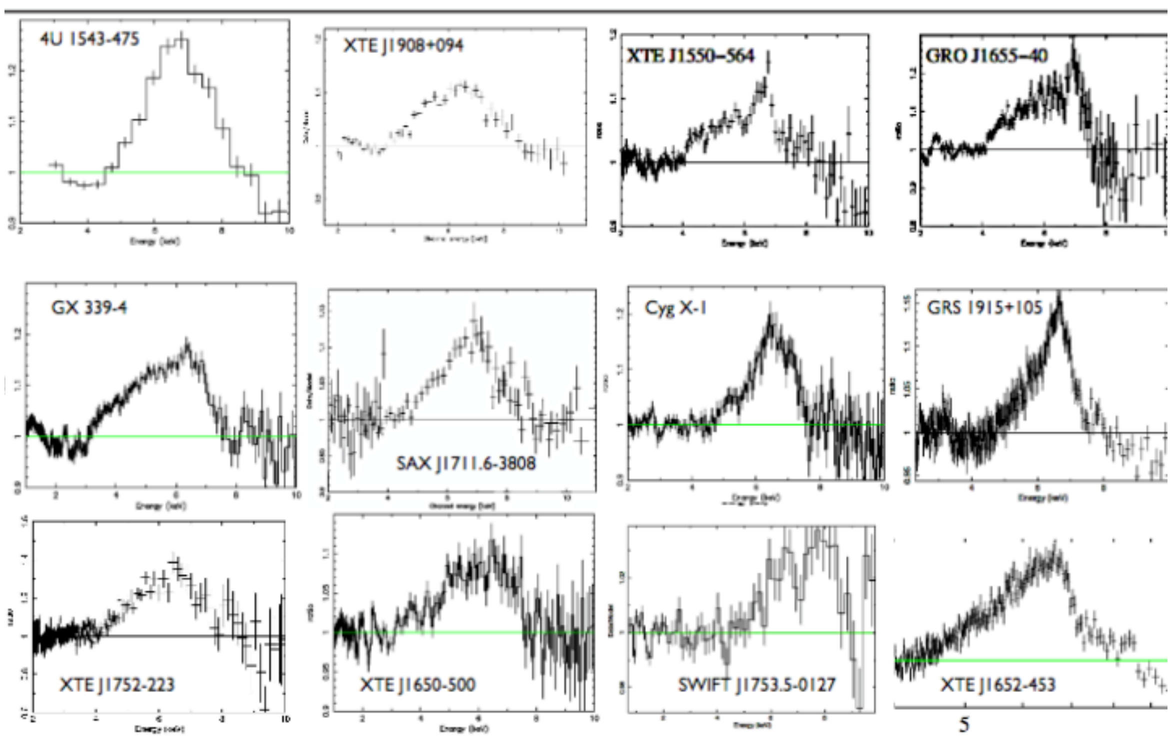
- Spin can be due to accretion
- Requires 'organized' accretion of angular momemtum

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



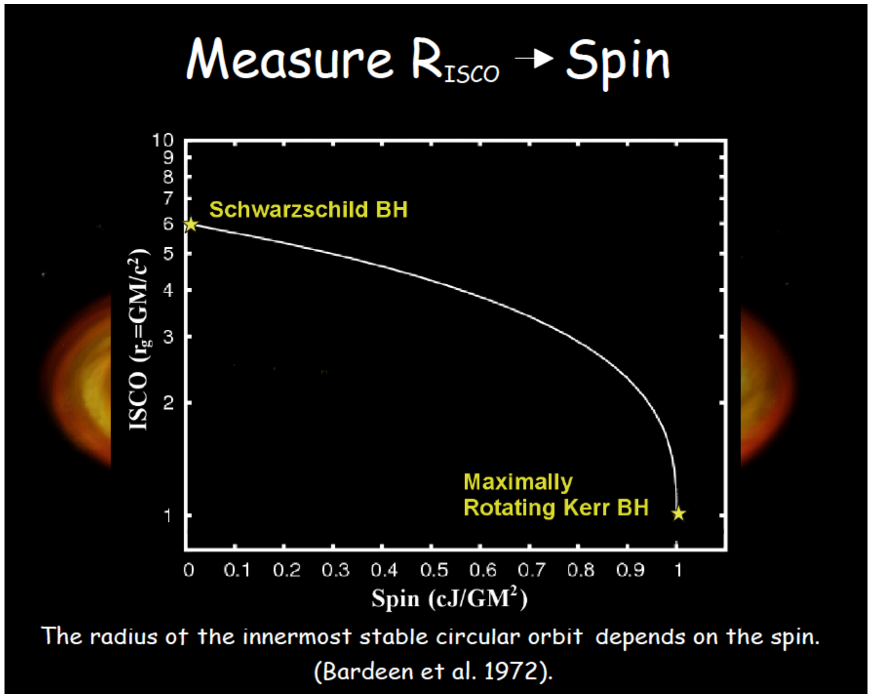
mergers only (left), mergers and prolonged accretion (center), and mergers and chaotic accretion

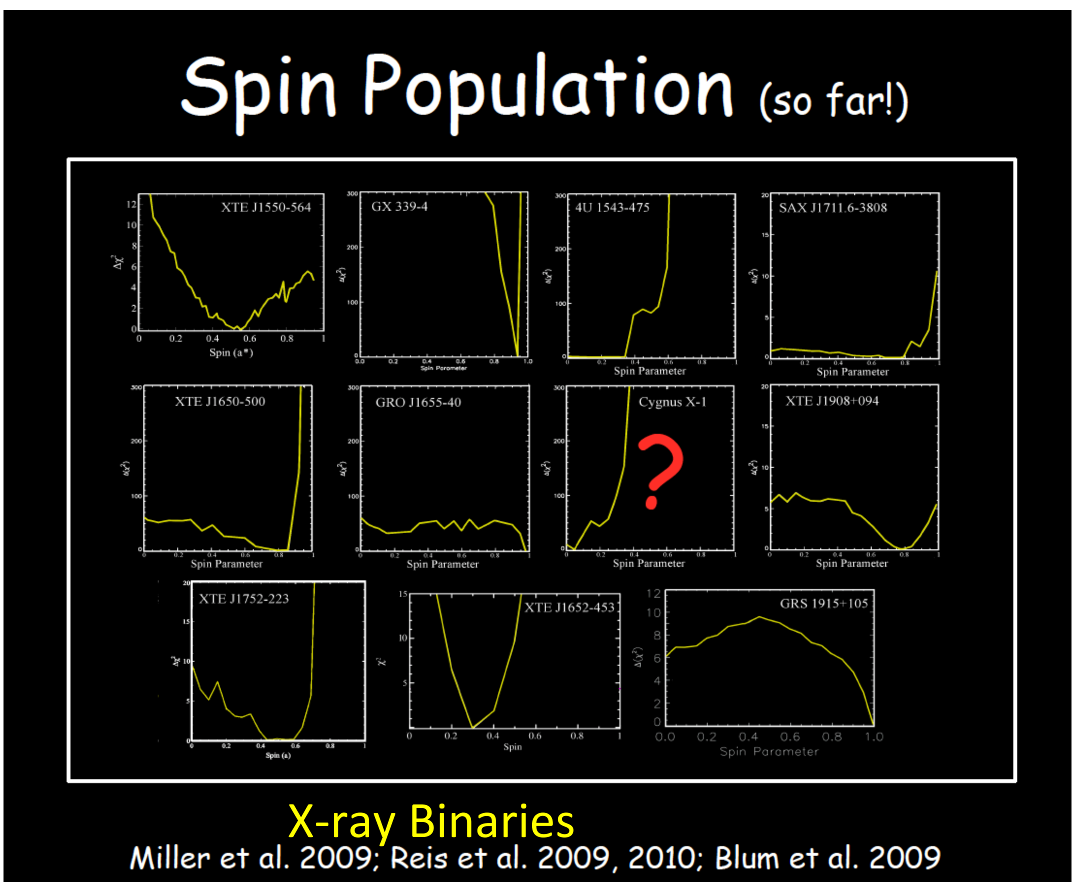
Black Hole Binaries



Reminder- Radius of ISCO depends on Spin

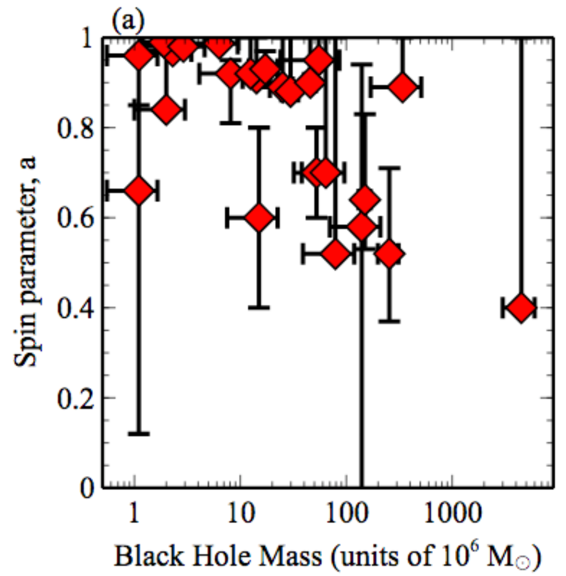
- Spin- is measured in units of c/ GM^2





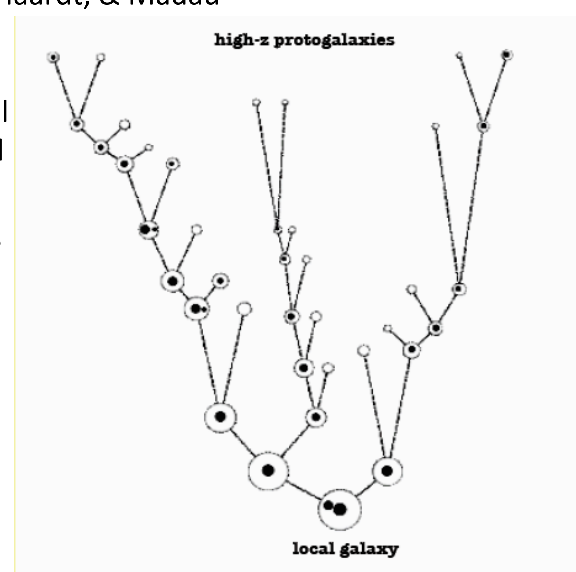
AGN Black Hole Spin from Fe K line

- Reynolds et al 2019
- It seems as most low mass AGN BHs have high spin



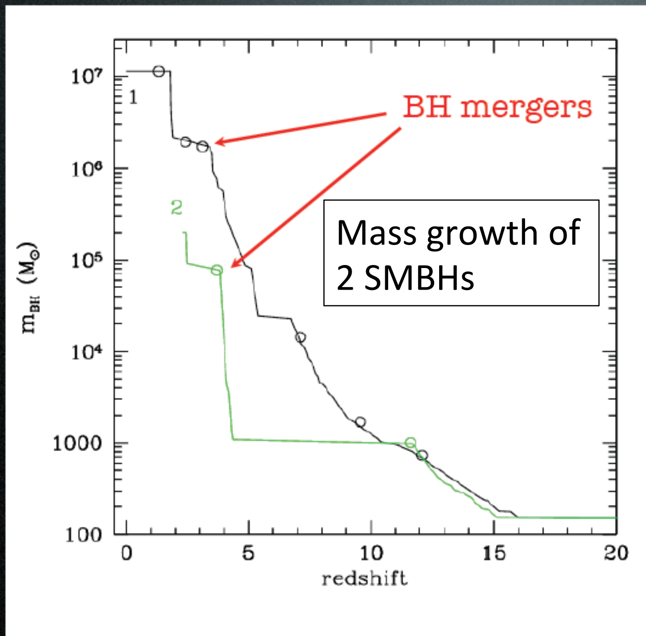
ASSEMBLY AND MERGING HISTORY OF SUPERMASSIVE BLACK HOLES IN HIERARCHICAL MODELS OF GALAXY FORMATION
Volonteri, Haardt, & Madau

- 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**
- Prime science goal of LISA



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)