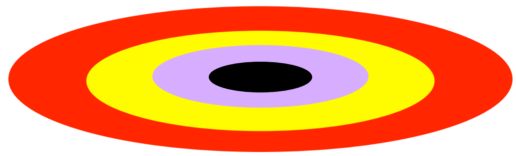
AGN and Galactic Black Hole Spectra

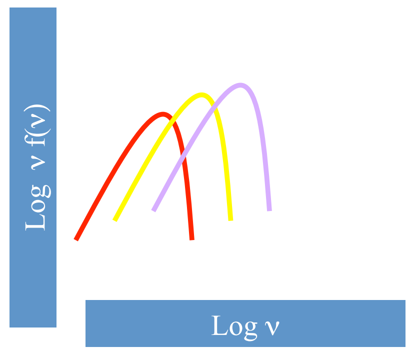
Todays Best Advertising for AGN- Ryan Hickox

Spectra of accretion flow: disc-

C. Done Review

- 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}

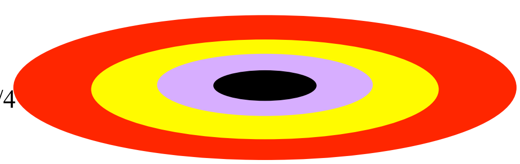


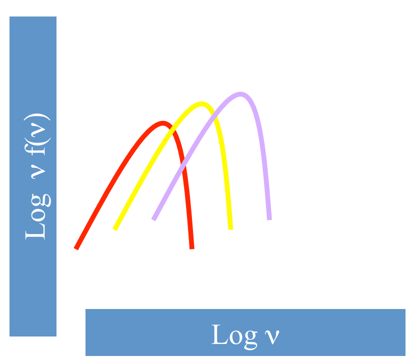


Spectra of accretion flow: disc-

C. Done Review

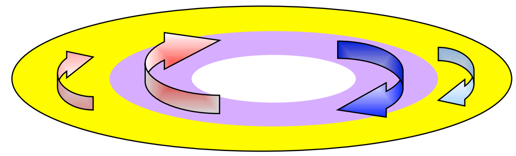
- GR last stable orbit gives minimum radius R_{ms}
- a=0: $T_{max} = (M/M_\odot)^{-1/4} (L/L_{Edd})^{1/4}$
  - 1 keV (10^7 K) for 10 $M_\odot$ if $L=L_{Edd}$
  - 10 eV (10^5 K) for 10^8 $M_\odot$ " "
- a=0.998 $T_{max} \sim 2.2\, T_{max}$ (a=0)
- AGN: UV disc, ISM absorption, mass more uncertain. XRB…

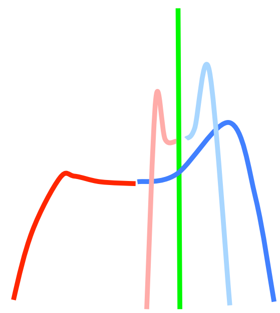




Relativistic effects- C. Done

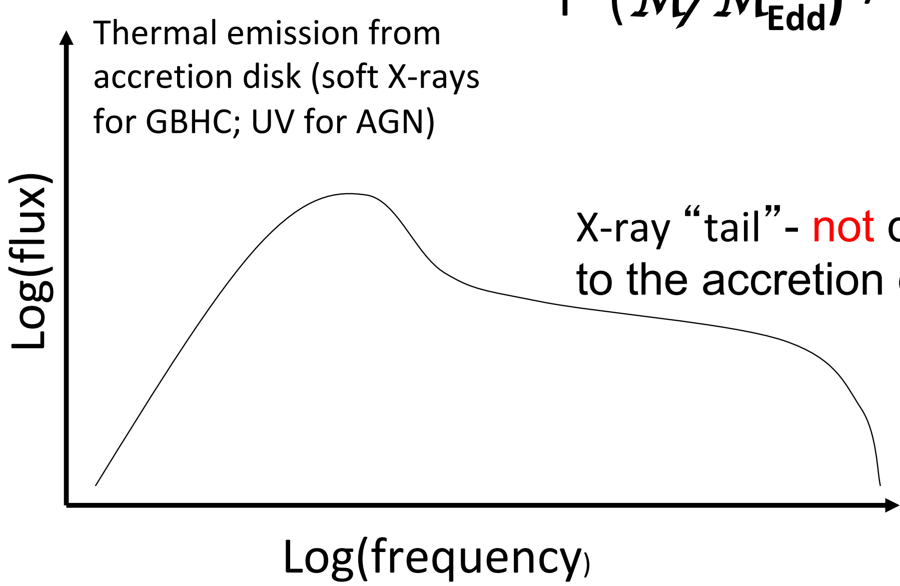
- Relativistic effects (special and general) affect all emission (Cunningham 1975)
- Hard to easily spot on continuum components
- Fe Kα line from irradiated disc – broad and skewed! (Fabian et al 1989)
- Broadening gives an independent measure of Rin – so spin if ISO (Laor 1991)
- Models predict increasing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





What Do Broad Band Spectra of Black Holes Look Like

$$T \sim (\mathcal{M}/\mathcal{M}_{\mathbf{Edd}})^{1/4} M^{-1/4}$$



How Hot is a Black Hole??

Lets go back to the accretion disk spectrum- Longair 14.52-14.54

$T(R)=[3G\mathcal{M}M/8\pi R^3]^{1/4}(R/R_{in})]^{-3/4}$

Temperature at fixed number of R_s <u>decreases as $M^{-1/4}$</u>
- **disks around more massive black holes are cooler at a <u>fixed</u> R/R_S and $\mathcal{M}/\mathcal{M}_{Edd}$**

now recasting in terms of the Eddington limit where $\mathcal{M}_{Edd}$ is the mass accretion rate for the Eddington limit and we assume that the conversion efficiency of mass into energy is 10% and M_8 is the BH mass in units of 10^8 $M_\odot$

$$T\sim 6.3\times10^{5}[\mathcal{M}/\mathcal{M}_{Edd}]^{1/4}[M/M_8]^{-1/4}(R/R_{in})]^{-3/4}k\text{-UV}$$
$$T\sim 6.3\times10^{7}[\mathcal{M}/\mathcal{M}_{Edd}]^{1/4}[M/M_\odot]^{-1/4}(R/R_{in})]^{-3/4}k\text{-Xray}$$

Galactic Black Holes

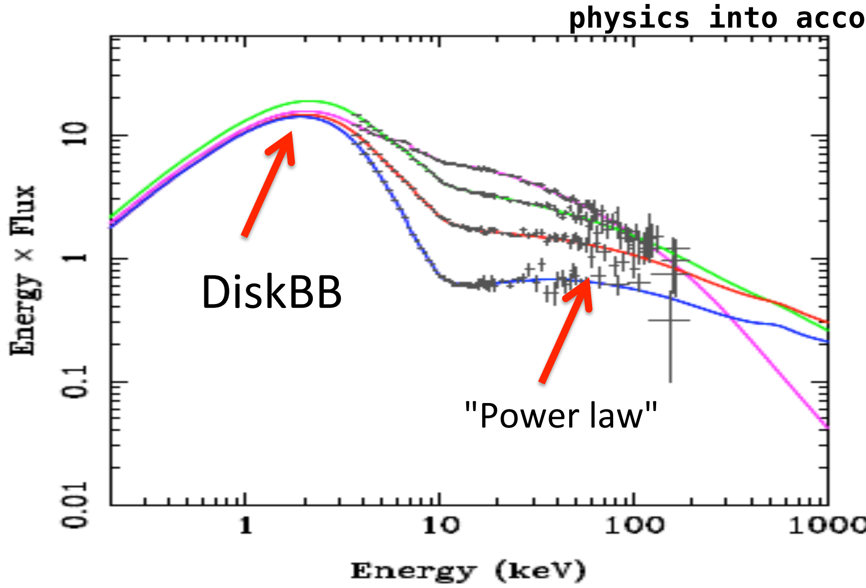
- Relatively low mass and so the disk are 'hot'

Adapted from Miller et al 2003

$L\sim 7\times10^{38}\ f(M_{10})^2(T_{in})^4$ erg/s

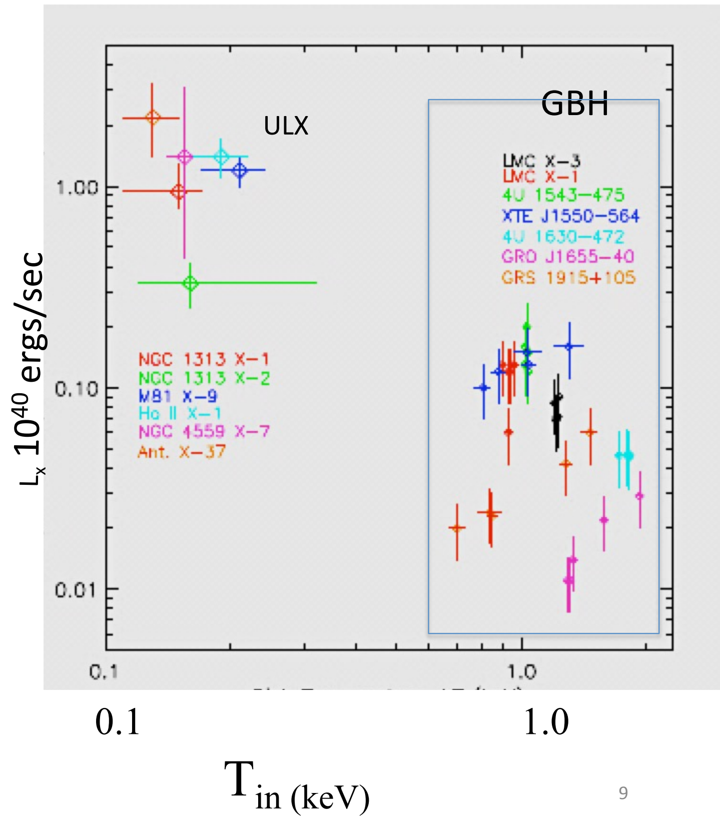
Where M_{10} is the mass in units of 10 $M_\odot$ and T_{in} is in keV

f is a factor taking some complex physics into account



Galactic Black Holes-GBH

- Relatively low mass and so the disk are 'hot'- most of the flux appearing in the x-rays



Adapted from Miller et al 2003

Reminder of Accretion Disk Spectrum

- 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

  $L=4\pi\sigma R^2 T_{in}^4$ σ 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

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

$T(r)=6.3\times 10^5\ (\mathcal{M}/\mathcal{M}_{Edd})^{1/4} M_8^{-1/4}\ (r/r_s)^{-3/4}$

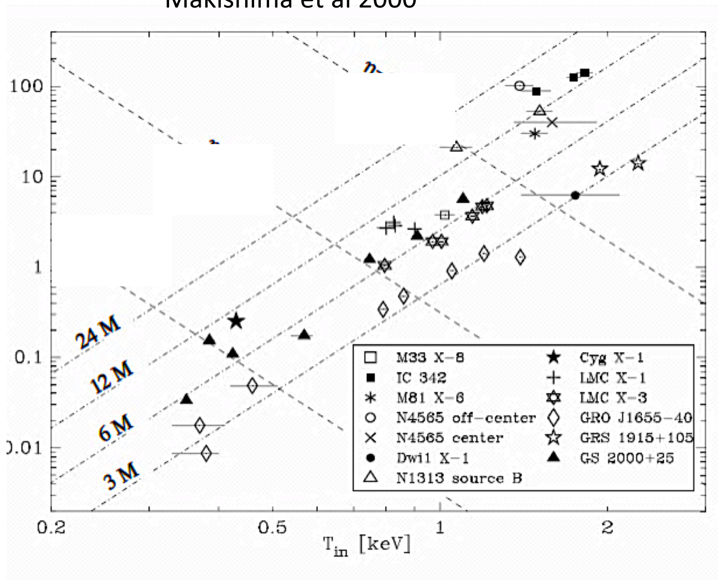
($\mathcal{M}_{Edd}$ *is the accretion rate in Eddington units,* $T=T_{in}$ for $r=r_s$)

Real Objects

Makishima et al 2000

- Data for **galactic black holes** agrees with the simple theory
- E.g assume that M_{BH} does not change and all changes luminosity due to changes in $\mathscr{M}$*- if so then expect* $T_{in} \sim \mathscr{M}^{1/4} \sim L^{1/4}$

Disk bolometric luminosity x10^{38}



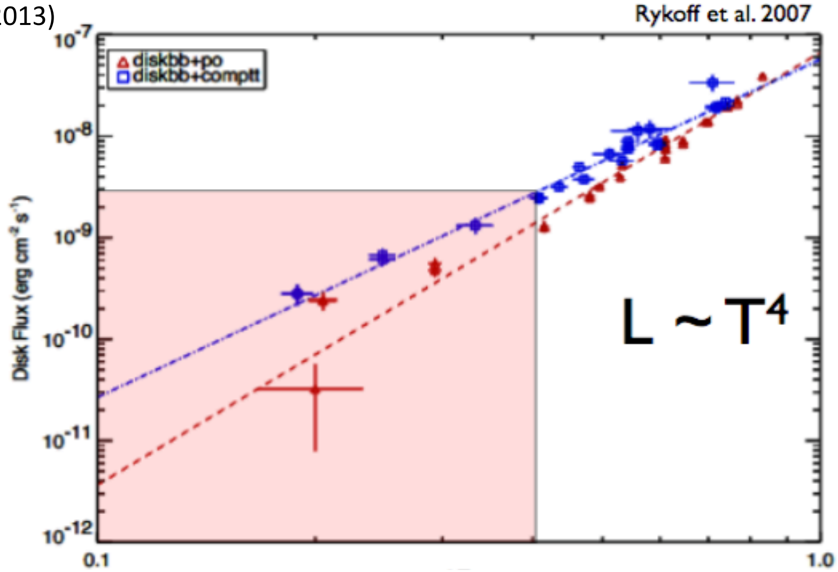
Fitted T_{in}

Swift Obs. of XTE J1817

black hole transient

Miller (2013)

Rykoff et al. 2007



Disk flux

kT (Kev)

Modifications to Disk Black Body

The disk model that is most widely used ("diskbb"; Mitsuda et al. 1984) does not include the inner torque condition.

$$D(R) = \frac{3GM\dot{M}}{8\pi R^3}\left[1-\left(\frac{R_{\rm in}}{R}\right)^{1/2}\right]$$

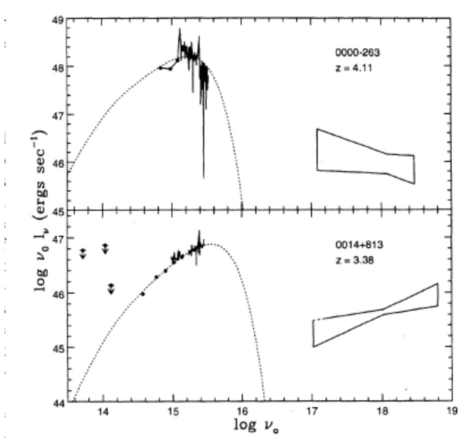
And, it was realized that radiative transfer through a disk atmosphere hardens spectra. kT too high, R too small (e.g. Shimura & Takahara 1995; Merloni, Fabian, Ross 2000).

And there are other corrections needed to get a "true" inner disk radius:

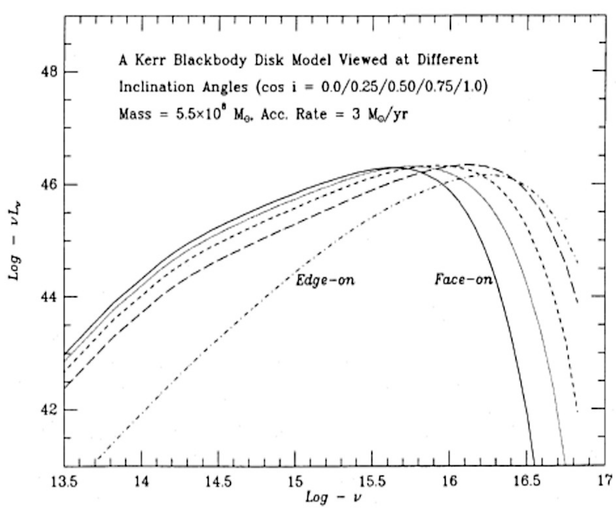
$$r_{in} = \eta g(i) f^2_{col} r_{col}$$

r_{in} is the "true" disk radius.
η ~ 0.65, corrects for real peak of disk emissivity.
$g(i)$ ~ 0.75, accounts for relativistic effects.
f_{col} ~ 1.7-3.0++, corrects for radiative transfer.
r_{col} is the color radius, related to sqrt(norm).

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



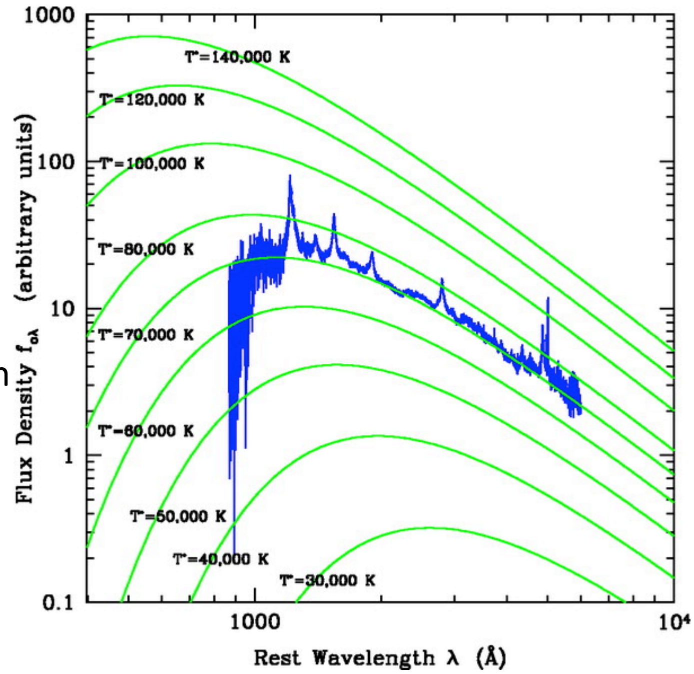
Malkan and Sun 1989



Effects of inclination on disk spectrum for $5x10^8 M_\odot$ BH

AGN

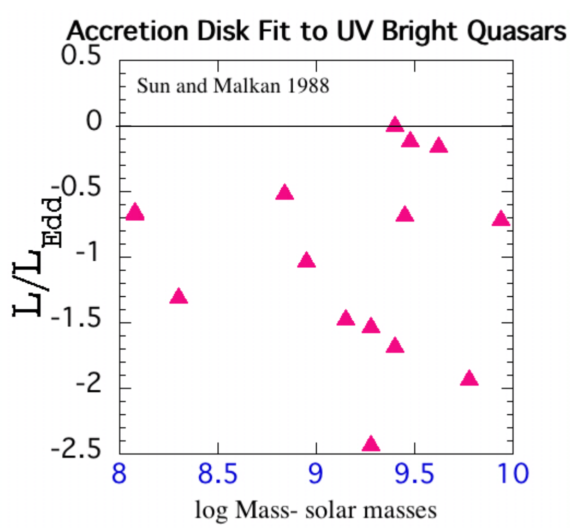
- AGN are very massive and so the predicted spectrum of the accretion disk is 'cool'- peaking in UV-EUV
- T~8x10^4 k for a Eddington limited M~10^{8}M$_\odot$ black hole
- Problems with observing in the EUV and so do not observe high energy exponential cutoff



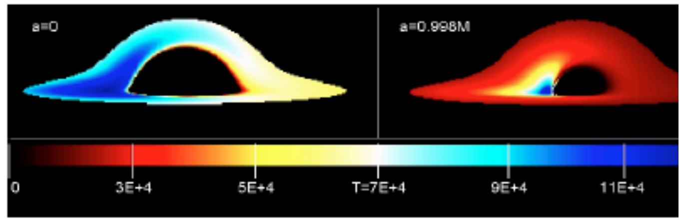
Fit of SS AD models to AGN spectrum (Malkan and Sun 1989

Fitted Parameters for UV Disk Fits

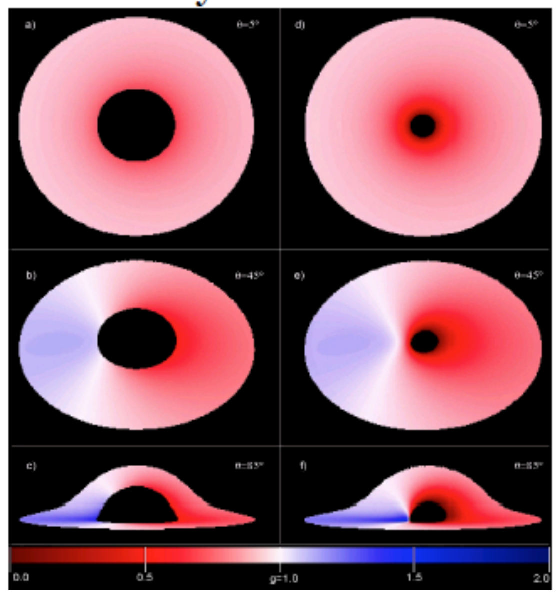
- Results are 'reasonable' but not unique
- Now have independent mass estimates- results can be checked
  - Find that values are not quite right- need more complex accretion disk models (surface is not simple BB, need to include relativistic effects)



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



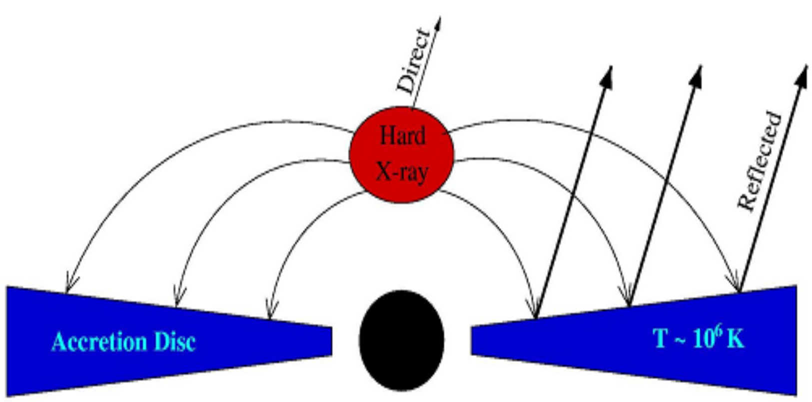
Courtesy of M. Calvani



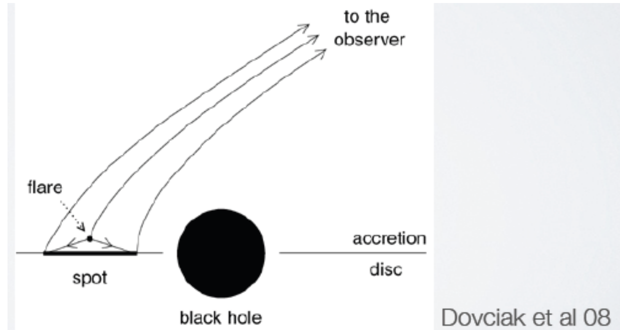
a is spin in GR units

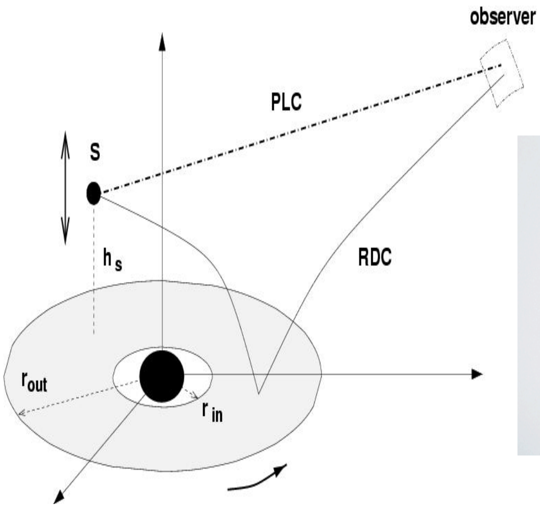
Relativistic Effects

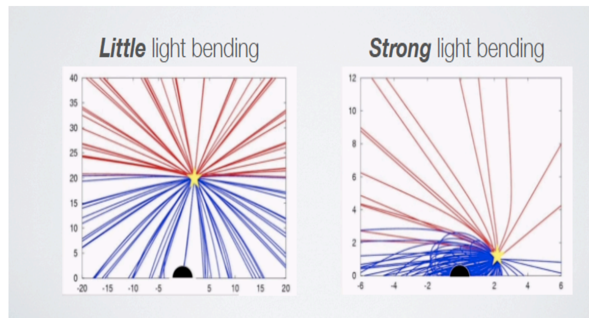
- Light rays are bent by strong gravity- making the geometry rather complicated



- 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







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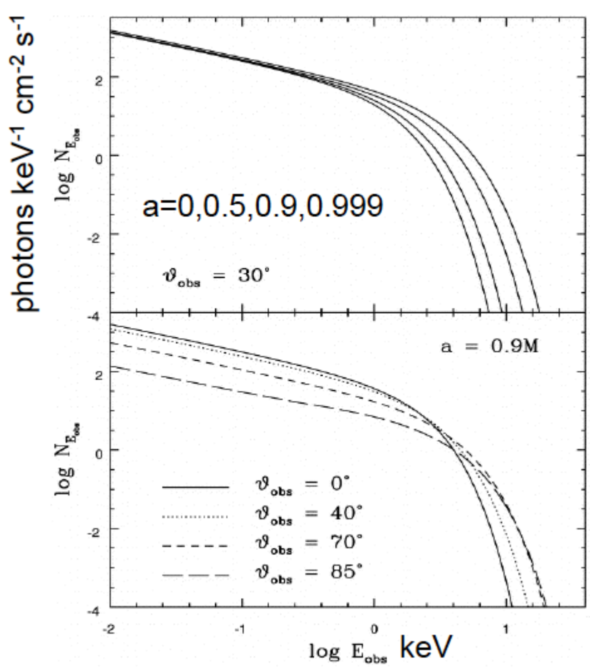
Effects of Strong Gravity (Spin), Inclination Angle on Spectrum of Disk (Merloni 2010)

Top panel is AD spectrum vs energy for fixed inclination angle, spin varies

Bottom panel fixed spin, inclination angle varies.



Zheng et al. 1997; Li et al. 2005; Shafee et
Nowak et al. 2008; Steiner et al. 2010; Ku

Next ...

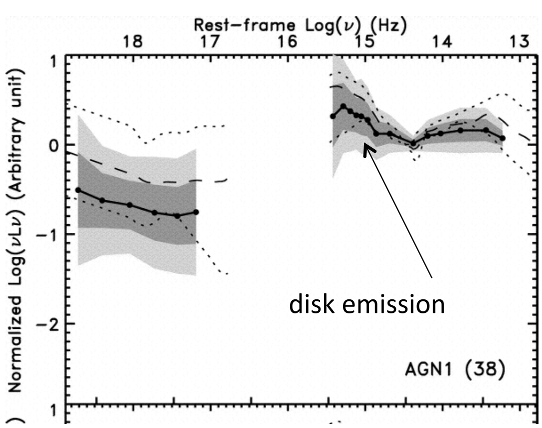
- Accretion Disk fits to AGN spectra

- 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

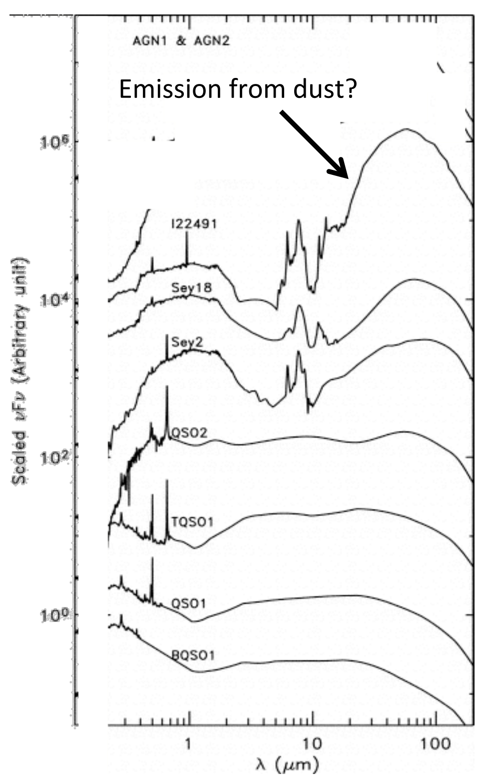
- Effects of 'reprocessing' - the disk 'sees' the hard x-ray radiation and there are measurable effects

Life is Not So Simple

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



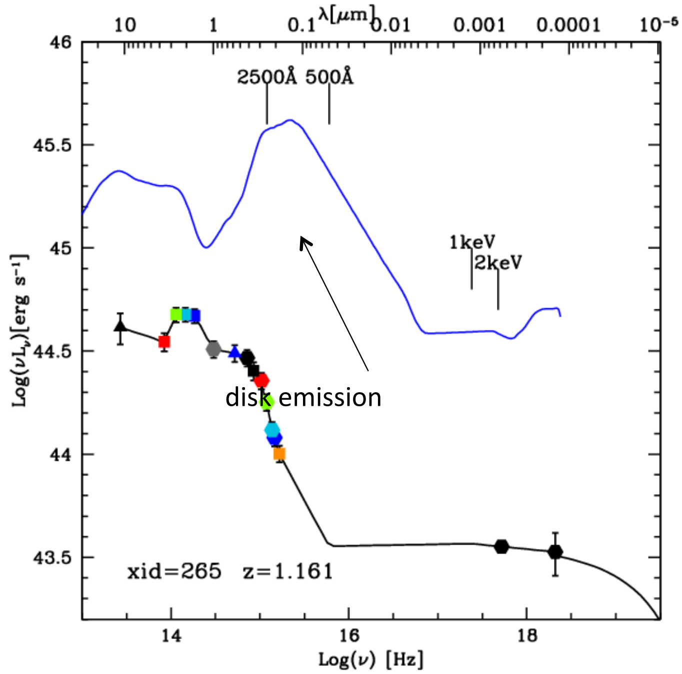
Adapted from Poletta et al 2007



AGN

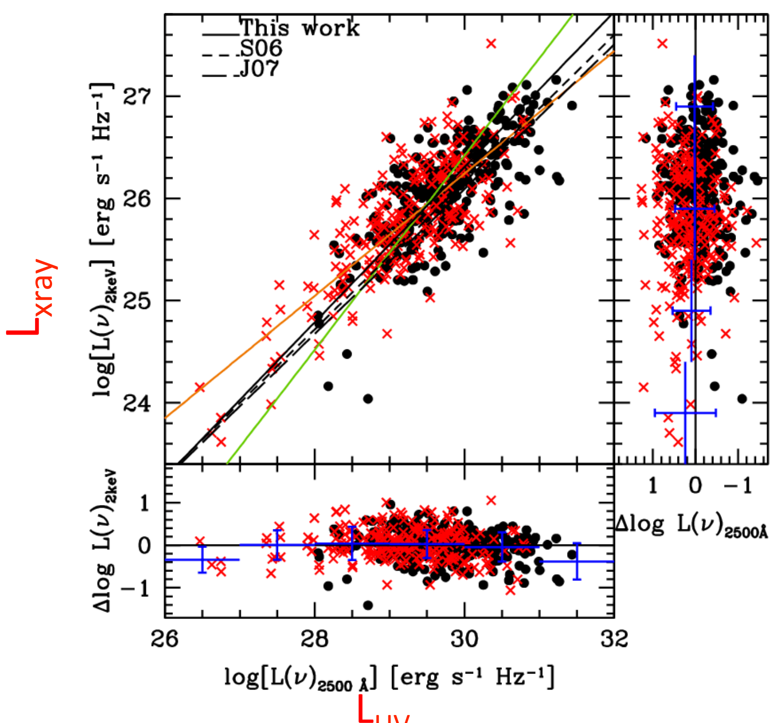
- A huge amount of work has gone into observing AGN across the entire electromagnetic spectrum
- There is a strong relationship between the optical-UV and the x-ray

Brusa et al 2009

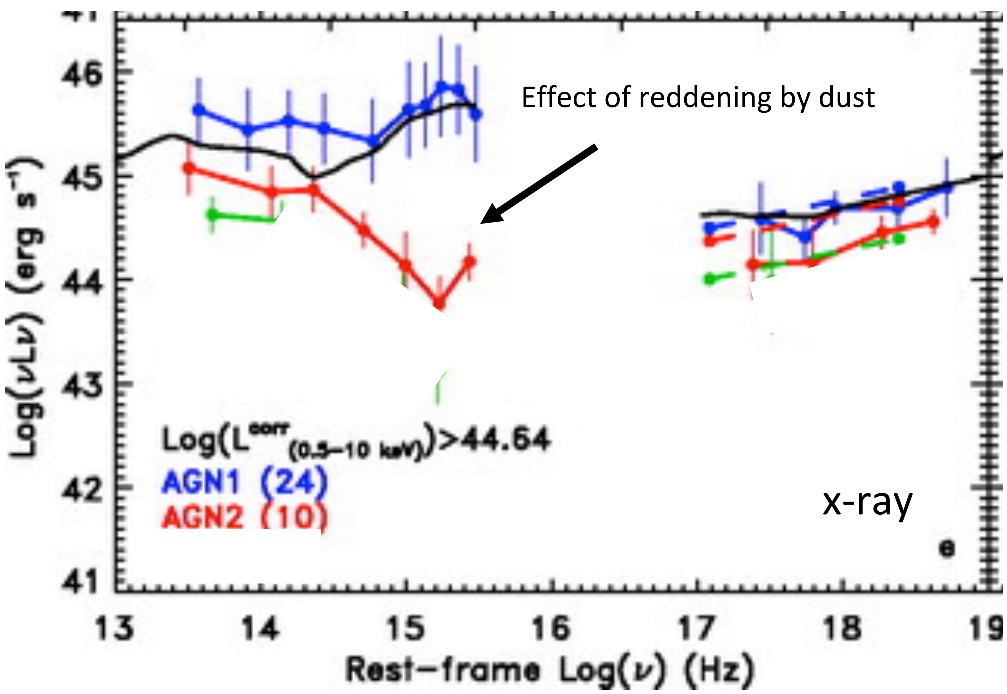


X-ray to UV Relationship

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



Lusso et al 2010



- Average Spectral Energy Distributions for 2 Classes of Objects Selected as X-ray Emitting AGN in a given x-ray luminosity bin (Polletta et al 2007)

General Shape of the Optical-X-ray SED

- As the luminosity of the source increases the ratio of x-ray to optical luminosity (α_{ox}) decreases slightly
- e.g more luminous AGN are x-ray 'quieter"

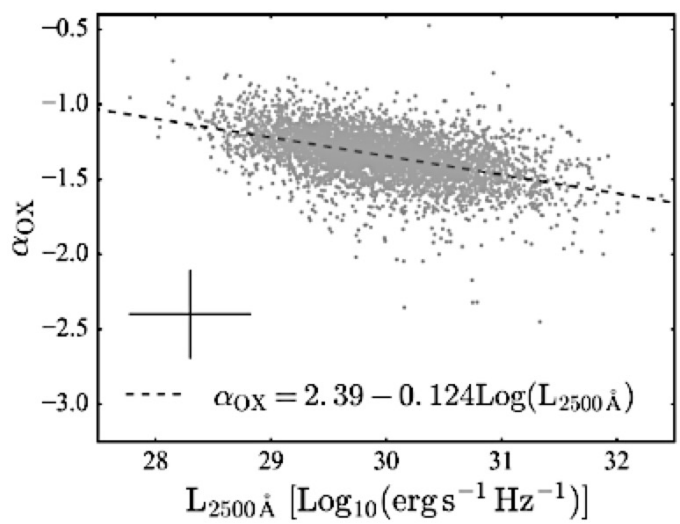


Fig. 14: α_{OX} versus UV luminosity. The dashed line is the best lin

Coffey et al 2019

$$\alpha_{ox}=[\log (F_x)-\log (F_{UV})]/2.605$$

Effects of Dust Can Be Dominant

- Remember for the M~10^8 T~$5x10^5$ K so 'roll over' is in the FUV ⁻ effects of dust are maximum in the UV
- E_{max}~3kT~ 10^{16} hz
- The effects of dust (Reddening) go at λ^{-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

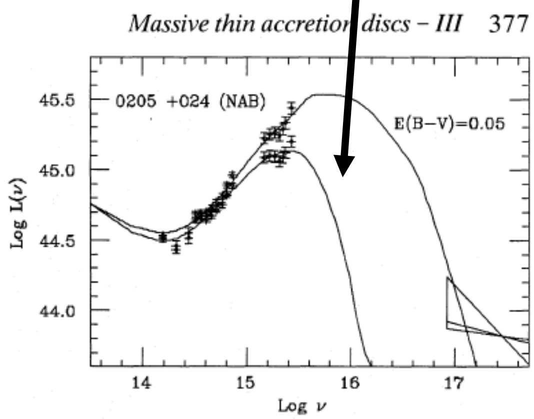
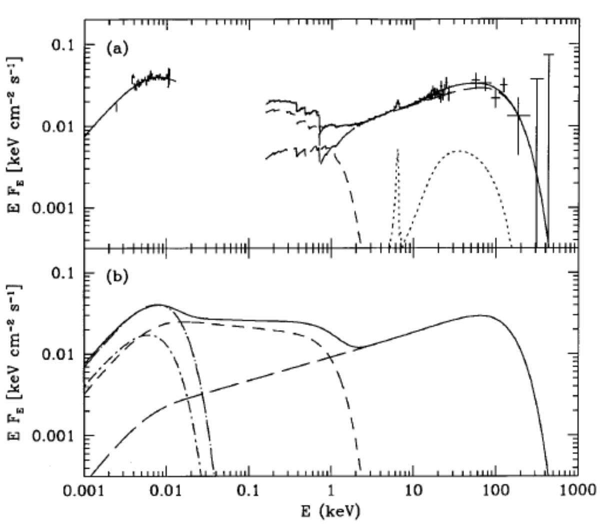


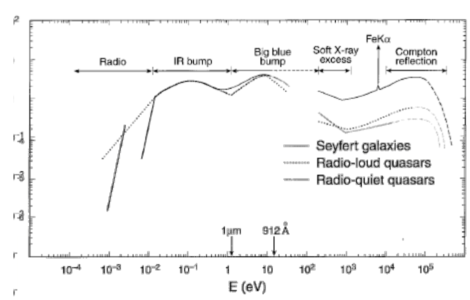
Figure 6. A fit for 0205 + 024 with and without a correction for internal reddening of $E(B-V) = 0.05$. The best fit parameters are

Laor 1990

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

AGN

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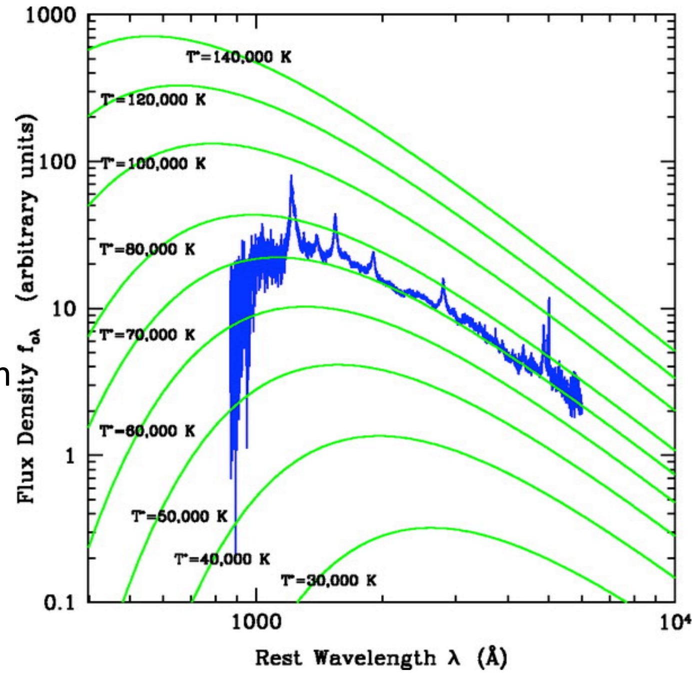
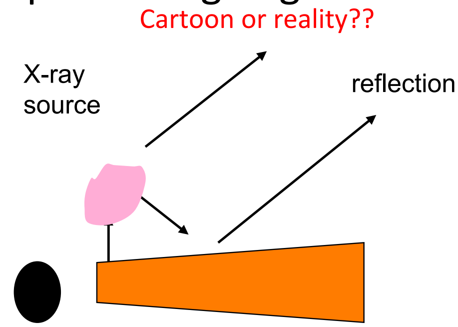
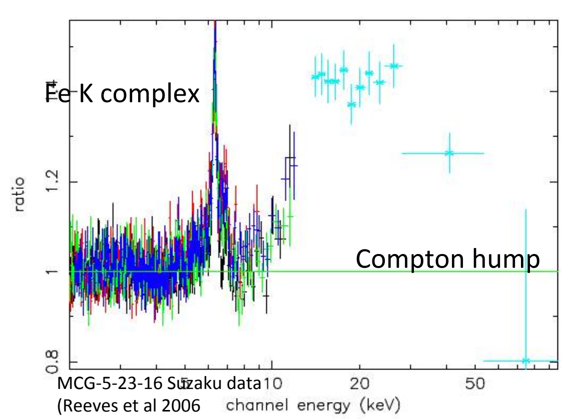


Fit of SS AD models to AGN spectrum (Malkan and Sun 1989

Connection of Fe K line and the Reprocessing Regions

- The **most prominent** spectral features in most x-ray AGN spectra are
  - the Fe K line complex
  - The Compton reflection ‘hump’
- Where are these regions
  - How are they connected
  - What do we learn about the geometry and chemical abundance of the central regions?
  - What is the physical state of the gas and how is it connected to other ‘places’ - e.g the regions responsible for producing the optical/UV/IR radiation
  - What can we learn about accretion



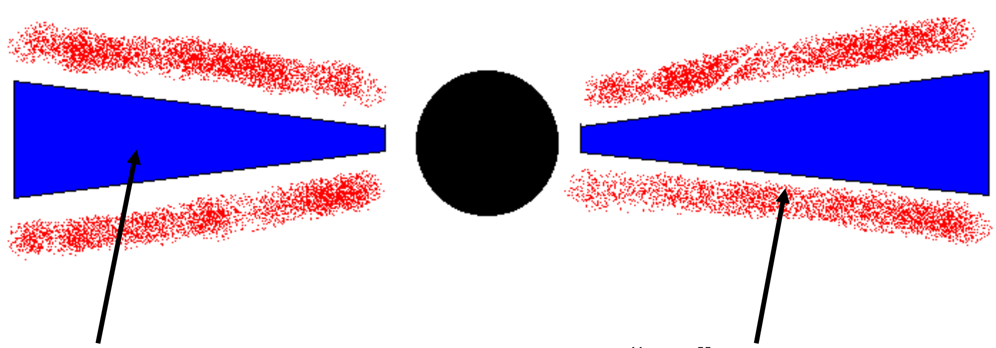


MCG-5-23-16 Suzaku data
(Reeves et al 2006

More Complexity

- 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?



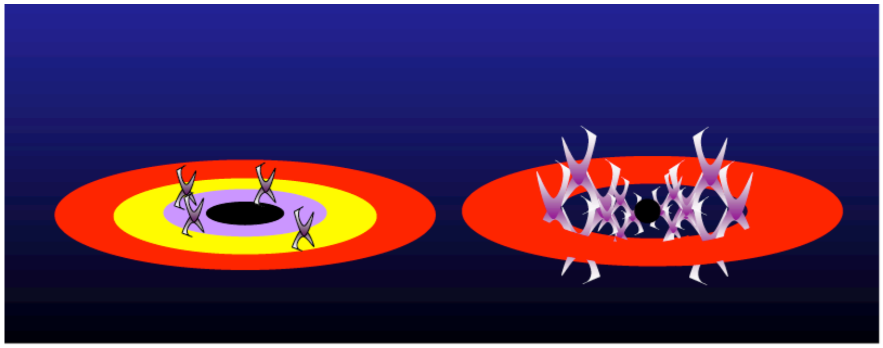
Optically-thick part of the accretion disk emits thermal spectrum… black body radiation with

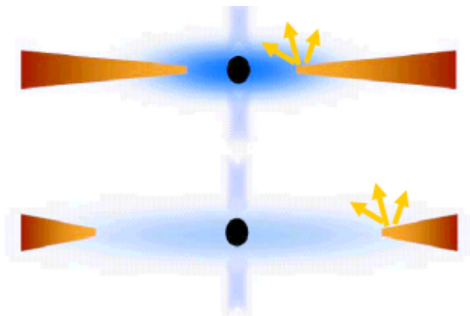
$$T = \left(\frac{3GM\dot{M}}{8\pi r^3 \sigma_{\rm SB}} \right)^{1/4}$$

X-ray "tail" probably comes from a hot corona

x-rays produced by inverse Compton scattering of thermal disk emission by electrons with T~10^9K

Even More Possible Geometries





From C. Done

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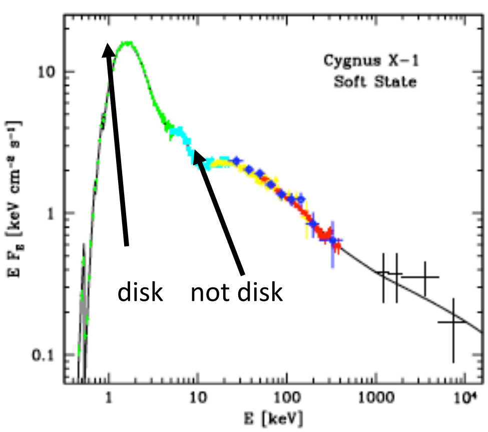
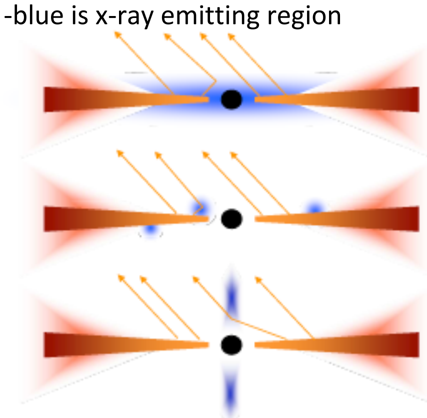
Real Data For Galactic BH



Possible geometries
-blue is x-ray emitting region



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

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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 $\alpha \sim -3/2 + (9/4 + y)^{1/2}$

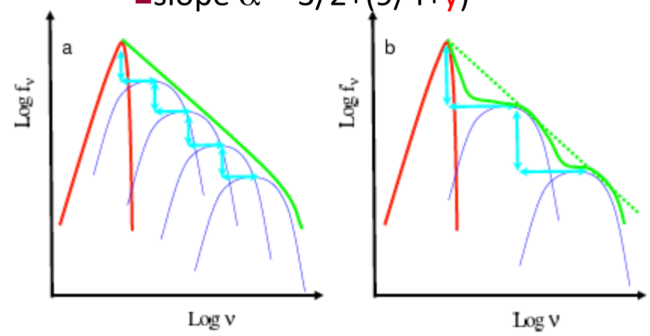

Figure 1.8 a) shows how the spectrum built up from repeated thermal Compton up scattering events for optically thin ($\tau \lesssim 1$) material. A fraction τ of the seed photons (red) are boosted in energy by $1 + 4\Theta$ and then these form the seed photons for the next scattering, so each scattering 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 Γ 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, $dN(E)/dE \propto E^{-\Gamma}$,

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

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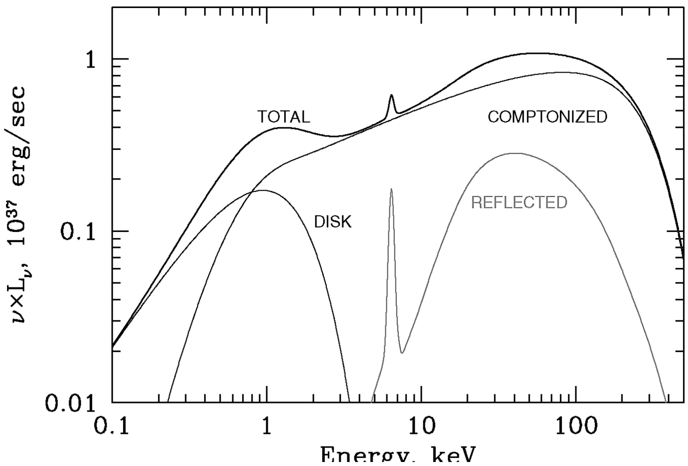

Typical slopes are ~-2
which gives τ_e~1 and
y =3/4

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

Thermal Comptonized Spectra

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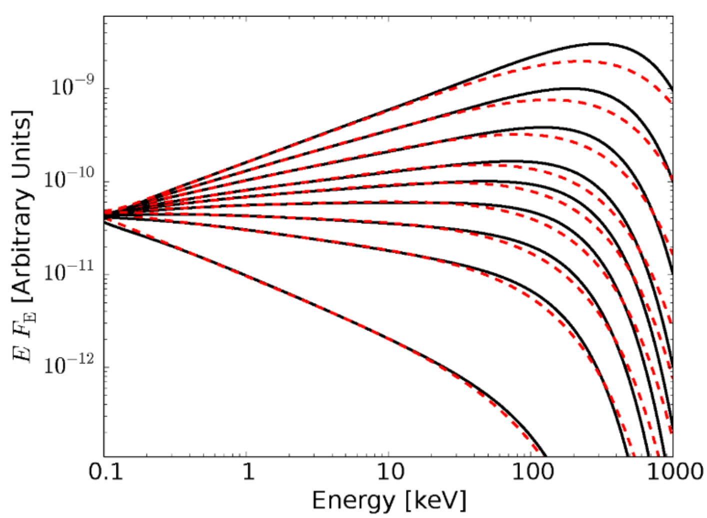
- which gives τ_e~1 and y =3/4

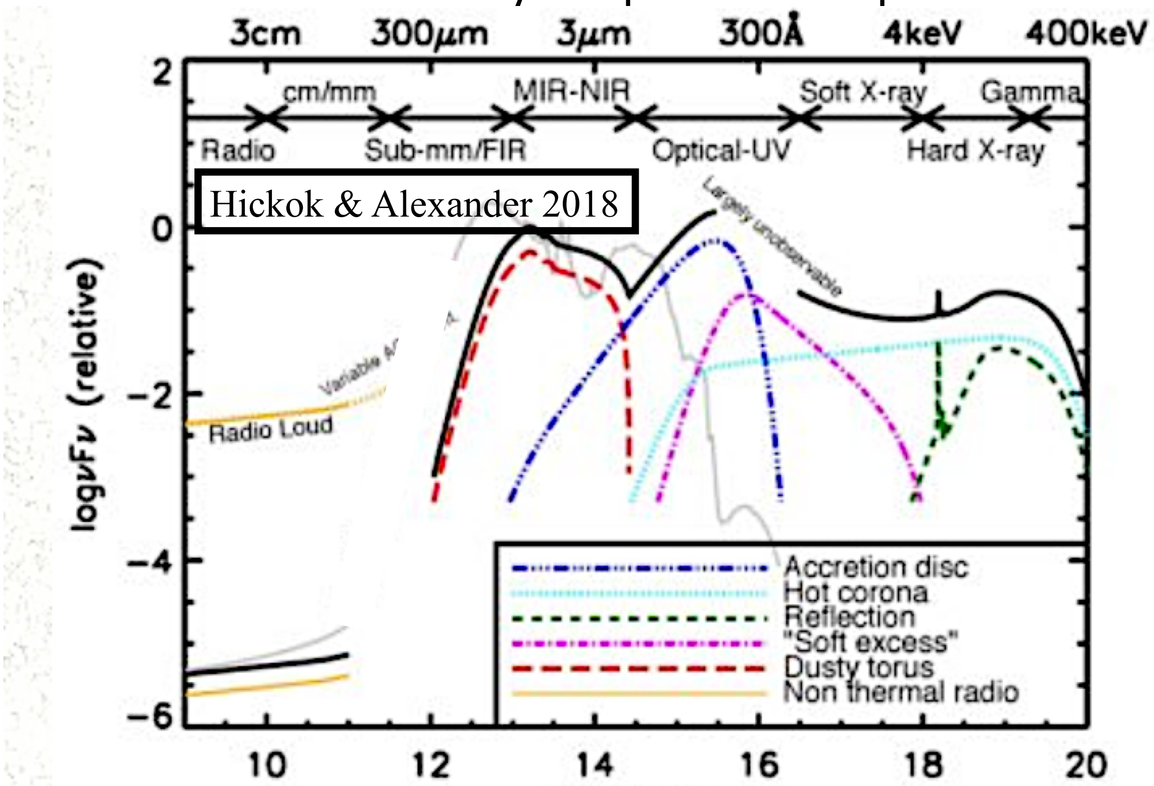
$y=4kT_e m_e c^2 \max(\tau_e,\tau^2_e$

- typical temperatures are 50-300 keV

Numerical calculations of Comptonized spectra
for different T,τ combinations



AGN- Summary of Spectral Components

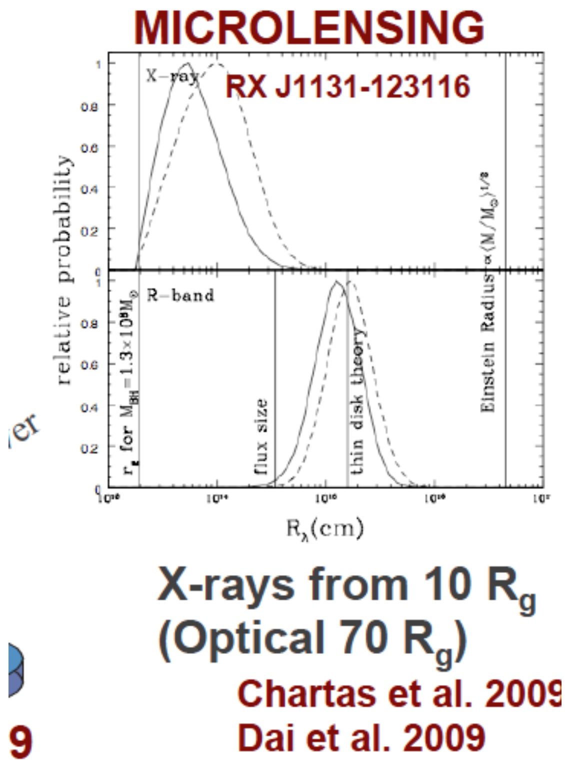


More On BH Spectra

- 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.



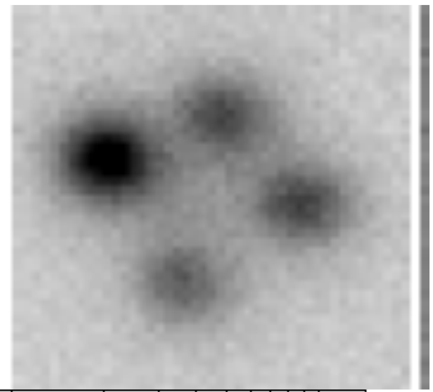
MicroLensing

- As we saw last time in a disk $T(r) \sim T_{max} r^{-3/4}$
- Writing it out in full
- $T_{eff}(r)=\{(3G^2 M_{BH}^2 m_p f_{Edd})/2c\sigma_{SB}\varepsilon r^3)\}^{1/4} (1-r_{in}/r)^{1/4}$
  - f_{Edd} is the Eddington ratio , M_{BH} is the BH mass, σ_{SB} the Stefan Boltzman constant , ε is the efficiency
- Thus the disk emits most of its short wavelength light at small radii and long wavelength light at large radii
- Integrating the disk temperature profile (Blackburne et al 2010) one gets that the half light radius as a function of size is

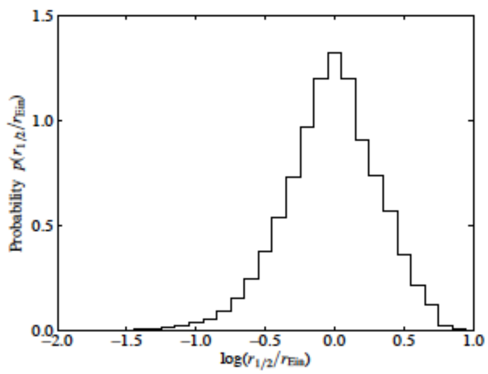
$$r_{1/2} \sim 1.7 \times 10^{16} \mathrm{cm} (M_{BH}/10^9 M_\odot)^{2/3} (f_{Edd}/\varepsilon)^{1/3} (\lambda/\mu)^{4/3}$$

- In other words the effective size $\sim\lambda^{4/3}$

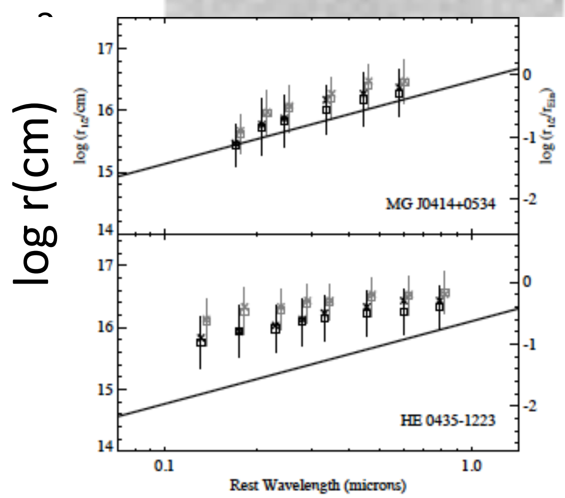
- The size of the disk is in Einstein radius units which are converted to cgs units with a model of the grav potential of the lensing galaxy



- Source is bigger at longer wavelengths- line is what a SS disk should be

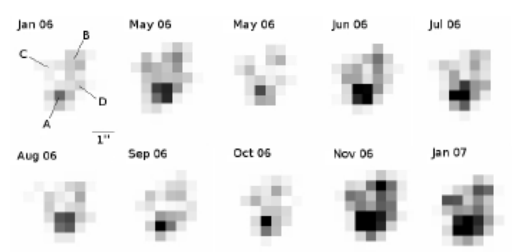


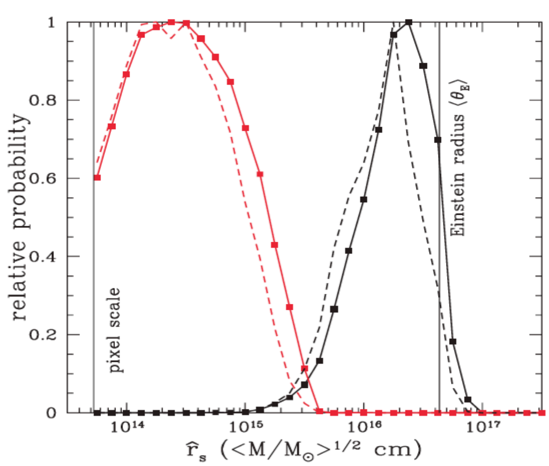
Size of PG1115 in Einstein radius units

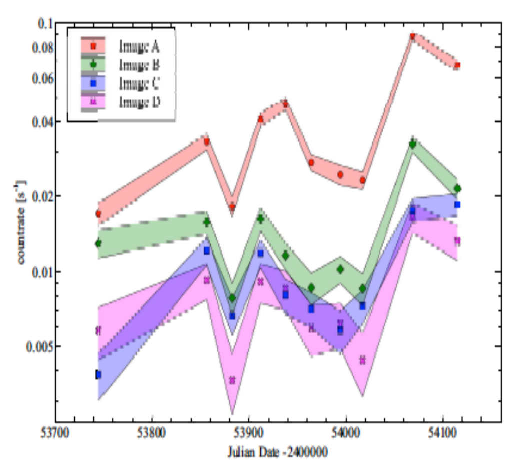


X-ray MicroLensing Also

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

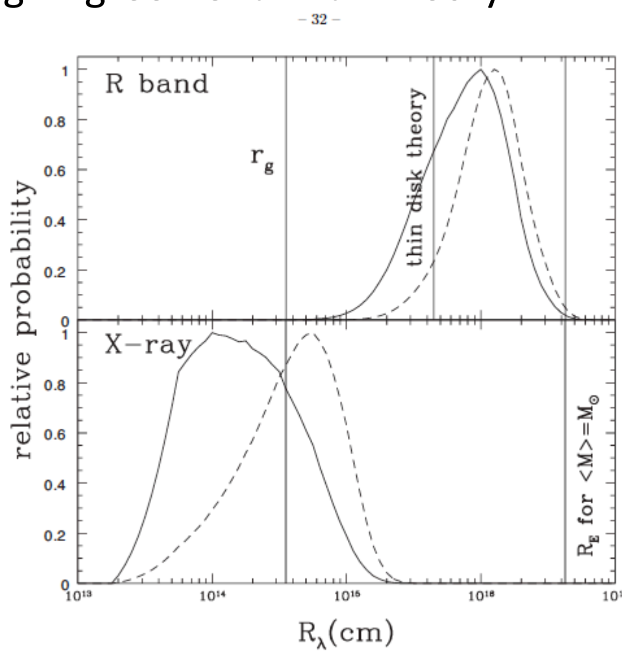






Results are In Rough Agreement With Theory

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



Chartas 2008