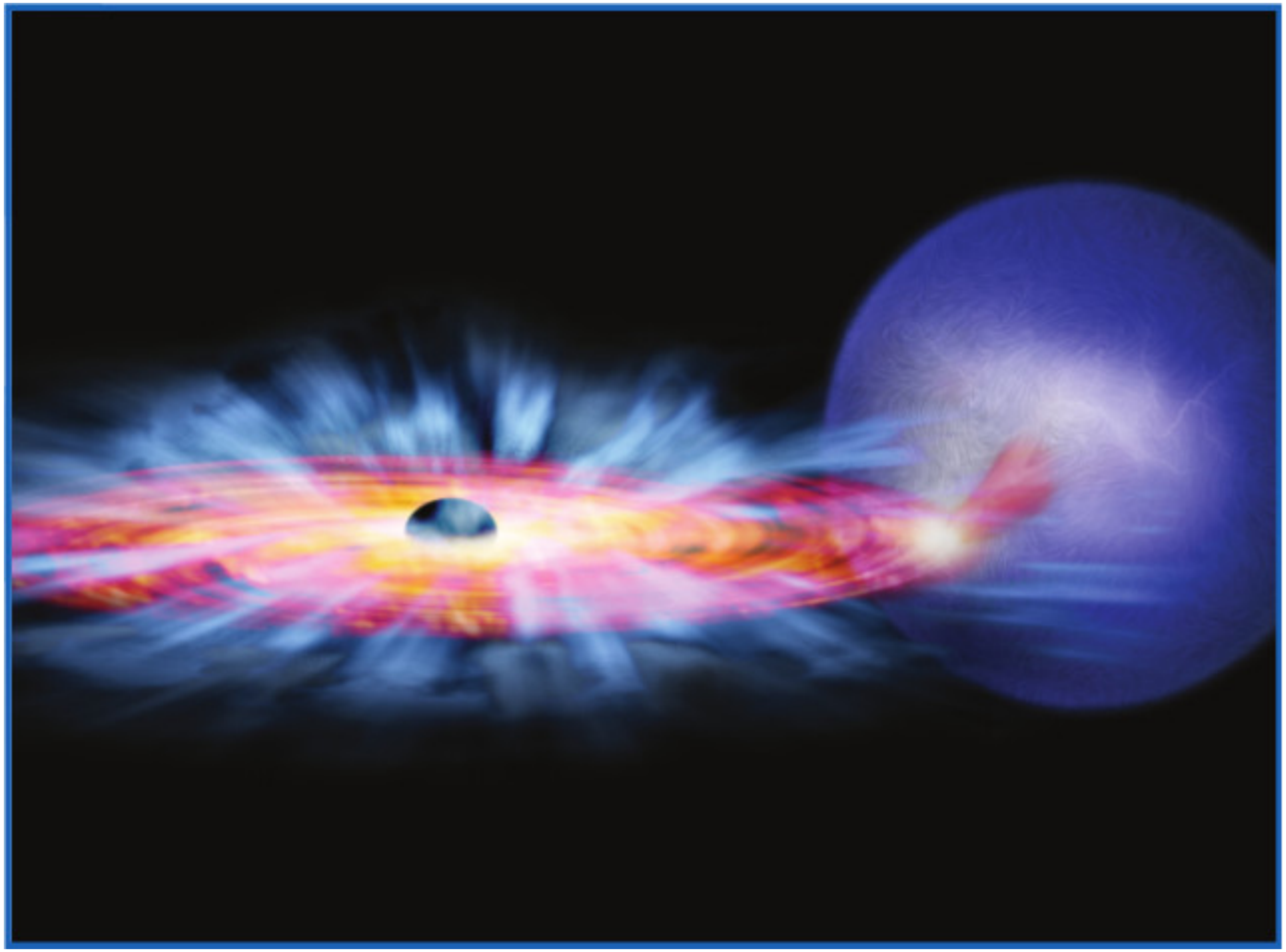
Accretion Disks



Accretion Disks

1. Accretion Efficiency

2. Eddington Luminosity

3. Bondi-Hoyle Accretion

4. Temperature profile and spectrum of accretion disk

5. Spectra of AGN

5.1 Continuum

5.2 Line Emission

AGN Accretion

Accretion is the extraction of gravitational potential energy from material which falls into a gravitating body and is the principle power supply for AGN's.

The **energy released** from bringing a mass from infinity to the surface of a body of mass M and radius R is:

$$\Delta E_{accretion} = \frac{GMm}{R} = \frac{GM}{Rc^2} mc^2 = \eta mc^2$$

For a neutron star $\eta \sim 0.1$
For a black hole $\eta \sim 0.06\text{-}0.42$
For a white dwarf $\eta \sim 0.001$

The efficiency of nuclear reactions is about 0.01-0.001

AGN Accretion

The **luminosity of an AGN** depends on the rate at which material is accreting.

At high luminosities, however, accretion may be impeded by photon pressure from Thomson scattering of photons off electrons of the accreting material.

$$L_{accretion} = \frac{G\dot{M}M}{R} = \eta\left(\dot{M}\right)c^2$$

To power a typical AGN requires an accretion rate of:

$$\dot{M} = \frac{L_{accretion}}{\eta c^2} \sim 1.8 \times 10^{-3}\left(\frac{L_{44}}{\eta}\right)M_{solar}yr^{-1}$$

where L_{44} is the central source luminosity in units of 10^{44} ergs s^{-1}

Eddington Luminosity of an AGN

We assume steady, spherically symmetrical accretion, with the accreting material being mainly hydrogen and fully ionized.

The **radiation force** from the compact object exerts a force on the free electron through Thomson Scattering.

Radiation force on electrons: (photon flux per cm^2)x(cross section)x(momentum of each photon) =

$$\frac{\left(L_{Edd}/h\nu\right)}{4\pi R^2}\sigma_T\left(\frac{h\nu}{c}\right)=\frac{L\sigma_T}{4\pi R^2 c}$$

We balance this force with gravity:

$$\frac{L_{Edd}\sigma_T}{4\pi R^2 c}=\frac{GMm_p}{R^2}\longrightarrow L_{Edd}=\frac{4\pi GMm_p c}{\sigma_T}\longrightarrow L_{Edd}=1.3\times 10^{38}\left(\frac{M}{M_{solar}}\right)erg/\sec$$

Notice that the photon scatter off the electrons but we take the proton mass in the above equation since the protons and electrons our bound.

AGN have luminosities close to L_{EDD} ie. $L/L_{EDD} \sim 0.1$ - 1

AGN Accretion Rate

The Eddington accretion rate is defined as the mass accretion rate necessary to sustain the Eddington luminosity L_E:

$$\dot{M}_E = \frac{L_E}{\eta c^2} \sim 2.2 M_8 \mathrm{M}_{\mathrm{solar}} \mathrm{yr}^{-1}$$

We note that this limit can be exceeded with models that are not spherically symmetric.

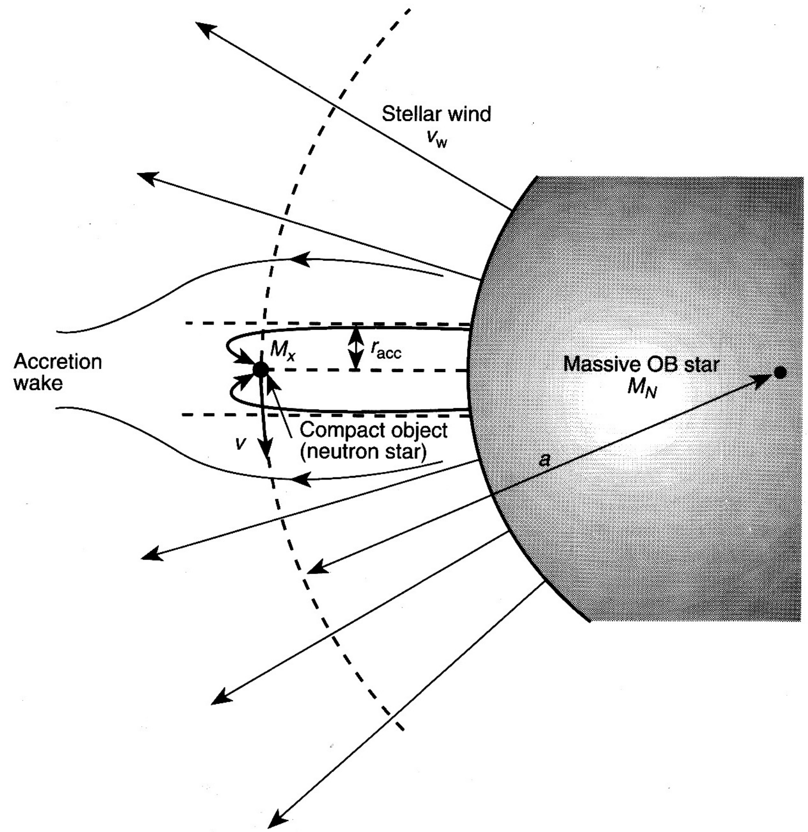
One of the problems in fueling AGN is finding a mechanism to liberate angular momentum from the infalling gas before it reaches the accretion disk. The angular momentum per unit mass m is:

$$\frac{|L|}{m} = (GMr)^{1/2}$$

where M is the mass interior to r. Possible mechanisms proposed for removing angular momentum are the MRI, gravitational interactions of galaxies, and AGN winds. Tidal disruption of stars is thought to be a mechanism of fueling quasars.

Bondi-Hoyle Accretion Rate

A massive star possesses a wind. Material that flows within a radius r_{acc} will be accreted onto the compact object whereas material outside this radius will escape.



If the kinetic energy of a mass m in the vicinity of the compact object is less than its potential energy then it will be accreted.

$$\frac{1}{2} m v_{rel}^2 = \frac{G M_X m}{r_{acc}} \Rightarrow r_{acc} = \frac{2 G M_X}{v_{rel}^2}$$

where v_{rel} is the relative velocity of the wind and the compact object.

$$v_{rel}^2 = v_{wind}^2 + v_{compact}^2 \quad \text{and} \quad v_{compact} = \sqrt{\frac{G M_N}{a}}$$

Bondi-Hoyle Accretion Rate

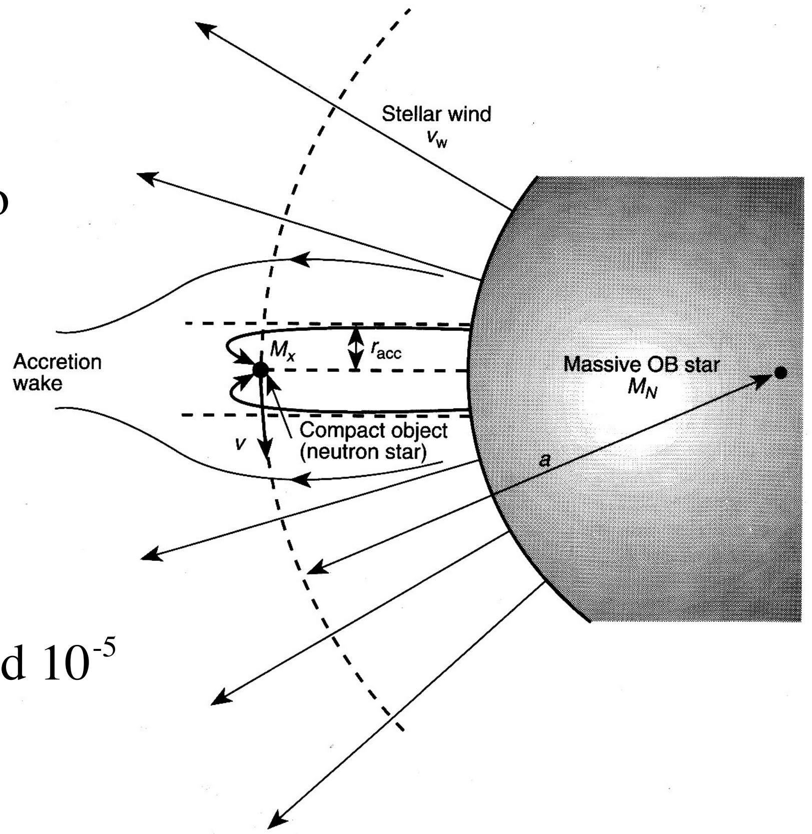
$$dm_{compact} = \rho v_{rel} dt \pi r_{acc}^2 \Rightarrow \dot{m}_{compact} = \rho v_{rel} \pi r_{acc}^2$$

$$dm_{wind} = \rho v_{wind} dt 4\pi a^2 \Rightarrow \dot{m}_{wind} = \rho v_{wind} 4\pi a^2$$

The fraction of the wind that is accreted onto the compact object is:

$$\frac{\dot{m}_{compact}}{\dot{m}_{wind}} = \left(\frac{M_X}{M_N}\right)^2 \frac{\left(v_{compact} / v_{wind}\right)^4}{\left[1 + \left(v_{compact} / v_{wind}\right)^2\right]^{3/2}}$$

This fraction turns out to be between 10^{-3} and 10^{-5} for typical massive X-ray binaries.



Temperature Profile of Accretion Disk

A simple temperature profile for the accretion disk of a black hole can be estimated if we assume that the observed luminosity is mainly produced by accretion, the medium is optically thick, and energy is dissipated locally. Under these conditions the local spectrum is approximately that of a blackbody.

The total energy of an accreting mass m in a Keplerian orbit at a radius r is:

$$E_{tot} = -\frac{GMm}{2r}$$

We assume the mass transfer rate is: $\frac{dm}{dt} = \dot{m}$

The energy change in a ring due to the transfer of mass m is:

$$dE = \frac{dE}{dr}dr = \frac{d}{dr}\left(-\frac{GMm}{2r}\right)dr = \frac{GMm}{2r^2}dr$$

$\left(\frac{dE}{dt}\right)_{disk} = \frac{GM\dot{m}}{2r^2}dr$ this is the rate of energy deposited into the disk from accretion at a rate of $\dot{m}$

Temperature Profile of Accretion Disk

Assume that the energy deposited in the ring *dr* during accretion is radiated as blackbody radiation.

$$\left(\frac{dE}{dt}\right)_{BB} = 4\pi r dr \sigma T^4$$

$$\left(\frac{dE}{dt}\right)_{Disk} = \left(\frac{dE}{dt}\right)_{BB} \Rightarrow \frac{GM\dot{m}}{2r^2} dr = 4\pi r dr \sigma T^4 \Rightarrow T^4 = \frac{GM\dot{m}}{8\pi r^3 \sigma}$$

A more thorough analysis which takes into account viscosity gives:

$$\mathrm{T}_{\mathrm{disk}}(r) = \left(\frac{3GM\dot{m}}{8\pi R^3 \sigma}\right)^{1/4} \left(\frac{R}{r}\right)^{3/4} \left(1 - \sqrt{\frac{R}{r}}\right)^{1/4}$$

where r is the radius of the compact object.

Temperature Profile of Accretion Disk

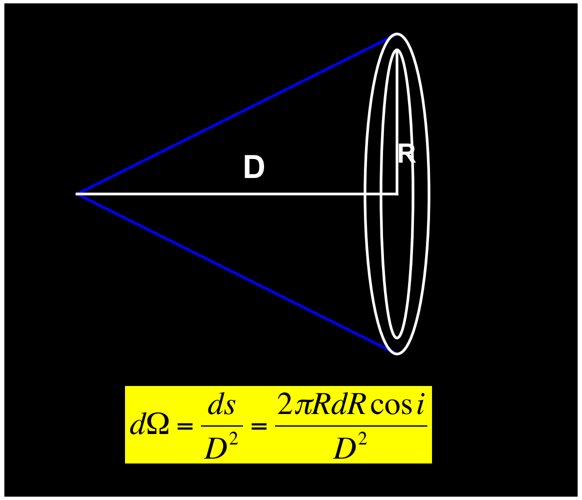
The emitted spectrum at a radius R is the Planck function :

$$B_\nu[T(r)] = \frac{2h\nu^3}{c^2\left(e^{h\nu/kT(r)}-1\right)}\left(erg\,s^{-1}\,cm^{-2}\,Hz^{-1}\,sr^{-1}\right)$$

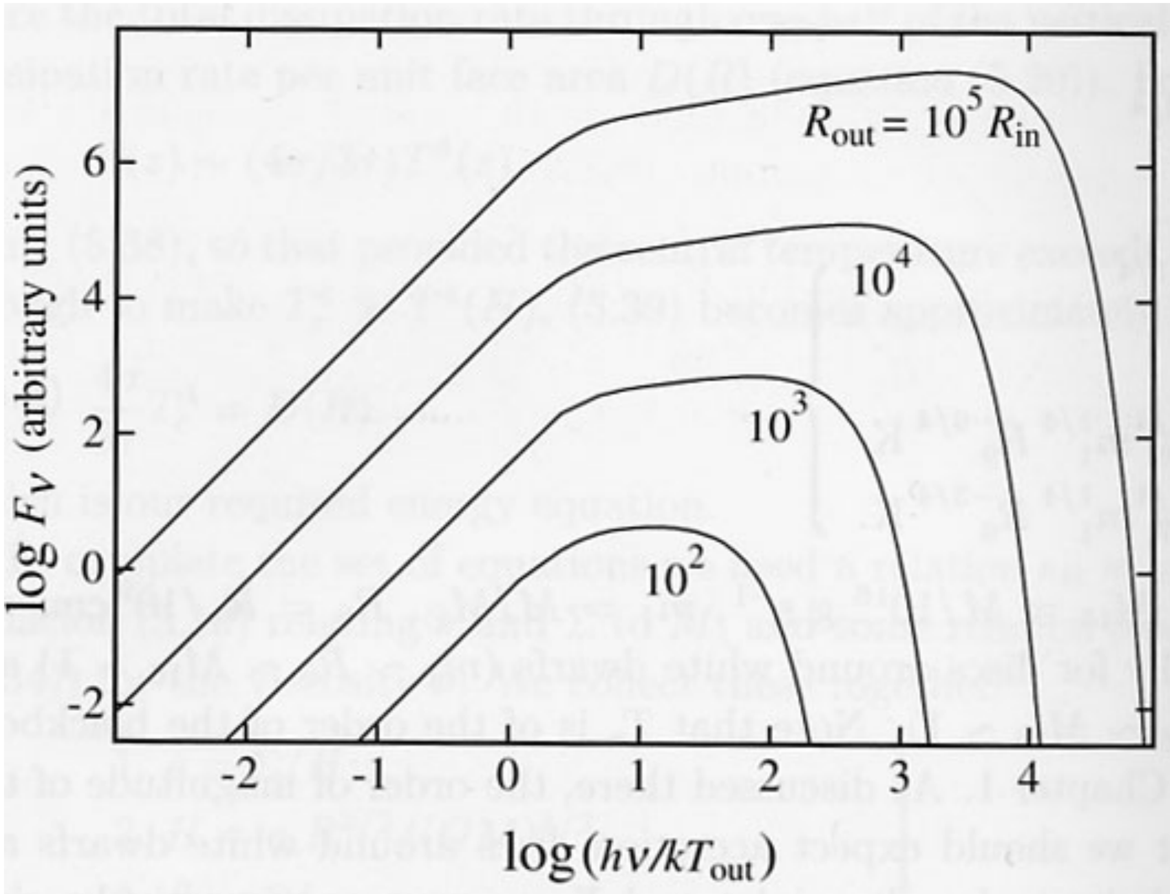
Integrating over the solid angle we obtain the flux

at a frequency ν:

$$F_\nu = \frac{2\pi\cos i}{D^2}\int_{r_{in}}^{r_{out}} \frac{2h\nu^3}{c^2\left(e^{h\nu/kT(r)}-1\right)} r\,dr$$



Temperature Profile of Accretion Disk



For $\nu << KT/h$, $F_\nu \sim \nu^2$,

For $\nu >> KT/h$, $F_\nu \sim e^{-h\nu/KT}$

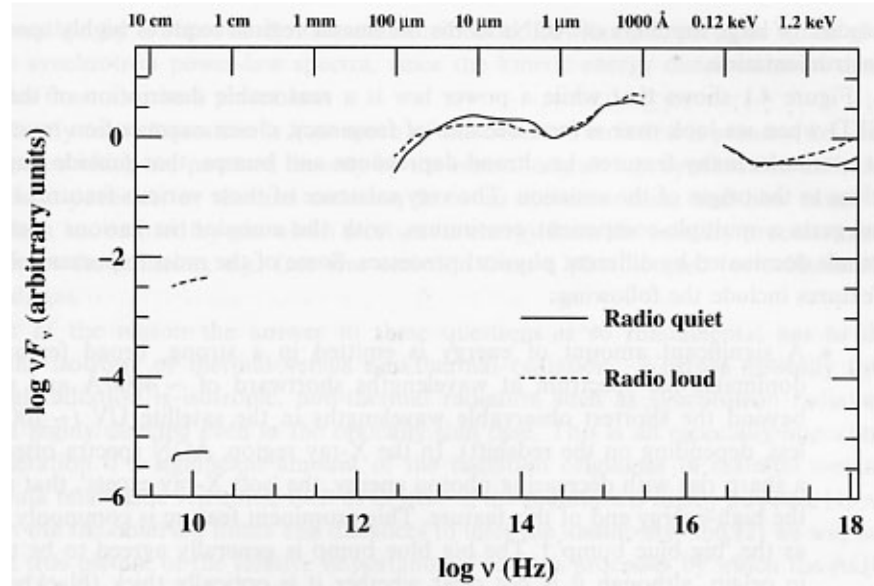
For intermediate frequencies $F_\nu \sim \nu^{1/3}$

Spectral Energy Distribution of AGN

Continuum Emission

AGN emission contains both thermal and non-thermal components.

The **Spectral Energy Distribution** (SED) of quasars extends over many orders of magnitude in frequency giving rise to many of the early proposals for the synchrotron nature of the emission.

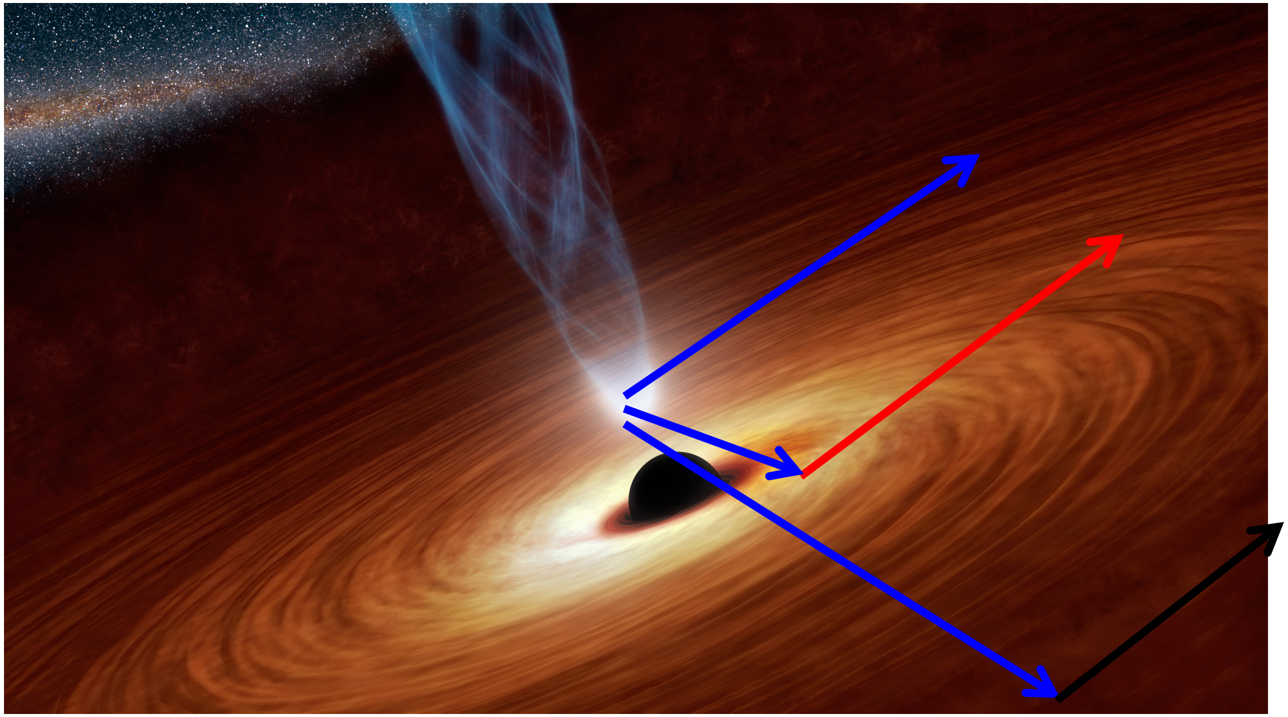


Mean spectral energy distribution for a sample of radio quiet (solid line) and radio loud quasars (Elvis et al. 1994).

Features in SED

- The gap in the data between 912Å to 100Å is due to the large opacity of the interstellar medium of our own Galaxy.
- The big blue bump between 4000Å and 400Å dominates the SED and is thought to be due to thermal emission from the optically thick accretion disk.
- A second bump commonly referred to as the IR bump is thought to be due to warm dust grains.

Fiducial Model



X-ray Power-Law from compact corona

Relativistically Blurred Reflection (line + continuum)

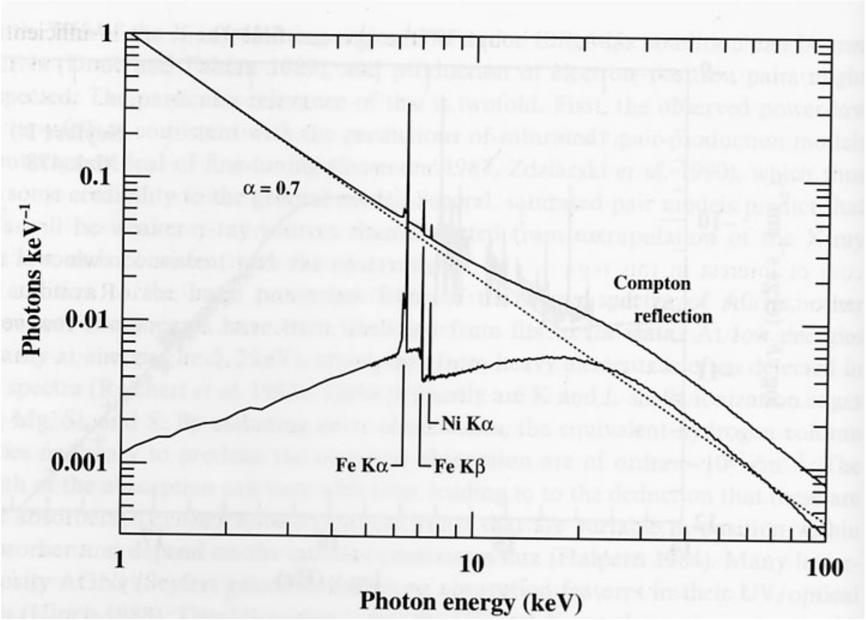
Distant Reflection (line + continuum)

Geometrically thin, optically thick accretion disk emitting primarily in UV/Optical

X-ray Spectra of AGN

Processes contributing to the observed X-ray spectra of AGN include:

- **Inverse Compton scattering** of photons in the coronae by UV photons originating from the disk, resulting in a boost of photon energies from the UV range into the soft X-ray range. (this is the mechanism that produces the observed power-law spectrum in the 2-10keV range)
- **Compton reflection** of photons from the corona by the disk, which becomes important at rest energies above ~ 10keV
- Absorption by gas, beamed X-ray emission from jets, which may be a large contributor for distant radio-loud quasars.

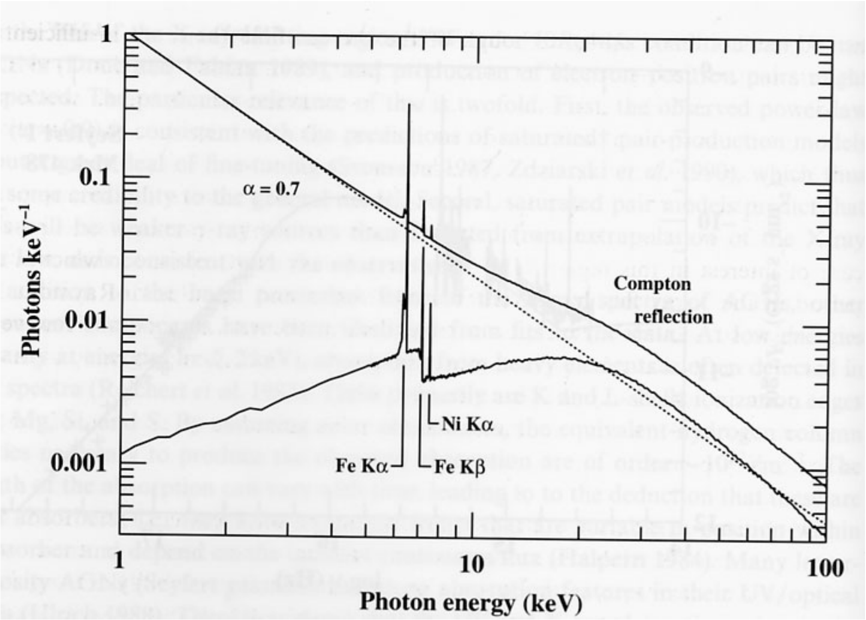


An X-ray reflection model. An input power law continuum with energy index a=0.7 (dotted line) irradiate a cold slab of gas. The lower spectrum shows the reflected X-ray spectrum. The combination of the Compton down-scattering (high-energy photons lose energy as they recoil off the electrons in the disk) and the photoelectric absorption of lower-energy photons in the disk results in a hump between ~20-100 keV. Courtesy of Ian George.

Spectra of AGN

Line Emission: Fe line

The line at ~6.4 keV is thought to be a fluorescence line of Fe due to emission from a cold or ionized accretion disk that is illuminated from a source of hard X-rays originating near the central object.



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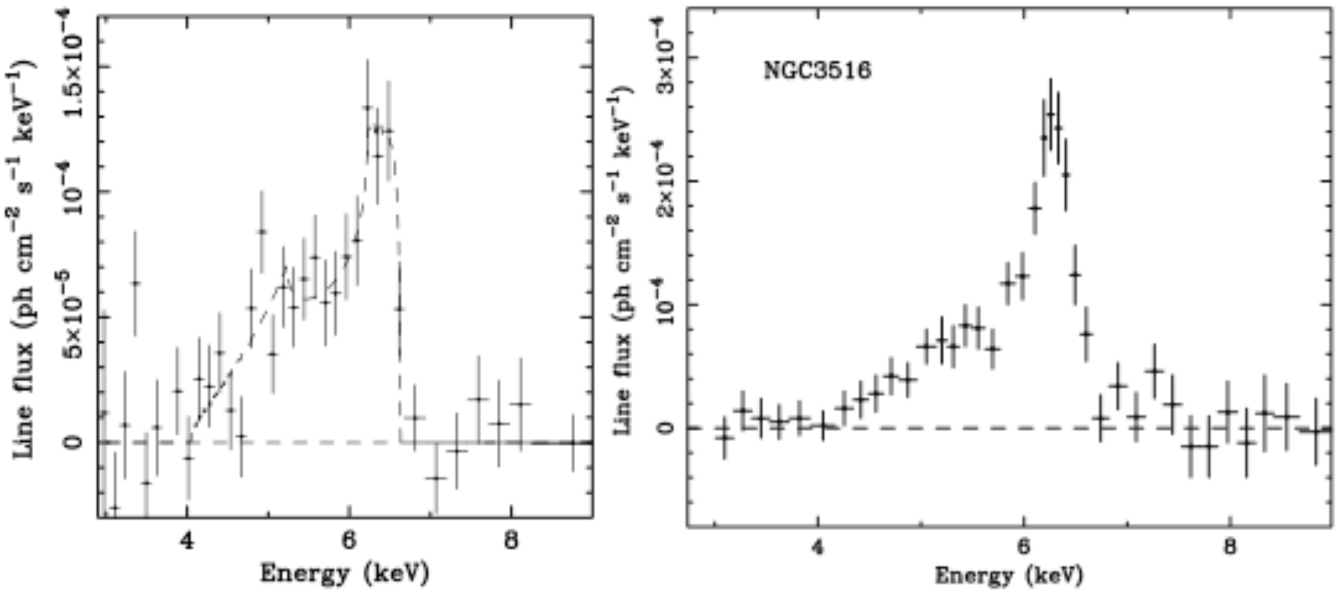
Spectra of AGN

Line Emission: Strong Gravity Effects



•Much of the X-ray emission from accreting black holes emerges from within a few 10s of gravitational radii. Aspects of this emission can provide us with a probe of the strong gravity of black hole.

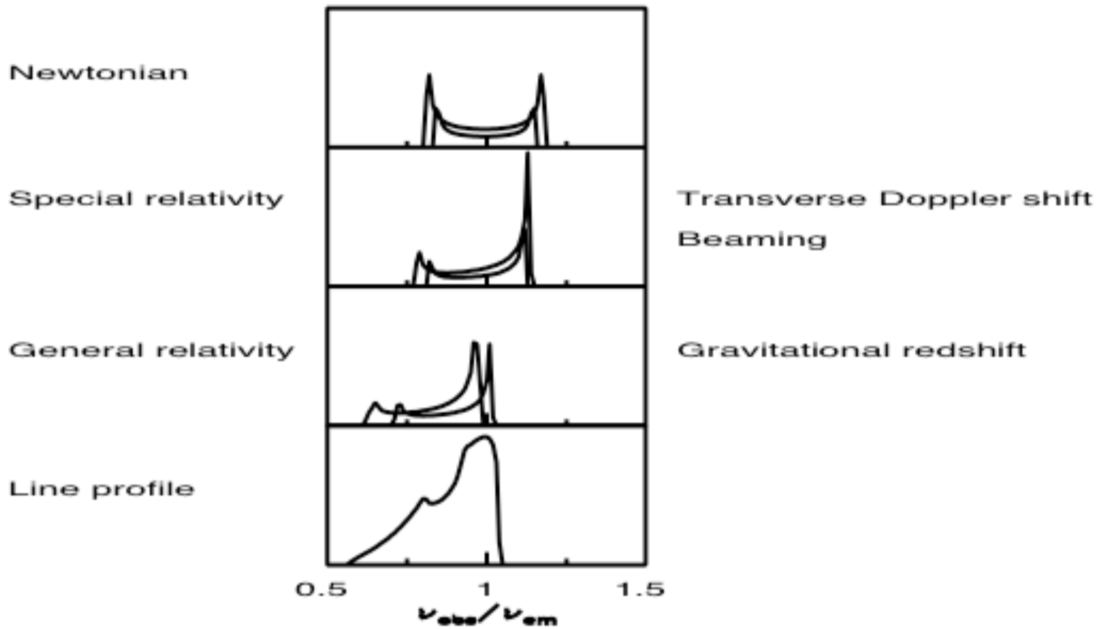
•The Fe line profile and its variability can reveal the geometry of the accretion flow, and strong gravitational effect, within a few Rs of the black hole.

•A clear broad line was first detected from the 1994 ASCA observation of the Seyfert 1 MCG-6-30-15 (Tanaka et al. 1995, left panel of above figure)

•A similar line was also seen in NGC 3516 (Nandra et al. 1999, right panel)

Spectra of AGN

Continuum Emission: Strong Gravity

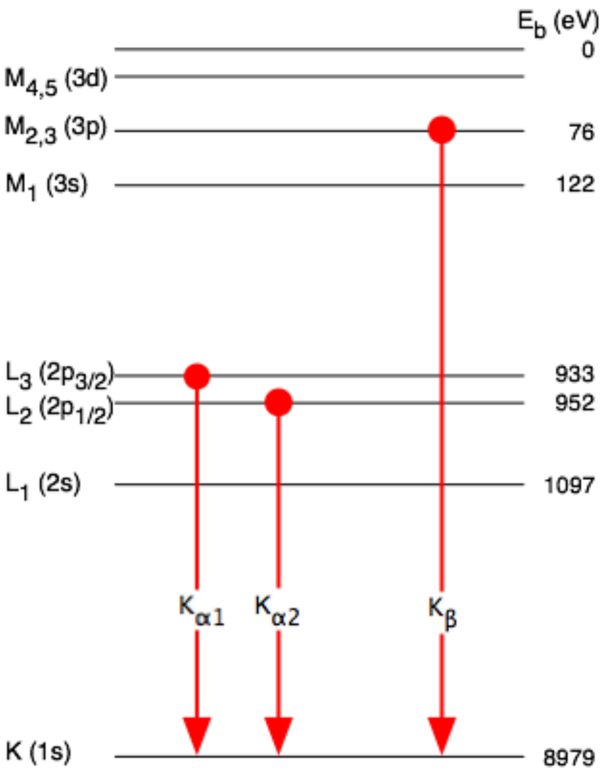


Line broadening from an intrinsically narrow line emitted from two radii in an accretion disk. The lowest panel shows the result obtained by summing many disc radii, weighted by the expected emissivity. Courtesy of A. C. Fabian, astroph/0103438

•The line is distorted due to Doppler broadening, special relativistic effects of beaming, the transverse Doppler effect and the general relativistic effect.

Fe Kα Line

Kα emission lines result when an electron transitions to the innermost "K" shell (principal quantum number 1) from a 2p orbital of the second or "L" shell (with principal quantum number 2).



Atomic levels involved in copper Kα and Kβ emission

http://physics.nist.gov/PhysRefData/XrayTrans/Html/search.html