ROMA TRE
UNIVERSITÀ DEGLI STUDI

Emission mechanisms. II

Giorgio Matt

(Dipartimento di Fisica, Università Roma Tre, Italy)

Reference: Rybicki & Lightman, "Radiative processes in astrophysics", Wiley
Kahn, in SAAS-Fee 2000, Springer

Outline of the lecture

- ***Basics on atomic transitions***
- ***Collisional equilibrium***
- ***Photoionization equilibrium***
- ***Line diagnostics***

Einstein's Coefficients (for atoms)

- **Spontaneous emission**. The system is in an excited level 2 at ener *E+h_0* and drops to a lower level 1 (energy E) by emitting a photon of energy *h_0*
  A_{21}: transition probability per unit time of spontaneous emission
- **Absorption**. The system, at level 1 with energy *E*, absorbs a photon of energy h_0 and reach the level 2 at energy *E+h_0*. The transition probability depends on the radiation field.
  $B_{12}J$: transition probability per unit time of absorption
- **Stimulated emission**. The system goes from level 2 to level 1 stimulated by the presence of a radiation field.
  $B_{21}J$: transition probability per unit time of stimulated emission

At the equilibrium, the rate of emission must be equal to the rate of absorption:

$$n_1 B_{12} J = n_2 (A_{21} + B_{21} J)$$

At thermodynamic equilibrium:

$$n_1/n_2=(g_1/g_2)e^{h\_/kT}$$

$J=B(T)$

and therefore:

$$J = \frac{A_{21}}{B_{21}\left[\left(\frac{g_1 B_{12}}{g_2 B_{21}}\right)e^{\frac{h\nu}{kT}} - 1\right]} \rightarrow \begin{aligned} g_1 B_{12} &= g_2 B_{21} \\ A_{21} &= \frac{2h\nu^3 B_{21}}{c^2} \end{aligned}$$

called "detailed balance relations" and valid universally (not only for thermodynamic equilibrium).

Not all atomic transitions are allowed. Selection rules are such that

_S=0, _L=0,±1, _J=0,±1 (but *J=0 _ 0 strictly forbidden*).

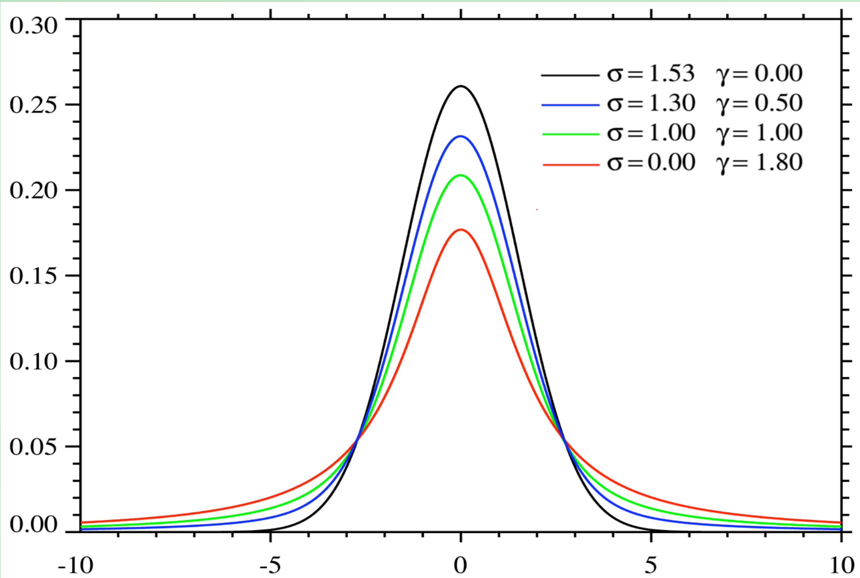
However, selection rules may be violated because they are derived in an approximated way. In practice, strictly forbidden means very low probability of occurrance.

Line profiles

Let us call *_(_)* the probability that the transition occurs by emitting or absorbing a photon with energy *h_ (emission or absorption line (∫_(_)d_ _ 1)* An unavoidable source of broadening is due to the uncertainty principle -- *dEdt ~ h/2π*, dt being the timescale of decay -- this natural broadening has the form of a Lorentzian function (_ is the decay rate):

$$\phi(\nu) = \frac{\gamma / 4\pi^2}{(\nu - \nu_0)^2 + (\gamma / 4\pi^2)}$$

Forbidden lines are narrower than resonant lines



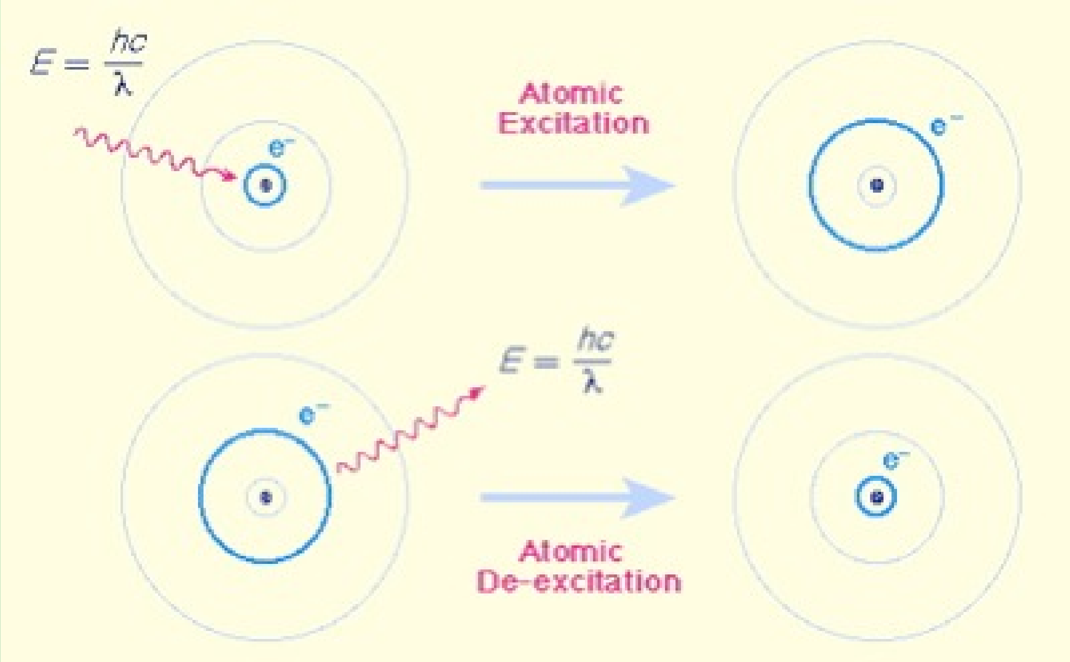
Further broadening is due to the thermal motion of atoms:

$$\phi(\nu) = \frac{1}{\sigma\sqrt{\pi}} e^{-\frac{(\nu-\nu_0)^2}{\sigma^2}}$$

$$\sigma = \frac{\nu_0}{c}\sqrt{\frac{2kT}{m}}$$

The combination of the two gives rise to the *Voigt profile,* composed by a Doppler core and Lorentzian wings

Photon Excitation/de-excitation



A photon can be absorbed by an electron in an atom, which jumps to a higher level (***excitation***). The probability of absorption depends on the ***oscillator strenght f*** (related to the Einstein coefficients). ***f*** is large for ***resonant lines***, low for ***forbidden lines.***

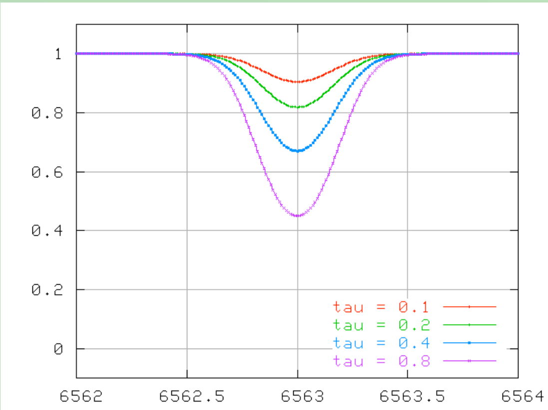
$$EW = \int \frac{I_\nu(c) - I_\nu(l)}{I_\nu(c)} d\nu$$

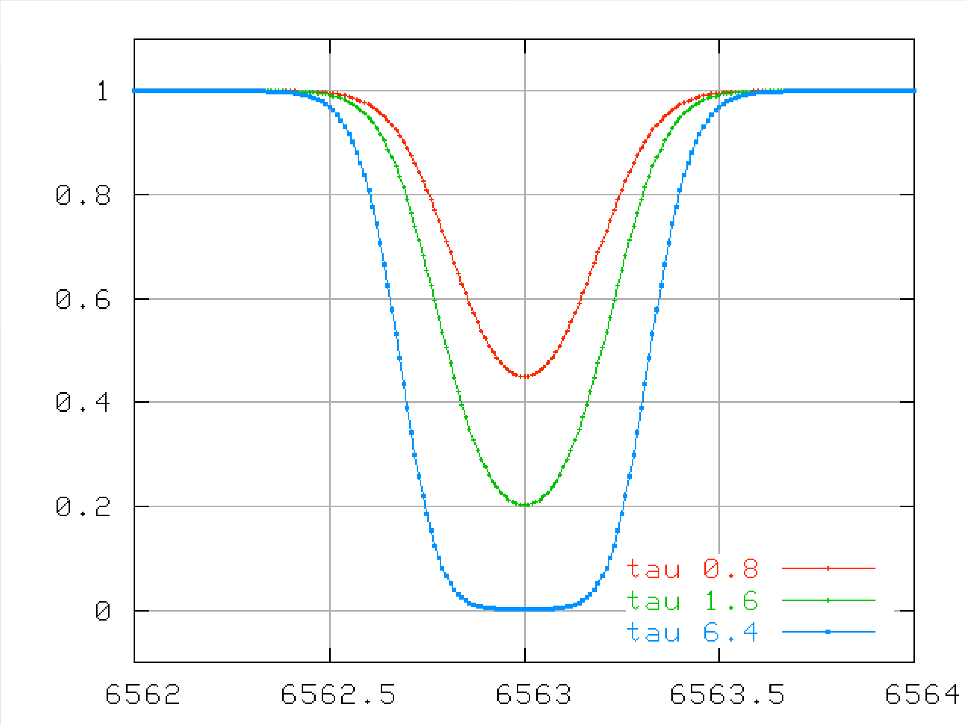
Line absorption from a population of atoms is measured in terms of the ***Equivalent Width (EW).***

I_(c) intensity of the continuum without absorption

I_(l) actual intensity of the continuum.

It corresponds to the area in the spectrum removed by the absorption, and depends on the probability of the transition and the amount of matter.





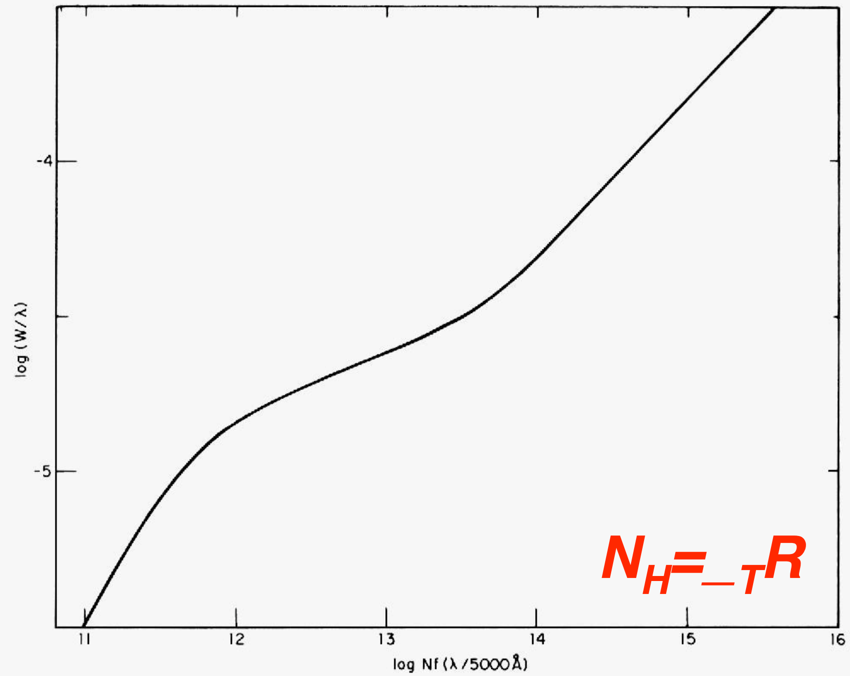
If matter is optically thin even at the line center, the line profile is unsaturated at any frequency. Increasing the optical depth, the line saturates, first in the Doppler core and then in the Lorentzian wings.

Optically thick in the wings ←

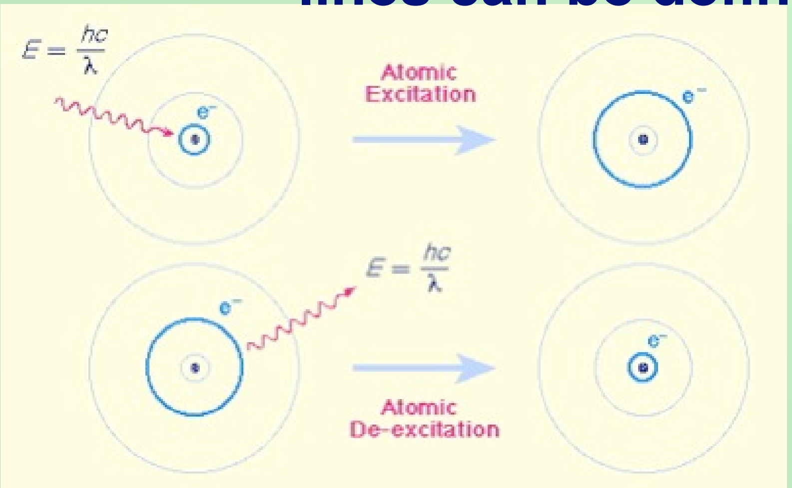
Optically thick in the core ←

Optically thin ←

Curve of growth



The inverse process is de-excitation, when an electron in an excited atom falls into a lower level by emitting one (or more, if the de-excitation occurs as a cascade) photon. Also for the emission
lines can be defined an equivalent width:

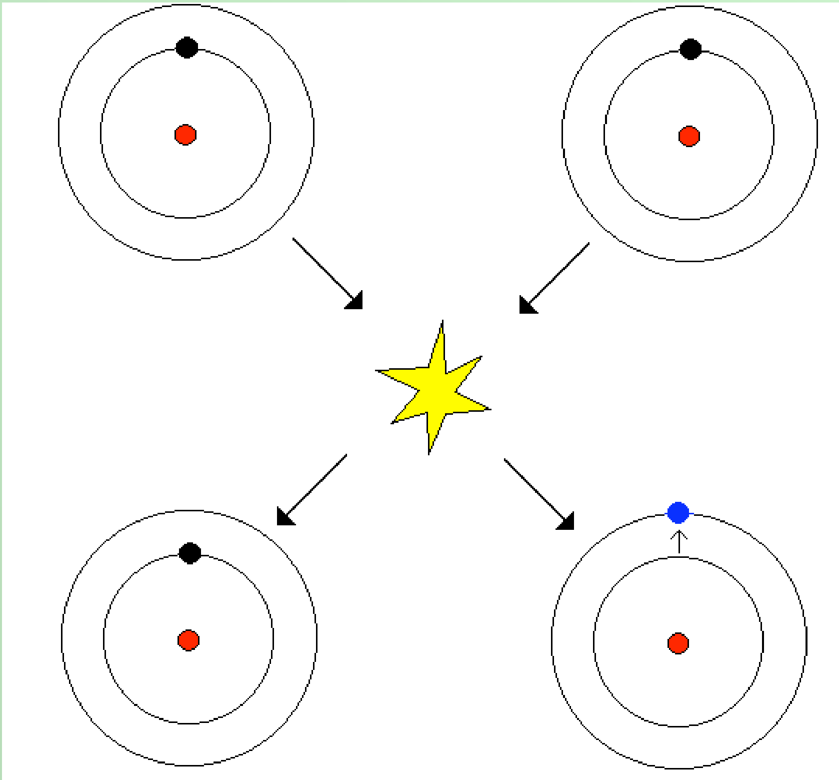


$$EW = \frac{\int I_\nu(l)\,d\nu}{I(c,\nu_l)}$$

$$\nu_l = line \quad centroid \quad energy$$

If line emission occurs via the exact inverse transition with respect to absorption, the process is called ***resonant scattering***. Resonant scattering is important for resonant lines, both because absorption is more likely (larger oscillator strengths) and because forbidden de-excitation occurs on long timescale (and therefore something different is likely to occur in the meantime).

Collisional Excitation/de-excitation



An atom can be excited by interacting with another atom or a free electron.

The inverse process is collisional de-excitation, when an electron in an excited atom falls to a lower level ceding the energy to the passing electron.

Ionization/recombination

Process (ionization)	Inverse process (recombination)
Collisional ionization	3-body recombination
Photoionization (Photoelectric absorption)	Radiative recombination
Autoionization (Auger effect)	Dielectronic recombination

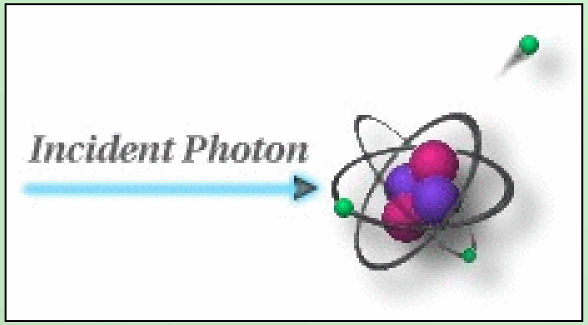
***Collisional ionization*: similar to collisional excitation, but the excited electron ends up in a continuum, rather than bound, state.**

***3-body recombination*: 2 free electrons interact with an ion. One of them gets captured, the other one remains free carrying out the excess energy**

***Autoionization*: an excited atom decays by ejecting an electron from an outer levels.**

***Dielectronic recombination*: capture of a free electron, with the excess energy used to excite the atom. The excited atom may then decay radiatively**

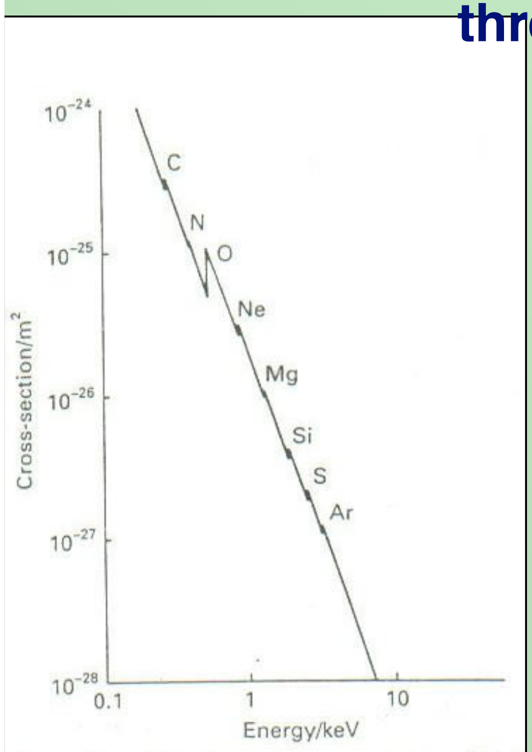
Photoelectric absorption



A bound electron is expelled from the atom by the absorption of a photon with $E \geq E_{th}$ with E_{th} the ionization potential. Above the threshold, the cross section is:

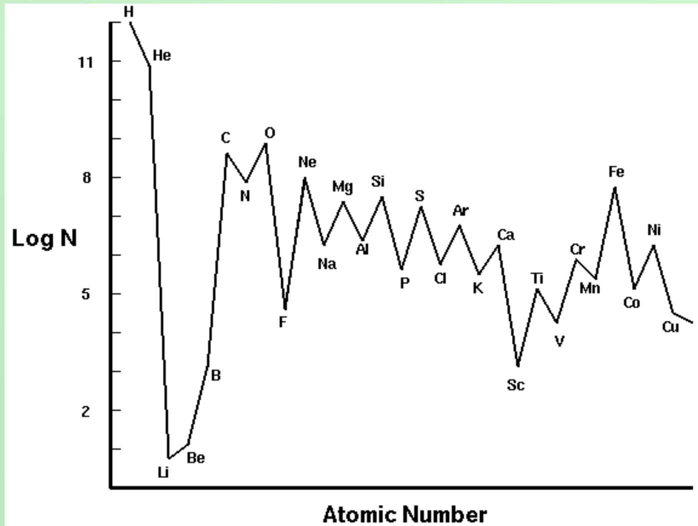
$$\sigma_{ph} = 4\sqrt{2}\sigma_T \alpha^4 Z^5 \left(\frac{mc^2}{E}\right)^{\frac{7}{2}}$$

Given the $E^{-3.5}$ dependence, the absorption is dominated by photons just above threshold.



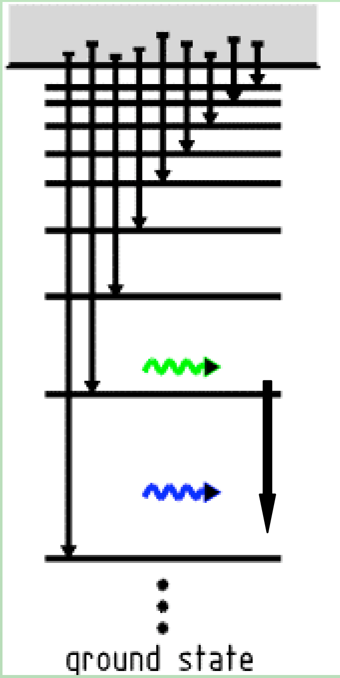
Summing over all shells and convolving with cosmic element abundances, the total cross section can be derived.

Photoionization is very important in the UV and soft X-ray band



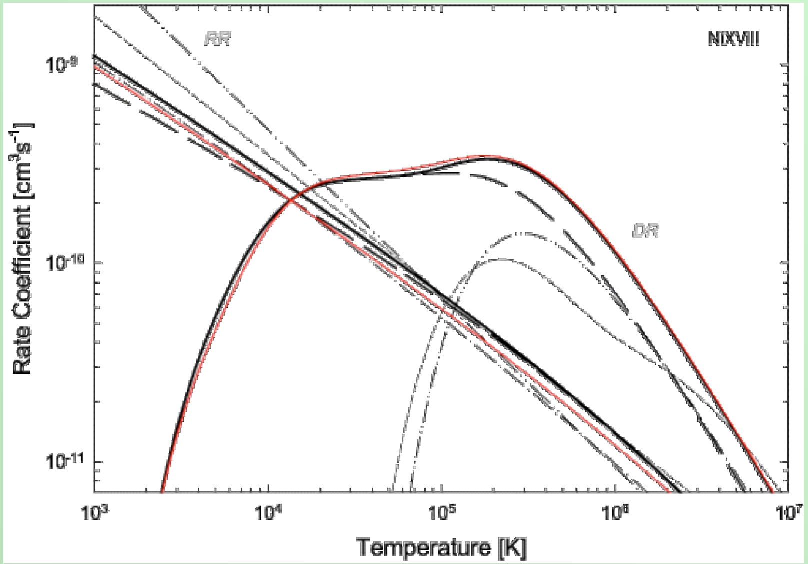
Radiative recombination

Radiative recombination (i.e. the capture of an electron by an atom with release of one or more photons) can occur either via a recombination cascade or directly to the ground state.



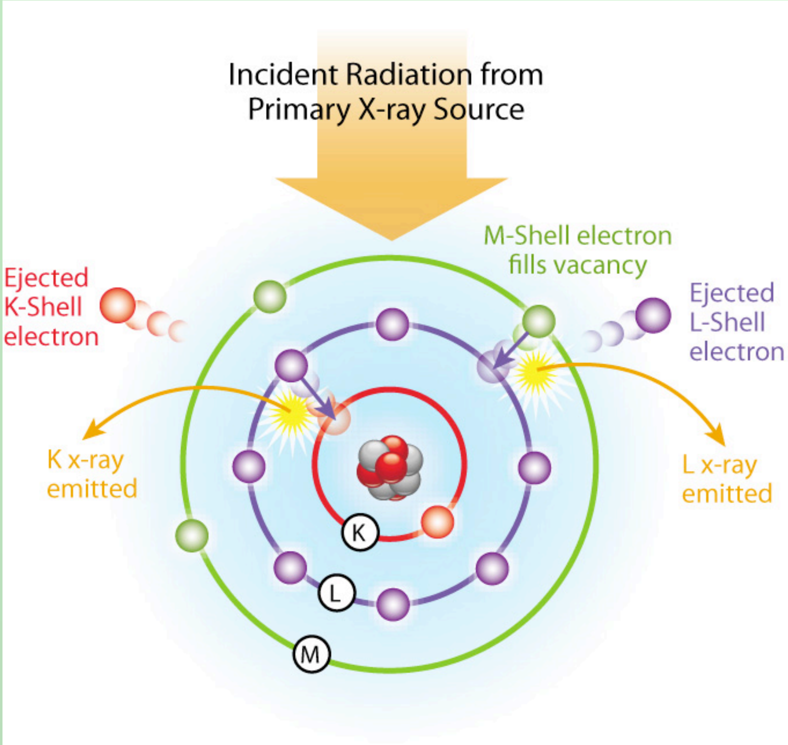
In the latter case, a pseudo continuum is created, as the photon carries out the ionization potential plus the kinetic energy of the electron.

→ *Radiative Recombination Continuum*



The recombination rate decreases with the electron velocity (temperature)

Fluorescent emission



If ionization occurs in an inner shell, the atom is not only ionized but also excited. De-excitation can occur via Auger effect (double ionization) or radiatively via emission of a *fluorescent photon*. The probability of a radiative de-excitation is called *fluorescent yield*

$$Y \approx \frac{Z^4}{Z^4 + 33^4}$$

If the ionization is in the K shell, fluorescence may occur via a L_K (K_ photon), M_K (K_ photon), etc.
K_ transition is the most probable (9/10 for iron)

Collisional equilibrium

Let us assume matter in thermal equilibrium. Let us also assume that the radiation field is negligible. At equilibrium, ionization and recombination rates must be equal.

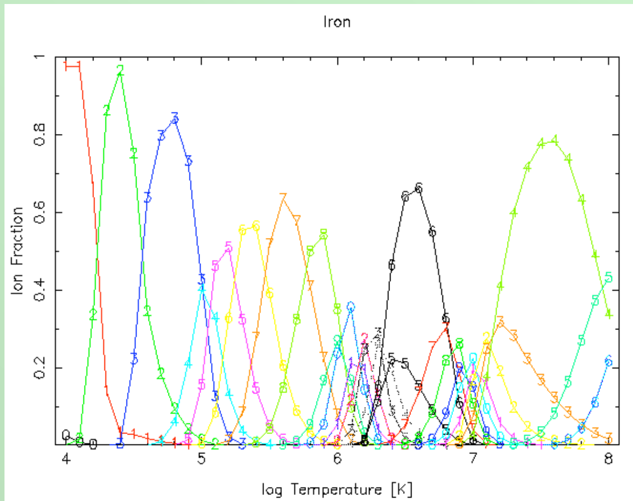
$$\left[C(X^i,T)+\alpha(X^{i-1},T)\right]n(X^i)n_e = C(X^{i-1},T)n(X^{i-1})n_e+\alpha(X^i,T)n(X^{i+1})n_e$$

$n(X^i)$ *density of i-th ion* – n_e *electron density*

$C(X^i,T)$ *ionization coefficient of i-th ion (to i+1)*

$\alpha(X^i,T)$ *recombination coefficient to i-th ion (from i+1)*

By solving this system of equations the ionization equilibrium (i.e. the fraction of each ion of each element) can be obtained as a function of temperature.



Line cooling

In collisionally ionized plasma, cooling by line emission may be important. Once solved for the ionization structure, and summing up the emissivity due to all ions, the total emissivity is:

$$\varepsilon_{lines} = \Lambda(T) n_i n_e$$
$$\Lambda(T) \propto T^{-0.7}$$

The main continuum emission process in a plasma is thermal bremsstrahlung, for which:

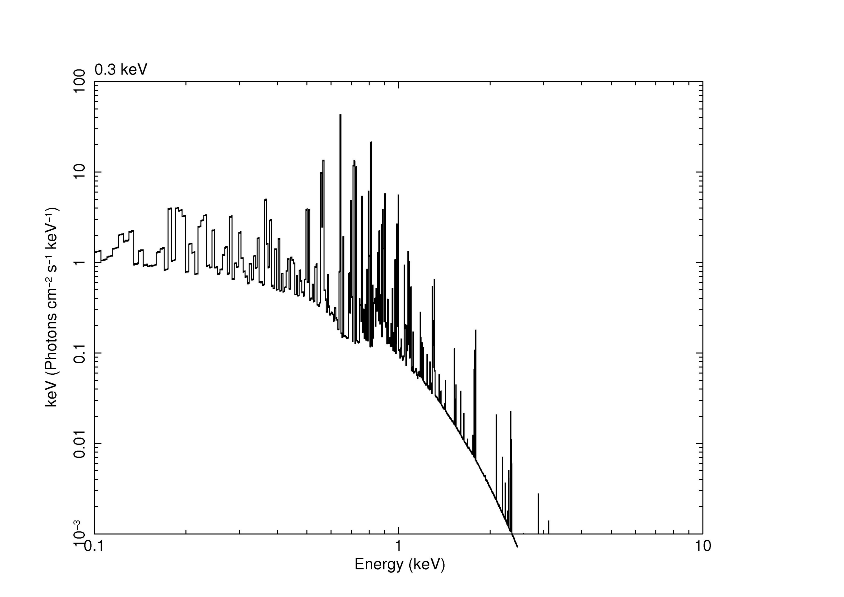
$$\varepsilon_{br} = g(T) n_i n_e$$
$$g(T) \propto T^{\frac{1}{2}}$$

For cosmic solar abundances, bremsstrahlung dominates above ~2x10^7 K (i.e. about 2 keV), line cooling below.

$$t_{cool,br} \propto T^{\frac{1}{2}}$$
$$t_{cool,lines} \propto T^{1.7}$$

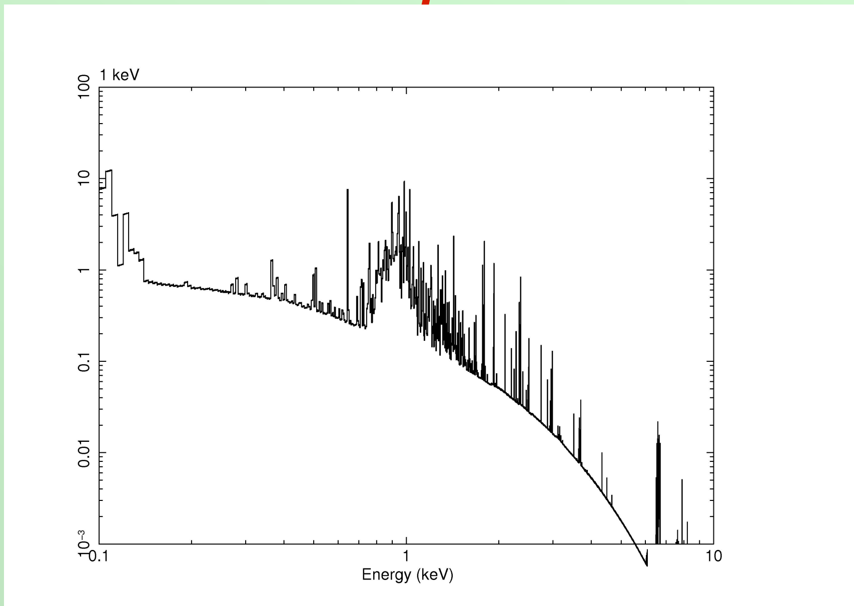
When in the line cooling regime, cooling becomes very fast

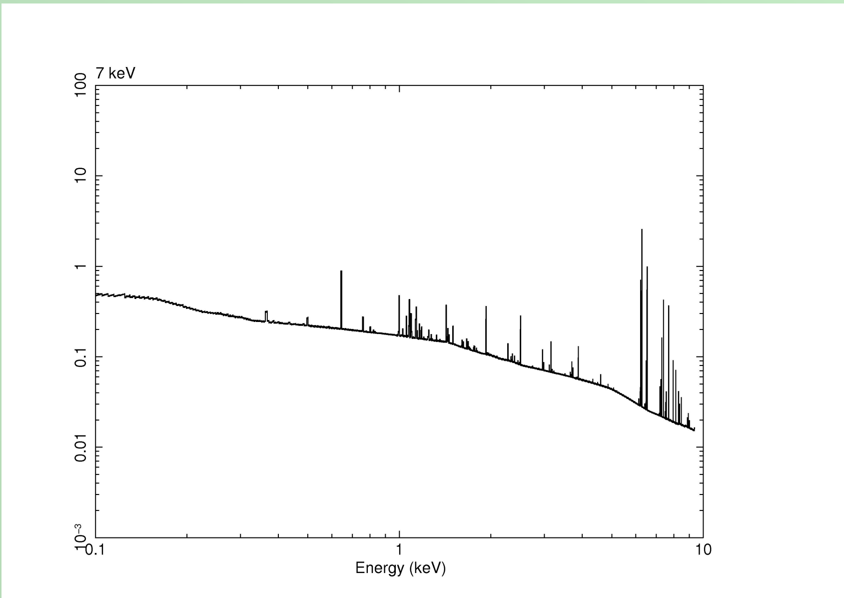
Spectra from collisionally ionized plasma



kT=0.3 keV – ***line emission dominates***

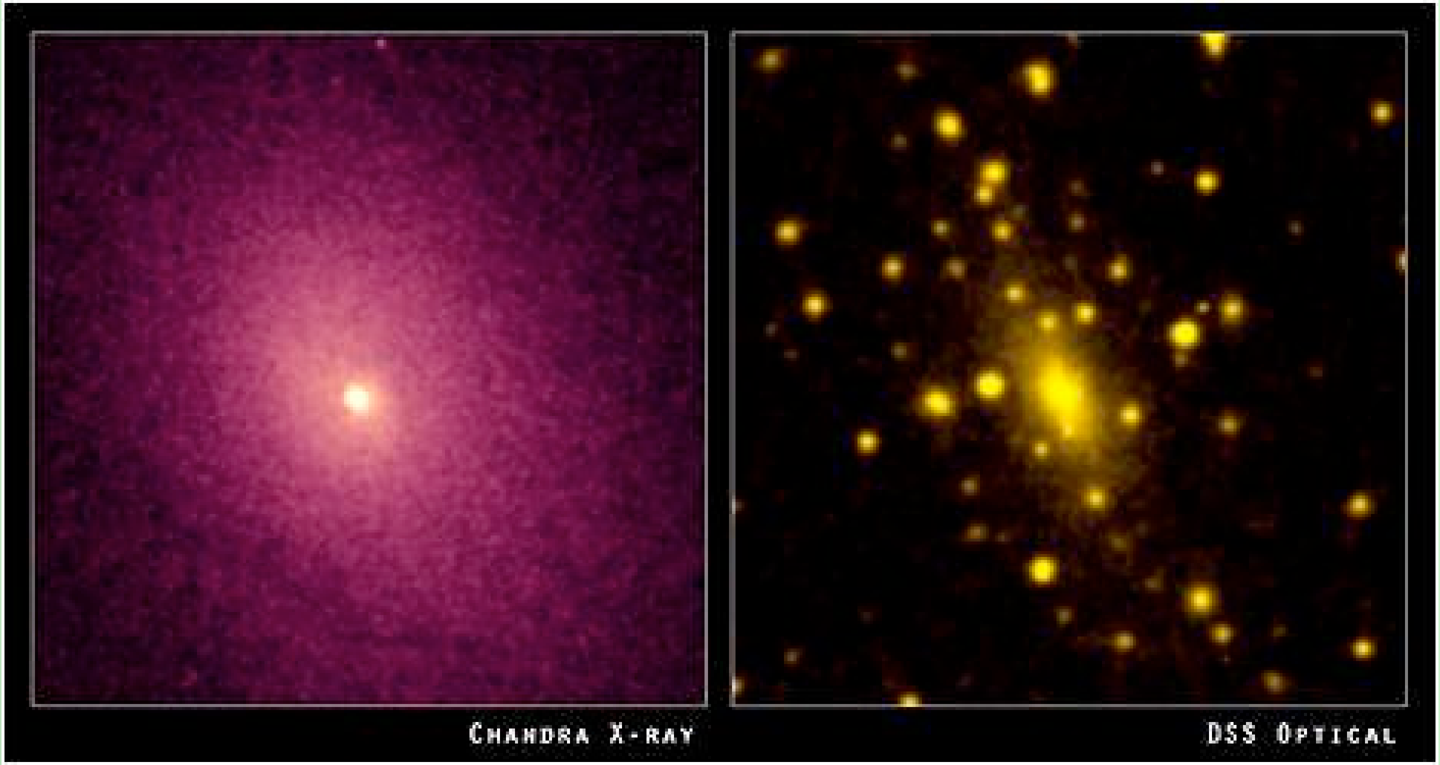
kT=1 keV – ***line and continuum emission both important***





kT=7 keV – ***continuum (brems.) emission dominates***

Example: Clusters of Galaxies



$$t_{eq}(e,e) \cong 3.3 \times 10^5 \, T_8^{\frac{3}{2}} n_{e,-3}^{-1} \quad yrs$$

$$t_{eq}(p,p) \cong \sqrt{\frac{m_p}{m_e}} t_{eq}(e,e)$$

$$t_{eq}(e,p) \cong \frac{m_p}{m_e} t_{eq}(e,e) \approx 6 \times 10^8 \quad yrs$$

IGM (Inter Galactic medium) is indeed in collisional equilibrium!

Photoionization equilibrium

Let us now assume that matter is in equilibrium with the radiation field. Photoabsorption may now be the main ionization process. Again, at equilibrium ionization and recombination rates must be equal. Assuming that the recombination time scale, *1/_(X^{i+1})n_e*, is short:

$$n(X^i)\int_{\nu_0}^{\infty}\frac{F_\nu e^{-\tau_\nu}\sigma_\nu\left(X^i\right)}{h\nu}d\nu = \alpha(X^i,T)n(X^{i+1})n_e$$

$n(X^i)$ *density of i-th ion* – n_e *electron density*

σ_ν *photoelectric cross section*

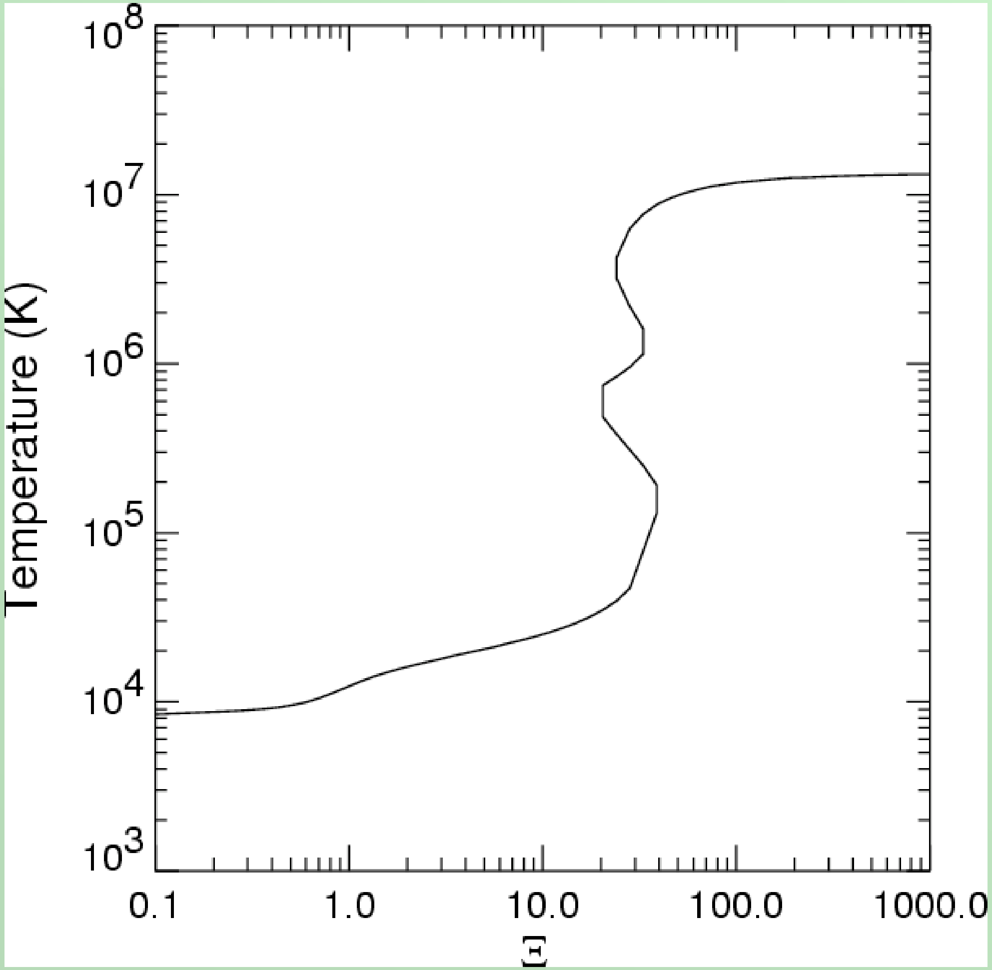
$\alpha(X^i,T)$ *recombination coefficient*

The ionization rate depends on the ionizing photon flux, the recombination rate on the matter density. The ionization structure is therefore governed by the so called *ionization parameter U*

$$U = \frac{\int_{\nu_0}^{\infty}\frac{F_\nu}{h\nu}d\nu}{n_e} \quad or \quad \Xi \propto \frac{U}{T} \propto \frac{rad.\ pressure}{gas\ pressure}$$

Photoionization equilibrium

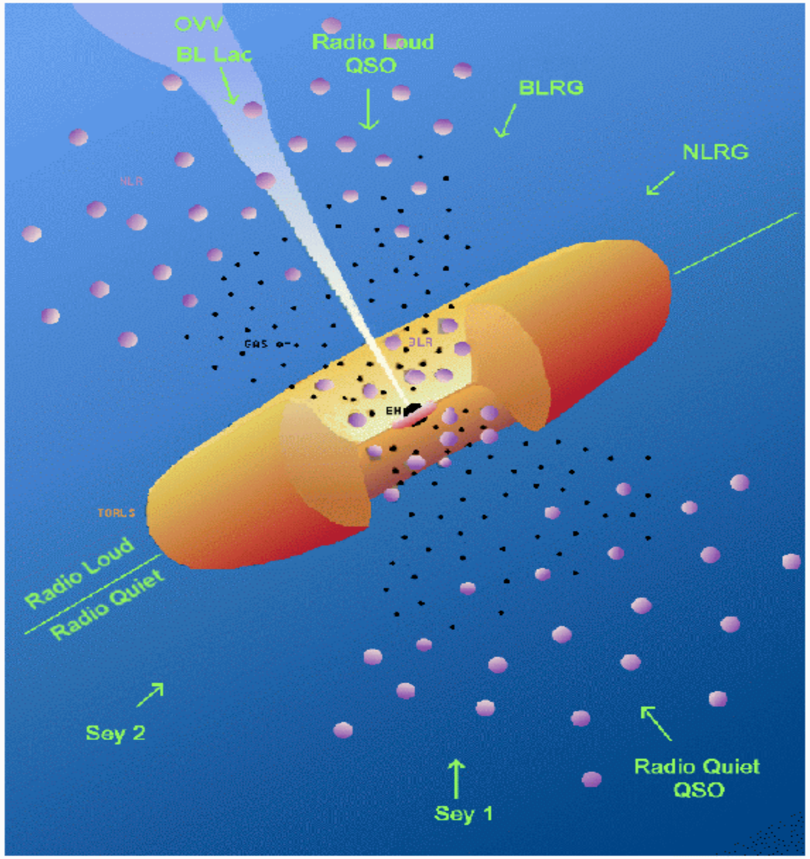
Temperature does not change much with the ionization parameter until the matter is completely ionized. At that point, photons can no longer be used for ionization, and the main interaction becomes Compton scattering.



The *Compton temperature* is then reached:

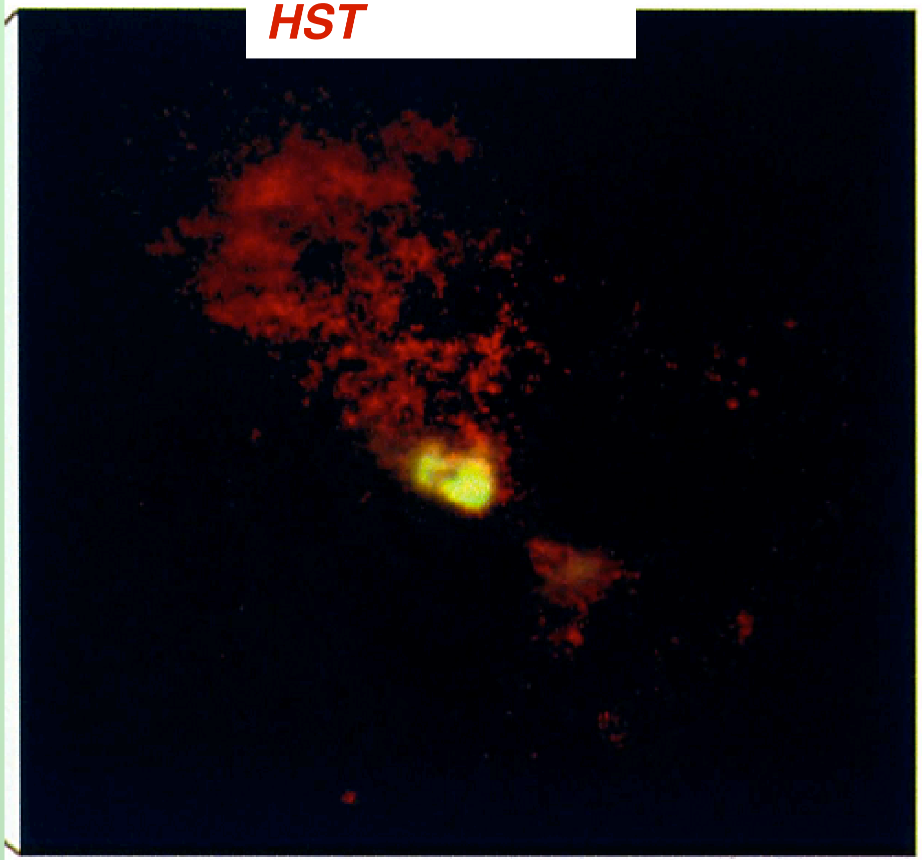
$$T_C = \frac{h\langle \nu \rangle}{kT}$$

Example: warm reflectors in AGN



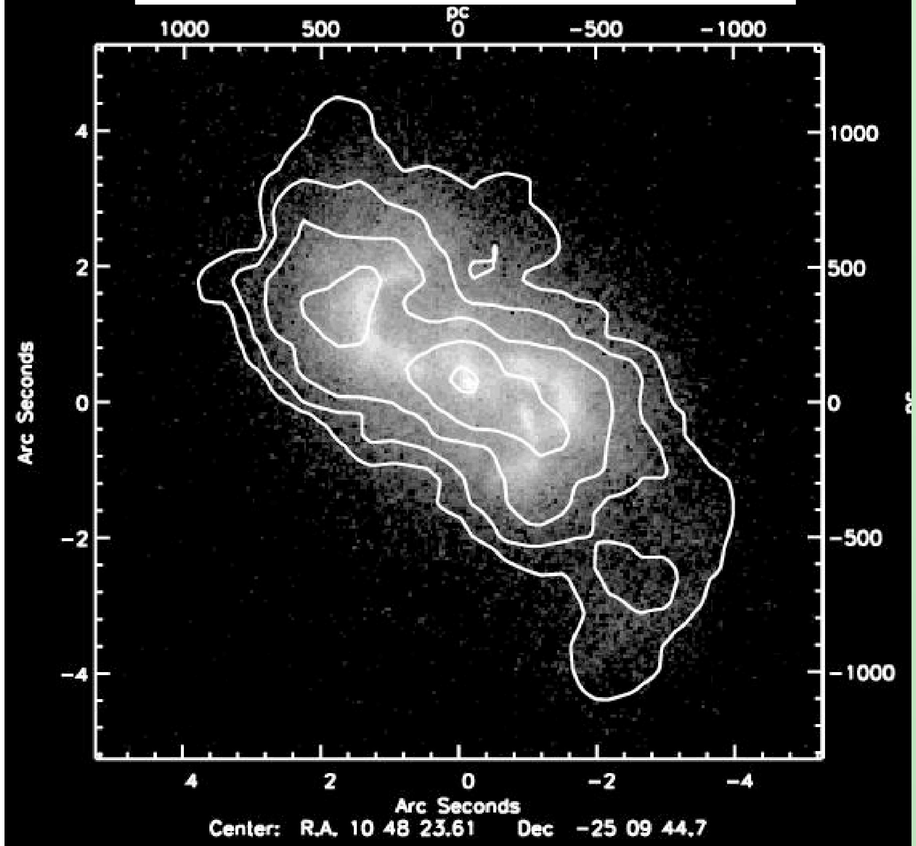
Urry & Padovani (1995)

NGC 5738 - HST

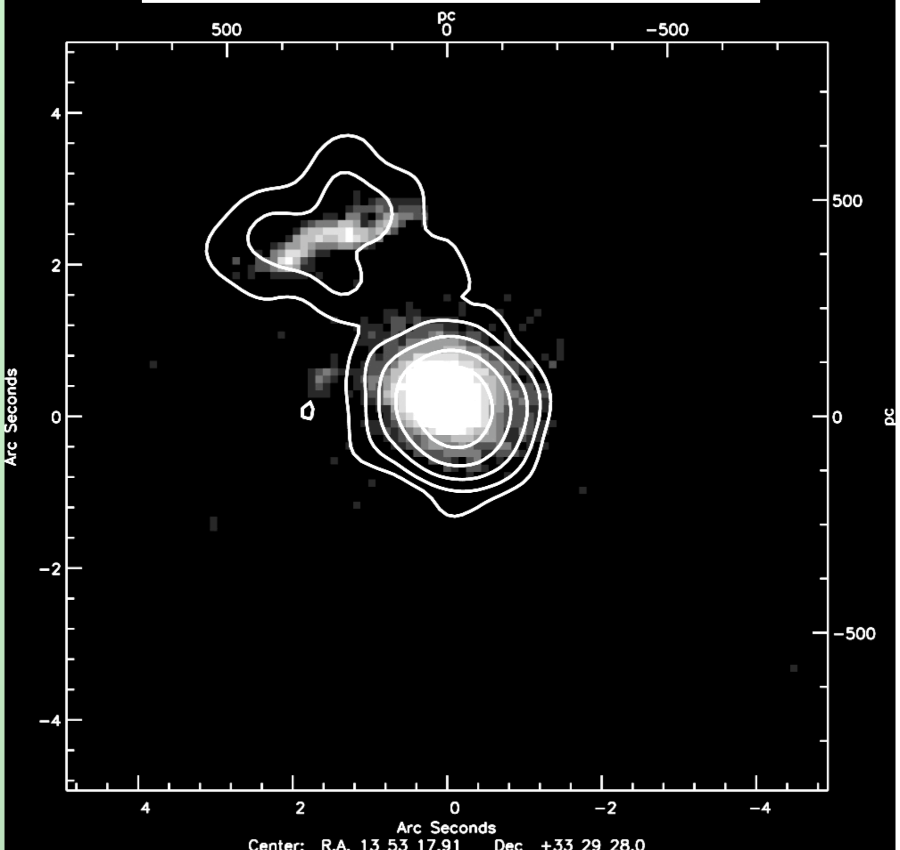


Example: warm reflectors in AGN

NGC 3393

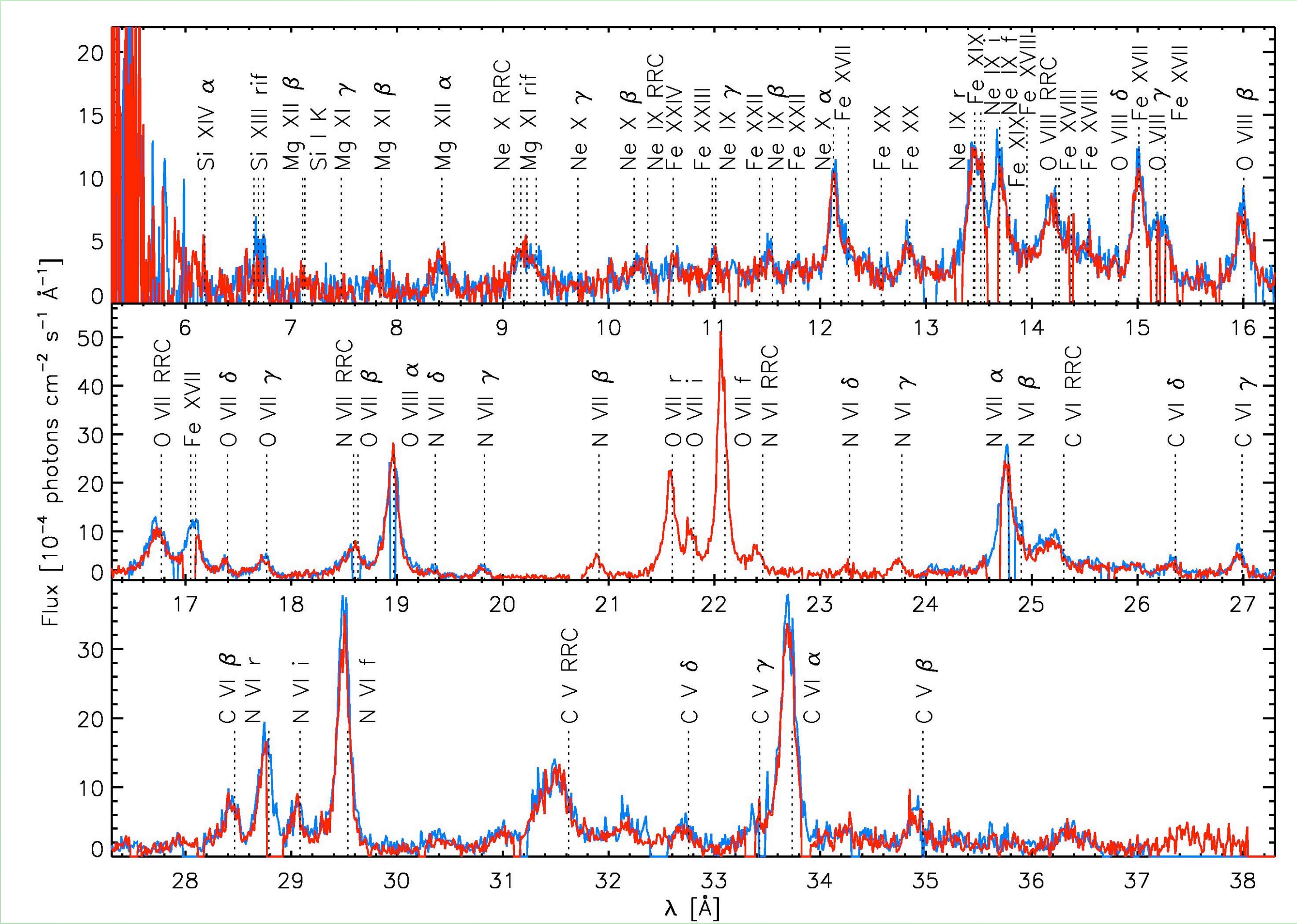


NGC 5347



Bianchi et al. 2006

Example: warm reflectors in AGN

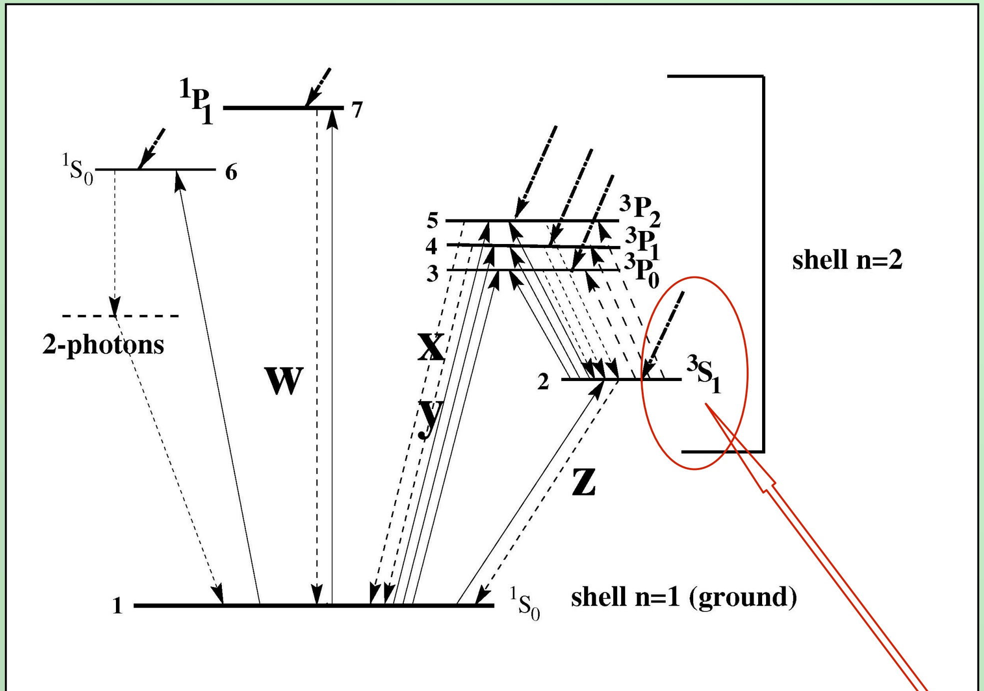


NGC 1068
(Kinkhabwala et al. 2002)

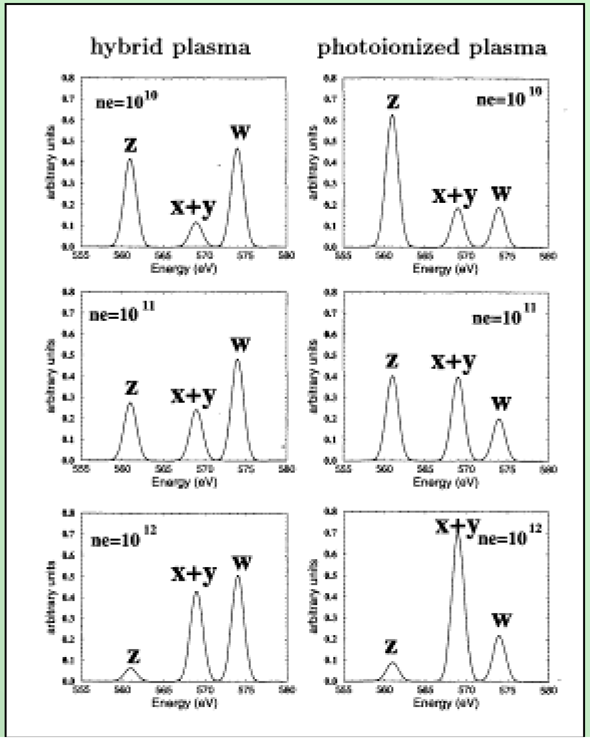
While in collisionally ionized plasmas lines tend to concentrate at energies around kT, in photoionized plasmas lines are more spread over the spectrum
(depending on the ionizing spectral distribution)

Line diagnostics

Apart from the broad band spectral fitting, other tools to distinguish between collisionally and photoionized plasma are:



Line ratios in He-like elements
(z=forbidden,
w=resonant,
x,y=intercombination)
Also density diagnostic

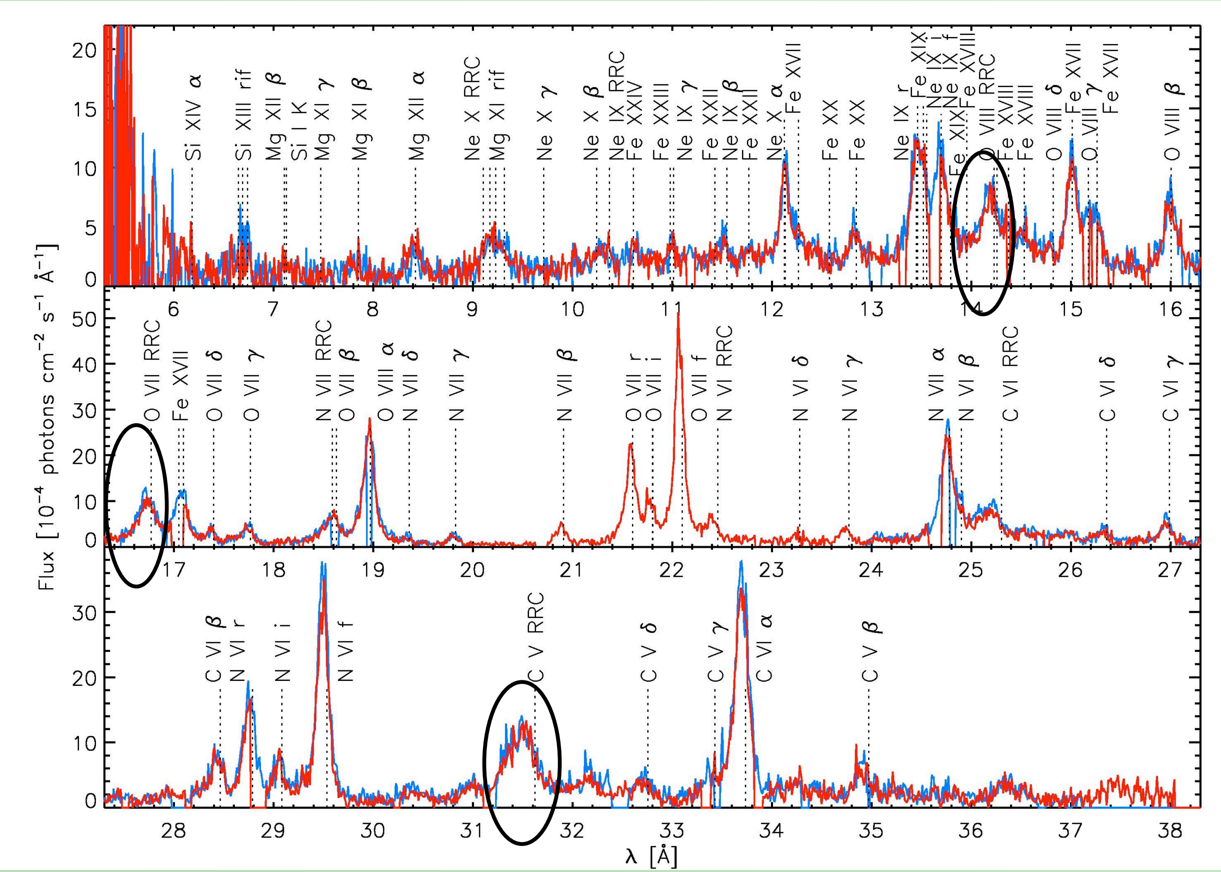


Radiative recombination preferentially occurs there

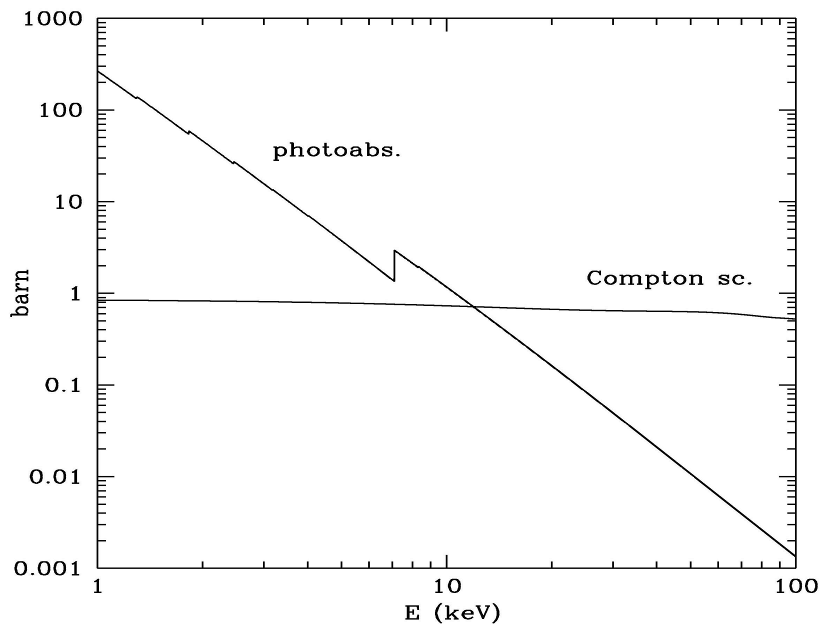
Porquet & Dubau 2000

Line diagnostics

The presence of a prominent RRC also indicates photoionized plasma (in collisionally ionized plasma it would be very broad and hard to detect).

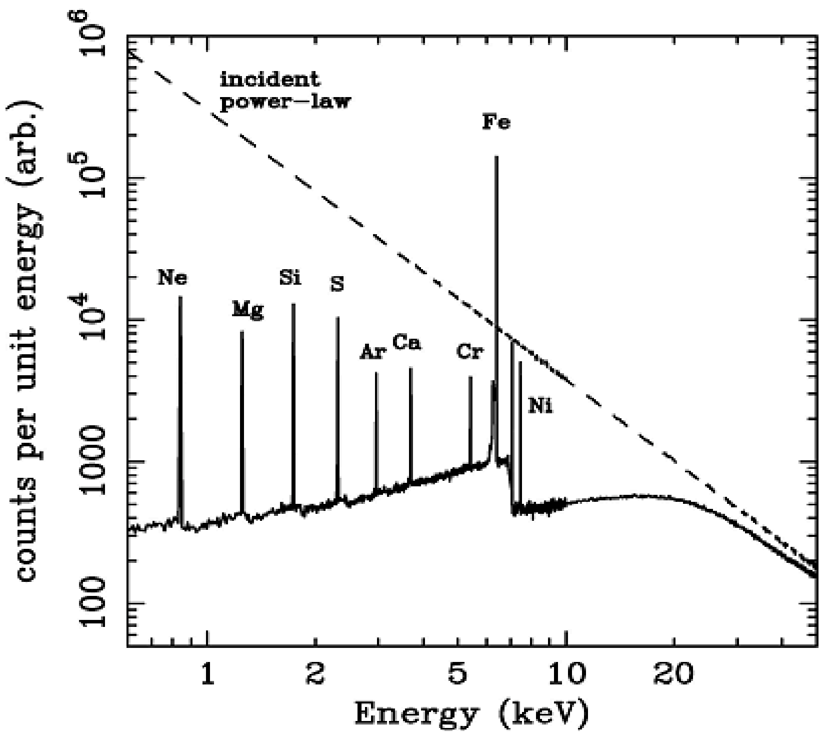


Compton Reflection



A rather common astrophysical situation is when X-rays illuminates `cold' matter.
It produces the so called *Compton reflection continuum*

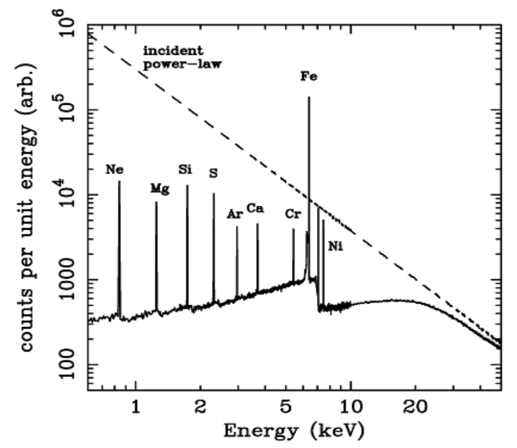
The shape of the continuum is due to the competition between photoabsorption and Compton scattering. Fluorescent lines are also produced, Fe K_ being the most prominent.

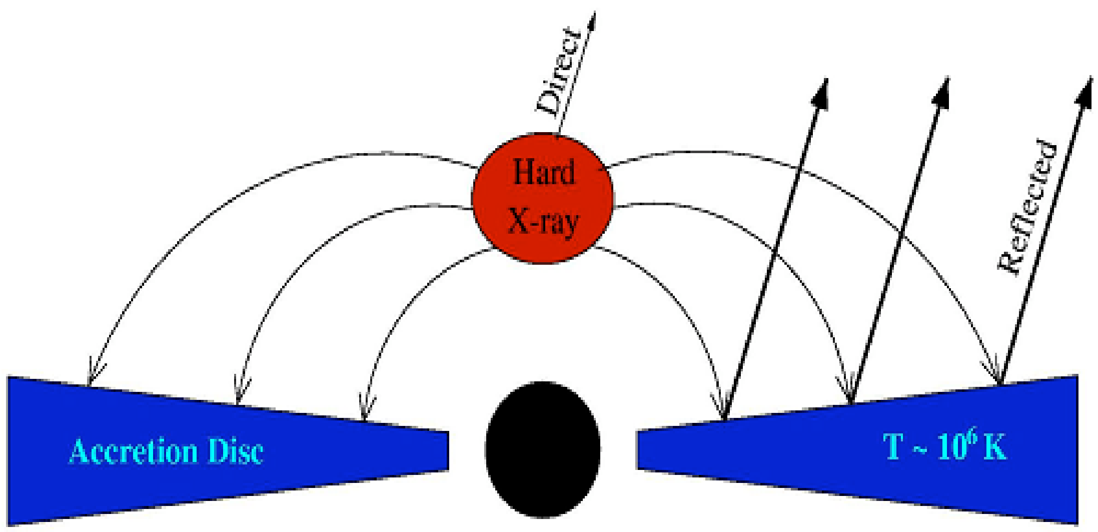


(Reynolds et al. 1995)

Iron line spectroscopy and GR

Iron line can be used to probe General Relativity effects around black holes in Active Galactic Nuclei and Galactic Black Hole systems





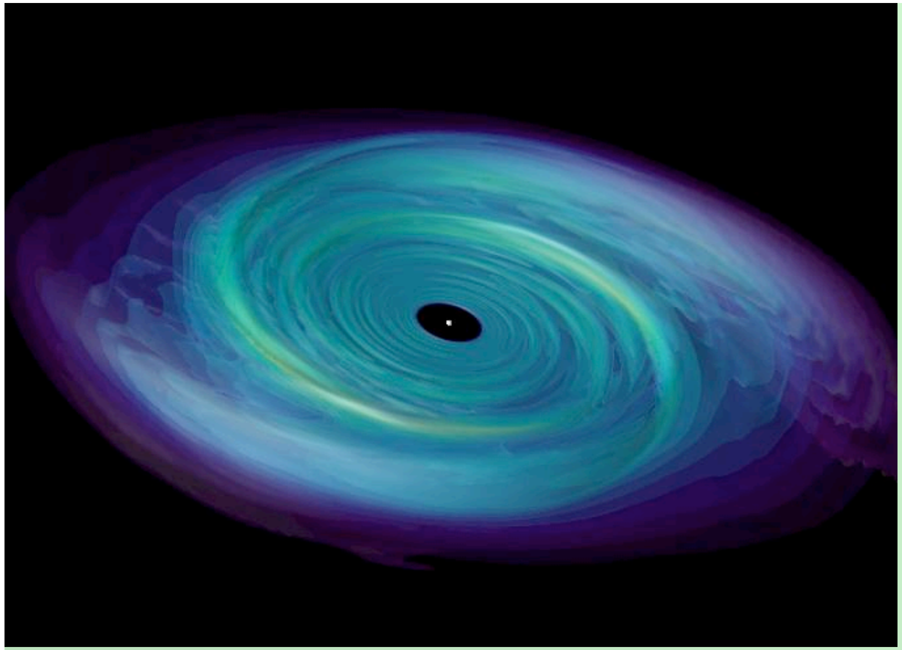
Black Holes

A Black Holeis fully described by three quantities:

The mass M
The angular momentum J
The electric charge Q

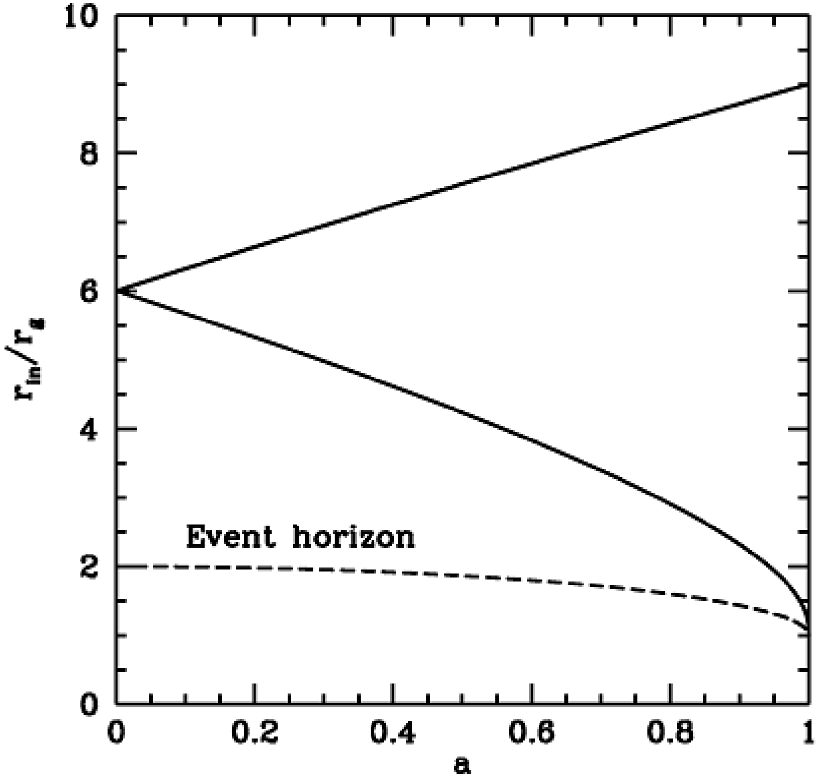
If Q=0 (as usually assumed), the space-time is described by the Kerr metric
If also J=0 (i.e. spherical symmetry), the (much simpler) Schwarzschild metric can be used

$r_g = GM/c^2$ is the gravitational radius. In the following, all distances will be given in units of r_g
$a = Jc/GM^2$ is the adimensional angular momentum per unit mass, 'spin' thereafter



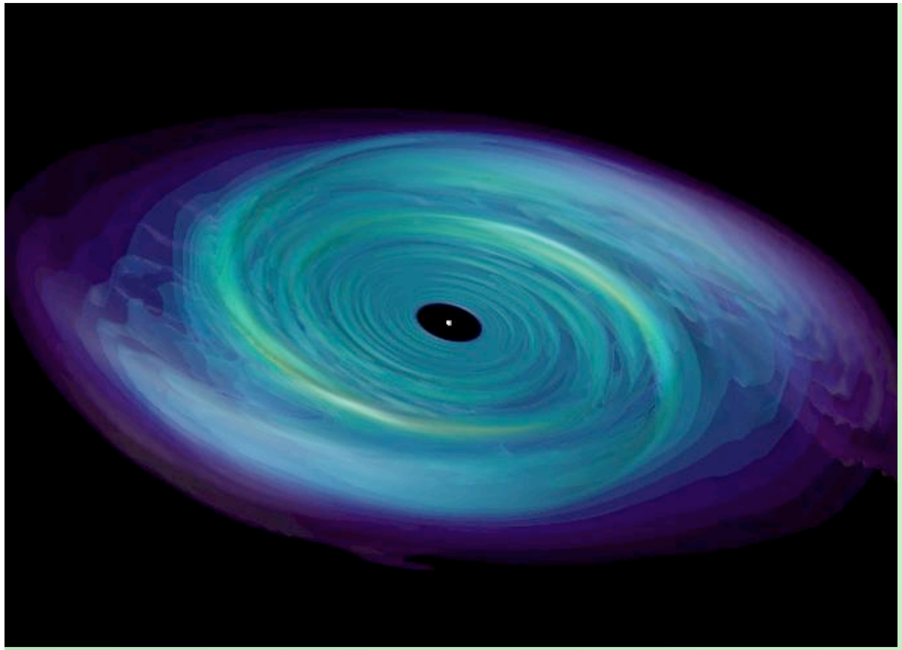
Accretion discs

Let us assume a geometrically thin, optically thick accretion disc. Matter rotates in (quasi) circular orbits (i.e. V_ >> Vr) with Keplerian velocities.

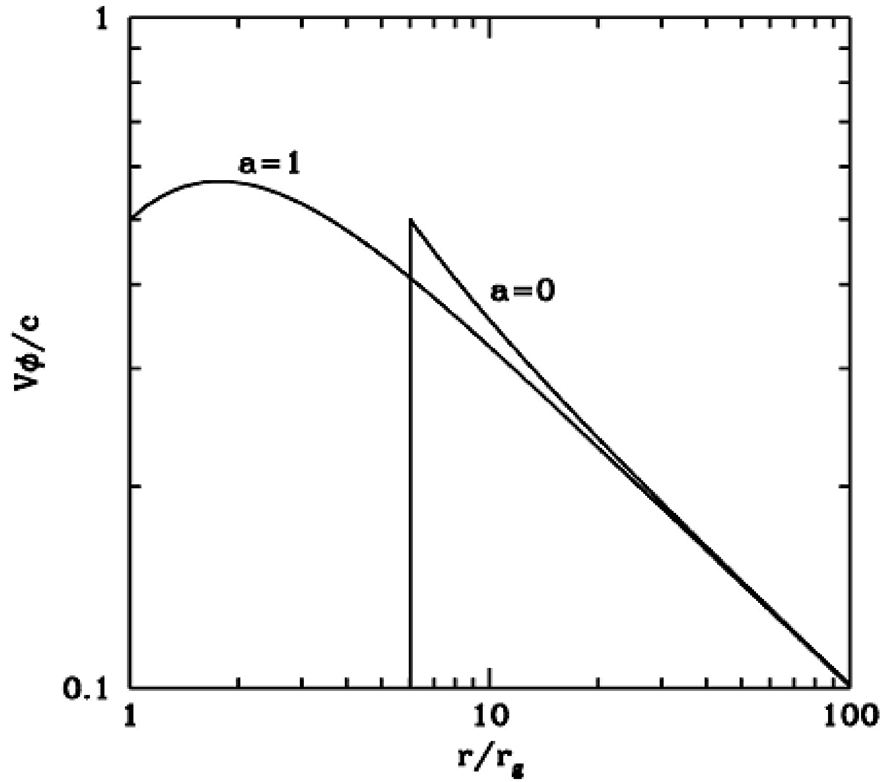


We can assume that the inner disc radius corresponds to the innermost stable circular orbit (ISCO)

The ISCO depends on the BH spin and on whether the disc is co- or counter-rotating with the BH



Accretion discs

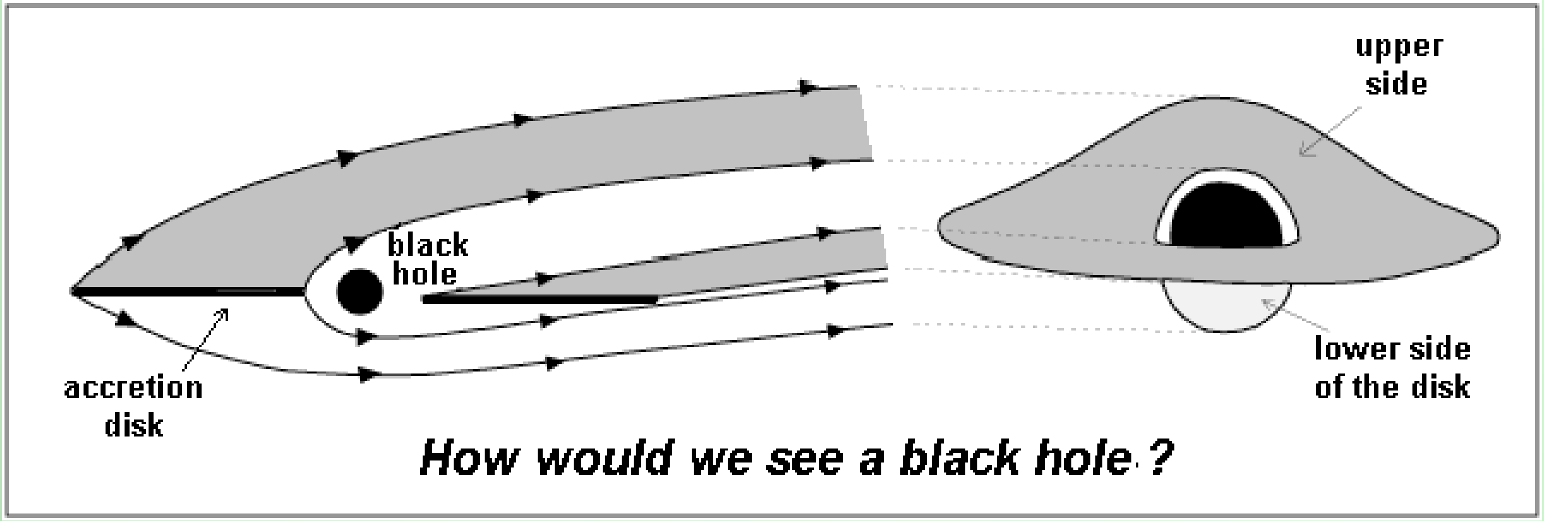


The Keplerian velocity (in the Locally Non-Rotating Frame) is given by:

$$V\_/c = (r^2 - 2ar^{1/2} + a^2) / (r^2 + a^2 - 2r)^{1/2} (r^{3/2} + a)$$

which, for small r, can be a significant fraction of *c*

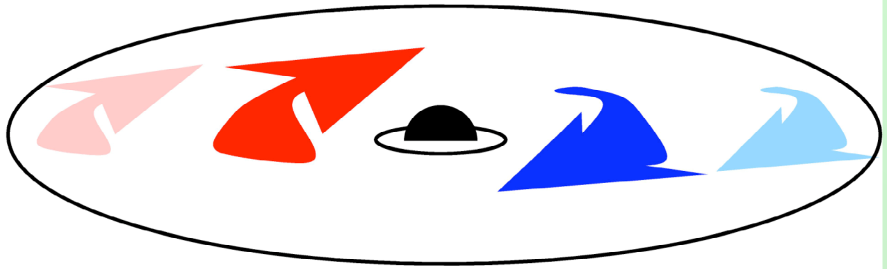
Photon trajectories



Luminet 1979

In GR, photon geodesics are no longer straight lines (light bending)

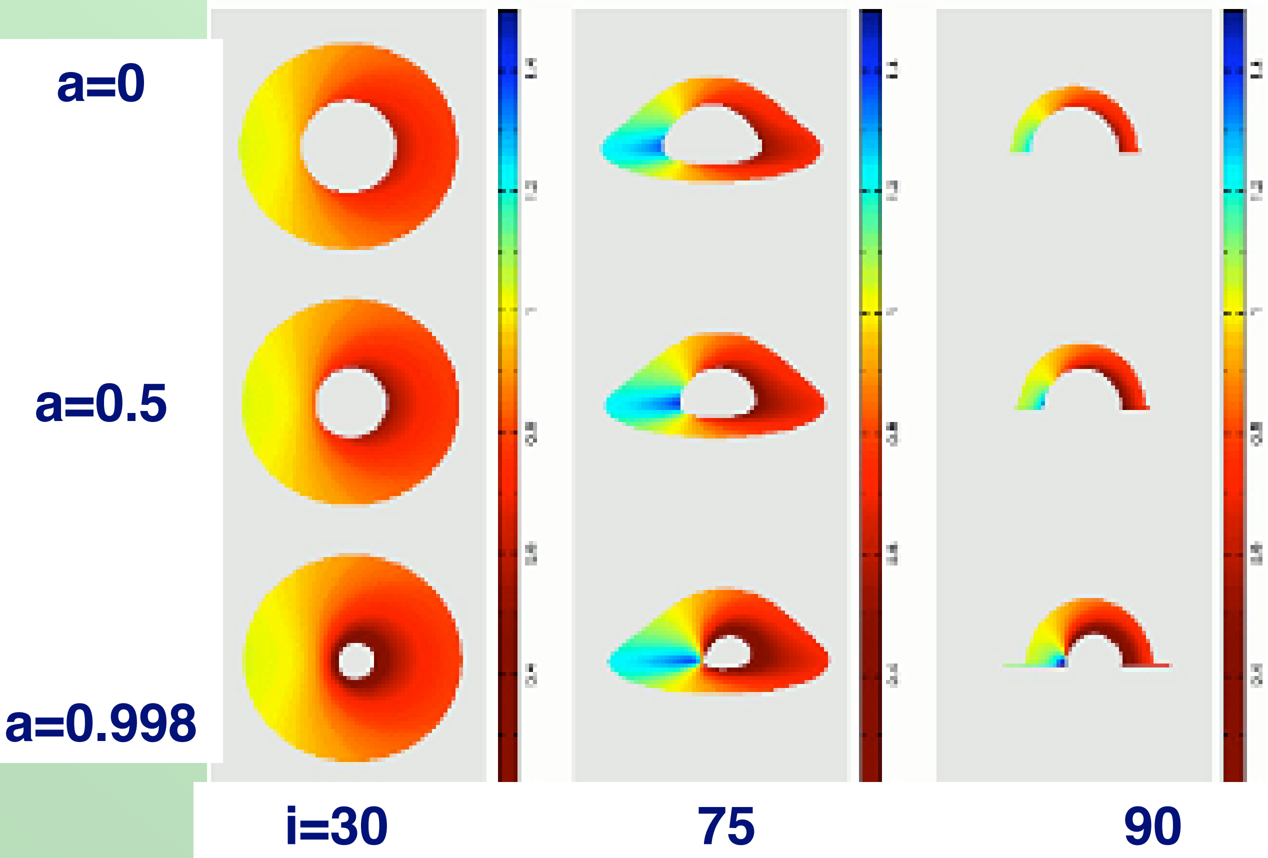
In Schwarzschild metric the trajectories are two-dimensional, in Kerr metric they are fully three-dimensional

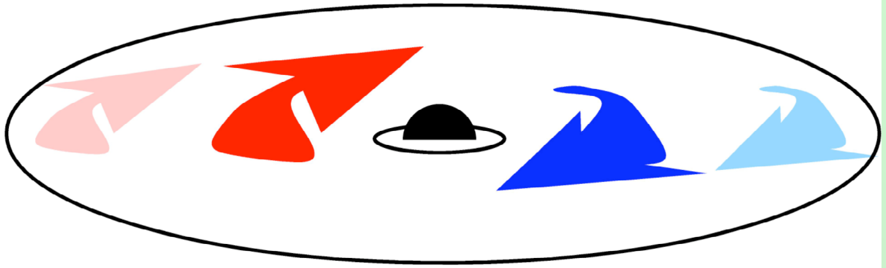


Photon shifts

Photons emitted in the accretion disc appear to the distant observer as redshifted because of the Gravitational redshift and the Doppler transverse effect, and blueshifted /redshifted by the Doppler effect when the matter is approaching/receding

(Dabrowski 1998)





Doppler boosting

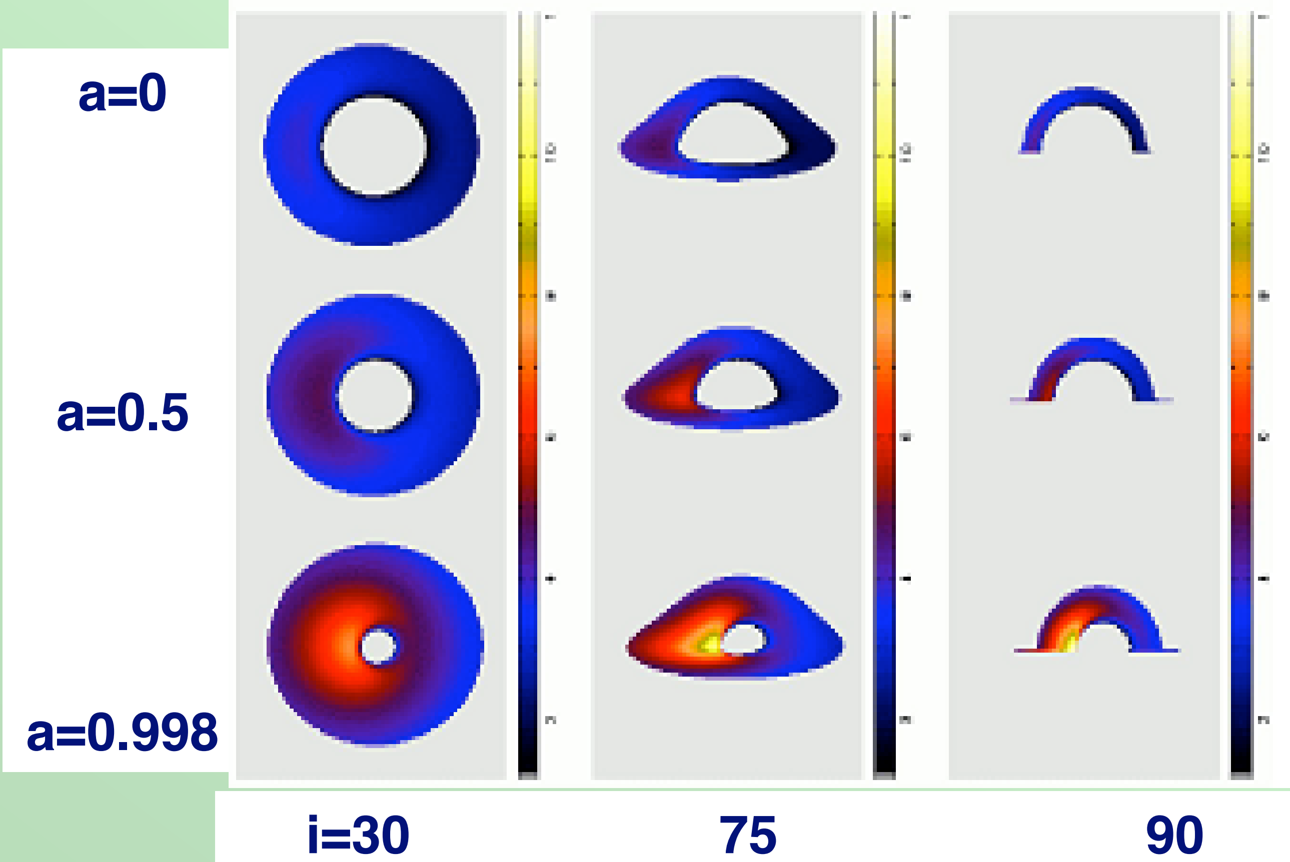
The quantity

I_ν/ν^3

is a Lorentz invariant.

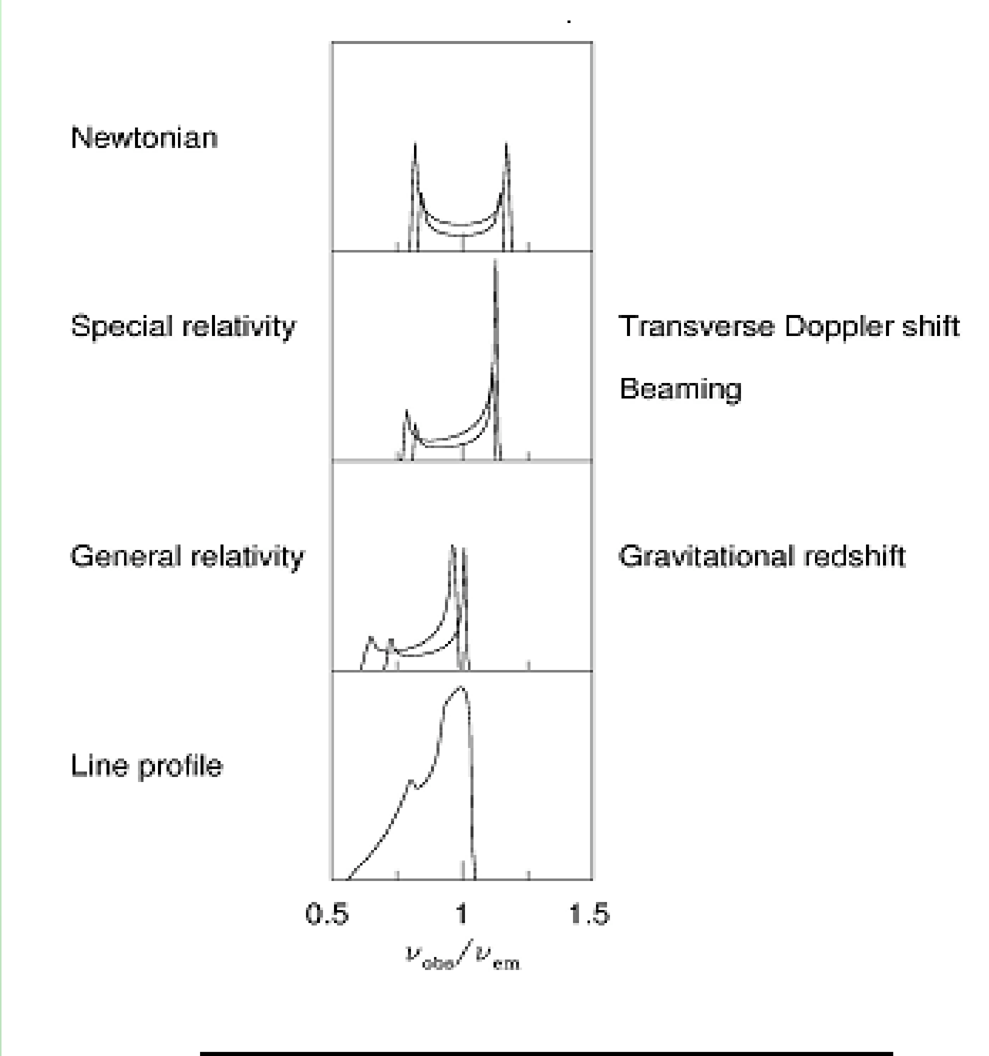
Therefore, the **blueshifted** radiation is brighter (*Doppler boosting*), the **redshifted** is fainter.

(Dabrowski 1998)



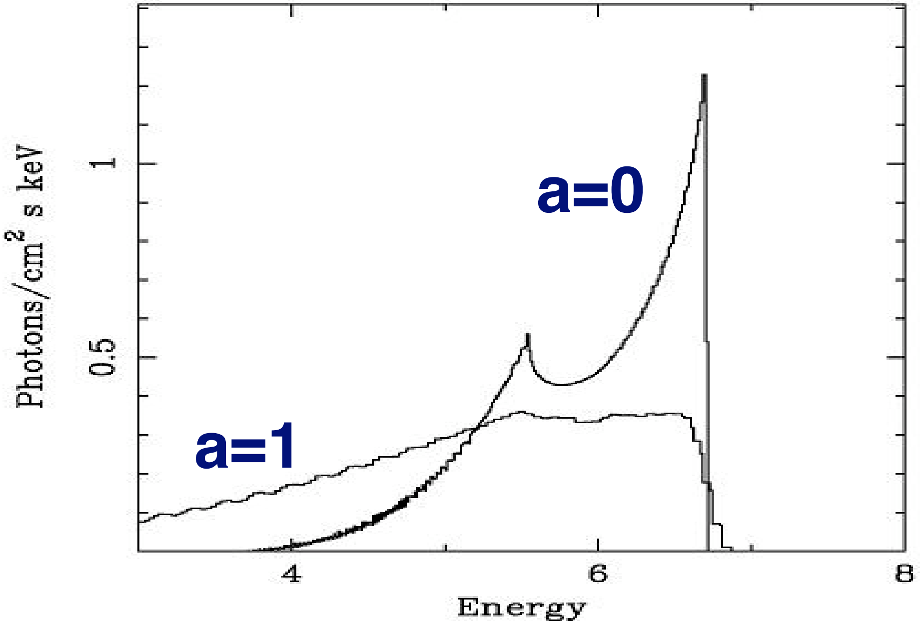
Iron Lines

The abovementioned SR and GR effects modify the line profile in a characteristic and well-recognizable way

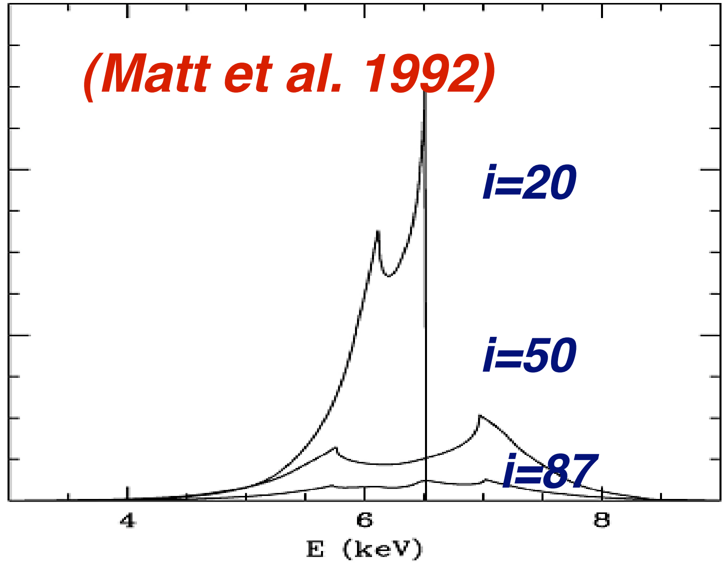


(Fabian et al. 2000)

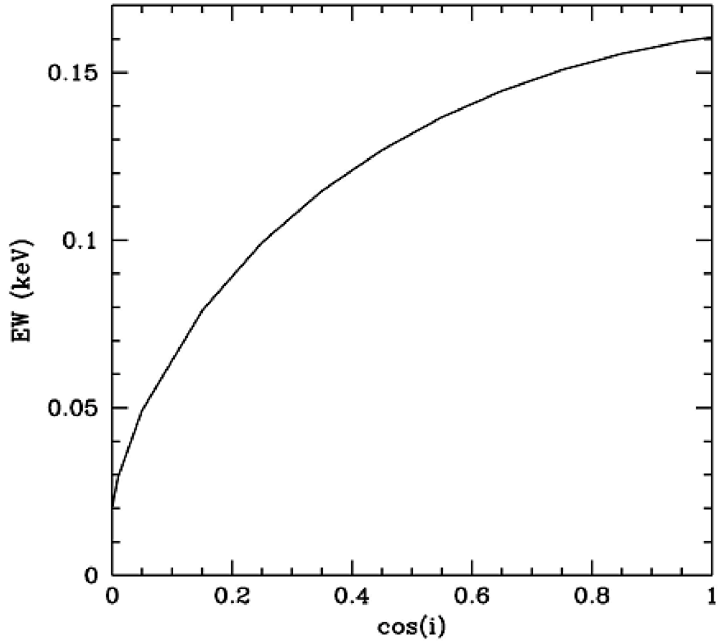
Iron Lines



Fabian et al. (2000)



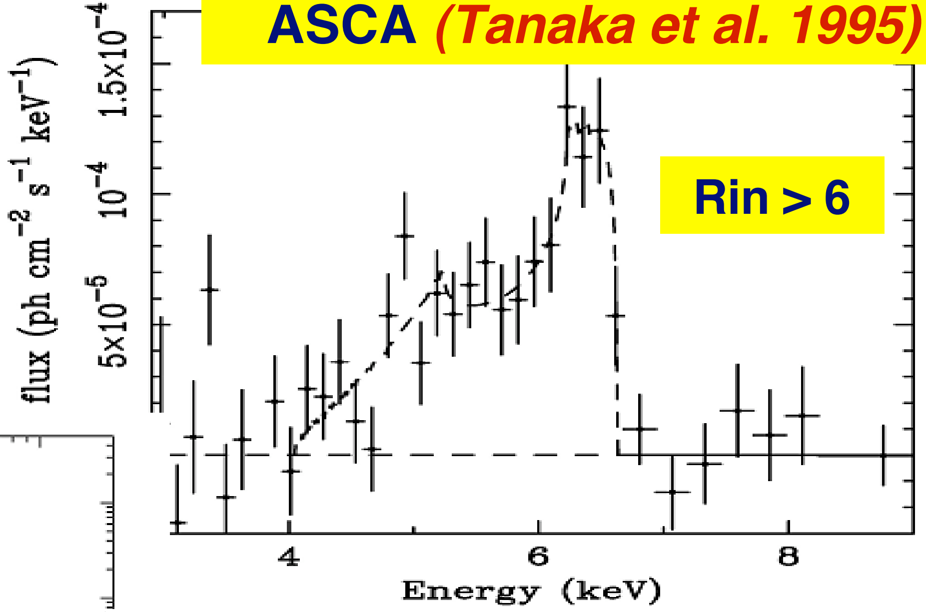
Isotropic illumination
(e.g. George & Fabian 1991, Matt et al. 1991, 1992)



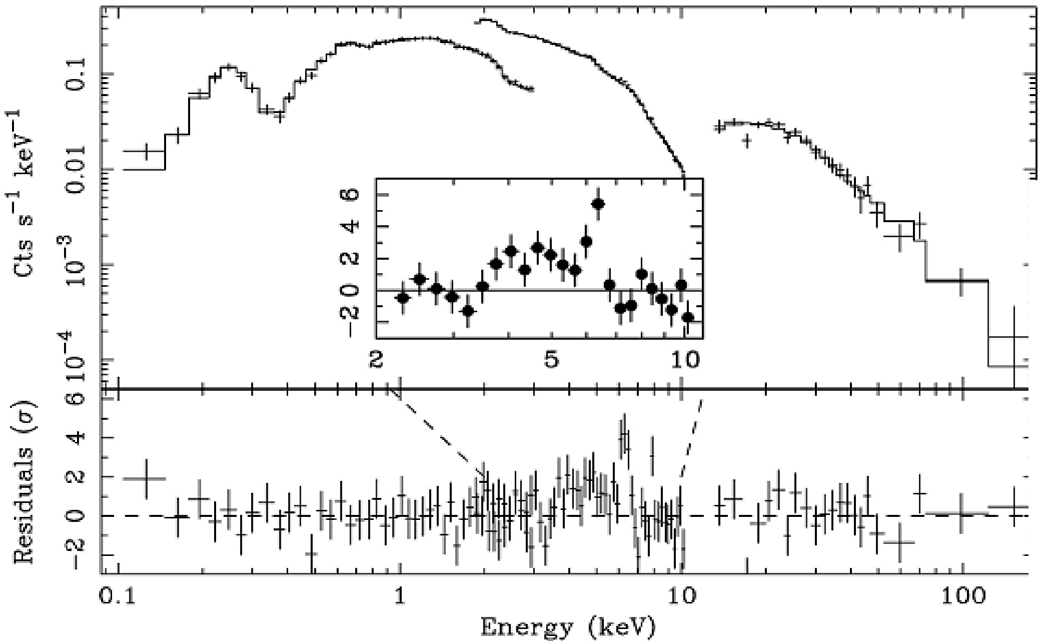
Observations

MCG-6-30-15

ASCA *(Tanaka et al. 1995)*

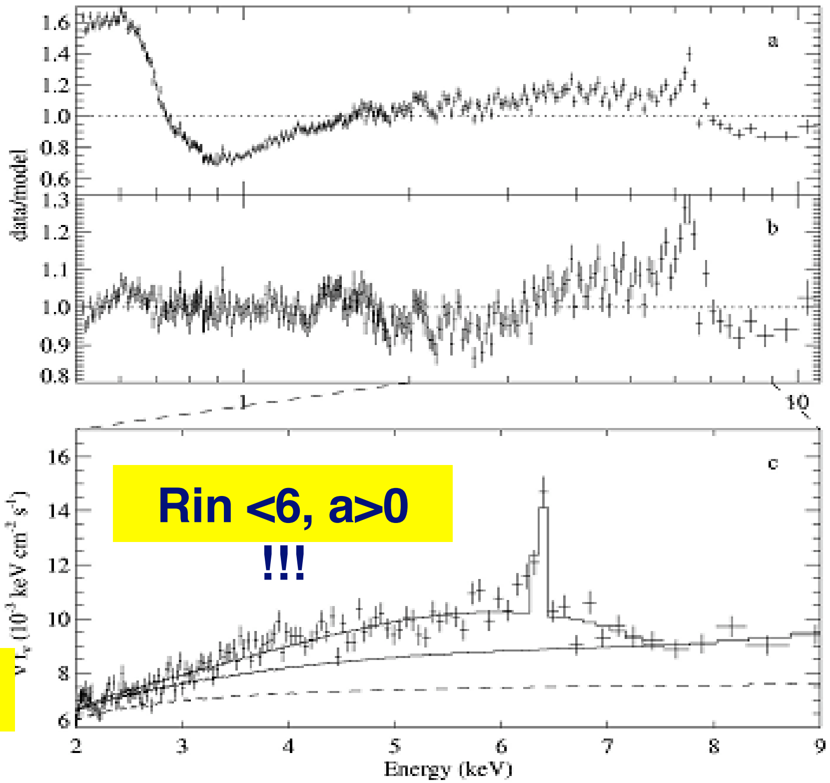


Rin > 6



BeppoSAX *(Guainazzi et al. 1999)*

XMM-Newton *(Wilms et al. 2001)*



Rin <6, a>0

!!!