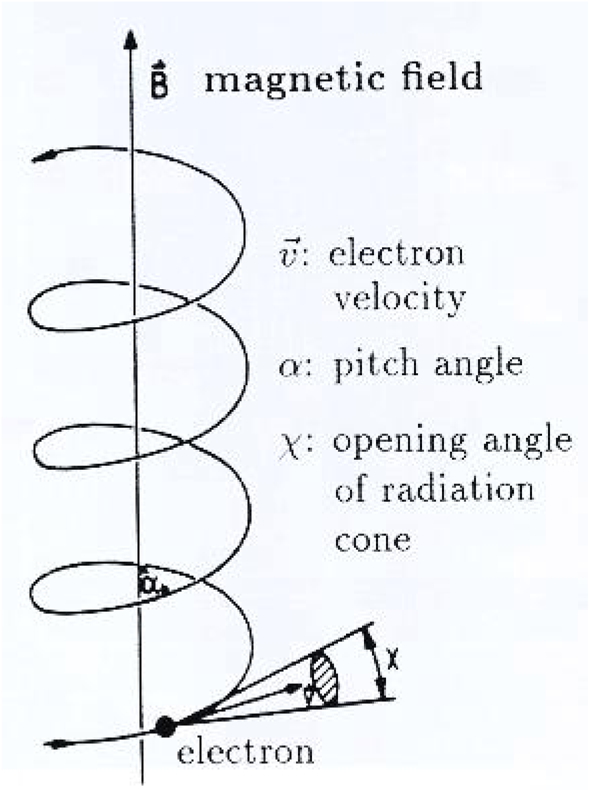
Curvature Radiation



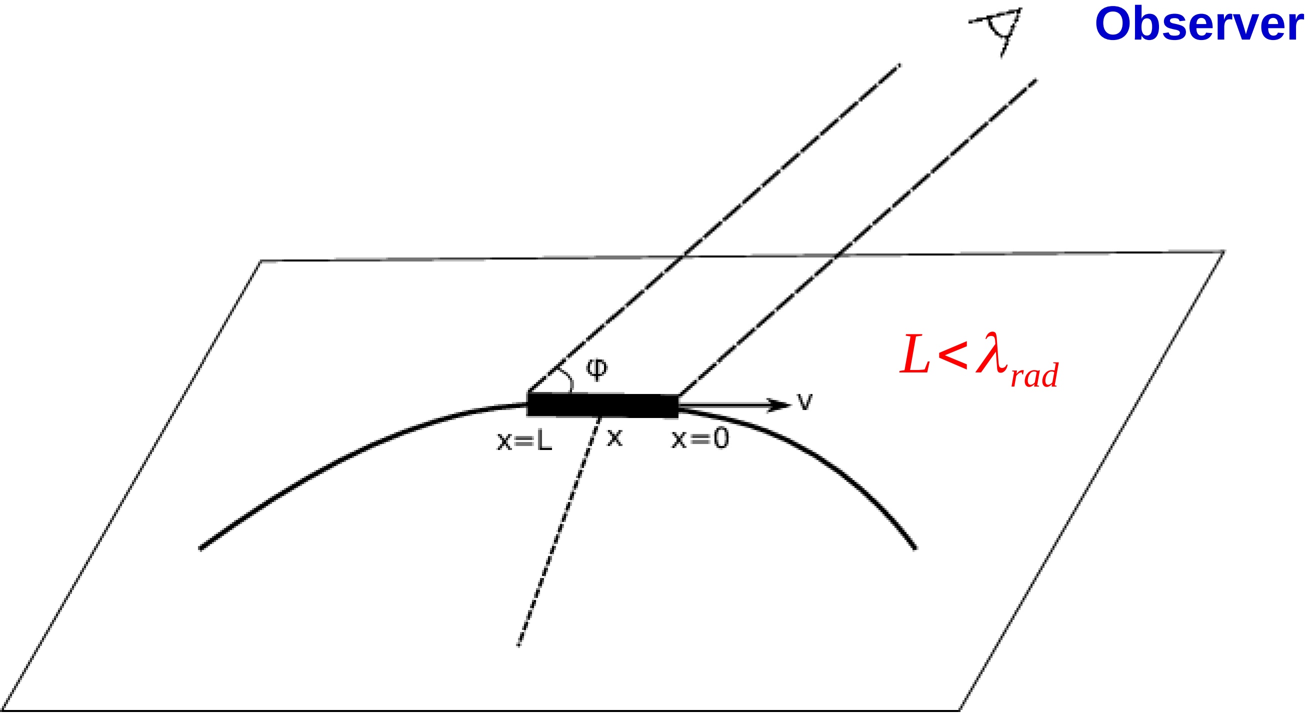
We saw that for synchrotron radiation the pitch angle alpha defines the direction of emission when the electron moves around a magnetic field line.

We saw that the parallel velocity is undisturbed and follows the straight parallel magnetic field component. The perpendicular component of the velocity changes because of the Lorentz force and the relativistic circular motion produces a beaming with half-width equal to 1/Lorentz factor.

But what happens if $B_{||}$ is also curved?

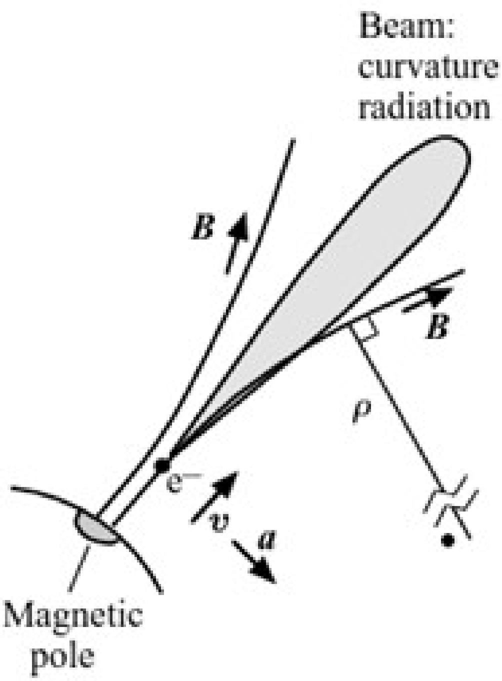
The electrons will emit radiation in this case, but the emission is in general much weaker than synchrotron.

Curvature Radiation



If the electrons are very energetic and bunched together, in the sense that they are very close together (closer than the typical wavelength of the radiation) then each bunch (in the figure is the black bar) radiates as a single *super-electron* and the power emitted can dominate.

Curvature Radiation



Because the electron bunches emit radiation while they are confined to a length $L < \lambda_{rad}$ their radiation might be **coherent**.

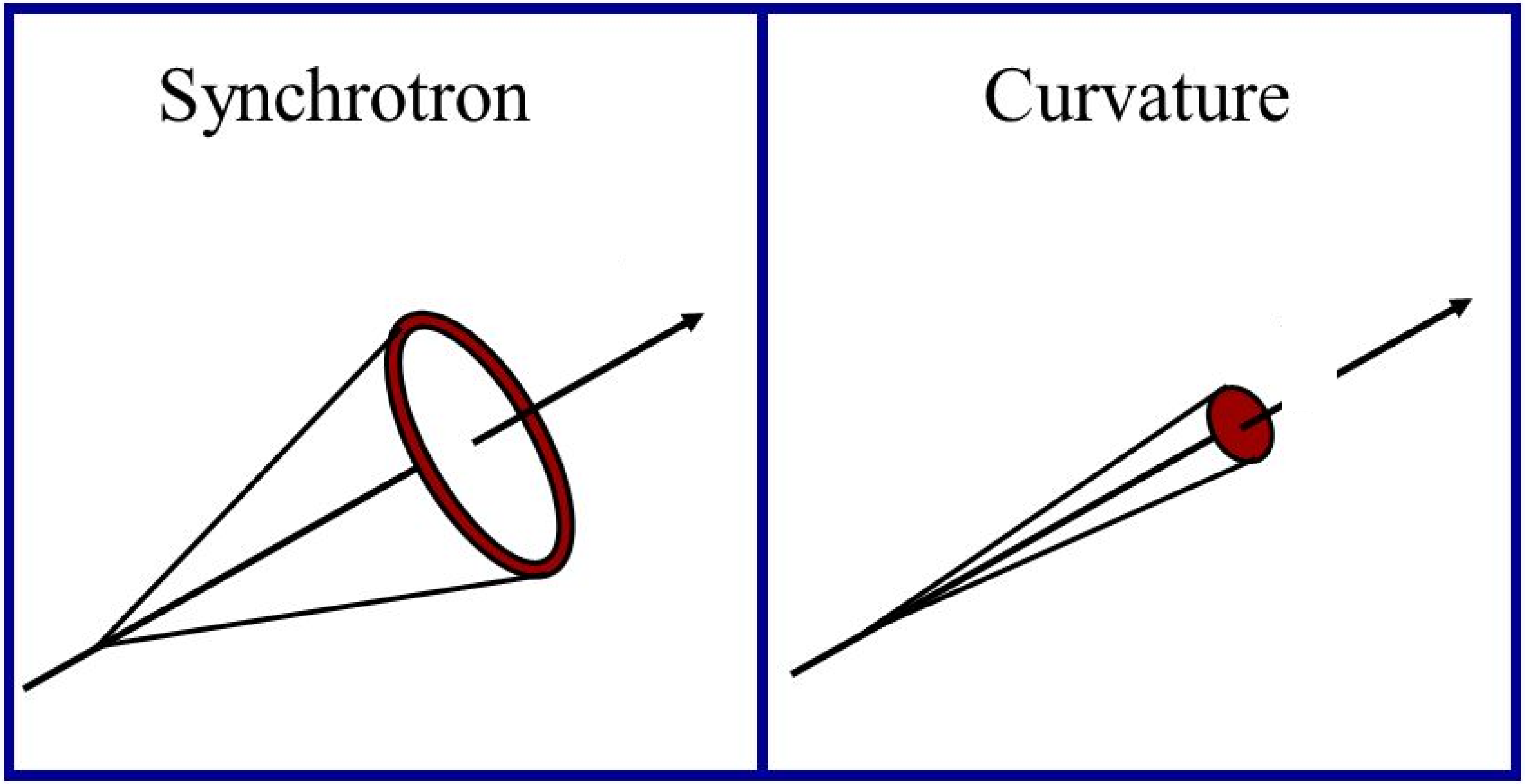
Note that synchrotron, Compton, bremsstrhalung and blackbody emission are all incoherent emission processes.

Because the length of the bunch is fixed, while the emitted power covers a broad range, coherent curvature radiation is observed typically in radio, while the optical/X-ray/gamma-ray photons will be incoherent.

Take RJ approximation and check if the temperature exceeds that of a blackbody. We said that blackbody is the most efficient radiatior (maximum entropy). No other incoherent emission process can be more efficient.

$$I(\nu) = \frac{2kT\nu^2}{c^2}$$

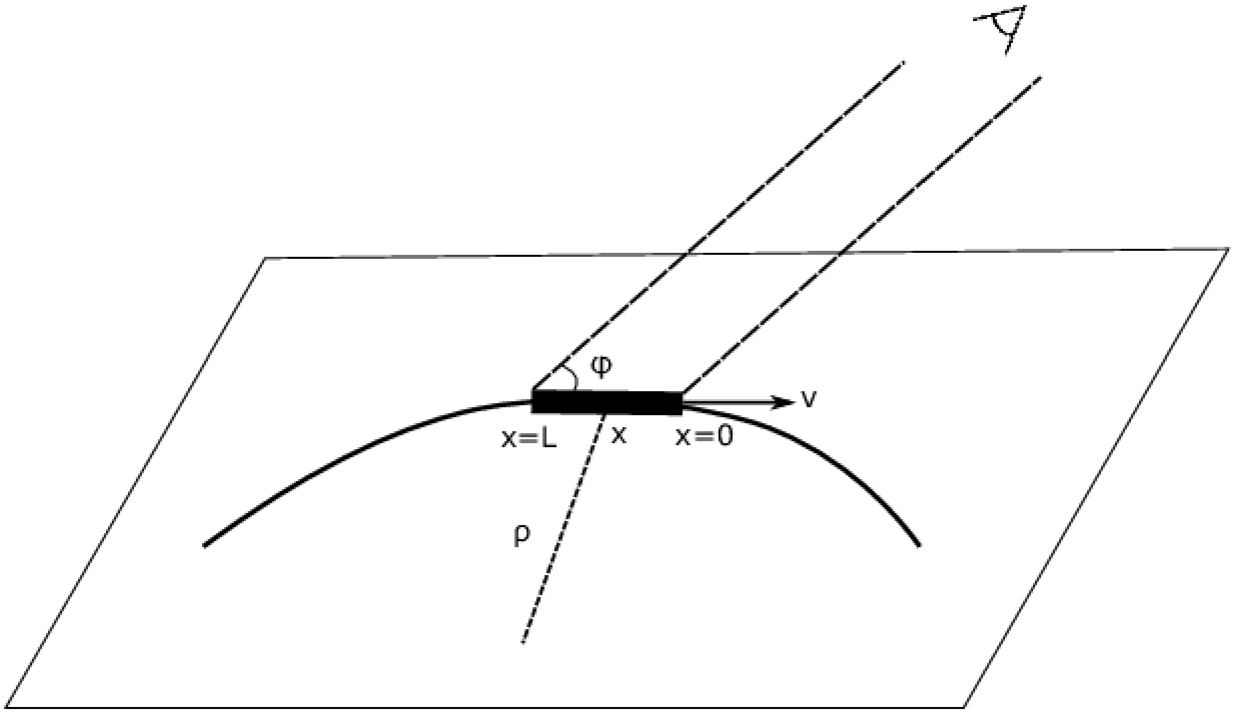
Curvature vs Synchrotron



Characteristic Frequency of Emission

The radius of curvature is:

$$\rho \simeq c\, v^2 / a$$



This generates a radiation at an effective frequency of emission:

$$\nu_{cur} = \nu_L\, \gamma^2 = \nu_B\, \gamma^3$$

where now the Larmor frequency is:

$$\nu_L = \frac{c}{2\pi\rho}$$

Curvature Radiation Power

Remember that emitted power of an accelerating chage is:

$$P \propto q^2 a^2$$

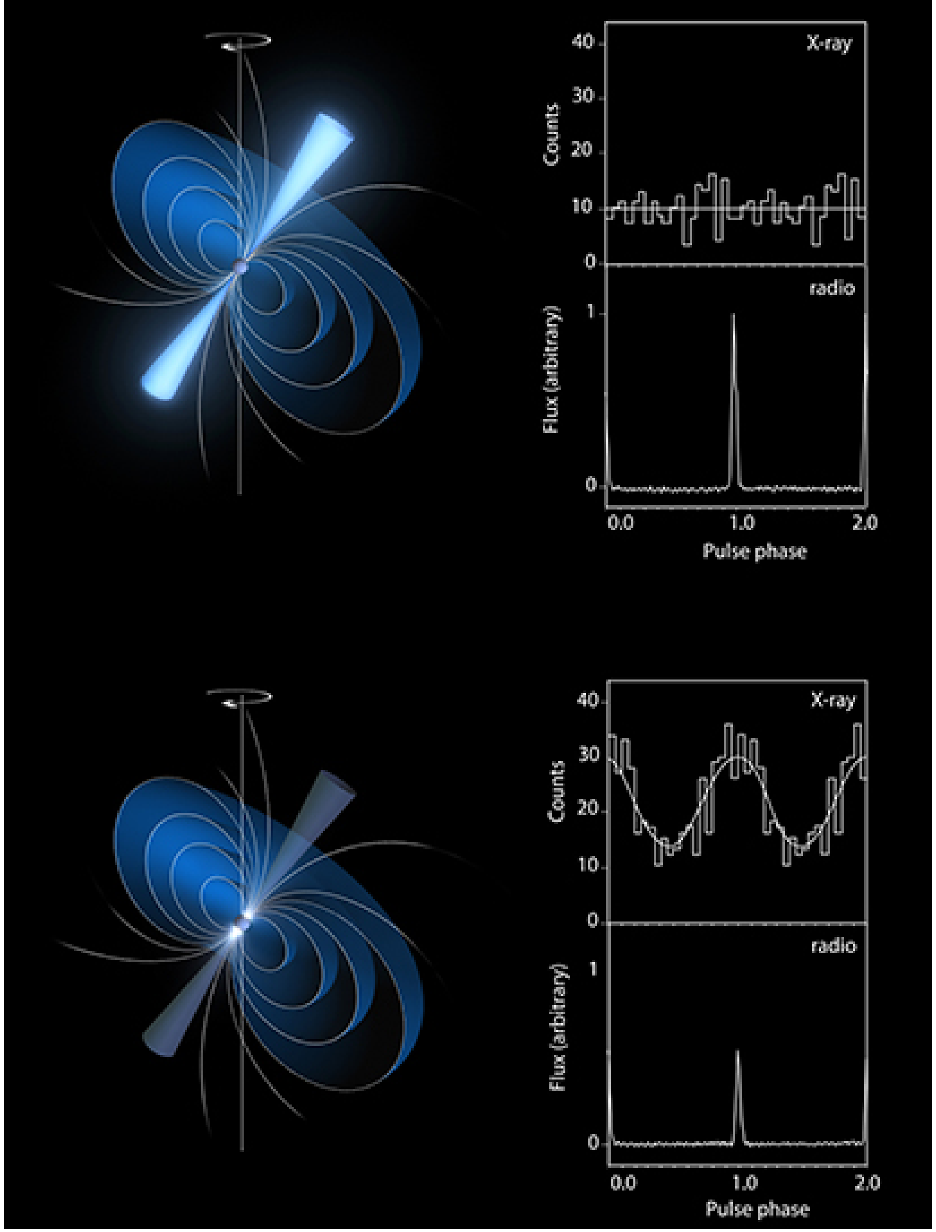
If you have N charges emitting *incoherently* (e.g., synchrotron):

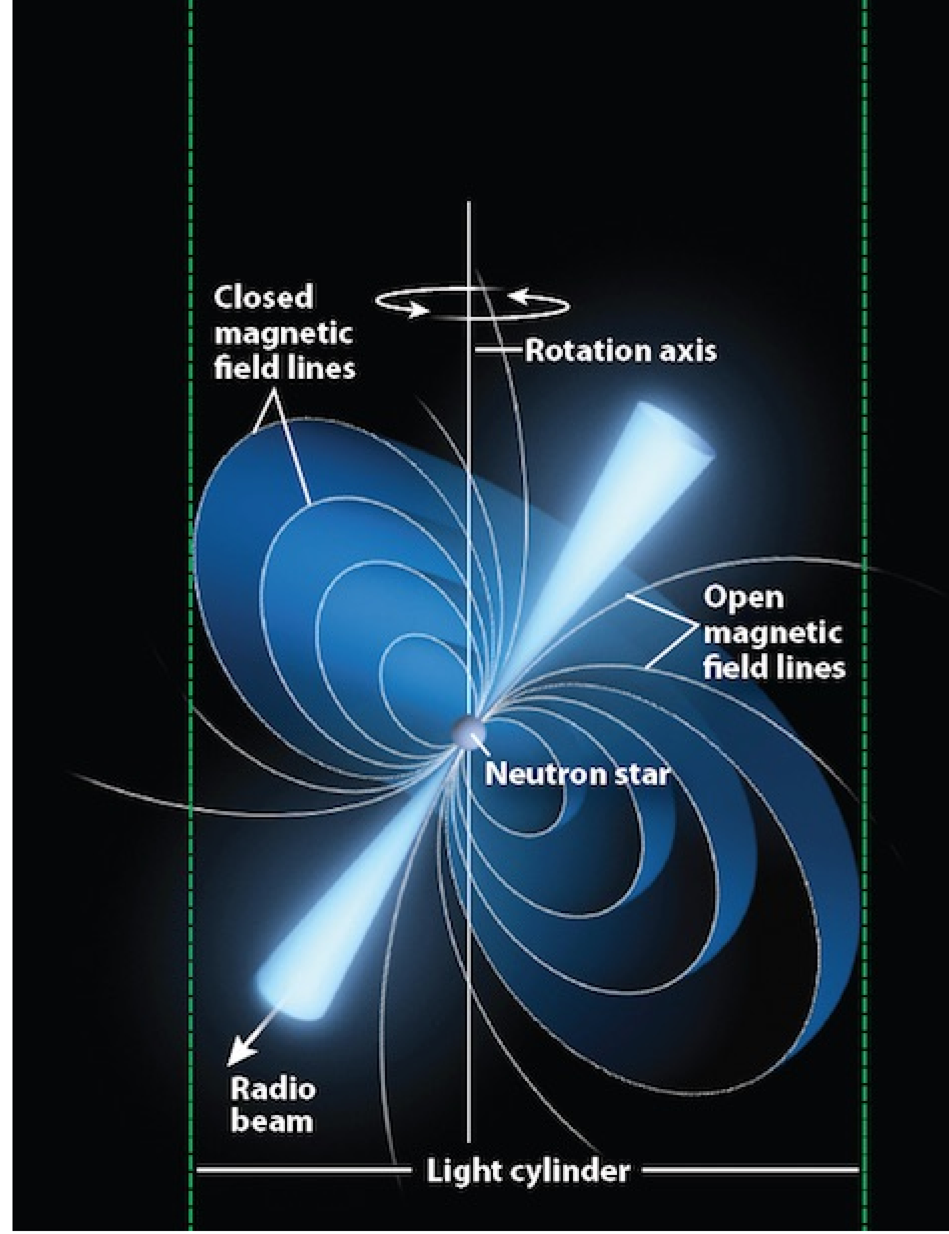
$$N \cdot P \propto N\, q^2 a^2$$

If you have N charges emitting *coherently* (e.g., curvature radiation):

$$N \cdot P \propto N^2 q^2 a^2$$

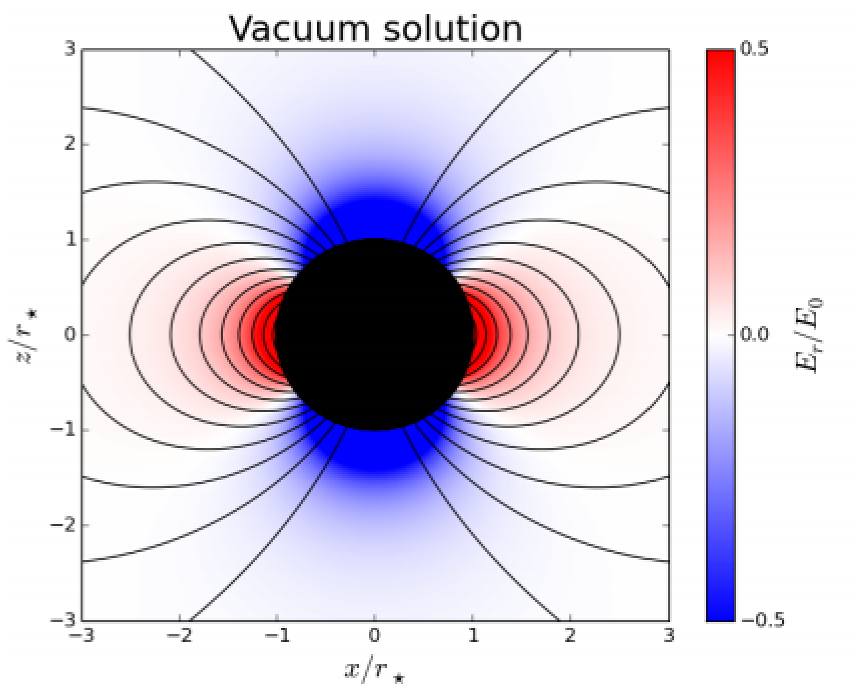
where (Nq) is a sort of “single charge” for our electron bunch.



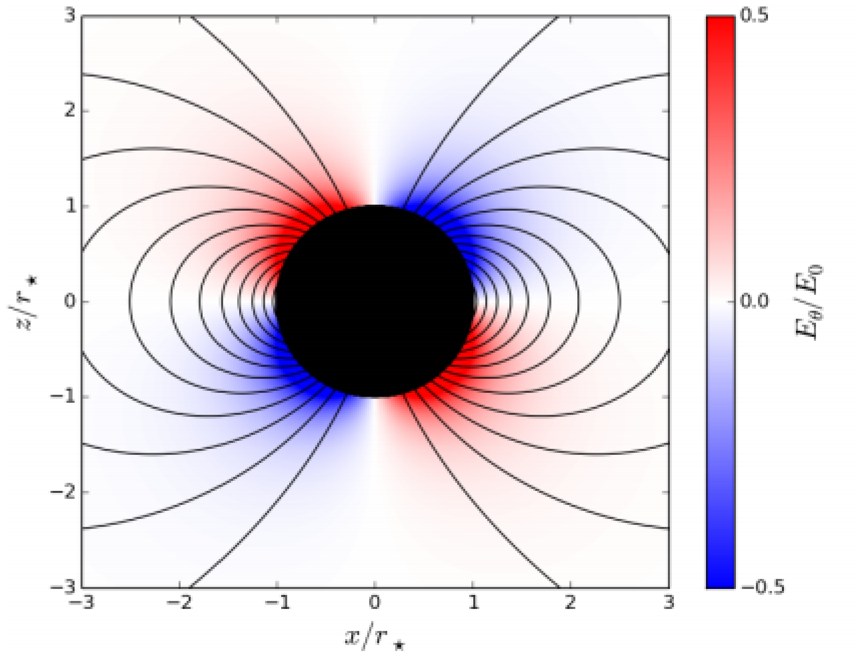


Two states of emission observed from pulsar PSR B0943+10, which is well known for switching between a 'bright' and 'quiet' mode at radio wavelengths. Observations of PSR B0943+10, performed simultaneously with ESA's XMM-Newton X-ray observatory and ground-based radio telescopes, revealed that this source exhibits variations in its X-ray emission that mimic in reverse the changes seen in radio waves. No current model is able to predict what could cause such sudden and drastic changes to the pulsar's entire magnetosphere and result in such a curious emission. (Bilous et al. 2014)

Electric Field Pulsars



Radial part of E field



Angular part of E field

X-Ray Notation & Iron line

In nuclear/atomic physics an electron shell corresponds to a principal energy level “n”.

The closest shell to the nucleus is called the "1st shell" (also called "K shell"), followed by the "2shell" (or "L shell"), then the "3 shell" (or "M shell"), and so on farther and farther from the nucleus. The labels K, L, M shells are typical of X-ray spectroscopy.

The difference between the s,p,d,… notation and the K,L,M… notation is that the first refers to the *orbital* of the electron, whereas the second refers to the principal quantum number **n.**

Example: K shell → 1s orbital
L shell → 2s & 2p orbitals
M shell → 3s, 3p & 3d orbitals

And so on…

One says that the K shell has 1 subshell, L shell has 2 subshells (2s &2p), M shell has three subshells (3s, 3p, 3d) etc.

Accretion disks

Fluorescent Iron K line

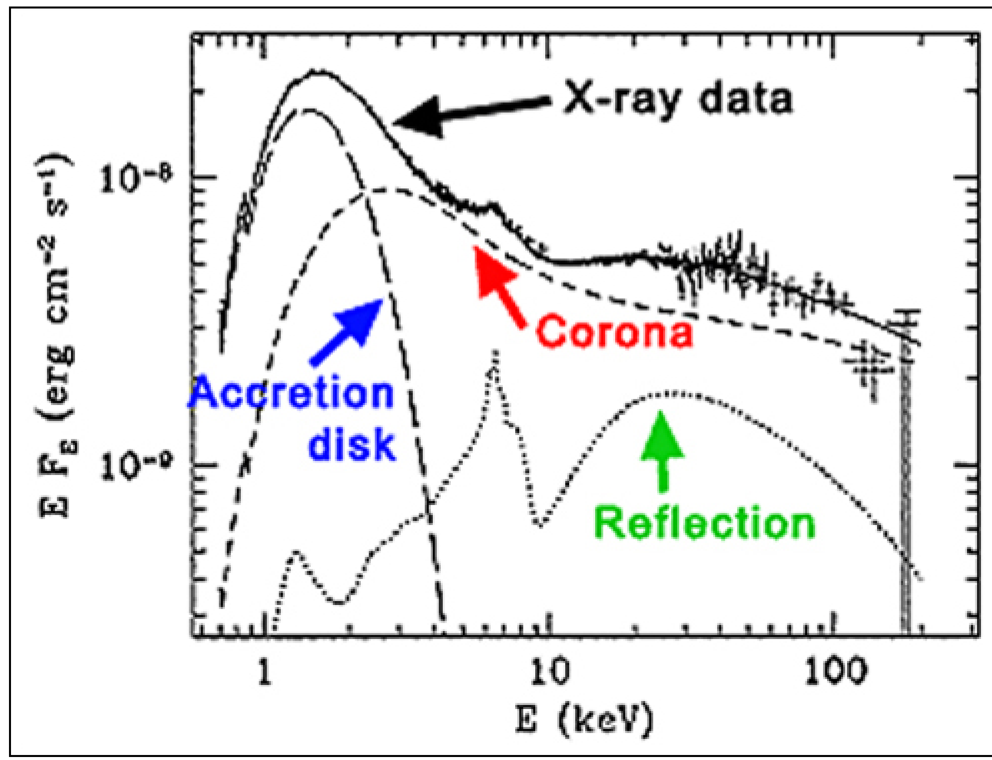
K-alpha emission lines result when an electron transitions to the innermost "K" shell (n=1, orbital 1s) from a 2p orbital of the L shell (n=2, 2s or 2p). K-alpha is typically by far the strongest X-ray spectral line for an element bombarded with energy sufficient to cause maximally intense X-ray emission. Such X-ray line photons are produced when an atom, or ion, of a heavy element, is left in an excited state following ejection from an inner K- or L-shell by an incident X-ray photon of sufficient energy. The ion may return to a lower energy state by emitting an electron from a higher shell (the 'Auger effect') or by a radiative transition. The relative probability of a radiative transition is referred to as the **fluorescence yield**. For K-shell electrons the fluorescence yield increases with atomic number; the largest product of element abundance and yield, by a factor of about 5, occurs for iron.

The energy of the line depends on the atomic charge Z: $E = (10.2eV)(Z-1)^2$

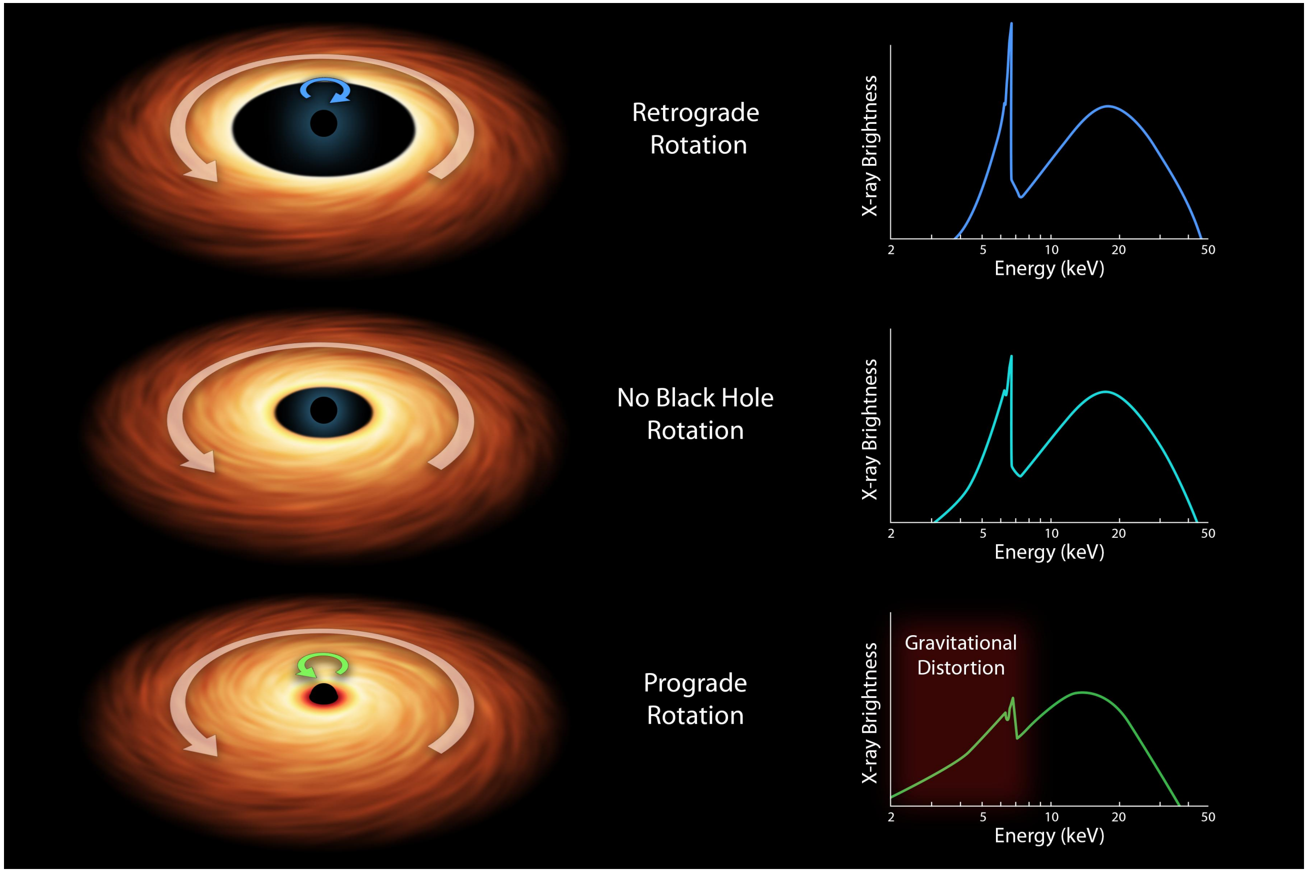
In X-ray binaries and AGNs, K-alpha Iron line emission is seen prominently.

Since Fe has Z=26, then E~6.4 keV.

(The line is actually a doublet, with slightly different energies depending on LS coupling as we will see later).



Iron K line to probe Strong Gravity



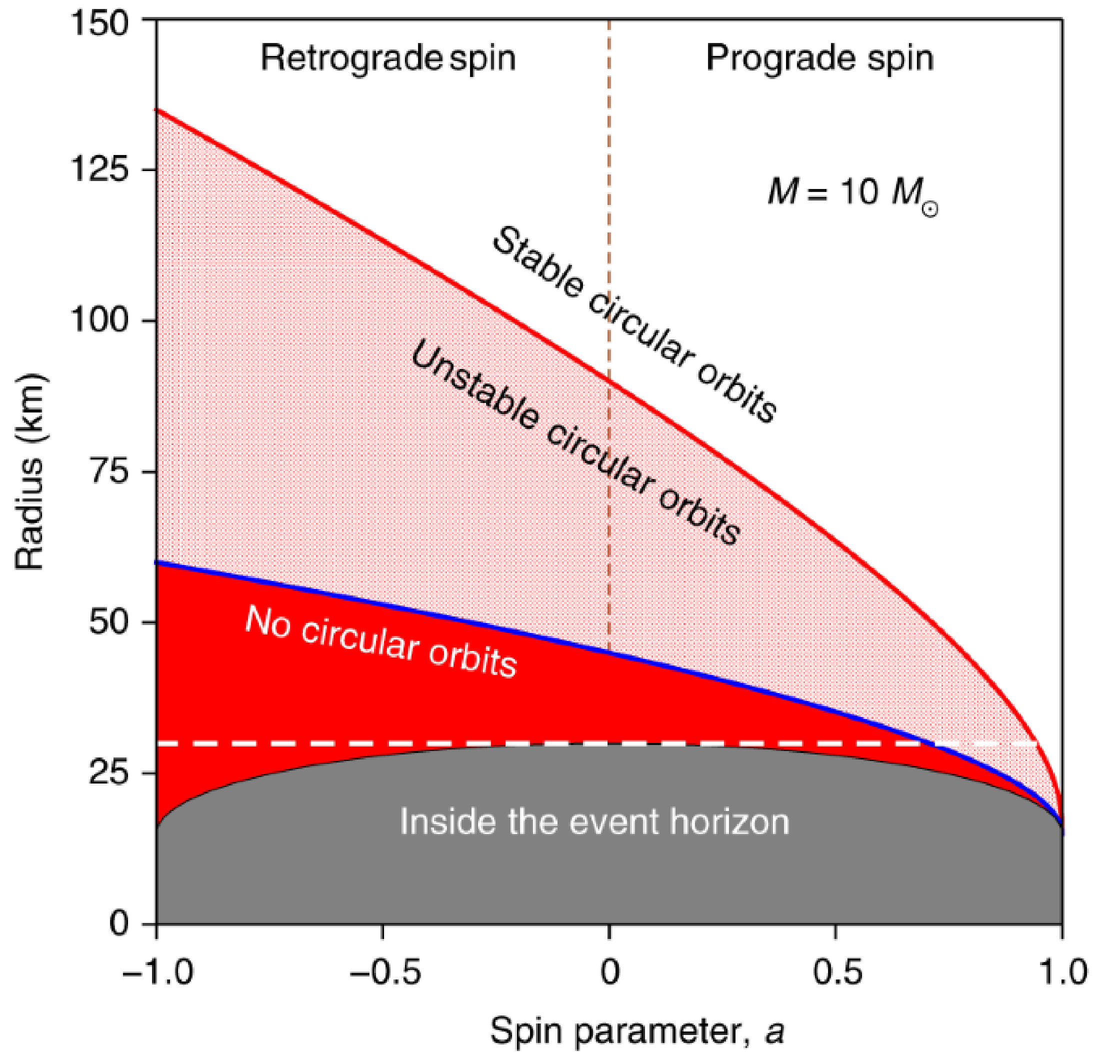
The shape of the Fe K-alpha line can be used to determine the rotation of black holes which is an important parameter to measure.

It has implications for the black hole formation, but also cosmological implications.

Doppler broadening due to the Keplerian accretion disk motion of the irradiated gas smears the Iron K-alpha line.

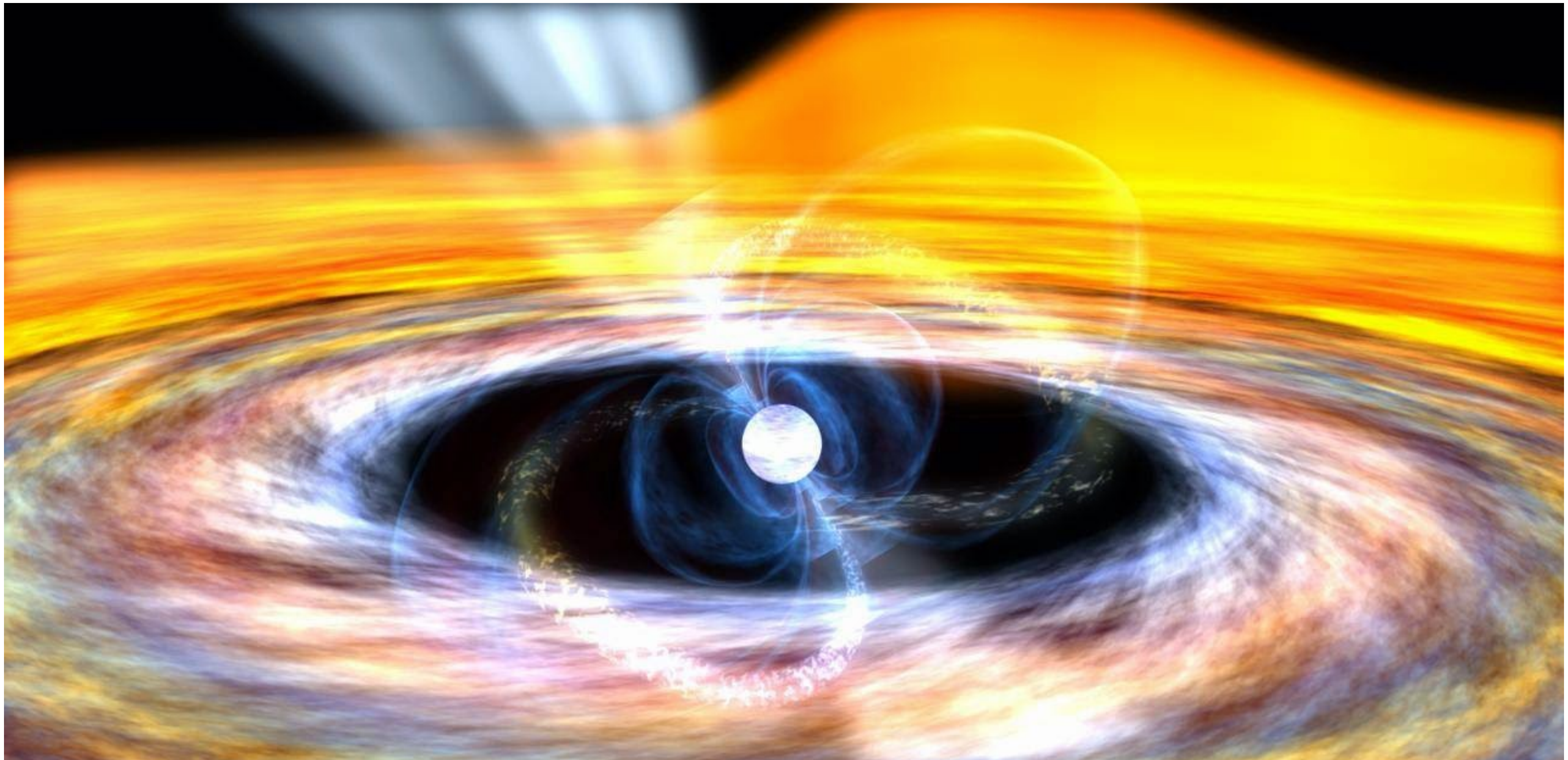
The truncation of the disk, due to general relativistic effects (known as the Innermost Stable Circular Orbit) determines how fast the gas rotates and thus the shape of the line.

Innermost Stable Circular Orbit

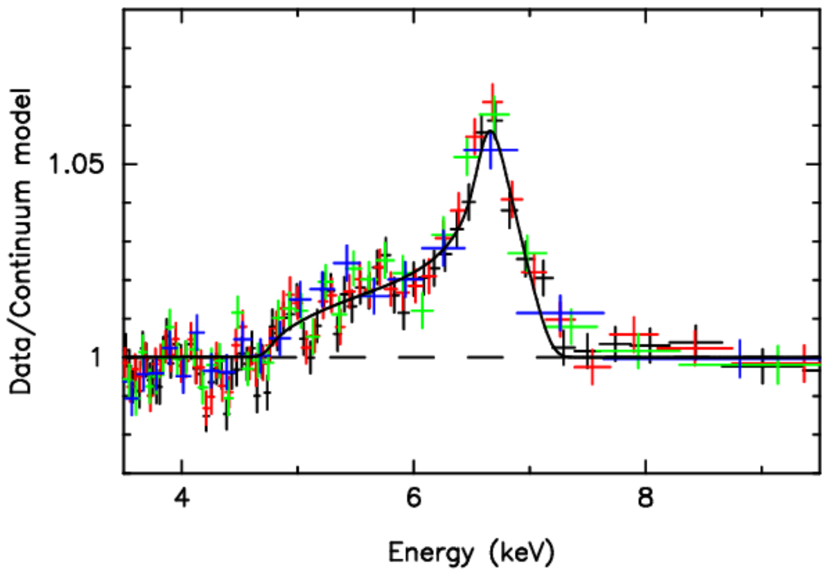


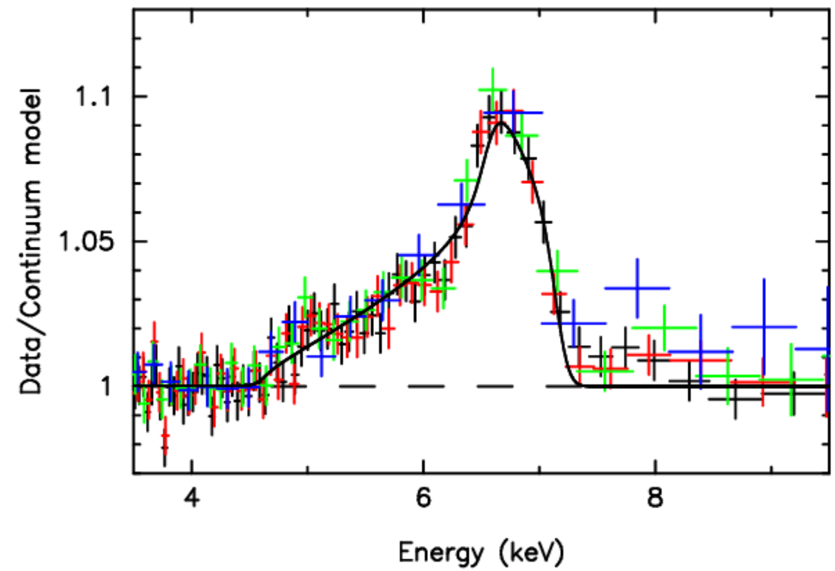
More on Physics with Iron line

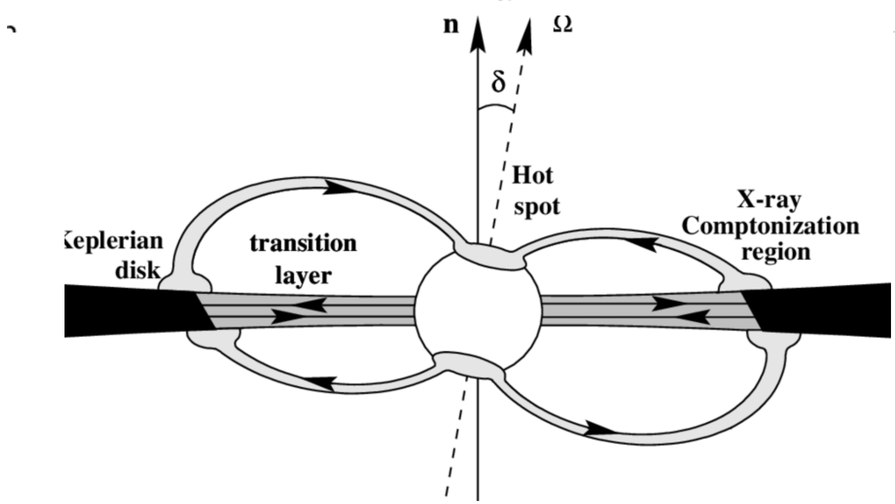
- The **energy** of the Kα Fe line (from 6.4 to 6.7 keV) tells about the ionization state of the iron, and thus the temperature of the disk.
- The **luminosity** of the line tells about the amount of iron, and thus about the abundance of metals of the disk.
- The **width** of the line tells about the velocities of the irradiated material forming the line.
- The **profile** (symmetric, double horned, skewed) tells about Doppler boosting and gravitational redshift.
- If the accretor is a *neutron star* then you can infer the strength of the neutron star **magnetic field** by looking at the truncation radius.

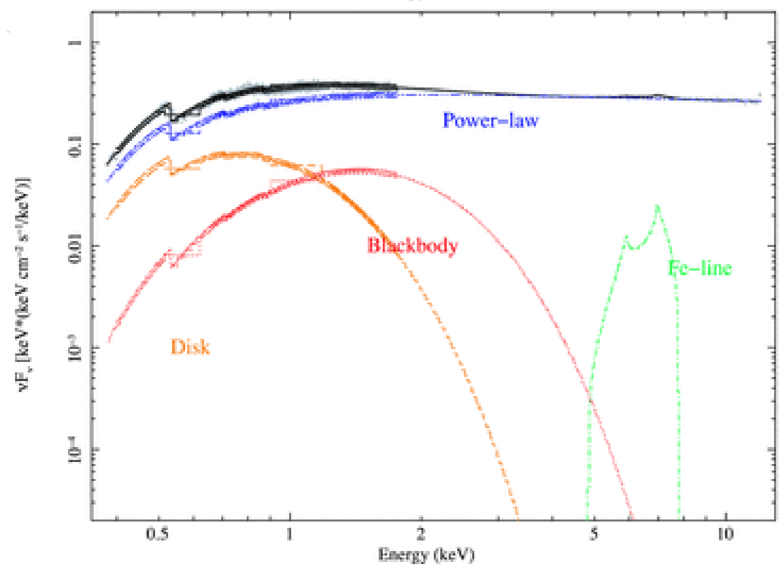


Iron K line in Accreting Pulsars









Cackett et al. (2009)

Fe K line Formalism

Remember how the specific flux is related to specific intensity:

$$F_{\nu,o} = \int_{\Omega} I_{\nu,o} \cos\theta \, d\Omega$$

The underscript "o" is for "observed", it's not a zero.

where Omega is the solid angle subtended by the accretion disk as seen from the observer and theta is the angle between the direction to the disk and the direction of the observed photon. Since the black hole/neutron star is assumed to be very far away from the observer, we can safely set cos(theta) = 1. Thus, we have to compute the specific intensity $I_{\nu,o}$ at infinity from the spectrum emitted on the surface of the accretion disk, call it $I_{\nu,e}$

In an axisymmetric accretion disk, $I_{\nu,e}$ is a function of the radial distance of the point of emission from the black hole, r_e, and of the inclination angle, i_e, of the emitted photon, measured with respect to the normal of the accretion disk.

(*See excellent review by Reynolds & Nowak 2003*)

Fe K line Formalism

The emitted and observed frequencies differ due to Doppler boosting and gravitational redshift. Call the shift factor as “**g**” relating the observed frequency *o* and the emitted frequency *e*

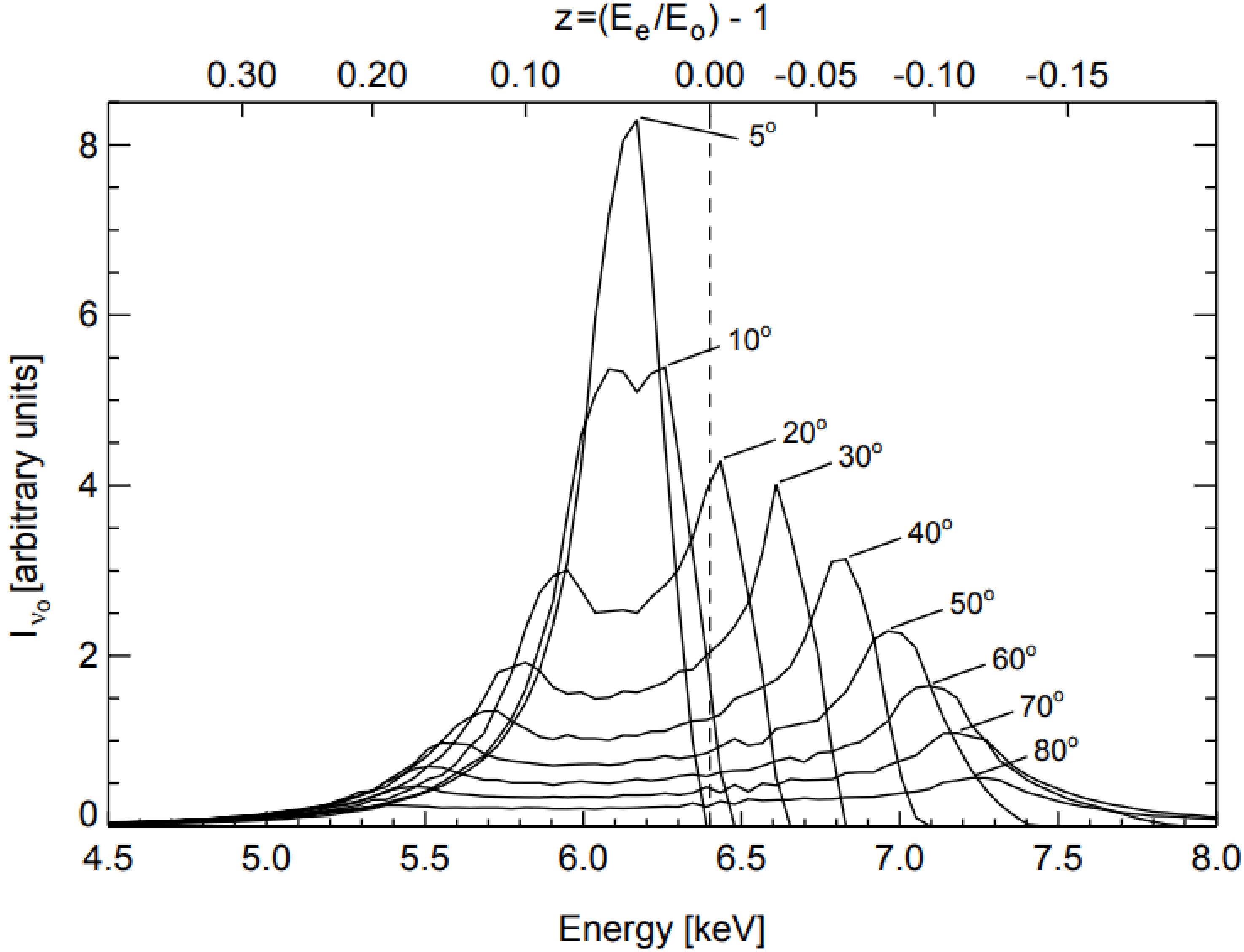
$$g = \frac{\nu_0}{\nu_e} = \frac{1}{1+z}$$

We can now use the property that the specific intensity divided by the cube of the frequency is an invariant, to write the *observed* specific flux in terms of the *emitted* specific intensity:

$$F_{\nu_0} = \int_\Omega \frac{I_{\nu_0}}{\nu_0^3} \nu_0^3 \, \mathrm{d}\Omega = \int_\Omega \frac{I_{\nu_e}}{\nu_e^3} \nu_0^3 \, \mathrm{d}\Omega = \int_\Omega g^3 I_{\nu_e}(r_\mathrm{e}, i_\mathrm{e}) \, \mathrm{d}\Omega$$

In other words, the computation of the emerging spectrum breaks down to the computation of **g**. In the weak field limit, when r/rs>>3, and in the Schwarzschild metric, g and therefore the line profile can be computed analytically.

Fe K line as a function of inclination



Fe K line as a function of BH rotation