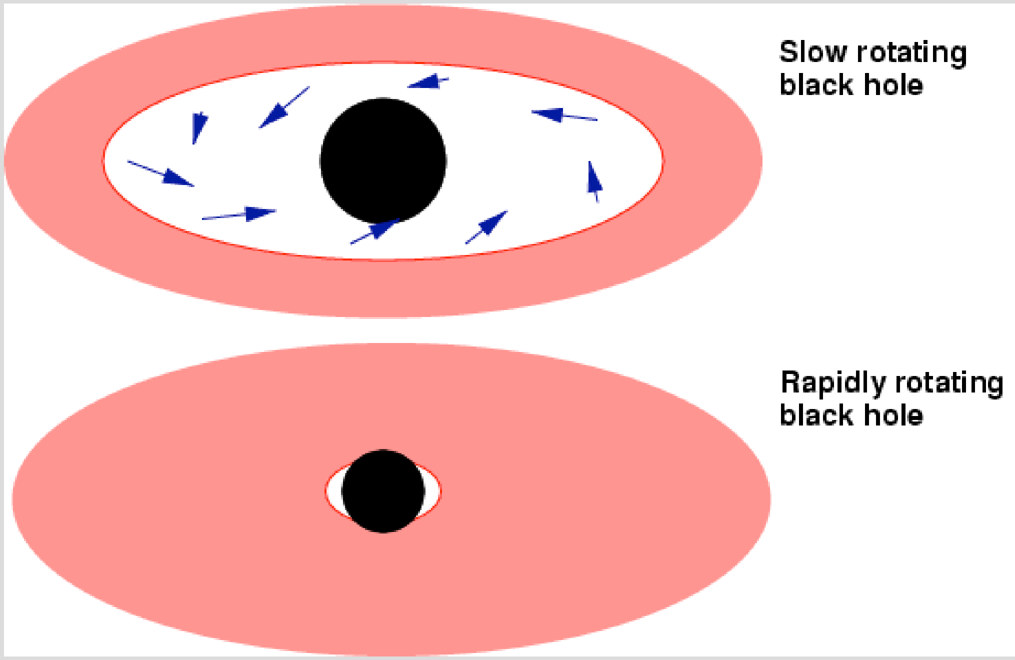
Measuring the spin of black holes

Important but difficult task - try to measure the spin of black holes. Only affects *local spacetime* around the hole.



Physics: last stable orbit R_{ms} varies depending upon spin parameter a:

- $6\ GM / c^2$ for $a = 0$
- -> GM / c^2 as $a \to 1$

Suggests several possible routes to measuring spin.

<u>Luminosity</u>: for the same accretion rate, rapidly spinning hole will be more luminous than non-rotating hole:

- □ = 0.06 (Schwarzschild)
- □ ~ 0.3 (near maximal Kerr)

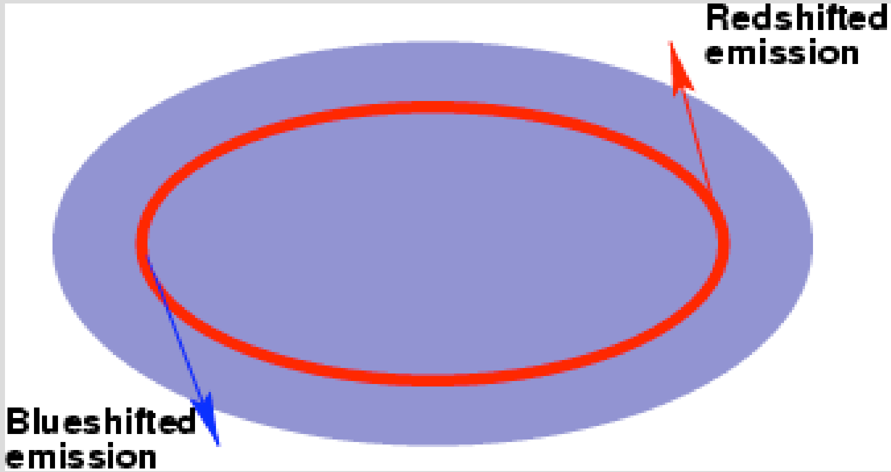
Variability: shortest orbital period for a Kerr black hole is less than for a Schwarzschild black hole. Rotation also introduces new effects (e.g. frame dragging) that may show up in variability…

Problem: details of variability poorly understood

Velocity: highest velocities in the disk are greater for a Kerr black hole than a Schwarzschild one. Observable if we can see a spectral line produced in the inner disk.

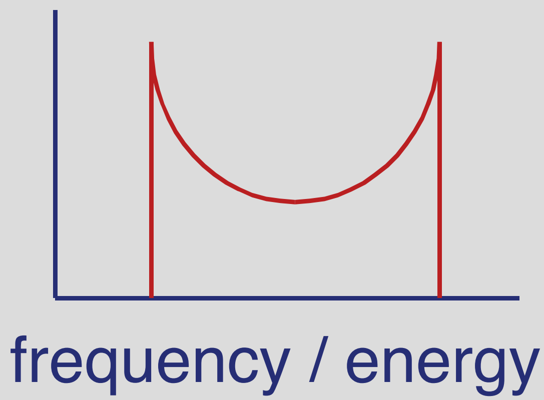
Note: gravitational radiation from a close black hole binary is probably a better (i.e. easier to interpret) probe. Possible with LISA.

Spectral lines from the inner disk



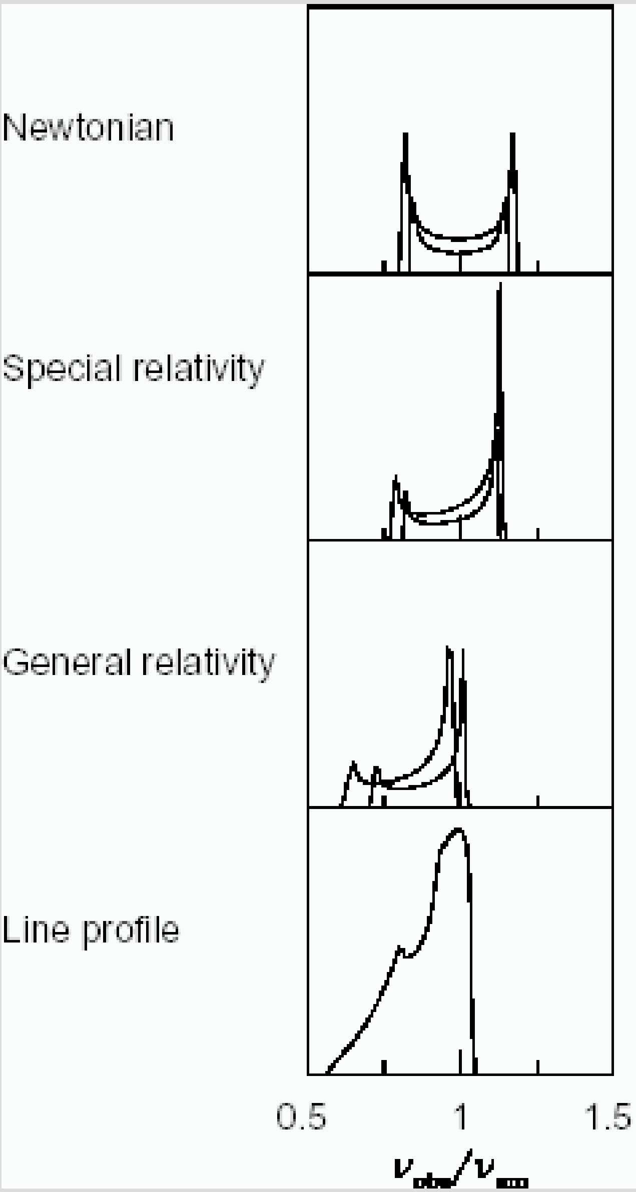
Newtonian case: Consider an annulus in the disk with orbital velocity v_ϕ. Projected velocity is $v_{obs} = v_\phi \sin i$, where i is the inclination. Leads to a Doppler shift:

$$\frac{\Delta\nu}{\nu} = \frac{v_{obs}}{c}$$



`Double-horned' profile
Doppler shift only effect for a Newtonian disk.

Relativistic disk: several new effects



Newtonian profile from single annulus

Transverse doppler effect: `moving clocks appear to run slow'. Observed frequency is reduced compared to rest frame value by factor:

$$\gamma = (1 - v^2 / c^2)^{-1/2}$$

Beaming

Boosts blue wing of the line, attenuates red wing

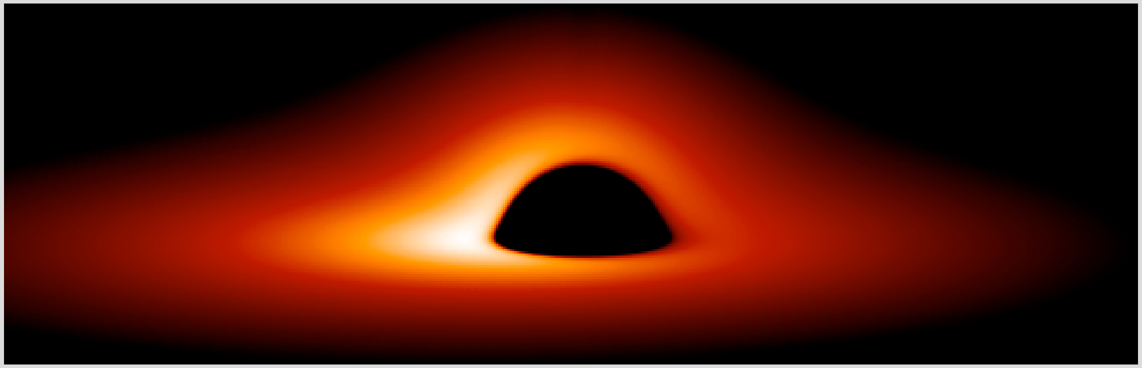
Gravitational redshift

Further shifts profile to lower energies

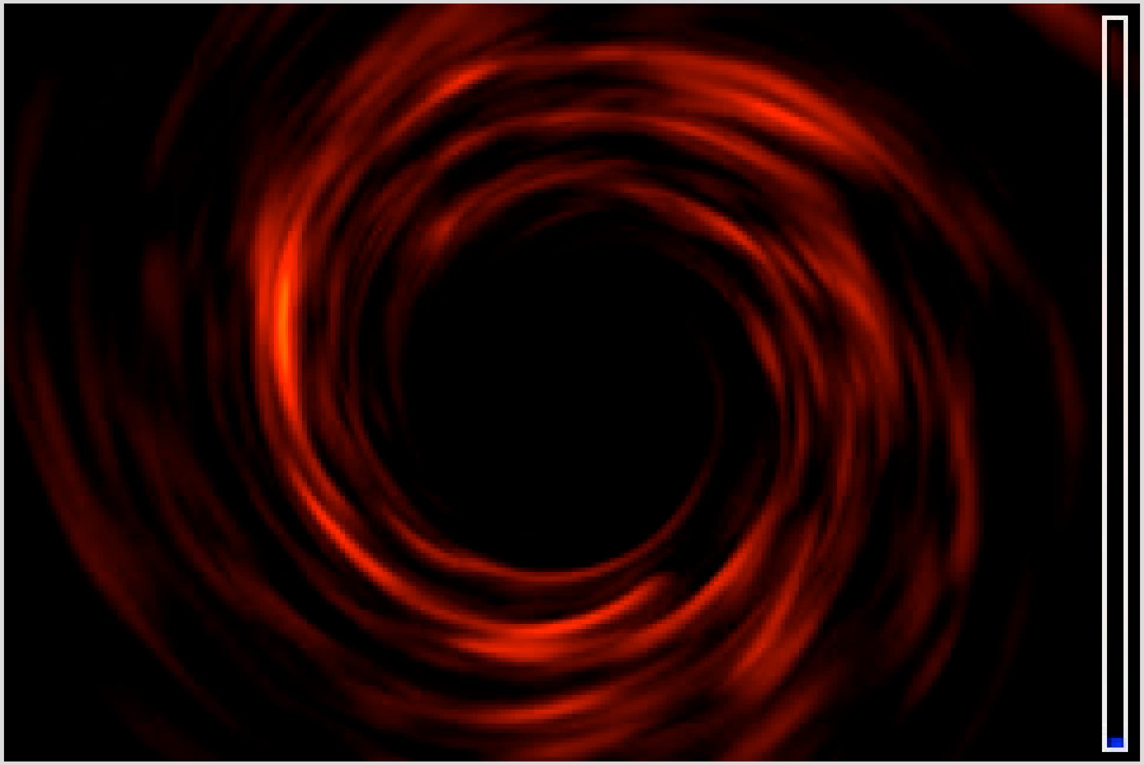
Finally integrate over all disk radii

Predict: **broad, asymmetric line profile with a sharp cutoff at high E**

For disks viewed almost edge-on, light bending around the black hole also affects the line profile:



Prediction assuming a smooth distribution of disk emissivity.



Prediction for a turbulent disk. Note:

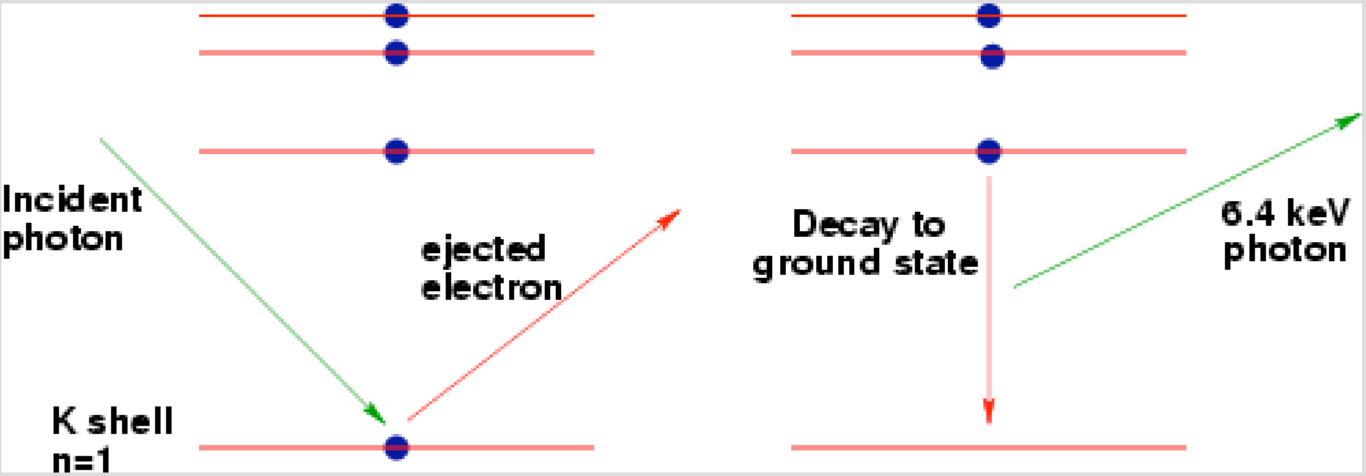
- Beaming
- Light bending

Redshift is **not** visualized…

Iron lines

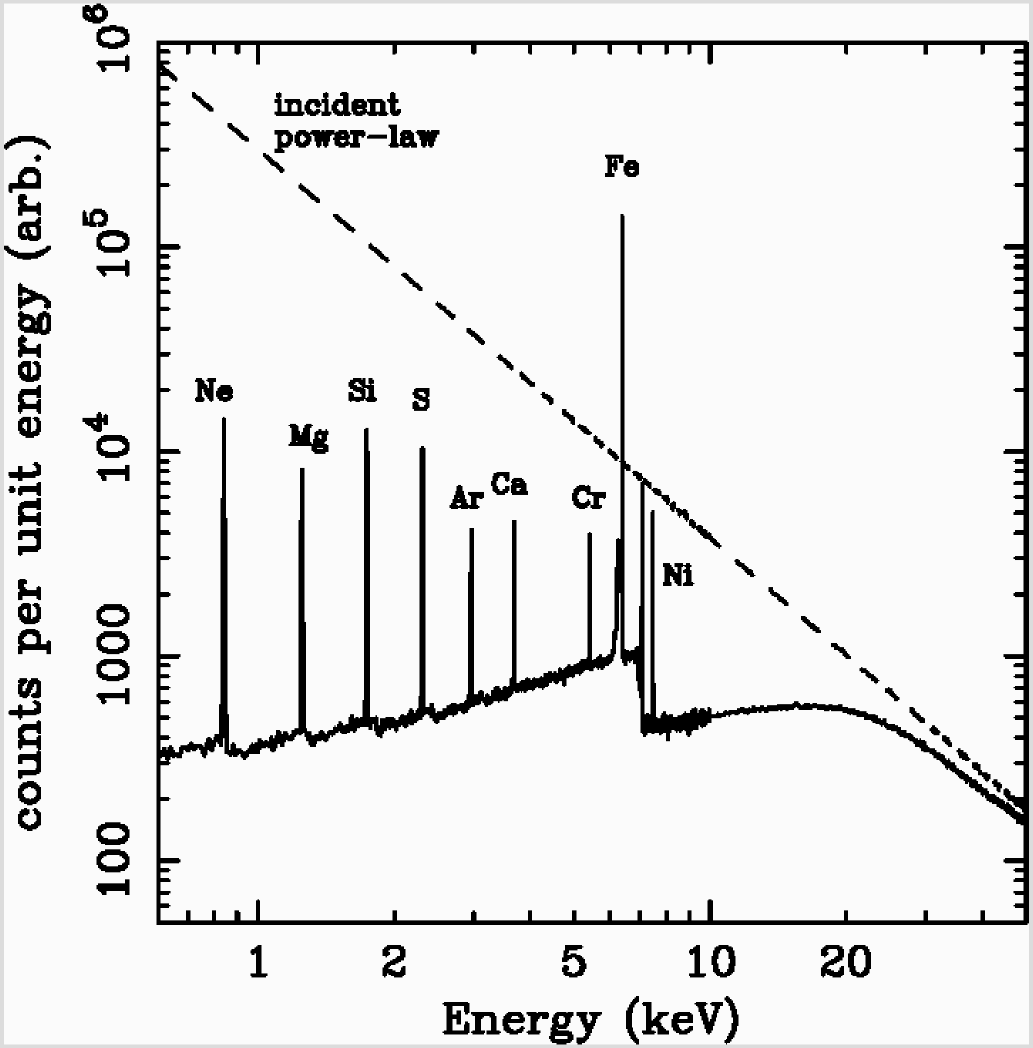
Inner disk is too hot to produce spectral lines in the optical.
In some Seyfert galaxies, detect fluorescent **iron line** in the X-ray spectrum.

Physics: assume `cold' (not fully ionized) disk is illuminated by high energy X-ray photons:



- Eject electron from ground state
- Electron from n=2 level drops down into ground state, energy emitted as photon at 6.4 keV

Detailed calculation shows the predicted spectrum from a cold slab of gas illuminated by X-rays:



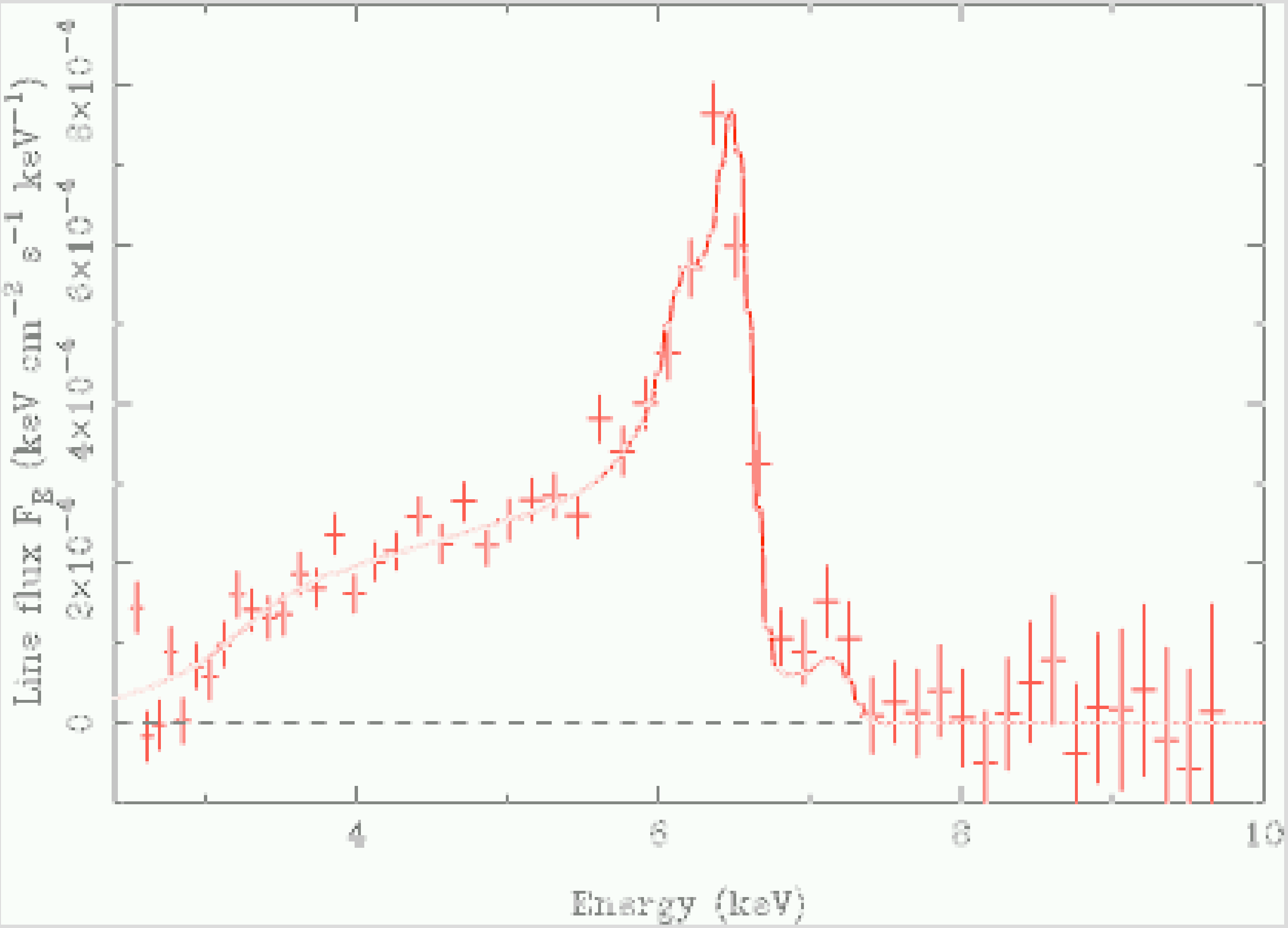
Range of photon energies can eject an electron, but emitted photon is always at single energy:

Strong line emission

Fluorescent yield scales as Z^4, so iron line is the strongest.

Low energy photons are mostly absorbed, high energy photons scatter back out of slab.

Iron line profile for the Seyfert galaxy MCG-6-30-15



Observation with XMM-Newton observatory.

Iron line profile is found to be:

- Often extremely broad
- Favors a rapidly spinning hole
- Variable - high and low states of the source have significantly different lines

Best `proof' to date of presence of black holes in AGN

Relativistically broad iron lines also detected in Galactic black hole candidate sources.