Spectral Line Investigations in Extragalactic Objects

2nd Summer School in Astronomy

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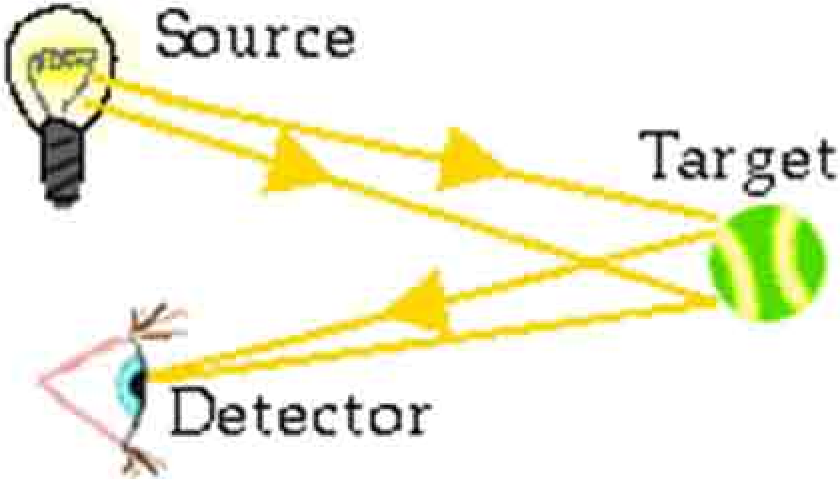
Belgrade, 30.09. 2008.

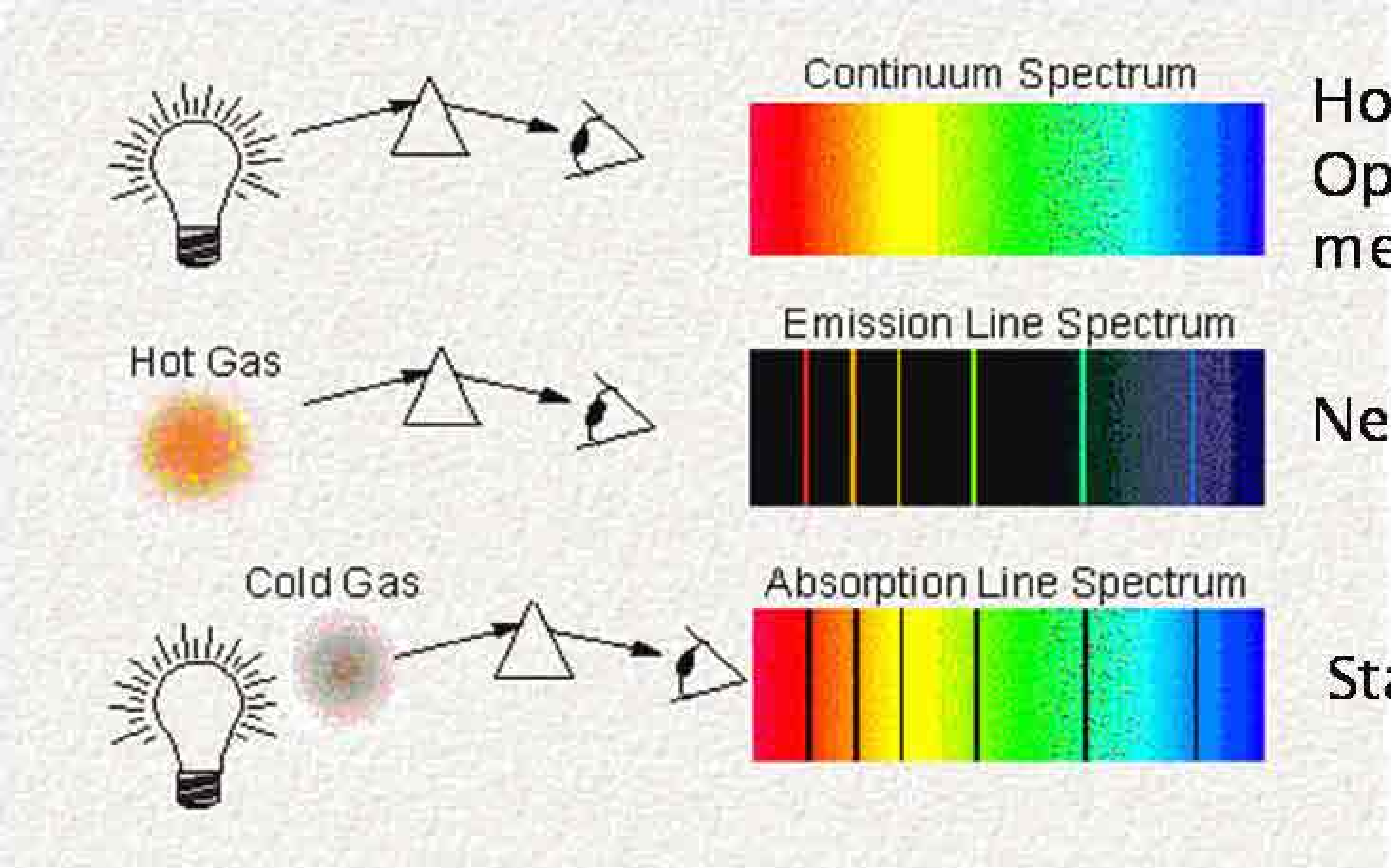
What can we observe?

- Object that reflects electromagnetic radiation (EMR) – planets, satellites, asteroids, etc.



- Object emits (sources of) EMR – Sun, stars, nebulae, galaxies etc.

Spectra: Type of spectral lines



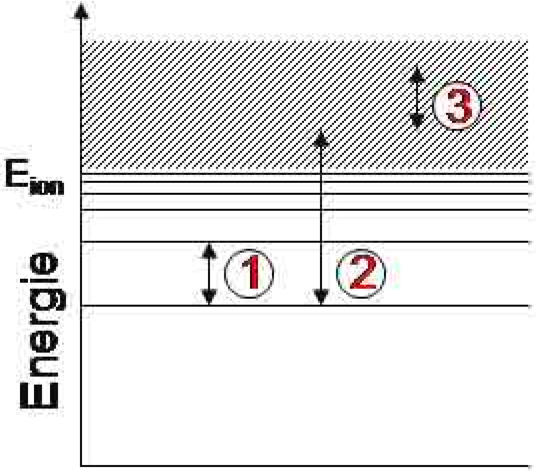
Hot,
Opaque
media

Nebulae

Stars

Transitions => lines

Transitions in atoms/ions



1. bound-bound transitions =lines
2. bound-free transitions= ionization and recombination processes
3. free-free transitions = Bremsstrahlung

$\kappa(\nu), \eta_{\nu}(\nu)$

We look for a relation between macroscopic quantities and microscopic (quantum mechanical) quantities, which describe the state transitions within an atom

Radiation Processes

	Spectral Lines	Continuum
Radio (20m- 1mm)	•**Neutral Hydrogen (HI) 21cm fine structure line** – neutral gas •**Hydrogen recombination lines** – ionised gas •**OH, H_2O etc. Masers** – dense, warm molecular gas •**Molecular Rotation lines** – cold molecular gas	•**Thermal Bremsstrahlung (free-free emission)** – HII regions •**Synchrotron Radiation** – Radio Galaxies, Pulsars, Supernovae. •**Thermal emission from dust** – cold, dense gas.
Submillimetre and far IR (600 microns – 5 microns)	•**Molecular Rotation Lines** – warm, dense gas. •**Solid State features (silicates)** – dust. •**Hydrogen recombination lines** – HII regions.	•**Thermal emission** – warm dust.

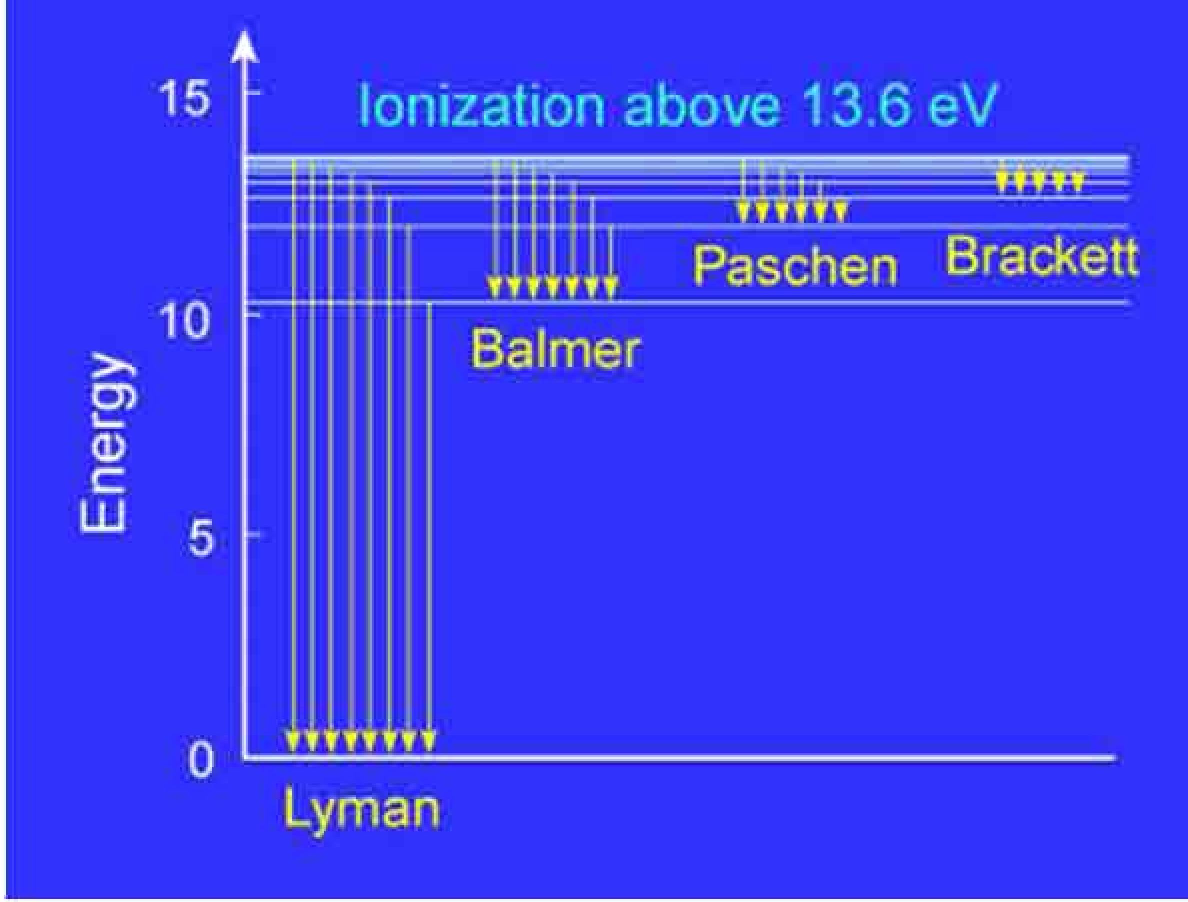
Radiation Processes

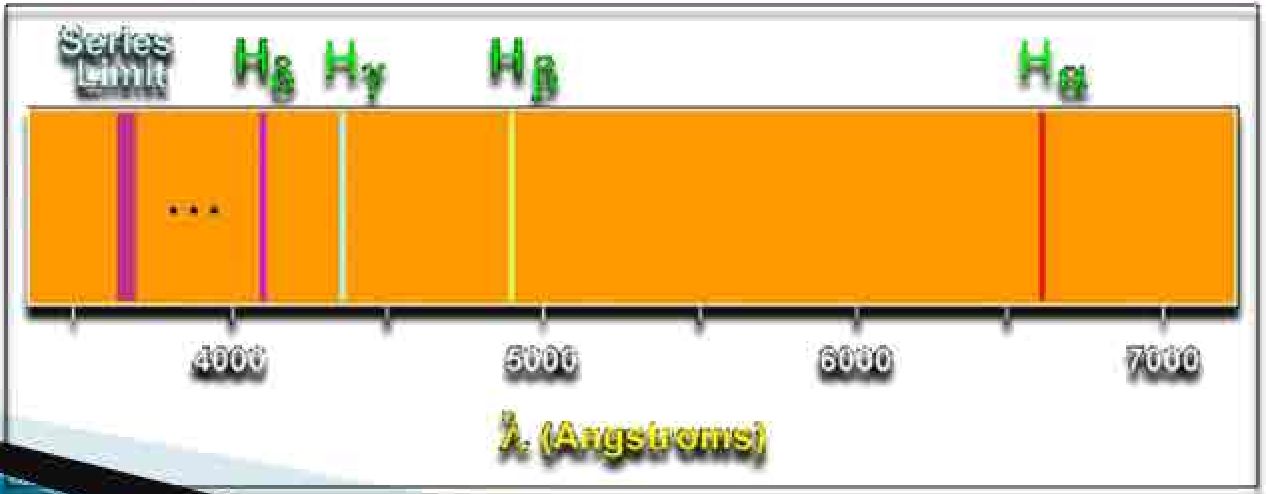
	Spectral Lines	Continuum
Near IR (5 microns – 800nm)	•**Hydrogen recombination lines** – ionised gas •**Molecular Vibration-Rotation lines** – shock or UV excited gas	•**Thermal emission** – Hot gas. •**Stars.**
Optical (800-300 nm)	•**Atomic Forbidden Lines** – hot, low density gas. •**Hydrogen recombination lines** – HII regions, denser gas.	•**Starlight** •**Extinction by dust.**
Ultraviolet (300-10 nm)	•**Atomic Forbidden Lines** – hot, low density gas – Quasars & AGN. •**Hydrogen recombination lines** – HII regions, denser gas •**220nm extinction feature** – carbon dust.	•**Continuum absorption at λ<912 Angstroms by Hydrogen.**

Radiation Processes

	Spectral Lines	Continuum
X-Ray (10 – 0.01 nm)	**•Hydrogen like lines from highly ionised gas**	**•Thermal emission** – Hot gas e.g in supernovae, accretion disks. **•Thermal Bremsstrahlung** – hot gas in clusters of galaxies **•Synchrotron** - Jets
Gamma-Ray (0.01 – 0.0001 nm)	•Electron-Positron annihilation.	**•Thermal emission from Relativistic shocks –Supernovae and GRBs.**

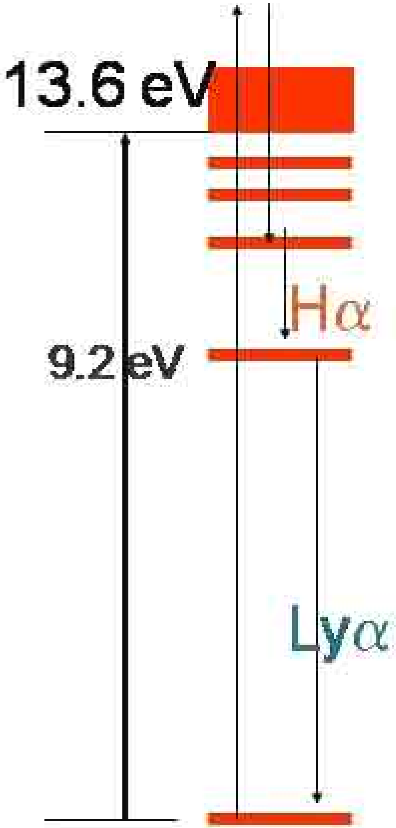
Example of Hydrogen spectra





Recombination lines

- Recombination lines are emitted when an atom is ionised, the electrons recombine with the nuclei, initially in high energy states, then cascade down to the ground state, emitting photons.
- Photons with energy > 13.6 eV (λ < 91.2 nm) can ionise hydrogen. For this reason the universe is opaque at wavelengths from about 30 to 91.2 nm.
- Collisions are the other principal ionisation mechanism.

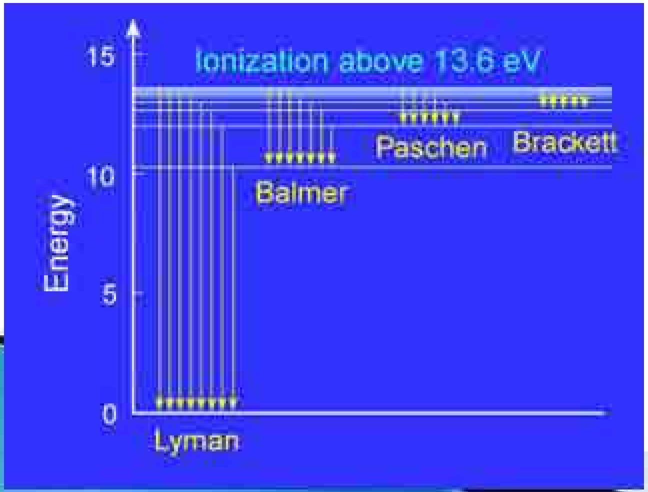


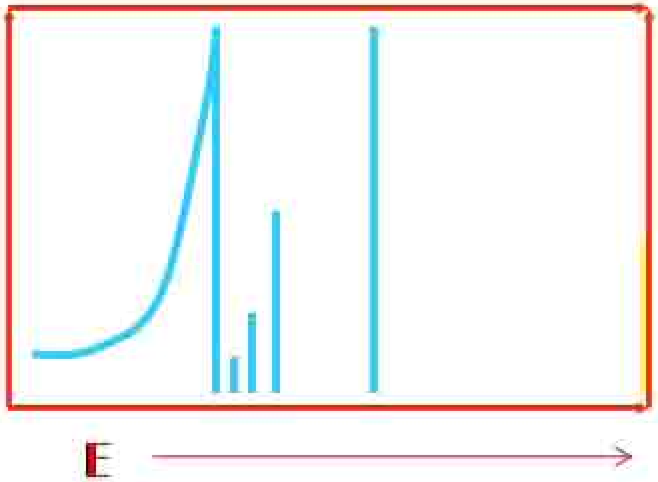
Recombination lines

- Hydrogen is the most abundant element in the universe, and hydrogen recombination lines dominate the spectra of many astrophysical objects at wavelengths from ultraviolet to radio.
- In a volume of hydrogen there will be a stable population of excited levels, and steady emission of the recombination lines.

Hydrogen recombination lines

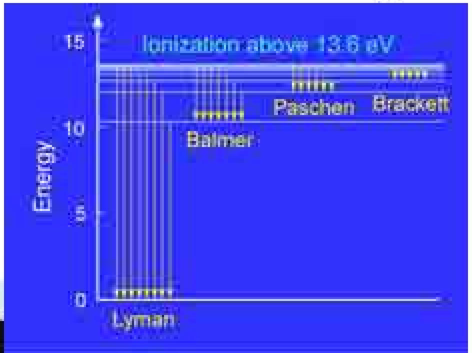
- **Lyman series in the Ultraviolet**
  - Lyman α, the transition between first excited state and ground state, is the strongest line in most quasar spectra.
  - Searches for high redshift galaxies concentrate on isolating the Lyman α line, or on isolating galaxies in which the Lyman break (i.e. Lyman ∞ wavelength or the ionisation potential of Hydrogen) can be detected as there is no flux at higher energies.



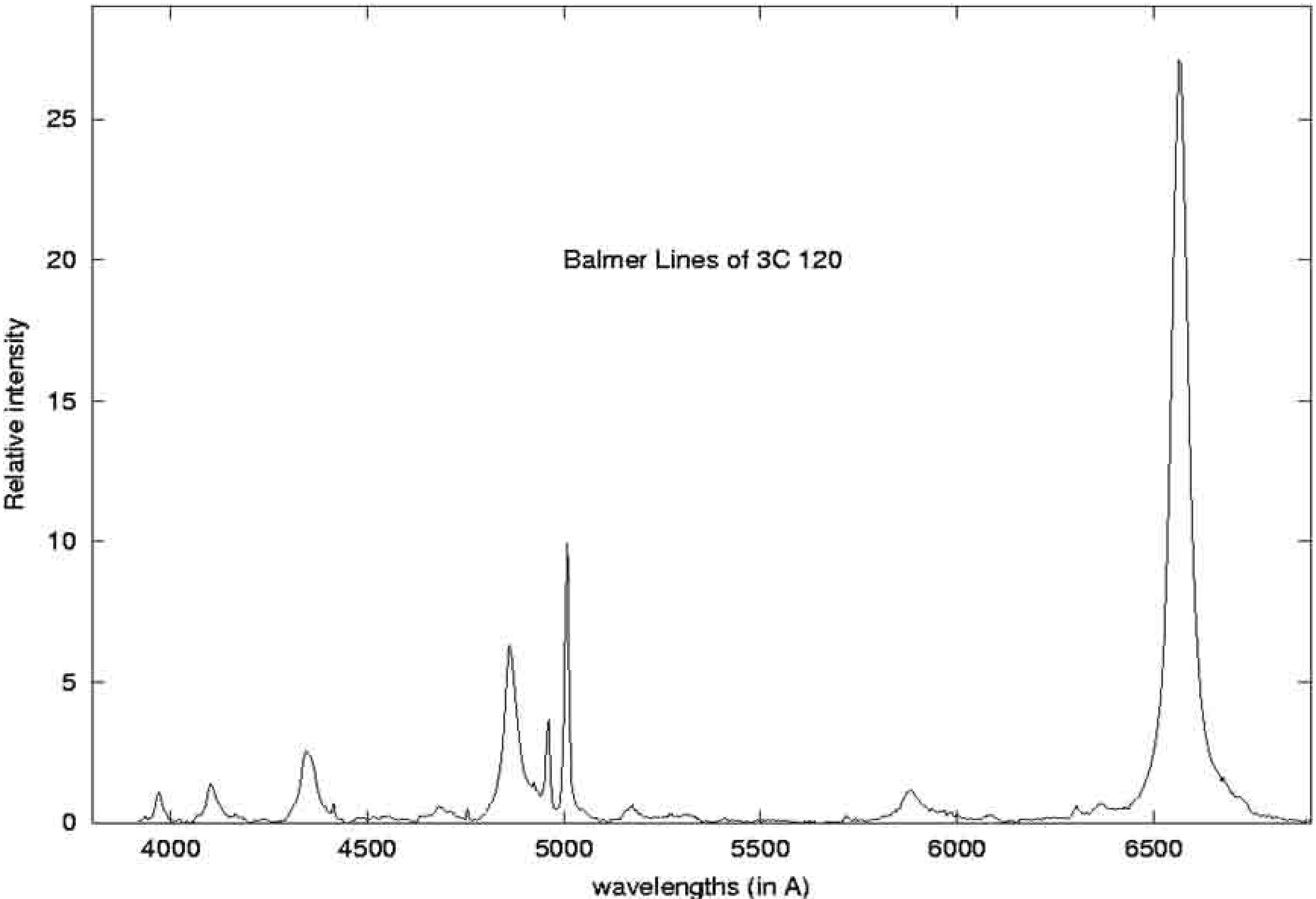


Hydrogen recombination lines

- **Balmer series in the optical**
  - Balmer α usually called Hα is the strongest line in the optical spectrum of HII regions, star forming regions and nearby galaxies.
  - Hα is used to measure star formation rates in nearby galaxies, and to measure motions (e.g. rotation curves in nearby galaxies).
  - As the Balmer line intensity ratios can be well determined from quantum mechanical and radiation physics calculations, the only think that can modify the ratios is dust extinction. Balmer ratios are used to measure dust content along the line of sight.

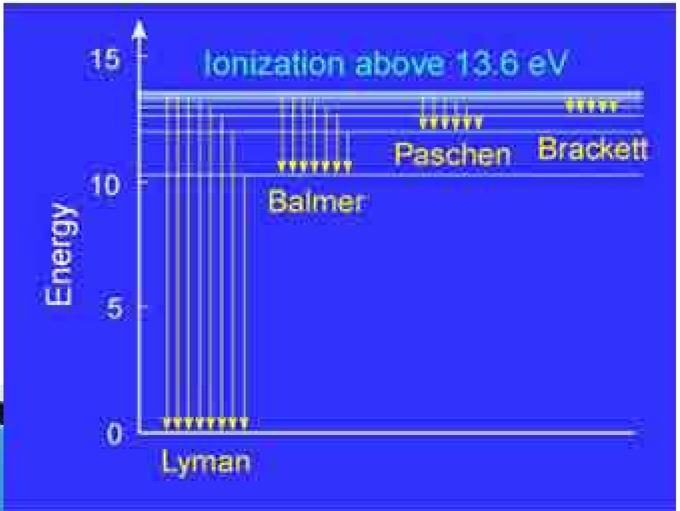


Optical lines; the most intensive the Balmer line series- e.g. AGN spectra



Hydrogen recombination lines

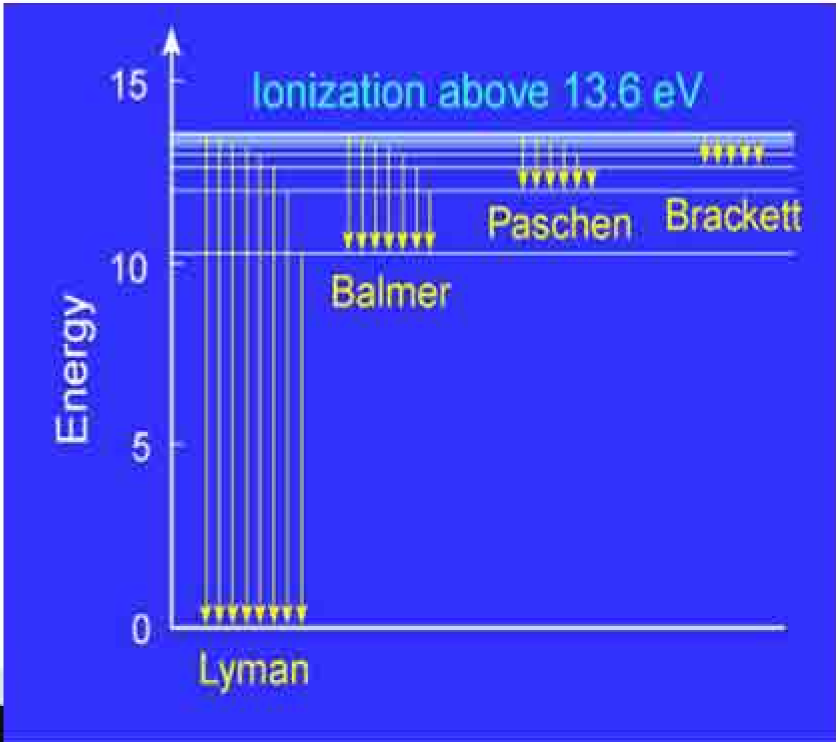
- Paschen, Brackett and Pfund lines in the infra-red
  - In general these have the same uses as the Balmer lines
  - Useful in regions heavily affected by dust obscuration, which affects the infra-red radiation less.
  - Brackett γ, which lies in the K window, is used for velocity measurements in dusty regions.



Radio recombination lines

- High order recombination lines e.g. H109α are observed at radio wavelengths.
- Analysis of several of these lines from the same source can tell us about the temperature and density

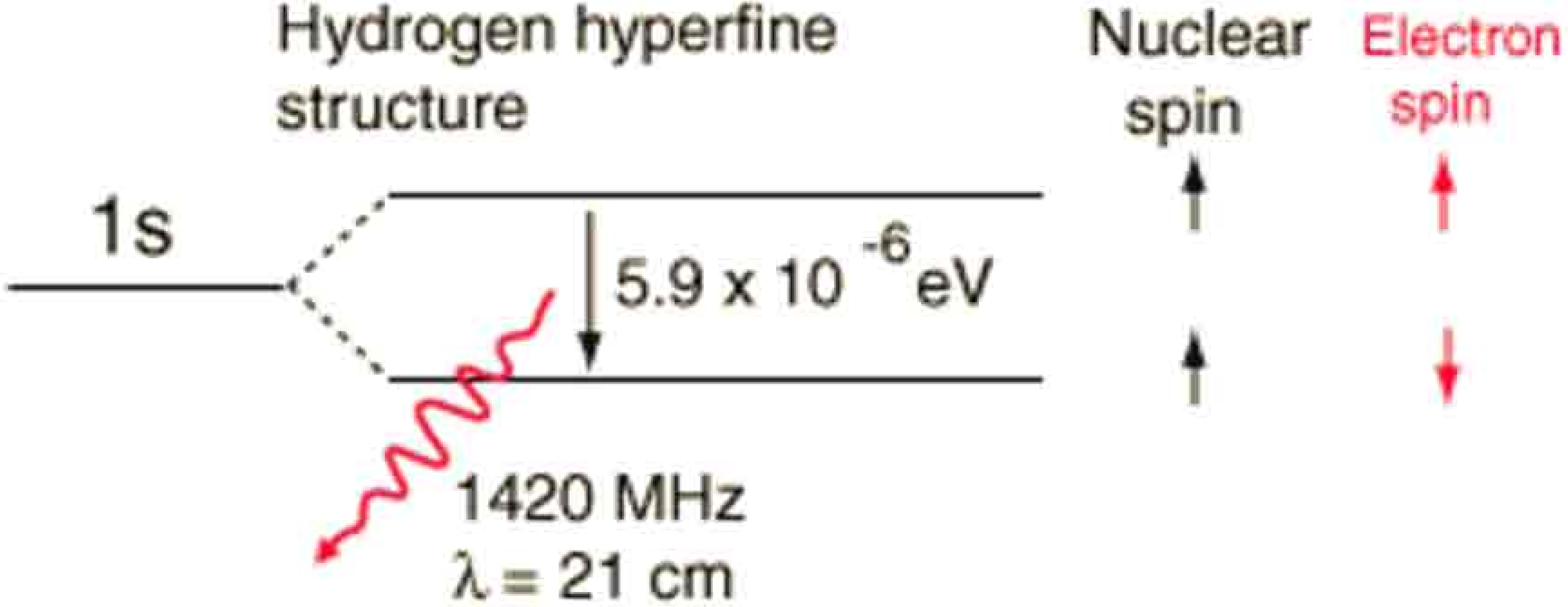
High n–>n'



The HI hyperfine structure line

- Energy levels of neutral hydrogen do not depend only upon the principal quantum number.
- Hyperfine structure is a splitting of levels which occurs when the spin of the nucleus is taken into account.
- The ground state of hydrogen has two levels with f=0 and f=1, which have electron and proton spin antiparallel and parallel

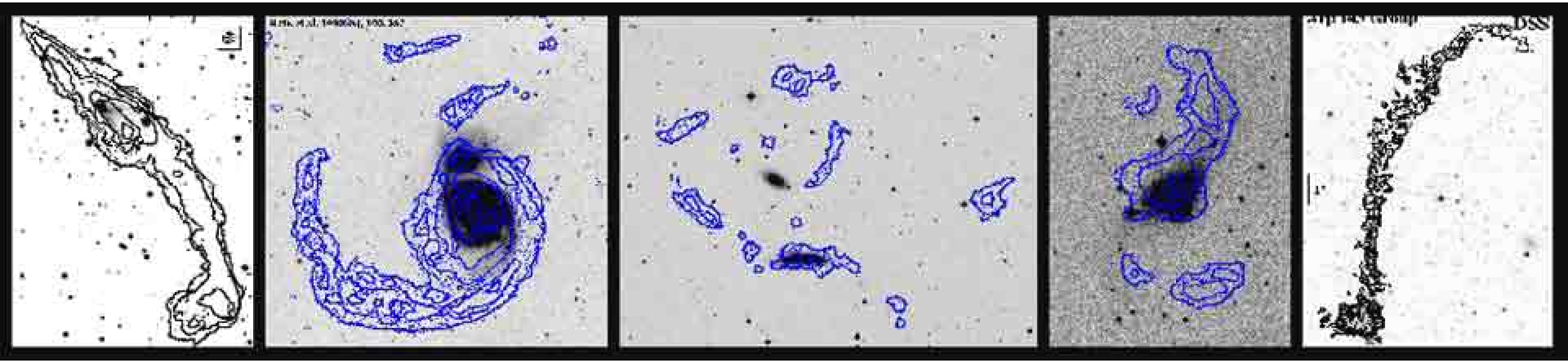
The HI hyperfine structure line



The HI hyperfine structure line

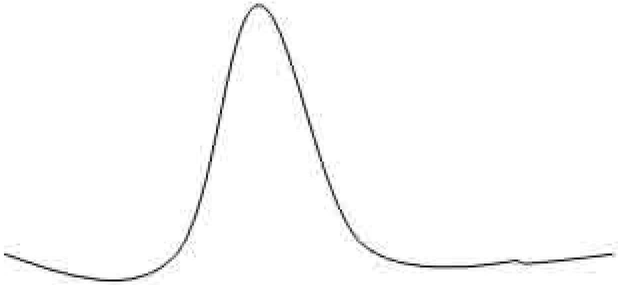
- This transition is forbidden as an electric dipole transition, since $\Delta l = 0$, but occurs as a magnetic dipole transition.
- Splitting between the levels is 5.9 x 10^{-6} eV, and the transition leads to a line at 1420 MHz or 21 cm wavelength.
- This is the most important line for detecting and mapping neutral hydrogen in our and other galaxies.

Images of galaxies at 21cm



Spectral line, what is it?

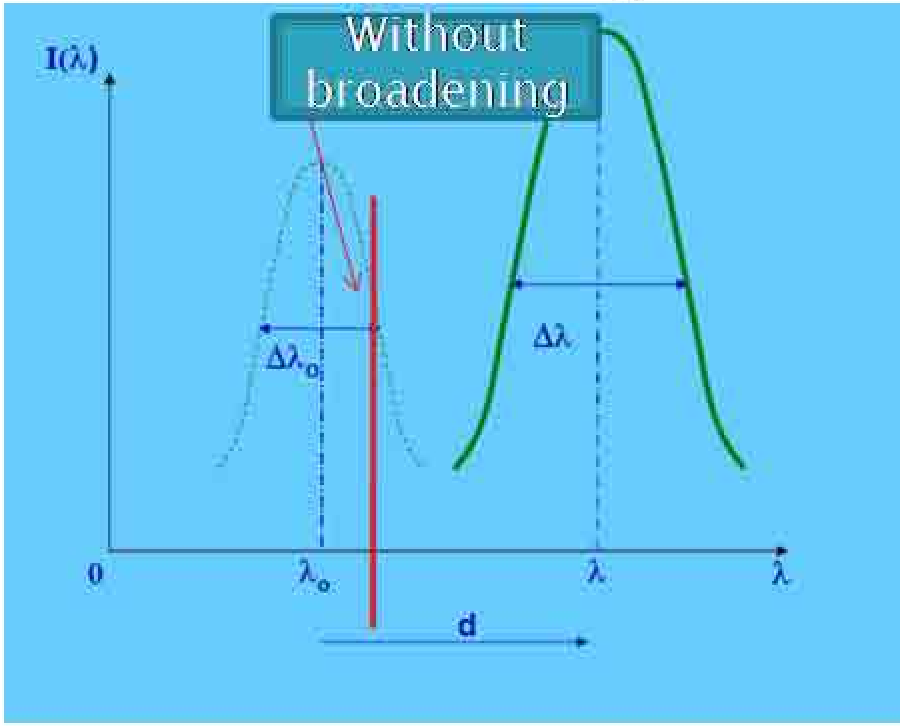
- ????????????



Line parameters

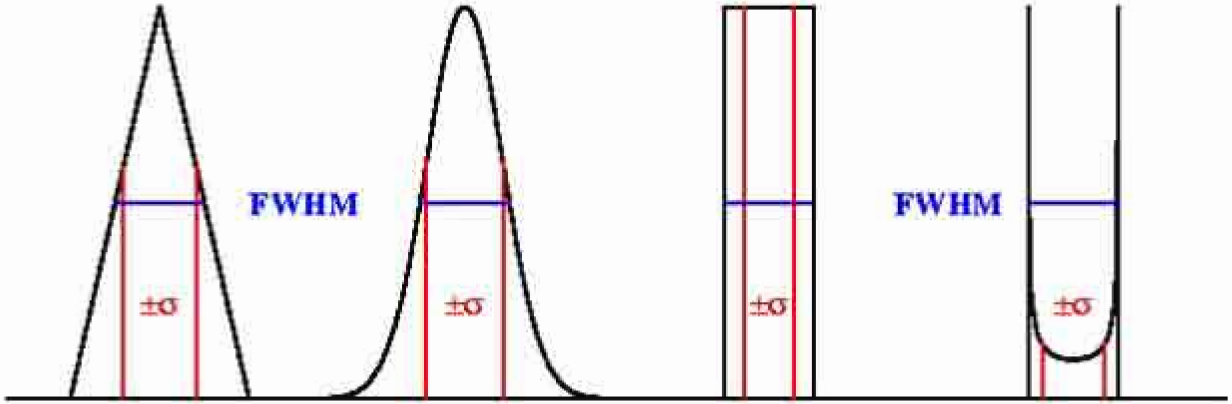
- I=f(λ)
- Ideally spectral line f(λ)=delta function
- Time-life of a level => natural broadening ~0.00001nm
- Broadening

connected with:
(i) characteristics of emitting plasma
(ii) nature of objects (rotation, disk, outflow)



Line width and shift – learn about emitting/absorbing sources

- **Some trivial profiles**

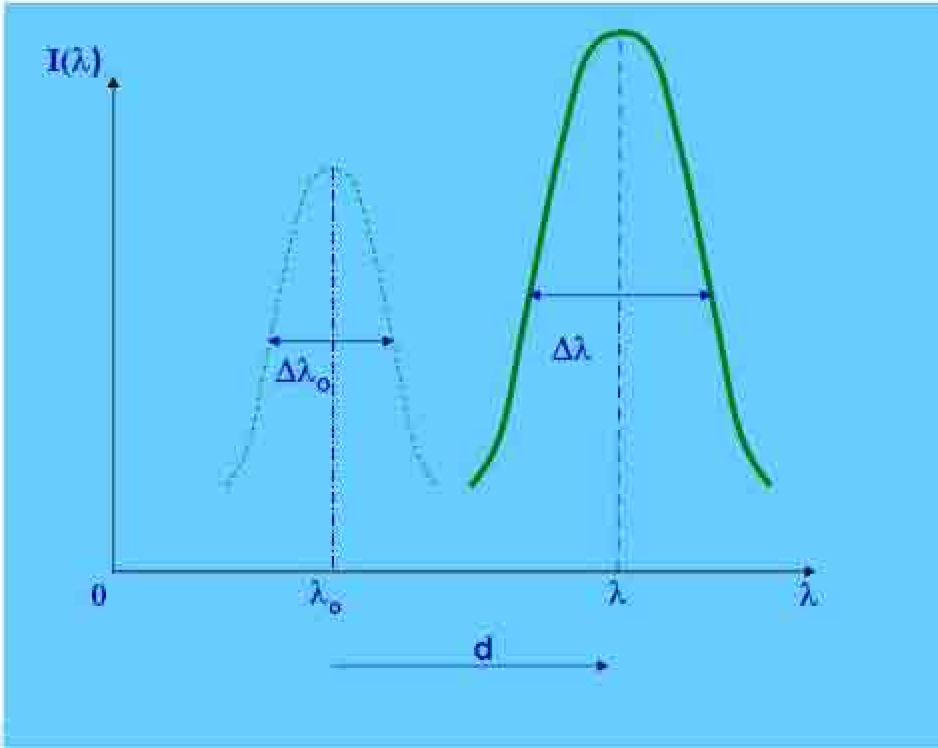


	$\sqrt{6}$	$2(2\ln 2)^{1/2}$	$2\sqrt{3}$	$2\sqrt{2}$
$\frac{\mathrm{FWHM}}{\sigma_{\mathrm{line}}} =$	2.45	2.35	3.46	2.83

Line parameters –width and shift

- Full width at half maximum (FWHM)
- Shift => $d = \lambda - \lambda_o$
- λ_o is the transition wavelength

- Three line profiles:
- Gaussian (Doppler broadening) & Lorentzian
- Voigt (convolution G & L)



Lorentz profile

$$L(x) = \frac{1}{\pi\gamma_L} \frac{\gamma_L^2}{\left(x^2 + \gamma_L^2\right)}$$

- When we have deformation connected with emitter structure (perturbation of energy levels)
- Processes:
- 1. Natural broadening
- 2. Collisional broadening
    - Van der Waals – collisions between emitter and atoms
    - Stark – collisions between emitter and electron/ion
    - Resonant broadening

Natural broadening – each line has this broadening

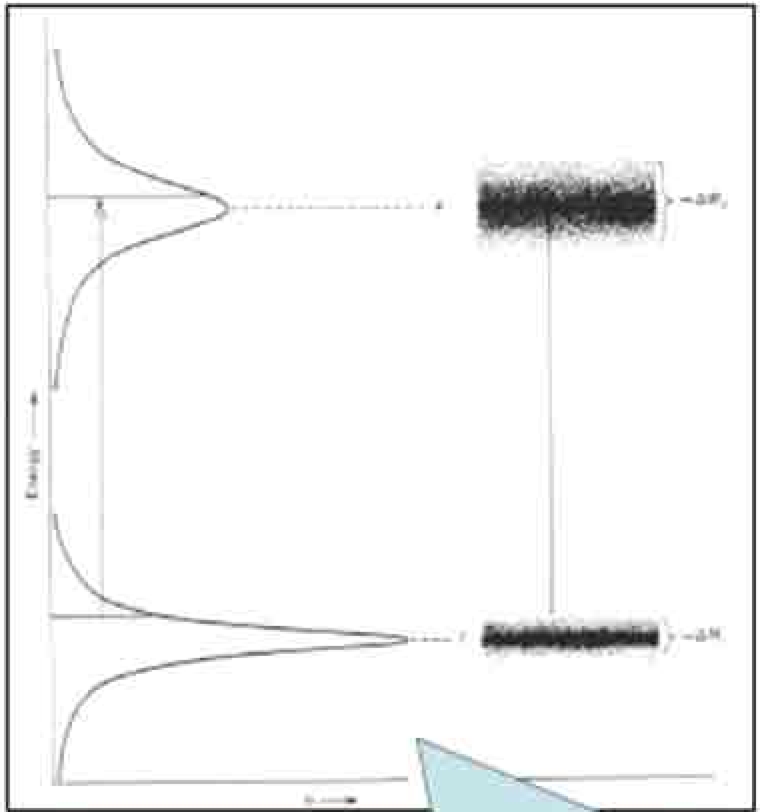
- *Natural Broadening* is due to the Heisenberg Uncertainty Principle - a direct result of Quantum Mechanics
- When an electron is moved to an excited state it occupies this state for a short period of time *Δt* and so the energy of this state, *E* cannot have a precise value
- The uncertainty associated with *E* is called *ΔE* and is given by Heisenberg's famous formula:

$$\Delta E = \frac{\hbar}{\Delta t}$$

- With a full calculation the uncertainty in the photon's wavelength thus becomes:

$$(\Delta\lambda)_{1/2} = \frac{\lambda^2}{\pi c}\frac{1}{\Delta t_0}$$

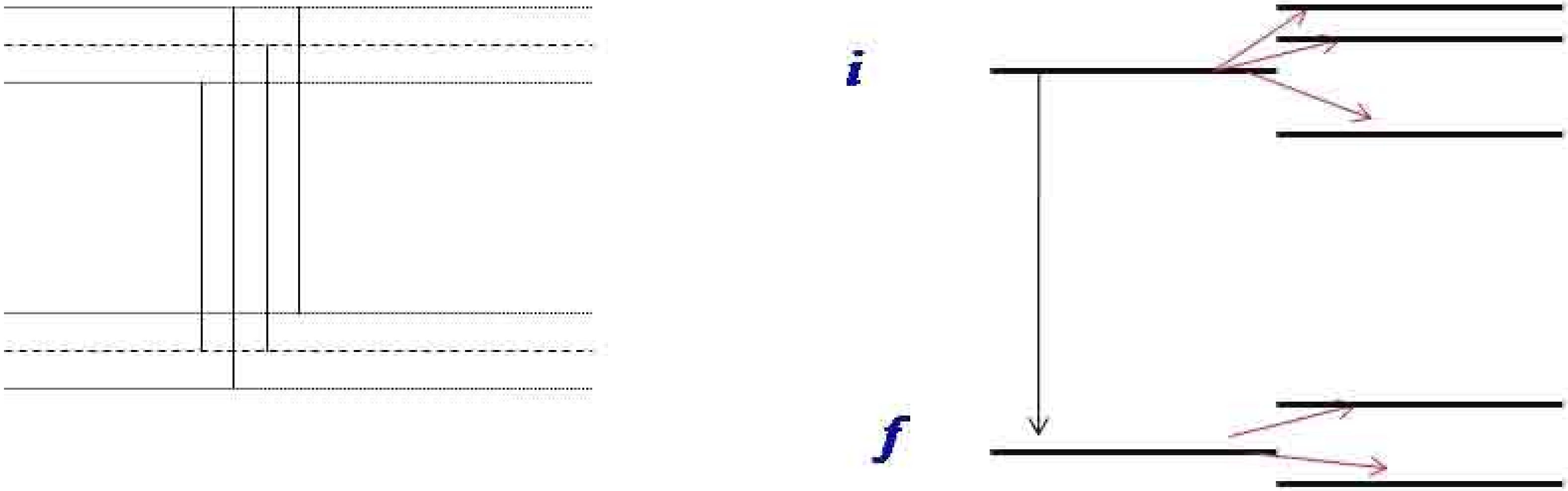
- Where $(\Delta\lambda)_{1/2}$ is the full width at half-maximum and Δt_0 is the average waiting time for a specific transition to occur



A typical value for natural broadening is given by: $(\Delta\lambda)_{1/2} = 2.4 \times 10^{-4}$ Å

Natural broadening – each line has this broadening

- Calculation
- $W=2.65\times10^{-20}\,\lambda^{2}\sum_{i'}A_{ii'}+\sum_{f'}A_{ff'}$
- **Where λ is in Å, Ajj' are transition probabilities all possible transitions between initial (i) and final (f) level**



Line broadening: Pressure broadening

- Semi-classical theory (Weisskopf, Lindholm), „Impact Theory“

  Phase shifts $\Delta\omega$:

$$\Delta\omega = C_p / r^p \,,\ \ p = 2,3,4,6 \ , \ r(t) = \text{distance to colliding particle}$$

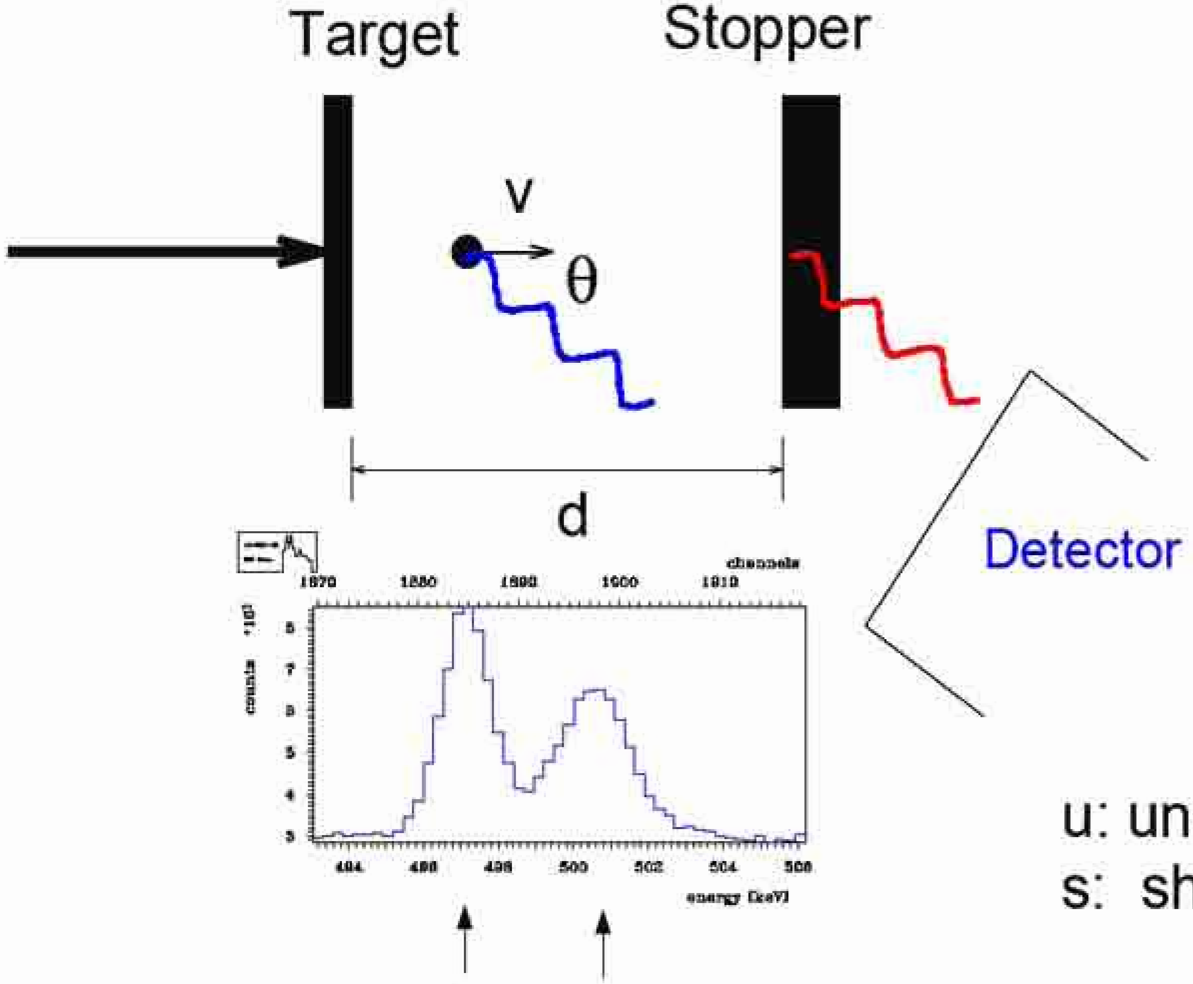
find constants C_p by laboratory measurements, or calculate

p=	name	dominant at
2	linear Stark effect	hydrogen-like ions
3	resonance broadening	neutral atoms with each other, H+H
4	quadratic Stark effect	ions
6	van der Waals broadening	metals + H

- Good results for p=2 (H, He II): „Unified Theory“ H Vidal, Cooper, Smith 1973 He II Schöning, Butler 1989 For p=4 (He I) Barnard, Cooper, Shamey; Barnard, Cooper, Smith; Beauchamp et al.

Doppler shift

$$E_s(\theta,t) = E_o\frac{\sqrt{1-\frac{v}{c}}}{1-\frac{v}{c}\cos\theta} \approx E_o\left(1+\frac{v}{c}\cos\theta\right)$$



u: unshifted
s: shifted

E_u $E_s = E_u(1+ v/c \cos(\theta))$

Doppler Broadening

- Two components contribute to the intrinsic Doppler broadening of spectral lines:
    - Thermal broadening
    - Turbulence – the dreaded microturbulence!
- Thermal broadening is controlled by the thermal velocity distribution (and the shape of the line profile)

$$\frac{dN(v_r)}{N_{Total}} = \left(\frac{m}{2\pi kT}\right)^{2/3} e^{-\left(\frac{mv_r^{\,2}}{2kT}\right)} dv_r$$

where v_r is the line of sight velocity component

- The Doppler width associated with the velocity v_0 (where the variance $v_0^2 = 2kT/m$) is

$$\Delta\lambda_D = \frac{v_0}{c}\lambda = \frac{\lambda}{c}\left(\frac{2kT}{m}\right)^{1/2} = 4.3x10^{-7}\lambda(T/\mu)^{1/2}$$

and λ is the wavelength of line center

More Doppler Broadening

- Combining these we get the thermal broadening line profile:

$$\frac{I_\nu}{I_{total}} = \frac{c}{\nu}\sqrt{\frac{m}{2\pi kT}}\,e^{-\frac{mc^2(\nu-\nu_0)^2}{\nu^2 2kT}}$$

- At line center, $\nu=\nu_0$, and this reduces to

$$\frac{I_\nu}{I_{total}} = \frac{c}{\nu}\sqrt{\frac{m}{2\pi kT}}$$

- Where the line reaches half its maximum depth, the total width is

$$2\Delta\lambda_{1/2} = \frac{2\lambda_0}{c}\sqrt{\frac{2kT\ln 2}{m}}$$

Line broadening: Microturbulence

Reason: chaotic motion (turbulent flows) with length scales smaller than photon mean free path

Phenomenological description: $w_{\mathbf{x}}(\mathrm{v}_x) = \frac{1}{\sqrt{\pi}\mathbf{v}_{\mathrm{micro}}} e^{-\mathbf{v}_x^2/\mathbf{v}_{\mathrm{micro}}^2}$

Velocity distribution:

i.e., in analogy to thermal broadening

$\mathrm{v}_{\mathrm{micro}}$ is a free parameter, to be determined empirically

Solar photosphere: $\mathrm{v}_{\mathrm{micro}}$ =1.3 km/s ; BLR of AGN~1000 km/s

Line profile – Gaussian

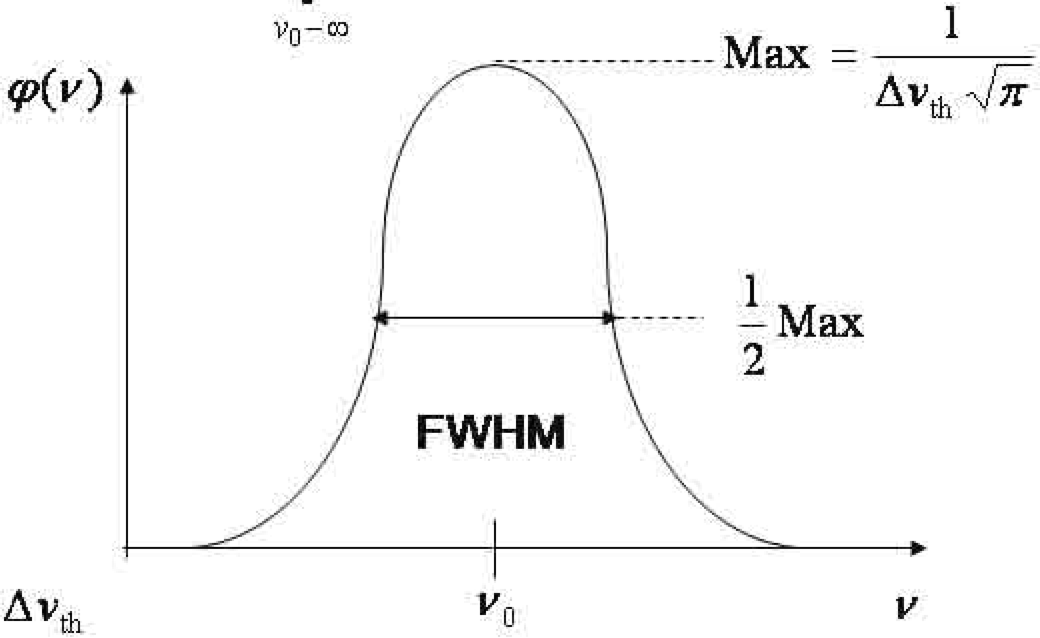
$$\frac{\Delta\nu}{\nu_0} = \frac{\mathrm{v}}{c}, \quad \frac{\Delta\nu_{\mathrm{th}}}{\nu_0} = \frac{\mathrm{v}_{\mathrm{th}}}{c}$$

Doppler effect:

profile function:

$$w_x(\mathrm{v}_x) \Rightarrow \varphi(\nu) = \frac{C_1}{\sqrt{\pi}\Delta\nu_{\mathrm{th}}} \frac{\nu_0}{c} e^{-\Delta\nu^2/\Delta\nu_{\mathrm{th}}^2}, \quad \text{with} \int_{\nu_0-\infty}^{\nu_0+\infty} \varphi(\nu)d\nu = 1 \quad \text{we obtain:}$$

$$\boxed{\varphi(\nu) = \frac{1}{\sqrt{\pi}\Delta\nu_{\mathrm{th}}} e^{-(\nu-\nu_0)^2/\Delta\nu_{\mathrm{th}}^2}}$$



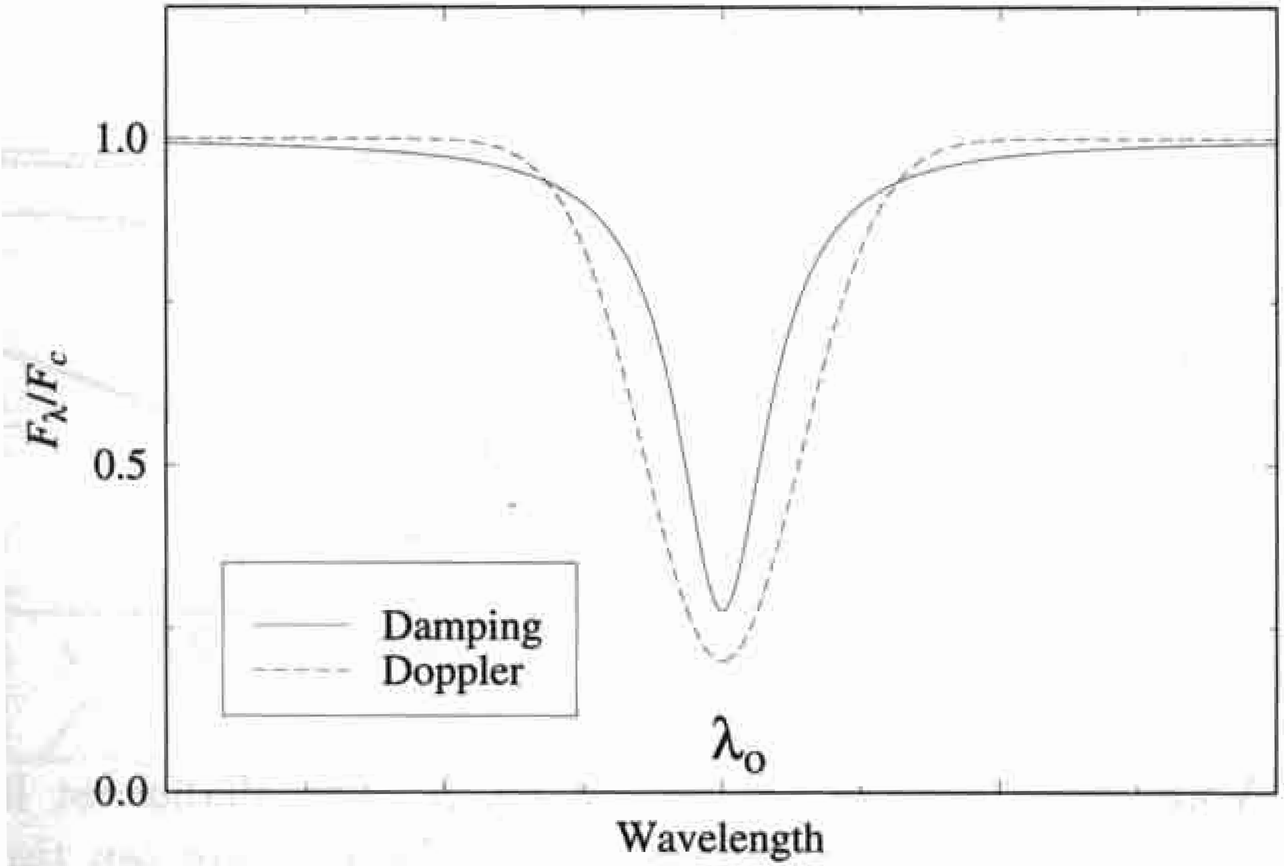
Line profile = Gauss

- Symmetric about ν_0
- Maximum: $1/\Delta\nu_{\mathrm{th}}\sqrt{\pi}$
- Half width:

  $$\Delta\nu_{\mathrm{FWHM}} = 2\sqrt{\ln 2}\Delta\nu_{\mathrm{th}} = 1.67\,\Delta\nu_{\mathrm{th}}$$

- Temperature dependency: $\Delta\nu_{\mathrm{th}} \sim \sqrt{T}$

Line Shapes



Voigt function – true line profile

Convolving Gauss and Lorentz profile (thermal broadening + damping)

$$G(\nu)=\frac{1}{\Delta\nu_D\sqrt{\pi}}\;e^{-(\nu-\nu_0)^2/\Delta\nu_D^2}\qquad L(\nu)=\frac{\gamma/4\pi^2}{(\nu-\nu_0)^2+(\gamma/4\pi)^2}$$

$V=G*L$ depends on $\nu,\Delta\nu,\gamma,\Delta\nu_D$: $V(\nu)=\int_{-\infty}^{\infty}G(\nu')L(\nu-\nu')d\nu'$

Transformation: $\mathrm{v}:=(\nu-\nu_0)/\Delta\nu_D$ $\;a:=\gamma/(4\pi\Delta\nu_D)$ $\;y:=(\nu'-\nu_0)/\Delta\nu_D$

$$G(y)=\frac{1}{\Delta\nu_D\sqrt{\pi}}\;e^{-y^2}\qquad L(y)=\frac{a/\Delta\nu_D\pi}{y^2+a^2}\qquad V=\frac{1}{\Delta\nu_D\sqrt{\pi}}\frac{a}{\pi}\int_{-\infty}^{\infty}\frac{e^{-y^2}}{(\mathrm{v}-y)^2+a^2}dy$$

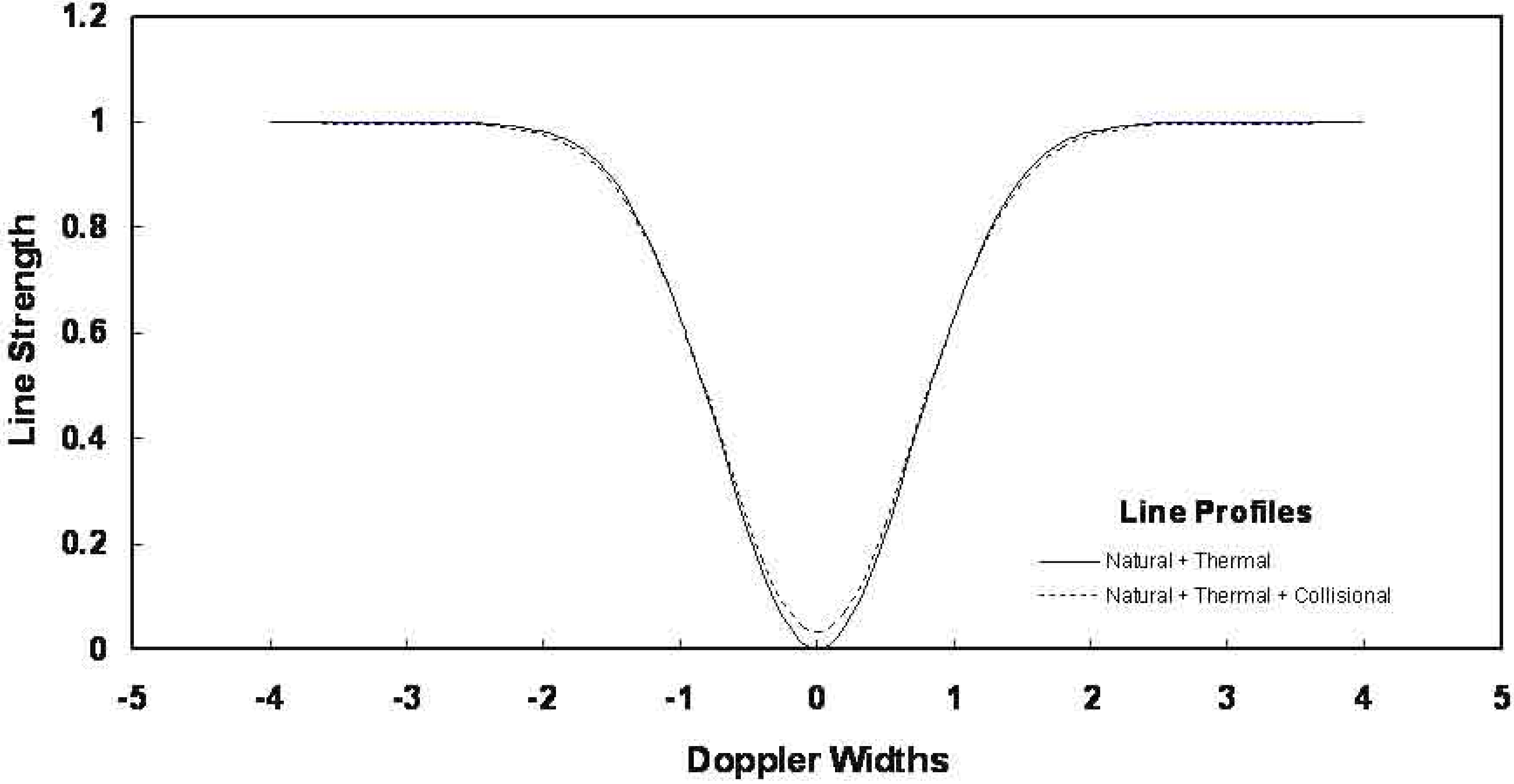
Def: $V=\frac{1}{\Delta\nu_D\sqrt{\pi}}H(a,\mathrm{v})$ with $\boxed{H(a,\mathrm{v})=\frac{a}{\pi}\int_{-\infty}^{\infty}\frac{e^{-y^2}}{(\mathrm{v}-y)^2+a^2}dy}$

Voigt function, no analytical representation possible.

(approximate formulae or numerical evaluation)

Normalization: $\int_{-\infty}^{\infty}H(a,\mathrm{v})d\mathrm{v}=\sqrt{\pi}$

Line Profiles – Voight



Examples

$$\Delta\lambda_D = \frac{v_0}{c}\lambda = \frac{\lambda}{c}\left(\frac{2kT}{m}\right)^{1/2} = 4.3x10^{-7}\lambda(T/\mu)^{1/2}$$

- At λ_0=5000Å:
- T=6000K, A=56 (Fe): $\Delta\lambda_{th}$=0.02Å
- T=50000K, A=1 (H): $\Delta\lambda_{th}$=0.5Å
- Compare with natural broadening: $\Delta\lambda_{FWHM}$=1.18 10^{-4}Å
- But: decline of Gauss profile in wings is much steeper than for Lorentz profile:

$$\text{Gauss } (10\Delta\lambda_{th}) \quad : \quad e^{-10^2} \approx 10^{-43}$$

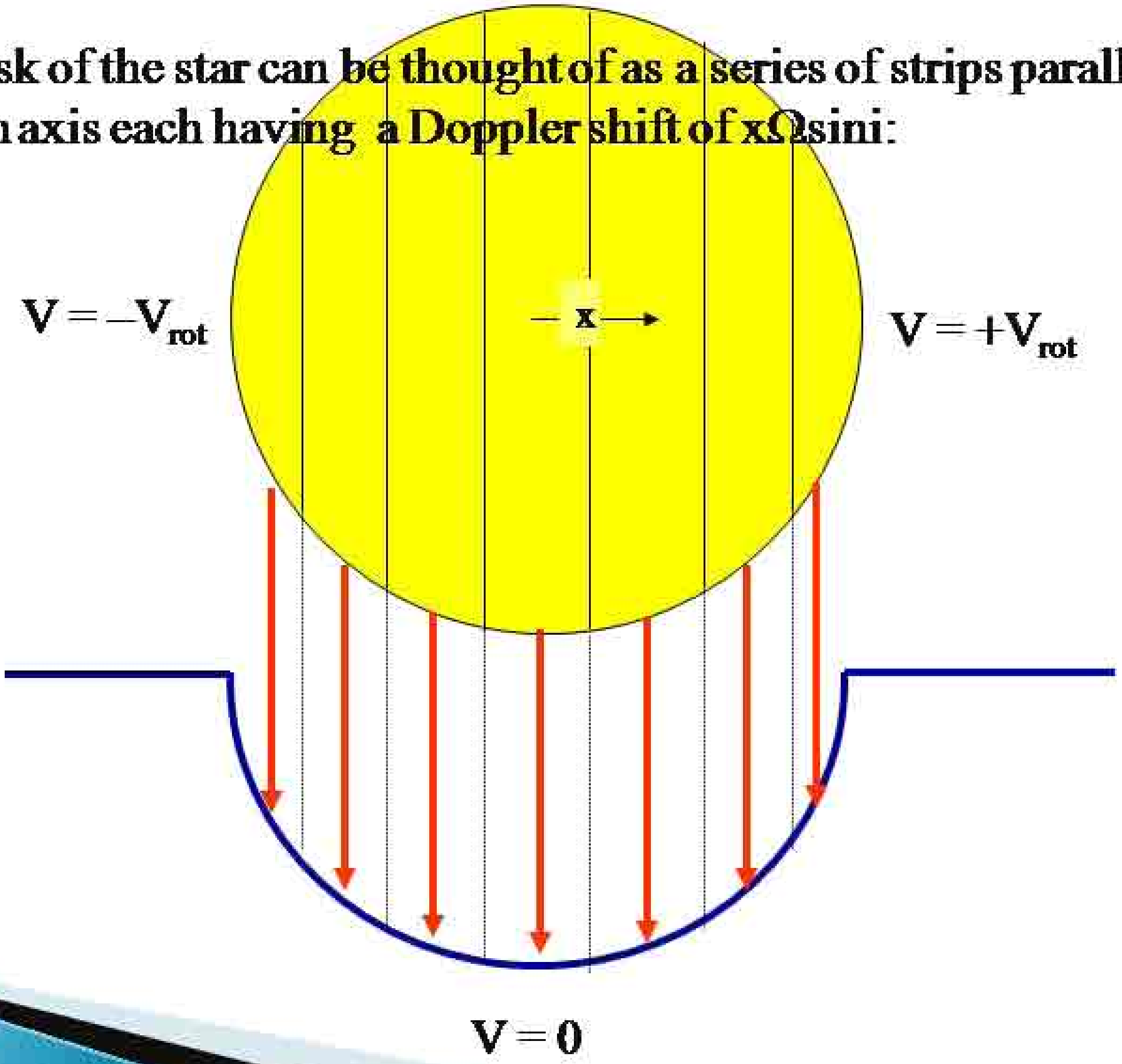
$$\approx$$

$$\text{Lorentz } (1000\Delta\lambda_{rad}) : \; 1/1000^2 \approx 10^{-6}$$

- In the line wings the Lorentz profile is dominant

Rotation broadening – macro motion

The apparent disk of the star can be thought of as a series of strips parallel to the projection axis each having a Doppler shift of $x\Omega \sin i$:



The Rotation Profile

$$G(\Delta\lambda) = G(\upsilon) = \frac{2(1-\varepsilon)[1-(\upsilon_z/\upsilon_L)^2]^{1/2} + \frac{1}{2}\pi\varepsilon[1-(\upsilon_z/\upsilon_L)^2]}{\pi\upsilon_L(1-\varepsilon/3)}$$

$$= c_1[1-(\Delta\lambda/\Delta\lambda_L)^2]^{1/2} + c_2[1-(\Delta\lambda/\Delta\lambda_L)^2],$$

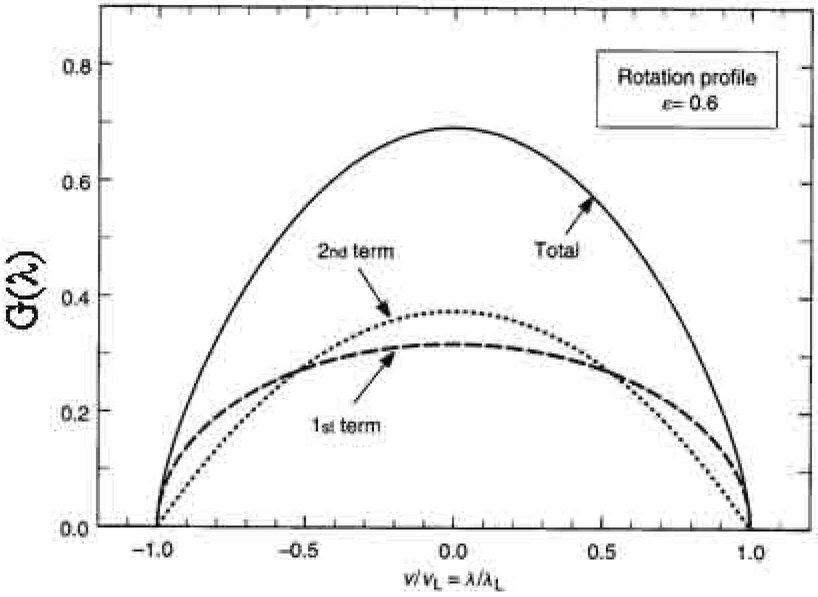


Fig. 18.5. The rotation profile, Eq. (18.14), is shown by the solid line for $\varepsilon = 0.6$ and labeled "total." It is the sum of the "1st term" and "2nd term" curves.

If ε = 0, the second term is zero and the function is an ellipse. If ε =1 the first term is zero and the rotation function is a parabola

The Rotation Profile

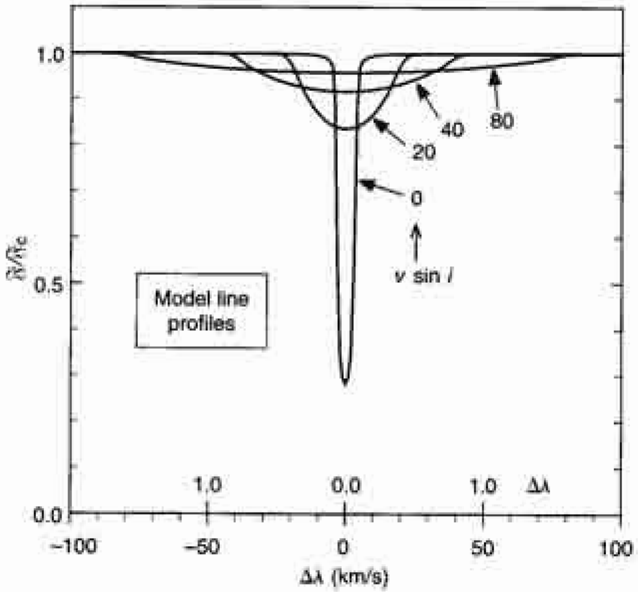


Fig. 18.6. Computed profiles illustrate the broadening effect of reta-tion. The profiles are labeled with $v \sin i$ in km/s. The equivalent width is conserved.

The equivalent width of the line is conserved under rotational broadening !!!!

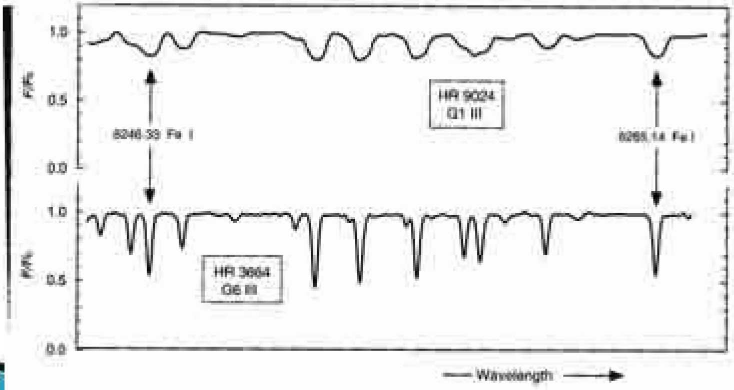


Fig. 18.7. These two G giants illustrate the Doppler broadening of the line profiles by rotation. HR 3664 shows low rotation, comparable to the macro-turbulence broadening, of a few km/s, while HR 9024 shows rotational broadening that is substantially larger. Data taken at the Elginfield Observatory.

To match the spectrum of a star that is rotating rapidly, take a spectrum of a slowly rotating star with the same spectral type and convolve with the rotation function

Rotation in Stars

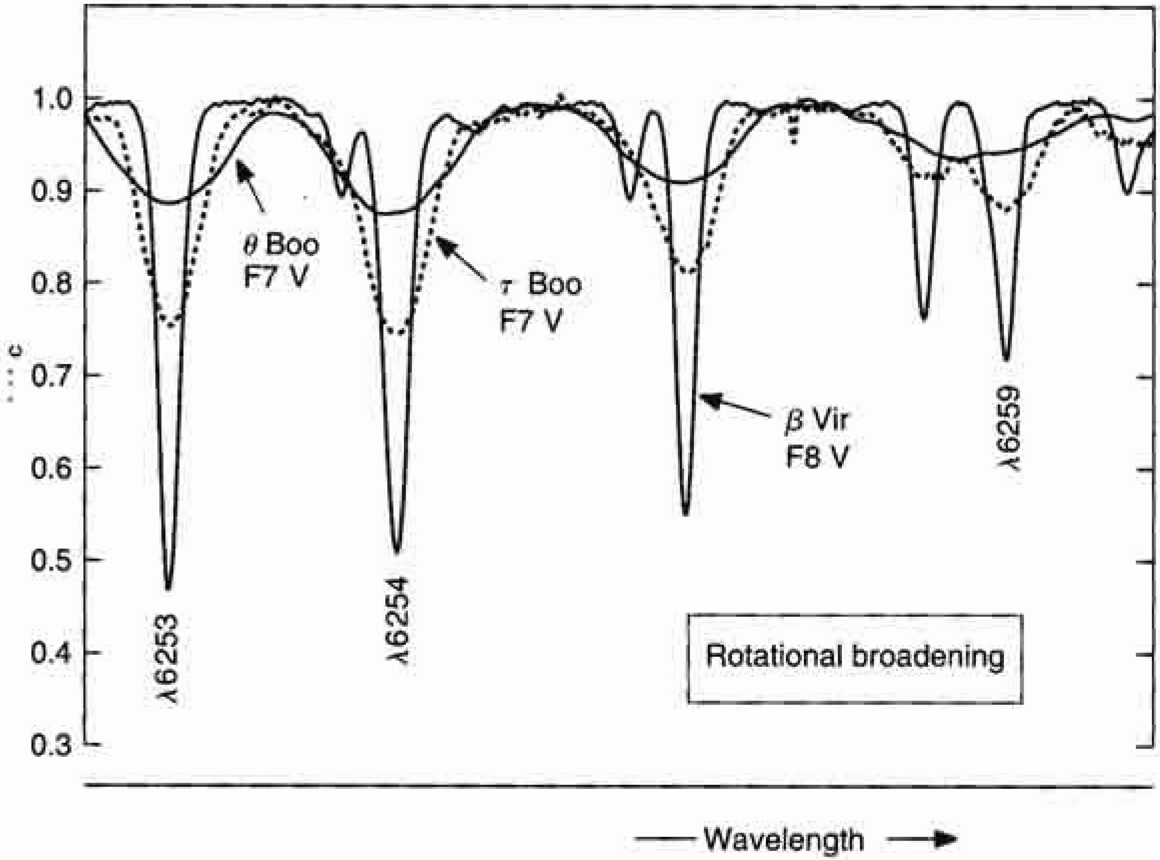


Fig. 18.8. The rotational broadening in three F dwarfs are compared. Data from the Elginfield Observatory.

What can we expect for different objects ?

Stars

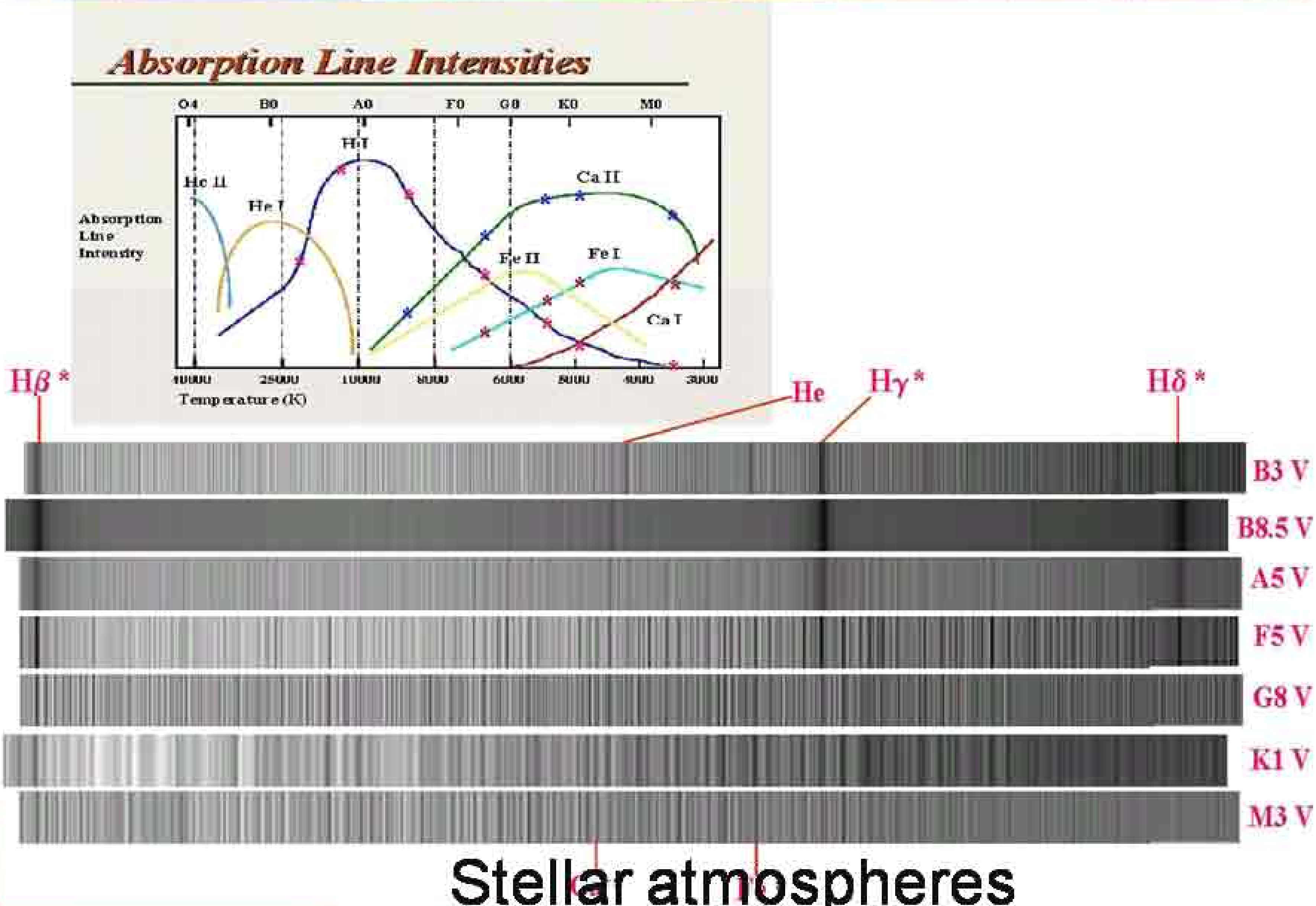
- absorption (some–time emission lines)
- Profiles => Voigt (termal+turbulence=Gauss; pressure broadening+natural=Lorenz)
- Rotation => classical rotation of a sphera

Emission nebulae

- Emission
- Profiles=> Gaussian (caused by turbulences in gas)

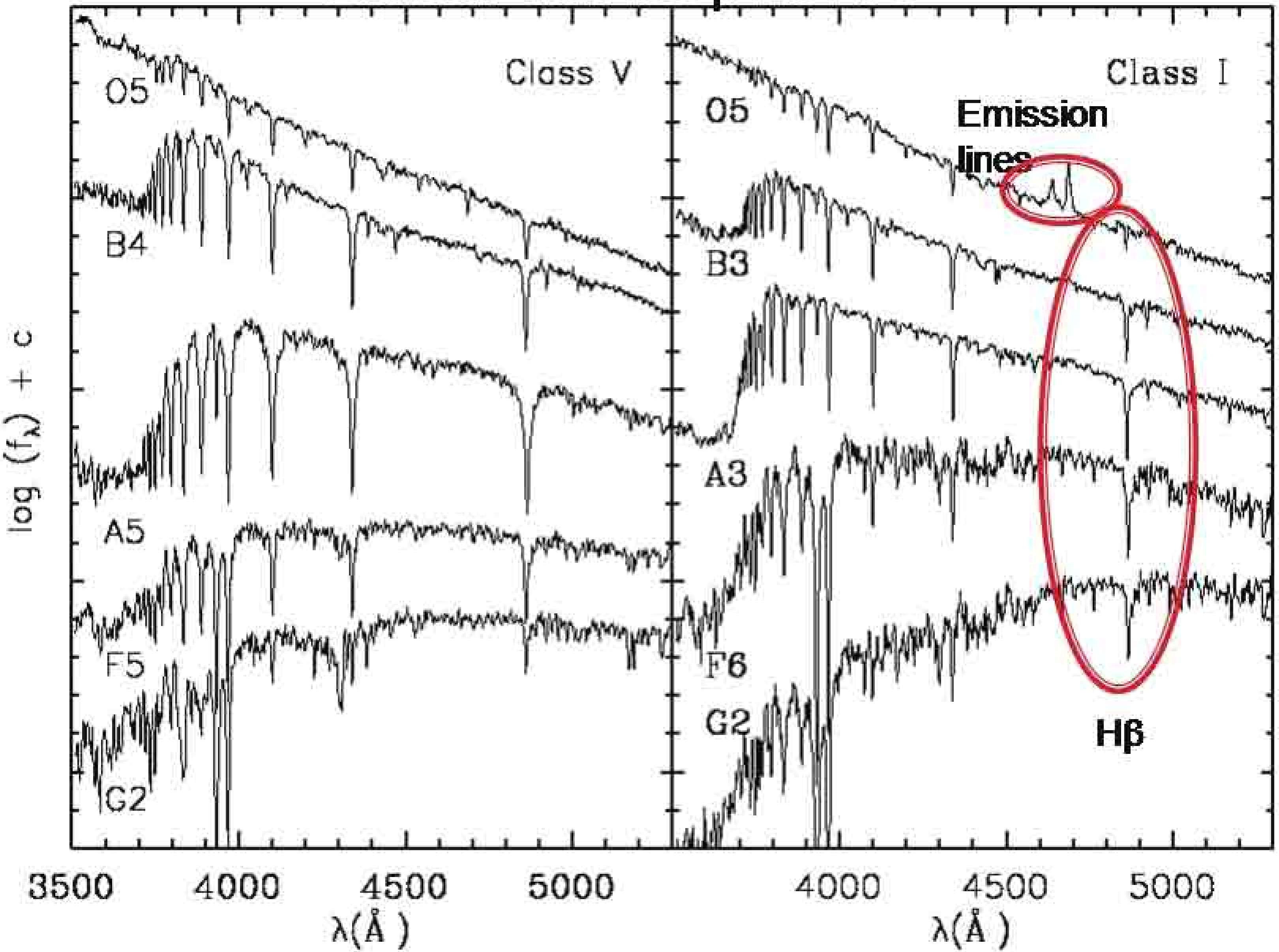
AGN

- Emission/absorption (caused by stars, or even in the region close to a nucleus)
- Profiles =>Gaussian (???); or affected also by rotation



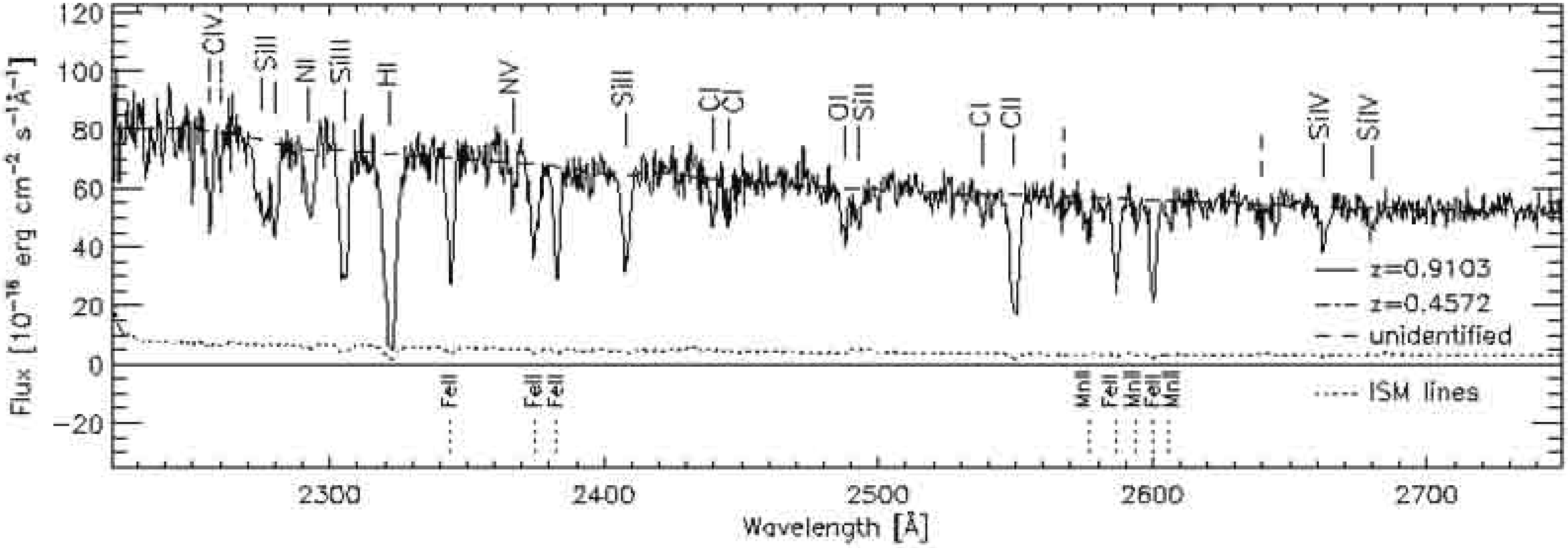
Stellar atmospheres

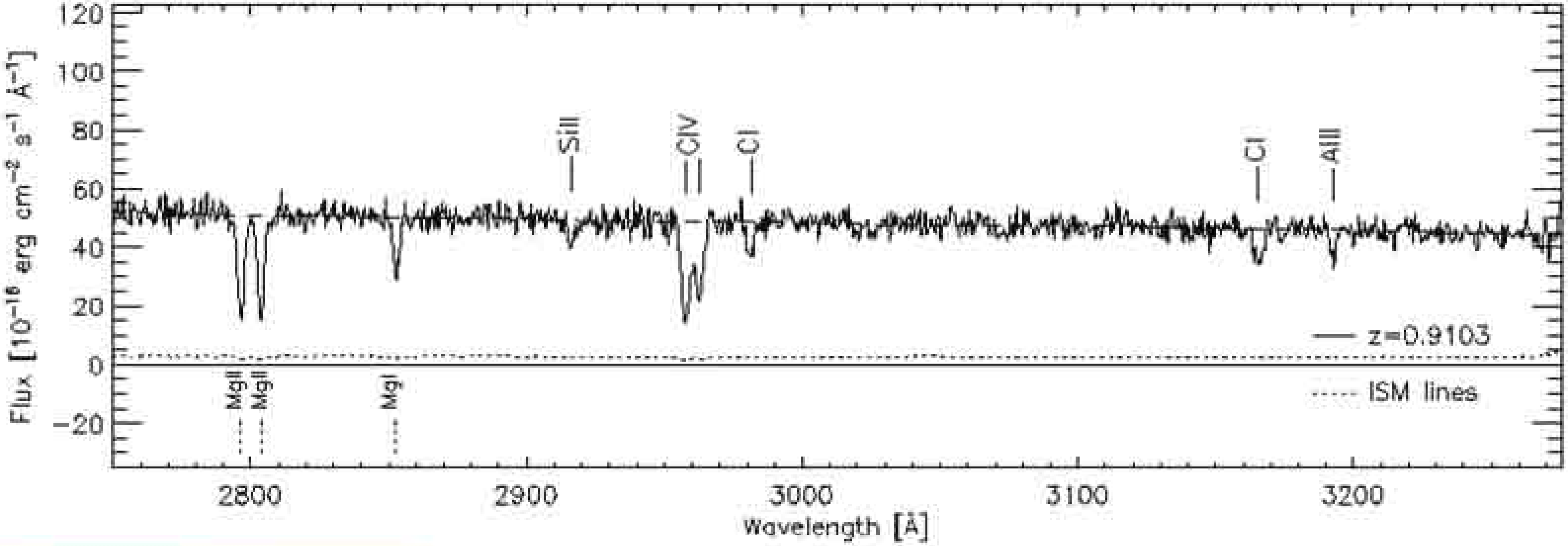
Stellar atmospheres



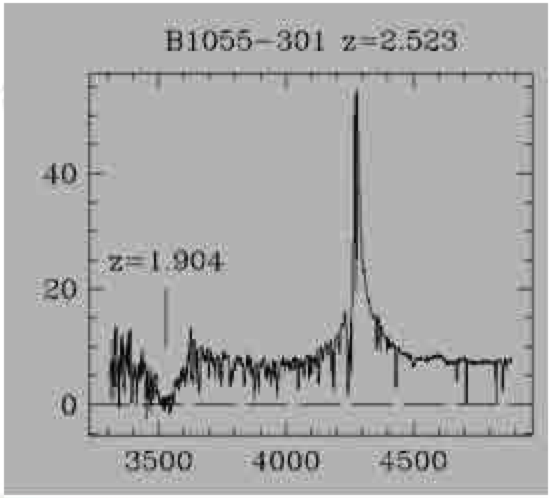
(from Jacoby et al. 1984)

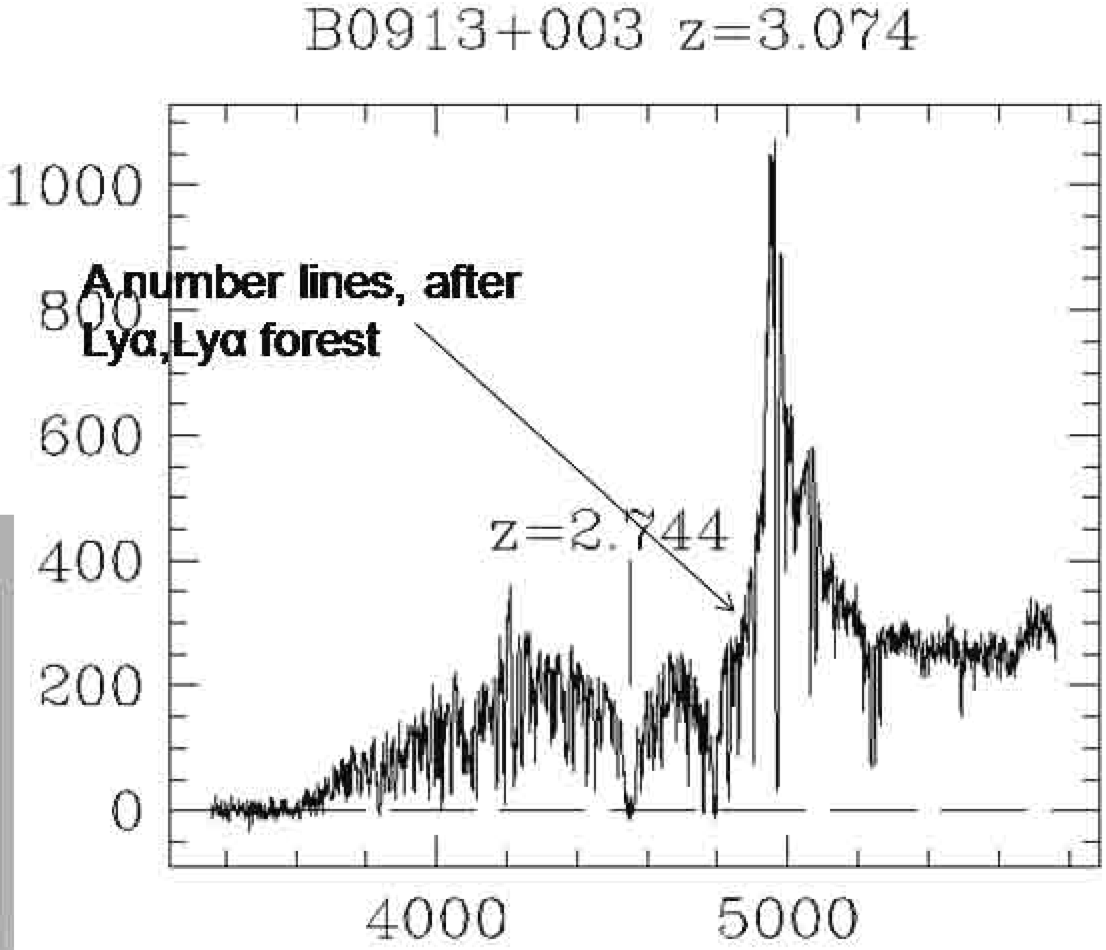
QSO Spectrum with IGM Absorption





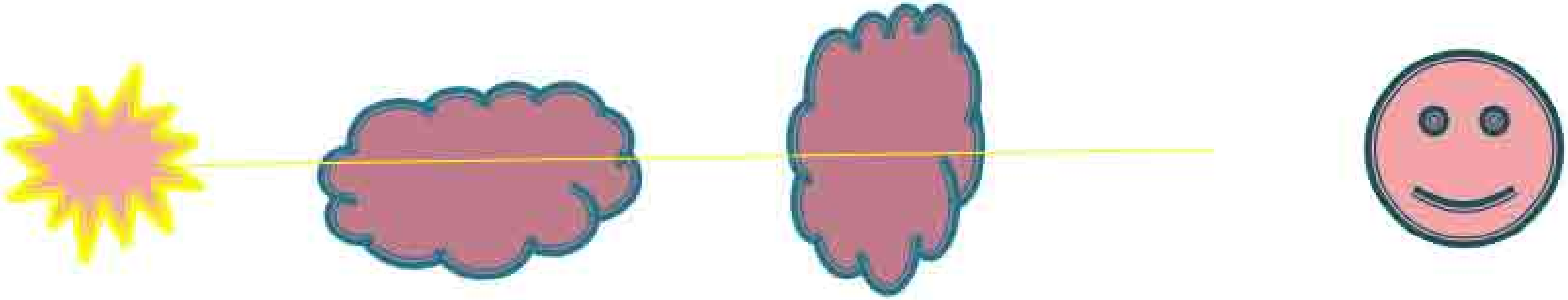
Absorption in spectra of QSOs

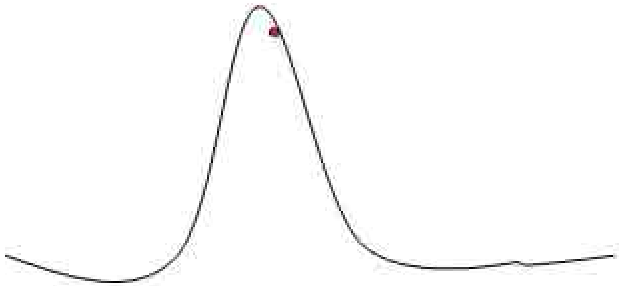




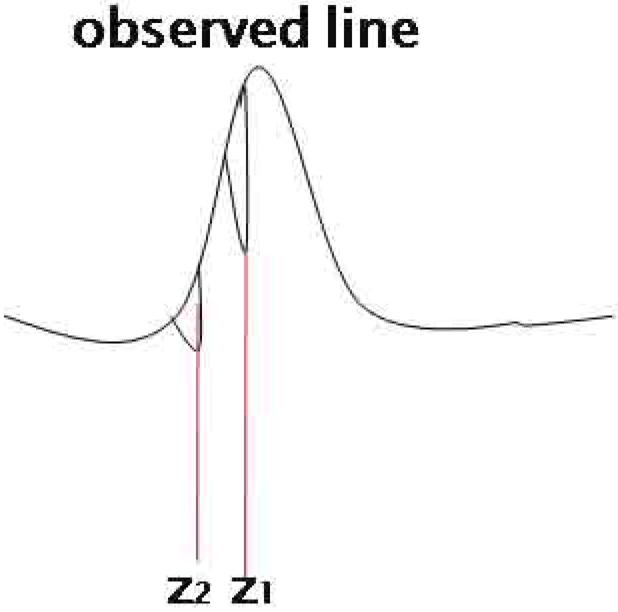
A number lines, after Lyα,Lyα forest

- QSO IGM1 (z_1) IGM (z_2) observer

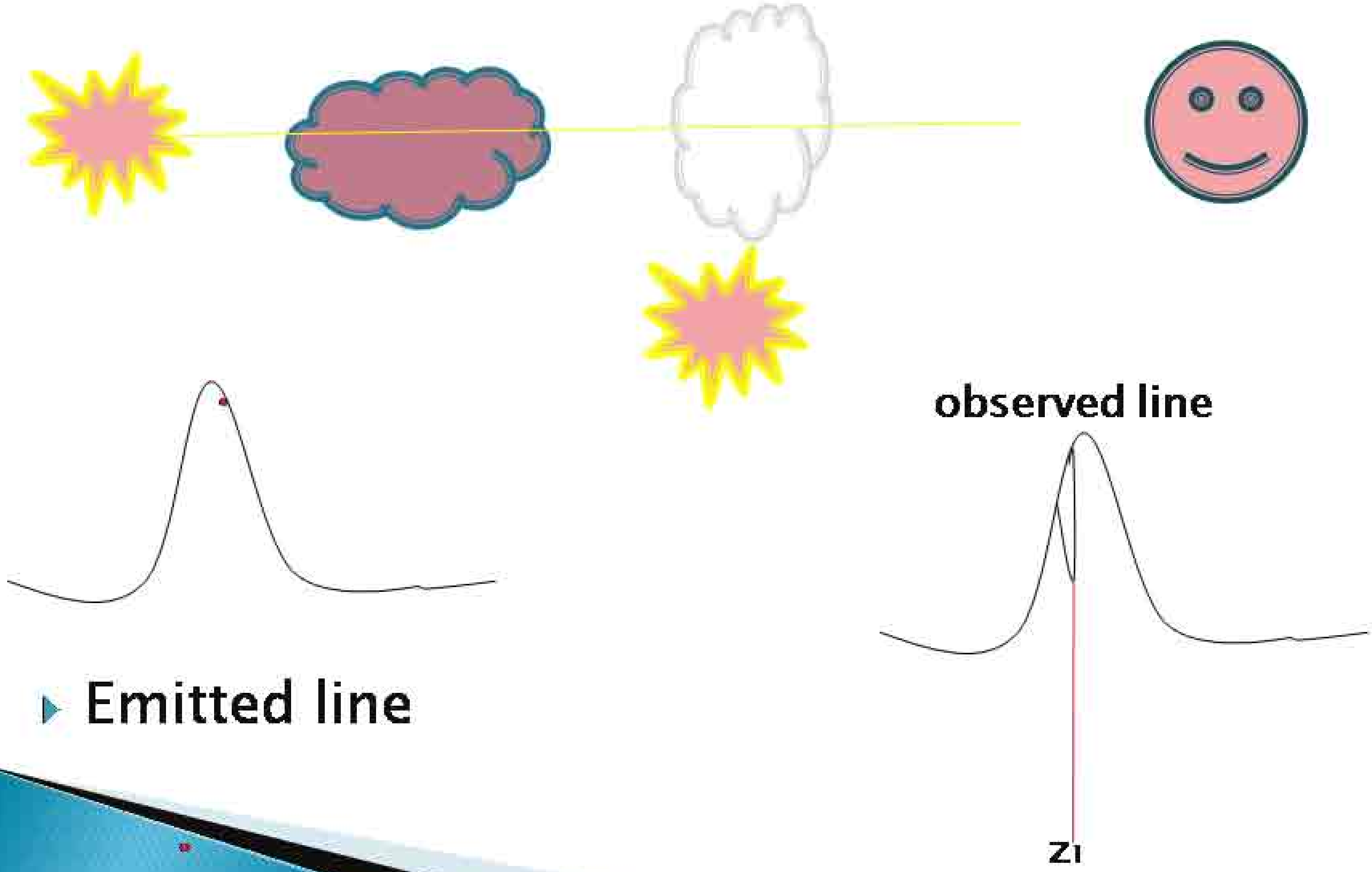




- Emitted line



- Some IGM is ionized by nearby QSOs
- QSO IGM1 (z_1) IGM (z_2) observer



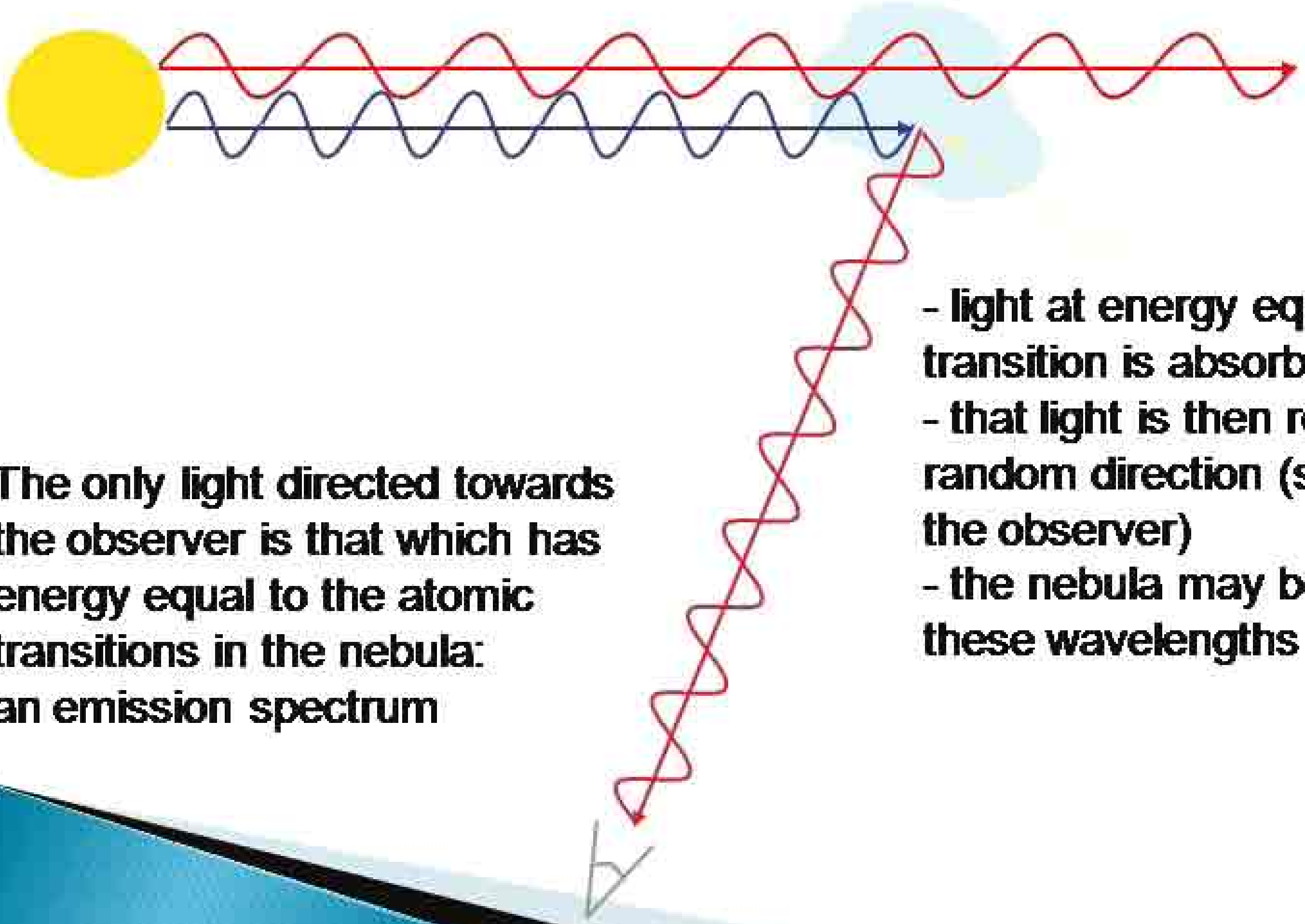
- Emitted line

Emission Nebulae

- Atoms in nebulae are excited by:
  - Incident photons
  - Collisions (high temperature or density)
- Excited atoms decay, emitting a photon of the characteristic energy (a spectral line)
- If the atoms are ionized, then the nebula will emit free-bound radiation (i.e. Balmer continuum) as well as spectral lines

Emission Nebula

(photo-excited or photo-ionized)



optically thin nebula:
passes most wavelengths

Source of the continuum

- light at energy equal to an atomic transition is absorbed
- that light is then reemitted in a random direction (some of it towards the observer)
- the nebula may be optically thick at these wavelengths

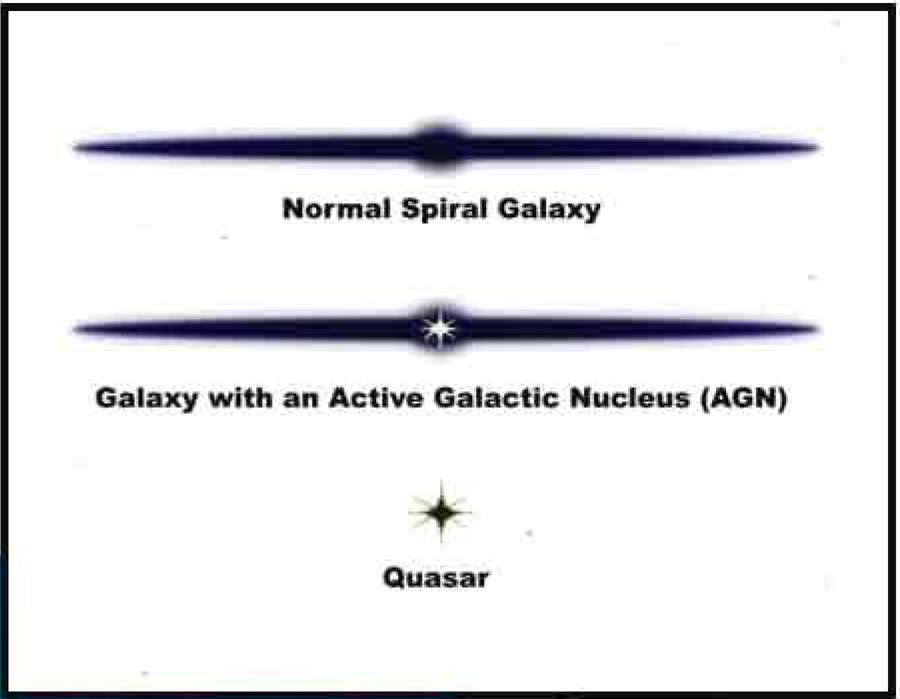
The only light directed towards the observer is that which has energy equal to the atomic transitions in the nebula:
an emission spectrum

AGN phenomenon

- Galaxies with bright central part (source of emission in the central part cannot be stars)
- Non-stellar continuum
- Emission (absorption) lines from the central part
- Variability (from a part of day to months/years) – period depends on wavelength band
- Etc.

Active Galaxies (Quasars,Sy1,Sy2, blazars, etc.)

- **small highly variable and very bright core embedded in an otherwise typical galaxy**

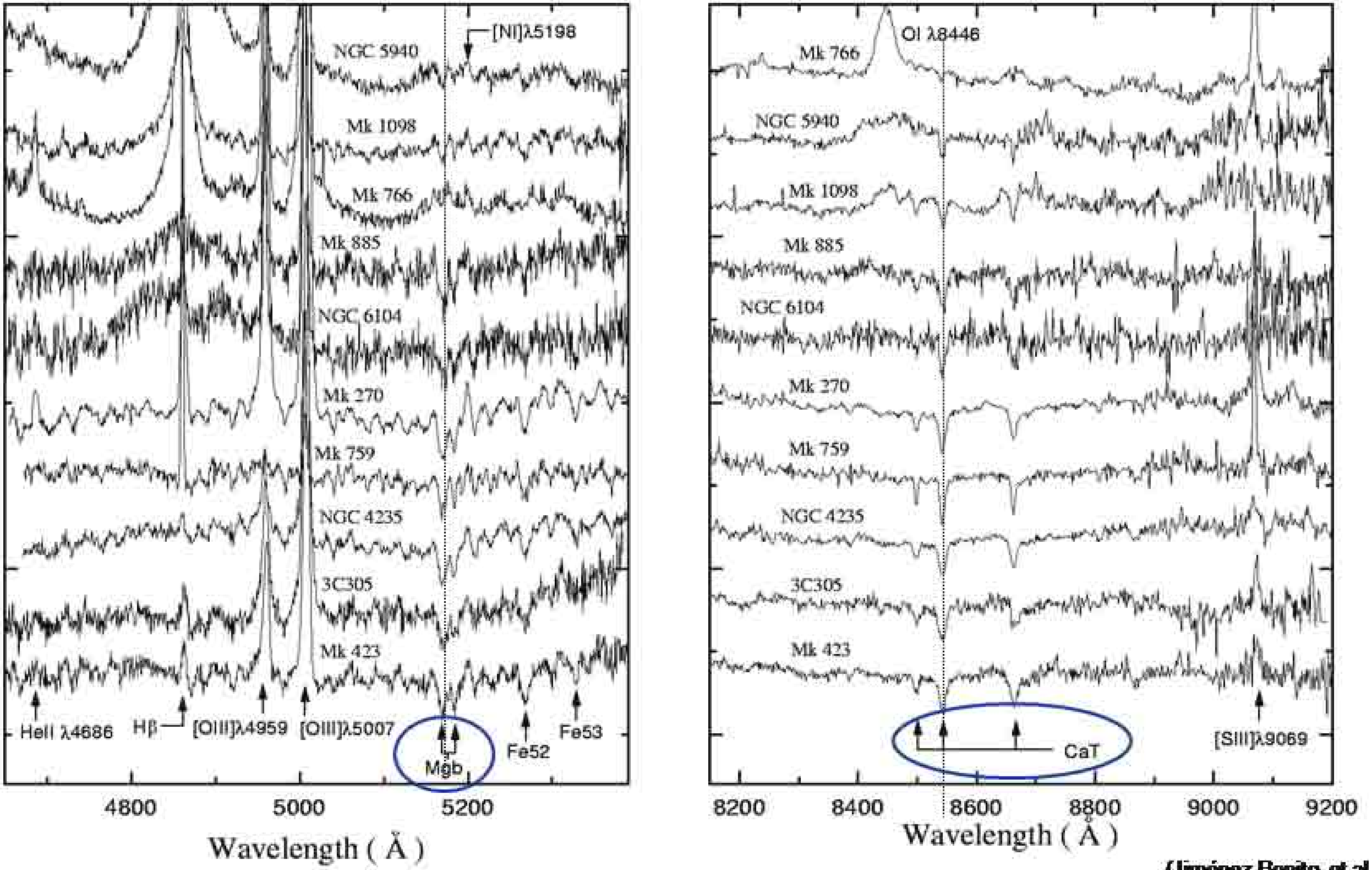


features:

- **10% of all galaxies**
- **10^4 times higher luminosity than typical galaxies**
- **tiny volumes ($\ll 1$ pc^3)**
- **radiation in broad range: from γ-rays to radio waves**
- **very small angular size depending on wavelength**
- **strong and sometimes very broad emission lines**
- **variability**
- **polarization**
- **radio emission**

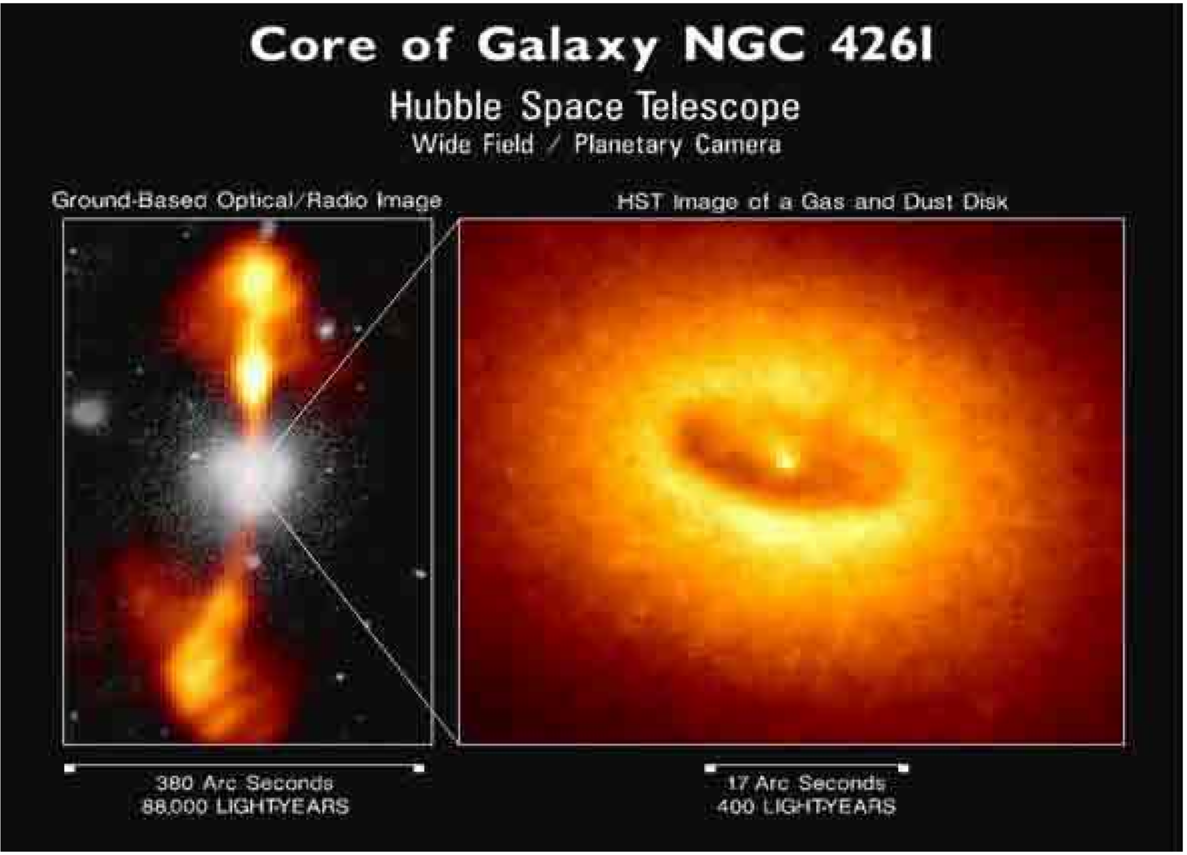
Spectra of AGN with stellar populations

The continuum of AGN has stellar features, more evident in Sy 2s than in Sy 1s

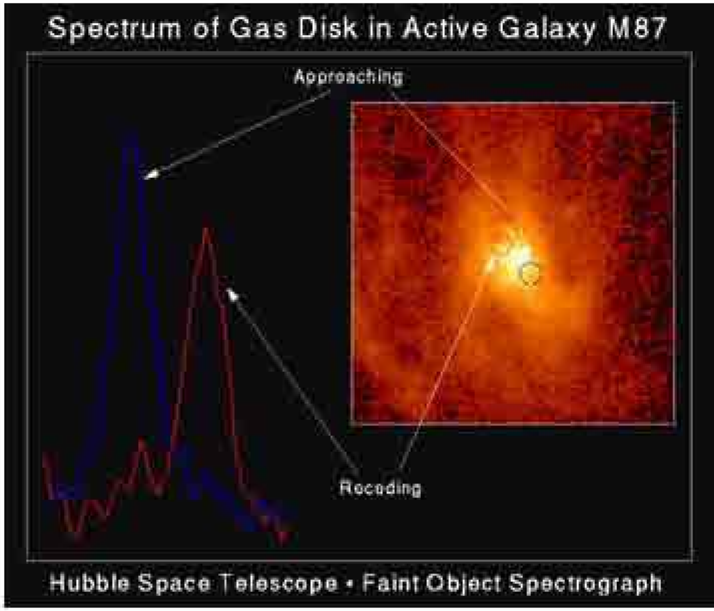


(Jiménez-Benito et al. 2000)

Some examples of AGN


Core of Galaxy NGC 4261

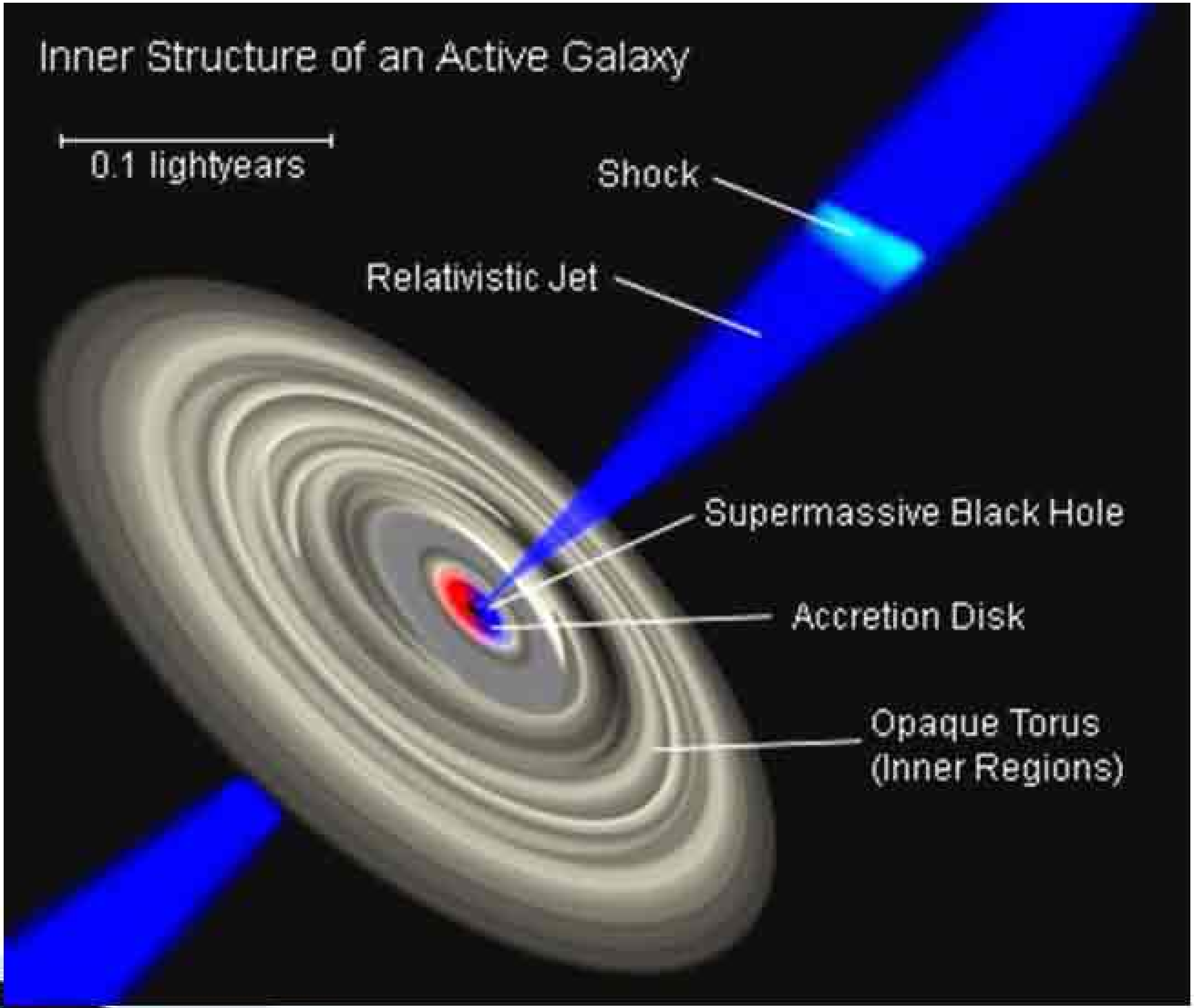
Hubble Space Telescope
Wide Field / Planetary Camera

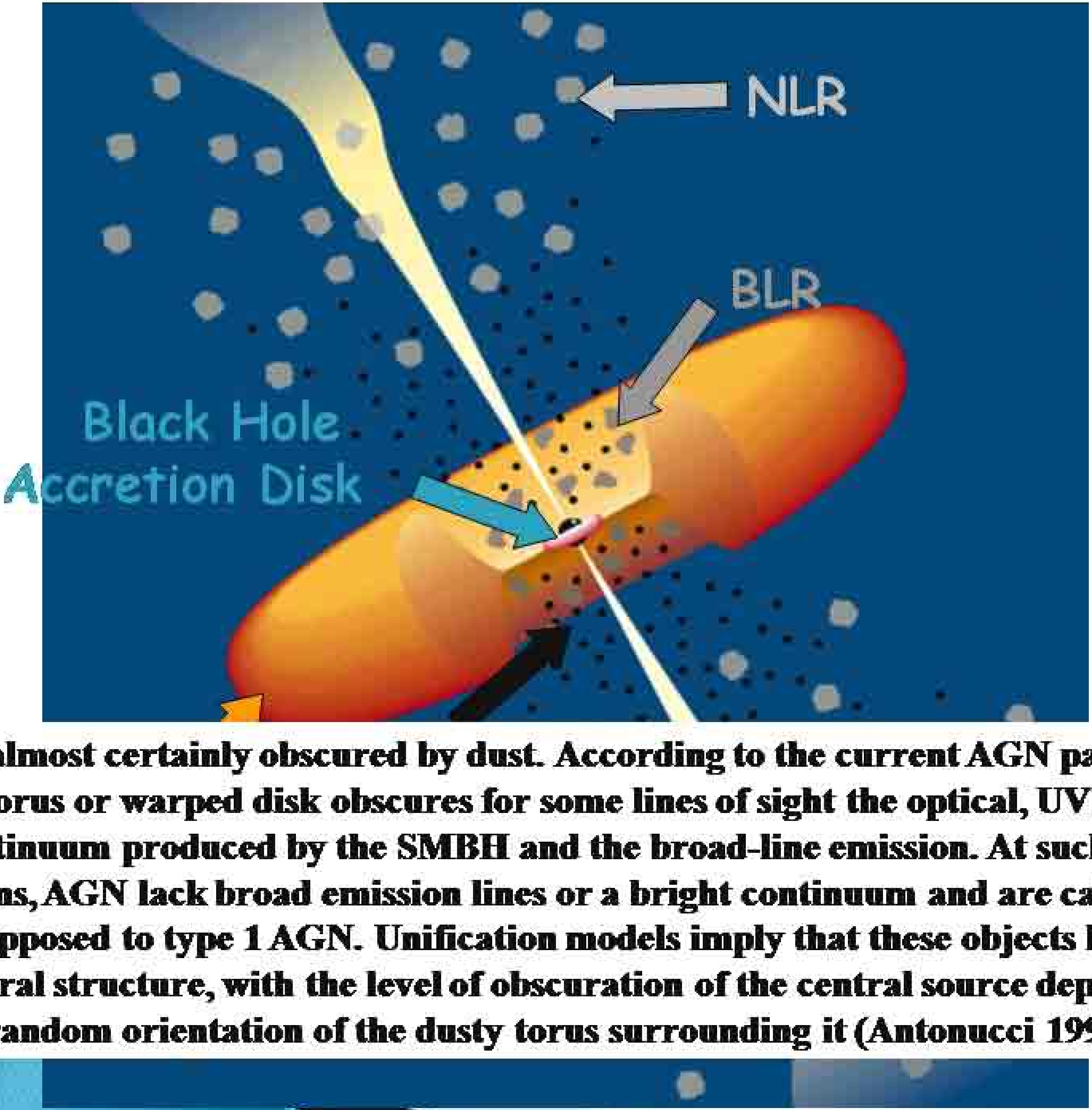

Spectrum of Gas Disk in Active Galaxy M87

Hubble Space Telescope • Faint Object Spectrograph

Emission Nebula – Active Galactic Nuclei

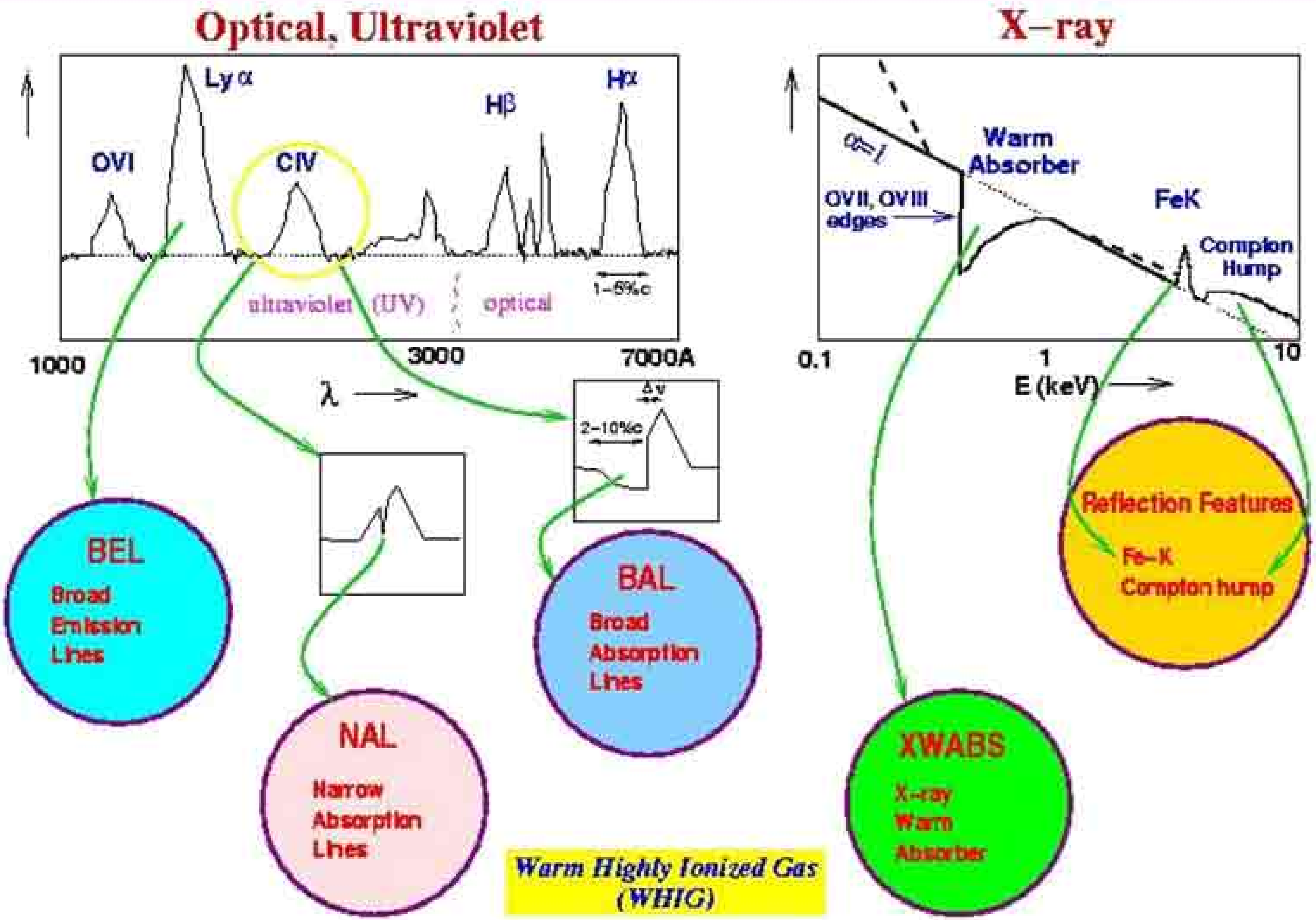
(photo-excited or photo-ionized)



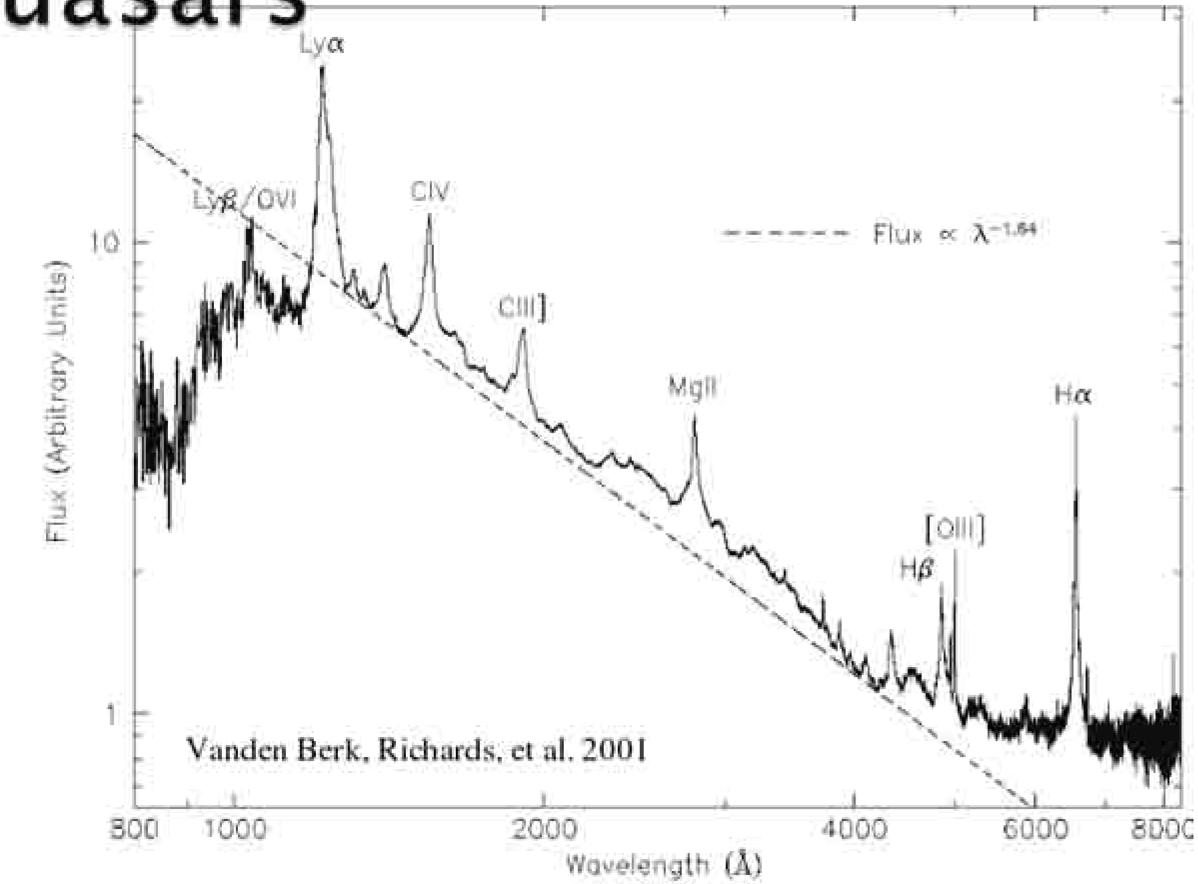


AGN are almost certainly obscured by dust. According to the current AGN paradigm, dust in a torus or warped disk obscures for some lines of sight the optical, UV and soft X-ray continuum produced by the SMBH and the broad-line emission. At such orientations, AGN lack broad emission lines or a bright continuum and are called type 2 AGN, as opposed to type 1 AGN. Unification models imply that these objects have the same general structure, with the level of obscuration of the central source dependent upon the random orientation of the dusty torus surrounding it (Antonucci 1993).

Lines in QSO spectra

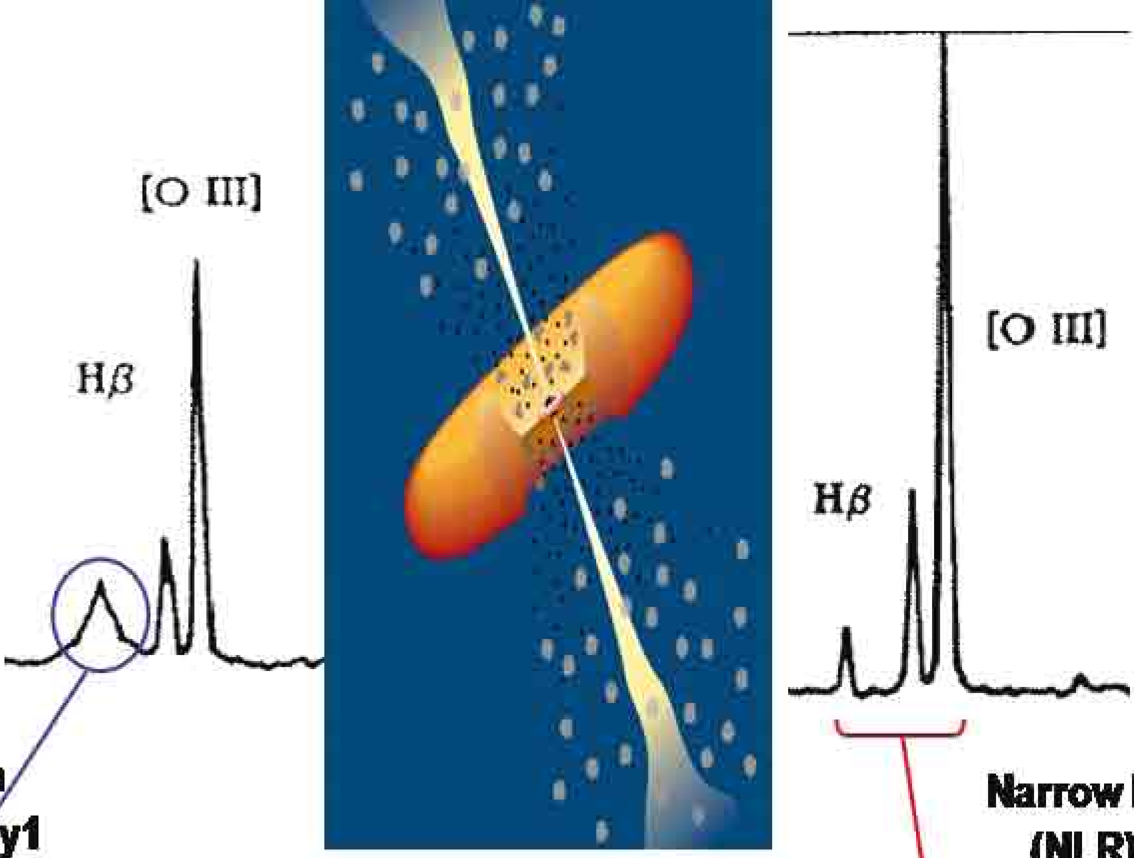


The average spectrum of quasars



Vanden Berk, Richards, et al. 2001

1. Hot (blue) continuum
2. Broad emission lines
3. Narrow emission lines



Broad Line Region
(BLR) - QSOs and Sy1
R~0.1pc

High velocity → **FWHM ~ 10^4 km s^{-1}**

High electron density :
- No broad [O III] lines
- Broad C III]1909 line

N_e~10^{9-10} cm^{-3}

T~10000 K

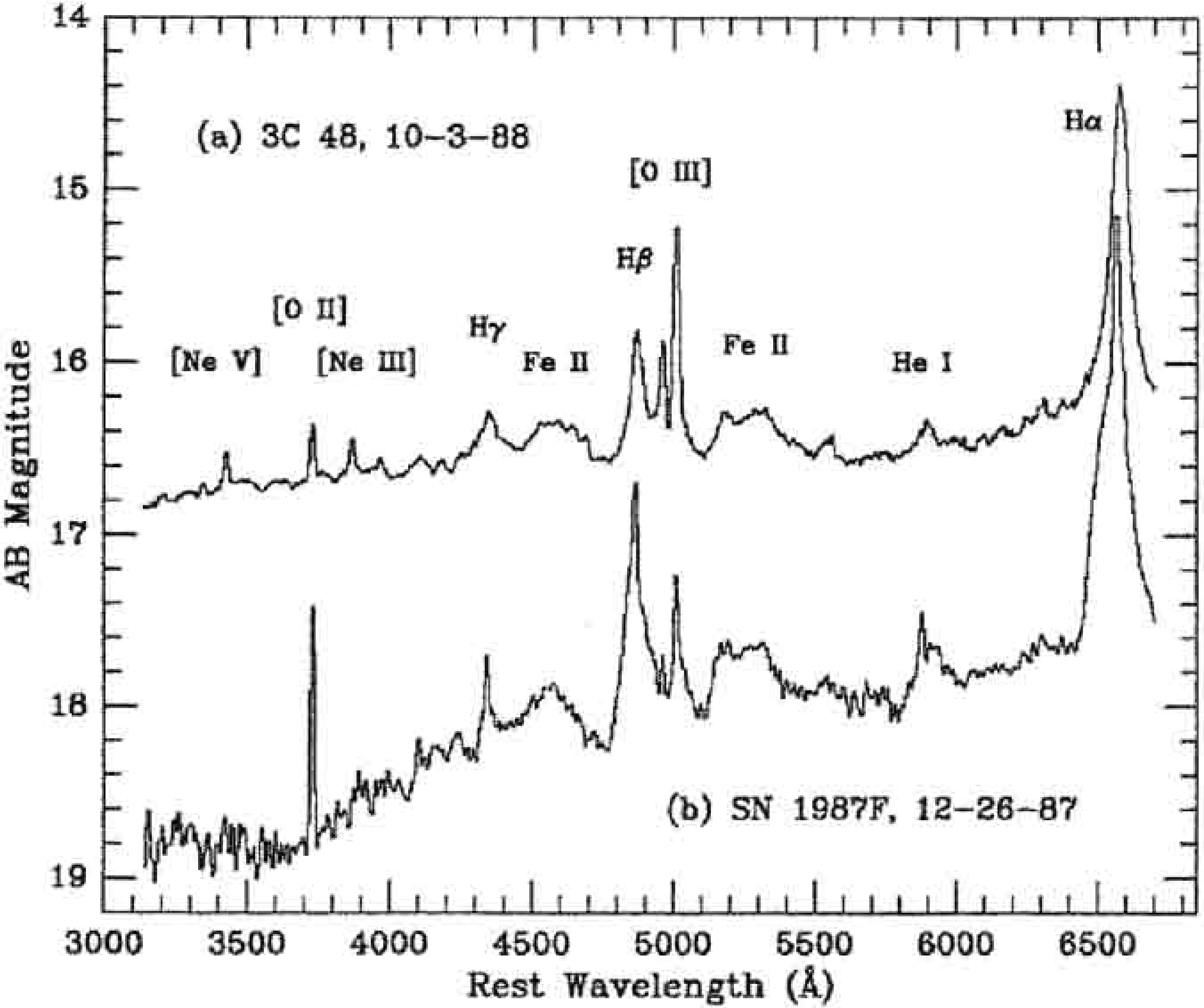
Narrow Line Region
(NLR) - all AGN
R~100pc

Low velocity → **FWHM ~ 10^3 km s^{-1}**

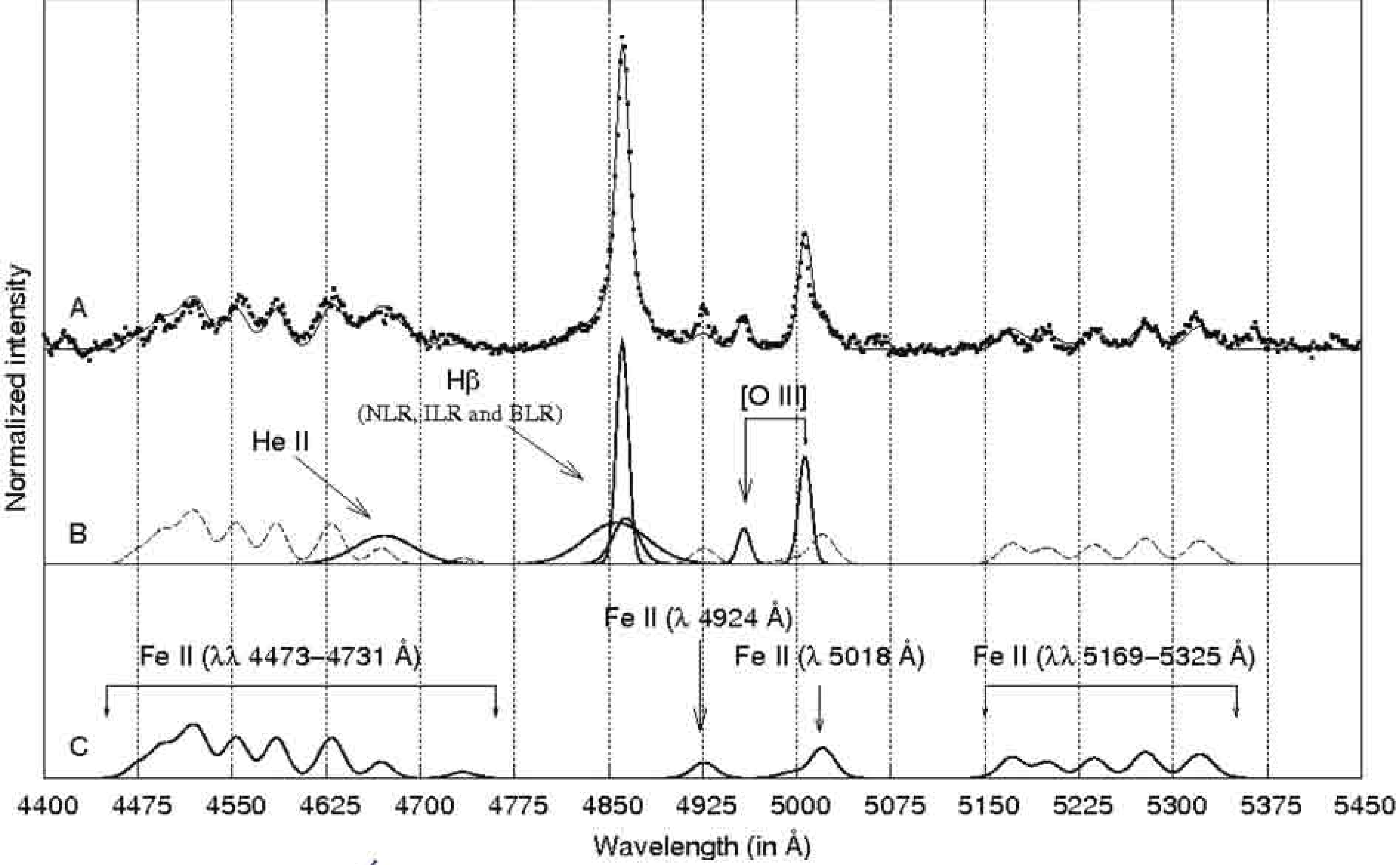
Low electron density : **N_e ~ 10^4 cm^{-3}**

T~10000 K, ratio of forbidden lines

type IIn Sne – similar to AGN spectra

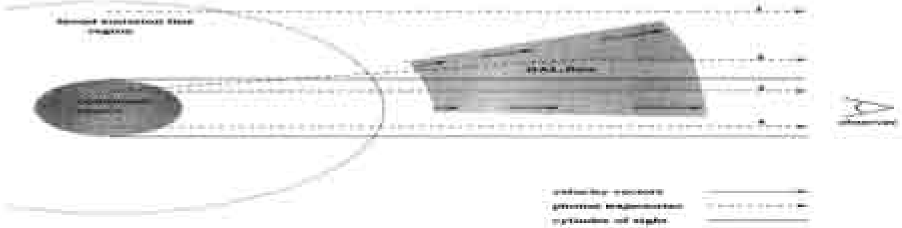


If one of these type IIn explodes in the centre of a S galaxy, this would be classified as a Seyfert 1



Broad Emission Lines

(BELs) - probably composed from more than one component

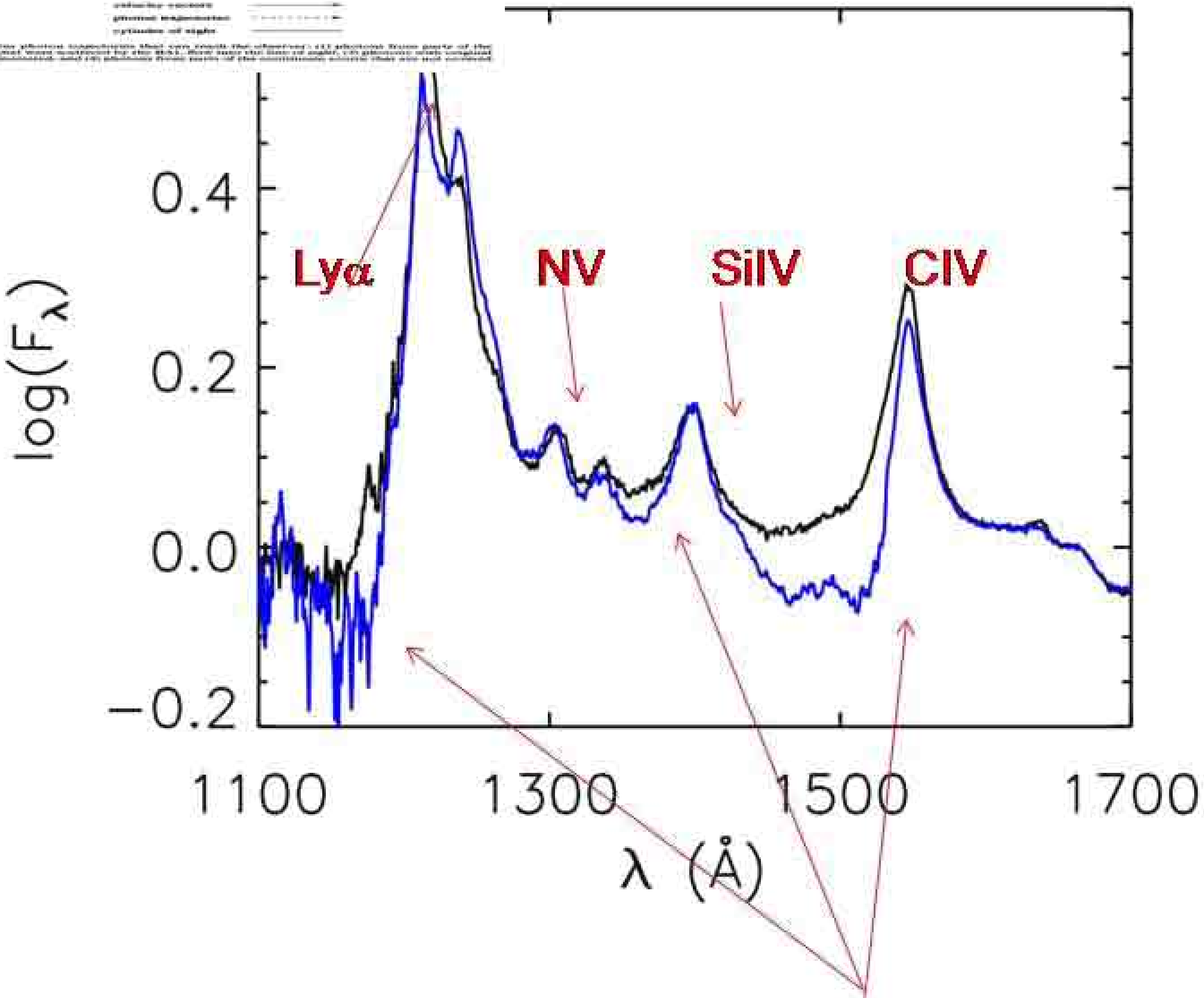


[illegible]

Two types:

1. **High Ionization Lines (C IV, Lyα) - HILs**
2. **Low Ionization Lines (Balmer Lines) – LILs**

Absorption present in HILs



Absorption

Line emission regions in AGN:
Line profiles and geometry of the BLR

- The Fe K line emitting region (probably from accretion disk) FWHM~ several 10000 km/s
- The Broad Line Emission Region (BLR) FWHM>1000 km/s (2000 km/s-5000 km/s)
- The Narrow Emission Region (NLR), FWHM<1000 km/s (200 km/s-700 km/s)

Plasma around massive black hole => Active Galactic Nuclei

Emission/absorption

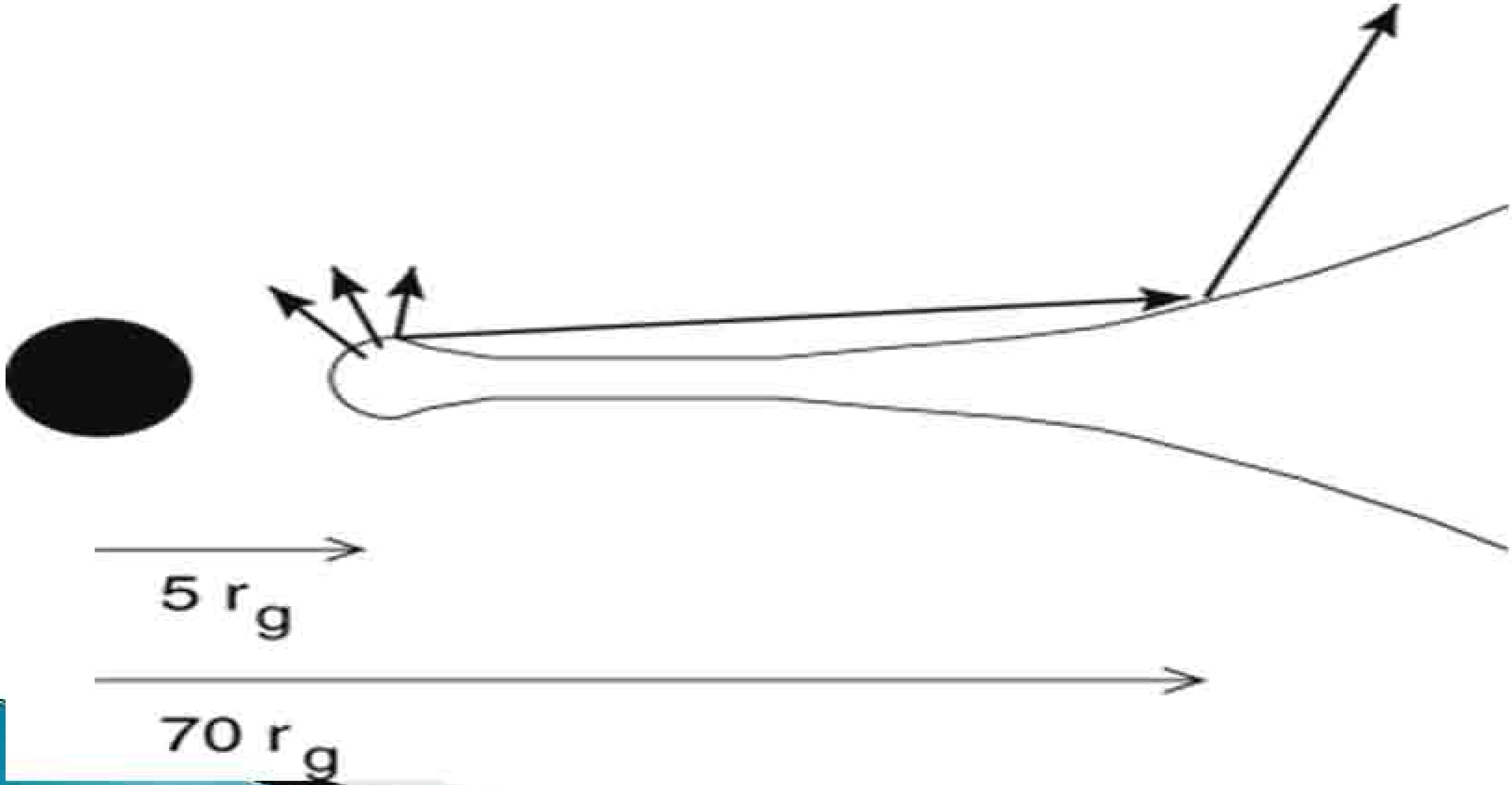
- X-ray emission
- Fe K-alpha line

What is special?

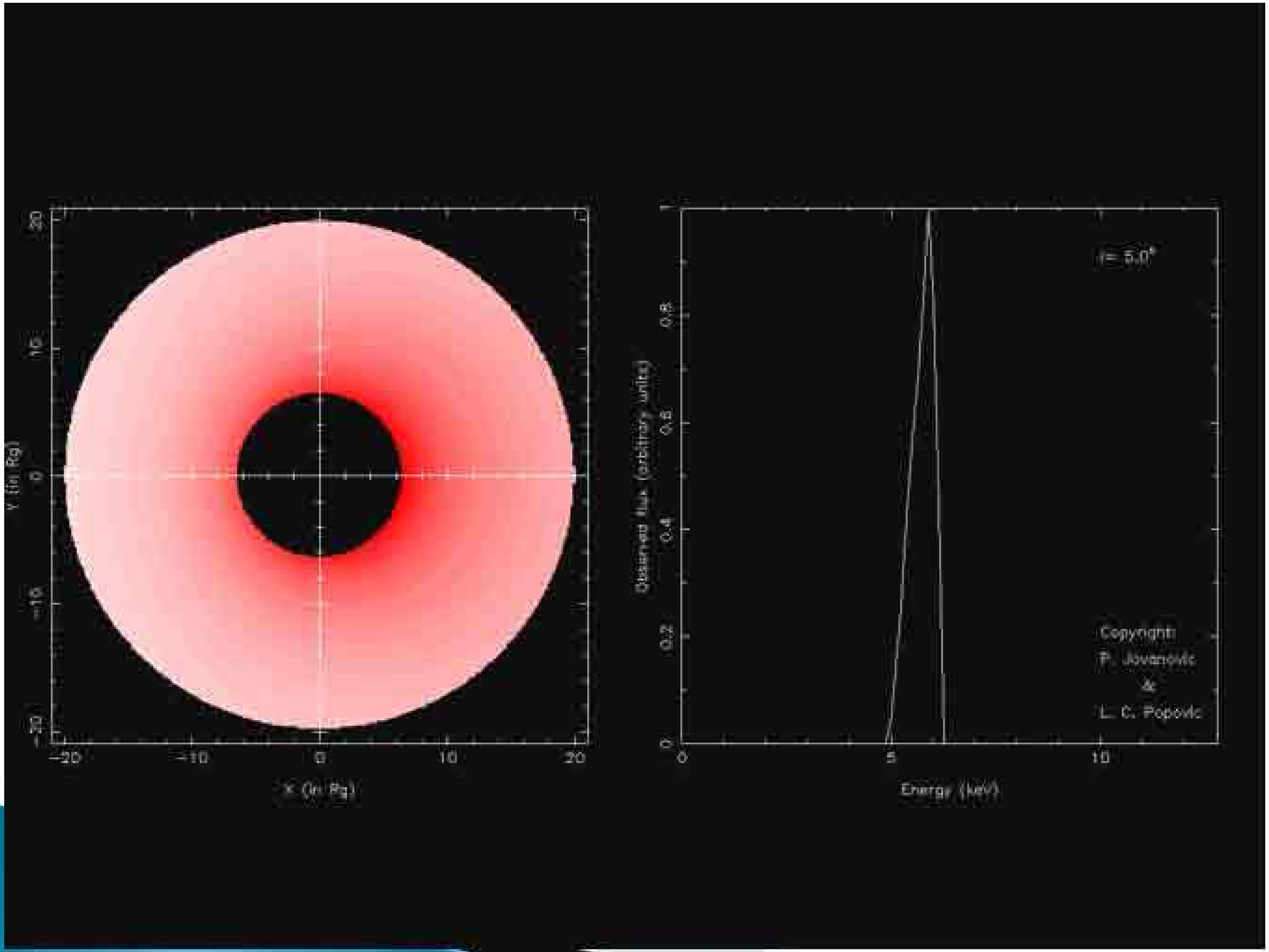
- – plasma in a strong gravitational field, high temperature

- – geometry (should be disk geometry?)

Fe K Emission Region: A schematic representation of a possible geometry implied by the double-reflection model. (Ballantyne et al. 2003, MNRAS, 342, 239)

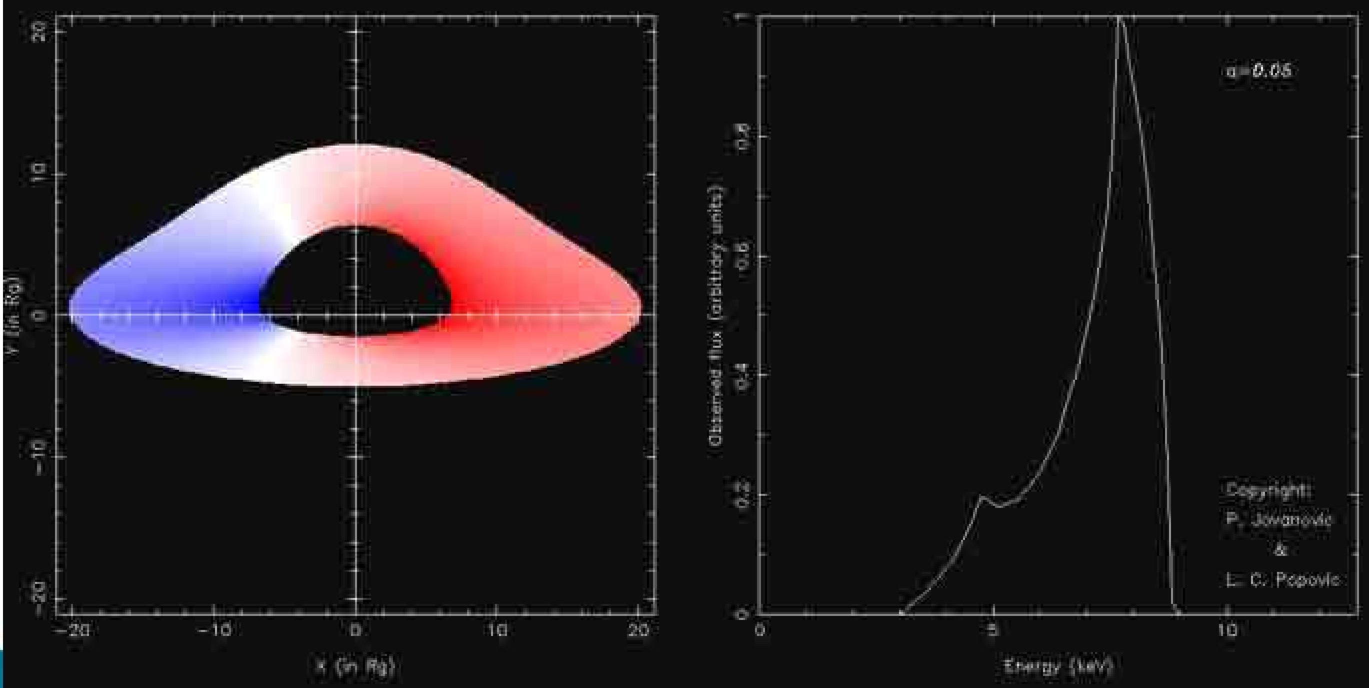


Numerical simulations of an accretion disk in Schwarzschild metric for different inclination angles *i* (left) and the corresponding profiles of the Fe Kα line (right)



Jovanović & Popović, 2008, *Fortschr. Phys.* **56** , 456

Numerical simulations of a highly inclined accretion disk (*i*=75°) for different values of angular momentum parameter *a* (left) and the corresponding profiles of the Fe Kα line (right), see Jovanovic & Popovic 2008, Fortschr. Phys. 56, 456



X-ray radiation from accretion disks of AGN

1. **in continnum**: 0.1 – 100 keV
   - soft and hard component
   - variations: from several part of an hour until several days
2. **in Fe Kα line:**
   - broad emission line on 6.4 keV
   - asymetric profile with narrow bright **blue** peak and wide faint **red** peak
   - Line width corresponds to velocity:

     v ~ 80000 – 100000 km/s (MCG-6-30-15)

     v ~ 48000 km/s (MCG-5-23-16)

     v ~ 20000 – 30000 km/s (many other AGN)
   - variability of both: line shape and intensity

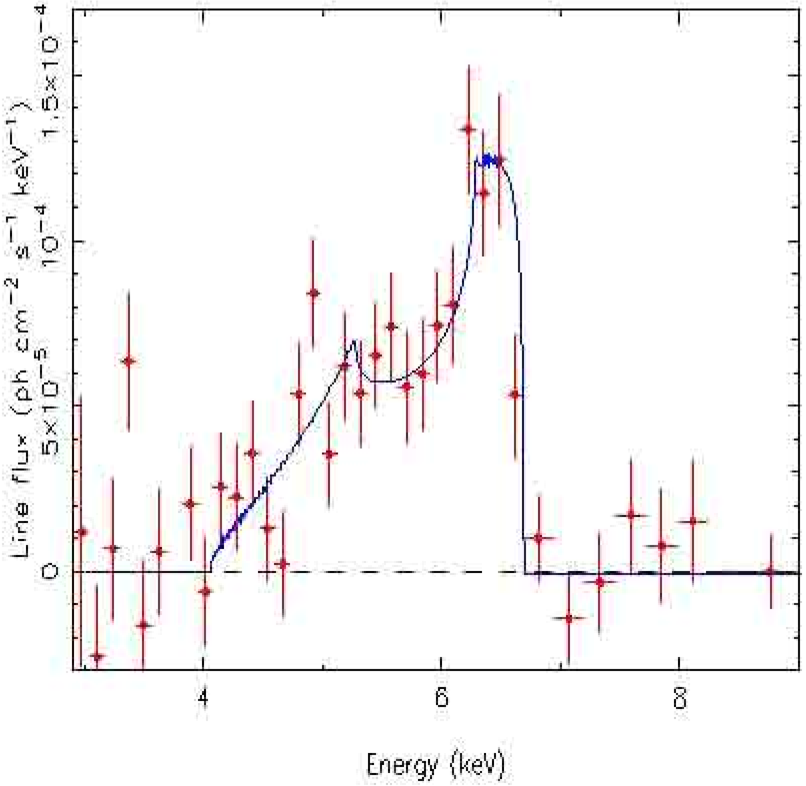
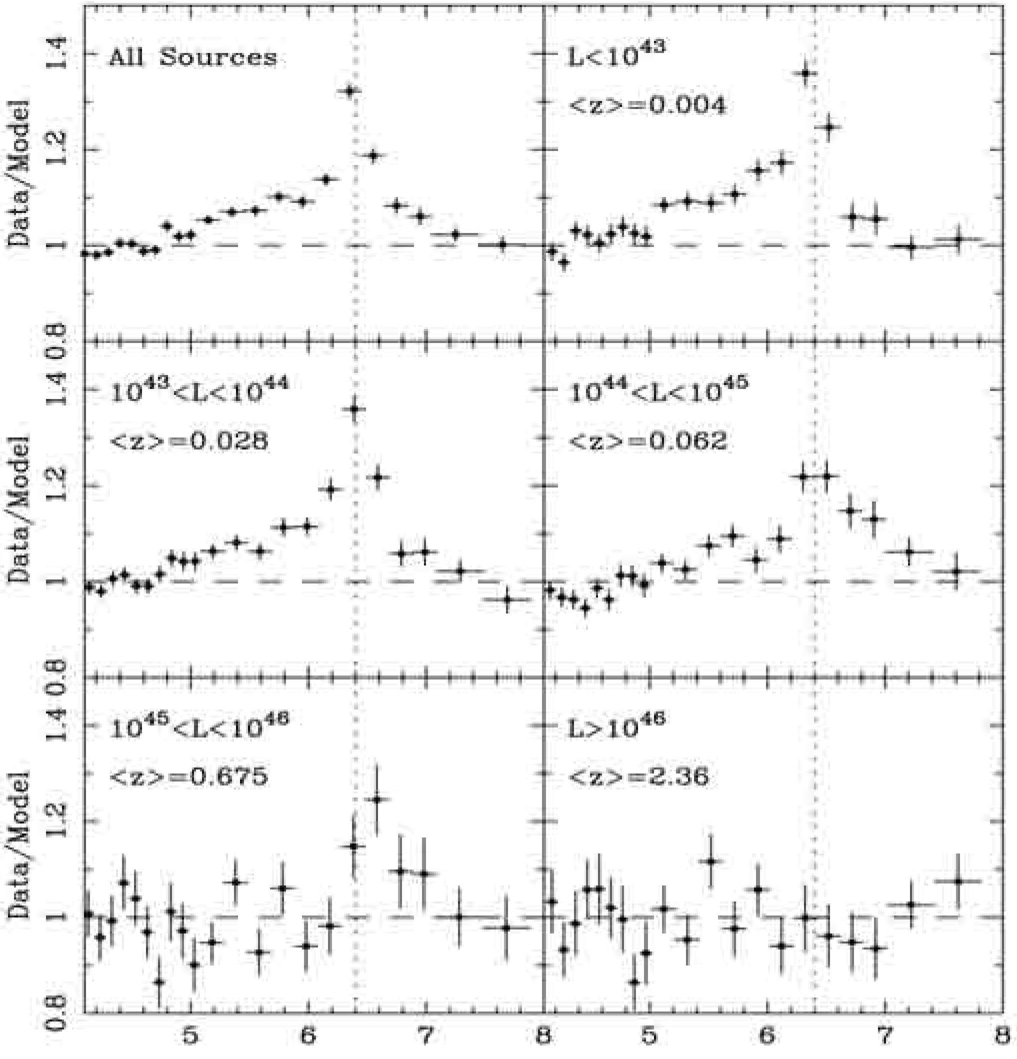


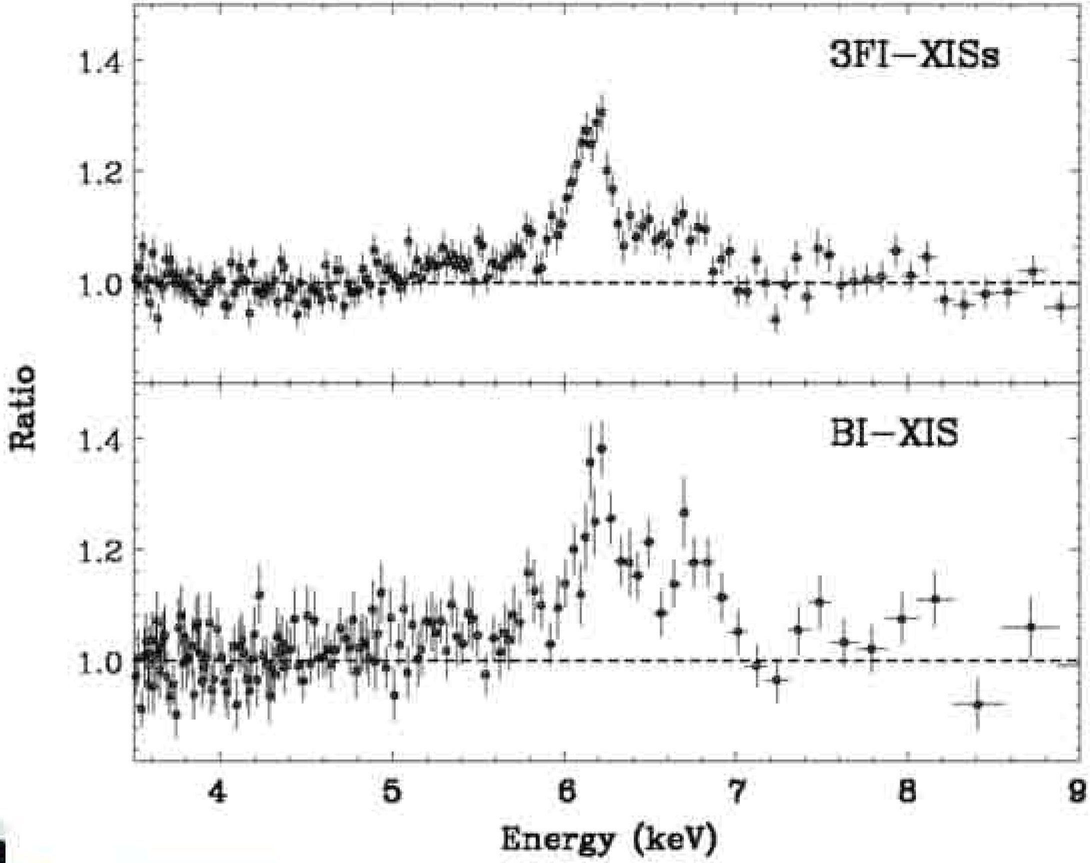
Figure: The Fe Kα line profile from Seyfert I galaxy MCG-6-30-15 observed by the ASCA satellite (Tanaka, Y. et al, 1995, *Nature*, 375, 659). The solid line shows the modeled profile expected from an accretion disk extending between 6 and 20 R_g around Schwarzschild BH.

In X-ray; Nandra et al. 1997, ApJ, 447,602

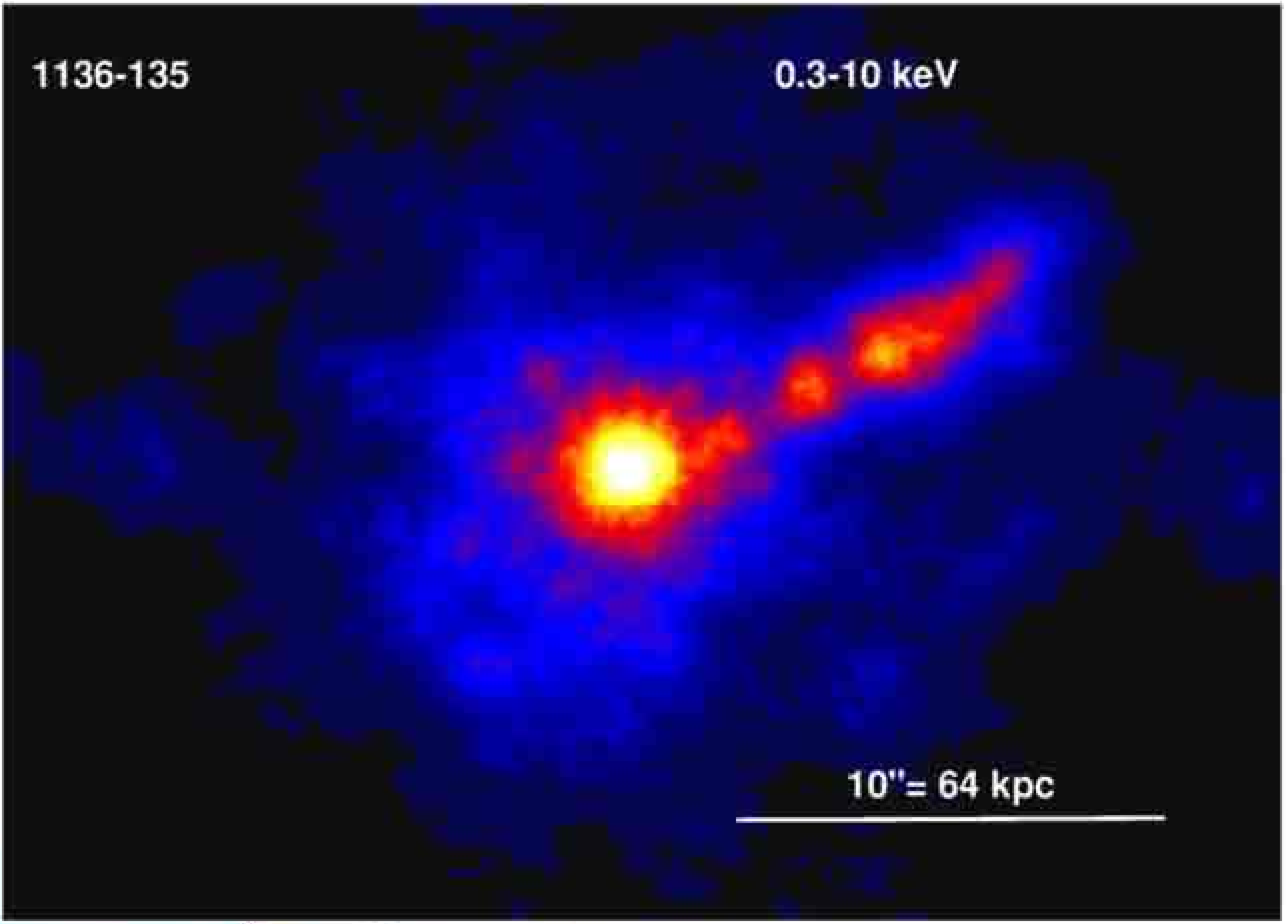


Fe K line of 3C 120 (Kataoka et al. 2007, PASJ, 59, 279)
- Jet + disk

Only ~ 30% Sy 1 with relativistic Fe K (Nandra et al. 2007, AN, 327, 1039)



Jet in the X-ray: 3C 179 observed with Chandra; Sambruna et al. 2006, ApJ, 652, 146

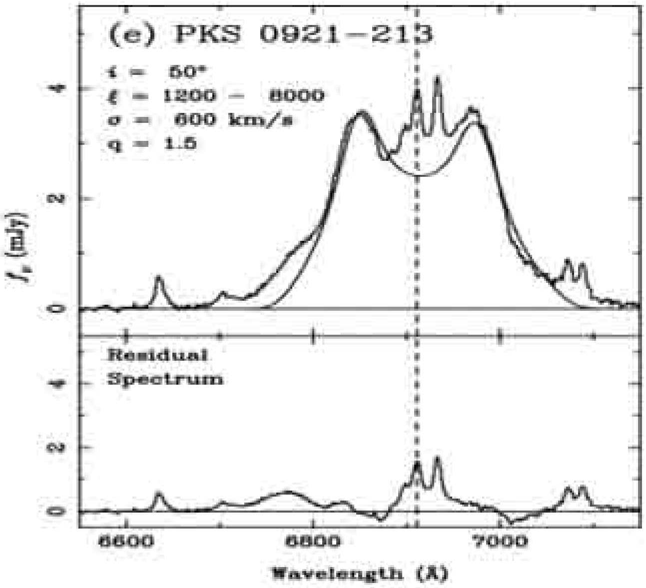


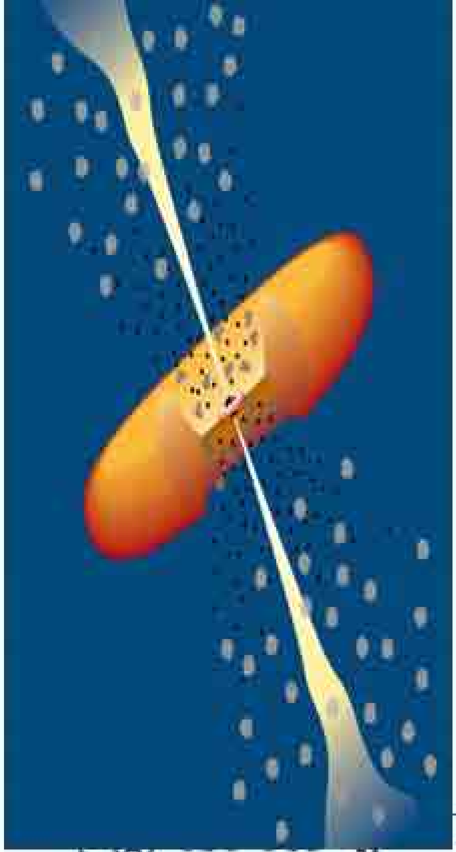
Fe K – emission region

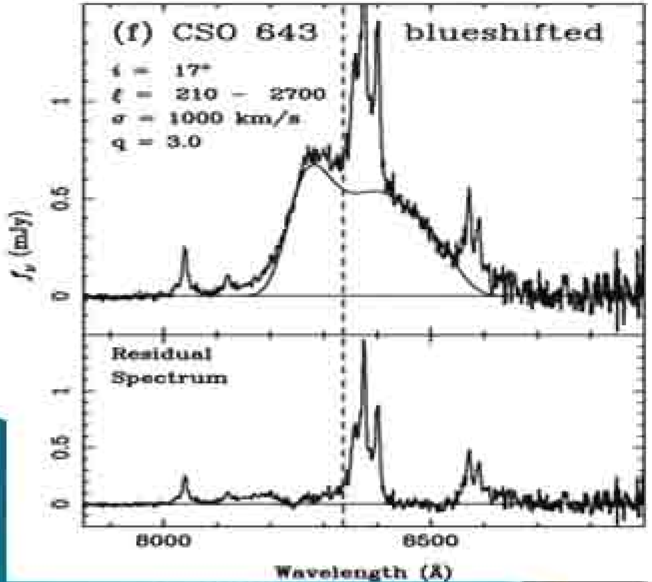
- Around 1/3 Fe K lines show clearly presence of AD (Nandra et al. 2006)
- A part of the Fe K may be emitted from jet as in the case of 3C 120 (Kataoka et al. 2007)
- Absorption in the Fe K far blue wing indicates an outflow (jet) in this region

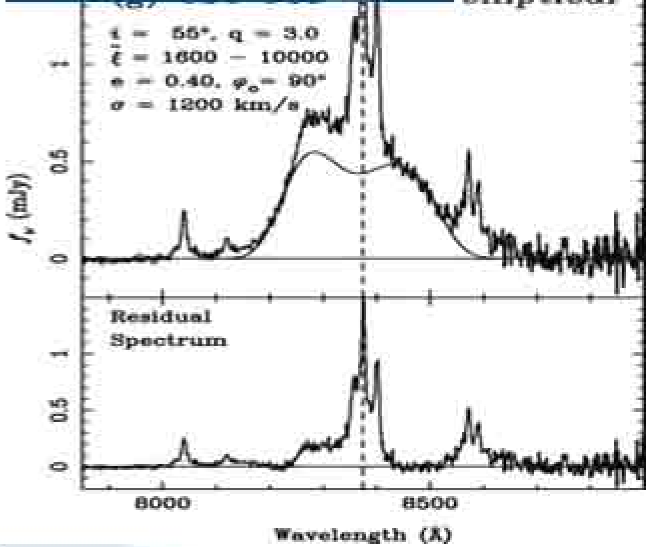
Geometry of the BLR: disk & jet (outflow)?

- Complex Balmer line shapes => complex geometry of the BLR – more about the BLR geometries see Sulentic et al. 2000, ARA&A, 38, 521
- Disk emission – Double-peaked broad LIL (Eraclous & Halpern 1994, ApJS, 90,1; 2003, ApJ, 599,886; Strateva et al. 2003, AJ, 126, 1720 etc.), but statistically unimportant (2% – 5%). To start from the disk geometry





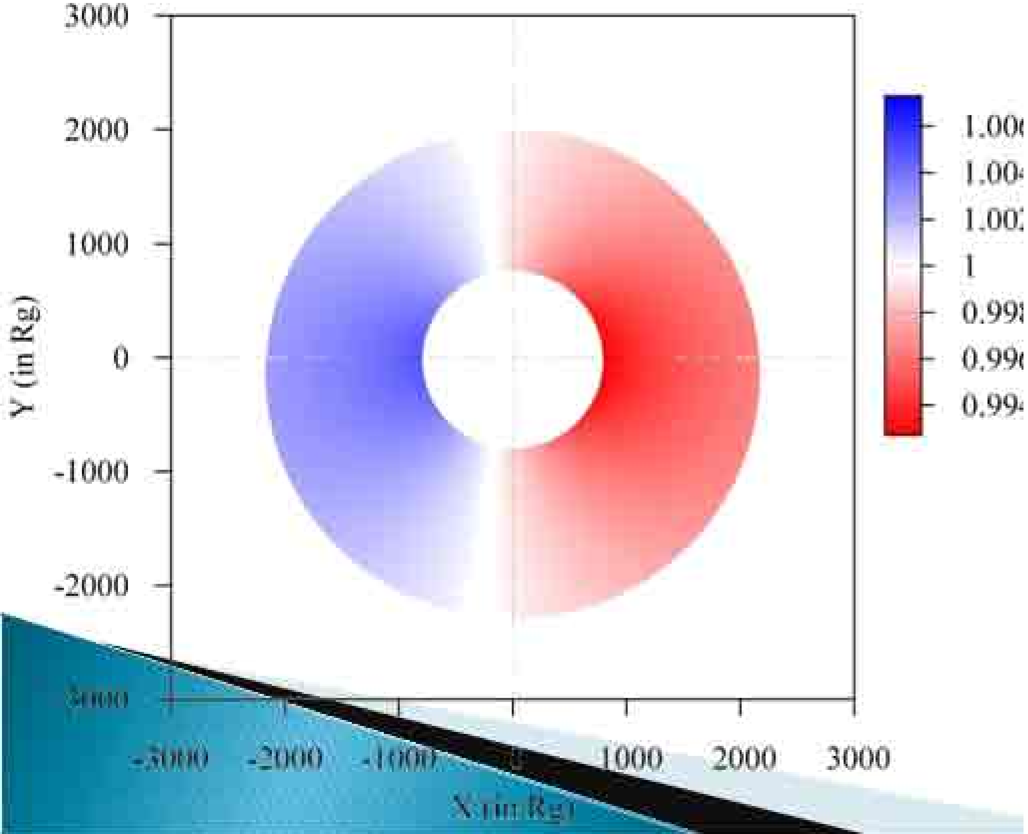


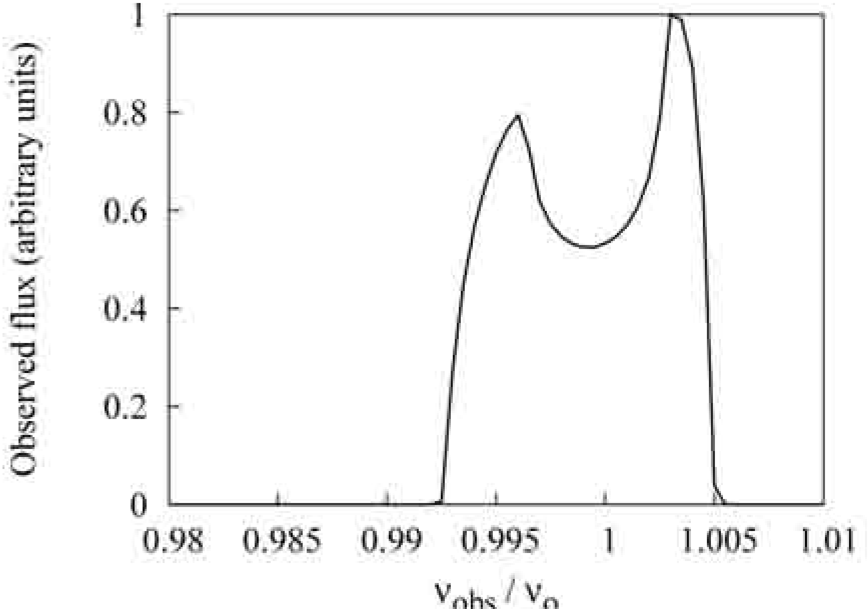


- Double-peaked line profile – mostly RL sources

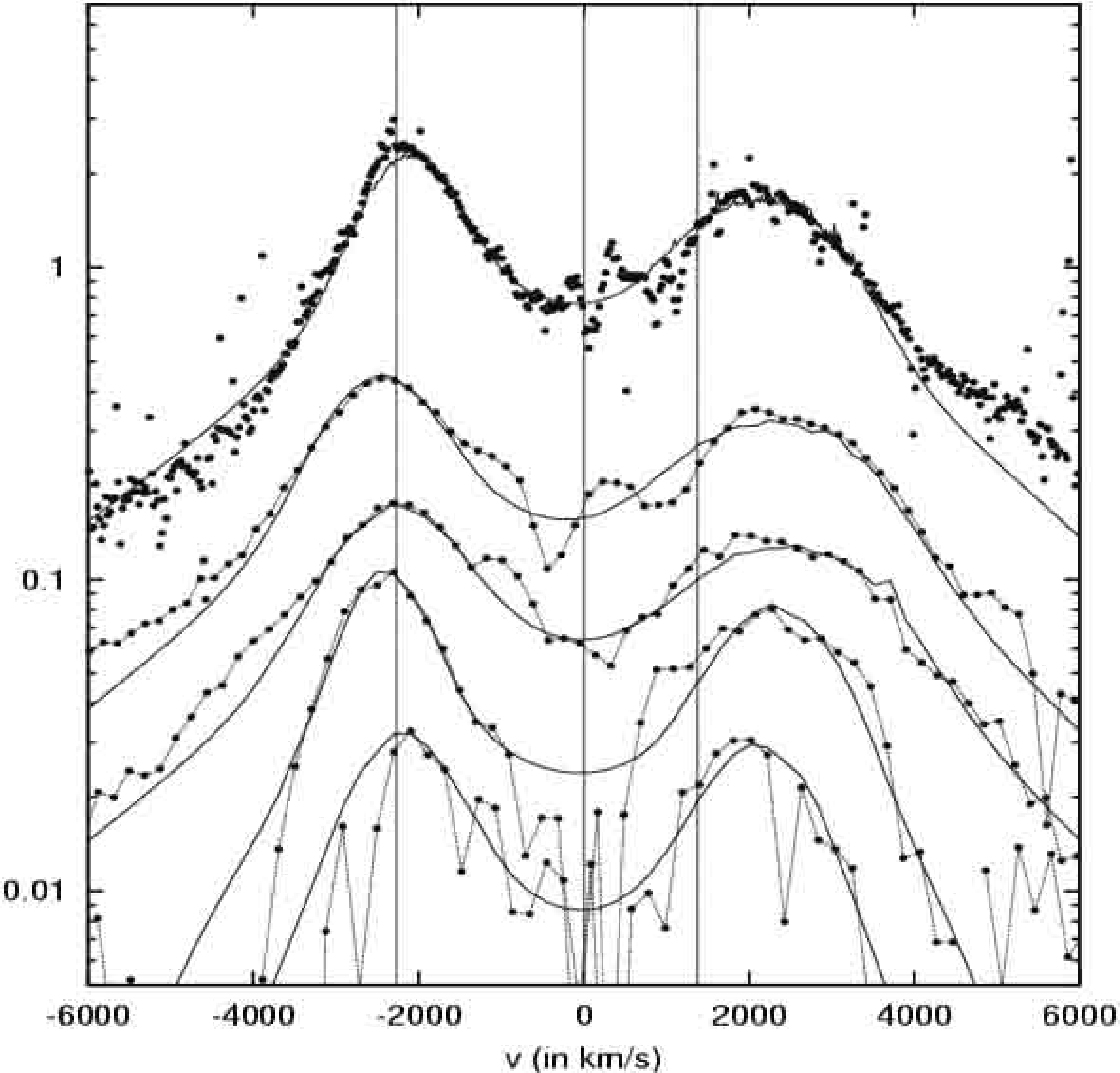
Optical lines, Rin>100 Rg;

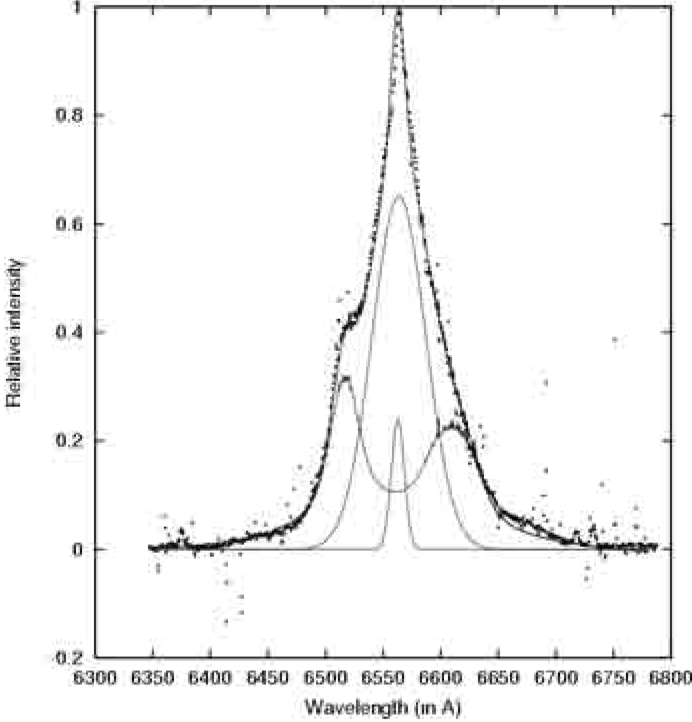
Chen et al. 1989 ApJ, 339,742; Chen & Halpern, 1989, ApJ, 344, 115

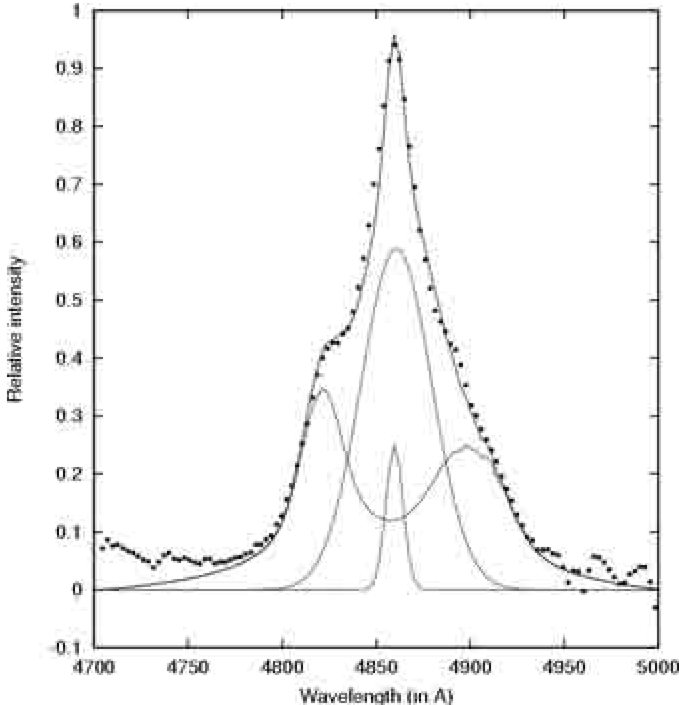


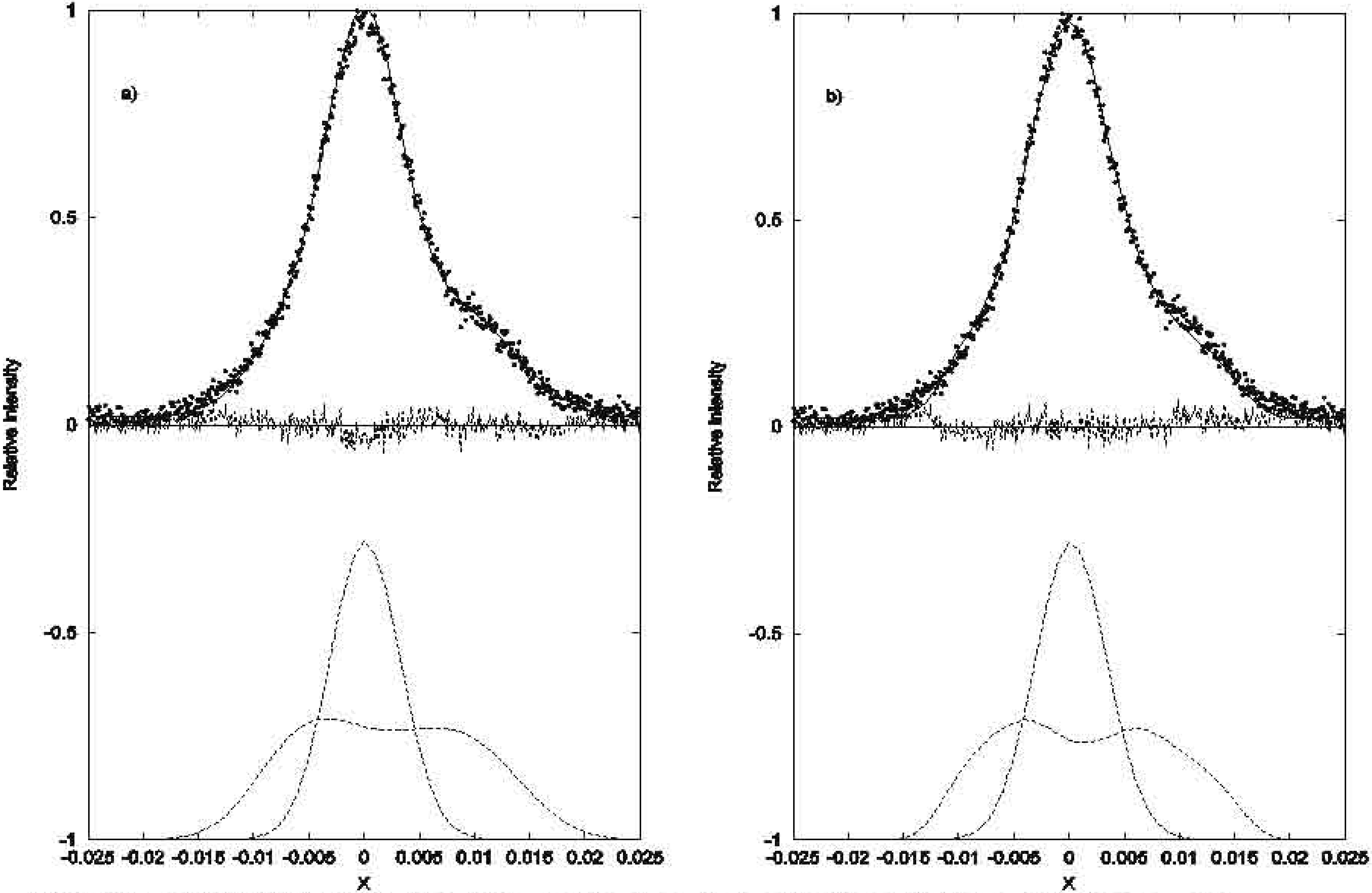


Example: NGC 3516 Balmer lines (Popovic et al. 2002, A&A, 390, 473)







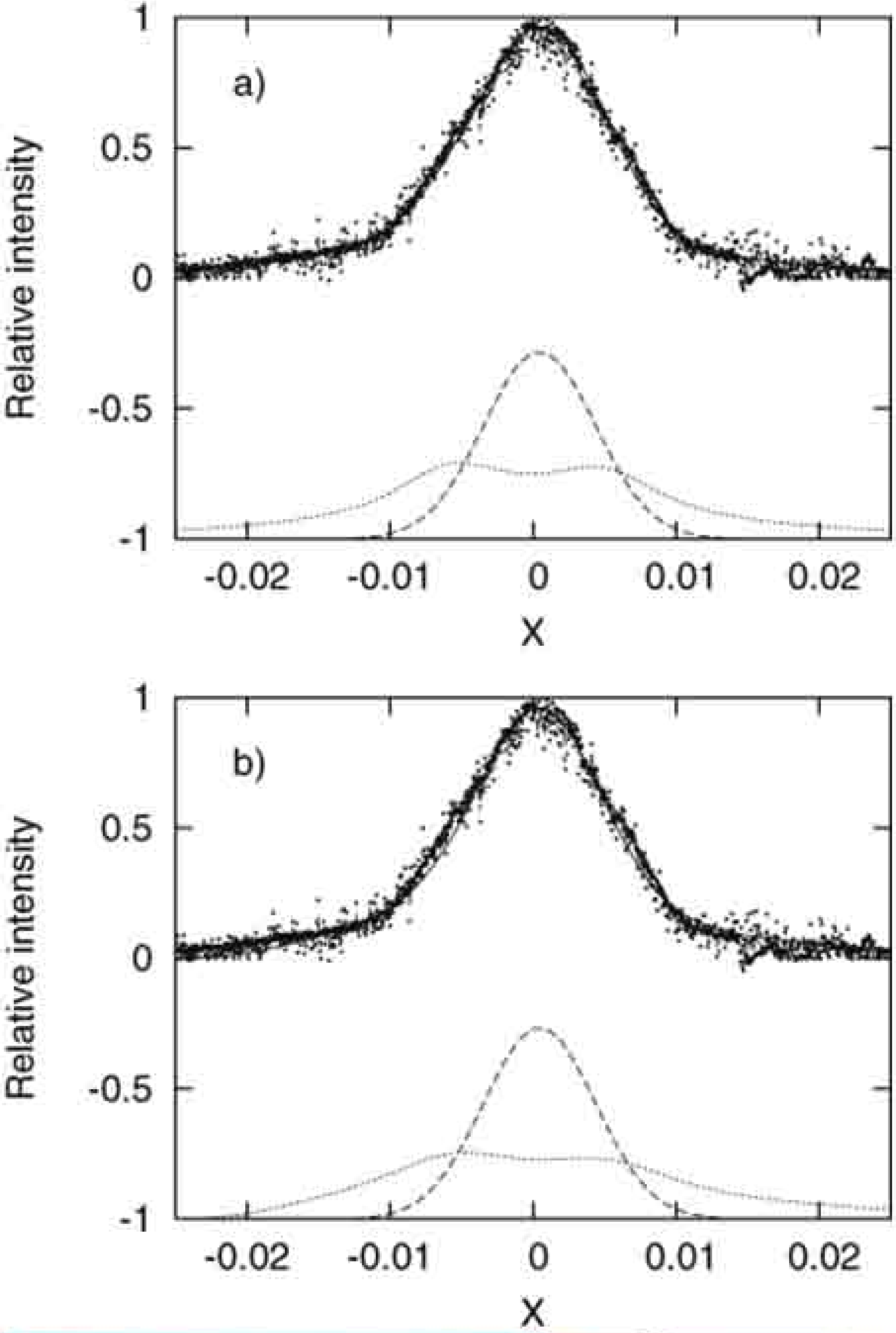


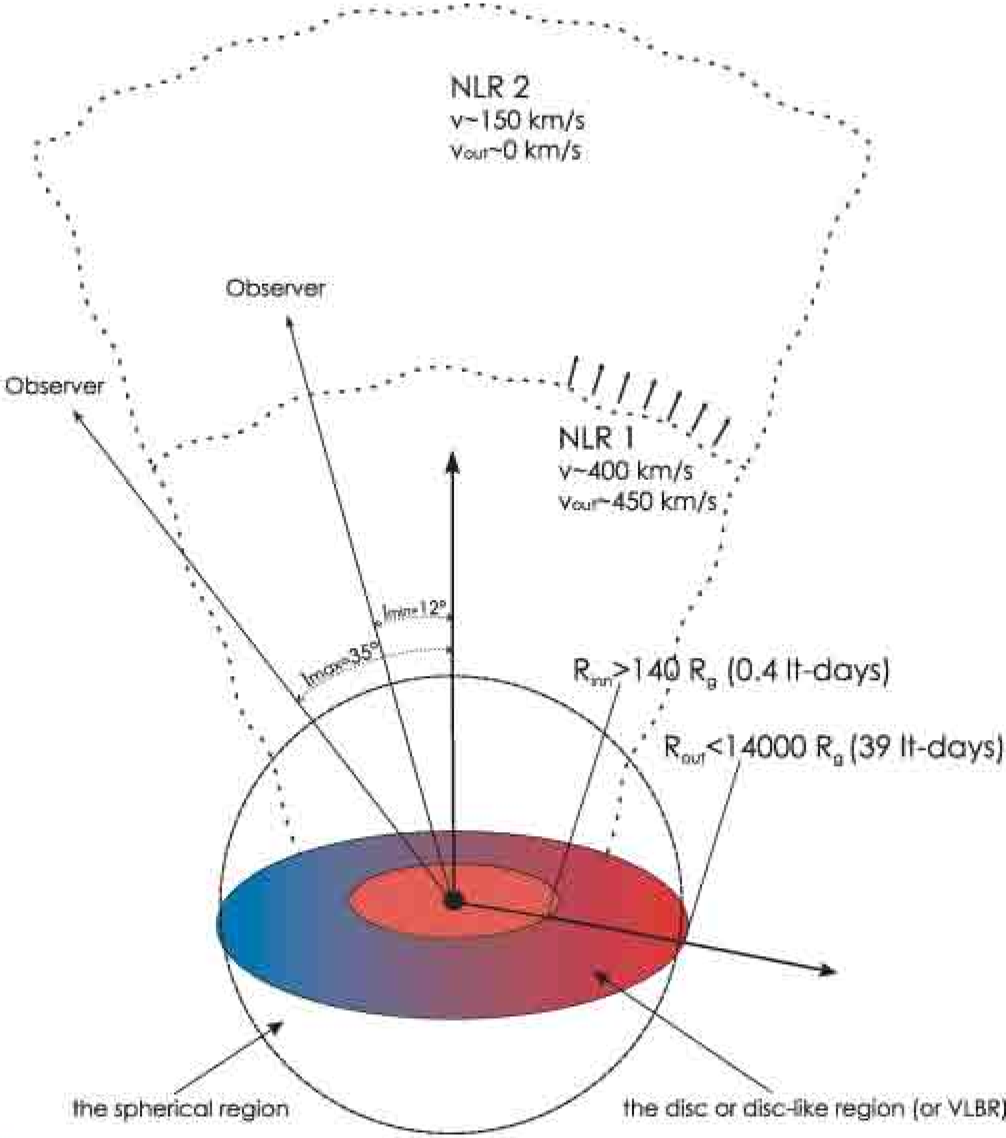
Two fits of 3C 273 with the two-component model the disk parameters are:

a) i=14°, Rinn=400 Rg, Rout=1420 Rg, Wd=1620 km/s, p=3.0 (WG=1350 km/s);

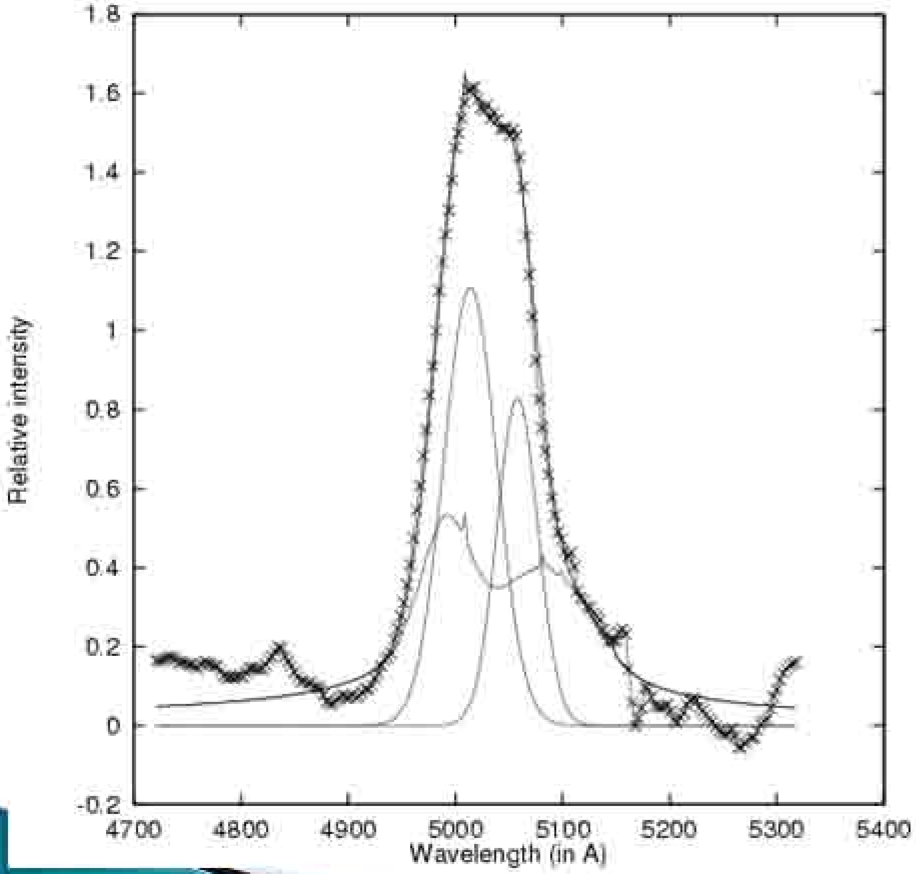
b) i=29°, Rinn=1250 Rg, Rout=15000 Rg, Wd=700 km/s, p=2.8 (WG=1380 km/s)

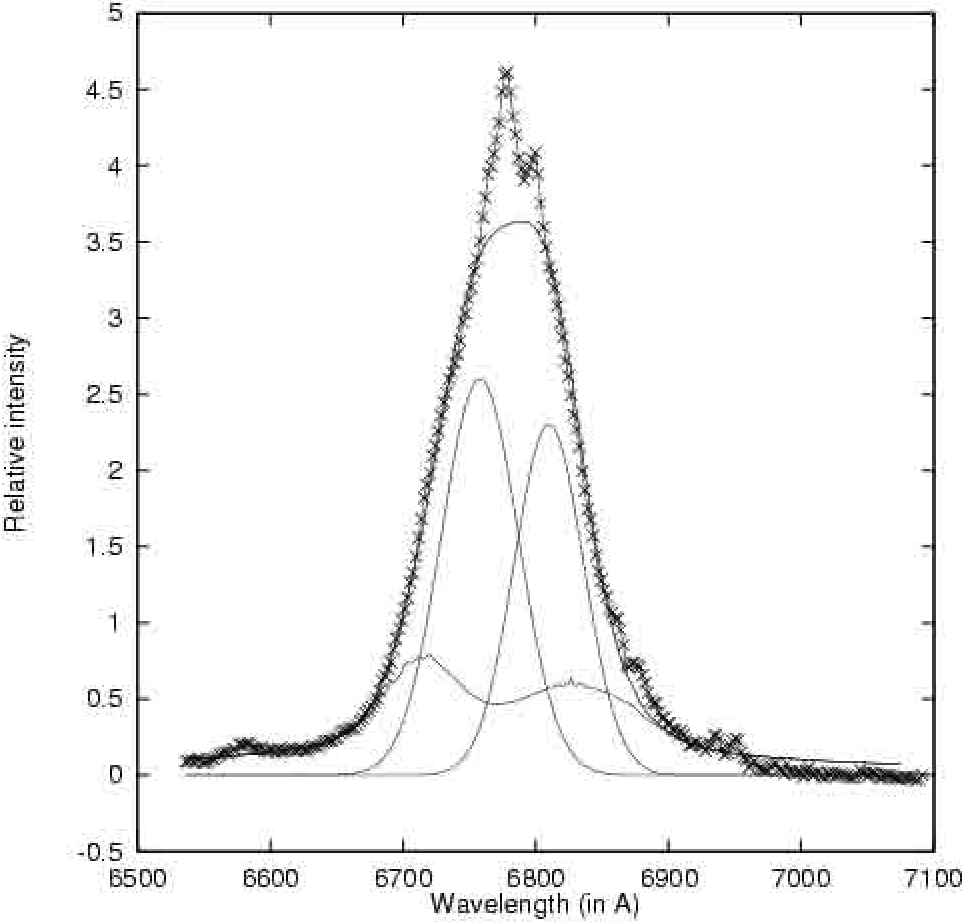
Disk in the center, outflow in the NLR



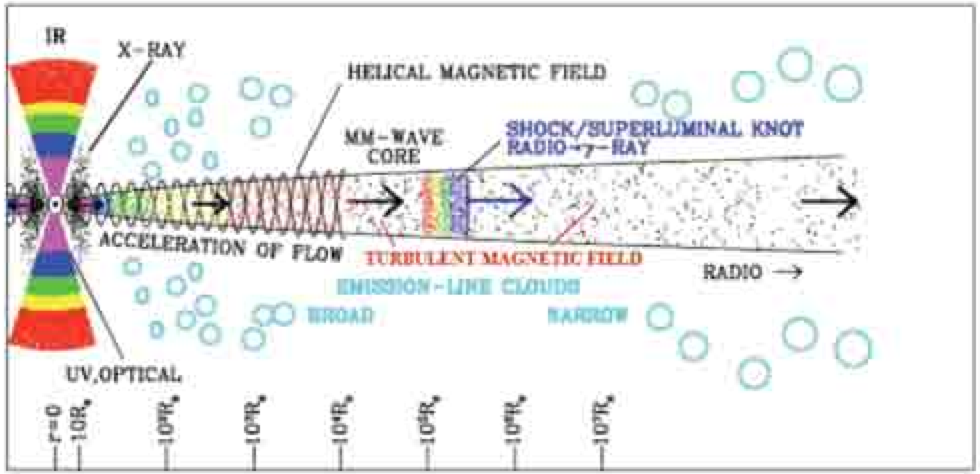


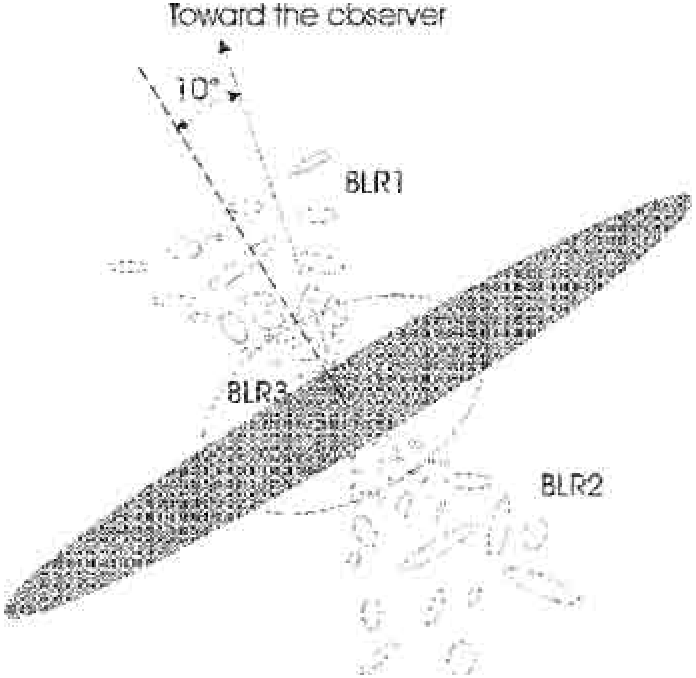
Ark 120: Jet in the optical lines (Popovic et al. 2001, A&A, 367, 780); Only two AGNs with indication of BLR jet

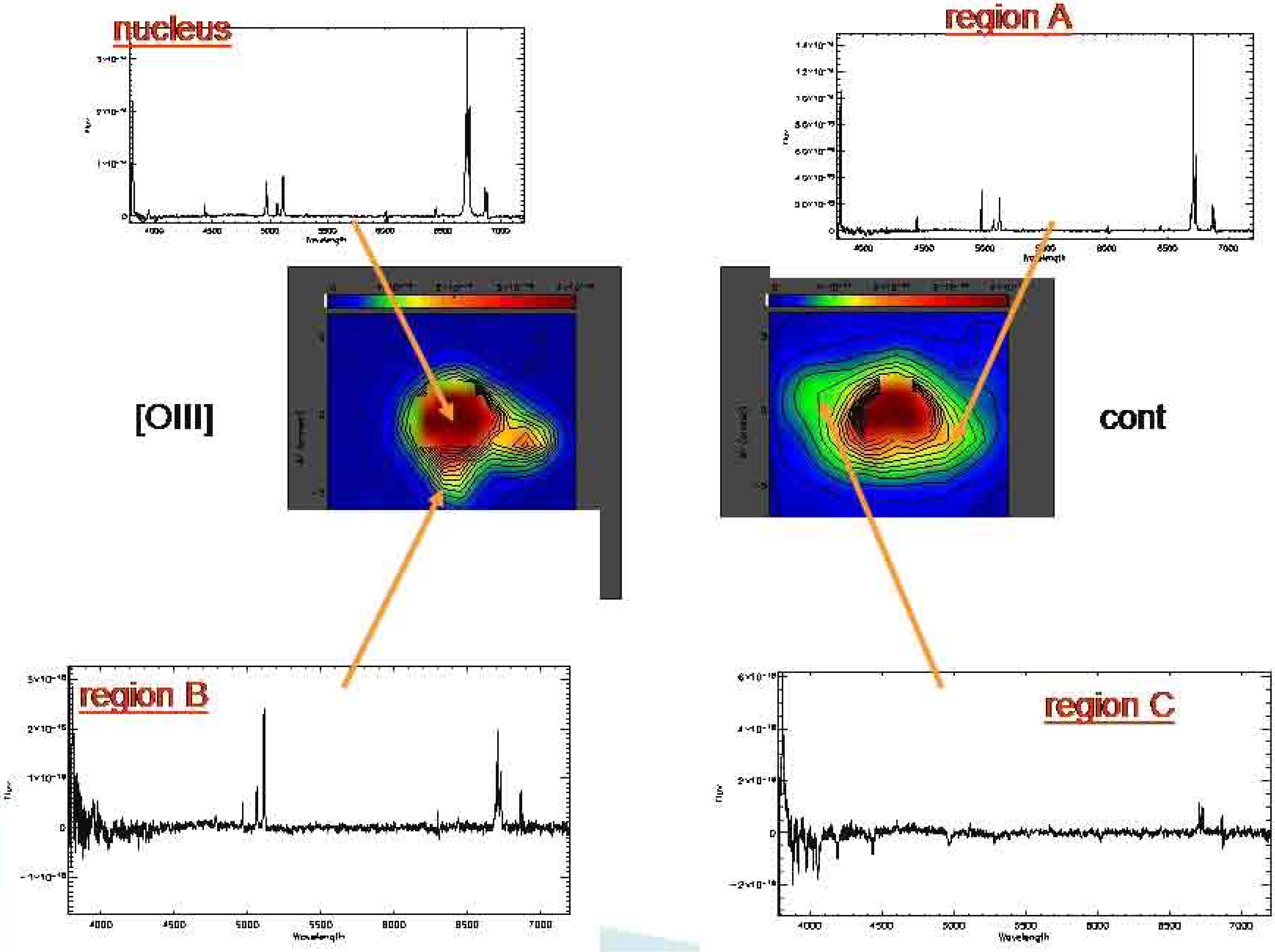




The model of the Ark 120 BLR






nucleus
region A
region B
region C
Flux
Wavelength
4000
4500
5000
5500
6000
6500
7000
0

[OIII]

cont

Spectral Lines in the Universe

- Absorption (stellar spectra, absorption matter, DLA in QSOs, outflow in QSOs, etc.)
- Emission lines (emission nebulae, hot stars, SN, AGN)
- Line profiles can give information about geometry, velocity of gas, etc.