Astronomická spektroskopie
Základy a aplikace

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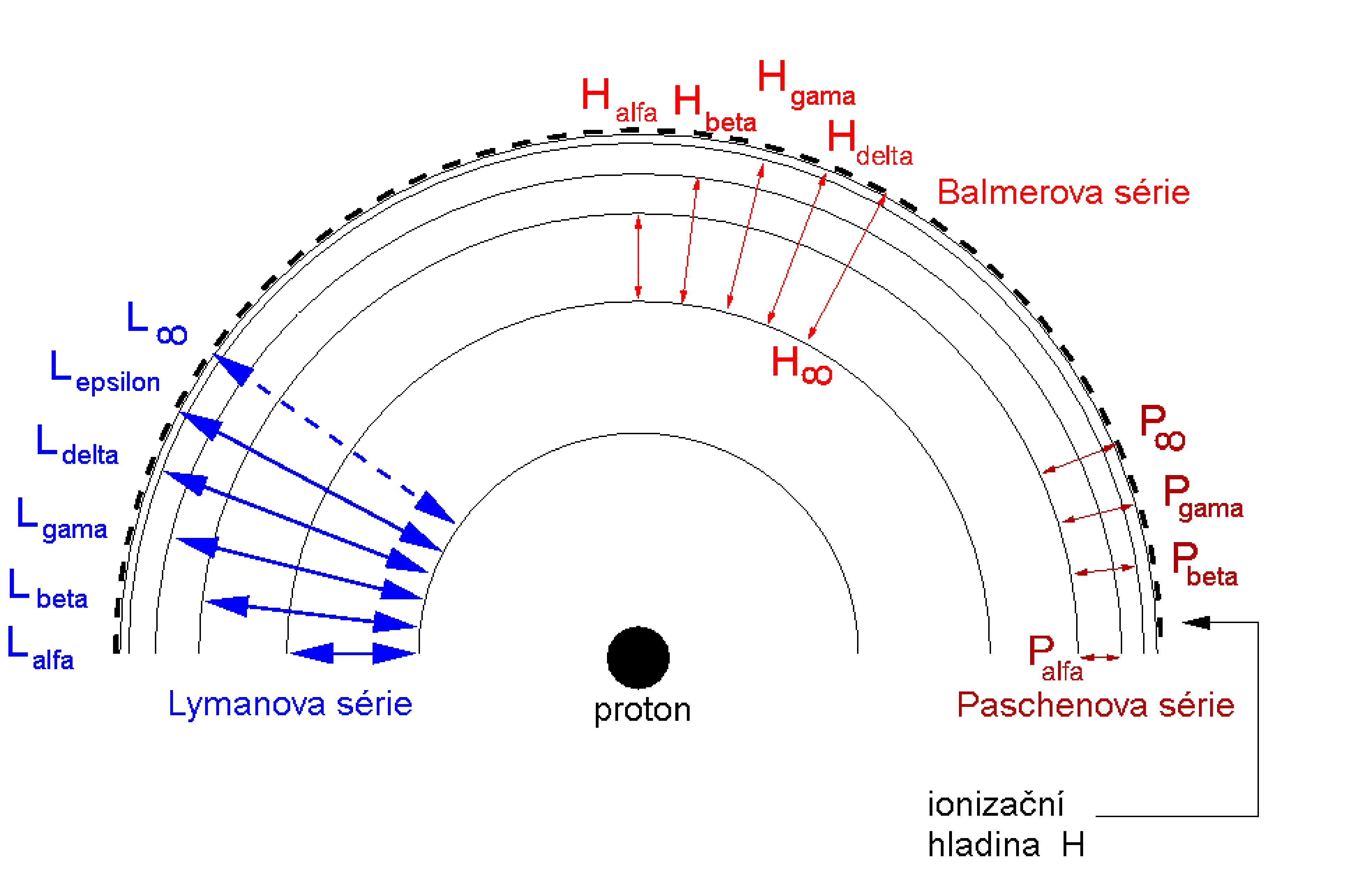
Astronomický ústav AVČR

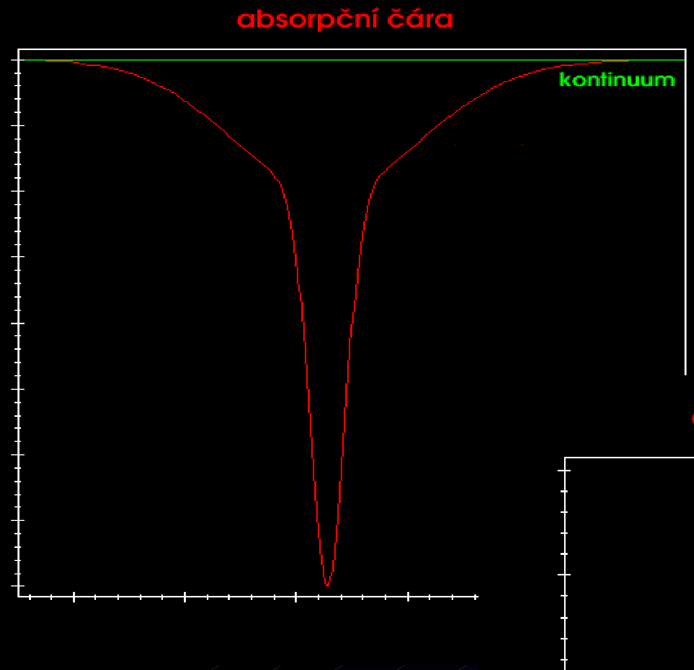
S použitím materiálu od J. A. Smithe (GEMINI) a M.Šlechty (ASU Ondřejov)

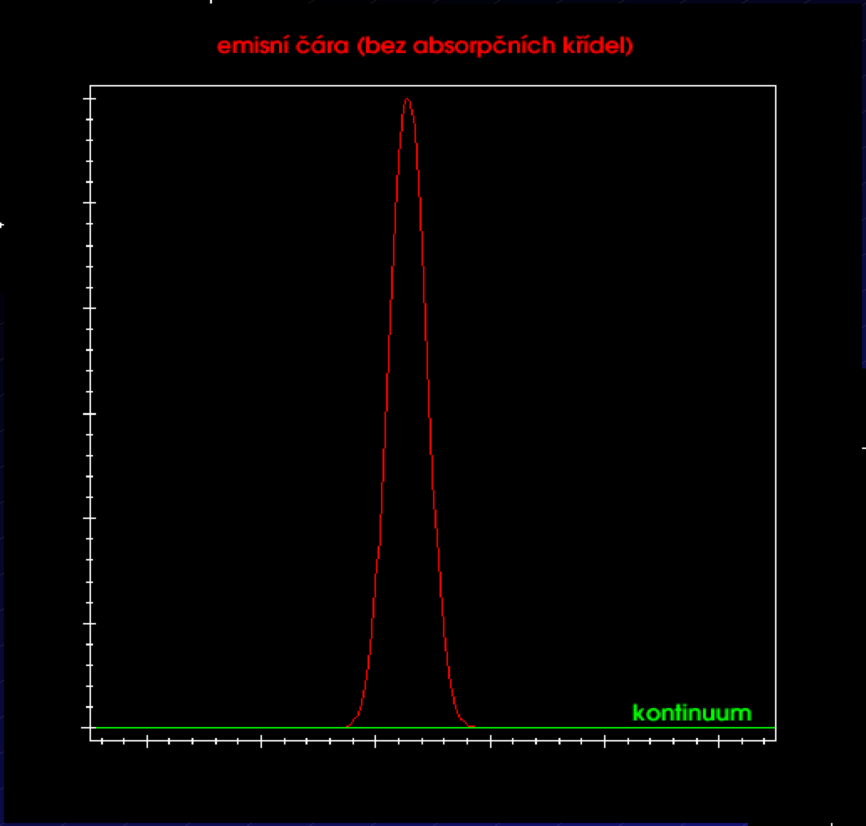
Workshop o amatérské spektroskopii, Valašské Meziříčí 5.5.2007

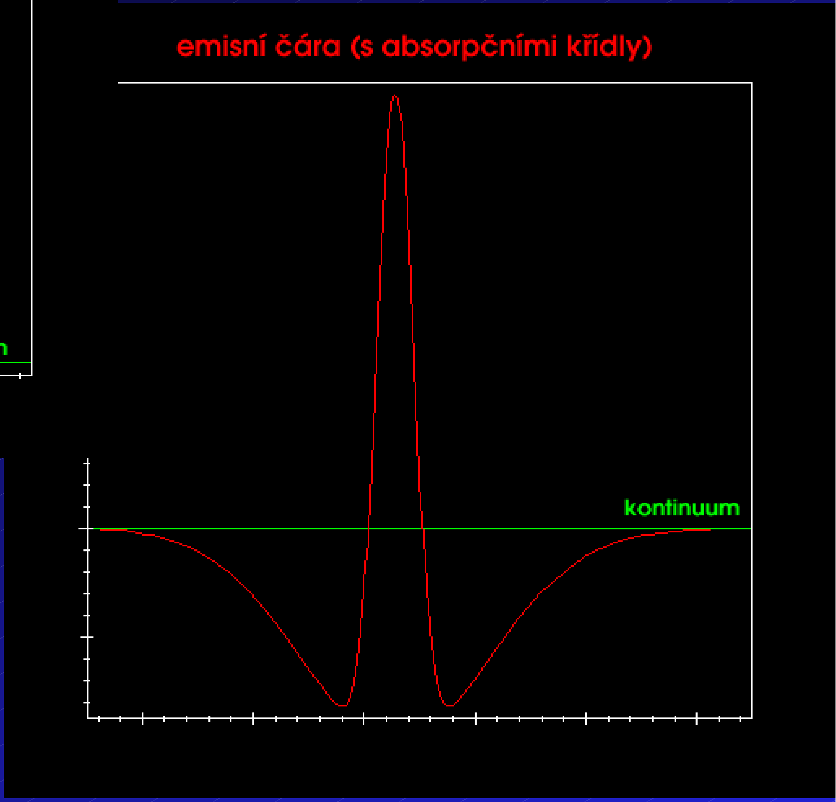
Vznik spekter



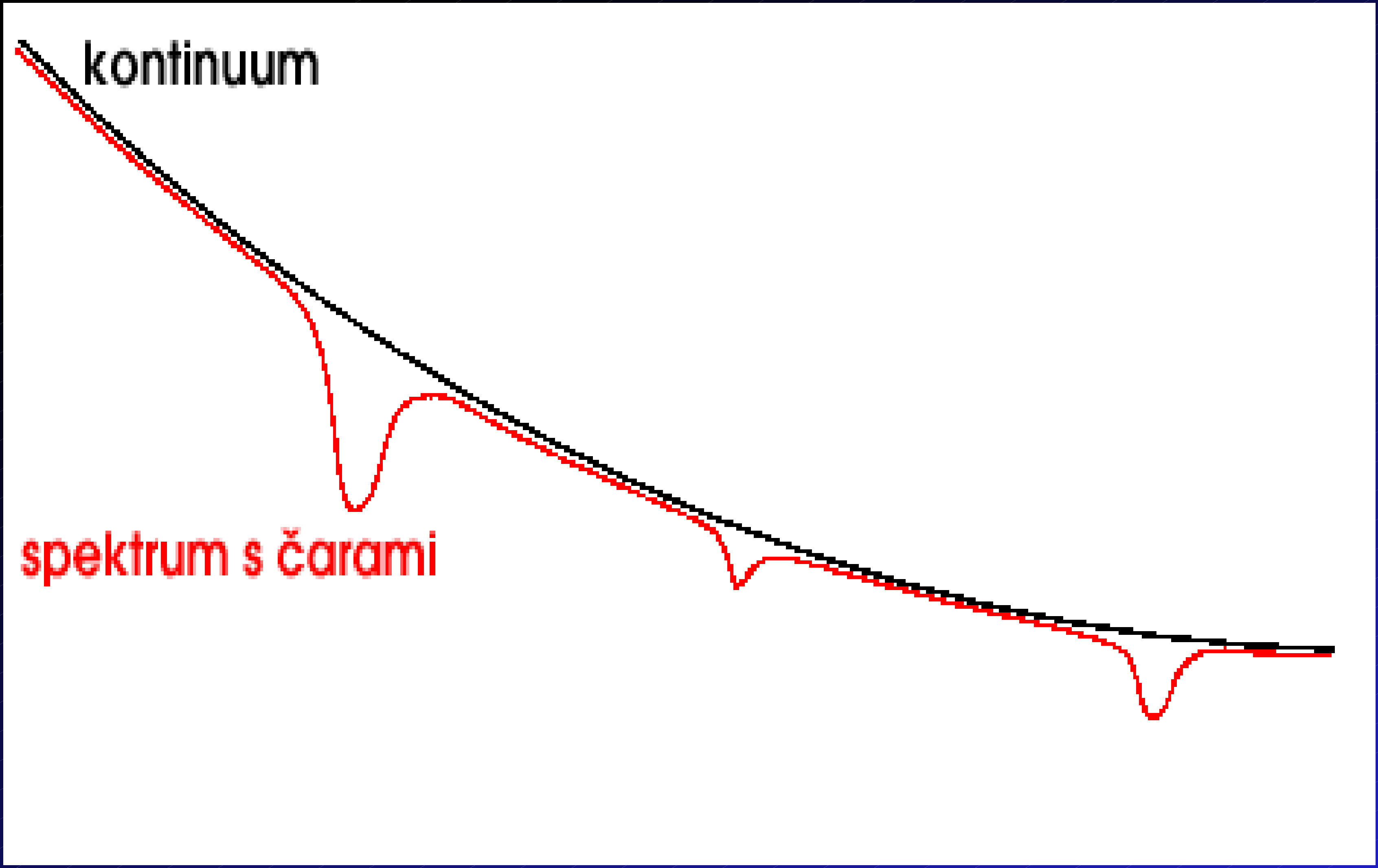
Typy čar


absorpční čára
kontinuum

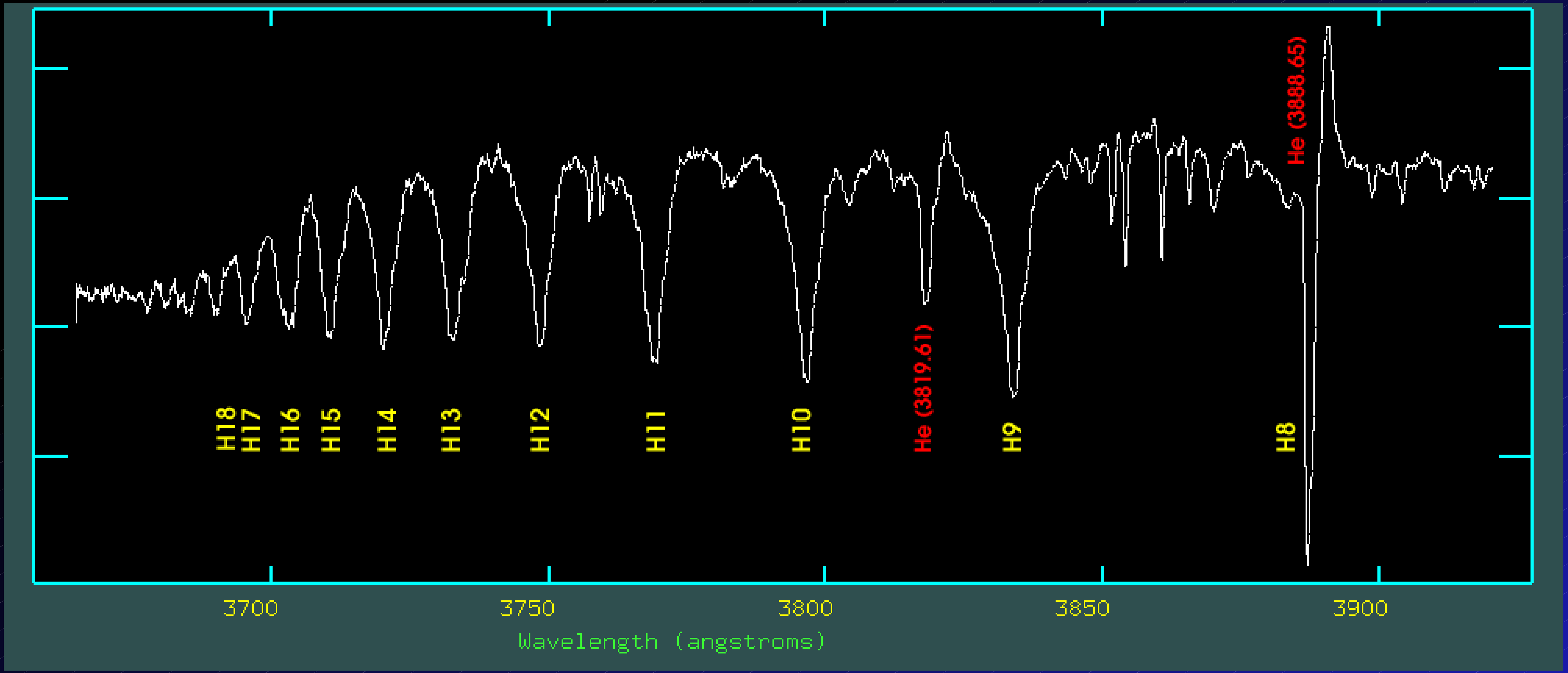

emisní čára (bez absorpčních křídel)
kontinuum


emisní čára (s absorpčními křídly)
kontinuum

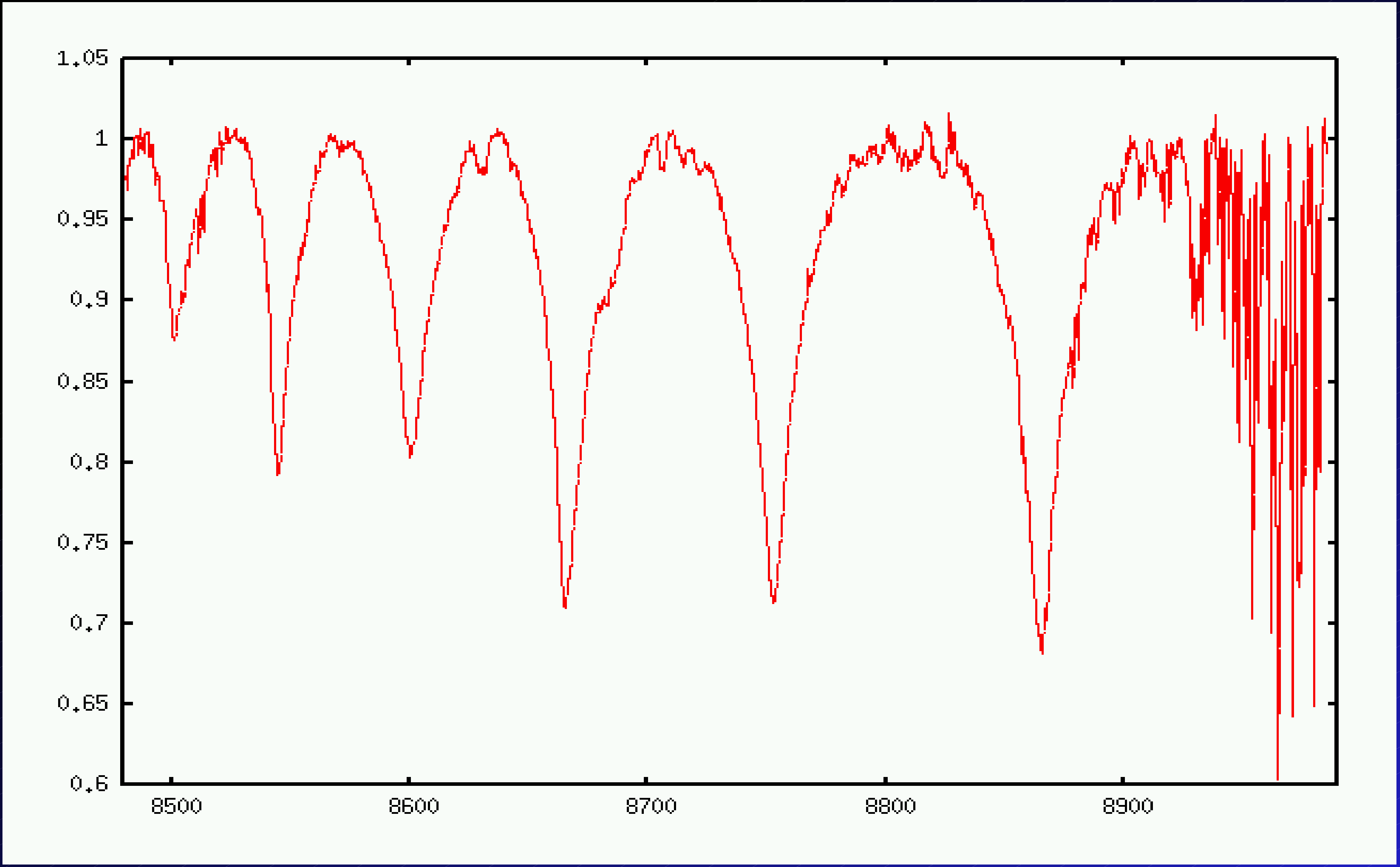
Tvar kontinua (Planck ?)



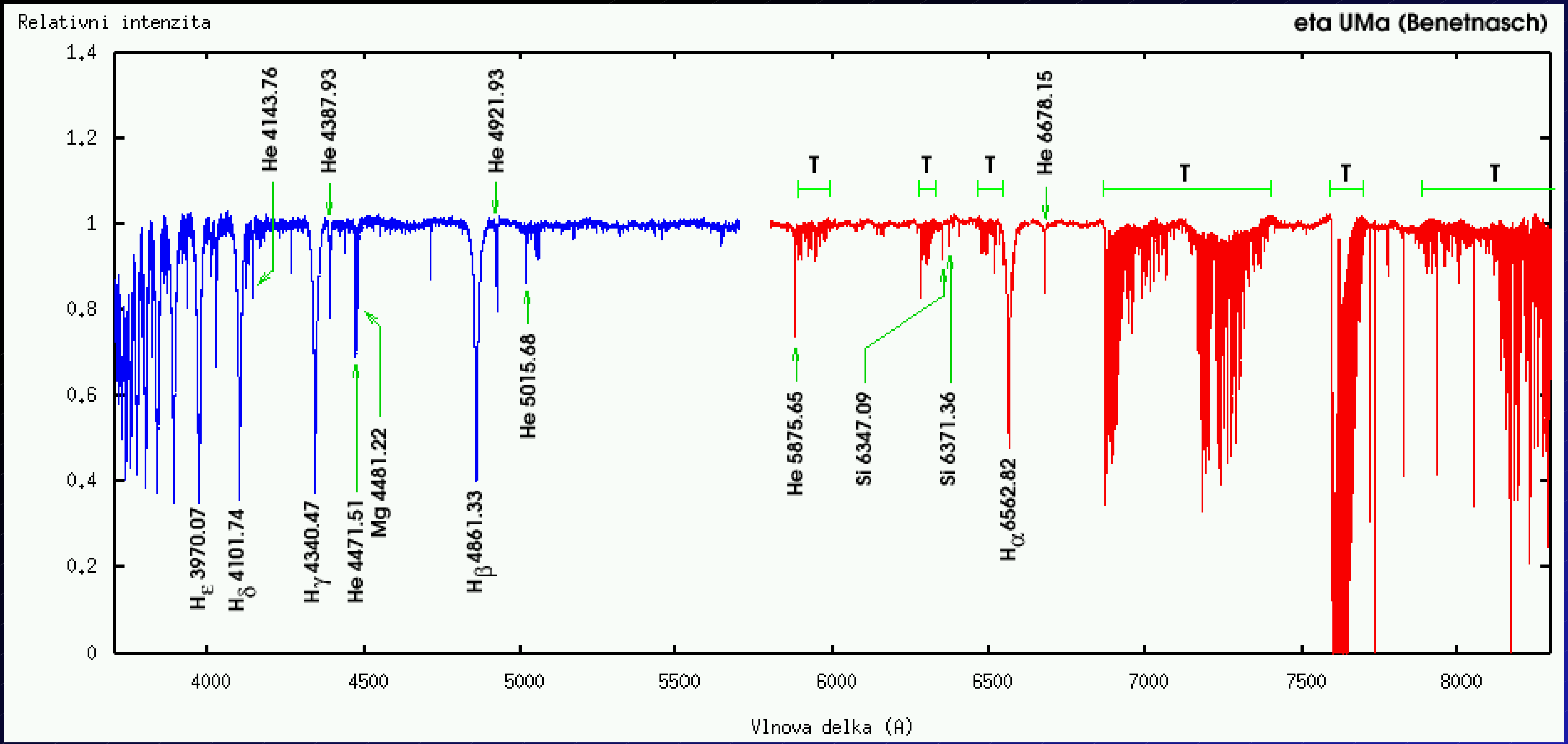
Balmerova hrana



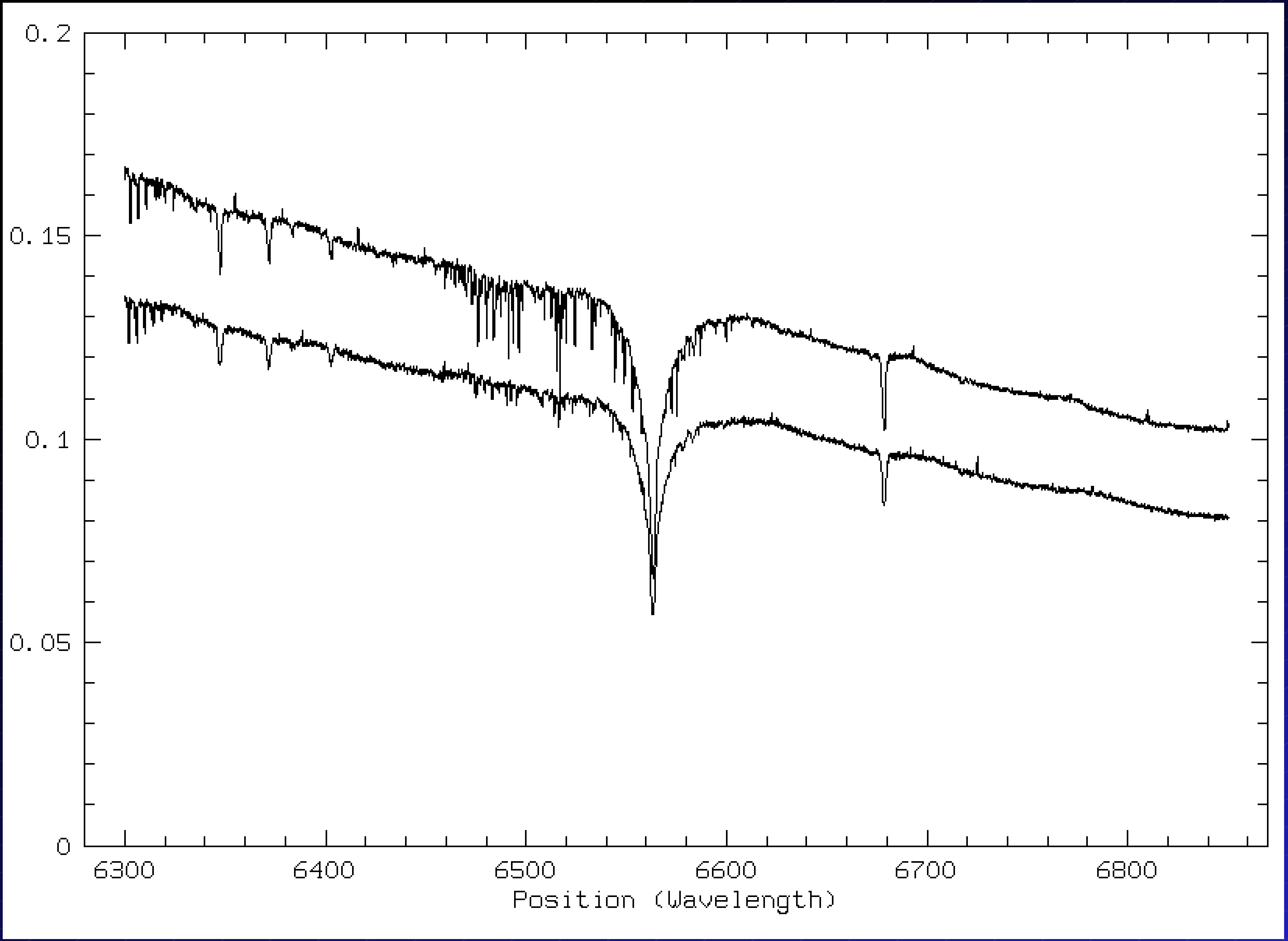
Paschenova hrana



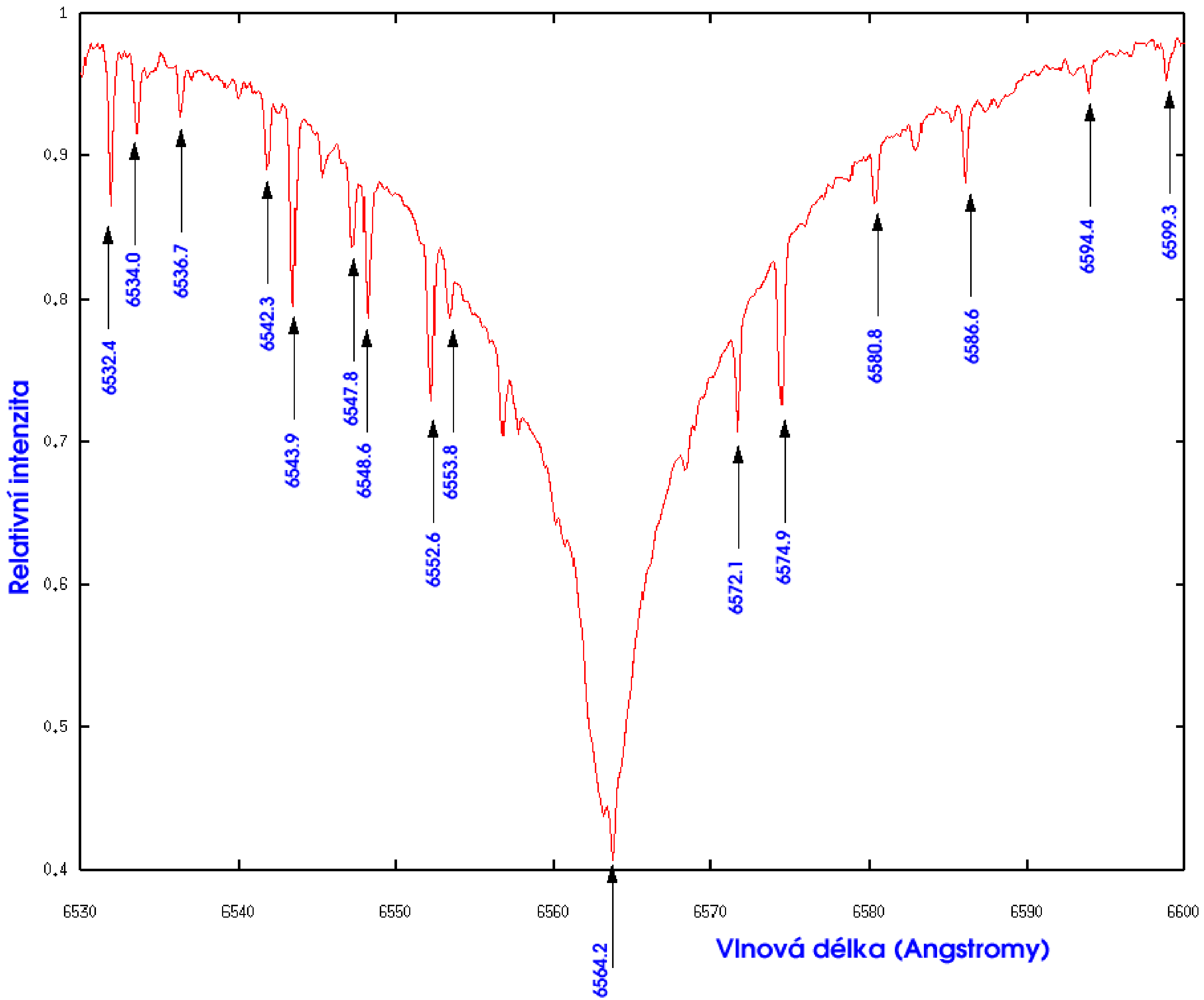
Typické čáry horkých hvězd



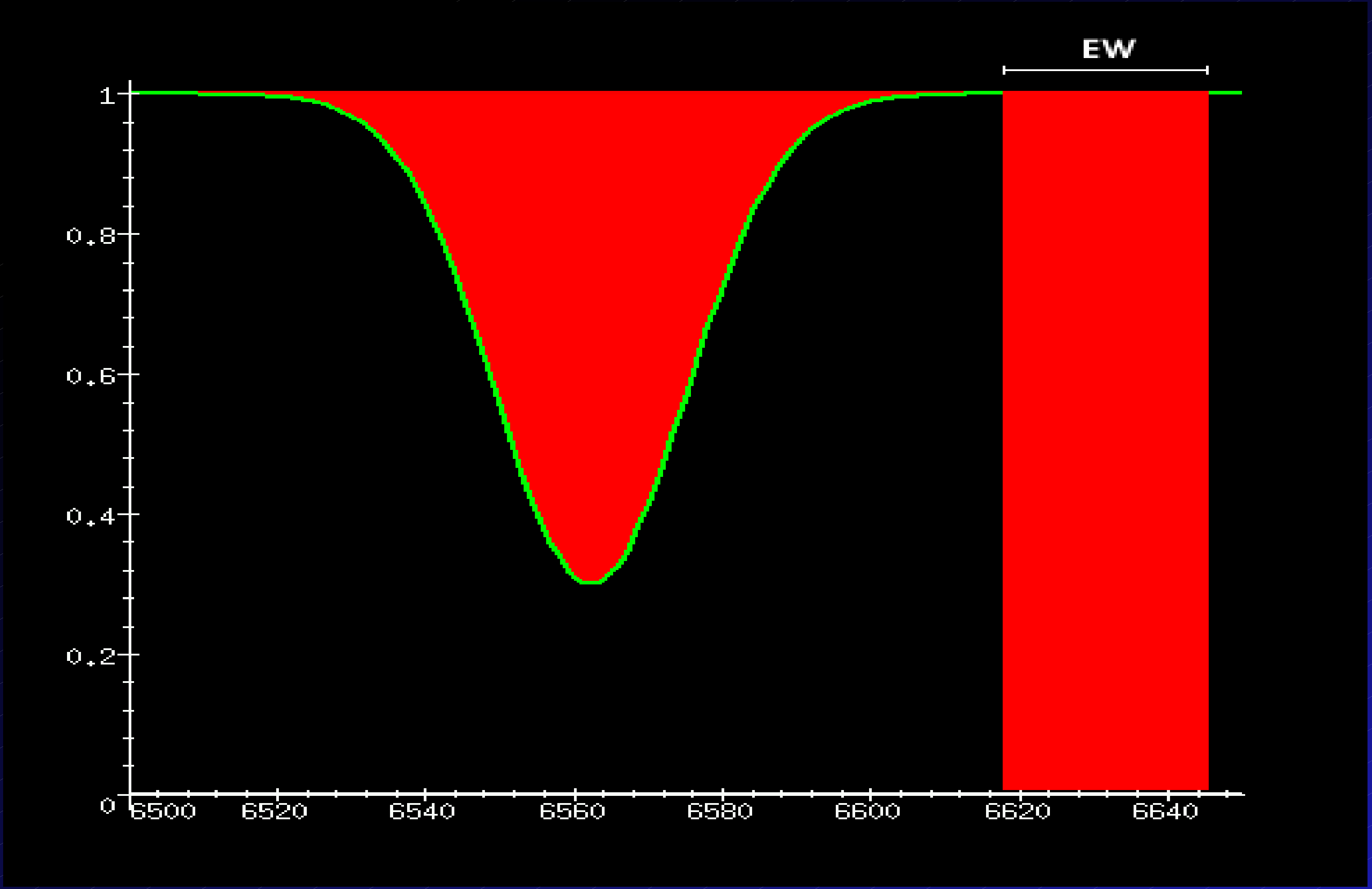
Telurické čáry – vlhkost



Polohy telurických čar v oblasti čáry vodíku H alfa

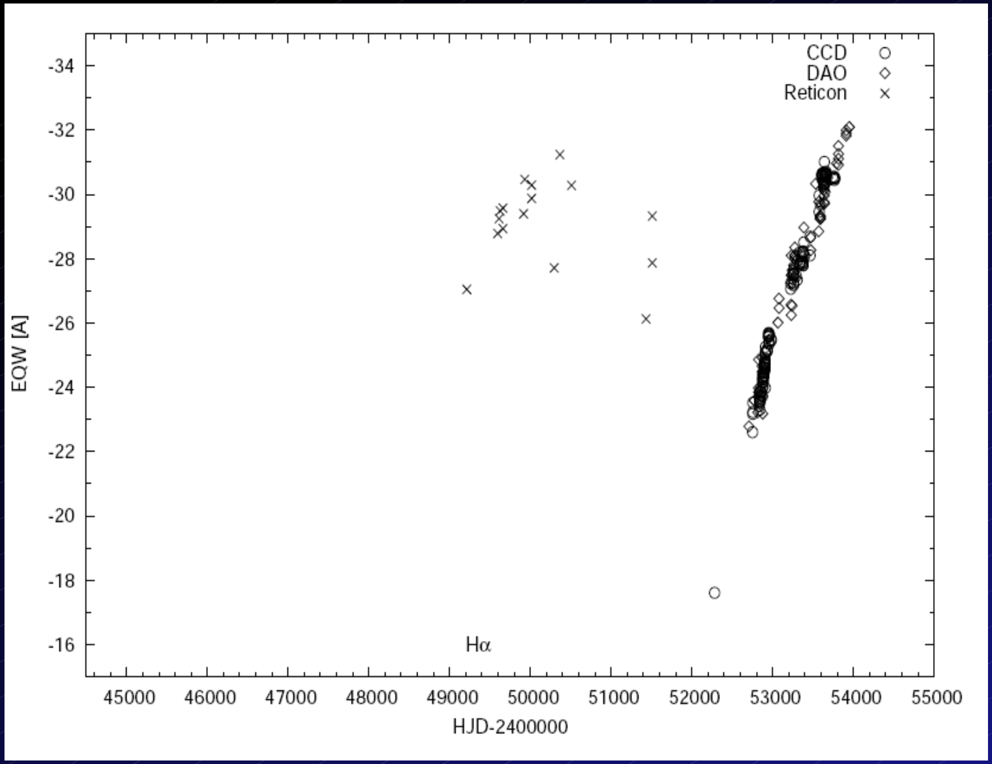


Ekvivalentní šířka

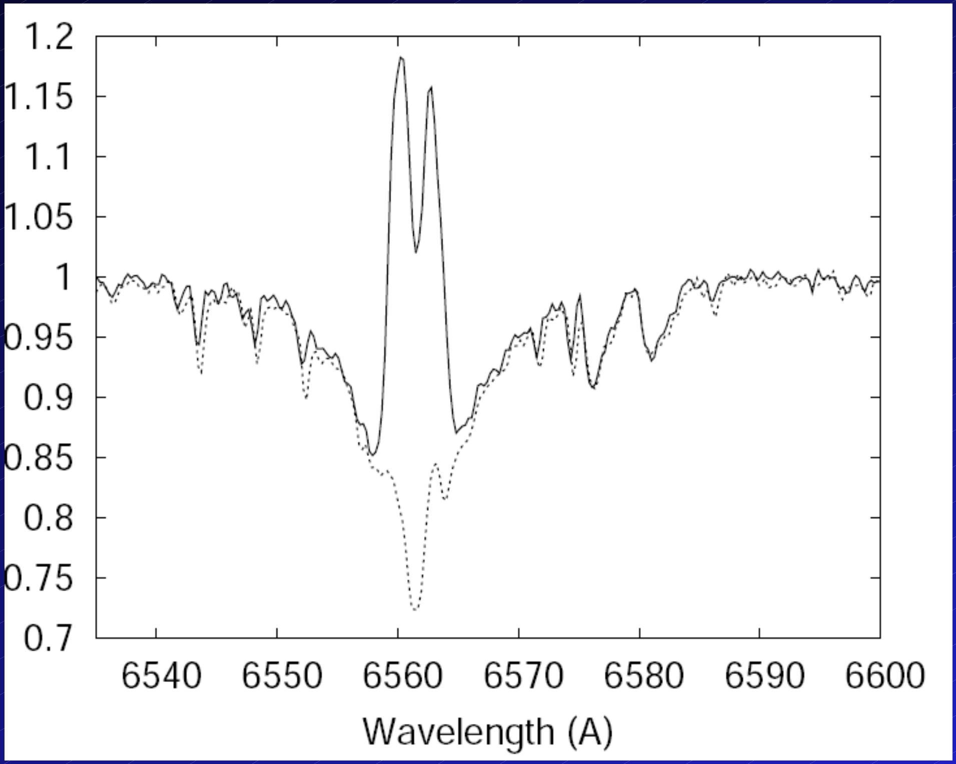


Changes of EW in Time

- Moments in general (asteroseismology – mode identification)
- Emission lines – negative EW
- Estimates of expanding shell
- Sensitive to continuum placement – shallow lines
- Abundances - check normalization – different lines same ion

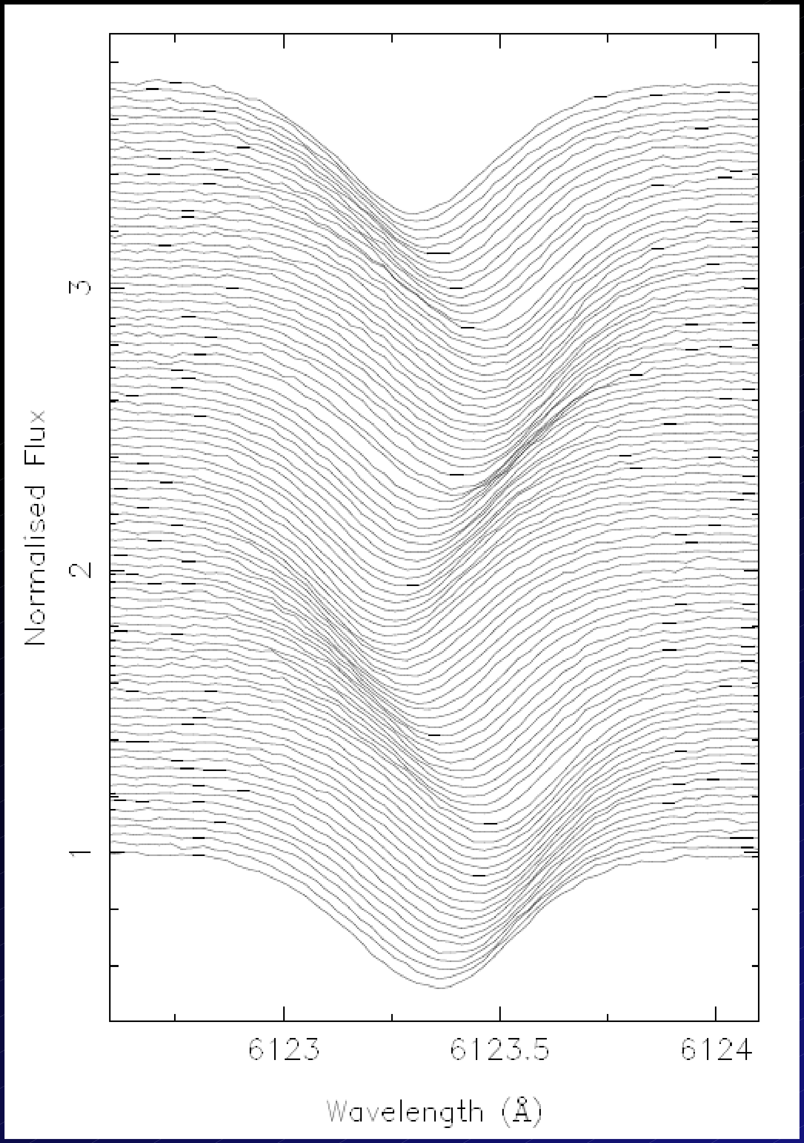


Omi Cas : Koubsky et al. 2004

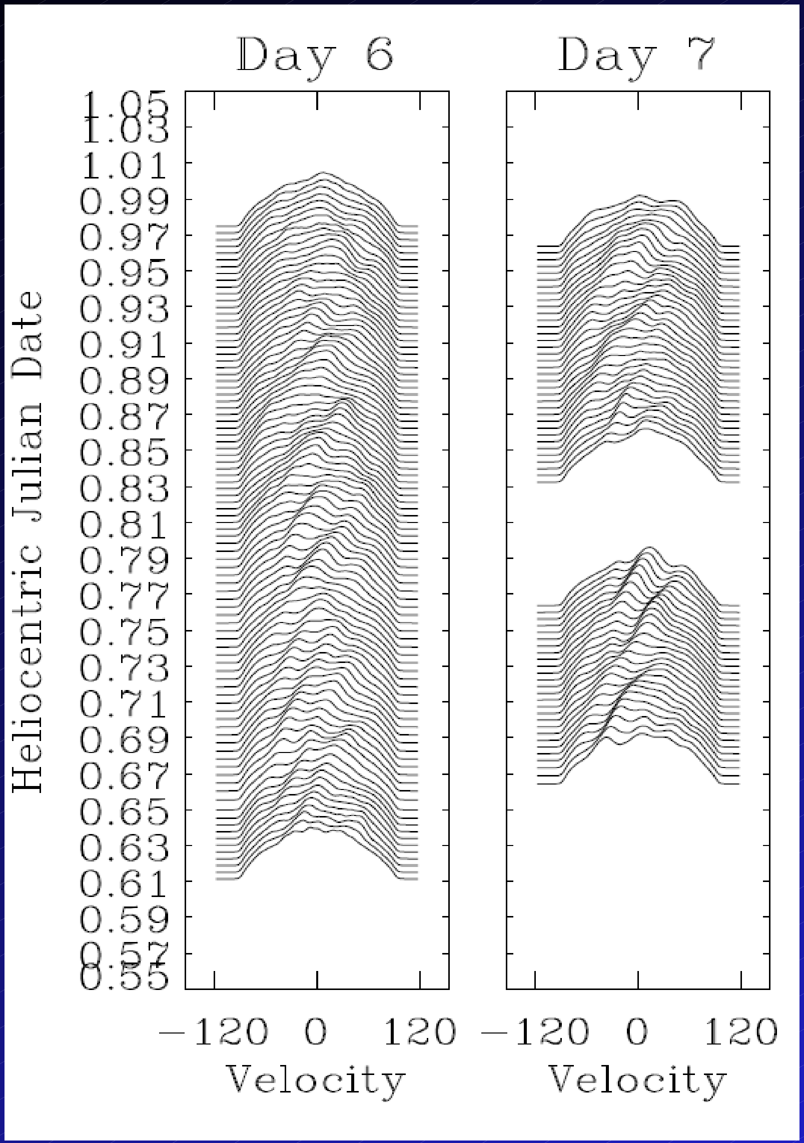


HD6226 : Slechta and Skoda 2004

Measured Pulsations

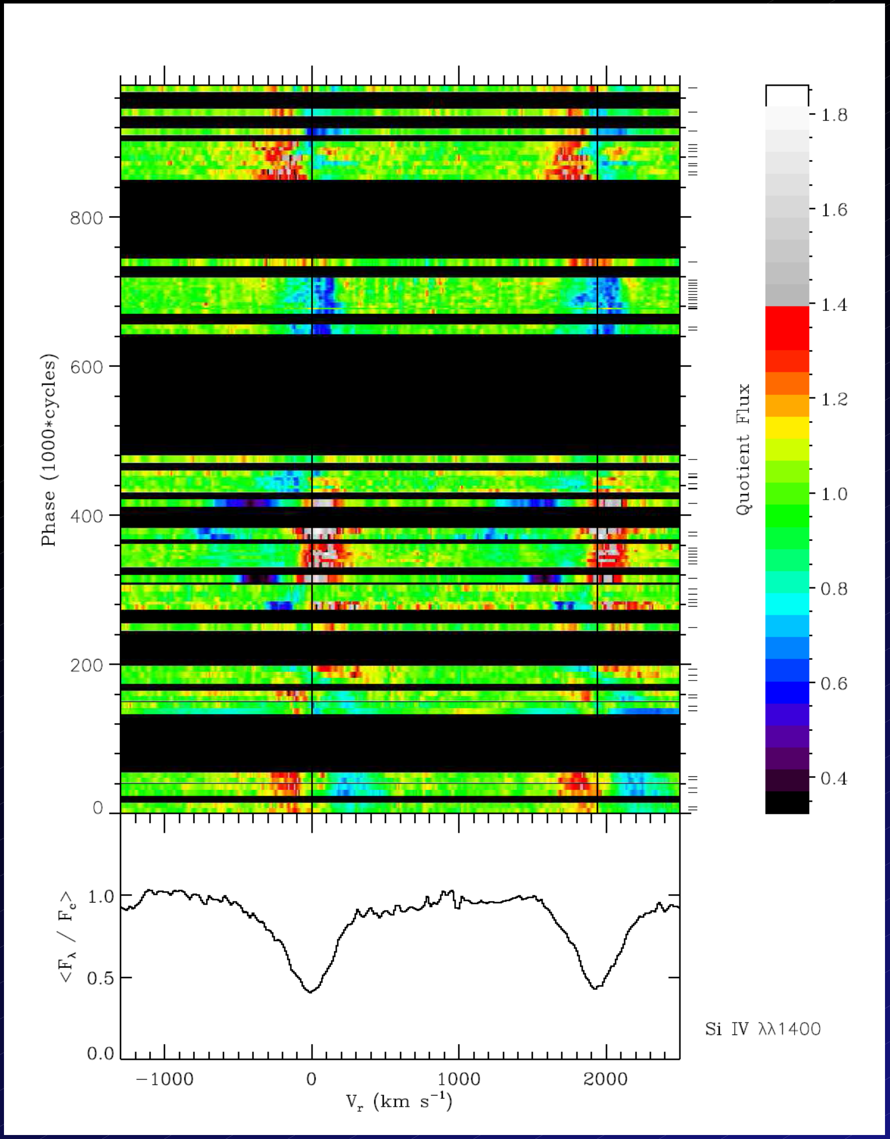


Rho Pup – del Sct type



Eps Cep - del Sct type

Dynamic Spectra

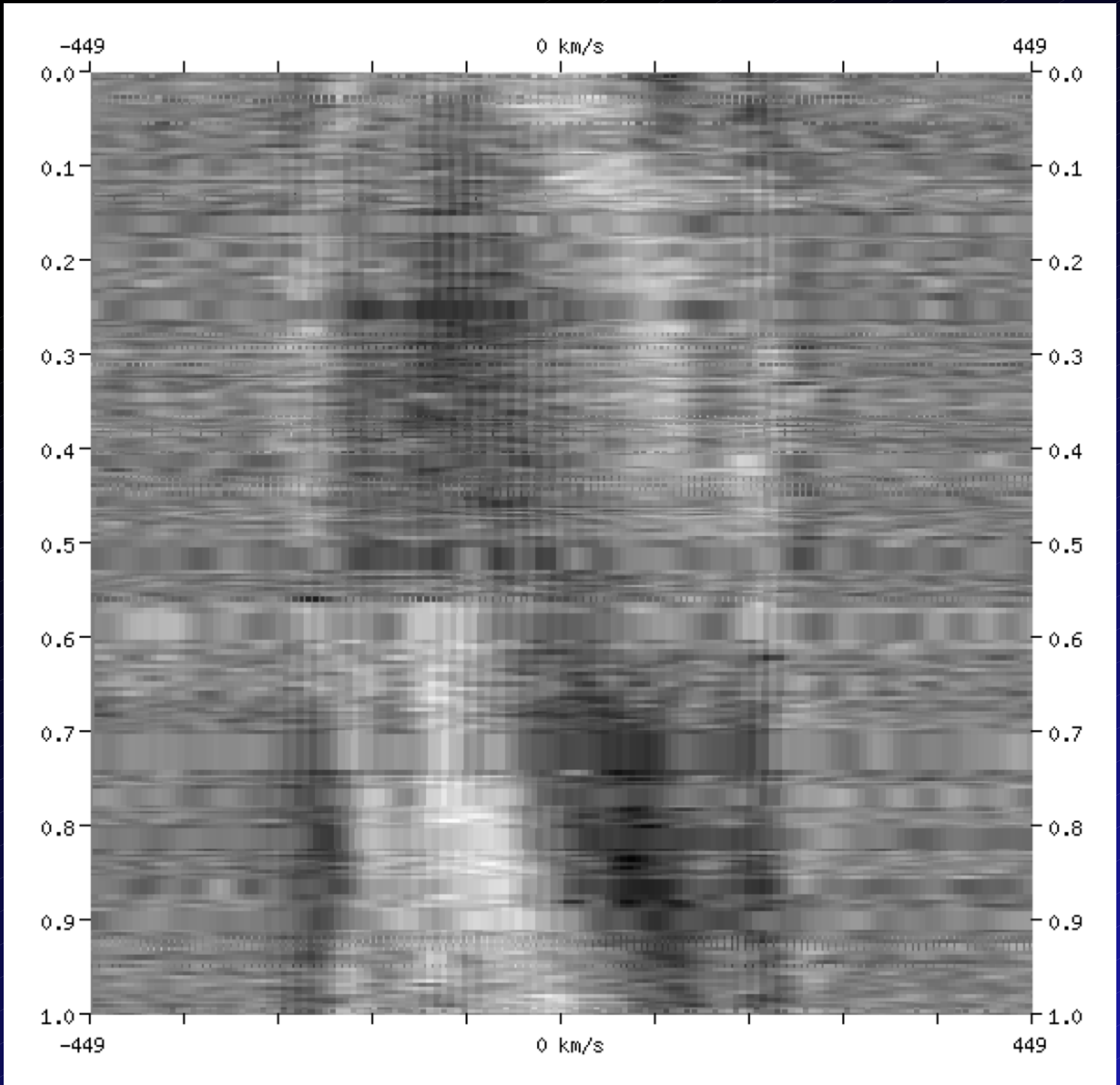


CX Dra: Skoda and Koubsky 1998

Interactive features, color cuts, LUT
Multiple lines at the same time
Quotient or Differential
X axis : lambda or RV
Y axis : phase or time

For study of LPV (asteroseismology, winds)
Requires
- time (JD) - winds
- period (see Period analysis) - phase (LPV)
- change of template (average, median)
- removing bad data (interactive overplotting)

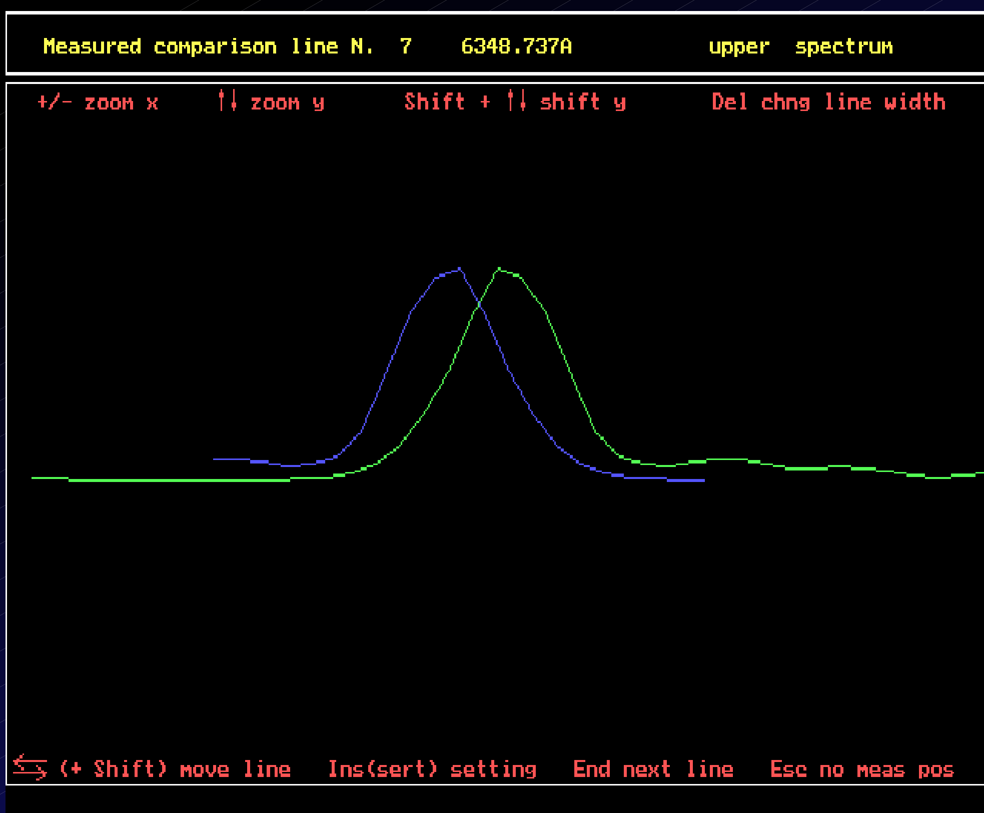
Dynamic Spectra



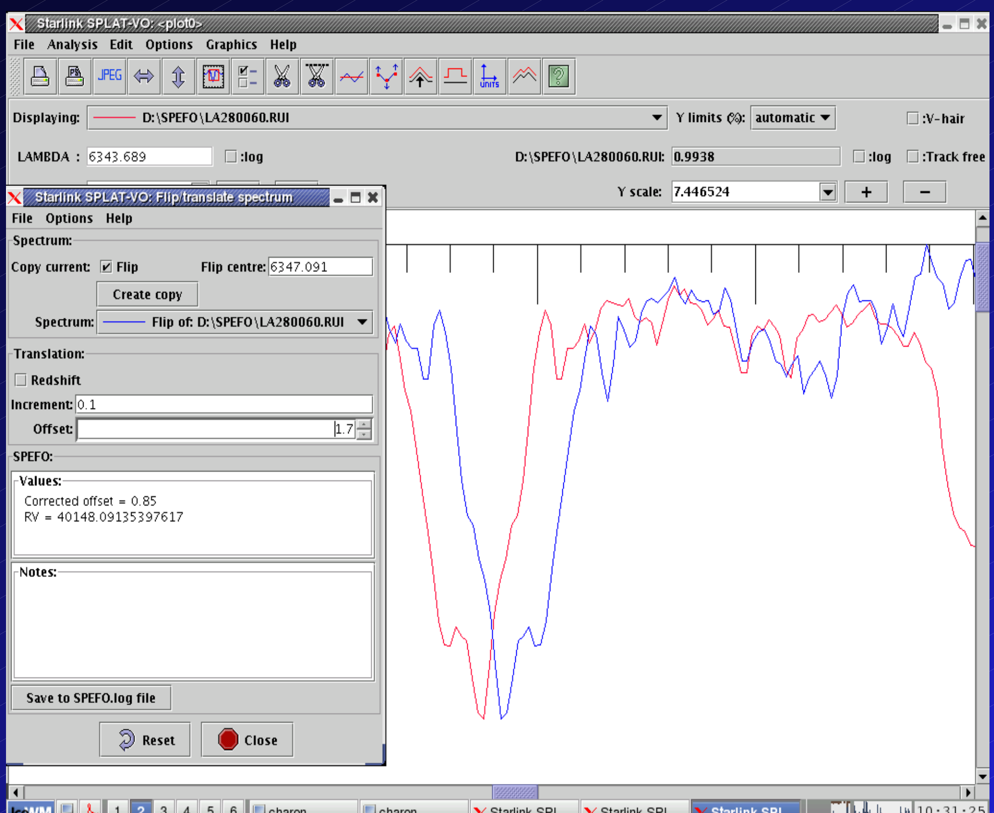
Netolický 2004

RV by Mirroring

- Shift until best match of direct and flipped profile - interactive
- Complicated profiles (Be)
- Adjustable region of interest (wing/core)
- Needs reference line position



SPEFO - Oscilloscopic



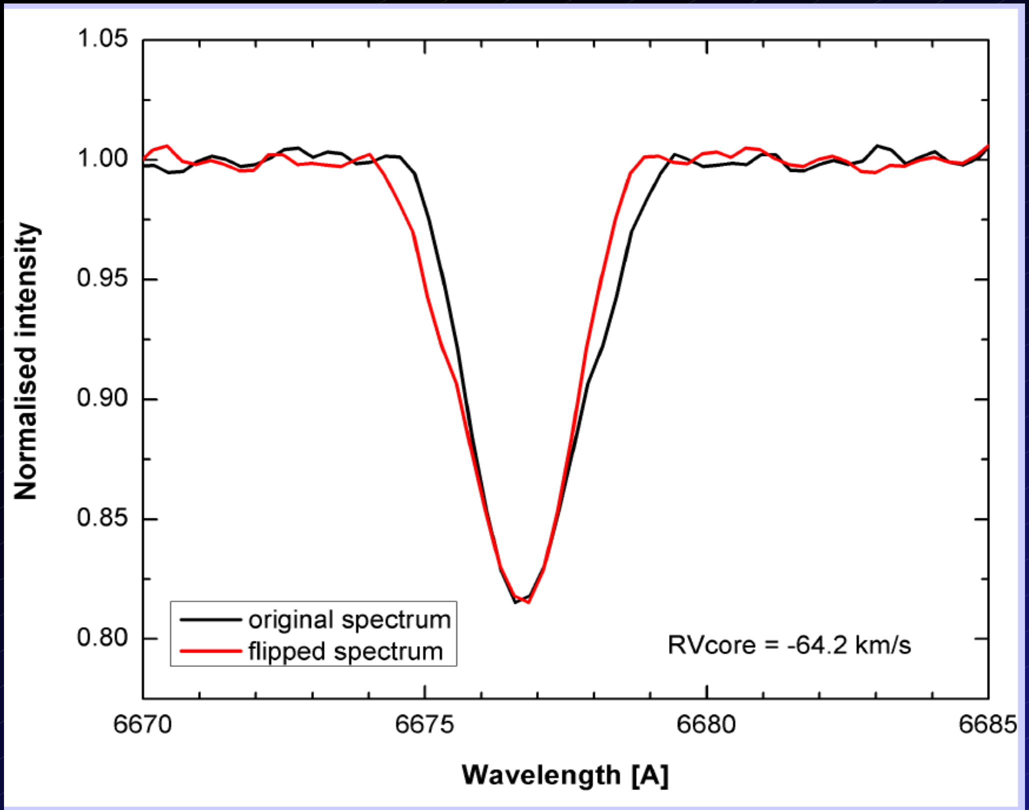
SPLAT

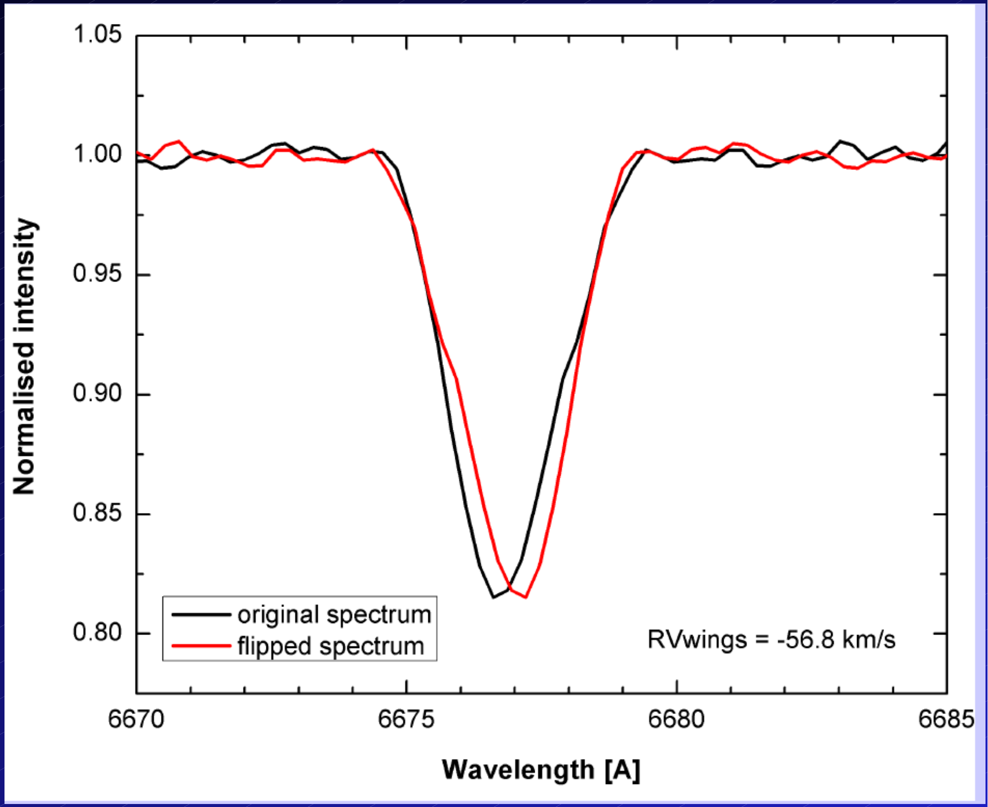
Mirorring Method

Separate match of core from match of wings – where in depth ?

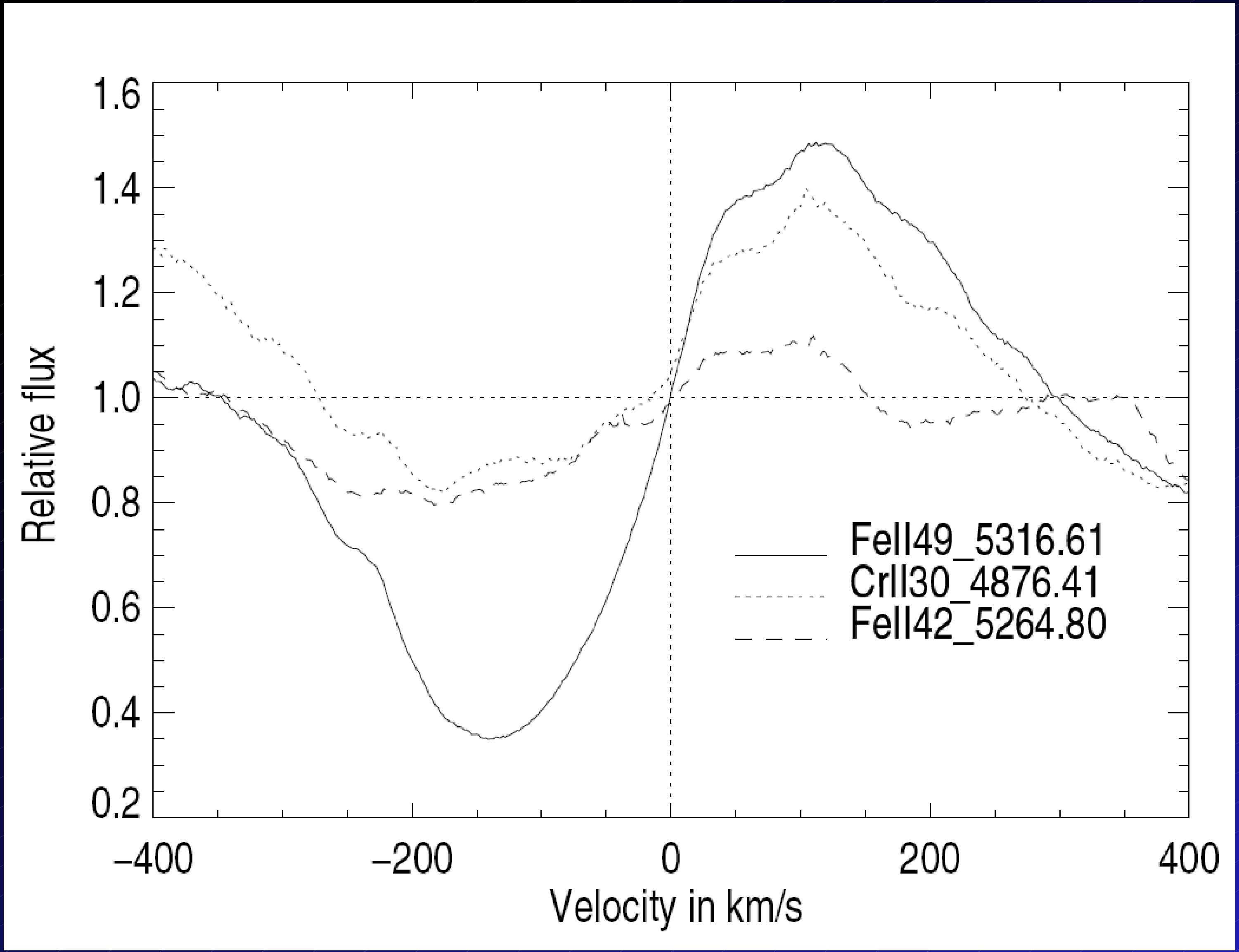
Different physics (shells, shears, winds)

Asymetry – how to handle ?





Different Lines overploted
RV scale

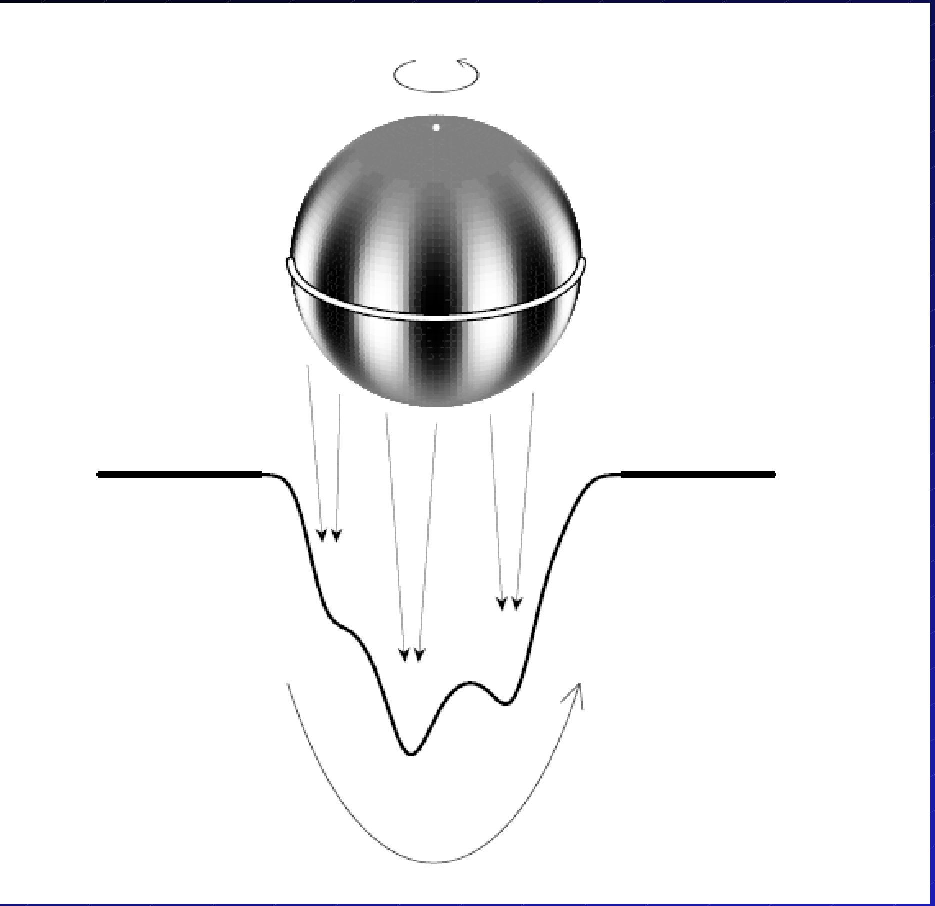


V838 Mon: Kipper et al. 2004

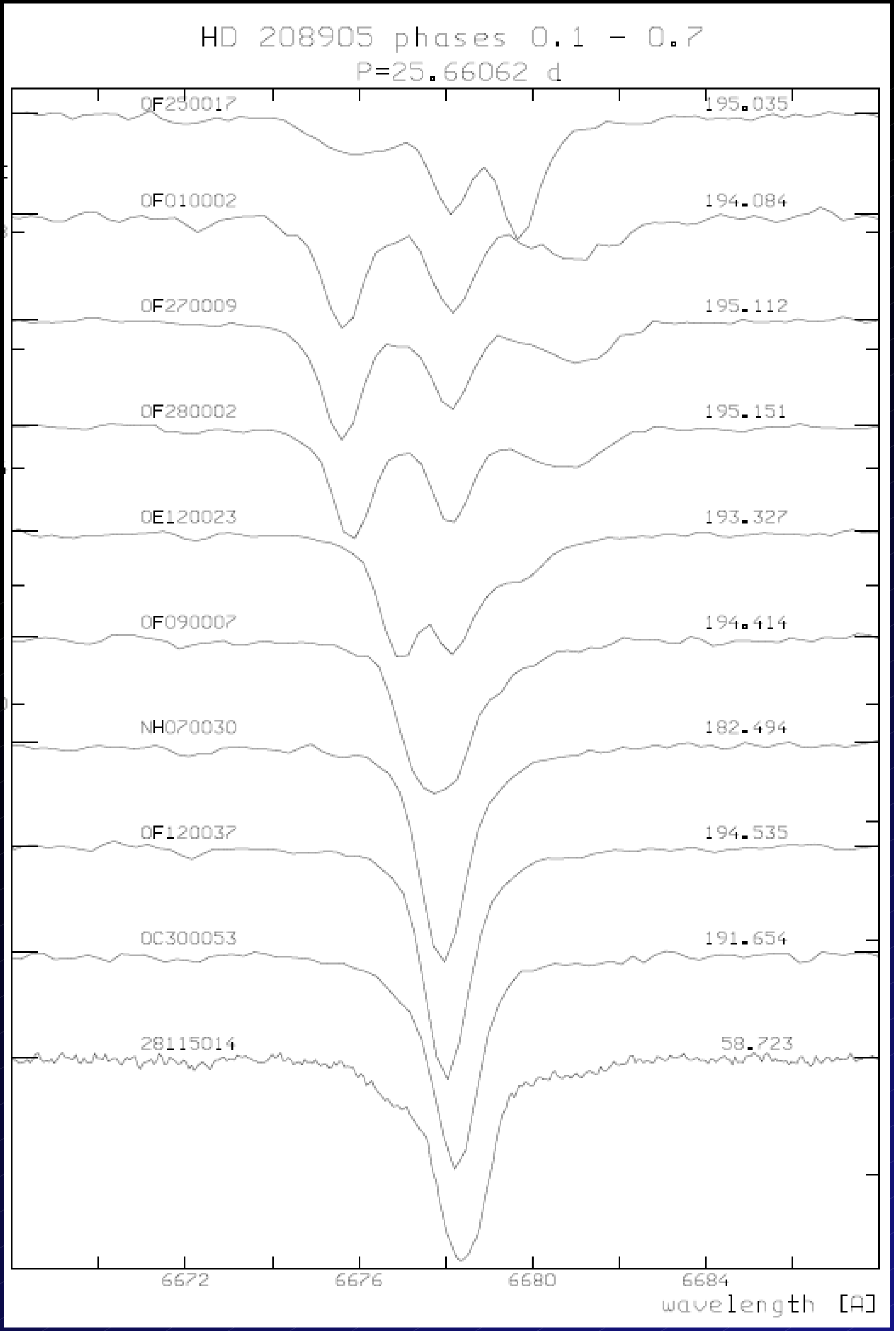
Doppler Imaging - Bumps

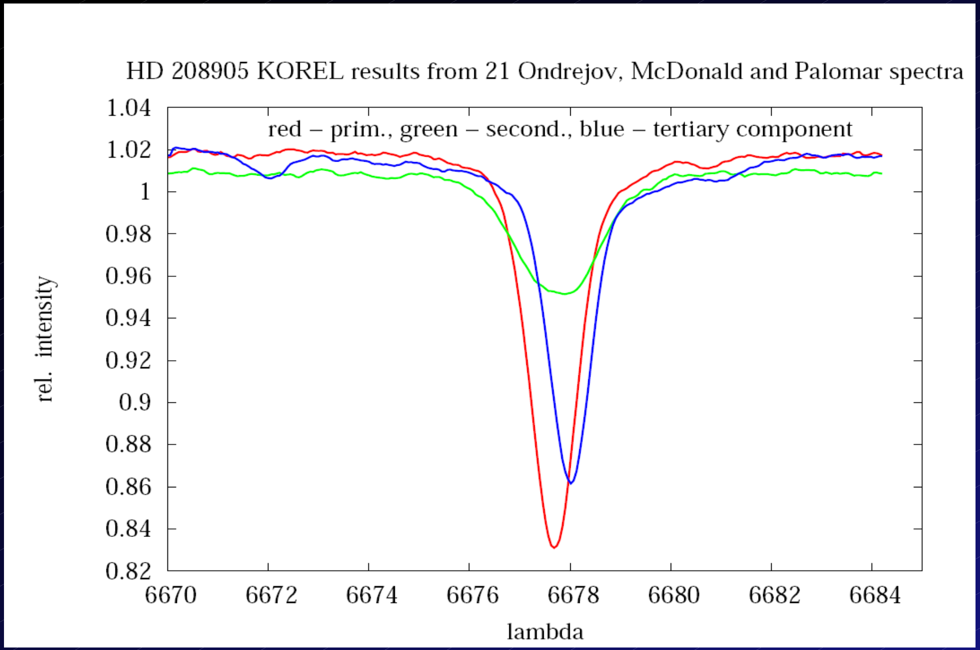
Vogt & Penrod -80s
Zet Oph
Ball VOGT

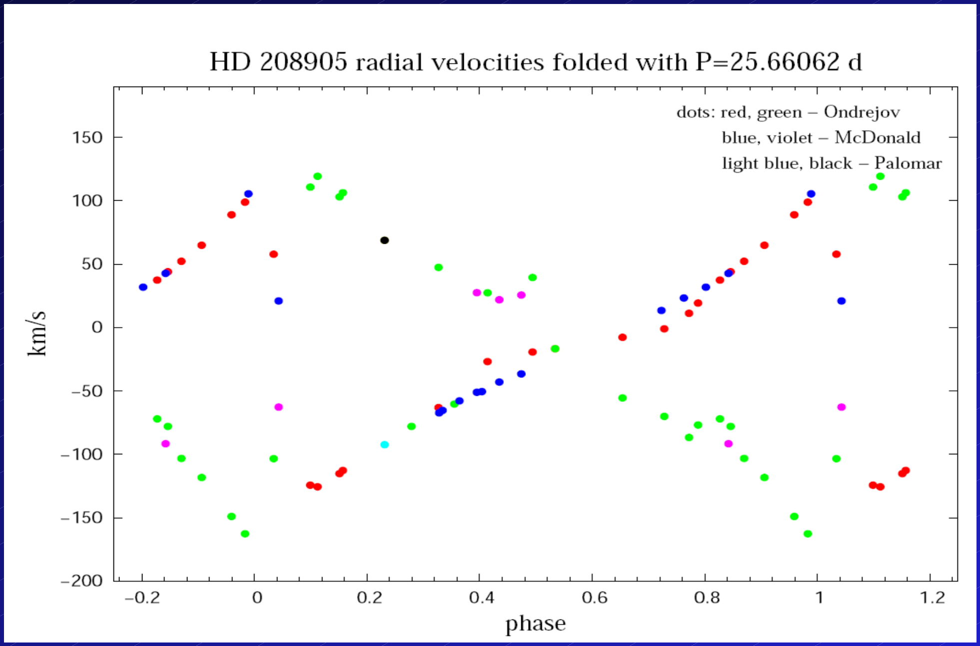
- Requires high SNR
  - (>300-500)
  - Perfect rotation coverage
  - Artefacts otherwise
  - NRP or solar spots
- Doppler Tomography
  - Accretion jets in Algols
  - Orbits in RV phase space



Spectra Disentangling in Fourier Space - KOREL

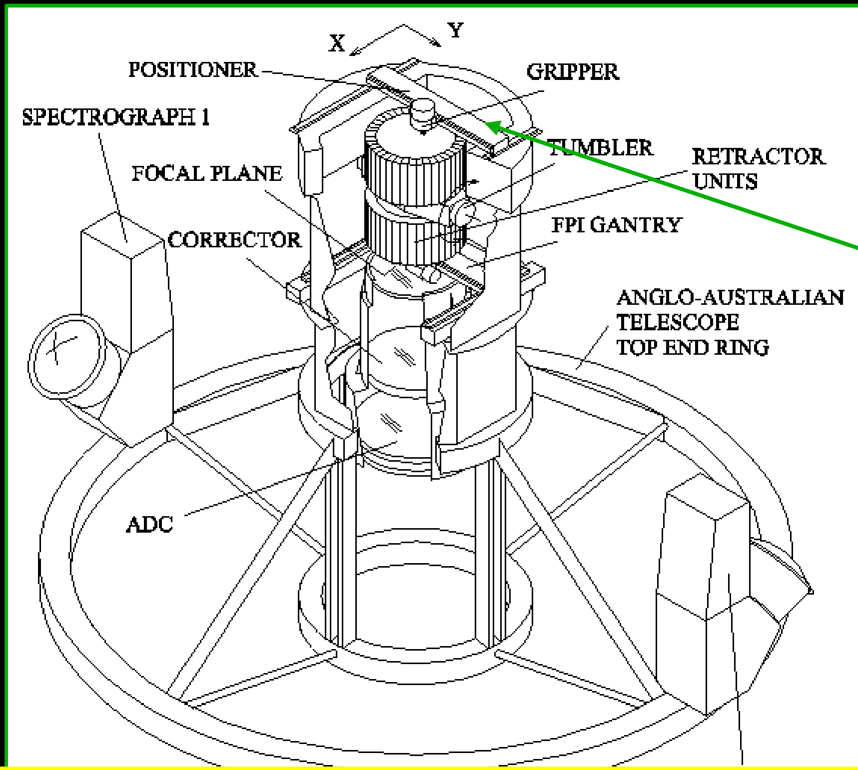


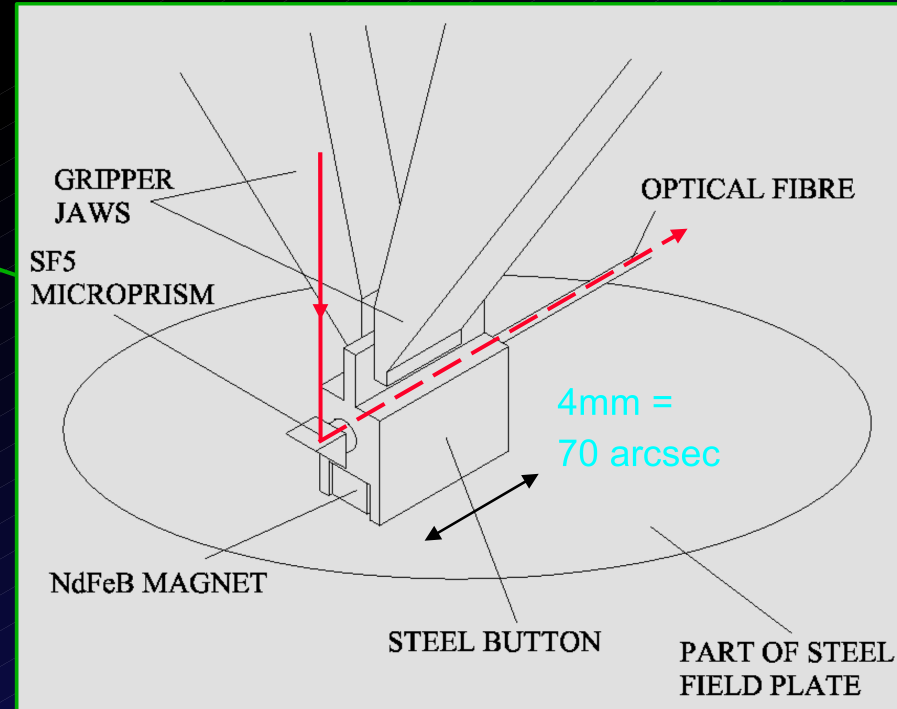


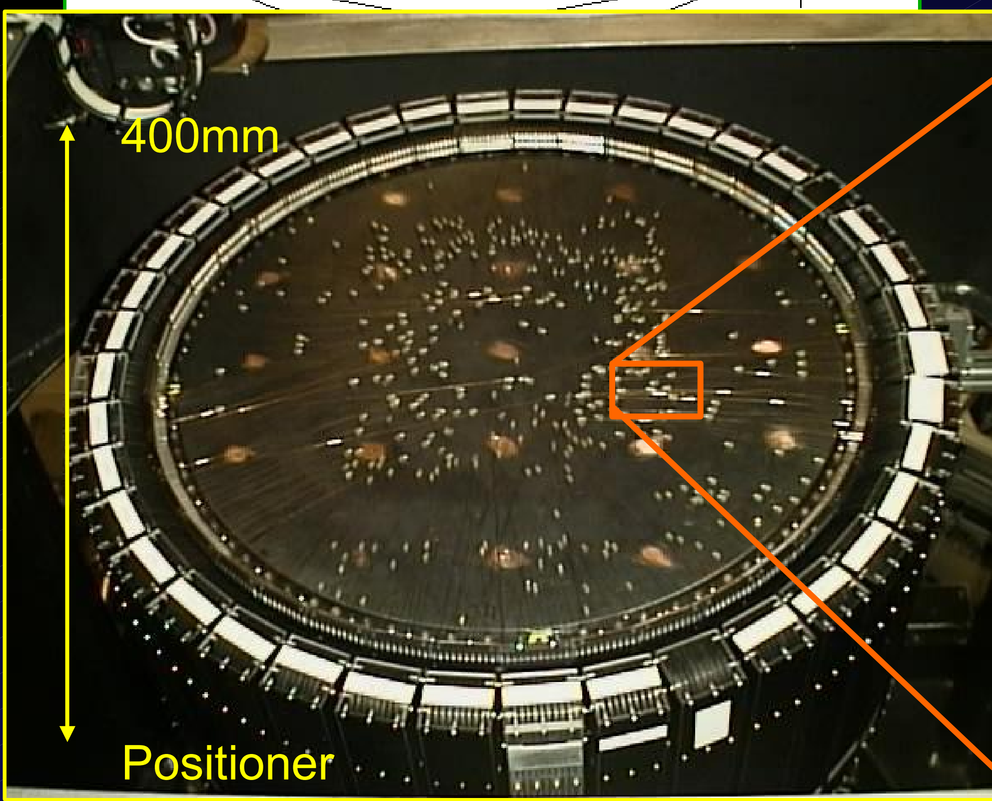


HD208905: Koubsky et al. 2006

2dF

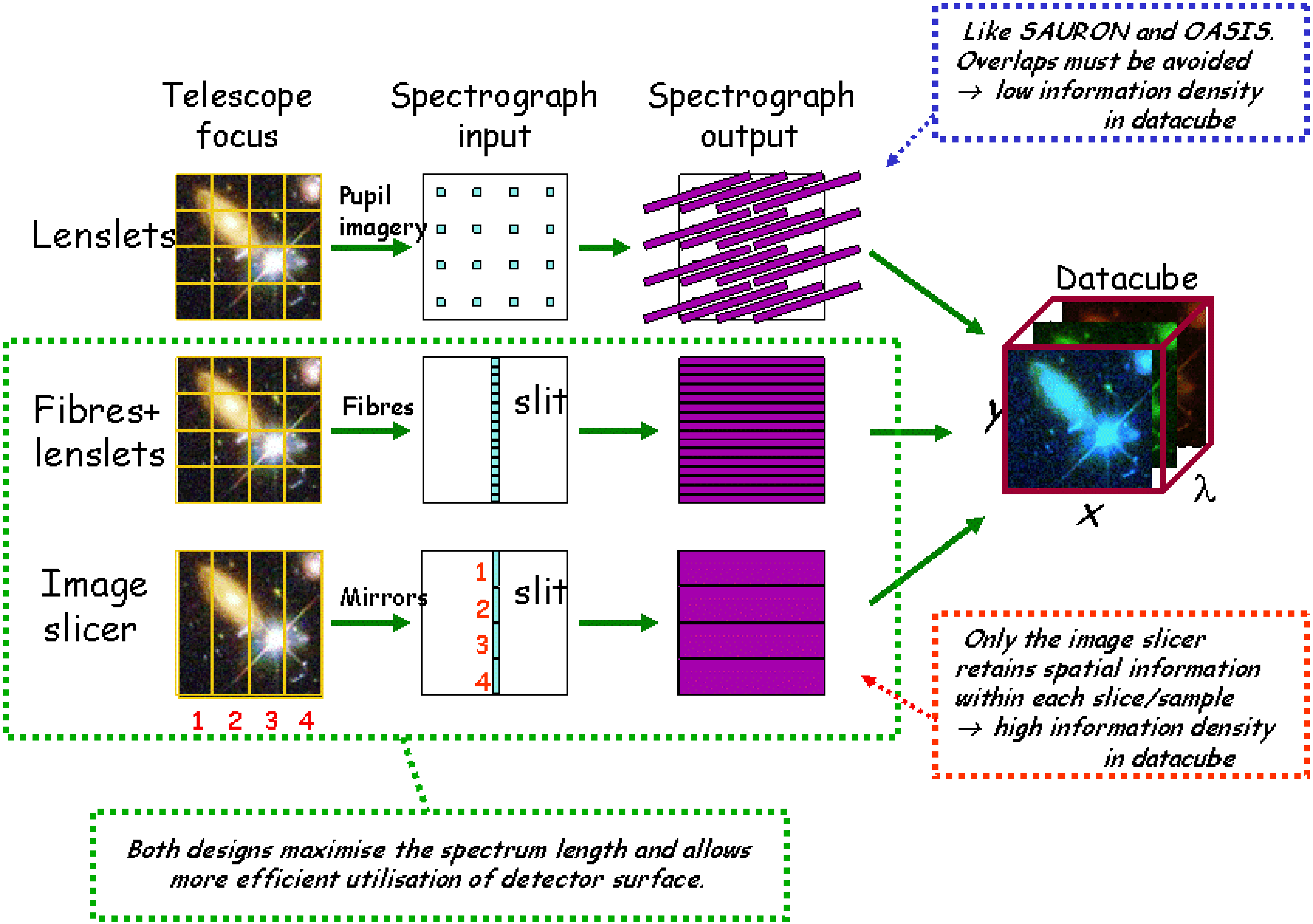

X
Y
POSITIONER
GRIPPER
SPECTROGRAPH 1
TUMBLER
RETRACTOR
UNITS
FOCAL PLANE
FPI GANTRY
CORRECTOR
ANGLO-AUSTRALIAN
TELESCOPE
TOP END RING
ADC


GRIPPER
JAWS
OPTICAL FIBRE
SF5
MICROPRISM
4mm =
70 arcsec
NdFeB MAGNET
STEEL BUTTON
PART OF STEEL
FIELD PLATE

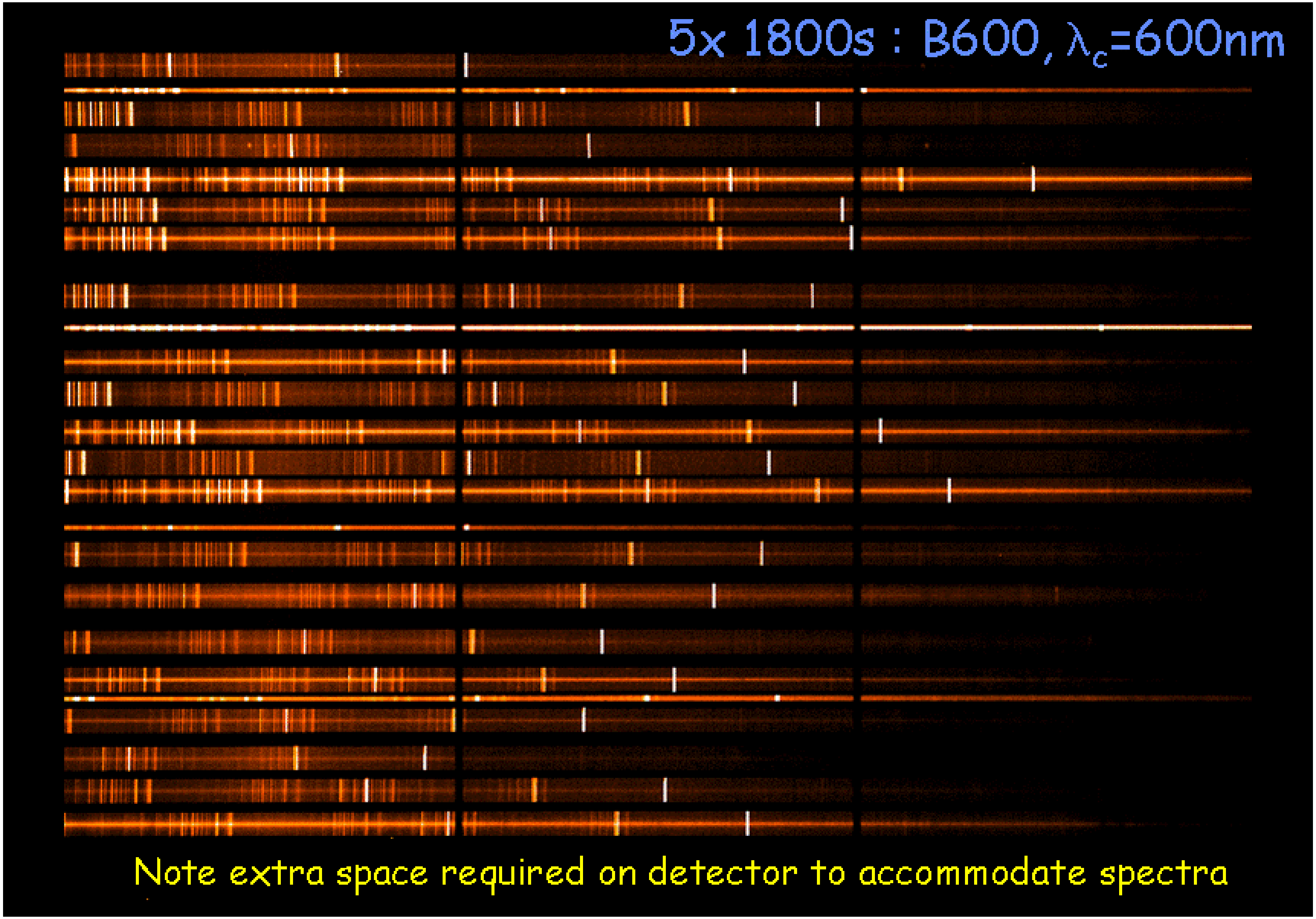

400mm
Positioner


1999/5/22

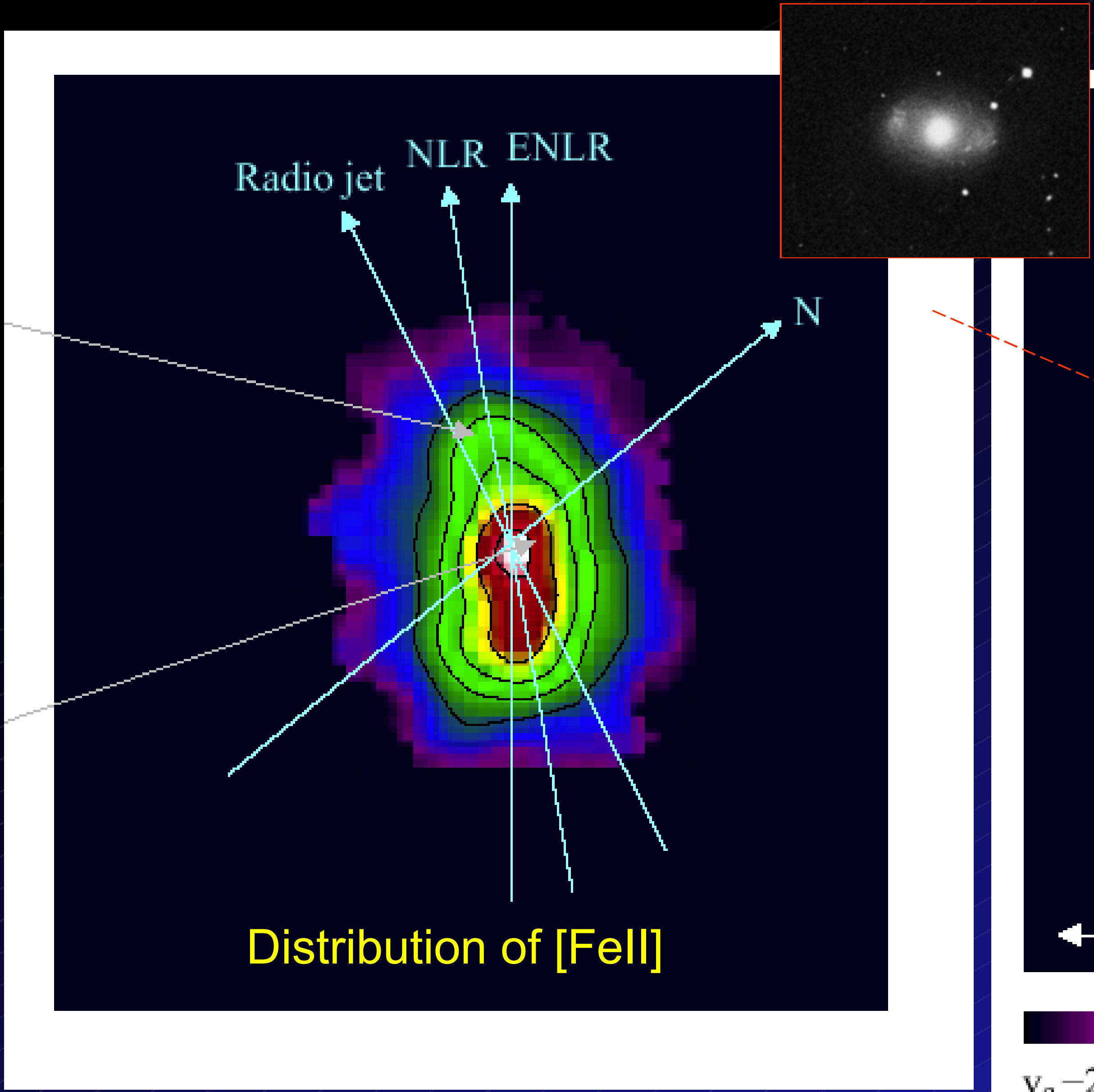
Techniques of *IFS*

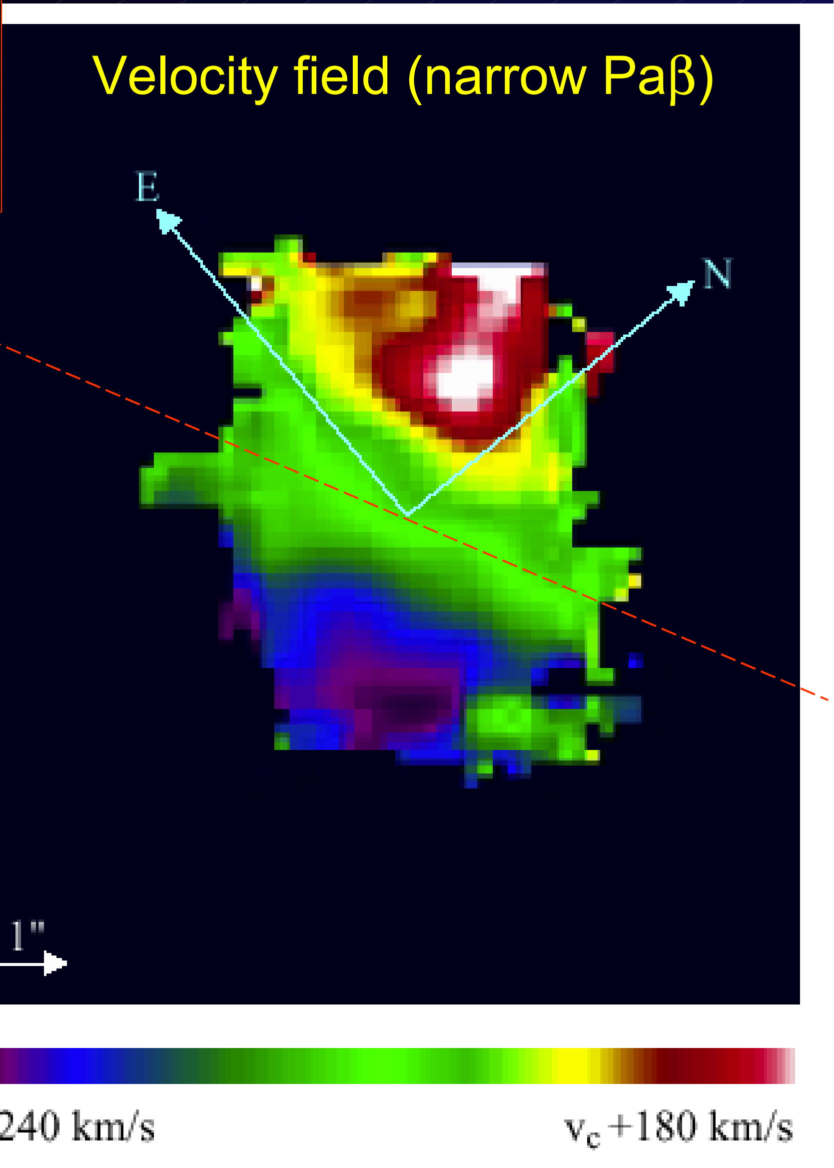


GMOS multislit example



Dissecting active galaxies

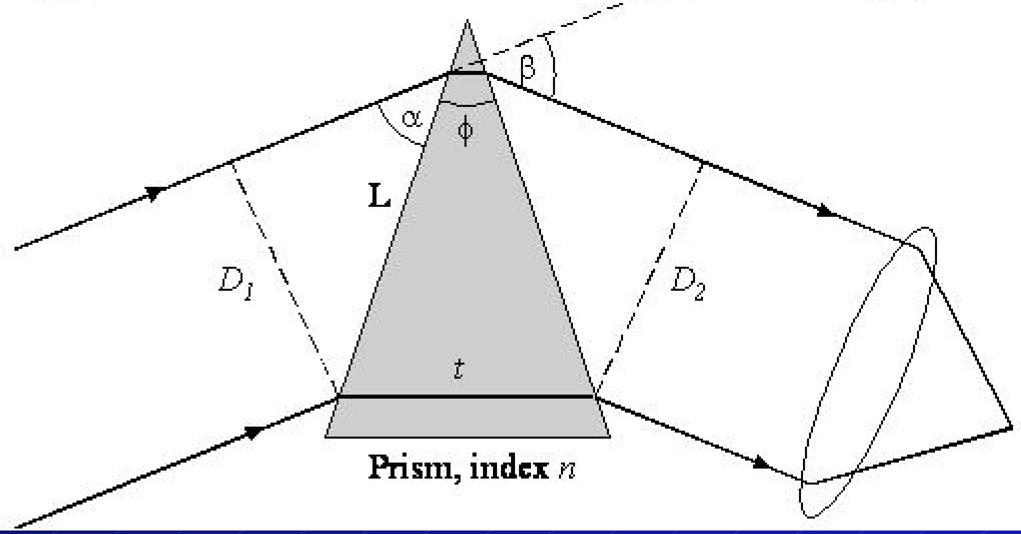




NGC4151 observed with SMIRFS-IFU in J-band - Turner *et al.* MNRAS 331, 284 (2002)

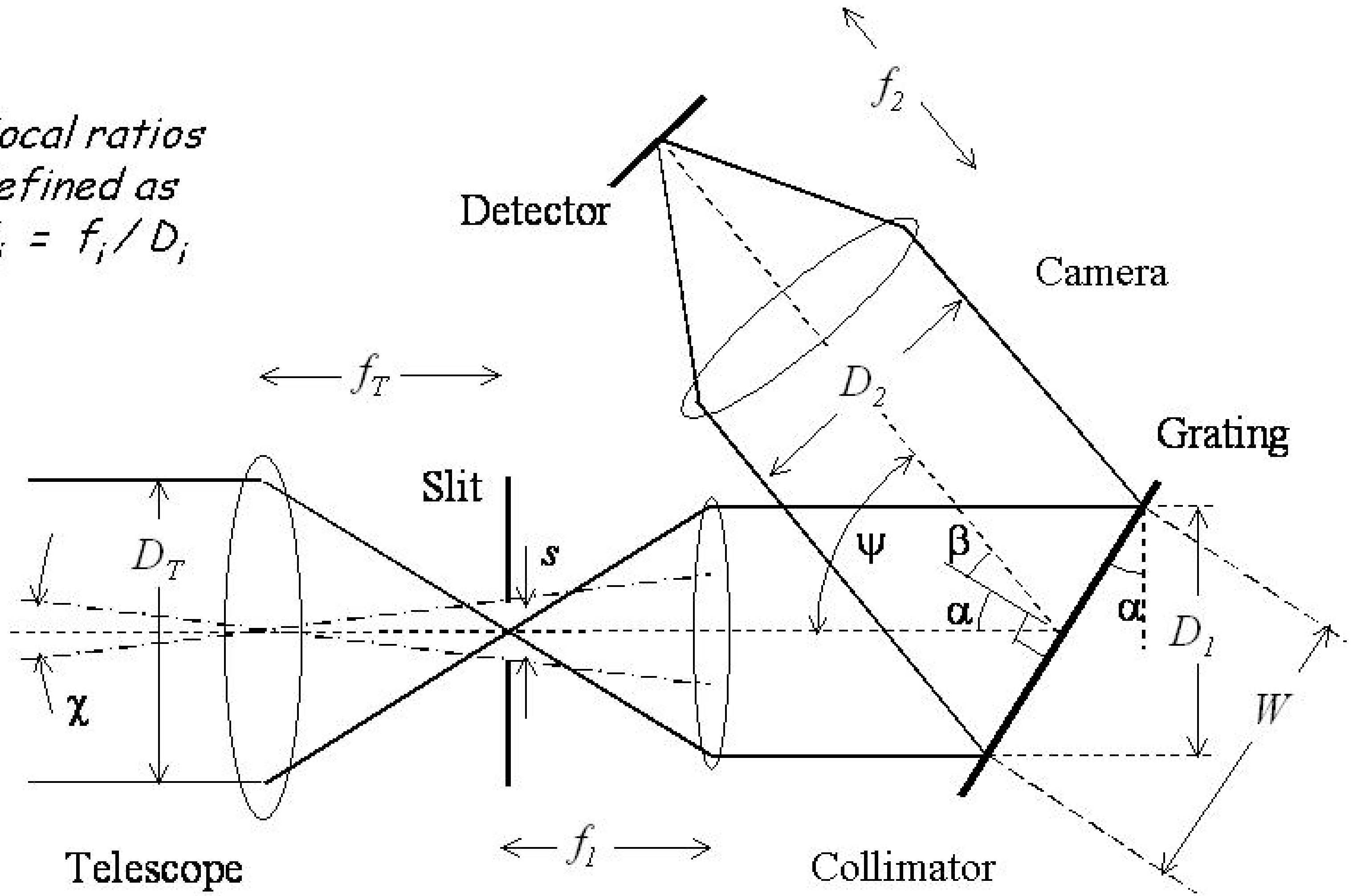
Prisms

- Useful where only low resolving power is required
- Advantages:
  - simple - no rulings! (but glass must be of high quality)
  - multiple-order overlap not a problem - only one order!
- Disadvantages:
  - high resolving power not possible
  - resolving power/resolution can vary strongly with λ

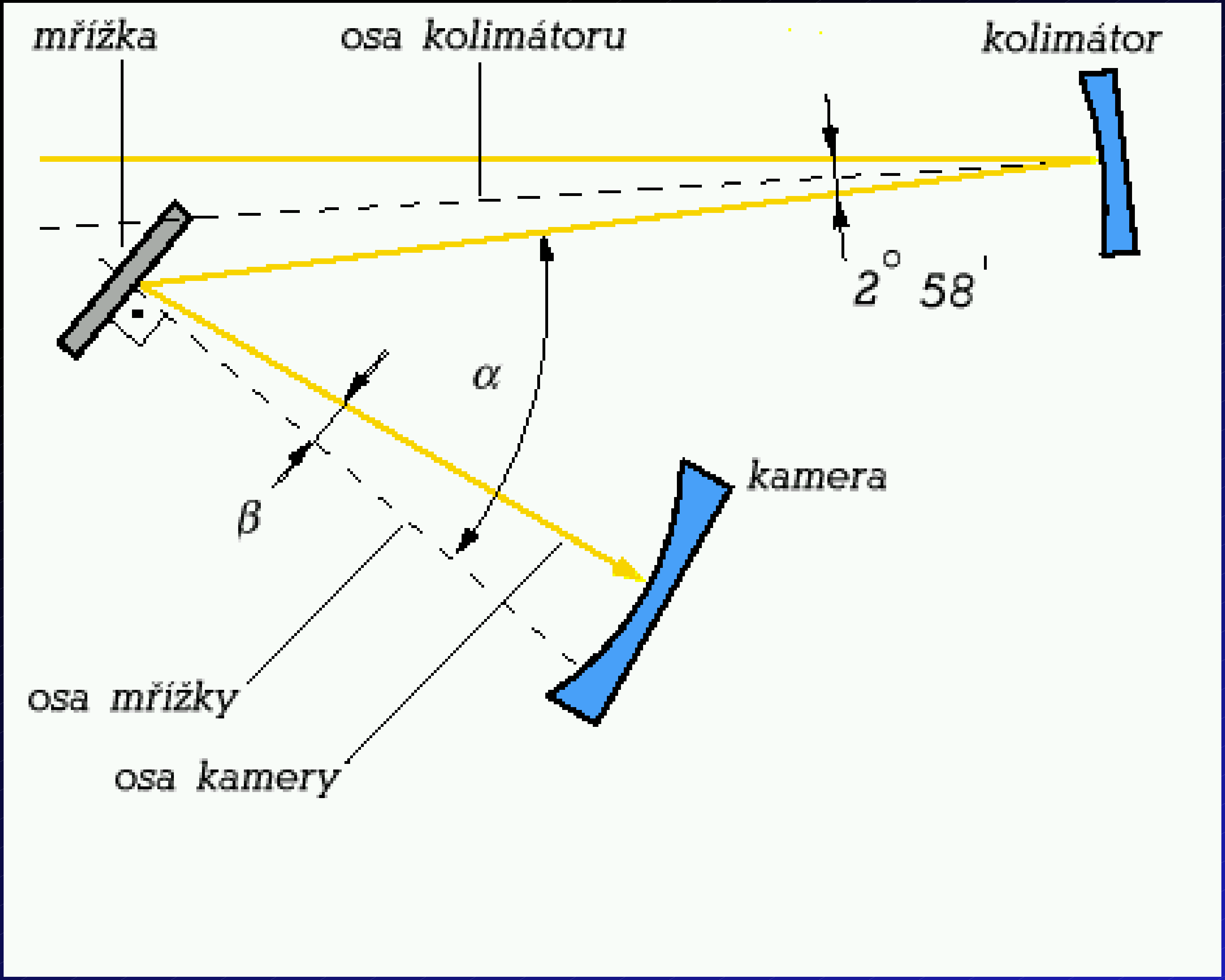


Generic spectrograph layout

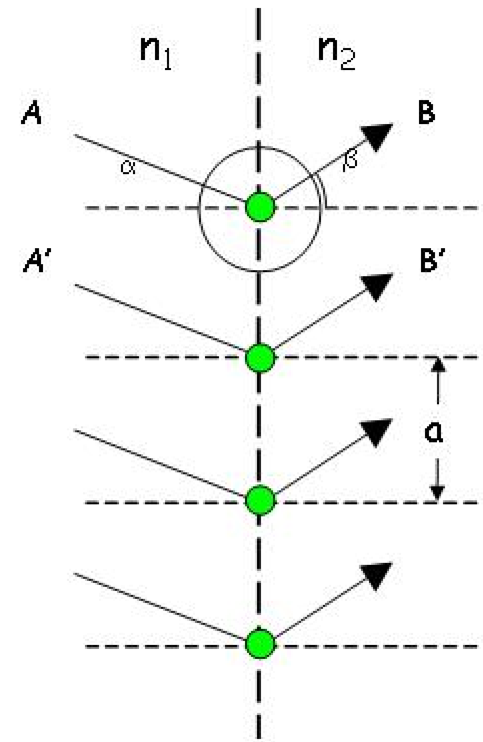
Focal ratios defined as $F_i = f_i / D_i$



Coudé spektrograf 2m v Ondřejově



Grating equation



- Interference condition:

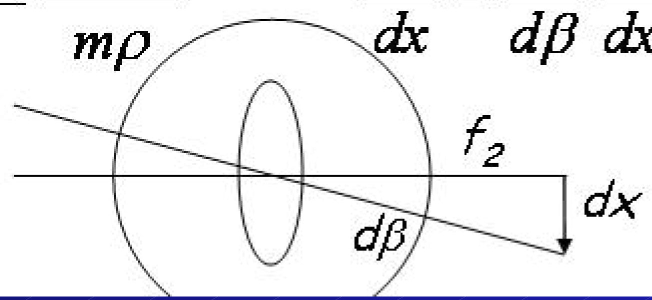
$\Rightarrow$ *path difference between AB and A'B'*

- Grating equation:

$$m\rho\lambda = n_1 \sin\alpha + n_2 \sin\beta \quad \text{where} \quad \rho = \frac{1}{a}$$

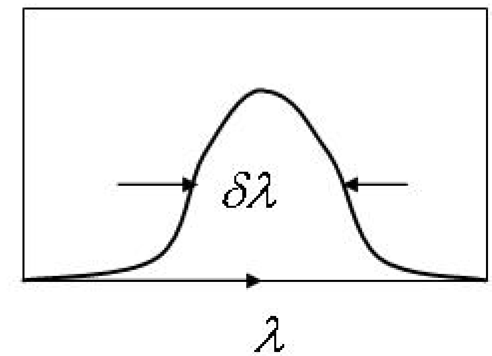
- Dispersion:

$$\frac{d\lambda}{d\beta} = \frac{\cos\beta}{m\rho} \qquad \frac{d\lambda}{dx} = \frac{d\lambda}{d\beta}\frac{d\beta}{dx} = \frac{\cos\beta}{m\rho f_2}$$



"Spectral resolution"

- Terminology (sometimes vague!)
  - Wavelength resolution $\delta\lambda$
  - Resolving power $R = \lambda/\delta\lambda$
- Classically, *in the diffraction limit,*



Resolving power = total number of rulings
× spectral order

I.e. $R^{*} = m\rho W$ ← Total grating length

- But in most practical cases for astronomy (χ < λ/D_T), the resolving power is determined by the width of the slit, so $R < R^{*}$

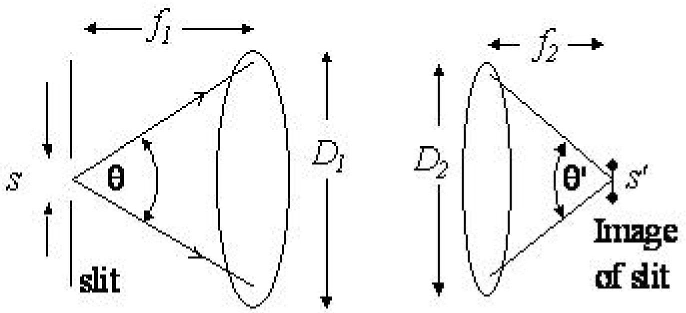
Spectral resolution

- Spectral resolution: $\delta\lambda = \left(\frac{d\lambda}{dx}\right)s' = \frac{\cos\beta}{m\rho f_2} s'$

Image of slit on detector

- Projected slit width:

Conservation of Etendue $(nA\Omega)$



$$\Rightarrow \quad \theta s = \theta' s' \quad \Rightarrow \quad s' = s\frac{\theta}{\theta'} = s\frac{F_2}{F_1}$$

$$\Rightarrow \quad \delta\lambda = \left(\frac{d\lambda}{dx}\right)s' = \frac{\cos\beta}{m\rho f_2} s \frac{F_2}{F_1} = \frac{sD_1\cos\beta}{m\rho D_2 f_1}$$

Camera focal length

Resolving power

- Illuminated grating length: $W = \dfrac{D_2}{\cos\beta}$
- Spectral resolution (width) $\delta\lambda = \dfrac{s}{m\rho F_1 W}$
- Resolving power:
  - expressed in laboratory terms $R \equiv \dfrac{\lambda}{\delta\lambda} = \dfrac{m\rho\lambda F_1 W}{s}$
  - expressed in astronomical terms $R = \dfrac{m\rho\lambda W}{\chi D_T}$

Collimator focal ratio

Physical slitwidth

Grating length

Angular slitwidth

Telescope size

since $s = \chi f_T$ and $\dfrac{f_T}{D_T} = \dfrac{f_1}{D_1} = F_T = F_1$

Size of spectrograph must scale with telescope size

Importance of slit width

- Width of slit determines:
  - Resolving power *(R)* since $R\chi = constant$
  - Throughput (η)
- Hence there is always a tradeoff between *throughput* and *spectral information*
- Function $\eta(\chi)$ depends on *Point Spread Function* (PSF) and profile of extended source
  - generally $\eta(\chi)$ increases slower than χ^{+1} whereas $R \propto \chi^{-1}$
    so ηR *maximised at small* χ
- Signal/noise also depends on slit width
  - throughput ($\rightarrow$ signal)
  - wider slit admits more sky background ($\rightarrow$ noise)

Blazing

- Diffracted intensity:

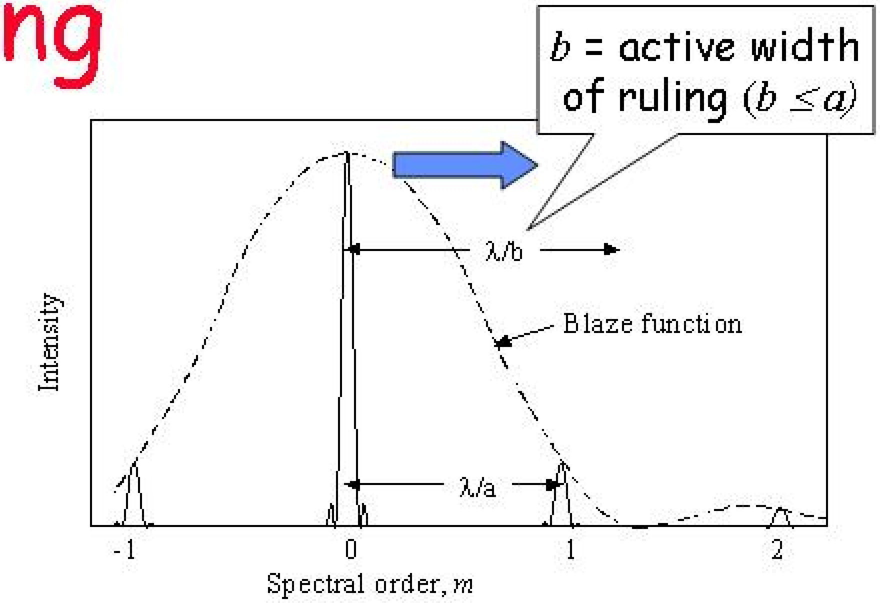
Interference pattern

Single slit diffraction

$$I = \left(\frac{\sin^2 N\phi}{\sin^2 \phi}\right)\left(\frac{\sin^2 \theta}{\theta^2}\right)$$

Φ = *phase difference between adjacent rulings*

θ = *phase difference from centre of one ruling to its edge*



→ Shift envelope peak to $m=1$

- Blaze condition

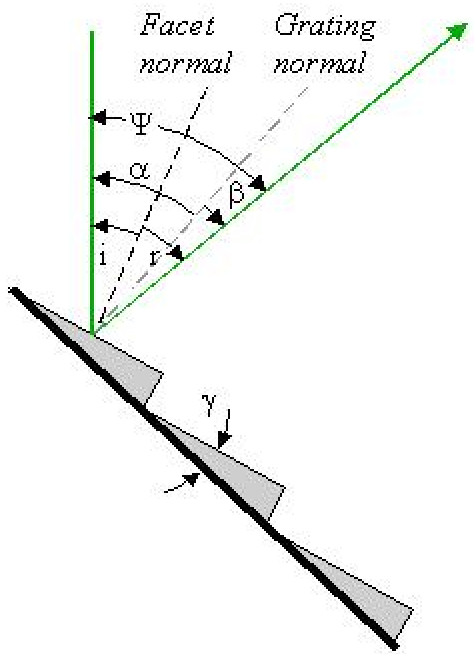
specular reflection off grooves:

$\alpha + \beta = 2\gamma$ also $\Psi = \alpha - \beta$

$$\Rightarrow \quad \rho m \lambda_B = \sin\alpha + \sin\beta = 2\sin\gamma\cos\frac{\Psi}{2}$$

$$\sin x + \sin y = 2\sin\frac{x+y}{2}\cos\frac{x-y}{2}$$

since



Efficiency vs wavelength

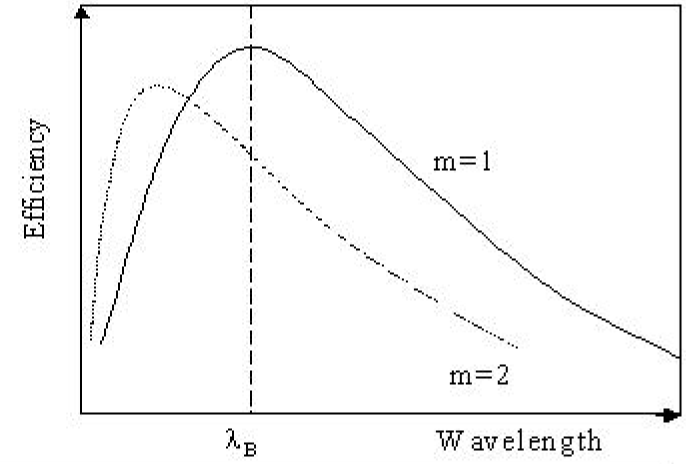
- Approximation valid for $a > \lambda$
- $\lambda_{max}(m) = \lambda_B(m=1)/m$
- Rule-of-thumb:

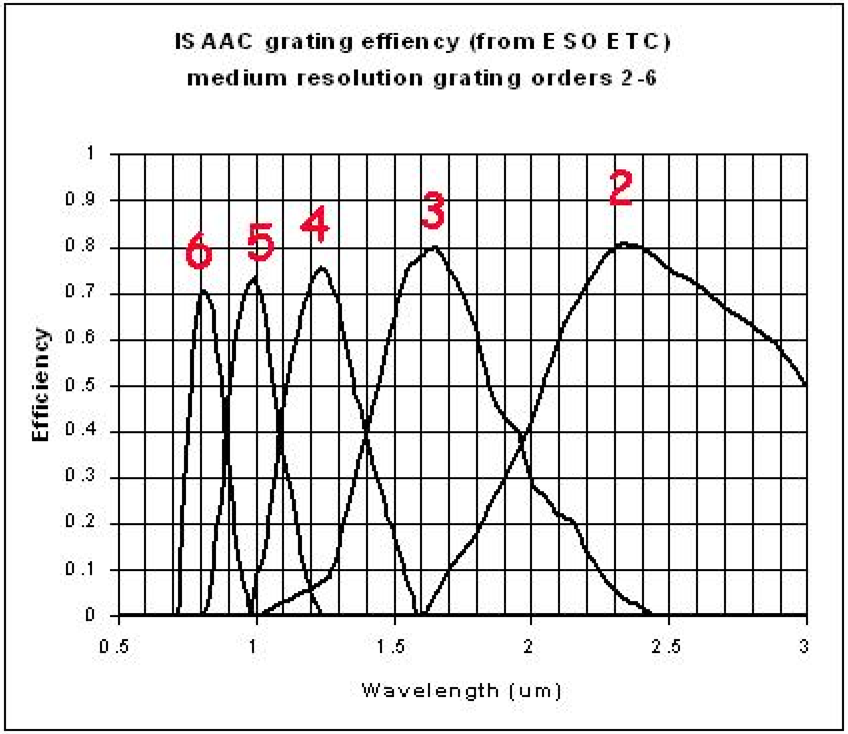
  40.5% x peak at

  $$\lambda_+ = \frac{2m\lambda_B}{2m-1} \text{ and } \lambda_- = \frac{2m\lambda_B}{2m+1}$$

  $$\Rightarrow \quad \lambda_+ - \lambda_- \approx \frac{\lambda_B}{m} \quad \text{(large } m\text{)}$$

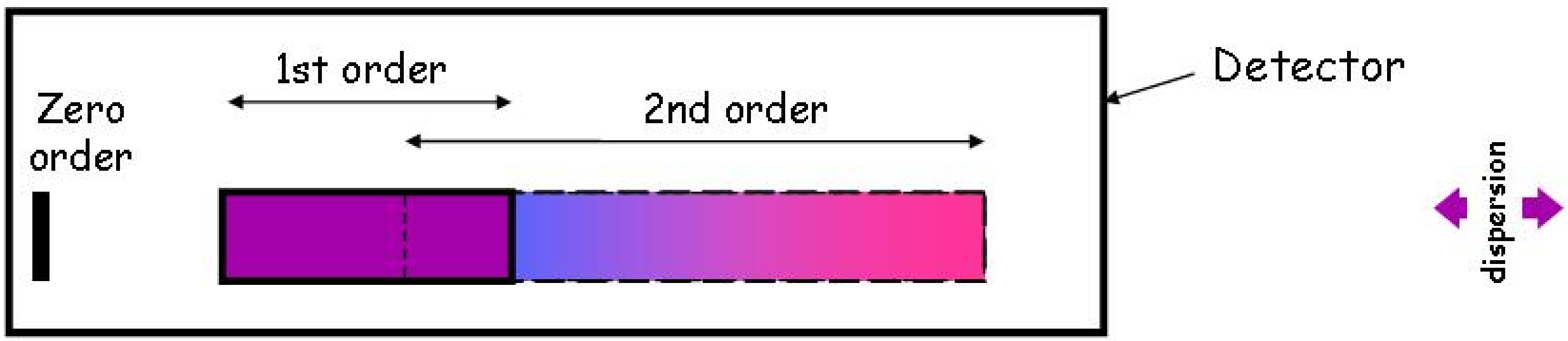
- Sum over all orders < 1
  - reduction in efficiency with increasing order





(See: Schroeder, *Astronomical Optics*)

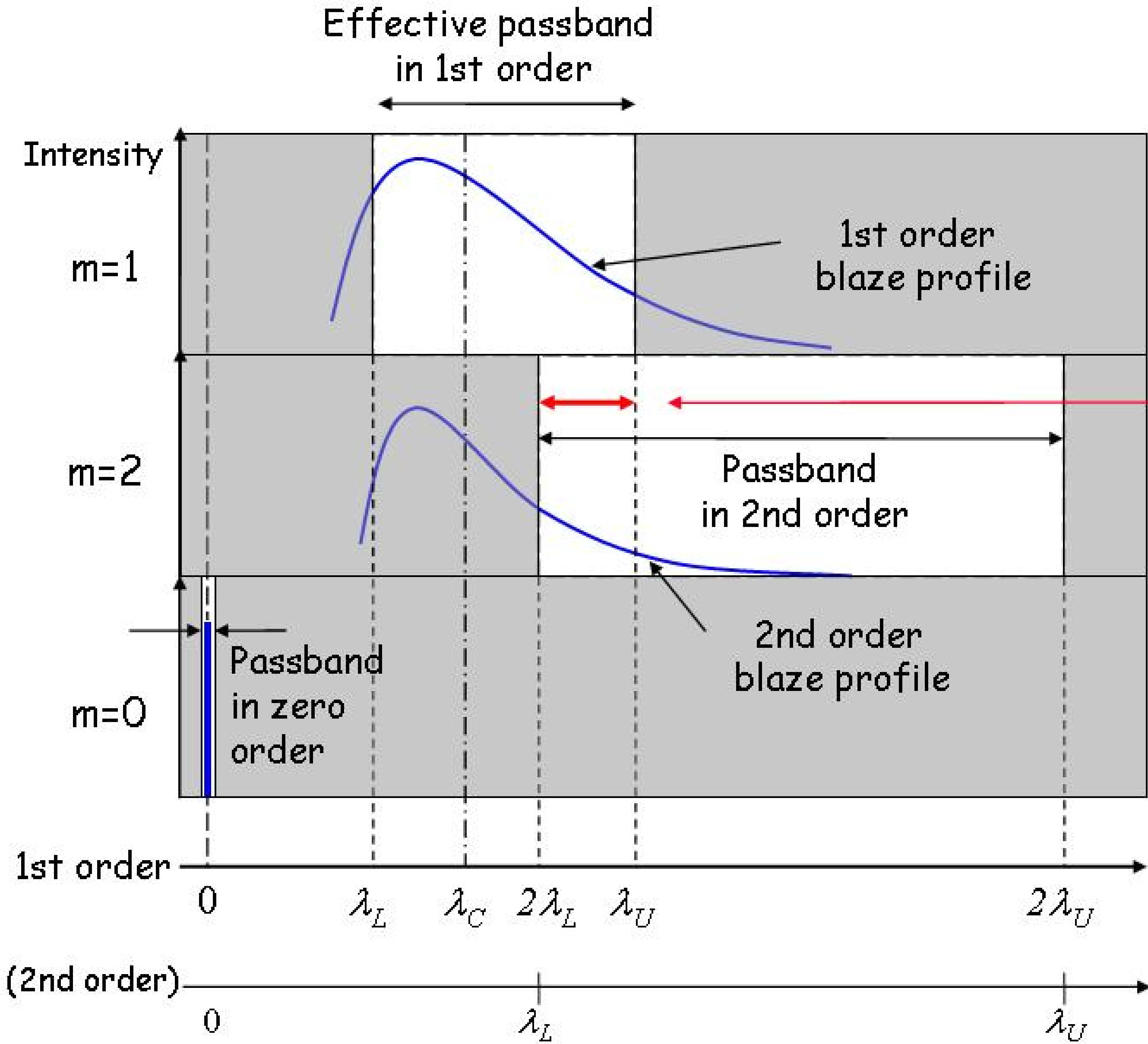
Order overlaps



To eliminate overlap between 1st and 2nd order

- Limit wavelength range incident on detector using *passband* filter or *longpass* ("order rejection") filter acting with long-wavelength cutoff of optics or detector (e.g. 1100nm for CCD)
- Optimum wavelength range is 1 octave (then $2\lambda_L = \lambda_U$)
- *Zero order* may be a problem in multiobject spectroscopy

Order overlaps



Don't forget higher orders!

First and second orders overlap!

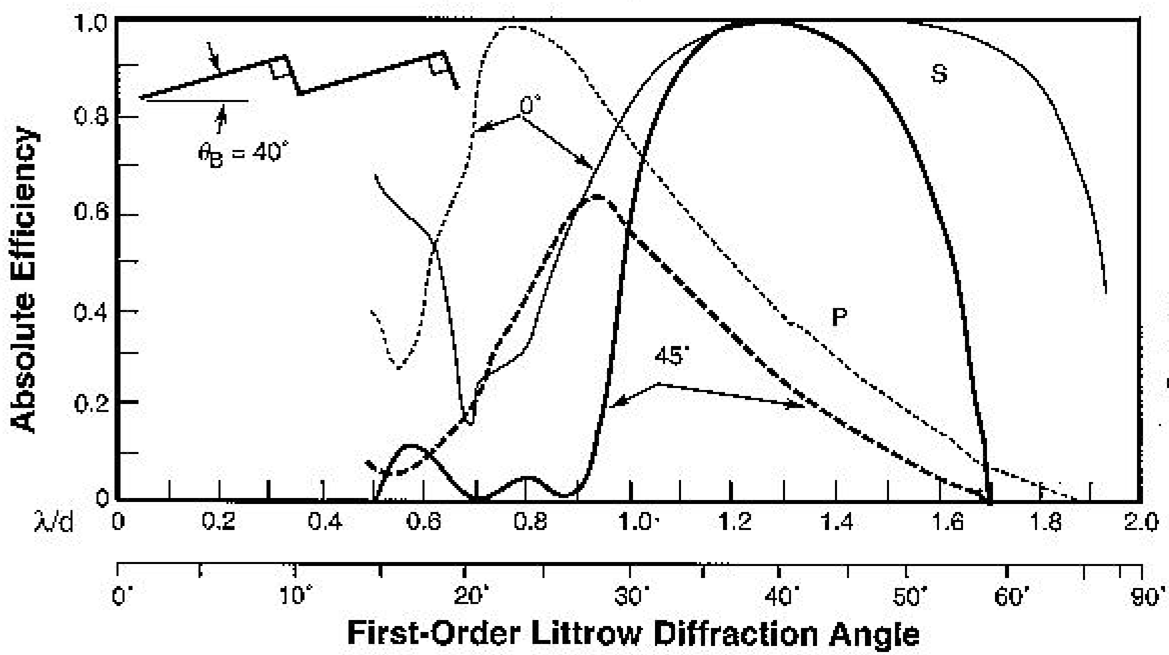
Zero order matters for MOS

Wavelength in first order marking position on detector in dispersion direction (if dispersion ~linear)

Efficiency - semi-empirical (contd)

Different regimes for blazed (triangular) grooves

$\gamma < 5°$	obeys scalar theory, little polarisation effect (P ≈ S)
$5 < \gamma < 10°$	S anomaly at $\rho\lambda \approx 2/3$, P peaks at lower $\rho\lambda$ than S
$10 < \gamma < 18°$	various S anomalies
$18 < \gamma < 22°$	anomalies suppressed, S >> P at large $\rho\lambda$
$22 < \gamma < 38°$	strong S anomaly at P peak, S constant at large $\rho\lambda$
$\gamma > 38°$	S and P peaks very different, efficient in Littrow only



NOTE
Results apply to *Littrow* only

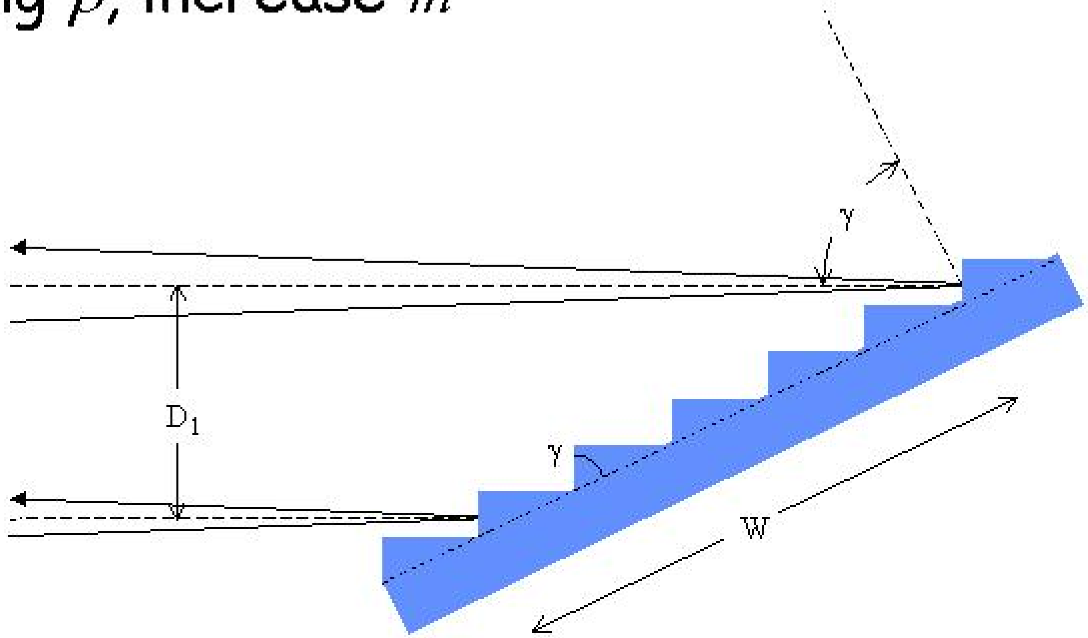
From: *Diffraction Grating Handbook*, C. Palmer, Thermo RGL, *(www.gratinglab.com)*

$\rho\lambda$ →

$\alpha=\beta$ →

Echelle gratings

- Obtain very high R ($> 10^5$) using very long grating
- In Littrow: $R = \frac{m\rho\lambda W}{\chi D_T} = \frac{2D_1}{\chi D_T}\tan\gamma$ ← Groove angle
- Maximising γ requires large $m\rho$ since $m\rho\lambda = 2\sin\gamma$
- Instead of increasing ρ, increase m
- *Echelle* is a coarse grating with large groove angle
- R parameter = $\tan\gamma$ (e.g R2 $\Rightarrow \gamma = 63.5$)



Multiple orders

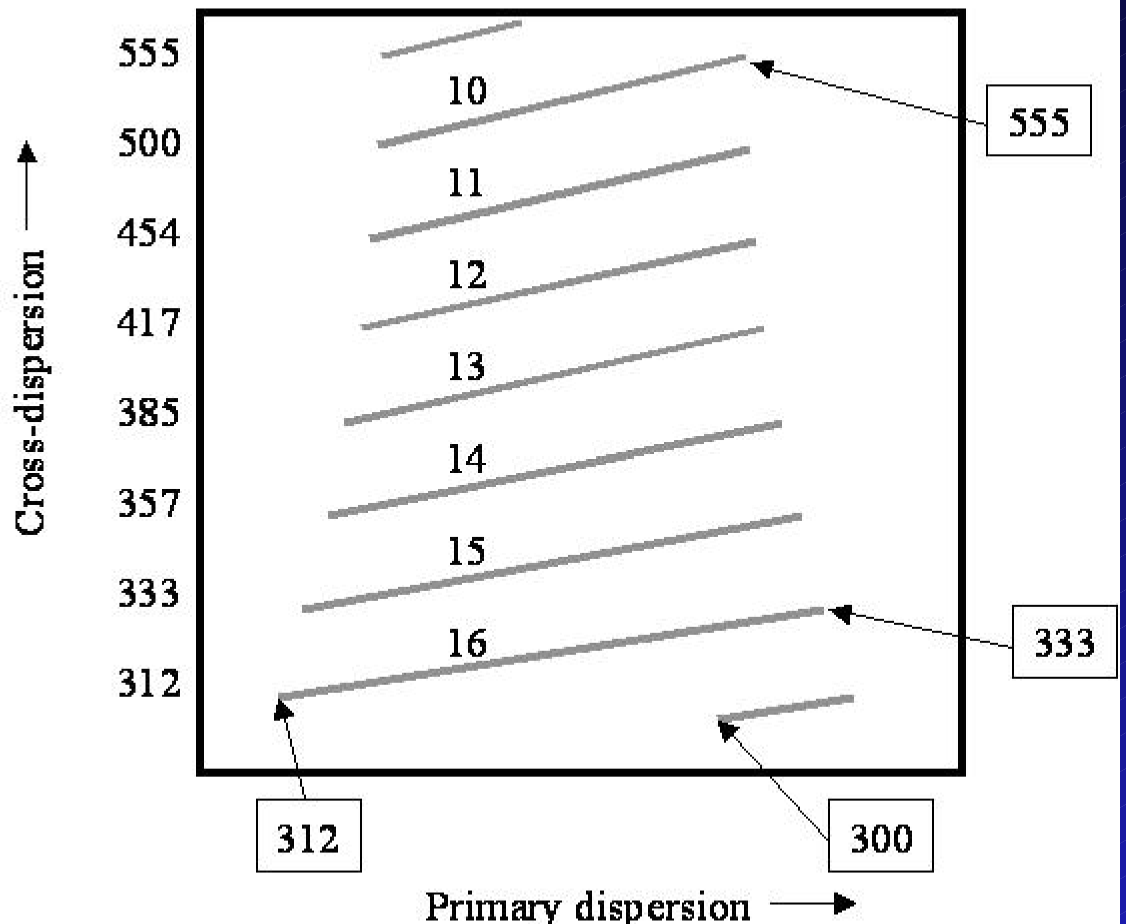
- Many orders to cover desired $\lambda\lambda$: *Free spectral range*

$\Delta\lambda = \lambda / m$

- Orders lie on top of each other:

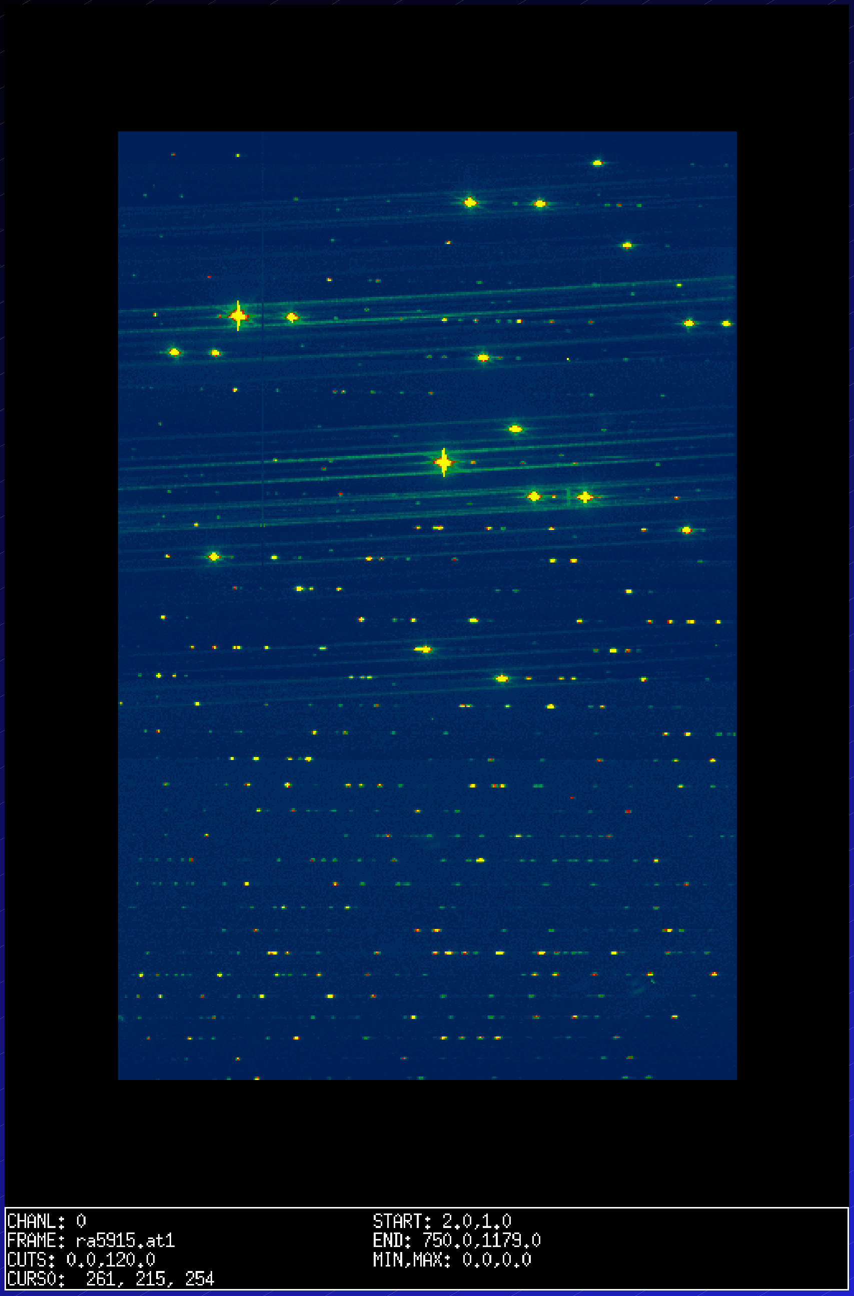
$\lambda(m) = \lambda(n) \times (n/m)$

- Solution:
  - use narrow passband filter to isolate one order at a time
  - cross-disperse to fill detector with many orders at once

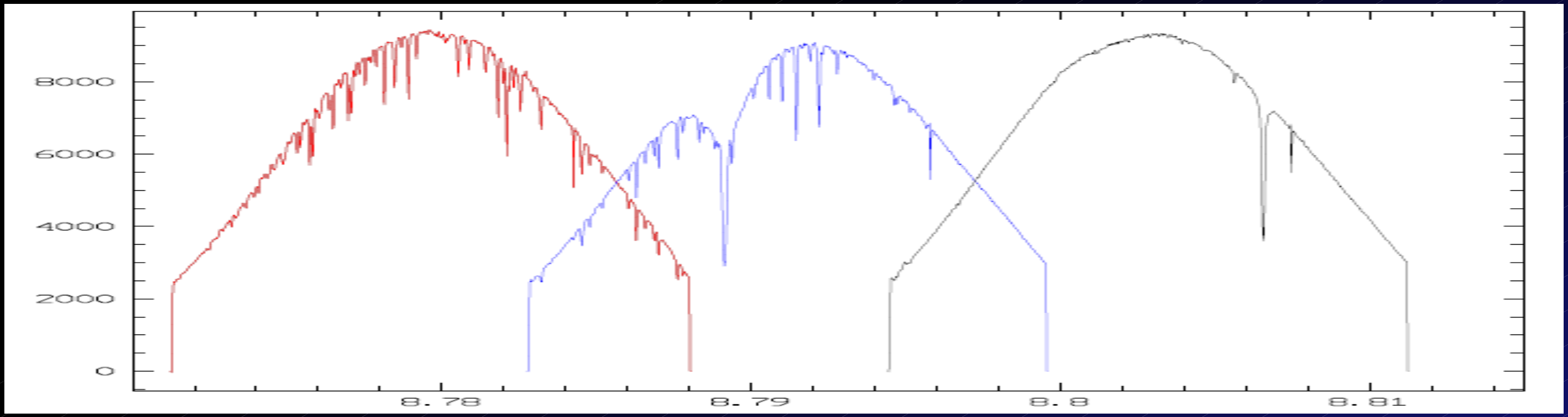


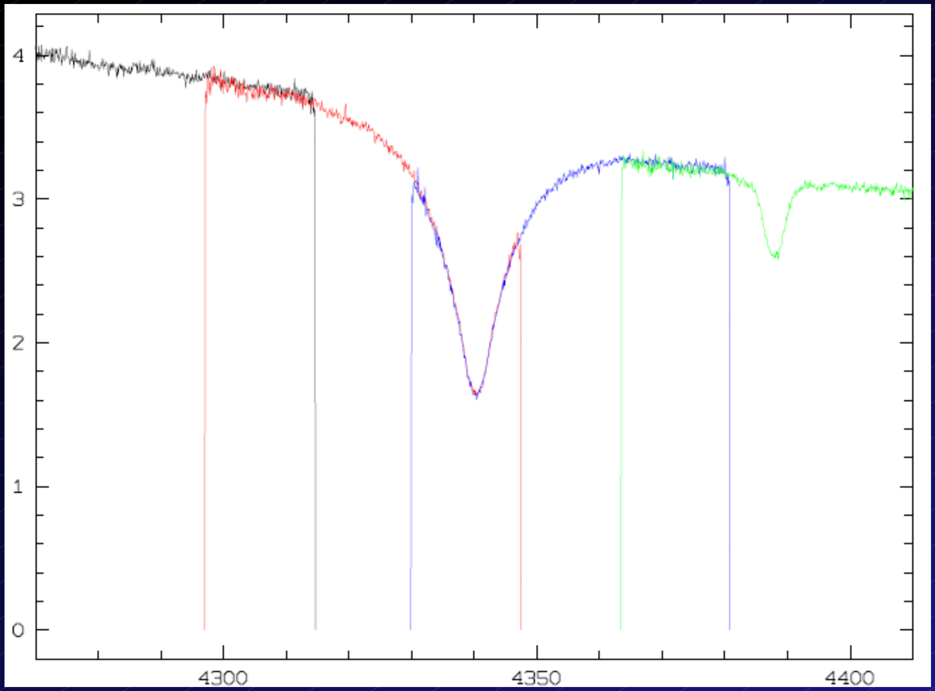
Cross dispersion may use prisms or low dispersion grating

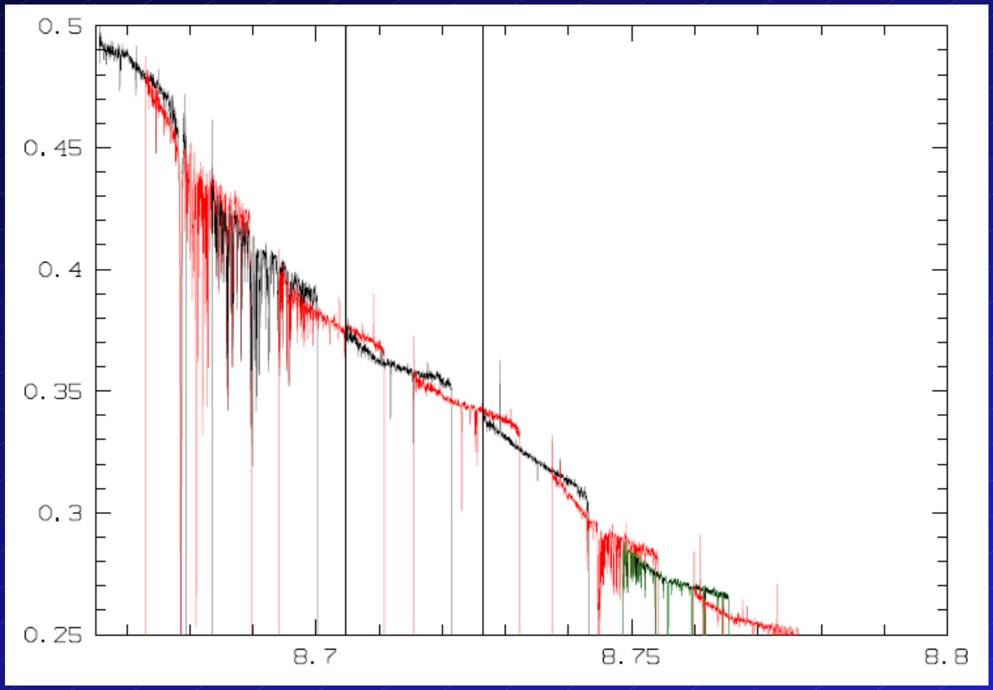

CHANL: 0
FRAME: ra5921.at1
CUTS: 0.0,1700.0
CURSO: 261, 215, 254
START: 2.0,1.0
END: 750.0,1179.0
MIN,MAX: 0.0,0.0


CHANL: 0
FRAME: ra5915.at1
CUTS: 0.0,120.0
CURSO: 261, 215, 254
START: 2.0,1.0
END: 750.0,1179.0
MIN,MAX: 0.0,0.0

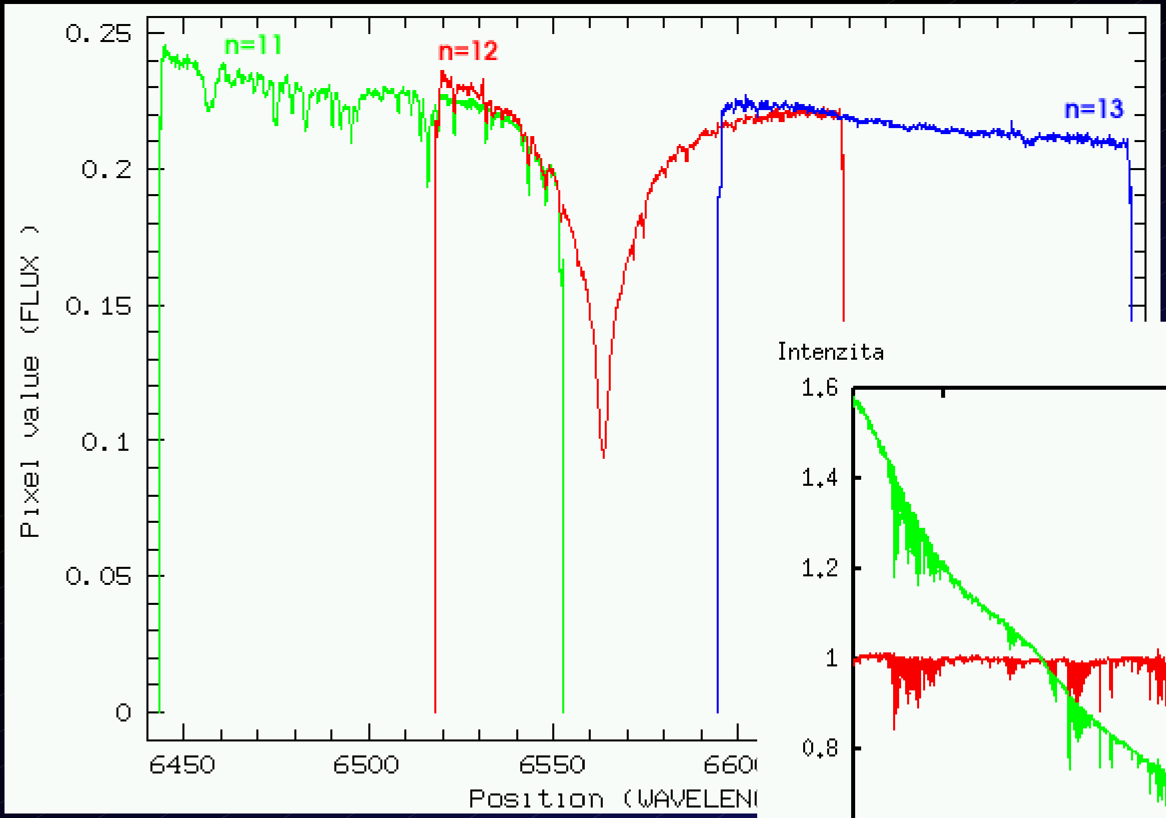
Echelle Spectra Problems

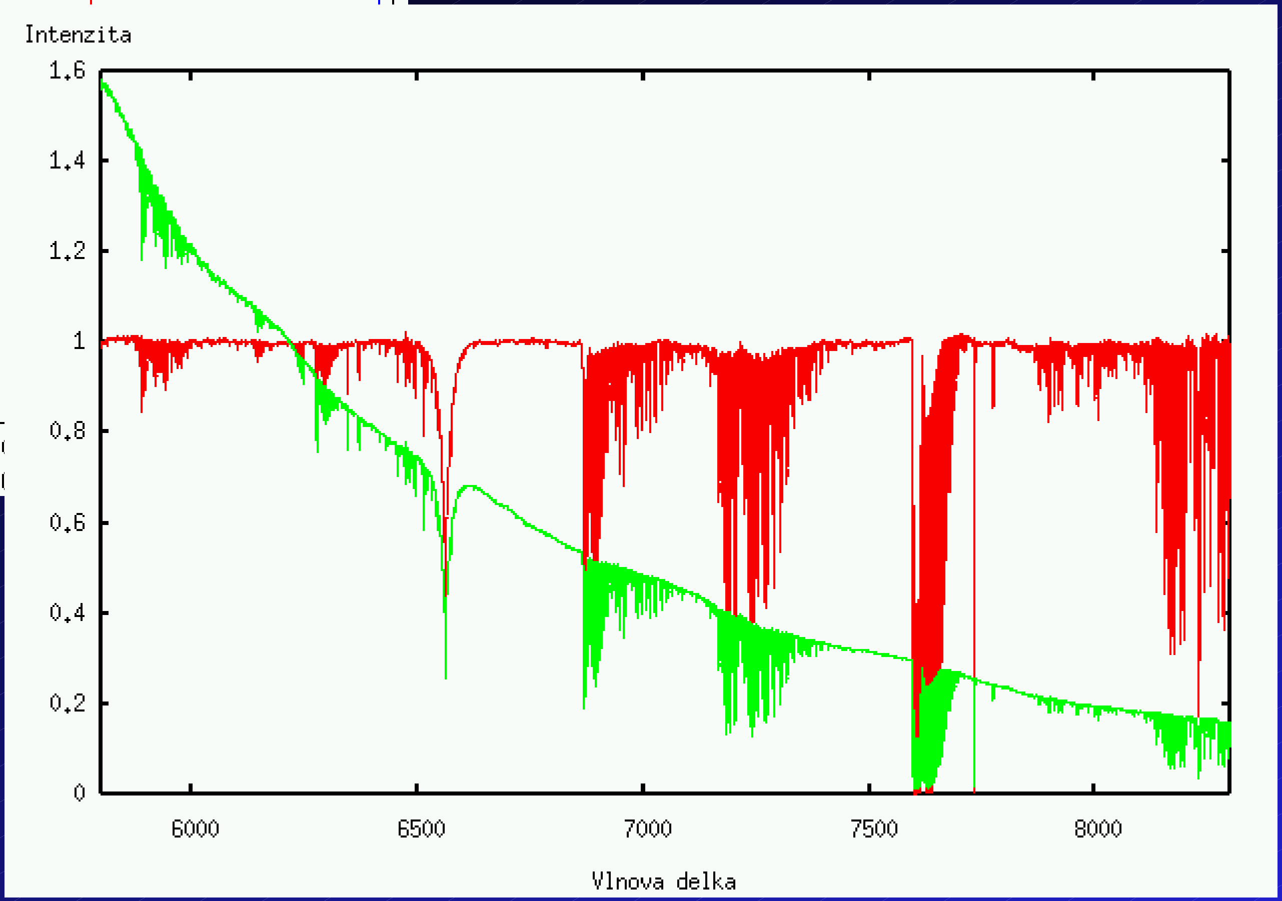




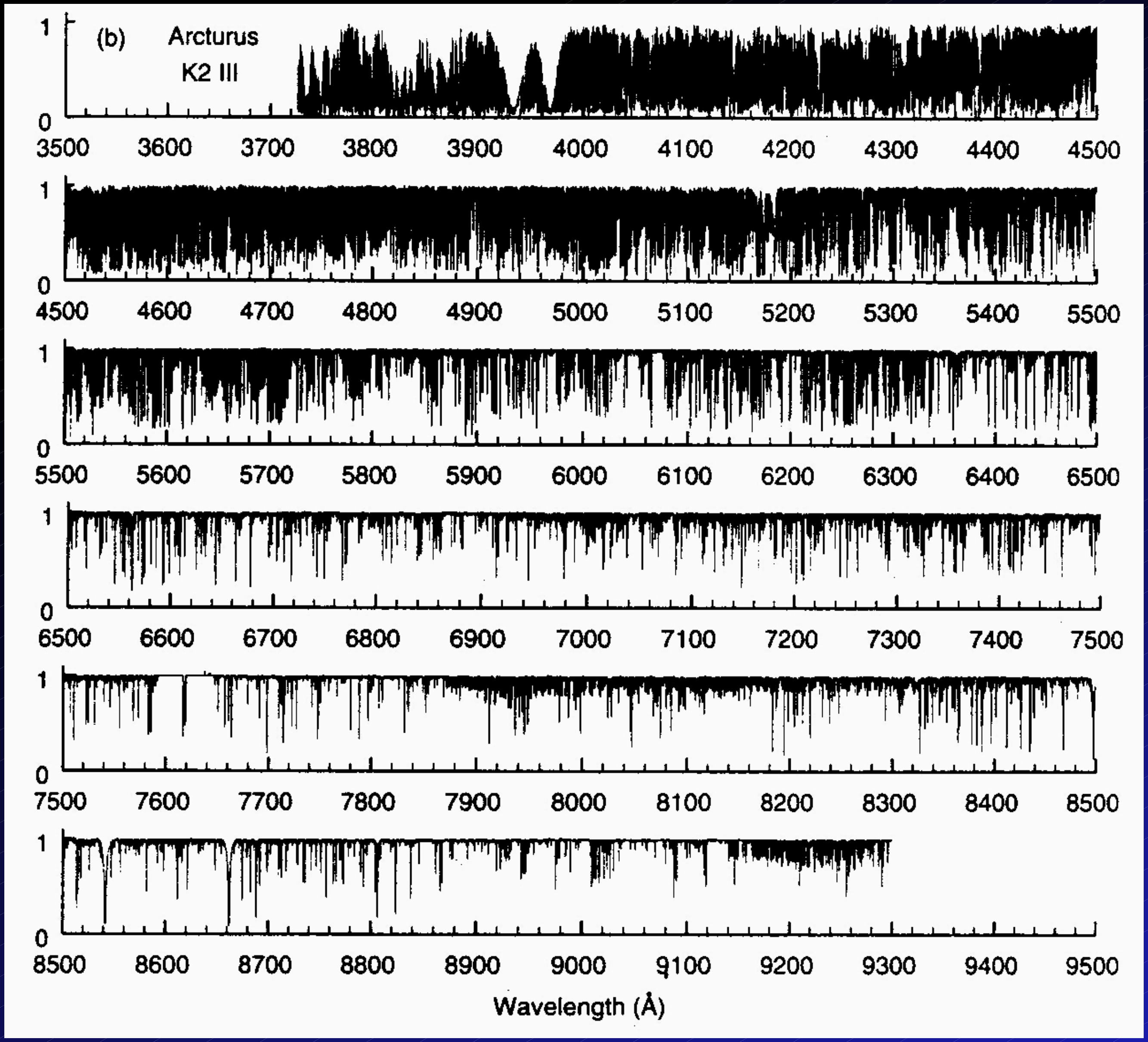


Echelle – spojování řádů





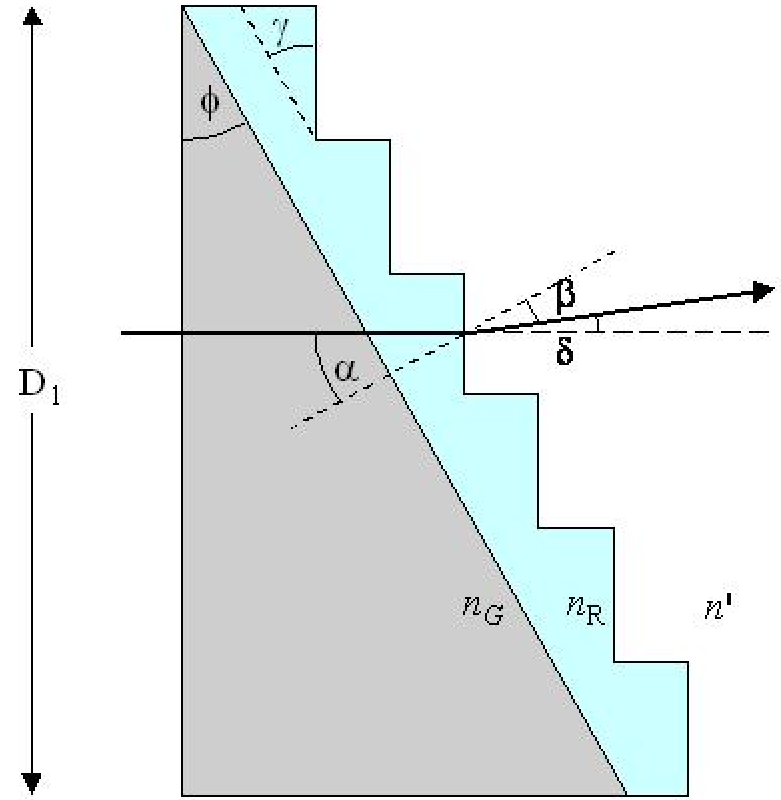
Merged Echelle



Arcturus: Hinkle et al.

Grisms

- Transmission grating attached to prism
- Allows in-line optical train:
  - simpler to engineer
  - quasi-Littrow configuration - no variable anamorphism
- Inefficient for $\rho > 600$/mm due to groove shadowing and other effects

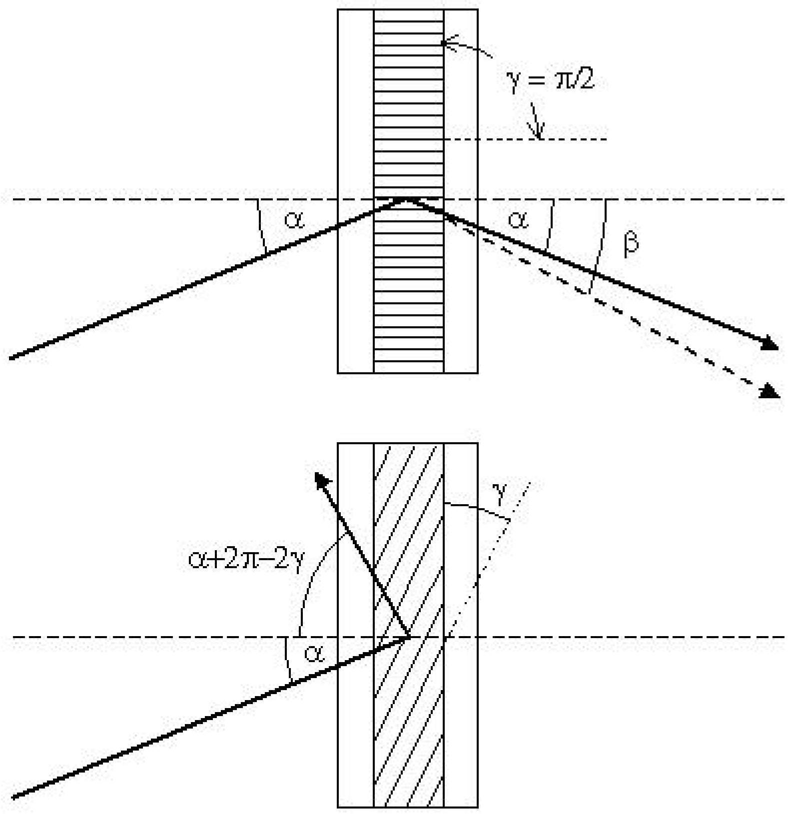


Volume Phase Holographic gratings

- So far we have considered *surface relief* gratings
- An alternative is *VPH* in which refractive index varies harmonically throughout the body of the grating: $n_g(x,z) = n_g + \Delta n_g \cos[2\pi\rho_g(x\sin\gamma + z\cos\gamma)]$
- Don't confuse with '*holographic*' gratings (SR)
- Advantages:
  - Higher peak efficiency than SR
  - Possibility of very large size with high ρ
  - Blaze condition can be altered *(tuned)*
  - Encapsulation in flat glass makes more robust
- Disadvantages
  - Tuning of blaze requires *bendable spectrograph!*
  - Issues of wavefront errors and cryogenic use

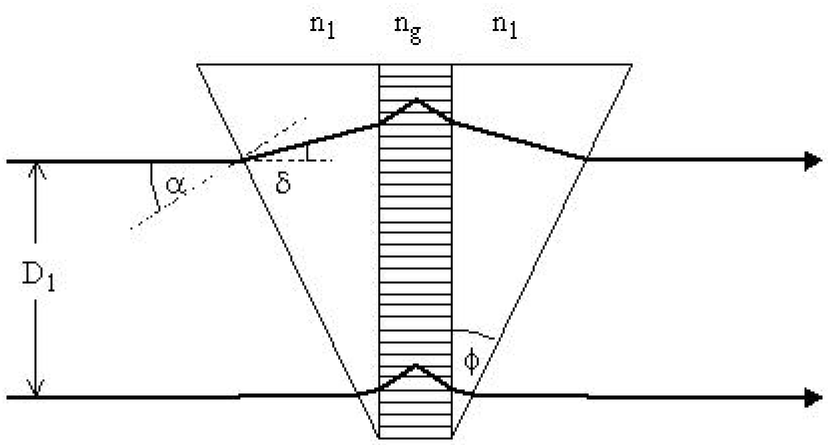
VPH configurations

- *Fringes* = planes of constant *n*
- Body of grating made from *Dichromated Gelatine* (DCG) which permanently adopts fringe pattern generated holographically
- Fringe orientation allows operation in transmission or reflection



VPH 'grism' = *vrism*

- Remove bent geometry, allow in-line optical layout
- Use prisms to bend input and output beams while generating required Bragg condition



$$R = \frac{m\rho\lambda W}{\chi D_T} = \frac{m\rho\lambda}{\chi D_T} D_1 (1 + \tan\delta \tan\varphi)$$

$$\delta = \varphi - \arcsin\left(\frac{\sin\varphi}{n_1}\right)$$

Limits to resolving power

- Resolving power can increase as m, ρ and W increase for a given wavelength, slit and telescope

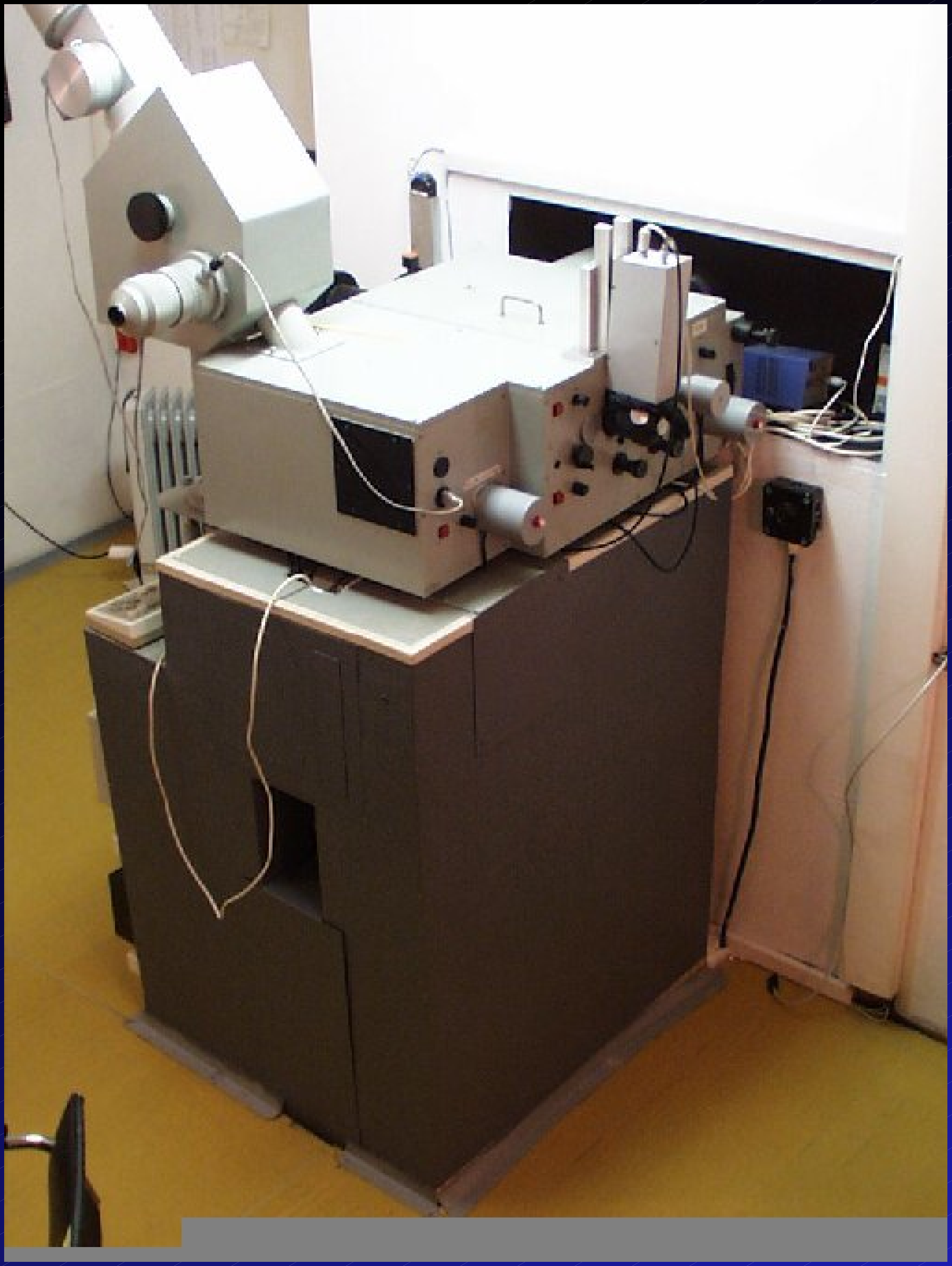
Grating parameters

Geometrical factors

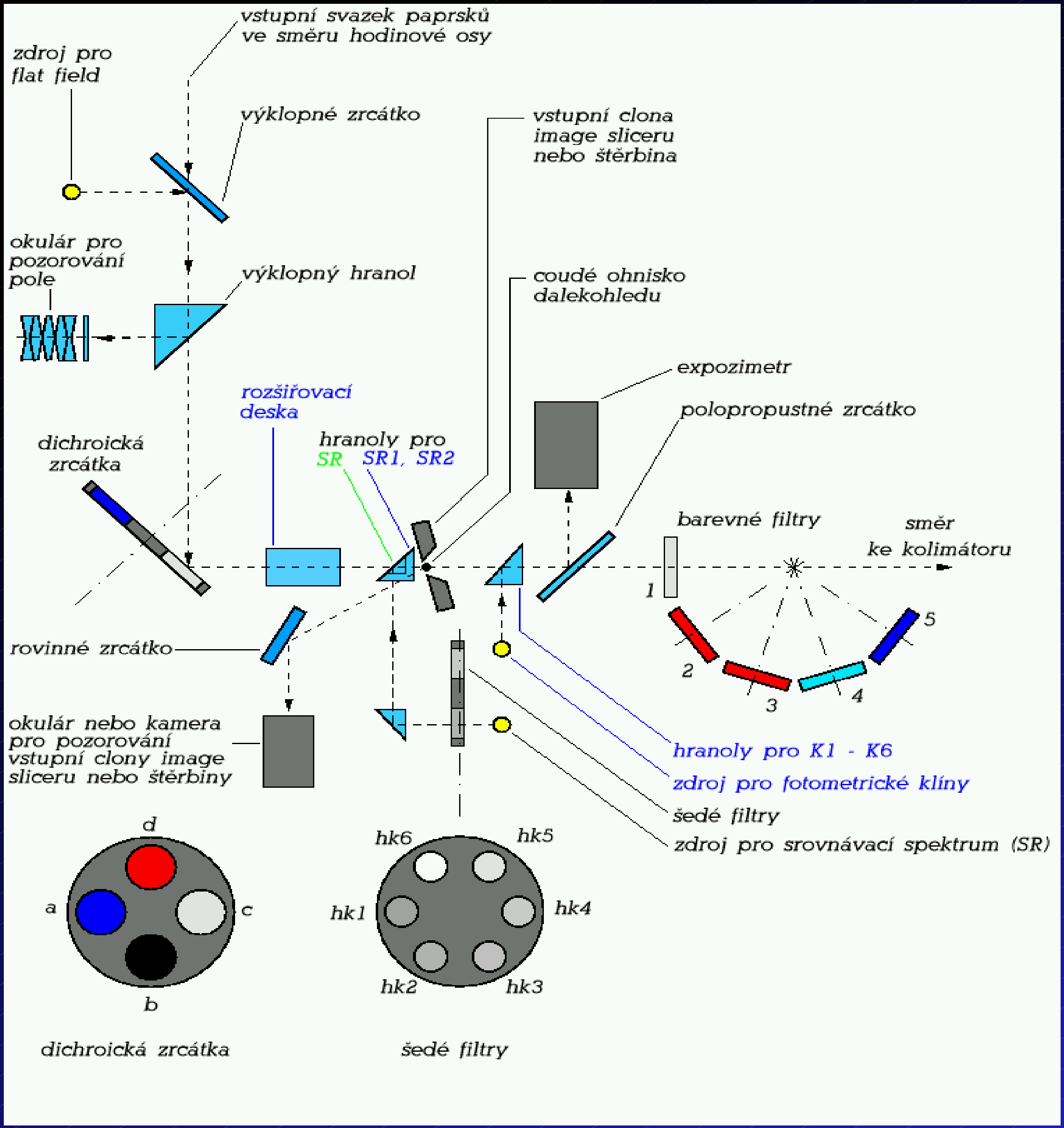
$$R = \frac{m\rho\lambda W}{\chi D_T} = \frac{D_1}{\chi D_T}\left(\frac{\sin\alpha + \sin\beta}{\cos\beta}\right)$$

- Limit depends on geometrical factors only - increasing ρ or m will not help!
- In practice, the limit is when the output beam overfills the camera:
  - W is actually the length of the intersection between beam and grating plane - not the actual grating length
  - R will increase even if grating overfilled until diffraction-limited regime is entered ($\lambda > \chi D_T$)

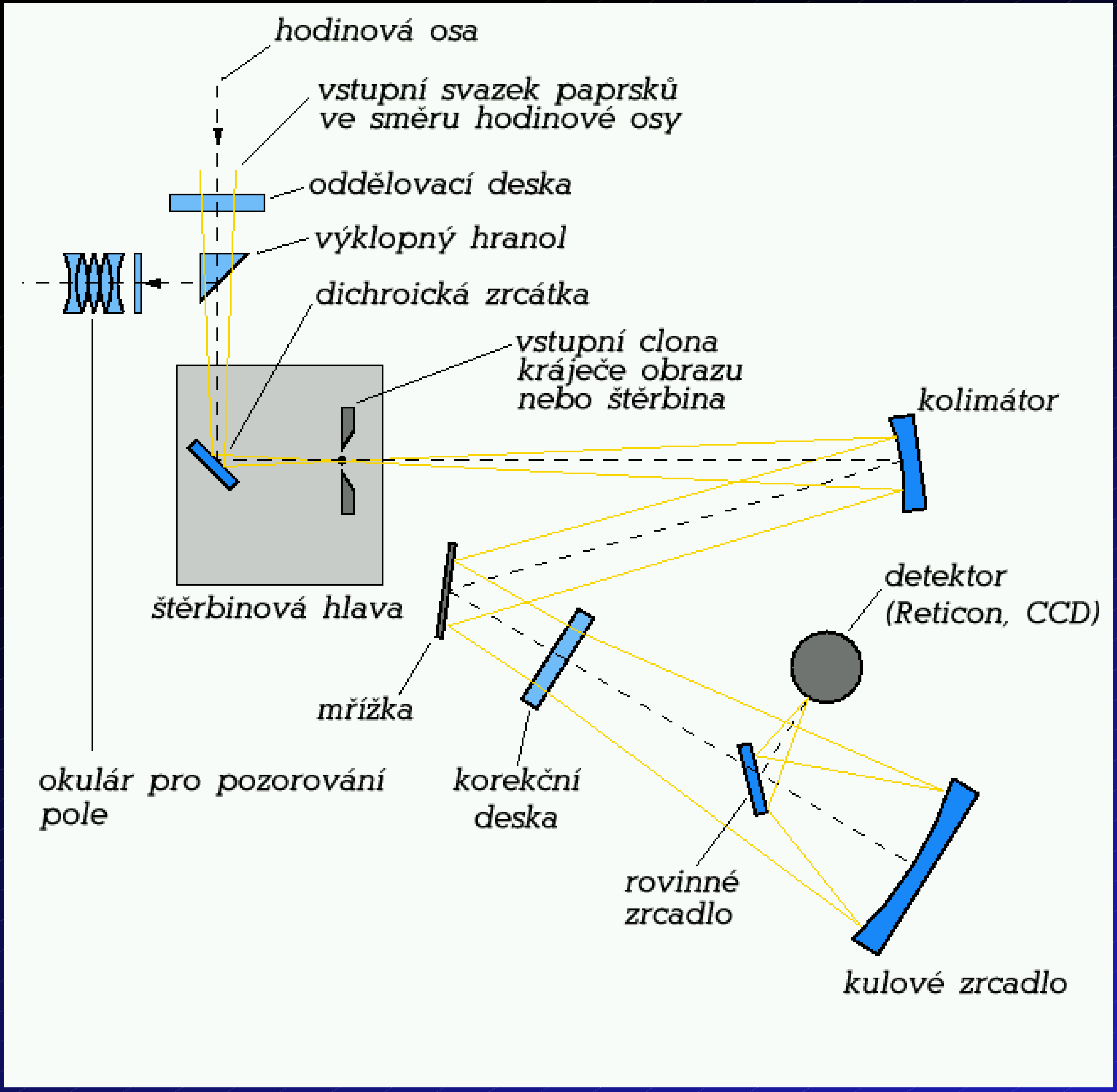
2m coudé

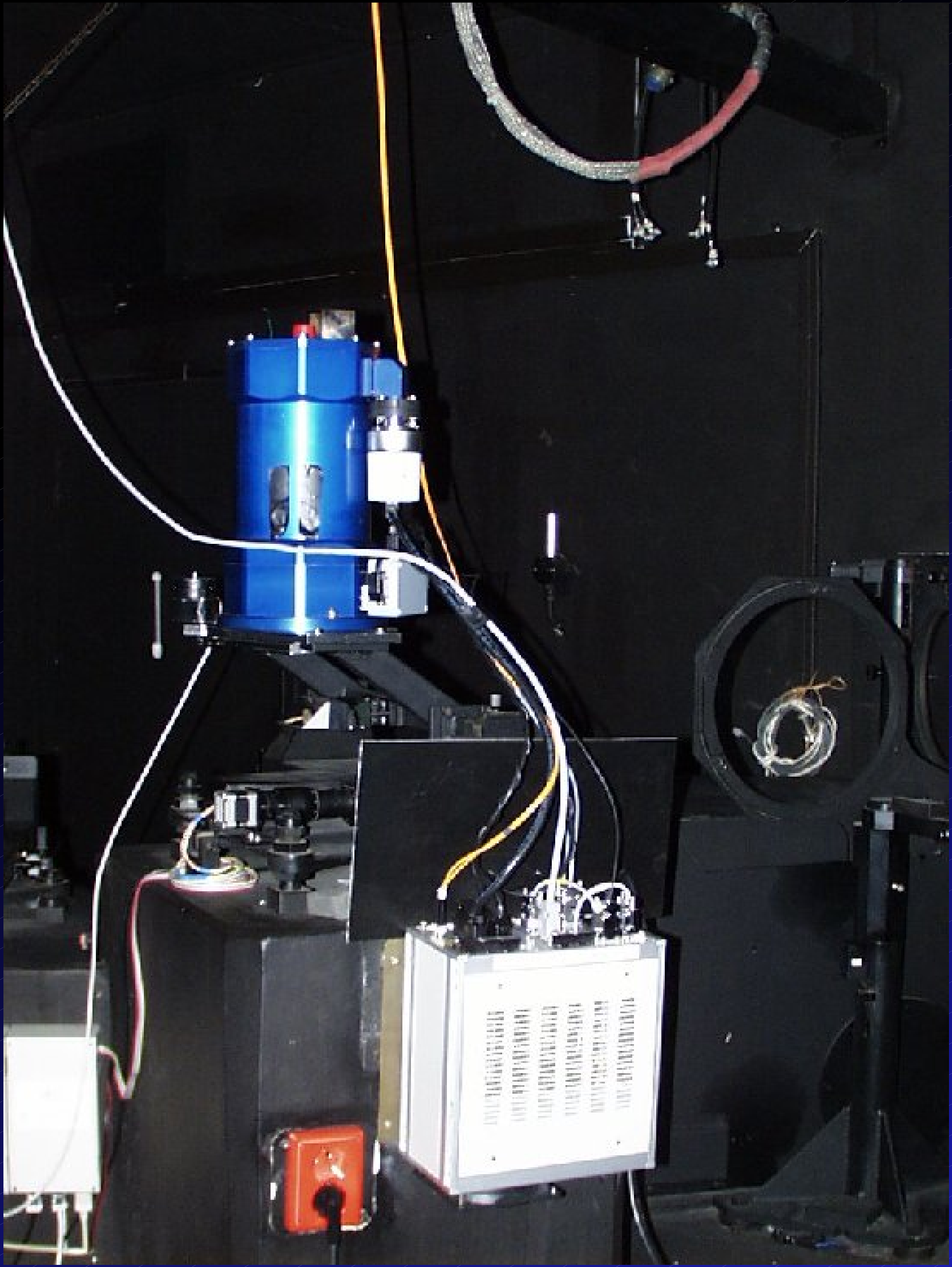


Štěrbinová hlava spektrografu 2m

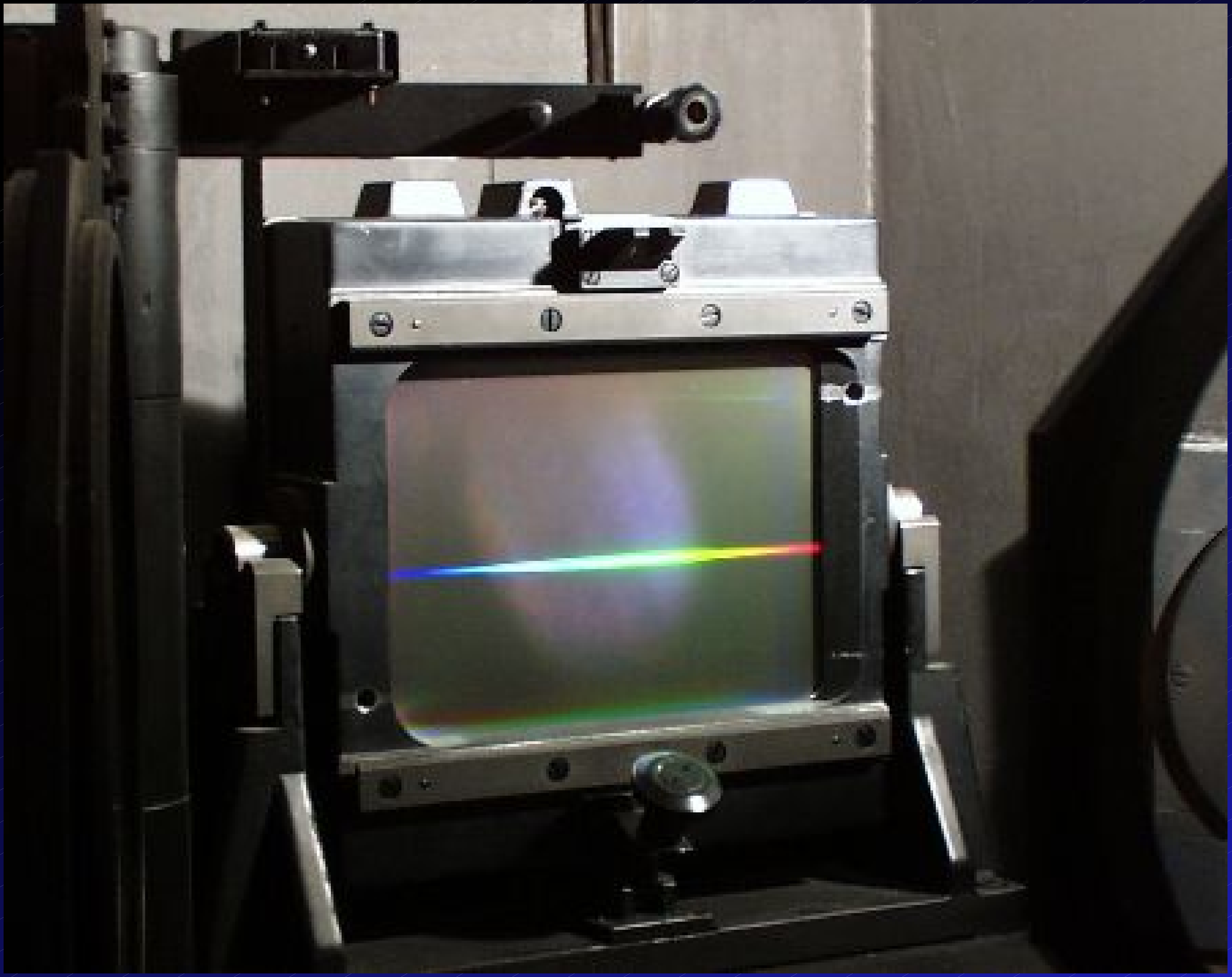


Coudé spektroraf 2m

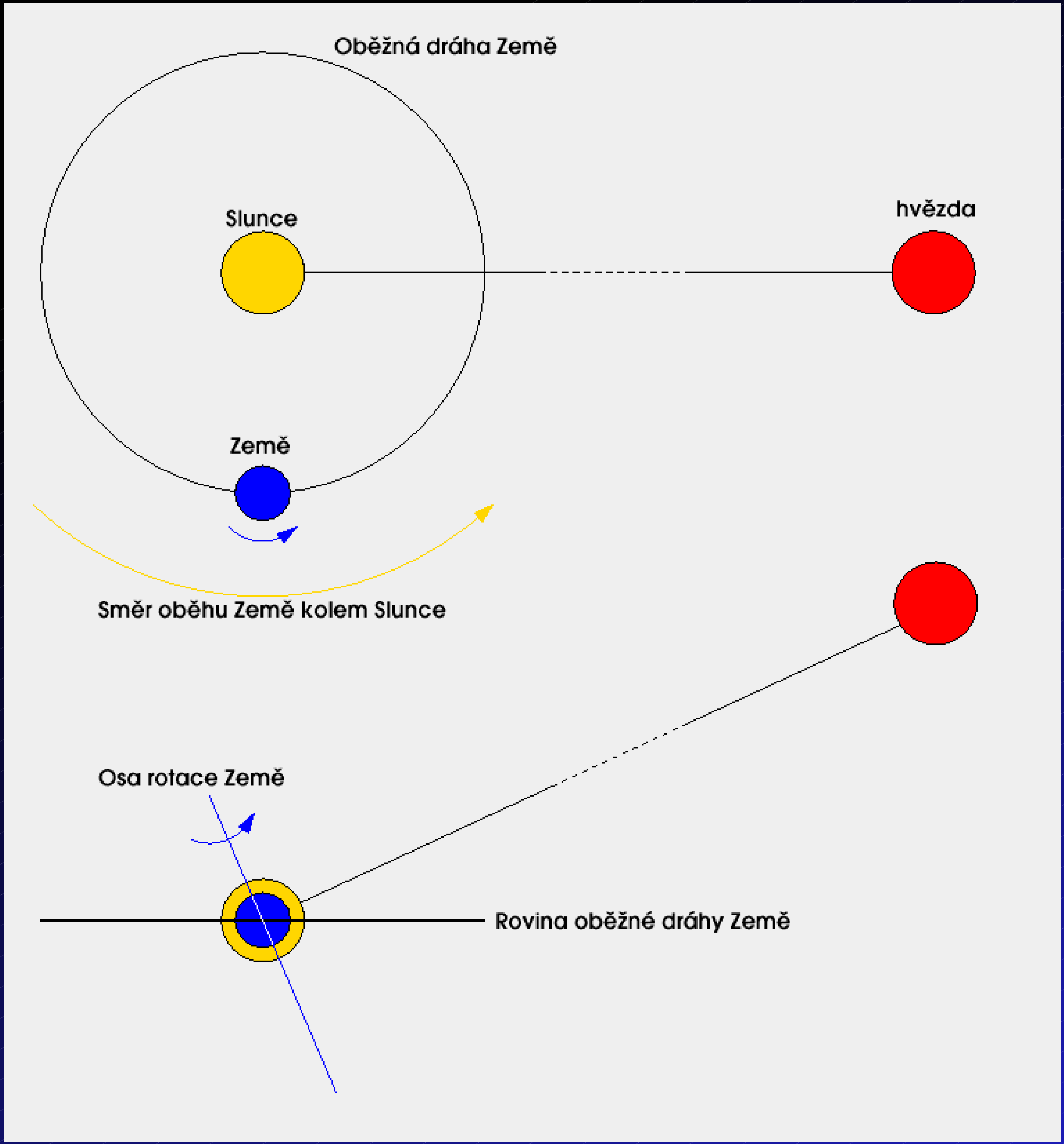




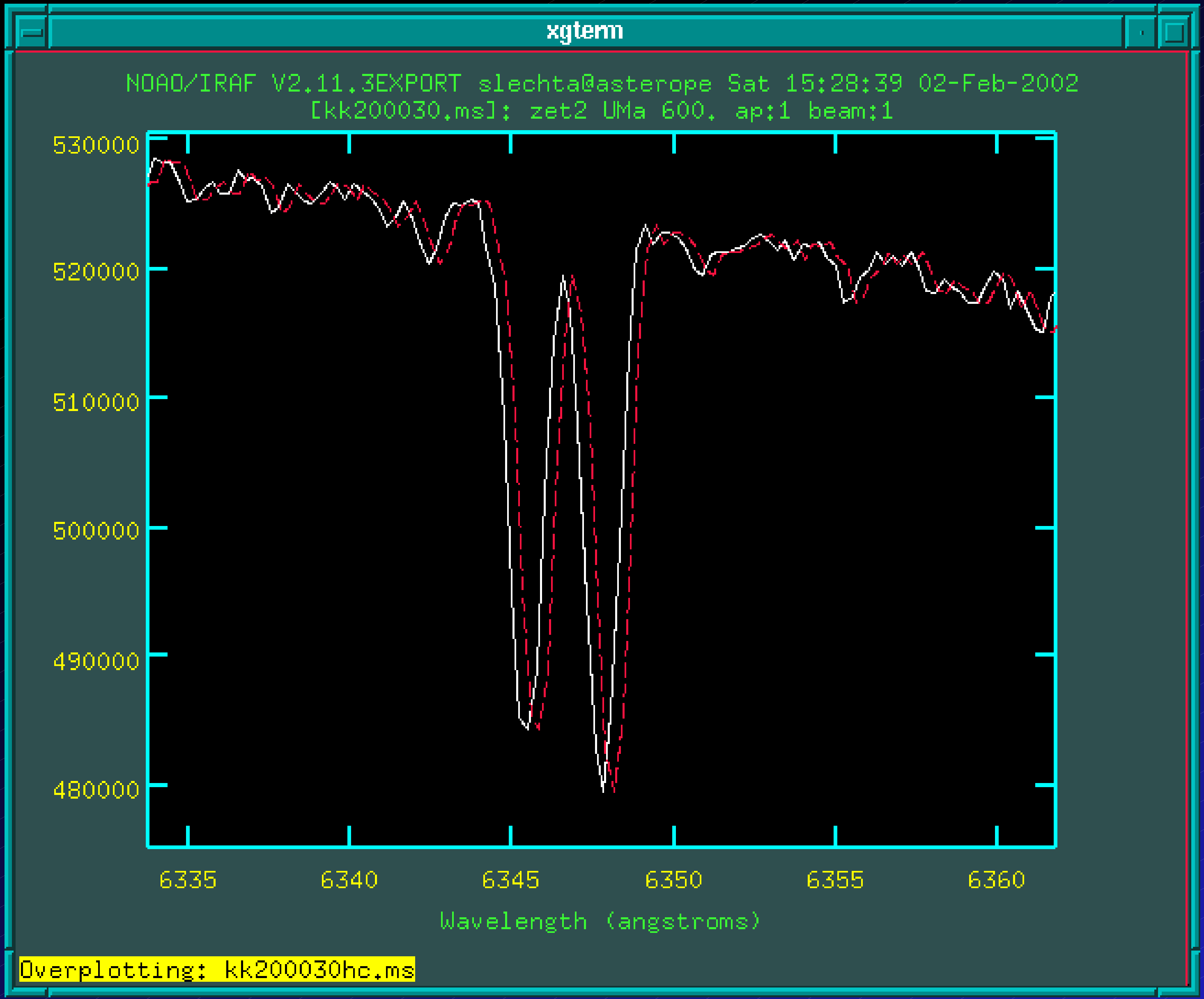
Mřížka 833/mm



Heliocentrická korekce



Posun čar díky heliocentrické korekci



Redukce – vyčtení COP

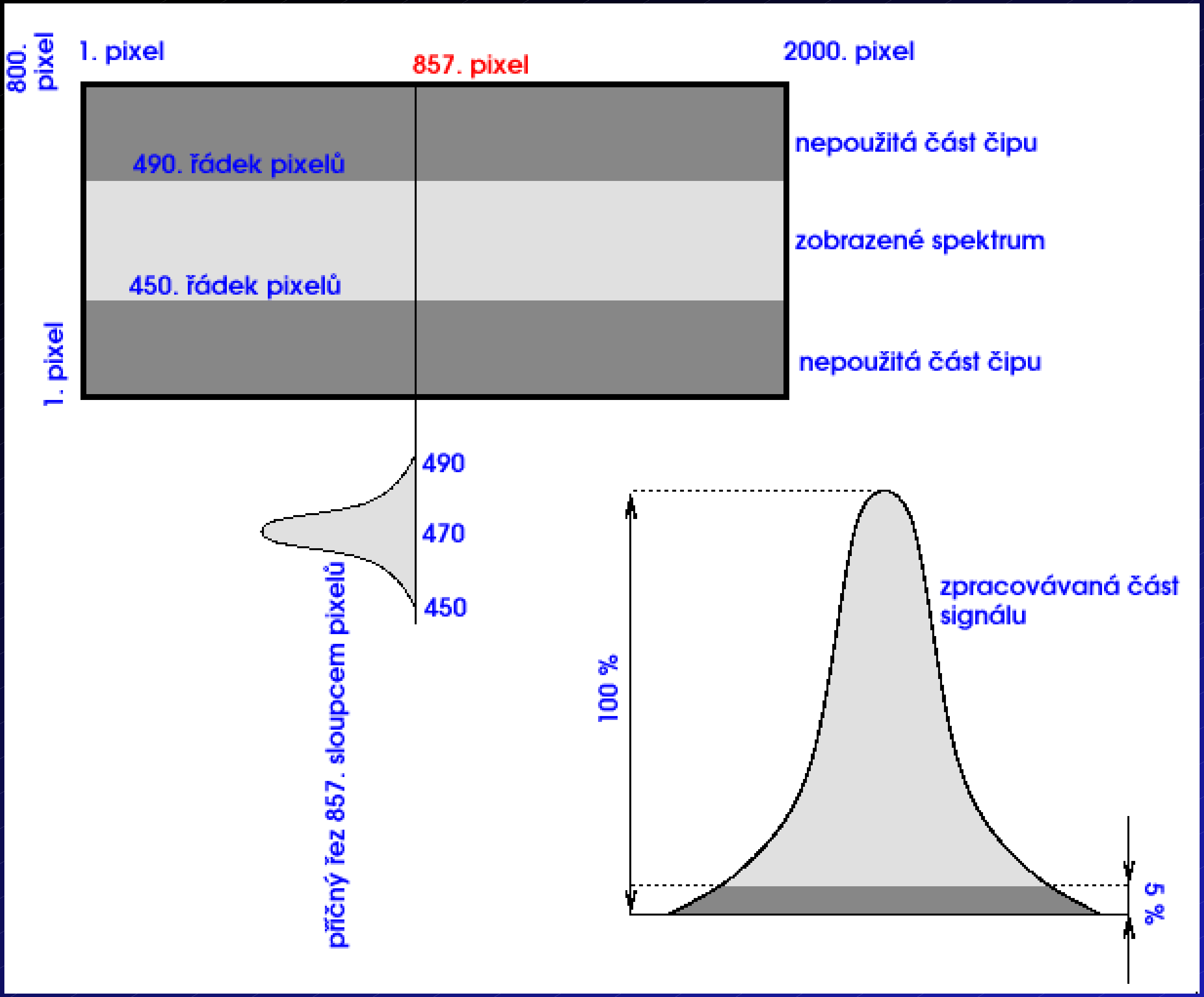
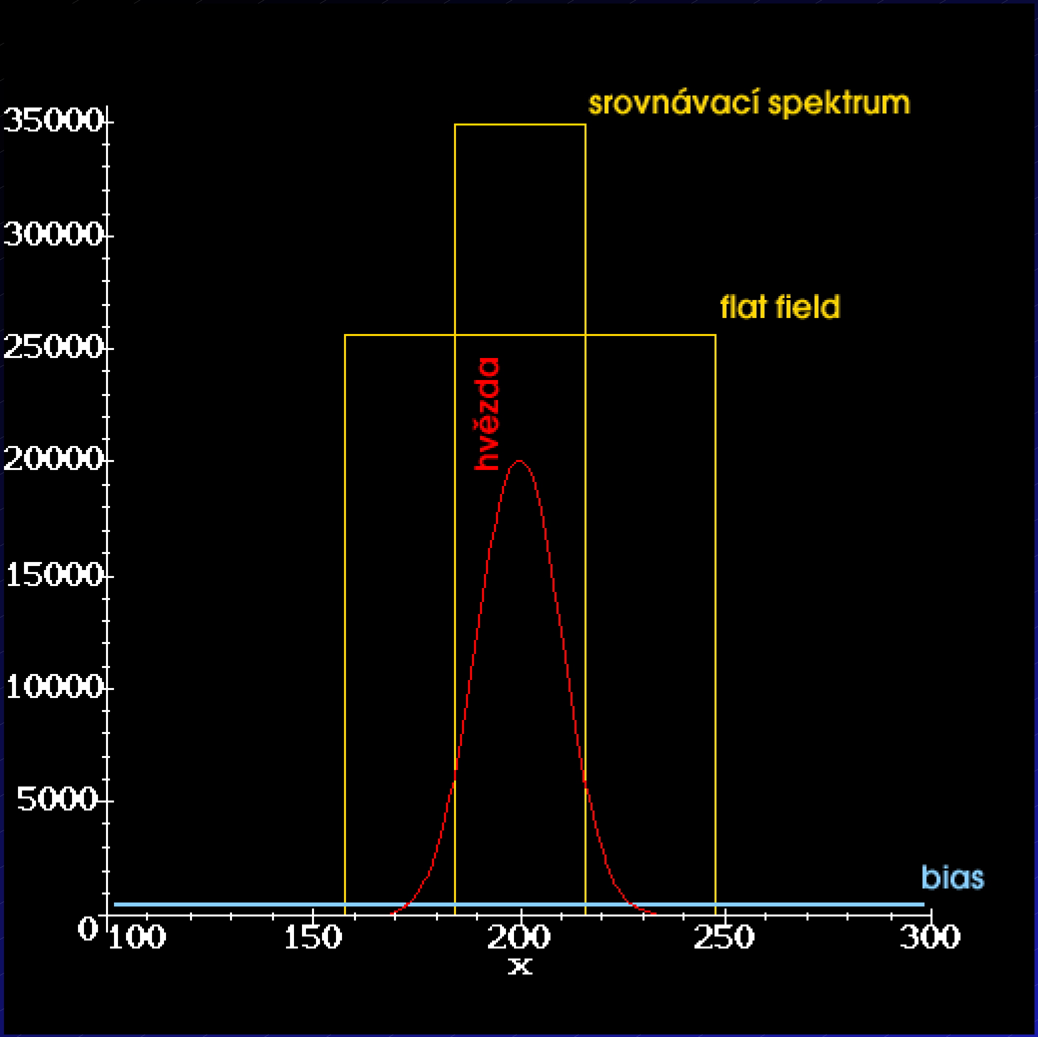
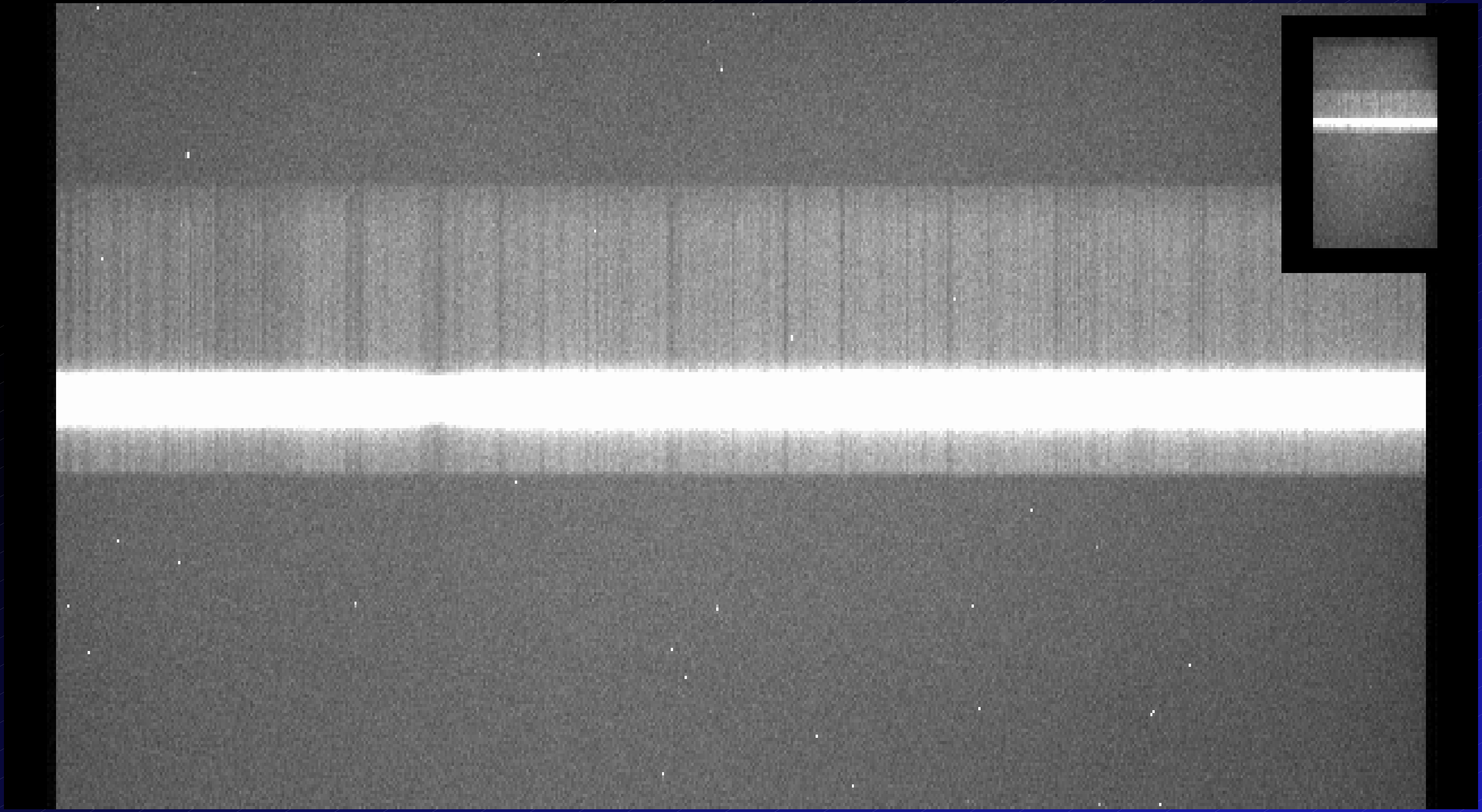


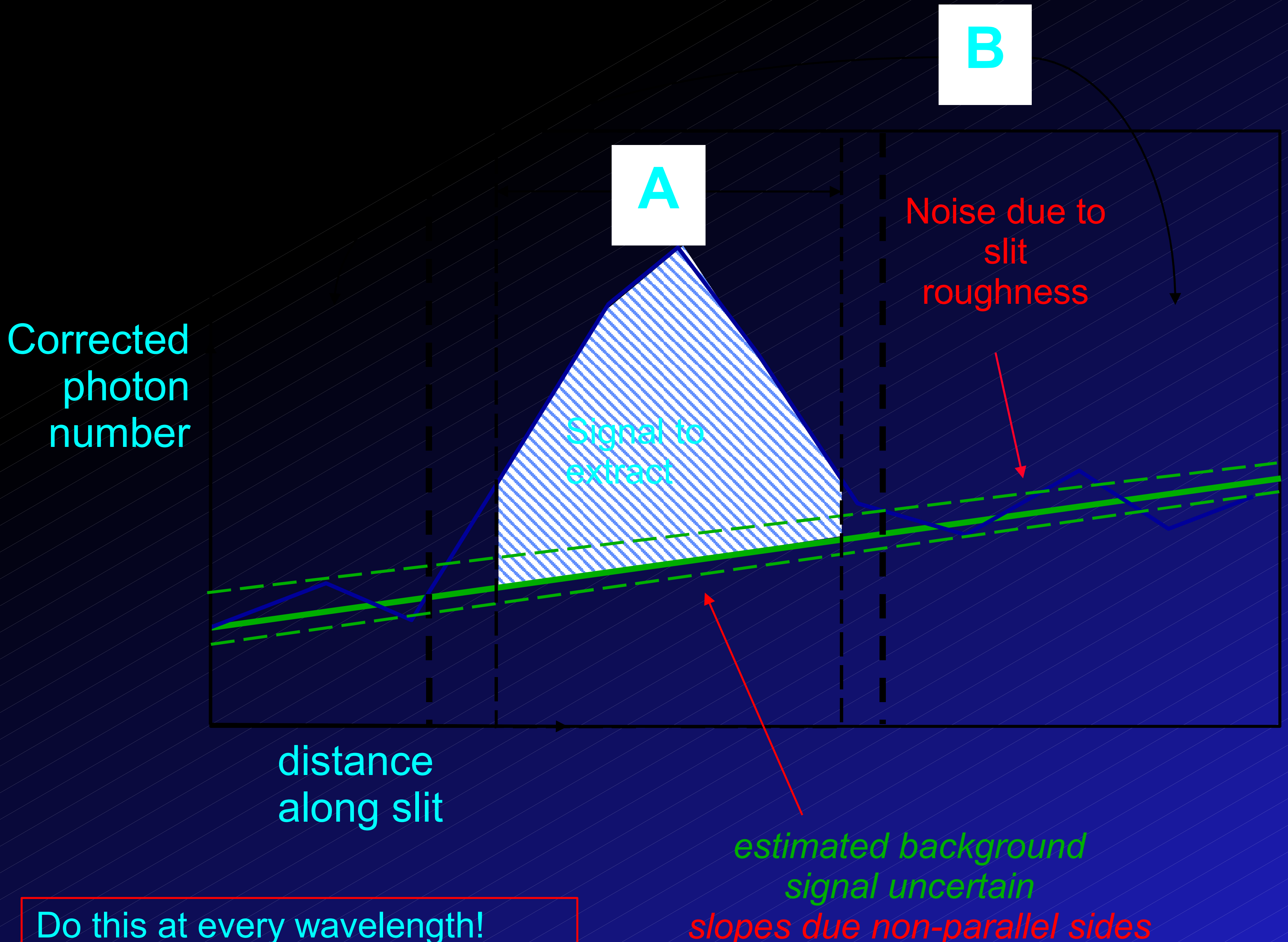
Schéma COP

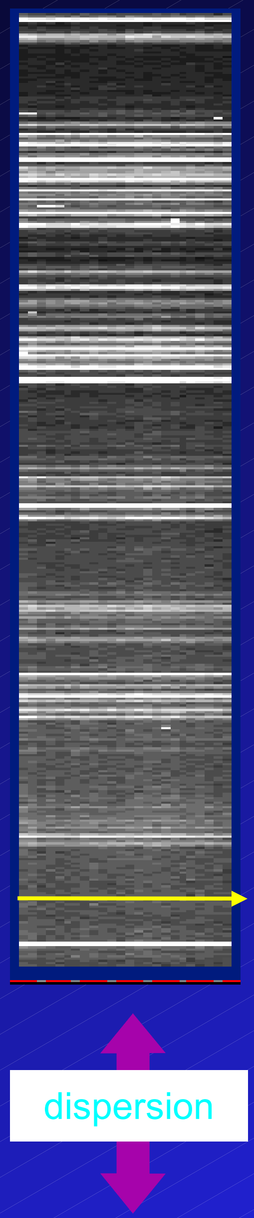

srovnávací spektrum
flat field
hvězda
bias
35000
30000
25000
20000
15000
10000
5000
0
100
150
200
250
300
x

Background a sky lines



Sky subtraction with slit



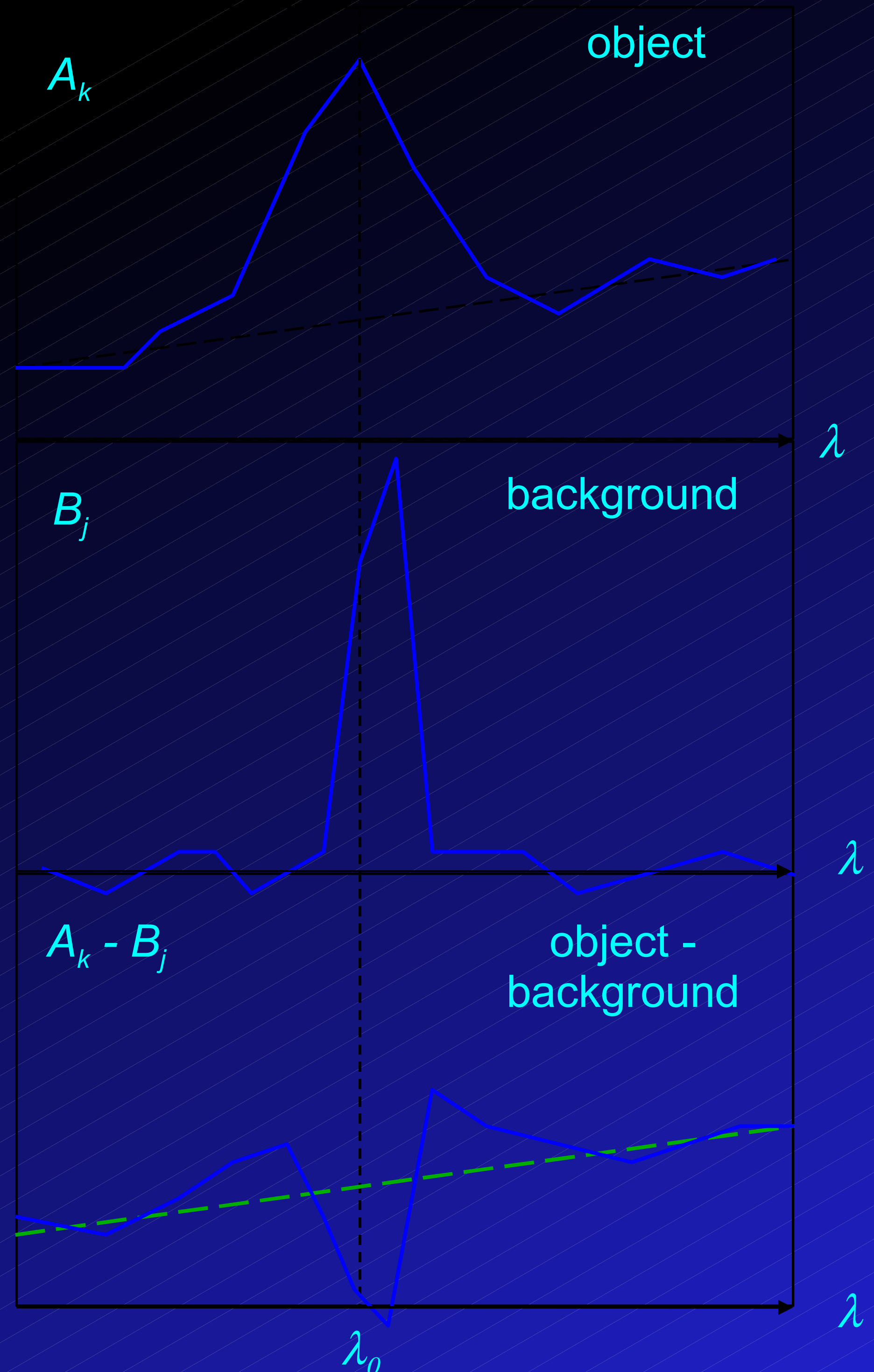


Do this at every wavelength!

Sky subtraction near bright sky lines

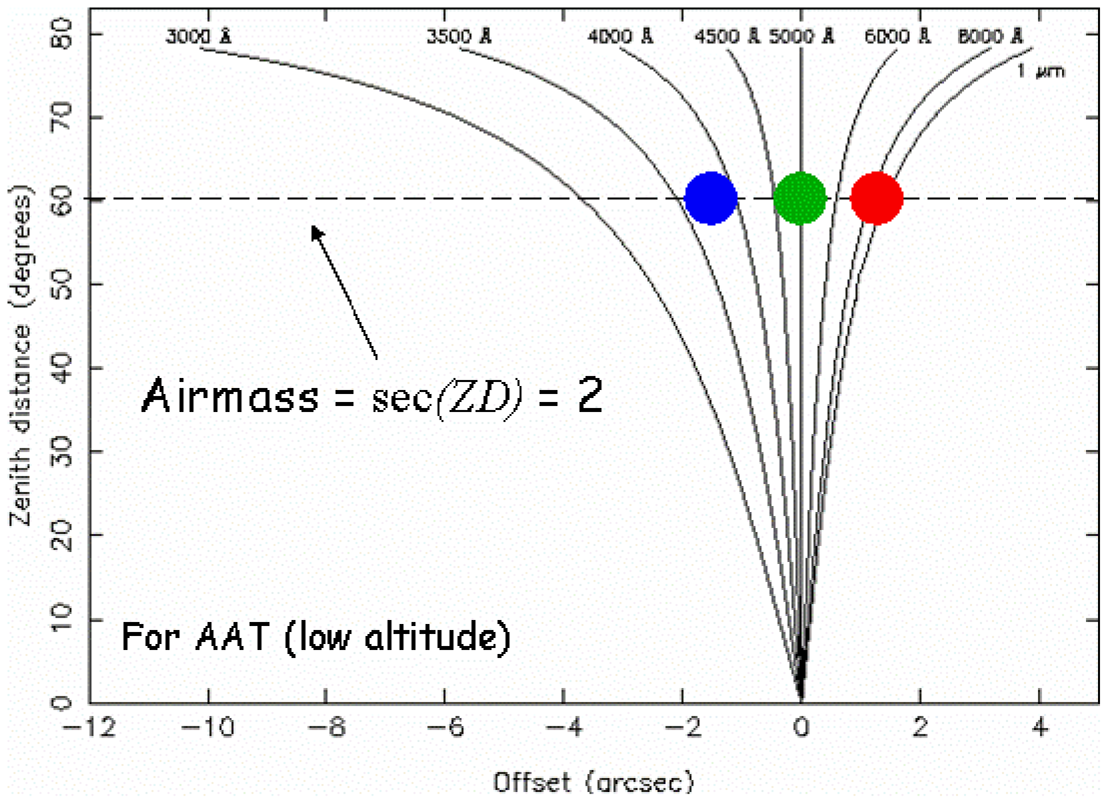
Poor cancellation of sky line due to:

- Difference in line *profile* due to:
  - uneven slit width
  - IQ varies over field
- Difference in line *location* due to:
  - tilt of slit
  - poor wavelength calibration/ solution/



Atmospheric dispersion
(differential refraction)

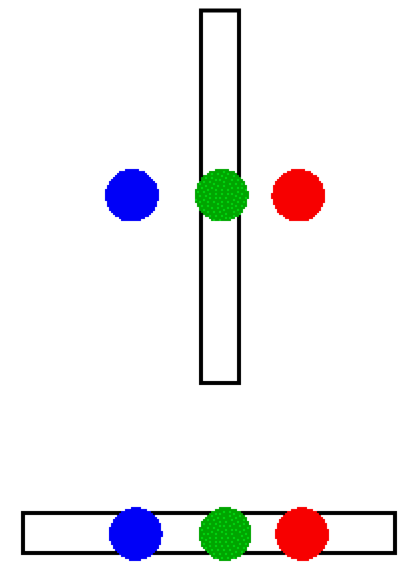
To zenith



Error in position
if guiding at 500nm

∝tan(ZD)

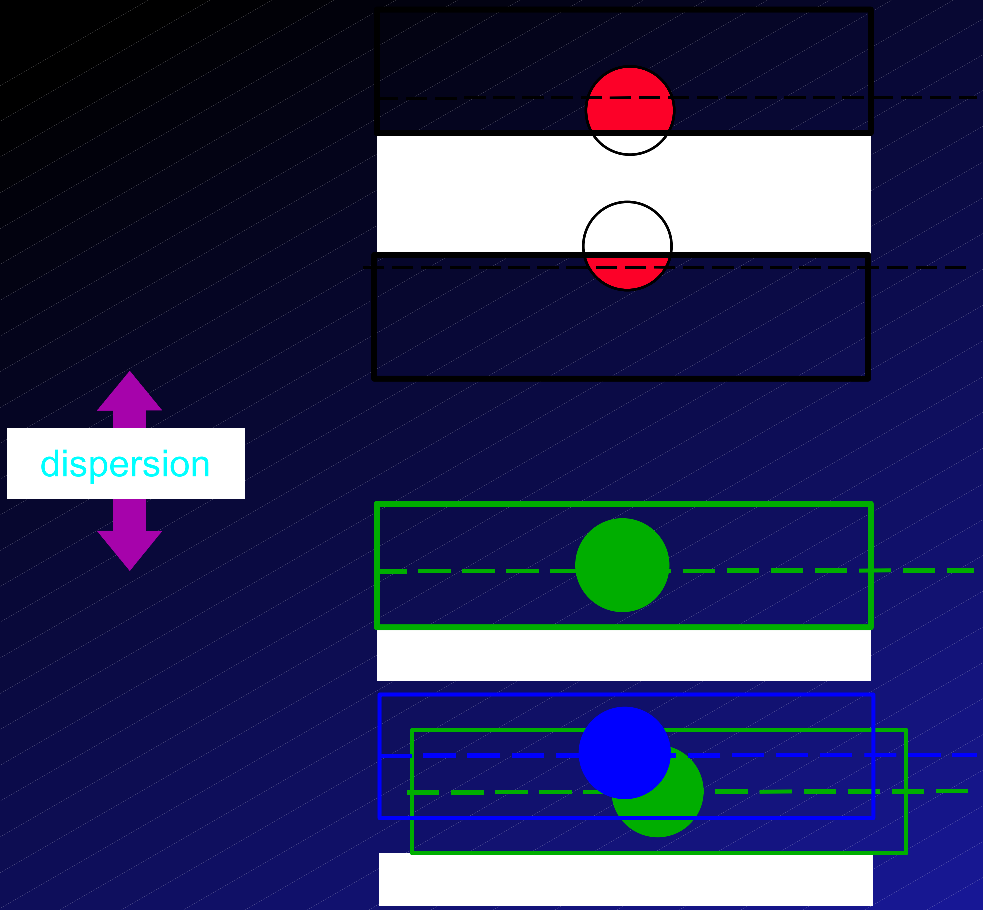
If slit is horizontal, light is lost at extreme wavelength



If slit is vertical, all light is in slit, but spectrum will be curved

Errors in centroid of VRE

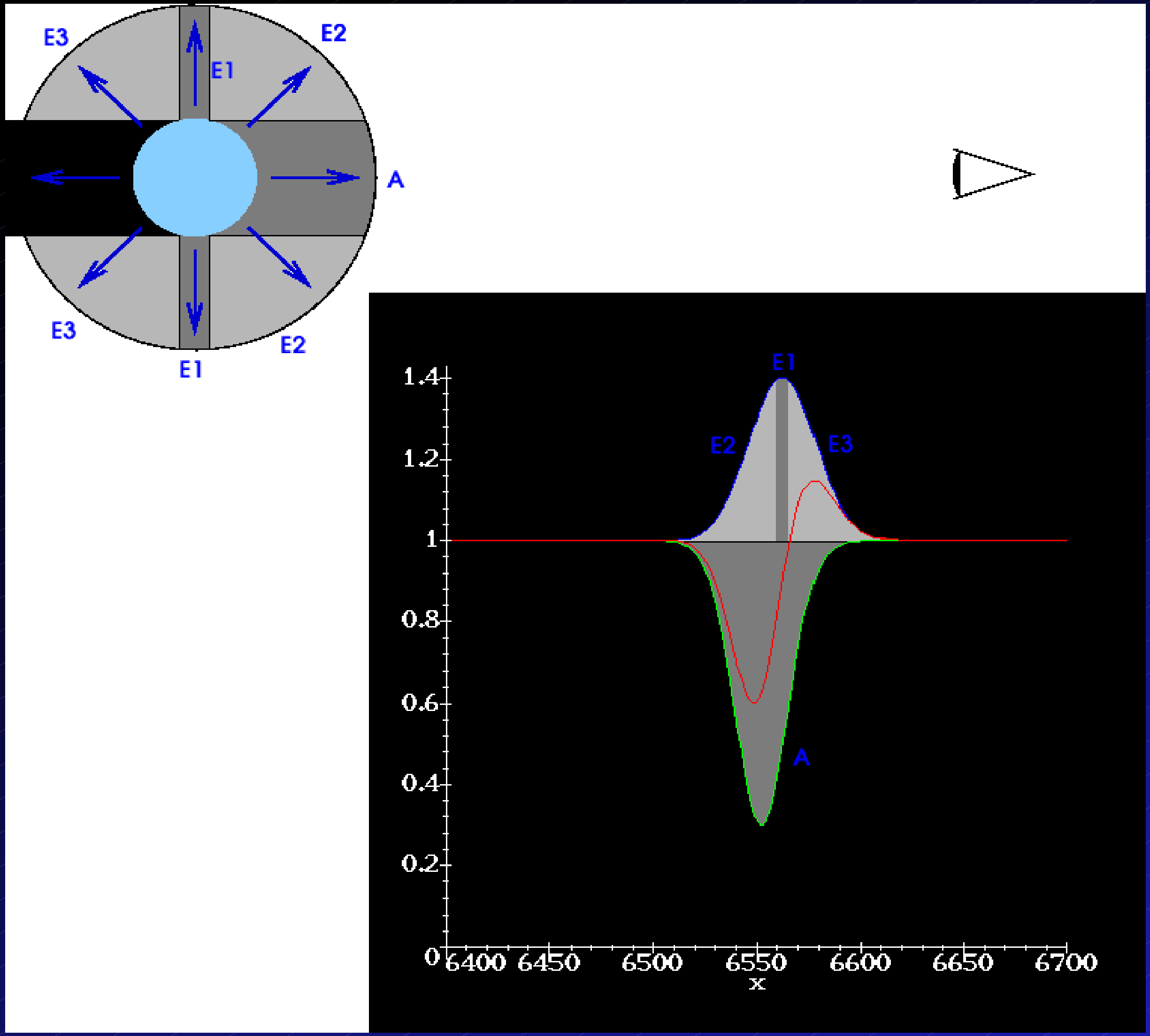
VRE = *velocity resolution element*,
the monochromatic image of the slit as recorded by the detector



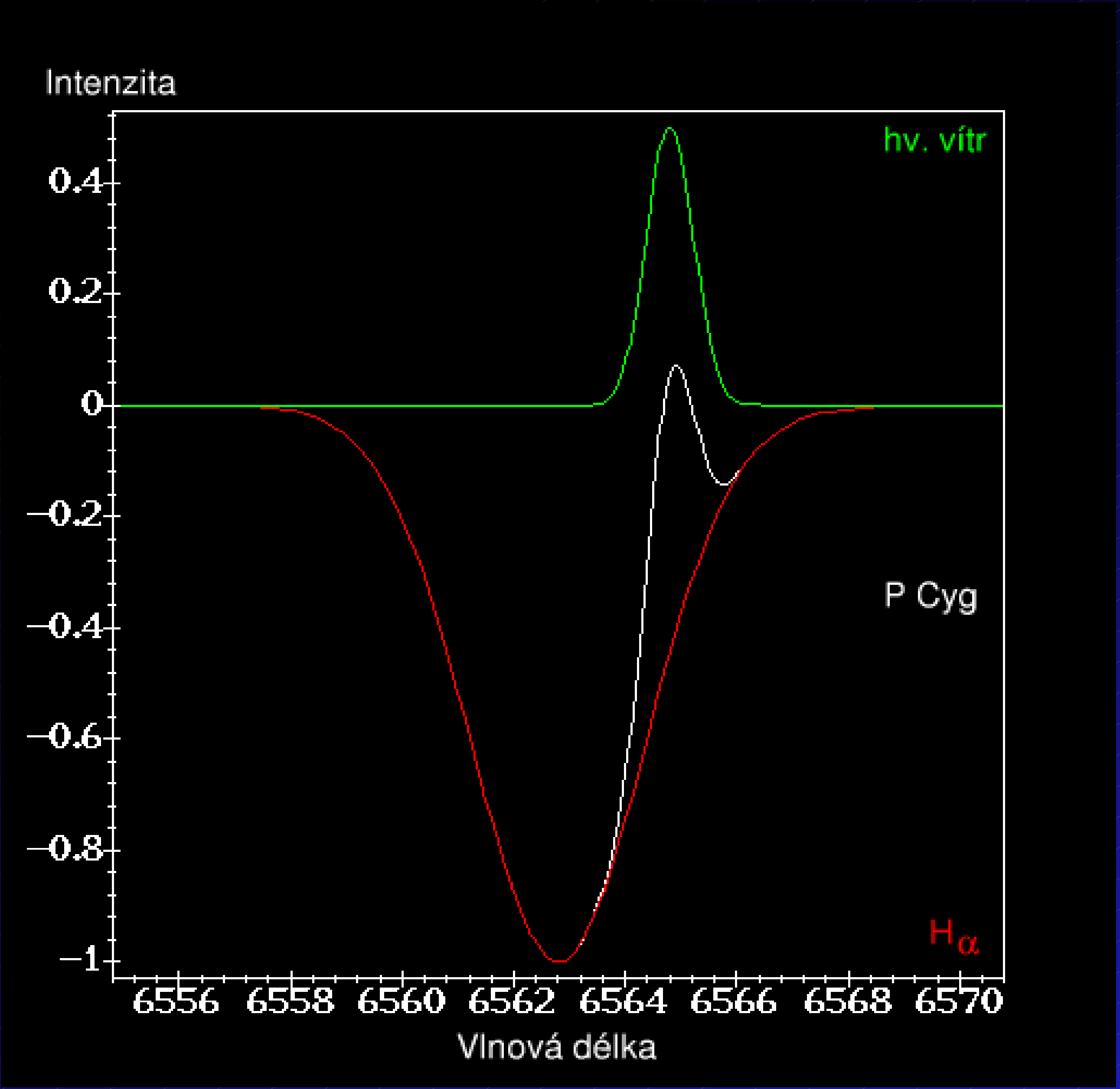
Target-slit error: Centroid varies depending on position of object with respect to slit due to guiding error or *movement between telescope and slit*

Slit-detector error: Centroid varies due to *movement between slit and detector*

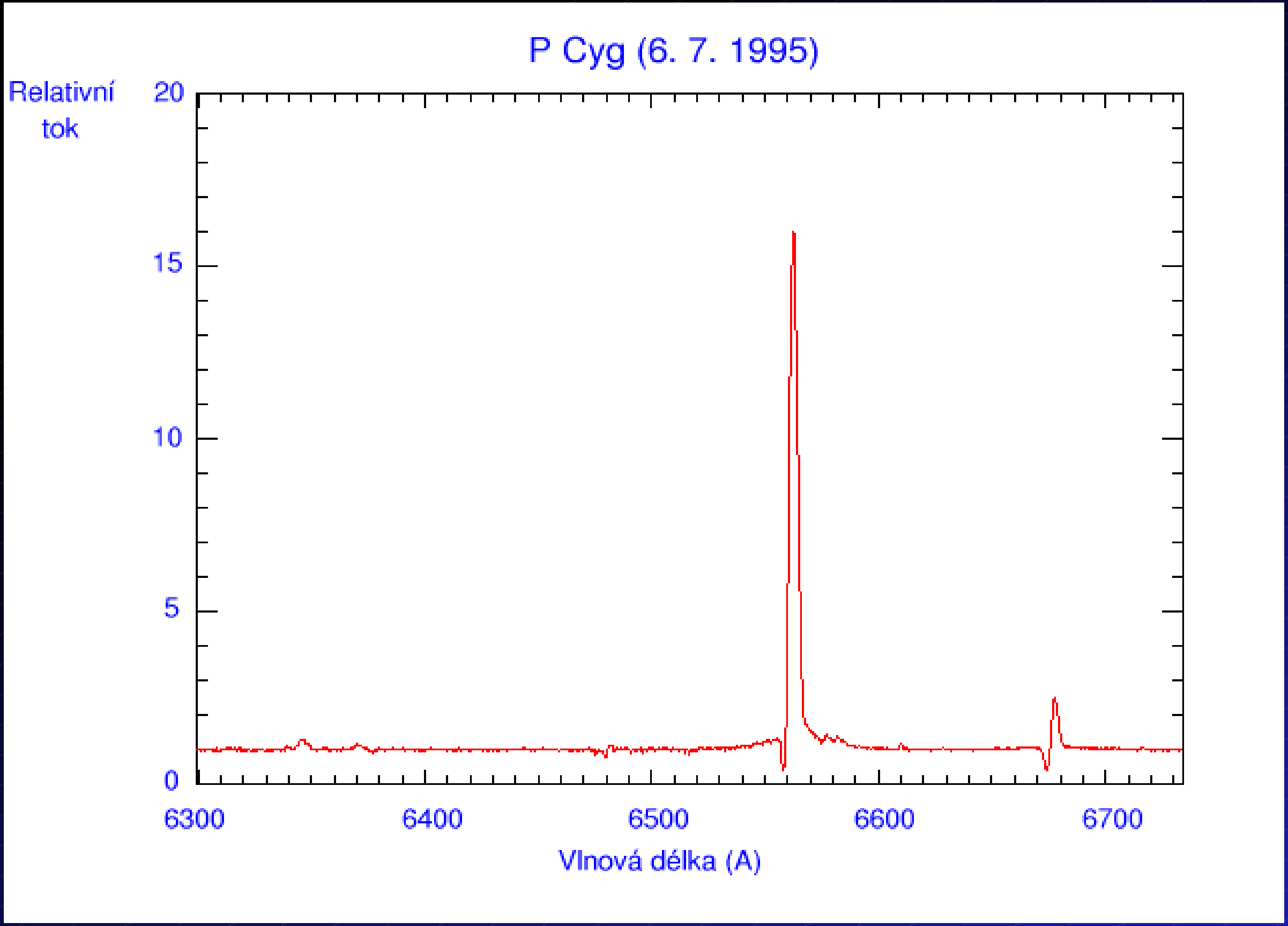
Vznik P Cyg profilu

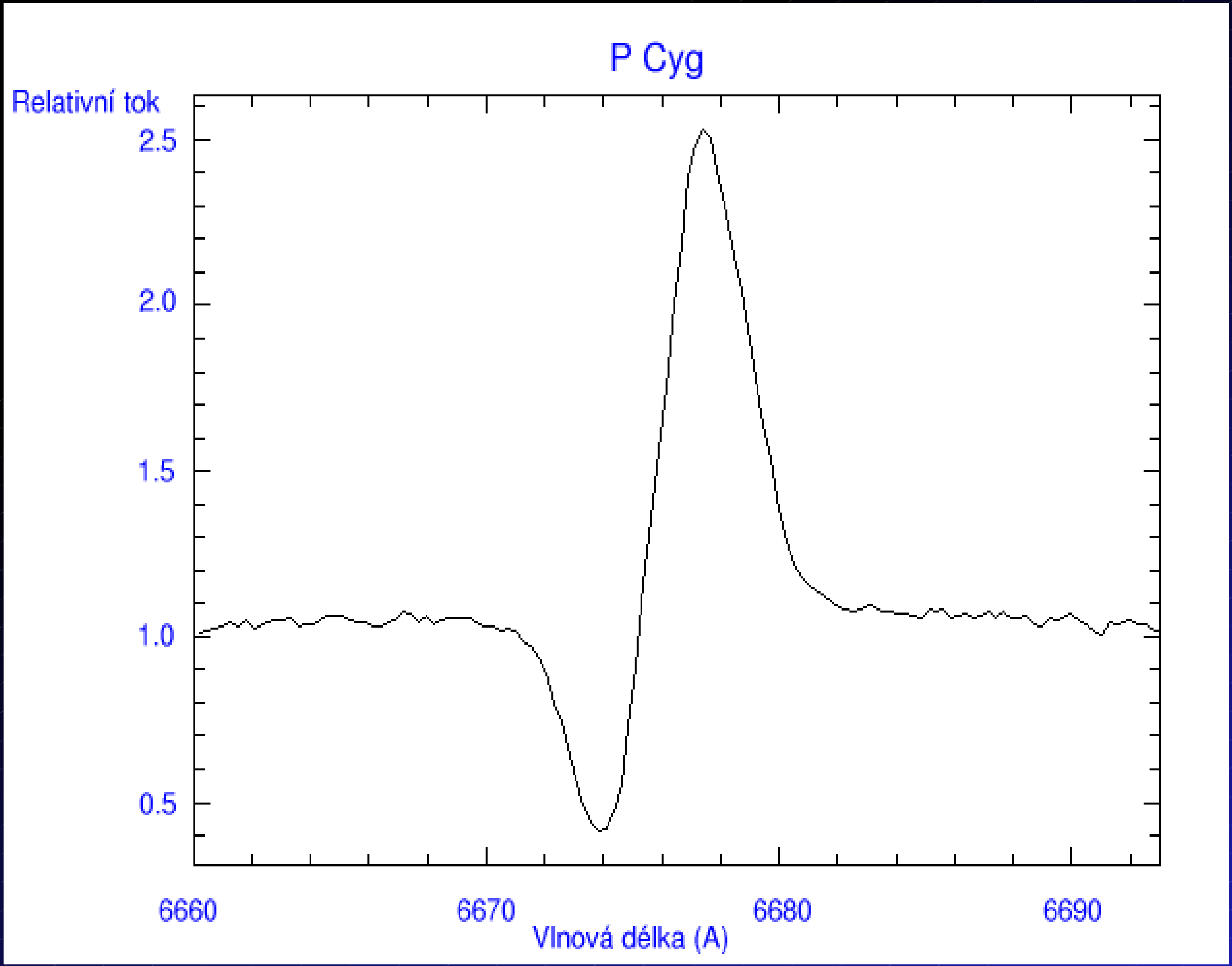


Vznik P Cyg profilu



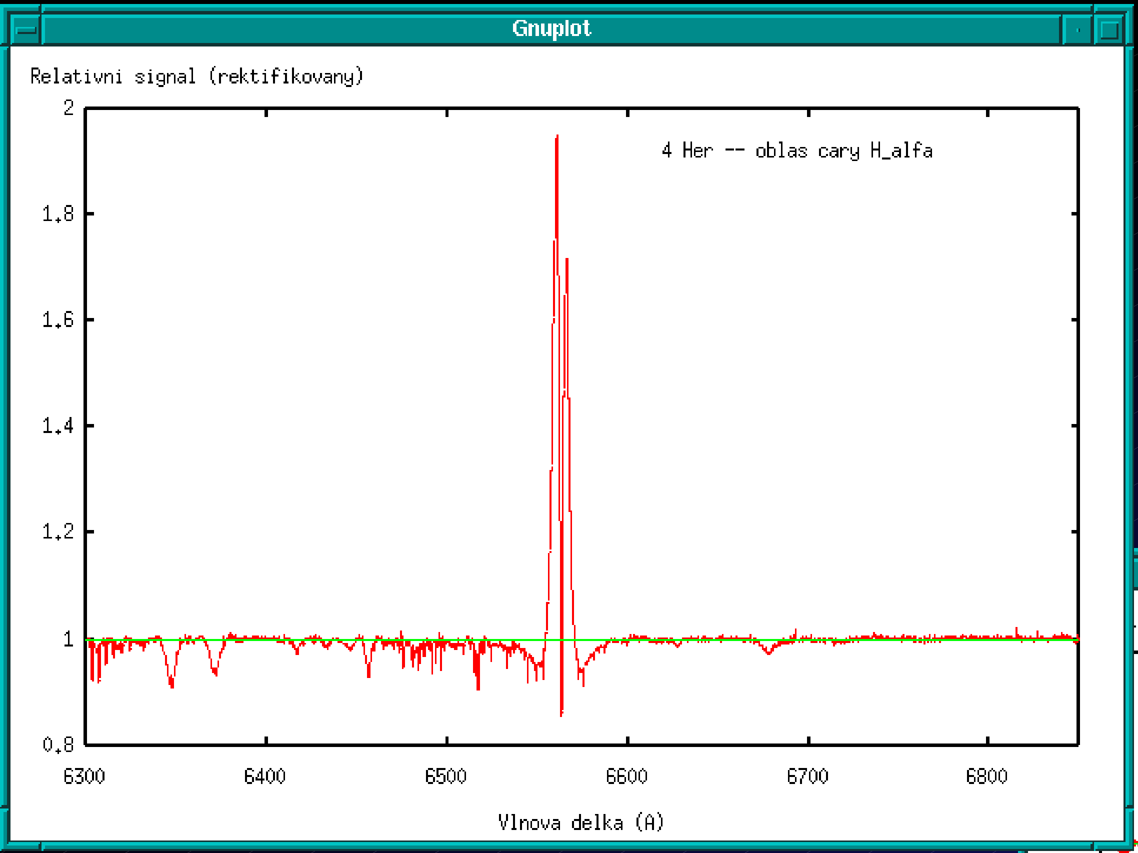
P Cyg


P Cyg (6. 7. 1995)
Relativní
tok
20
15
10
5
0
6300
6400
6500
6600
6700
Vlnová délka (A)

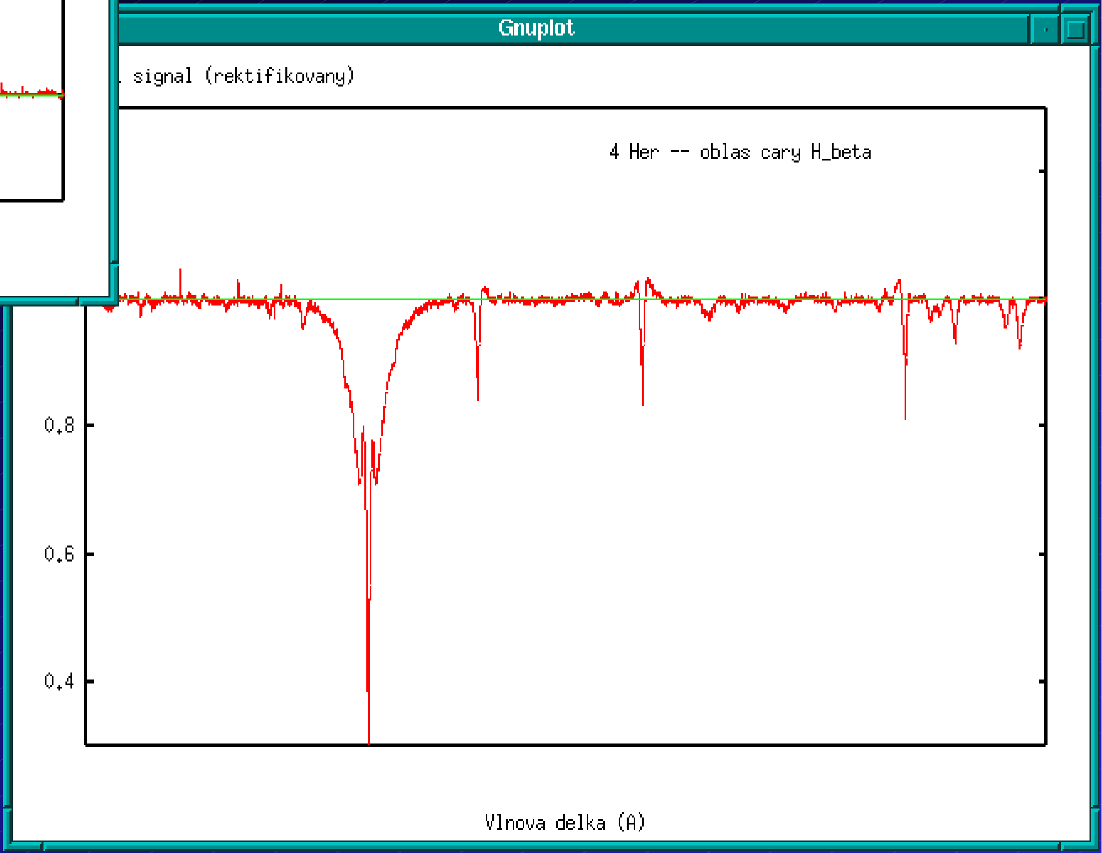


P Cyg
Relativní tok
2.5
2.0
1.5
1.0
0.5
6660
6670
6680
6690
Vlnová délka (A)

4 Her

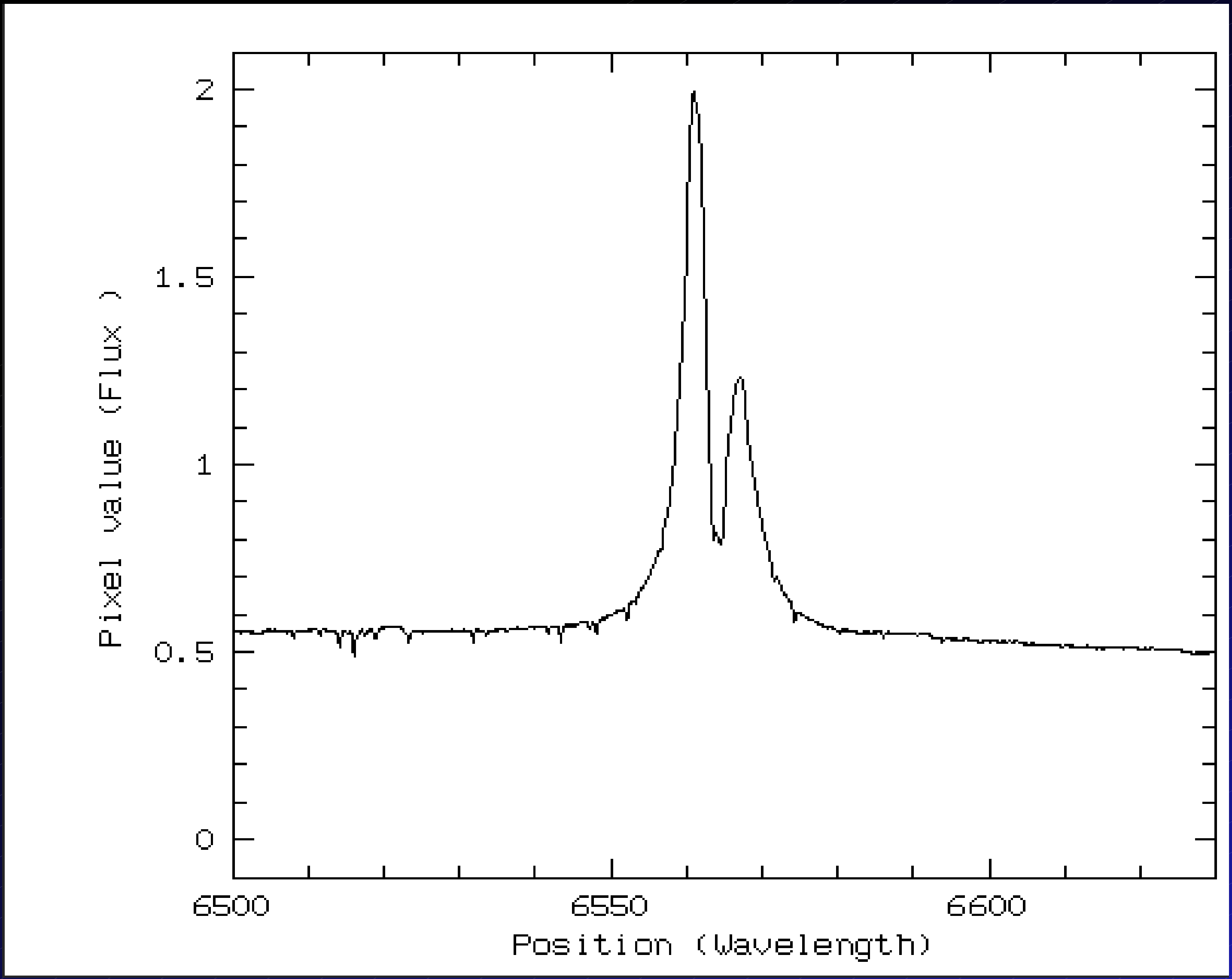


Gnuplot
Relativni signal (rektifikovany)
4 Her -- oblas cary H_alfa
2
1,8
1,6
1,4
1,2
1
0,8
6300
6400
6500
6600
6700
6800
Vlnova delka (A)



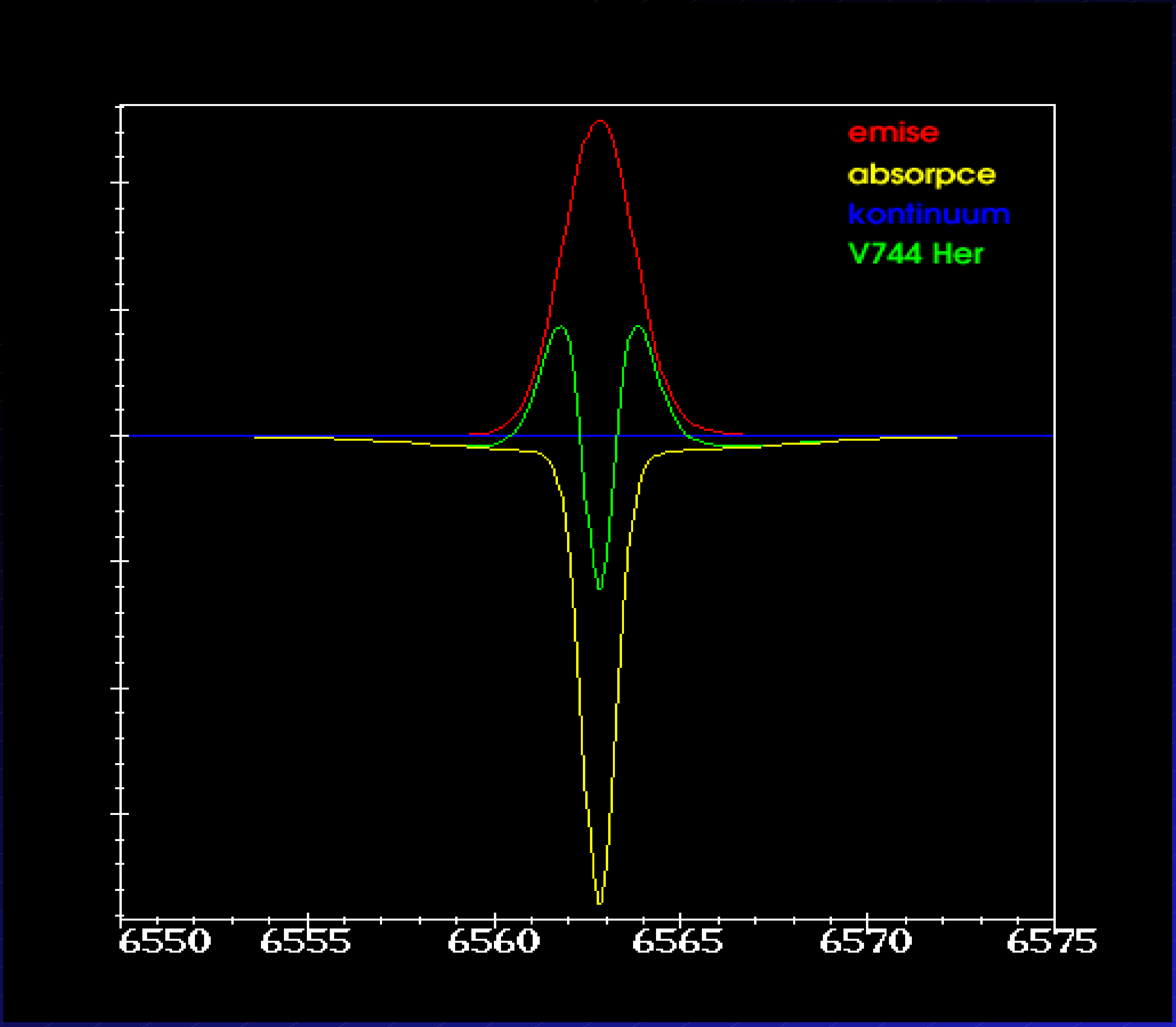
Gnuplot
signal (rektifikovany)
4 Her -- oblas cary H_beta
0,8
0,6
0,4
Vlnova delka (A)

Zet Tau

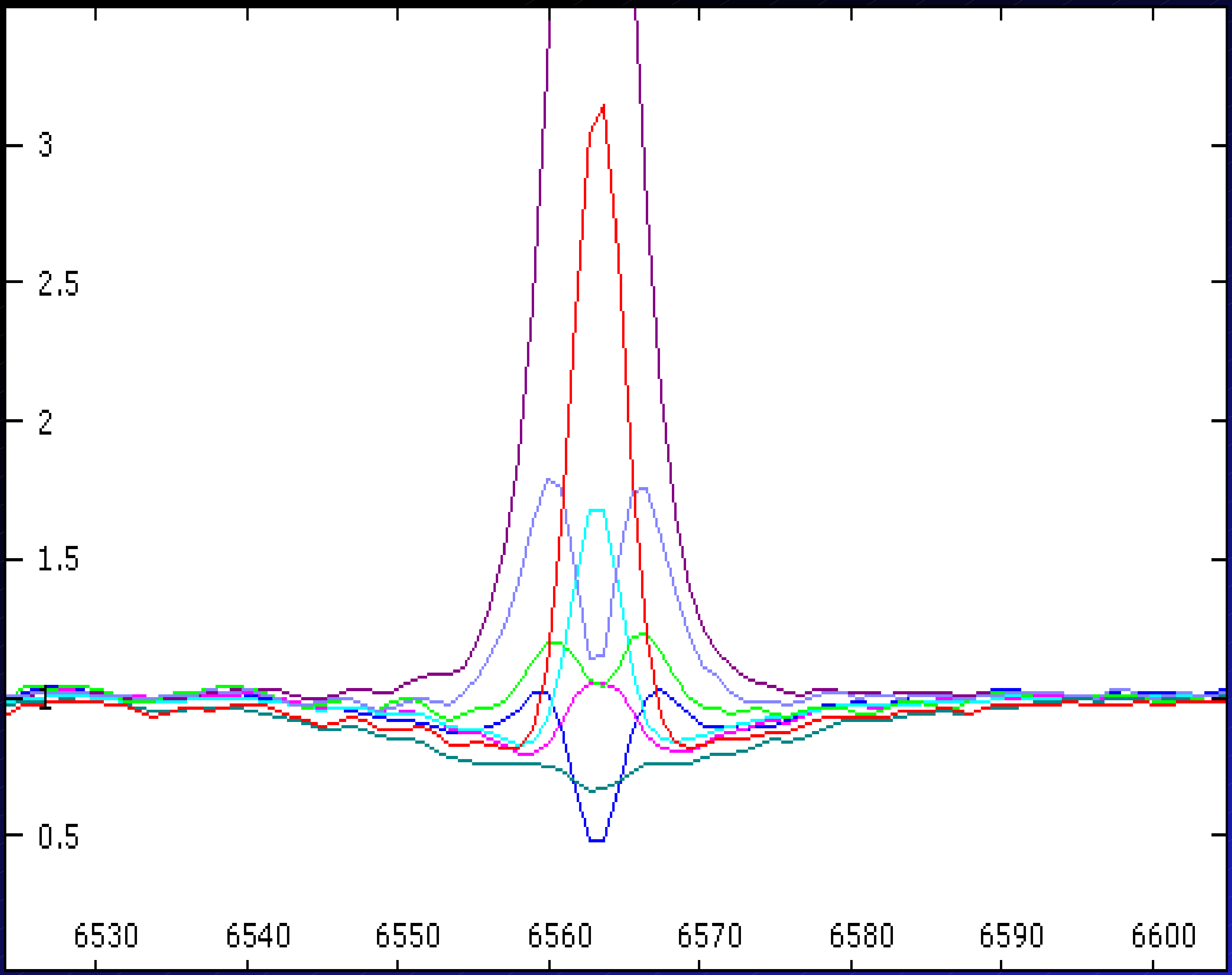


2
1.5
1
0.5
0
Pixel value (Flux)
6500
6550
6600
Position (Wavelength)

Shell čára u Be hvězd

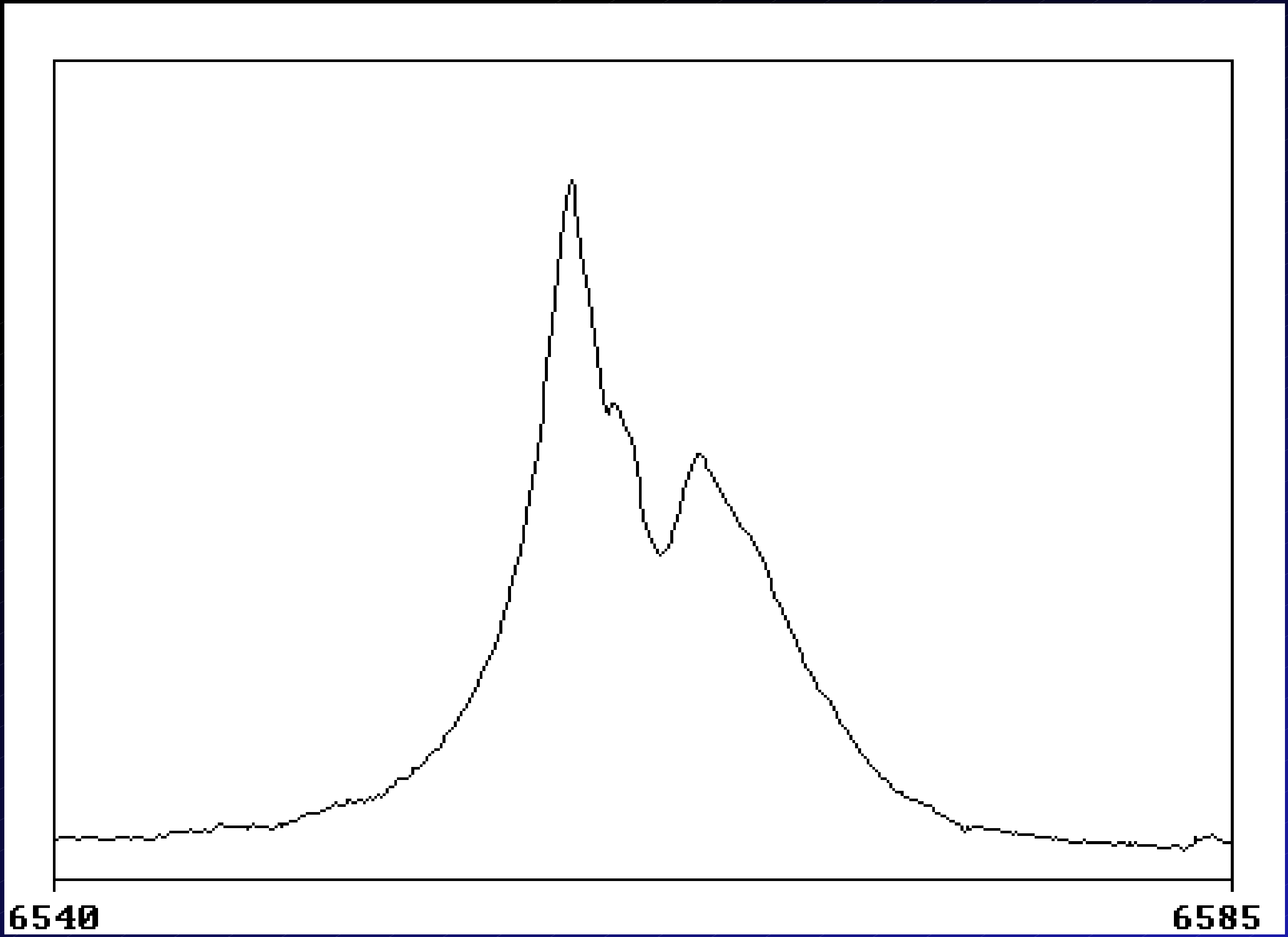


Be profily (Buill)

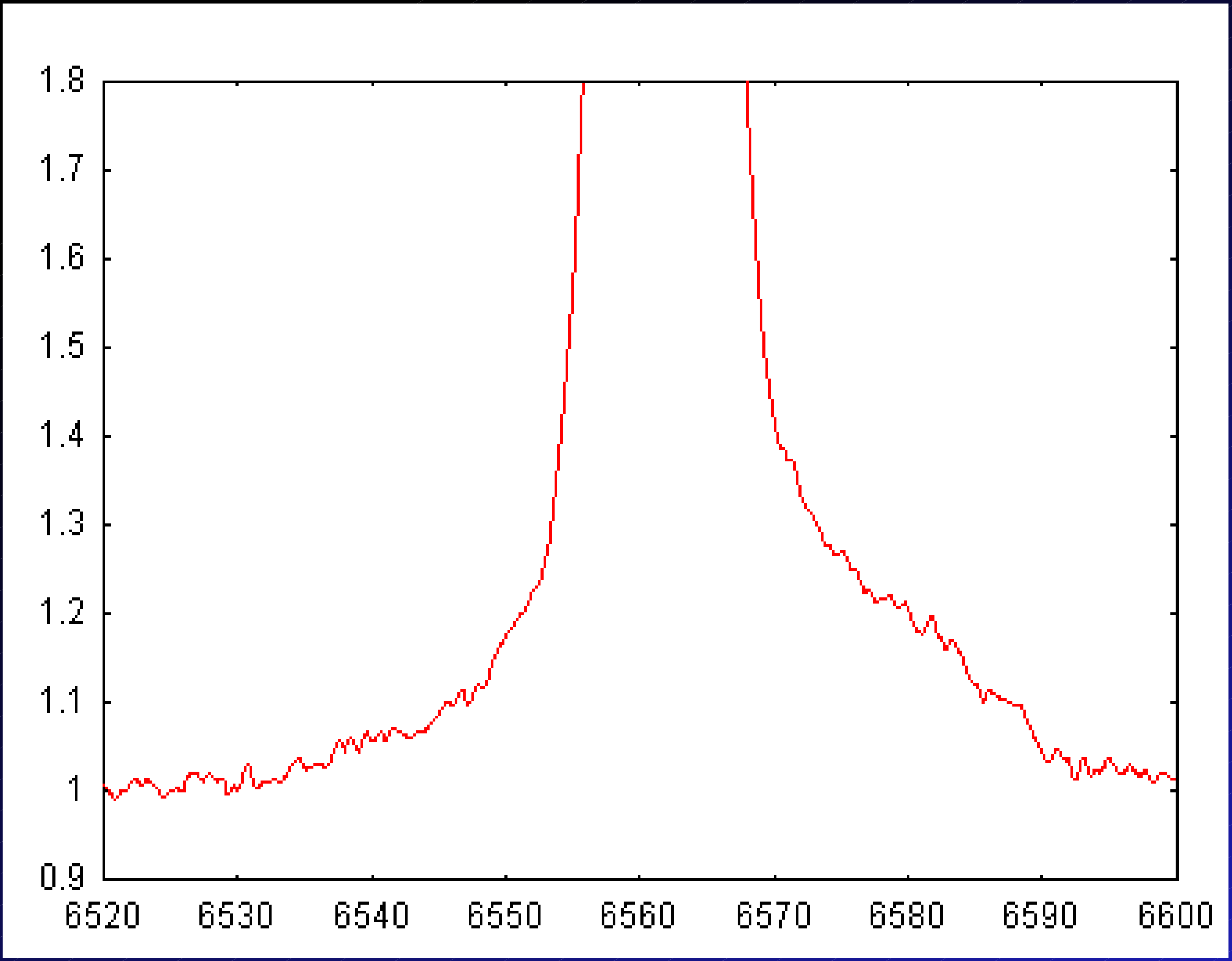


V 838 Mon

Zet Tau (Buill)

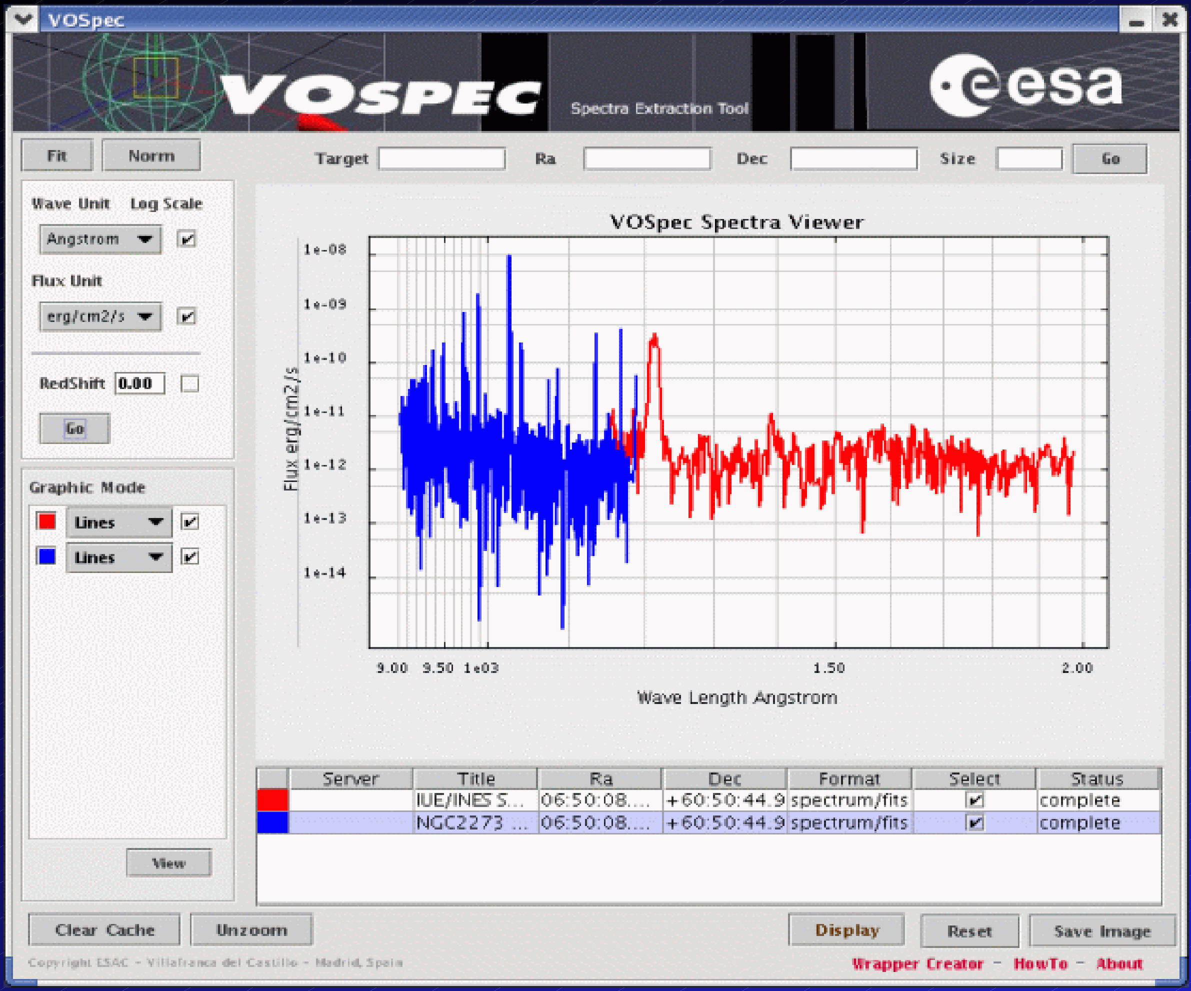


HD 206773 (Buill)

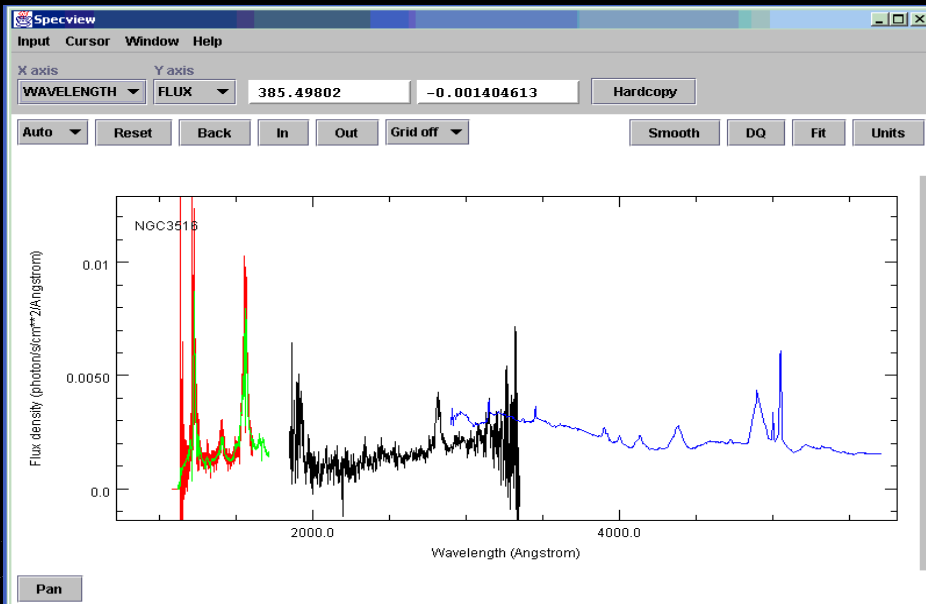


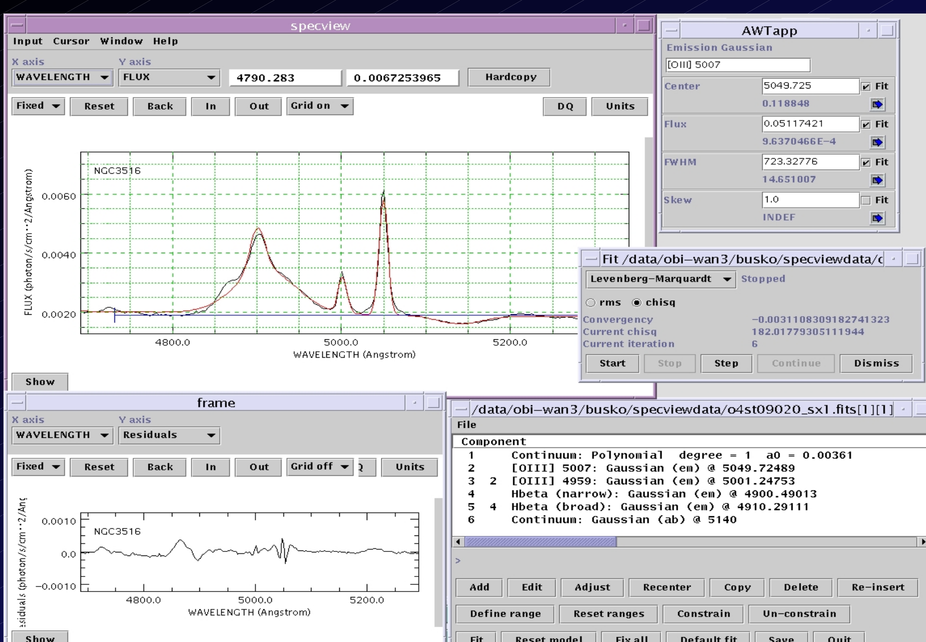
VOSpec (ESAC)

- Very simple
- Polynomial fits
- No RV measurement
- No complex operations
- In VizieR now
- Can work with SLAP!
- Theoretical VO supported
- Rapid development :-)



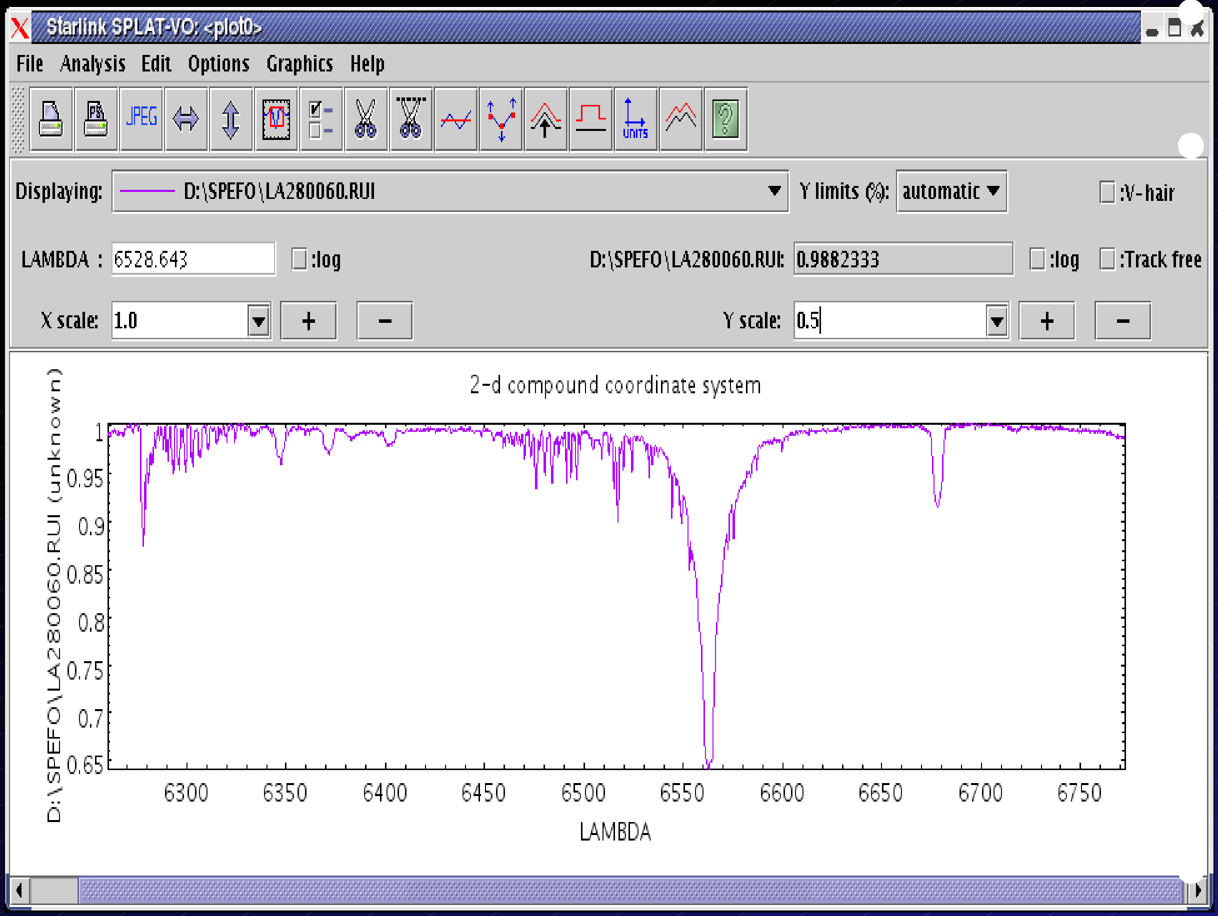
SpecView (STScI)





- Fitting profiles from models
- Simple polynomials
- Analysis strong (deredening, CLOUDY)
- Supported !!
- Not good for IRAF WCS (1D FITS)
- BinTables+Extension

SPLAT-VO



- Custom line list
- Development not justified ?
- Most advanced for stellar astronomy
- JCMT now
- Plastic
- Reads 1D FITS...