Observational Astronomy

SPECTROSCOPY
and
spectrometers

Kitchin, pp. 310-370
Chromey, pp. 362-415

Spectroscopic methods

- Different purposes require different instruments
- Main spectroscopic methods:
  - *Low resolution*
  - *Long slit, high resolution*
  - *High resolution*
- Spectroscopic observations are characterized by *spectral resolution* and *wavelength coverage*

Definition of resolution

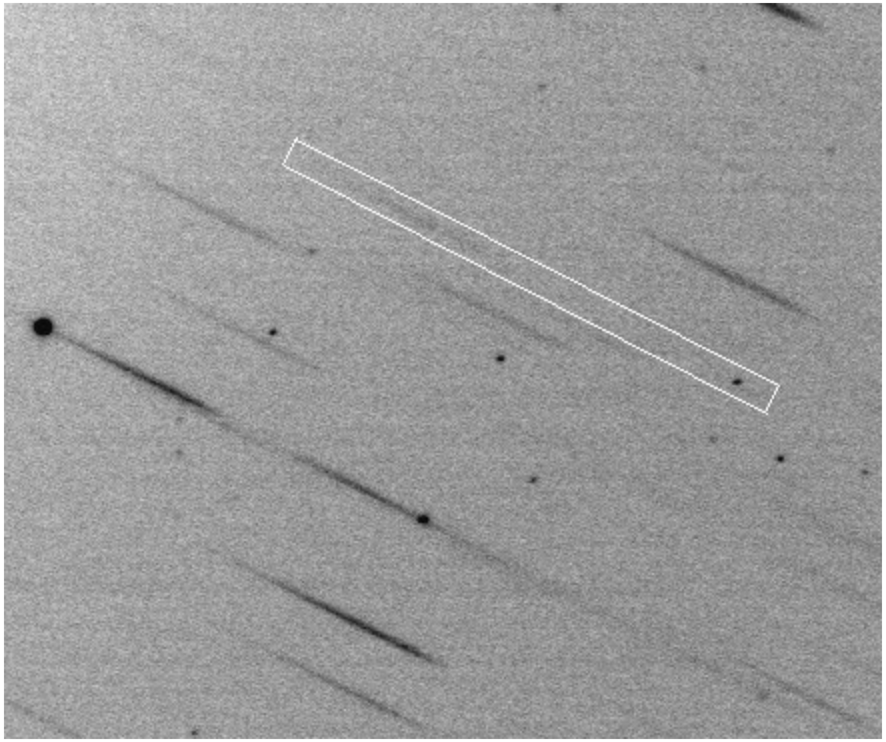
- Resolution R is defined as $\lambda/\Delta\lambda$
- $\Delta\lambda$ is the smallest distinguishable separation between two wavelengths around λ
- High resolution is above 30000
- Low resolution is below 1000

Low-resolution

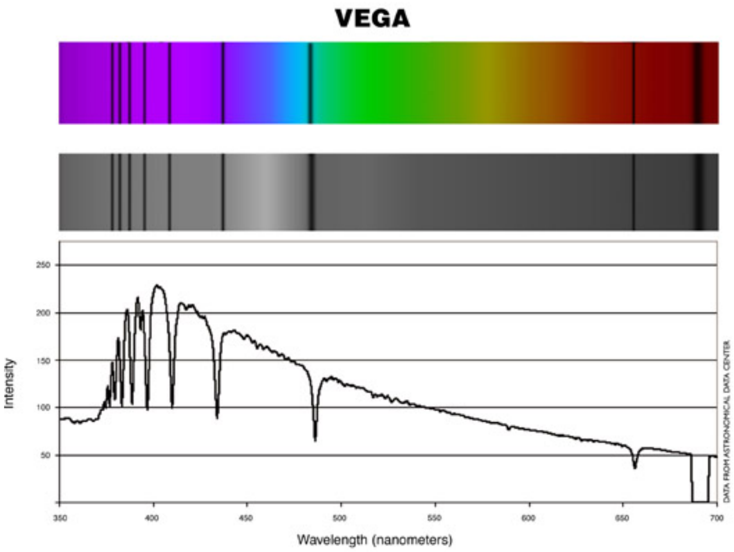
- Typical goal: search for objects with specific spectral features
- Method 1: objective prism, telescope "sees" the source through a prism, therefore each point source looks like a small spectrum
- Method 2: spectrophotometry - narrow band filters for given spectral features. Often, such filters have the possibility to change central wavelength – these are called tunable filters.

There is no slit!

Objective prism spectra



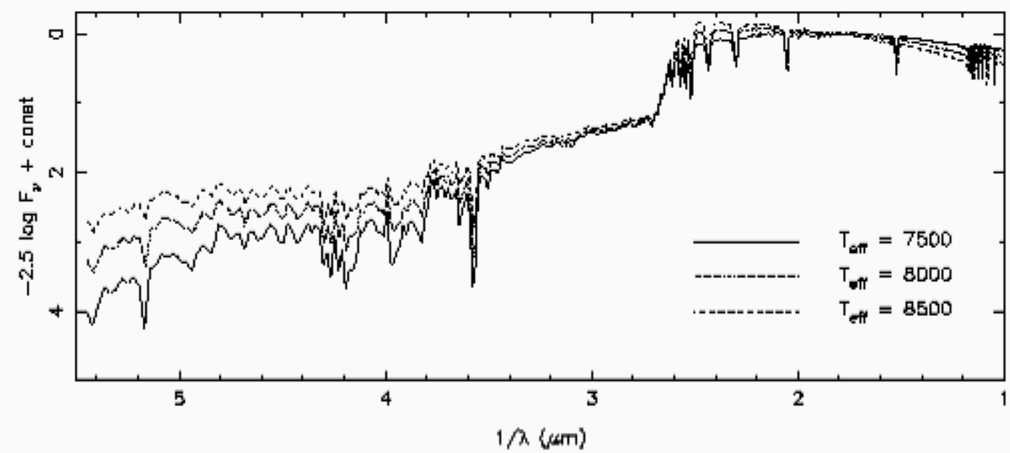
Sky viewed through a prism. White box marks a single spectrum



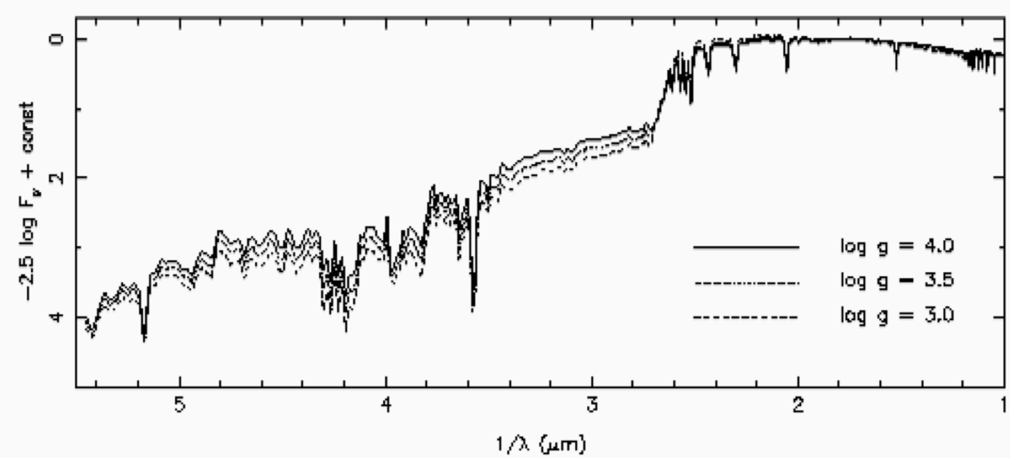
Spectrum of Vega taken with objective prism. Theoretical model is shown in color.

Spectrophotometry

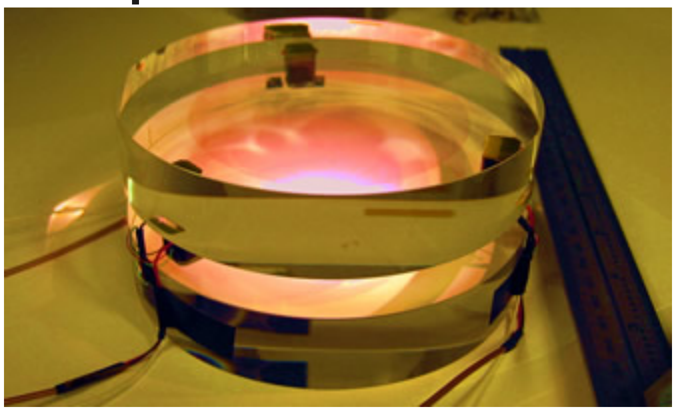
Spectral energy distribution as a function of stellar temperature



Spectral energy distribution as a function of stellar surface gravity

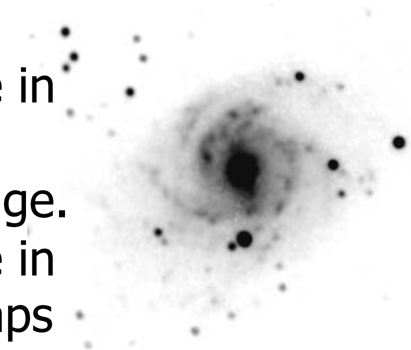


Fabry-Perot interferometer

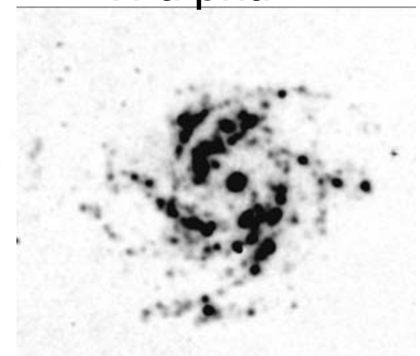


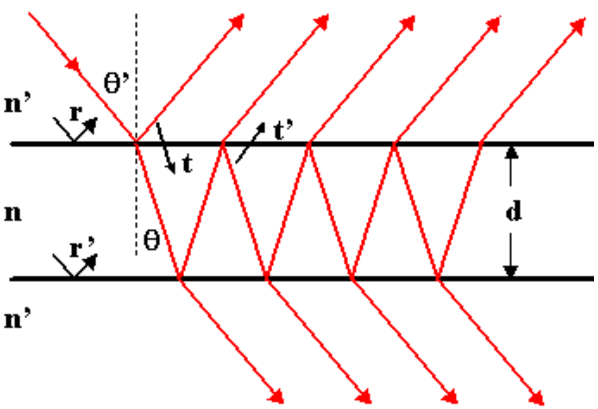
Monochromatic point source produces rings.
Extended source in white light produces an image.
Extended source in emission line maps velocities.

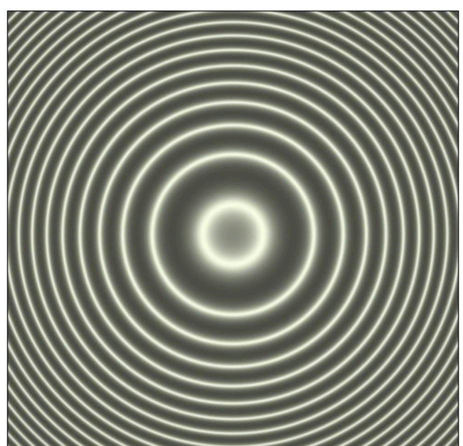
Continuum

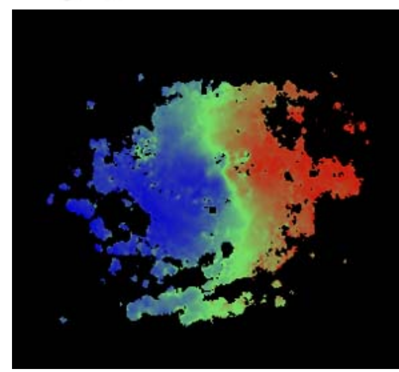


H alpha

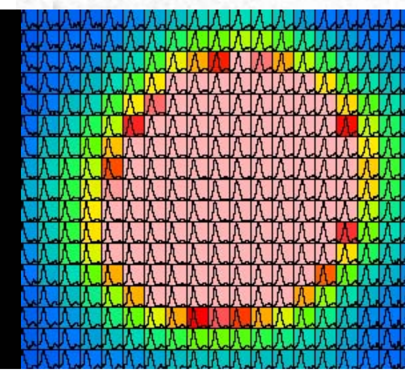






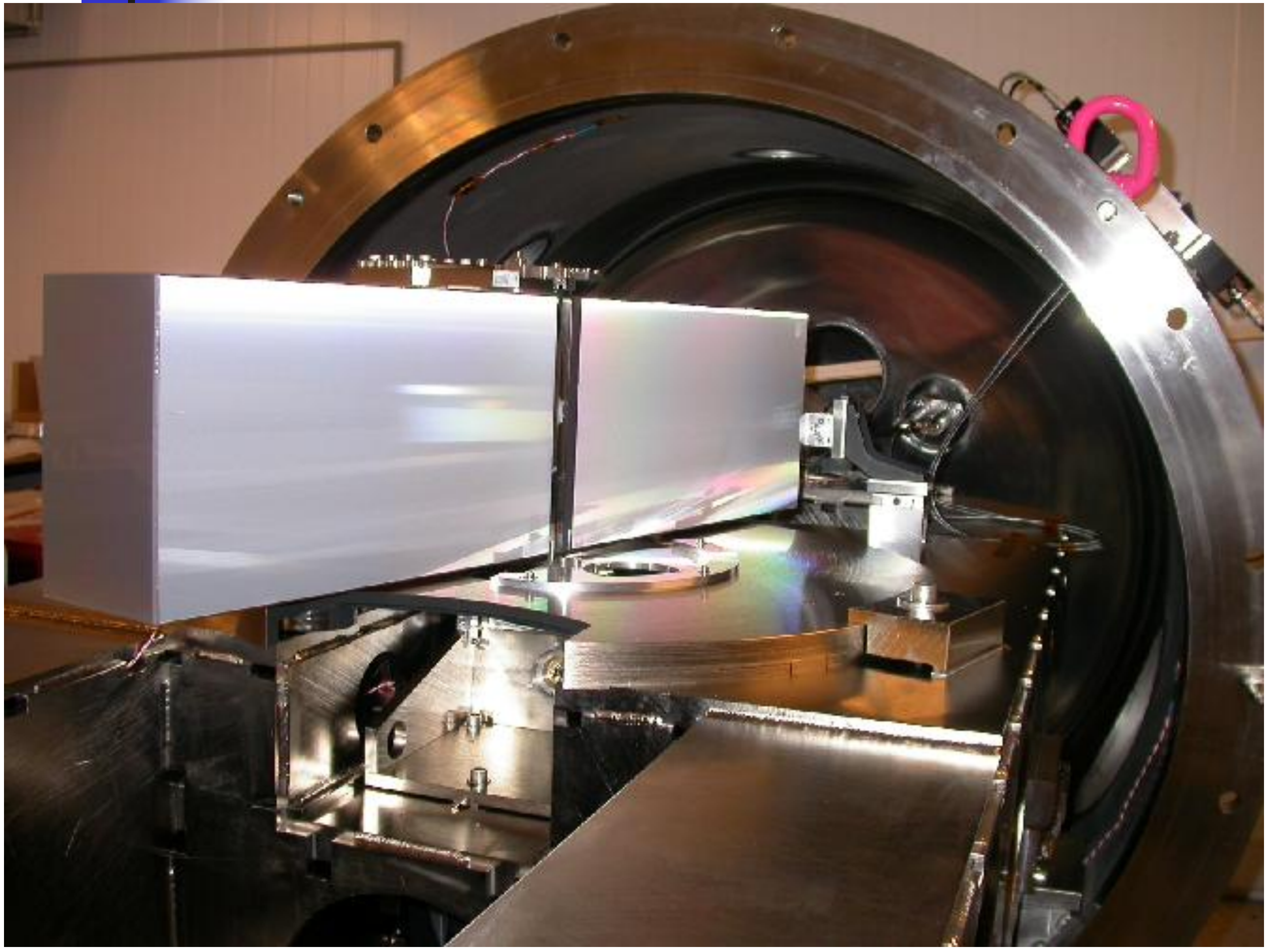


Velocity field

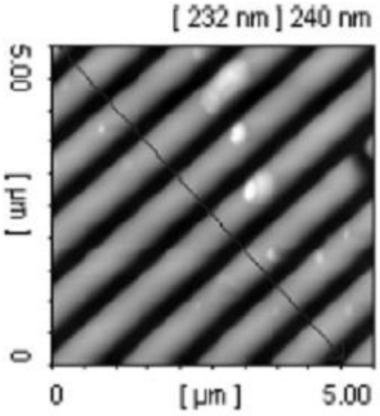


H alpha profiles

Grating spectroscopy

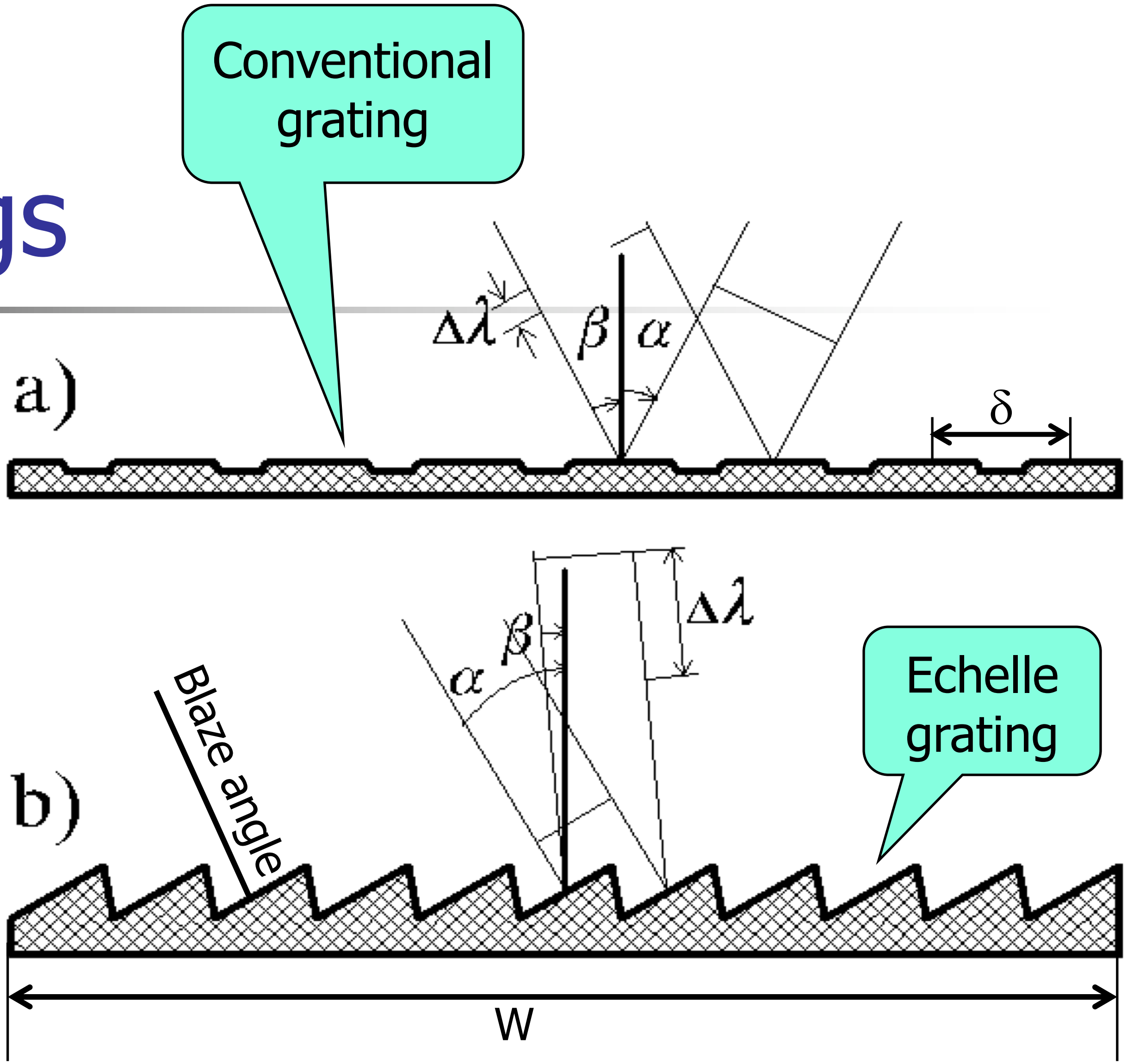


ESO HARPS spectrometer uses two echelle gratings aligned to a few nanometers



Gratings

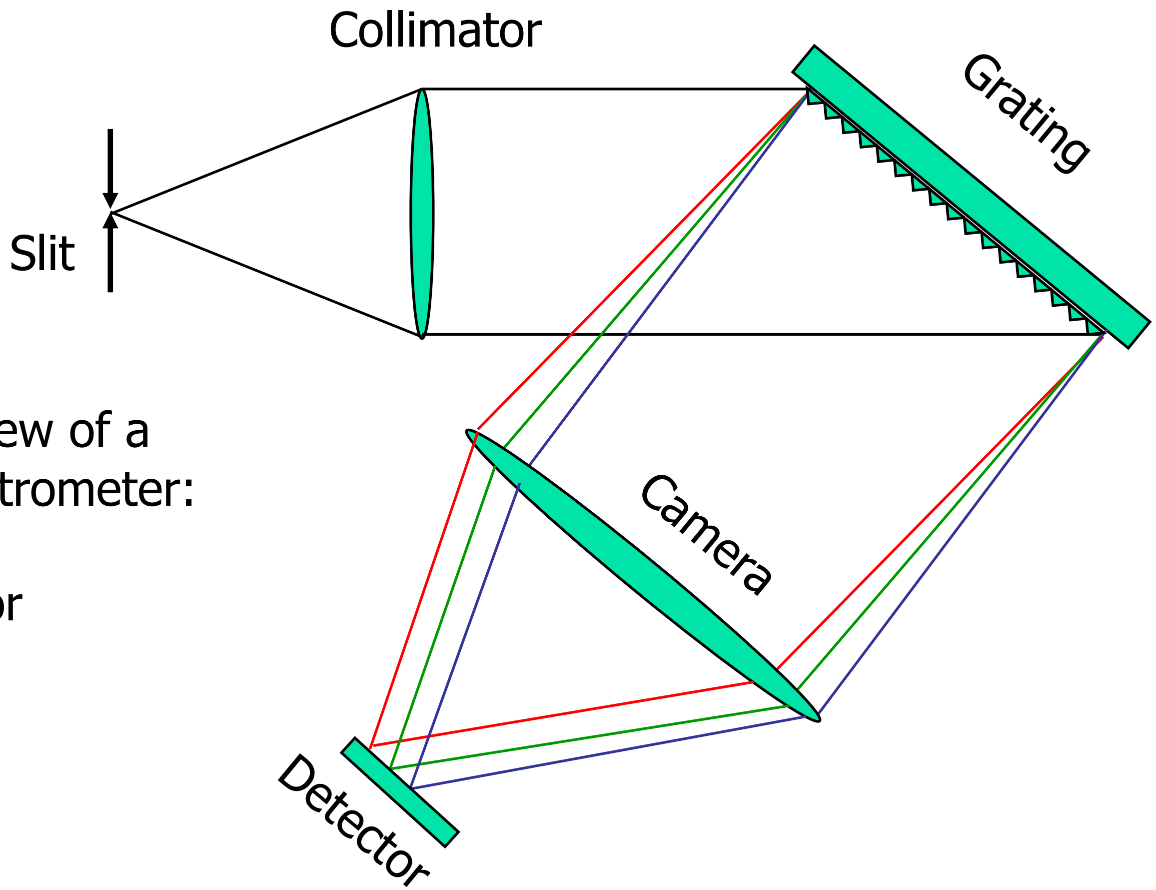
Interference between grooves



Grating formula: $\mathrm{OPD} = \delta \sin\alpha + \delta \sin\beta = m\lambda$

ptical ath ifference

Grating spectrometers



Simplified view of a grating spectrometer:

1. Slit
2. Collimator
3. Grating
4. Camera
5. Detector

A bit of math:

- Expression for angular dispersion is found by differentiating the grating equation, assuming constant incidence angle:

$$m d\lambda = \delta \cos\beta \, d\beta$$

$$\frac{d\lambda}{d\beta} = \delta \cos\beta / m$$ Angular dispersion

- Linear dispersion is readily obtained for a given focal length of the camera:

$$\frac{d\lambda}{dx} = \delta \frac{\cos\beta}{m \cdot f_{\mathrm{cam}}}$$ Linear dispersion

… and some more …

- Angular resolution. Think of a grating as a mirror, its diffraction angle is given by:

$$\Delta\beta = \lambda / (W \cdot \cos\beta)$$

Projected size of the grating

- Angular dispersion equation gives the corresponding wavelength interval:

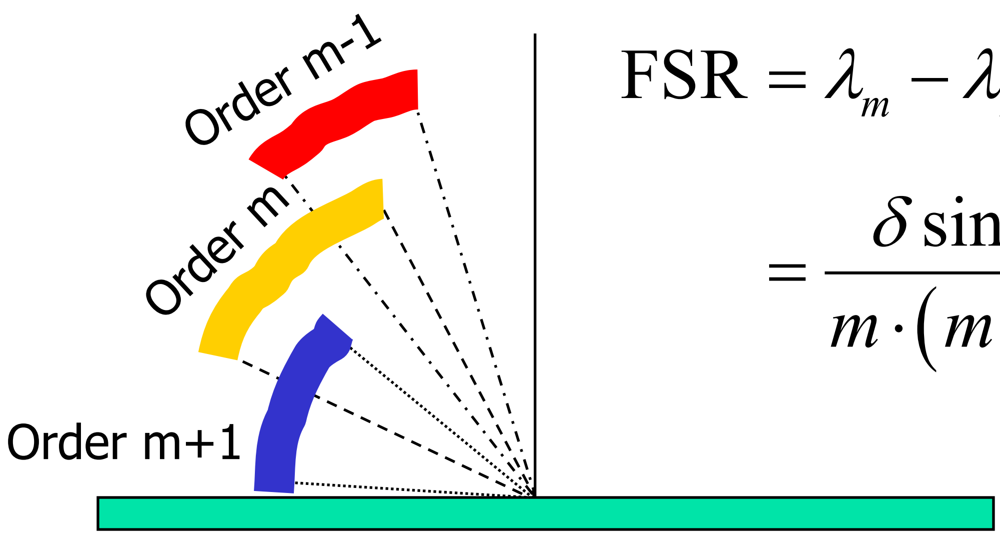
$$\frac{\lambda}{\Delta\lambda} \equiv R = m \cdot \frac{W}{\delta} = m \cdot N$$

?

- *Resolving power depends in the number of illuminated grooves!*

Free spectral range

The free spectral range (FSR) of a diffraction grating is defined as the largest bandwidth in a given order which does not overlap the adjacent orders.



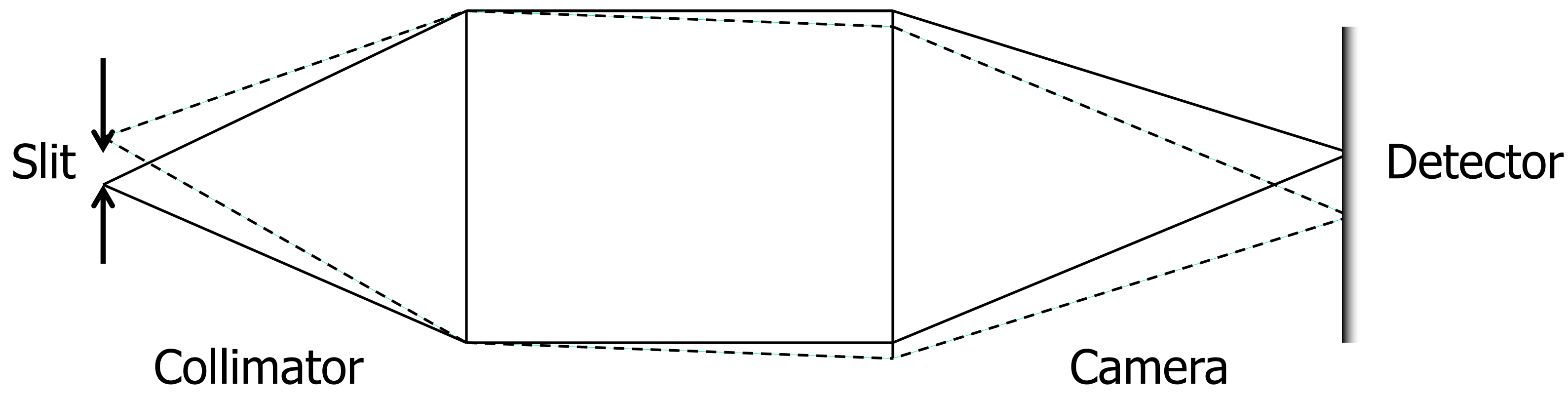
$$\mathrm{FSR} = \lambda_m - \lambda_{m+1} = \frac{\delta \sin\beta}{m} - \frac{\delta \sin\beta}{m+1} =$$

$$= \frac{\delta \sin\beta}{m \cdot (m+1)}$$

For a prism FSR is the whole spectral range!

Real world: the slit size and seeing

- A spectrometer also works as an optical system that creates and image of the slit on the detector.
- Slit image can be magnified or de-magnified depending if the focal length of the camera is larger or smaller than the focal length of the collimator



- If, given the two focal lengths, we try to match the size of the slit image to the diffraction image of the grating, the slit will have to be too narrow compared to the images of stars produced by a telescope. We will loose light!

Real world: the seeing and the pixel size

- The slit is located in the focal plane of the telescope.
- If the seeing (image quality) is such that point sources (stars) are 1″ on the sky, the image on the slit will be ≈1/200000 rad x focal length of the telescope.
- For BWT, the diameter is 0.9m and the focal ratio is f/4 so the focal length f_{tel}=3.6m. Typical seeing is 2″, so image of a star is 35 micron across.
- A 20cm echelle grating with 72 groves/mm and 60 degrees blaze angle will have a one-to-one relation between order number m and the central wavelength of the order λ in microns:

$$m\lambda_m = 2\sin\theta_{\text{blaze}} \cdot \delta = 2 \cdot 0.866 \cdot 10^3/72 \approx 24$$

- Thus 500nm wavelength is best observed in order 48 (24/0.5=48) and 600nm falls into order 40 (24/0.6=40).

Real world: the seeing and the pixel size

- In order to achieve the theoretical resolving power of the grating we have to match the diffraction angle of the echelle to the slit size.
- In other words we need to match the angular size of the slit to the angular resolution element of the grating:

$$\Delta\alpha = \lambda/(W \cos\theta_{\rm blaze})$$

- The right-hand side is 6×10^{-6} radian at 600nm. For the grating to see the 35 micron slit width at this angle to collimator focal length must be $35/6\times10^{-6}$ = 5.83m!
- This value scales with the diameter of the telescope.
- In practice we select shorter focal length (1m) sacrificing resolving power.

Real world: matching the seeing and the pixel size

- The angular slit size as seen by the grating is:

$$\Delta\alpha = s / f_{\text{coll}}$$

where f_{coll} is the focal length of the collimator and s is the linear width of the slit. Grating equation connects this to the angular resolution element. For a fixed wavelength:

$$\Delta\alpha \cos\alpha = s / f_{\text{coll}} \cos\alpha = -\Delta\beta \cos\beta$$

$$|\Delta\beta| = \frac{s \cdot \cos\alpha}{f_{\text{coll}} \cdot \cos\beta}$$

- In practice, we select the slit matching the seeing and select the camera focal length to match the pixel scale.
- The resolution is then defined by the slit image size!

Putting some numbers

Home work

The spectrograph for the BWT is based on a 20 cm grating with a blaze angle of 66.5º and 72 grooves per mm

- Find diffraction-limited resolving power of the grating at 4000 Å, 6000 Å and 8000 Å
- Find the optimal slit size with collimator focal length of 80cm
- Take a realistic seeing (2”) and the matching entrance slit size. Compute the resolving power R and the camera focal length to have 3 pixel sampling of the resolution element set by the seeing (for 15 micron CCD pixel size)
- Why is it hard to make high-resolution spectrometers for large telescopes? How the size of the primary mirror affects elements of a spectrometer?

Solution

1) Grating constant is:

$$m\lambda = 2\delta \sin\theta_{\text{blaze}} = 2 \cdot 10^3/72 \cdot \sin 66.5^\circ = 25.474\mu$$

2) Thus the order numbers are: 64, 42, 32
3) Diffraction-limited resolving power is 921600, 604800 and 460800
4) Angular size of the resolution element is: $\Delta\alpha = \lambda/(W \cos\theta_{\text{blaze}})$ and scaled by the collimator length we get: 4, 6 and 8 microns.

5) Find the real slit size and resolving power:
   - 2" seeing and the 0.9m x 4 telescope focal require 36**μ** entrance slit size. 36**μ** must be re-imaged onto three pixels or 45**μ.** Thus the focal length of the camera should be 45 / 36 x 0.8m = 1m.
   - From the expression for angular dispersion you can convert the angular size of the slit image 45**μ**/1m to the interval in wavelength, which is all that is needed to compute R for each wavelength.

Equation summary

$m\lambda = \delta \sin \alpha + \delta \sin \beta$	Grating equation
$m\lambda_m = 2\delta \sin \theta_{\mathrm{blaze}}$	Central wavelength of an order
$\Delta\lambda = \delta \cos \beta / m \Delta\beta$	Angular dispersion
$\Delta\beta_{\mathrm{diff}} = \lambda / (W \cos \beta)$	Diffraction limit to spectral resolution

Modern concepts

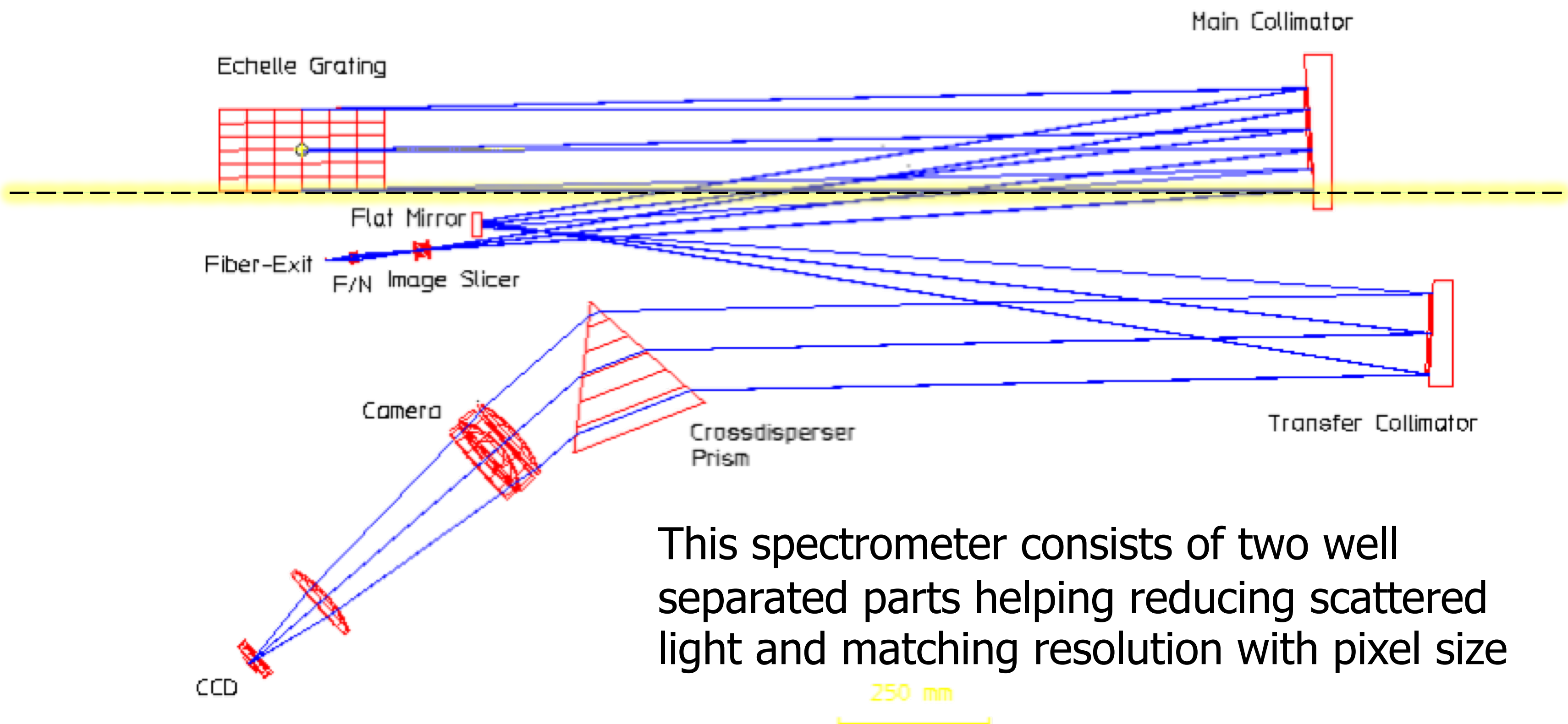
- Echelle gives high resolving power (high orders) and high efficiency (no dark stripes)
- Spectral orders overlap (maximum reflection at blaze angle) $\Rightarrow$ order selection or cross-disperser is needed (e.g. grating or prism)
- Central wavelength of order m is given by:

$$\lambda_m = 2\delta \sin\theta_{\text{blaze}} / m$$

- With a cross-disperser the whole spectrum is packed in a rectangular 2D format, perfect for an electronic detector

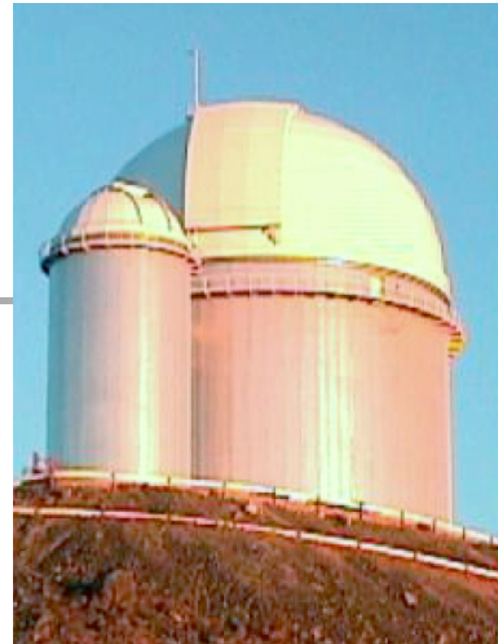
Spectrograph designs

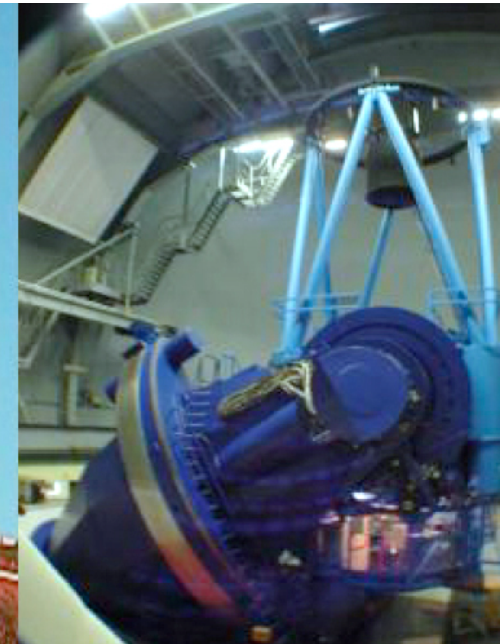
Echelle, white pupil scheme (e.g. FEROS)

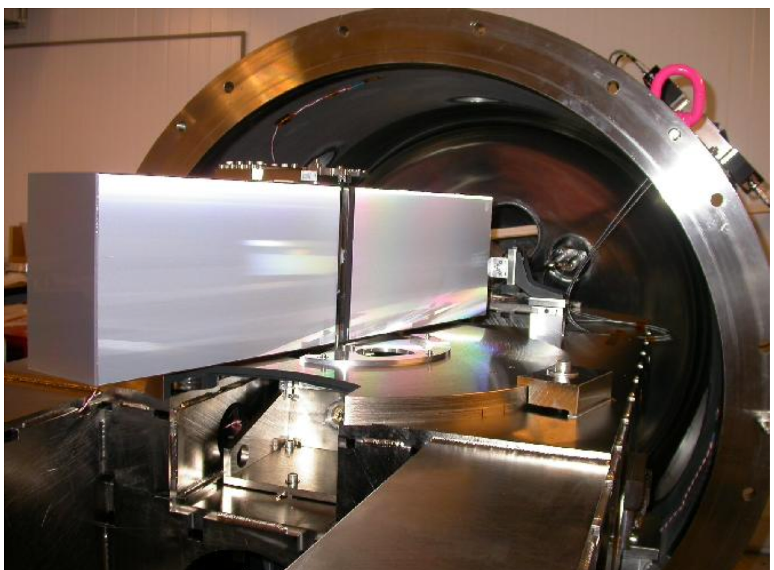


This spectrometer consists of two well separated parts helping reducing scattered light and matching resolution with pixel size

HARPS

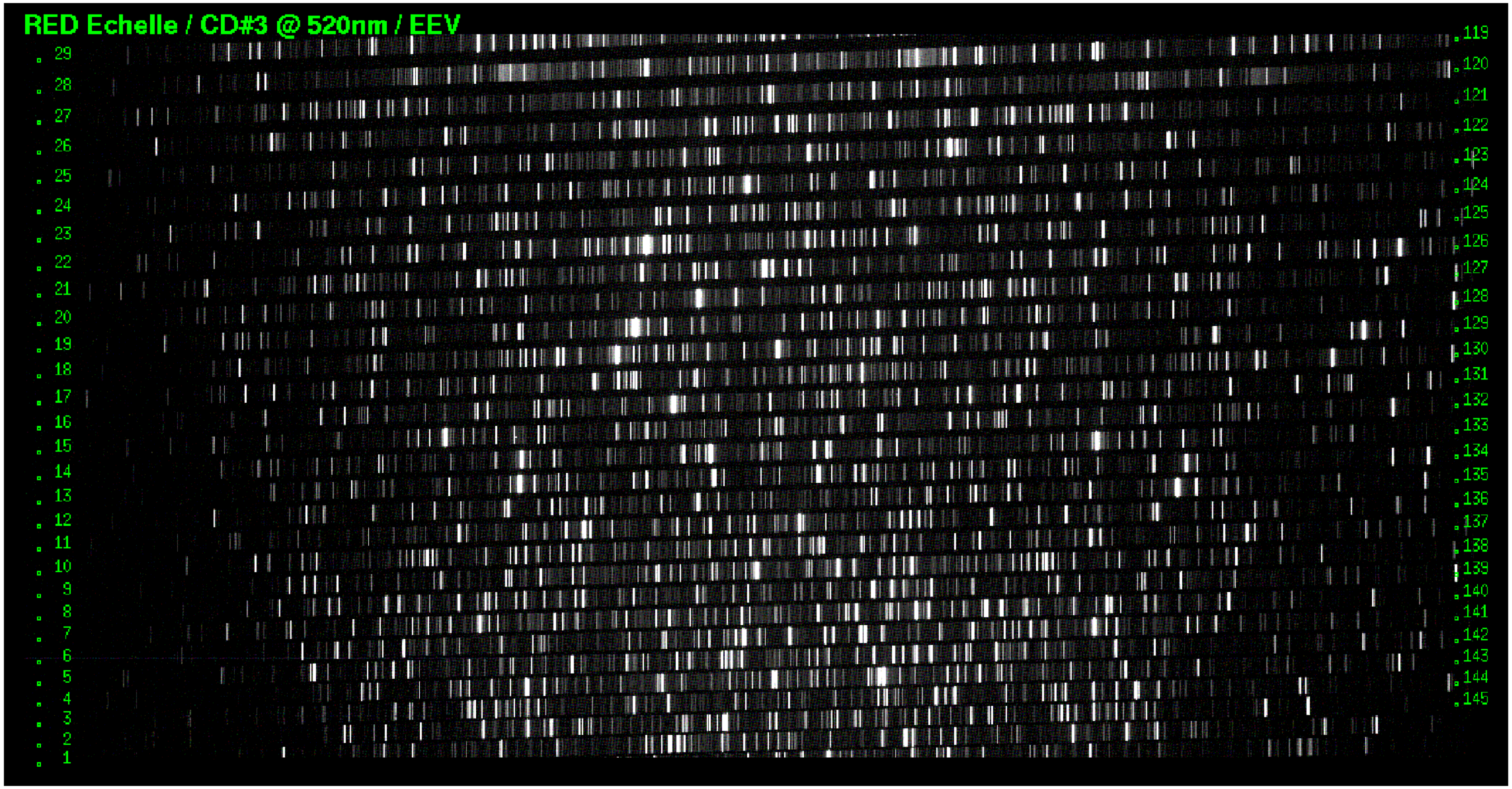




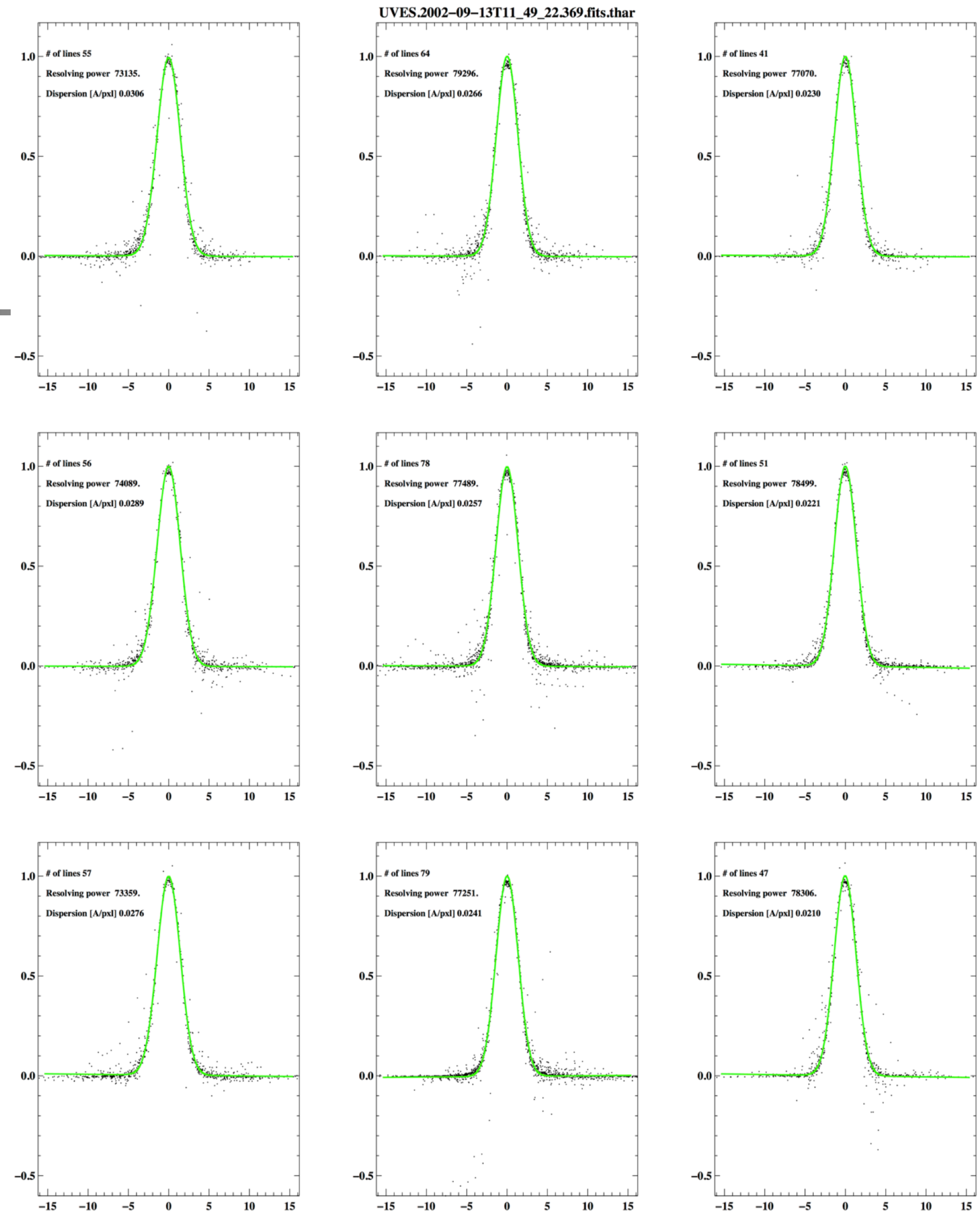


Echelle focal plane layout

Thorium Argon emission line spectrum

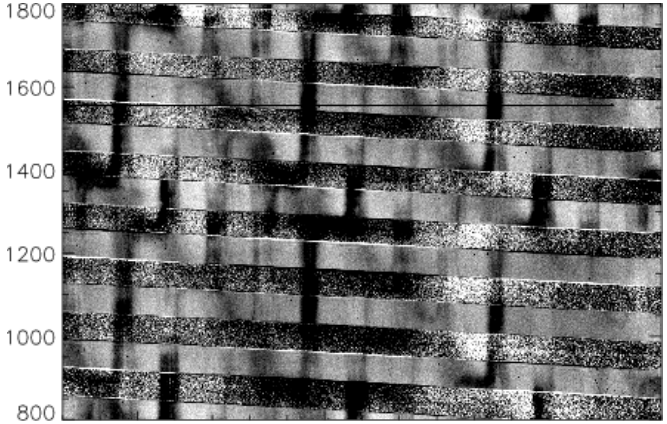


PSF example for UVES



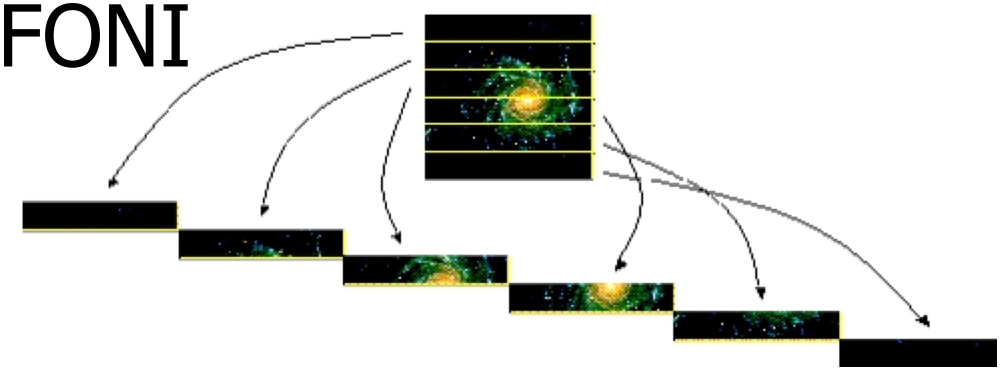
Side effects

- Orders are curved
- Order spacing changes
- Short FSR
- Camera aberrations directly affect resolution
- Strong fringing

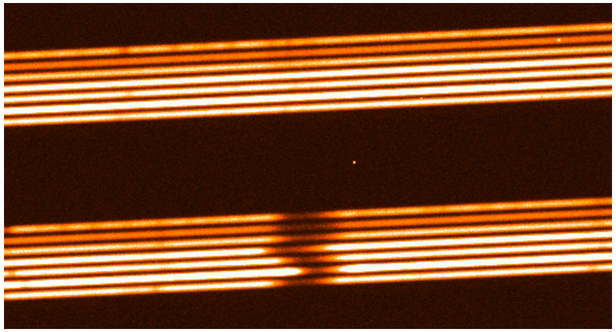


Other spectroscopic instruments

- IFU instruments
  2D image slices are re-arranged in 1D slit. E.g. SINFONI



- Multi-object instruments.
  E.g. FORS, FLAMES



Next time

Astronomy on the web
by Oleg Kochukhov