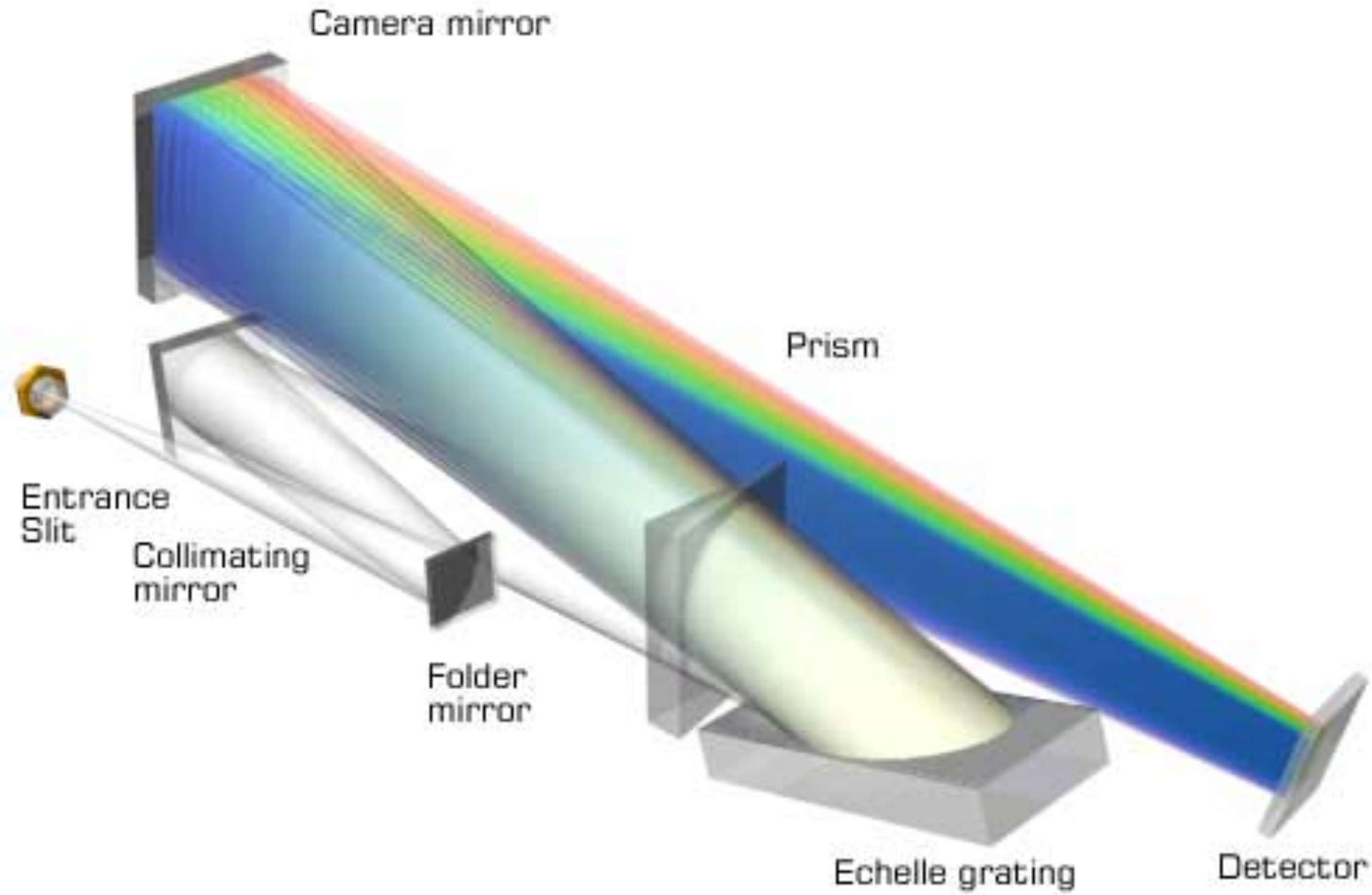
Cross-dispersed Spectra

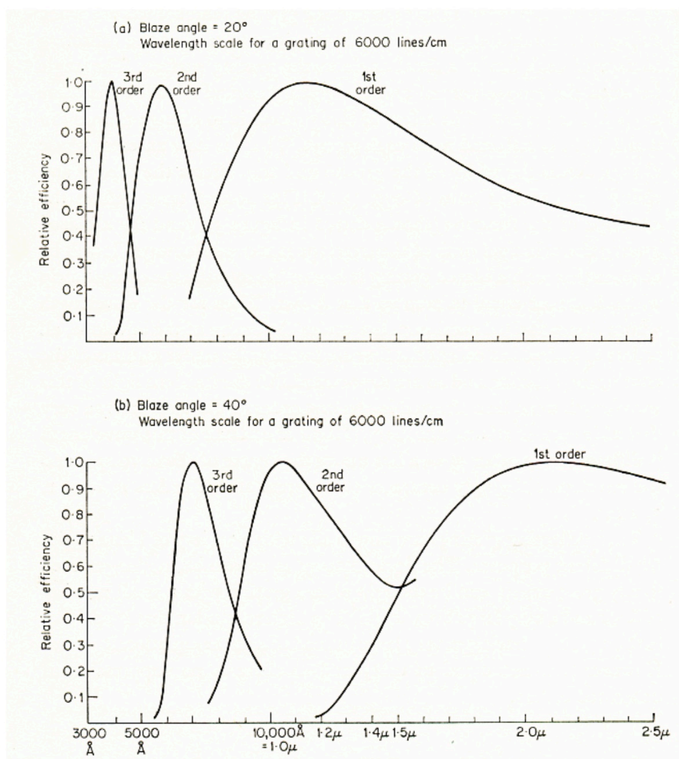


Echelle spectrometers for high R in a compact format

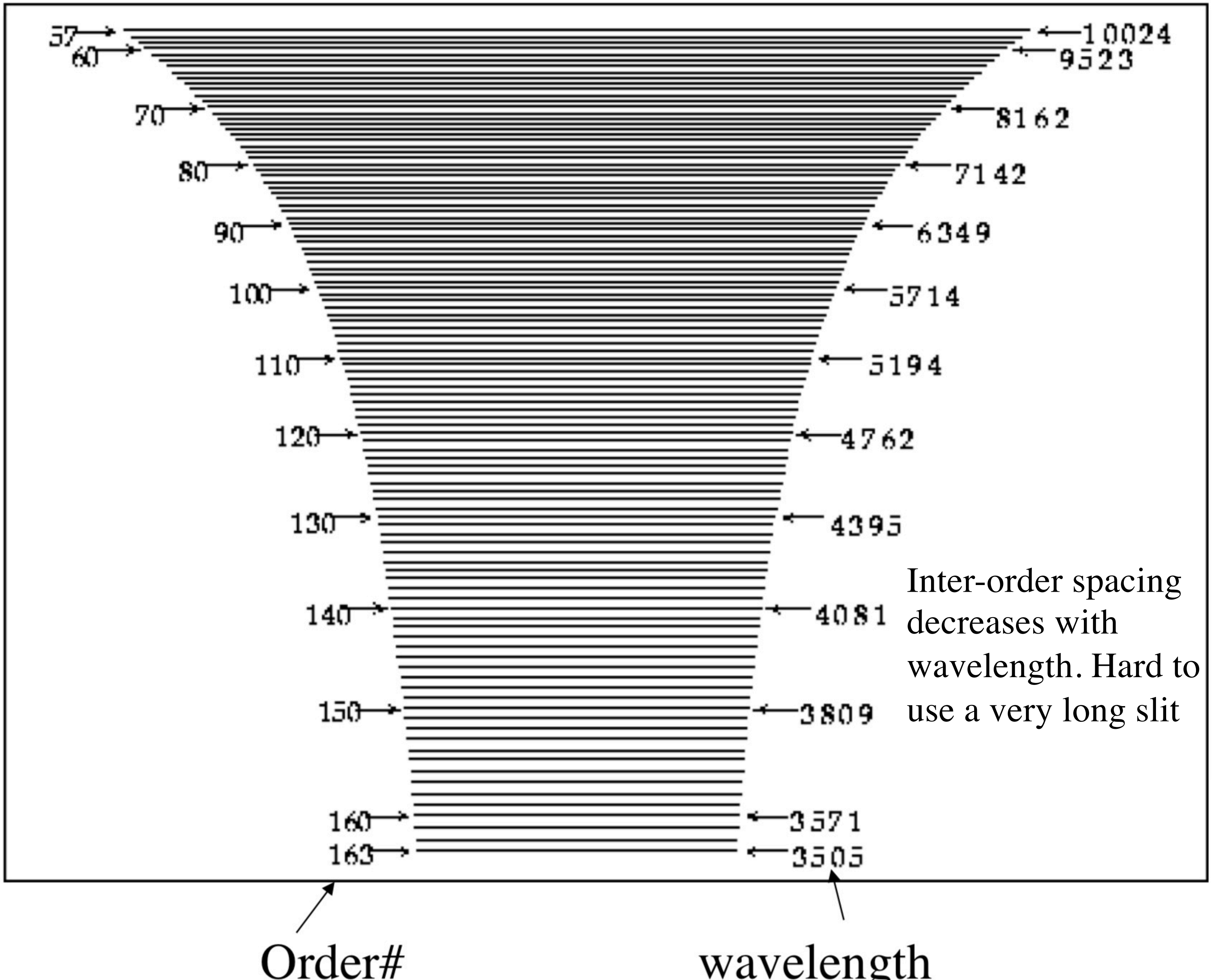
- Grating resolution R ∝ mN (order, #lines)
- If work in higher orders, have higher spectral resolution at cost of blaze width. Blazed to work at high m, usually N is small (like 30 l/mm)

> There is strong order overlap so a prism of second grating is used to "cross disperse" the spectrum and in a space-efficient way fill the detector with many orders

Grating Efficiency

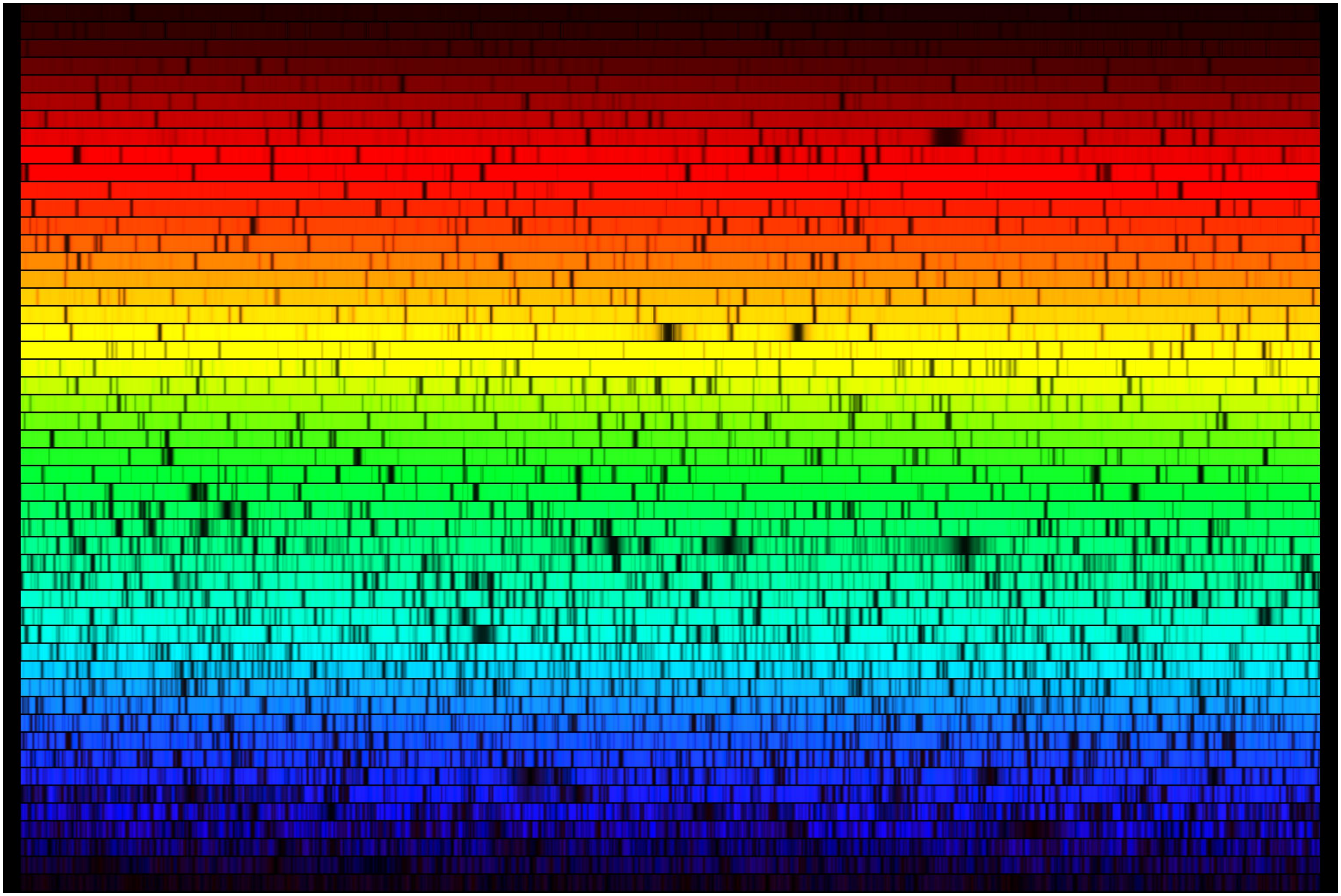


A Schematic View of an Echelle Spectrogram (HIRES)

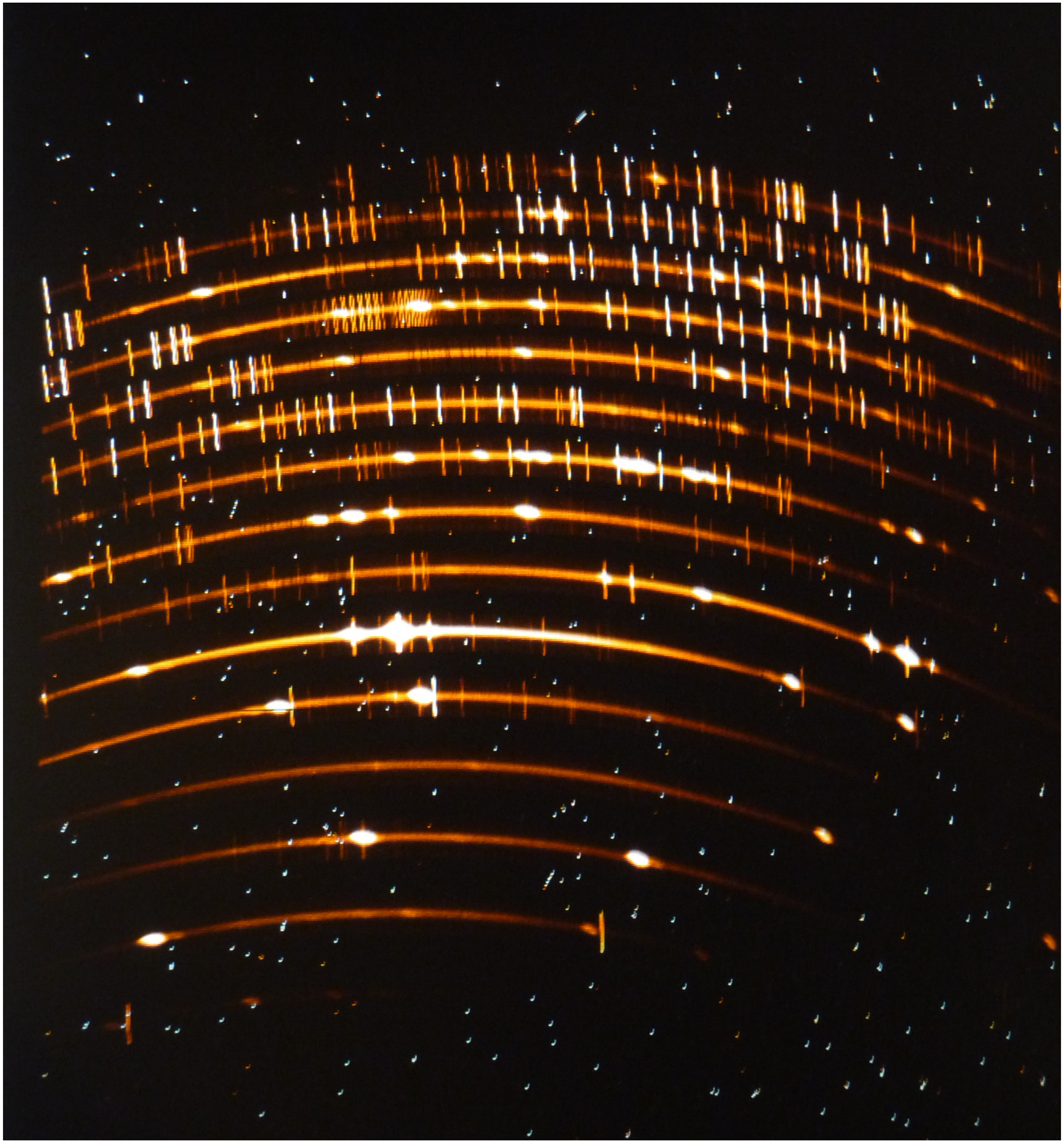


Inter-order spacing decreases with wavelength. Hard to use a very long slit

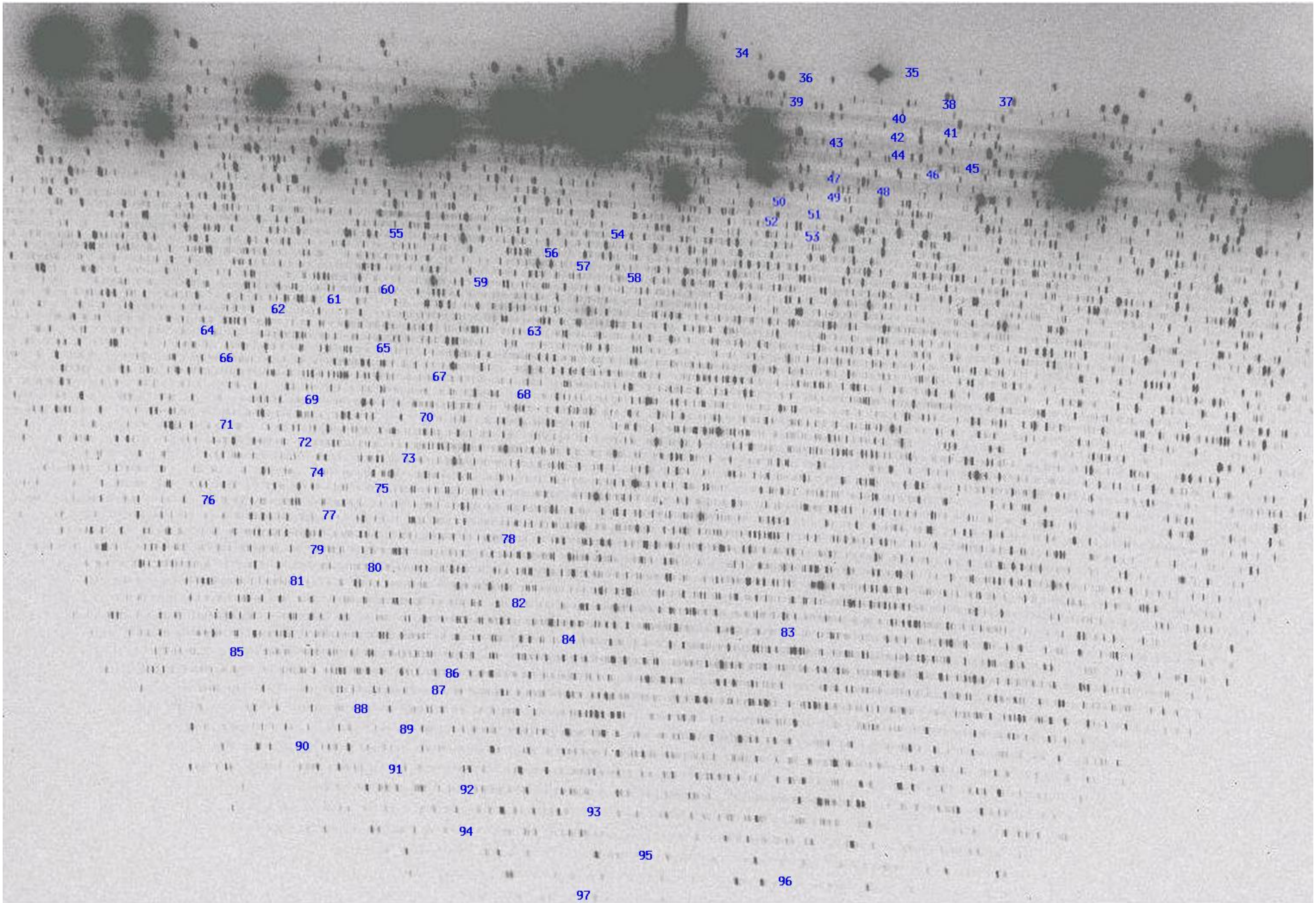
Typically have orders > 20 so spectral resolution is high.



orders

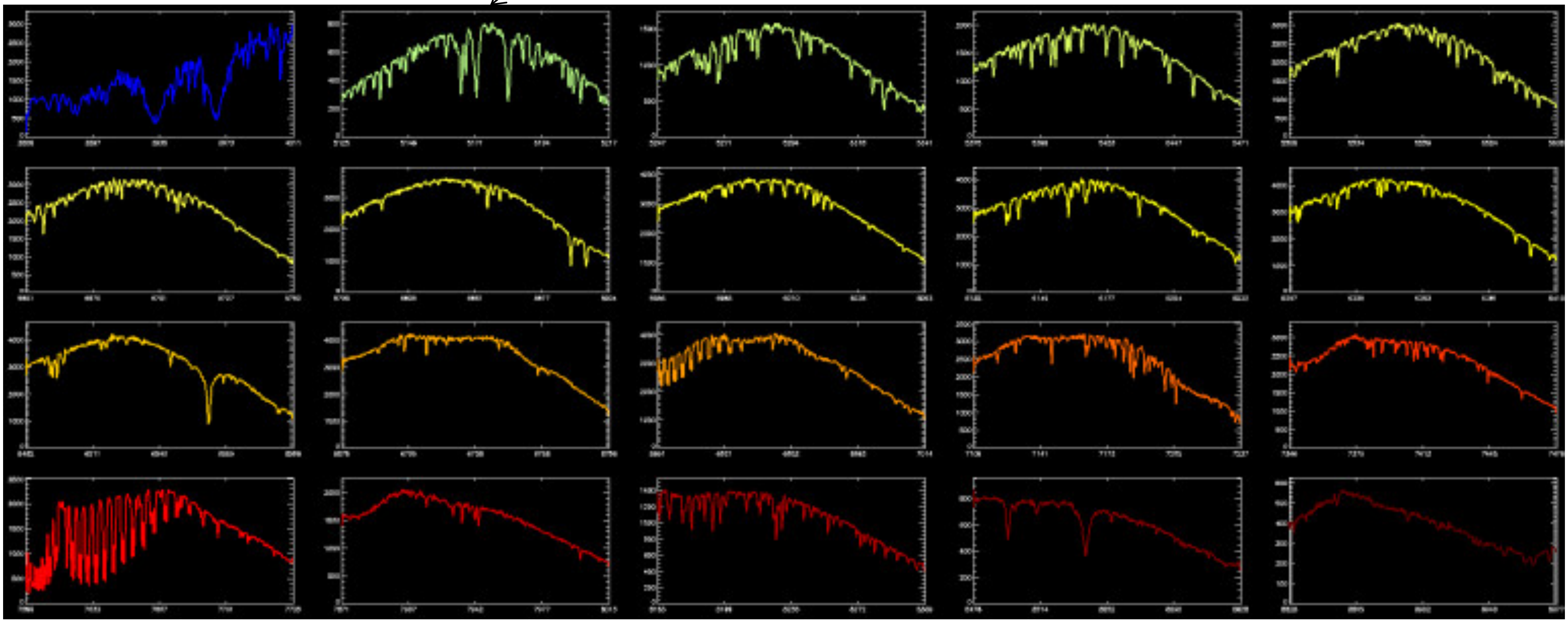


X-shooter VLT



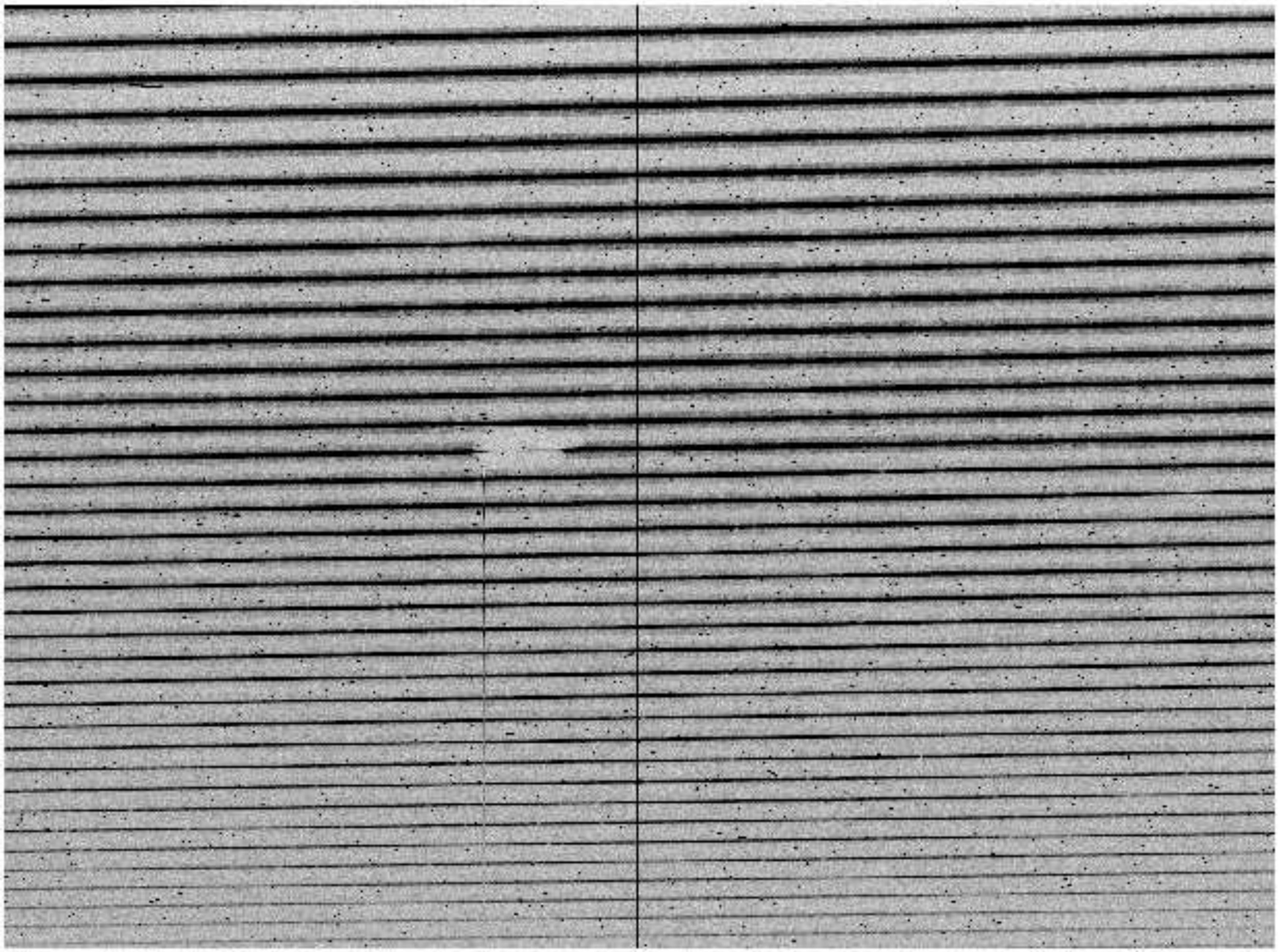
IMACS Magellan 6.5

Each order has a blaze function

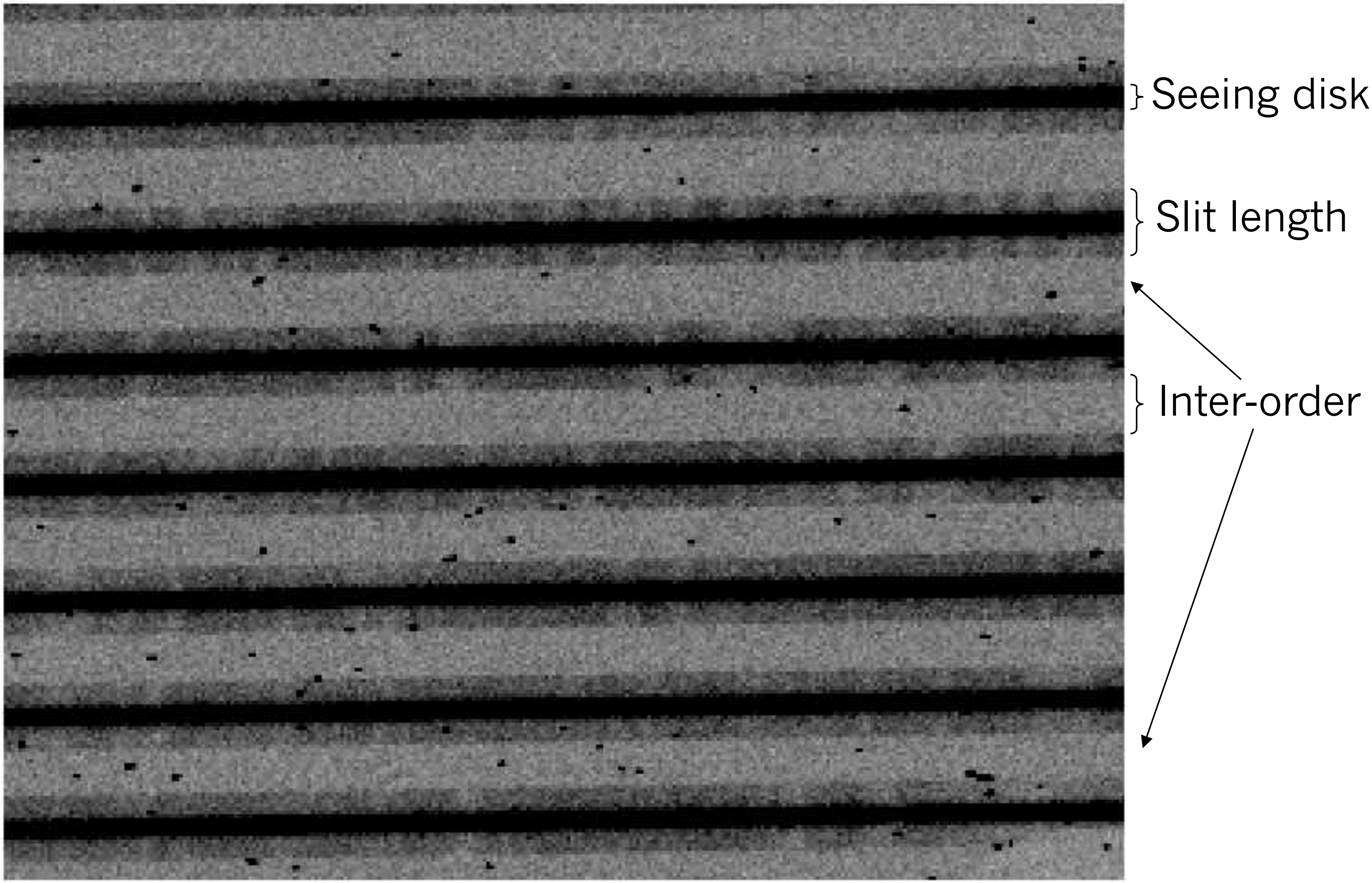


Often the orders overlap and you can increase S/N by combining

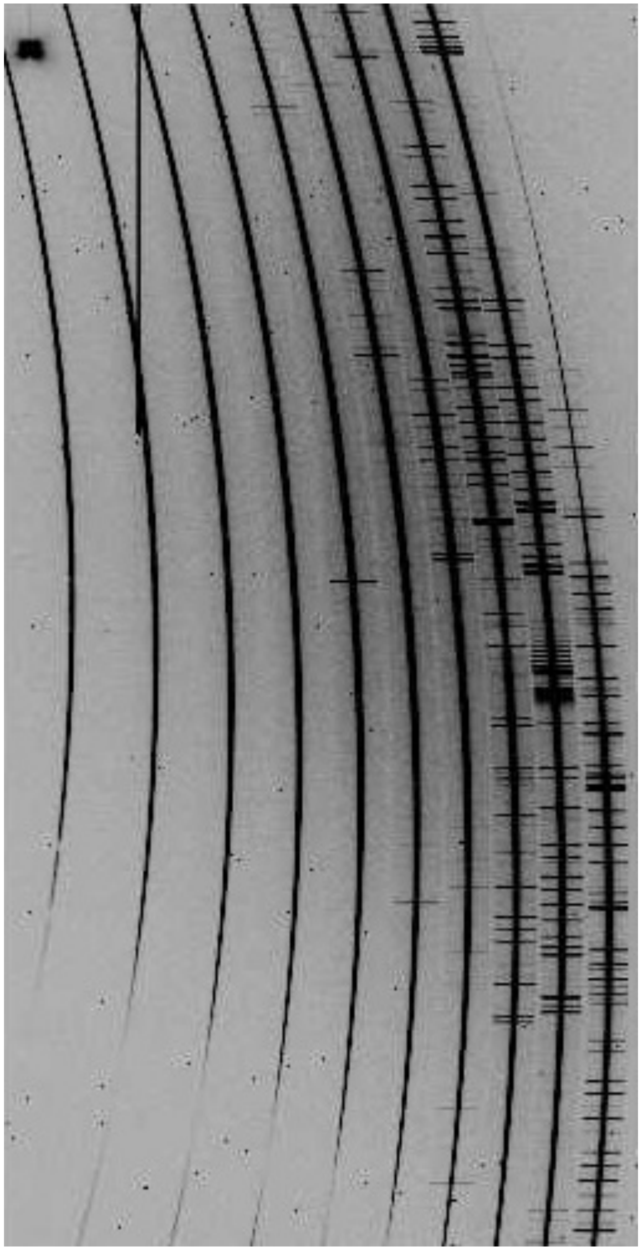
Echelle format spectra reduction

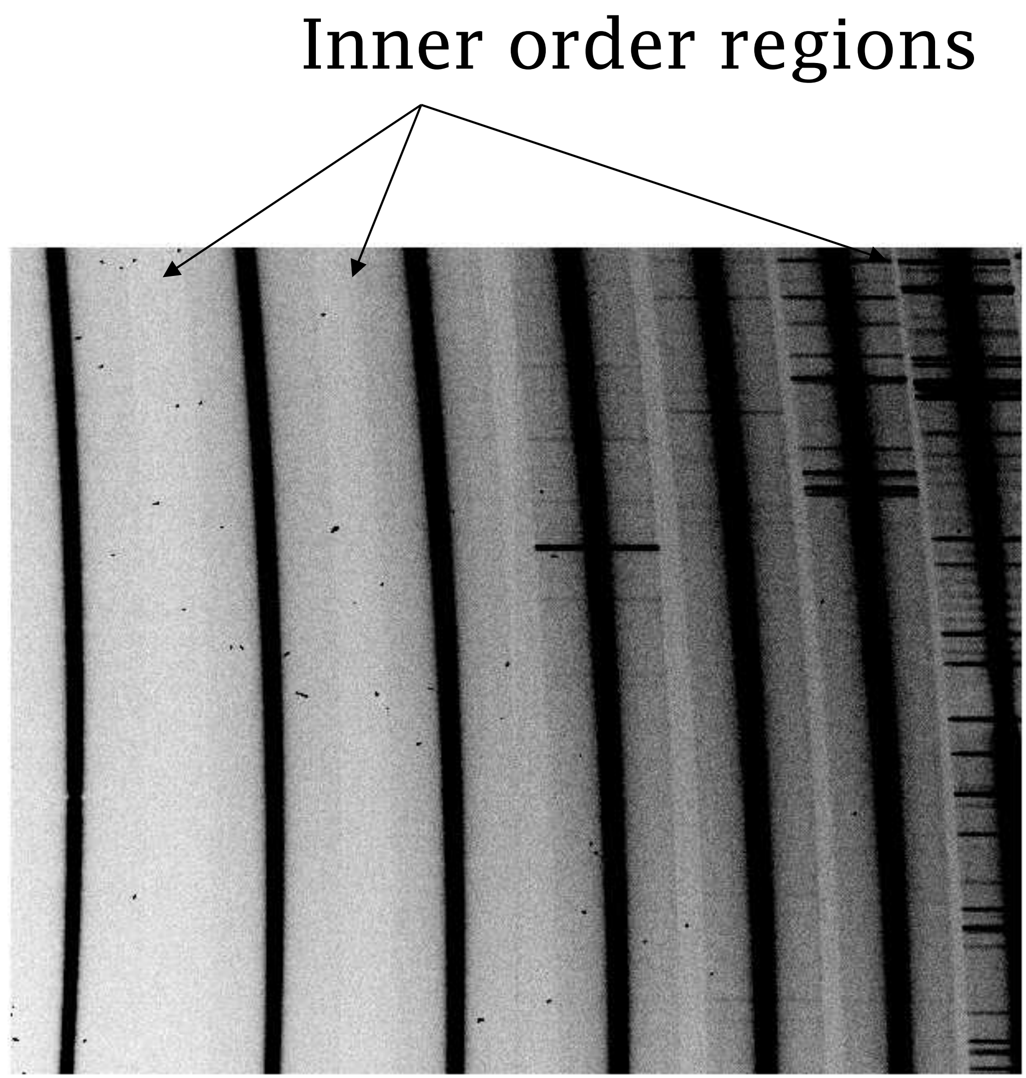


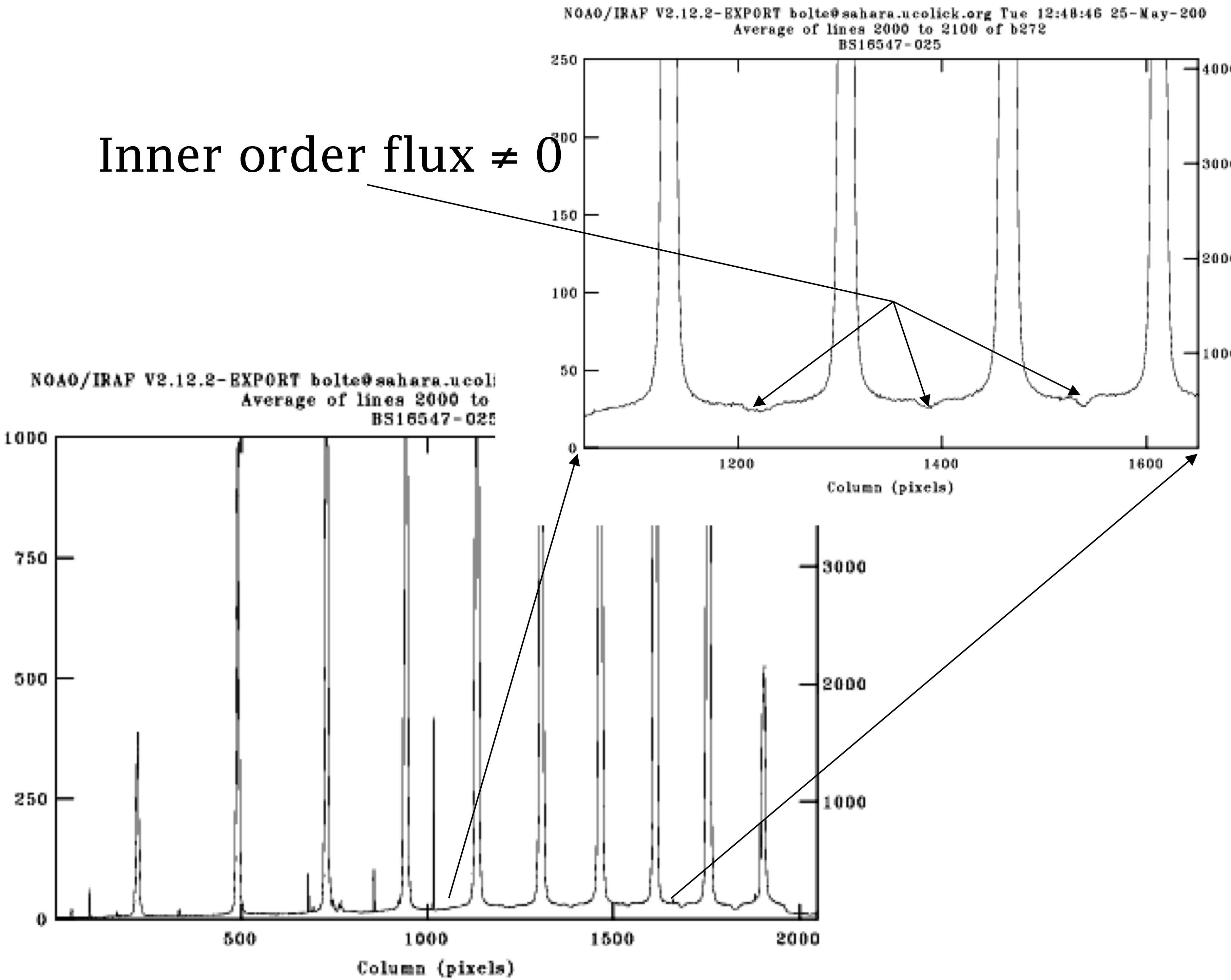
- When extracting spectra, each order is an aperture
- Often have to set up sky manually for each aperture initially


Seeing disk
Slit length
Inter-order

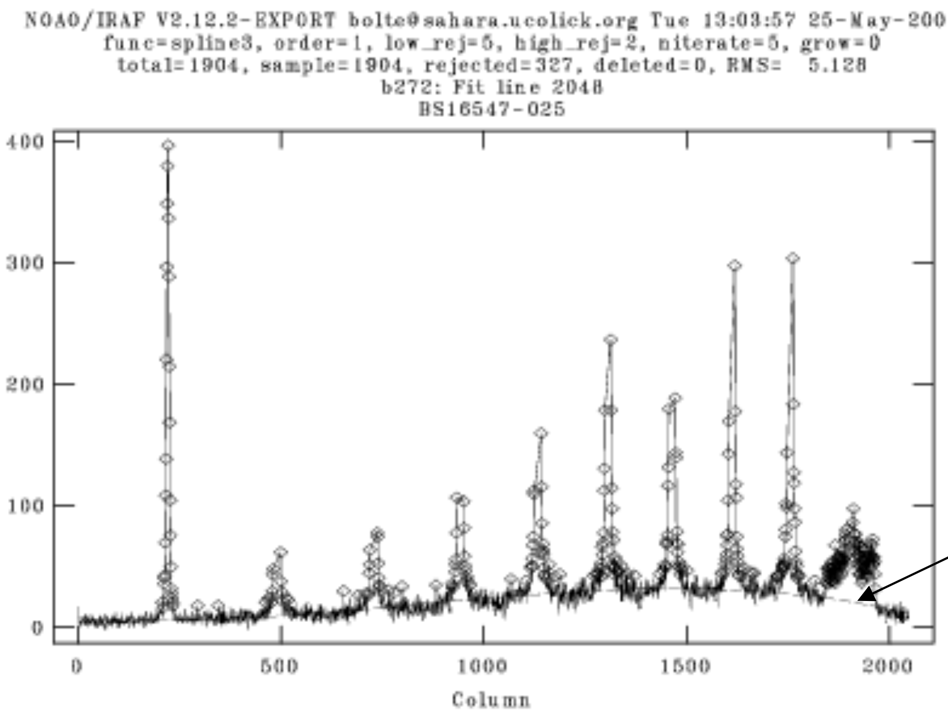
ESI spectra






Inner order flux ≠ 0
NOAO/IRAF V2.12.2-EXPORT bolte@sahara.ucolick.org Tue 12:48:46 25-May-200
Average of lines 2000 to 2100 of b272
BS16547-025
Column (pixels)
NOAO/IRAF V2.12.2-EXPORT bolte@sahara.ucoli
Average of lines 2000 to
BS16547-025
Column (pixels)

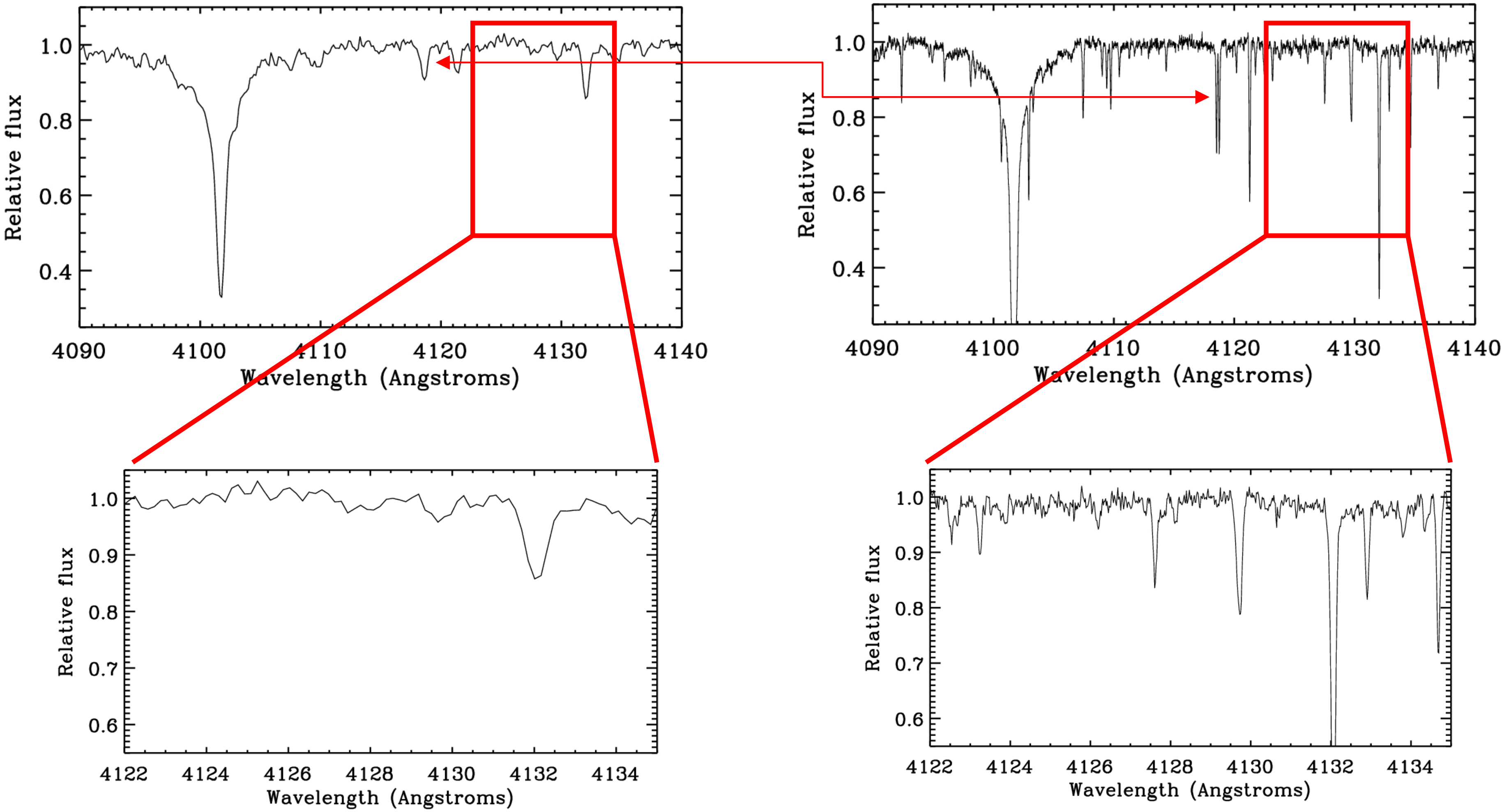
- For most echellegrams, need to take an extra step of removing scattered light. The idea is to fit a 2-d surface to the inner-order light and subtract this surface before aperture extraction.
- noao.echelle has a task *apscatter* to do this.



Need to identify and trace orders to identify the inner-order regions

Scattered light fit

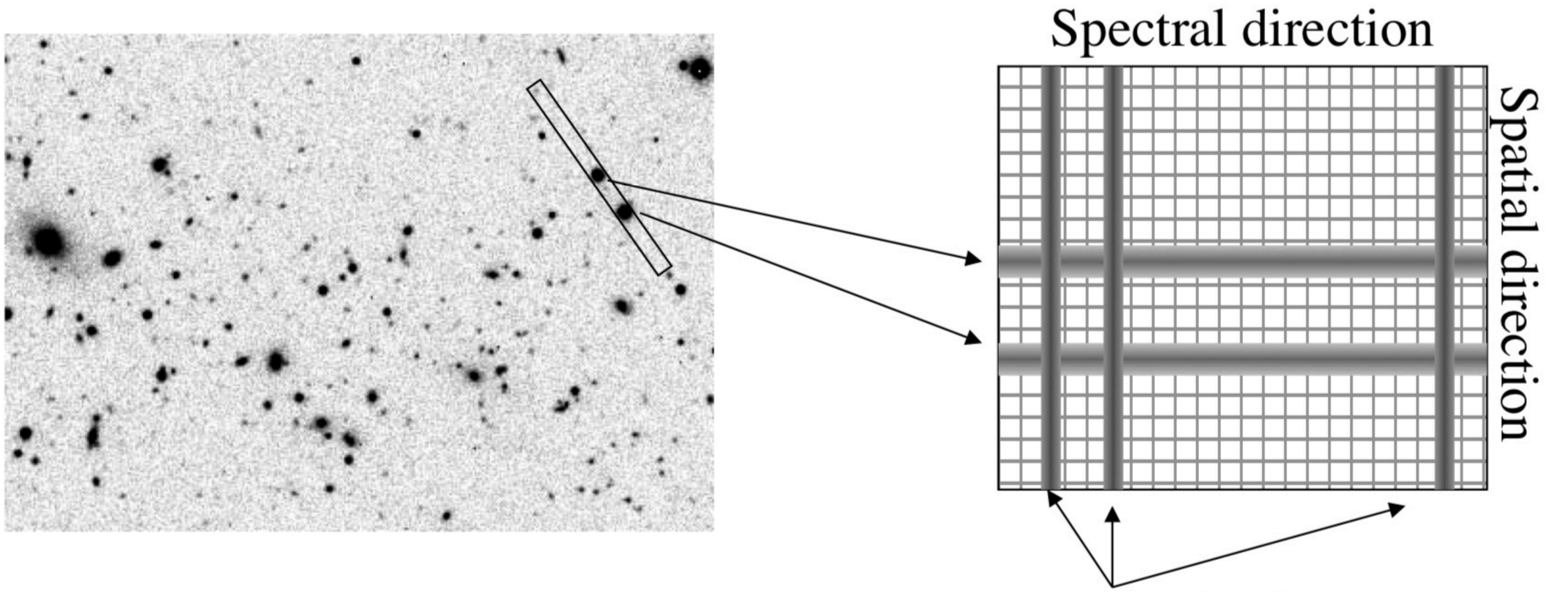
High spectral resolution



Multi-object spectra

- Two most common approaches are slit masks (variable wavelength coverage). DEIMOS, LRIS, IMACS, MOSFIRE
- Fiber-fed spectrometers

Remember the simple case: carefully rotated long slit. Note: better have an ADC.

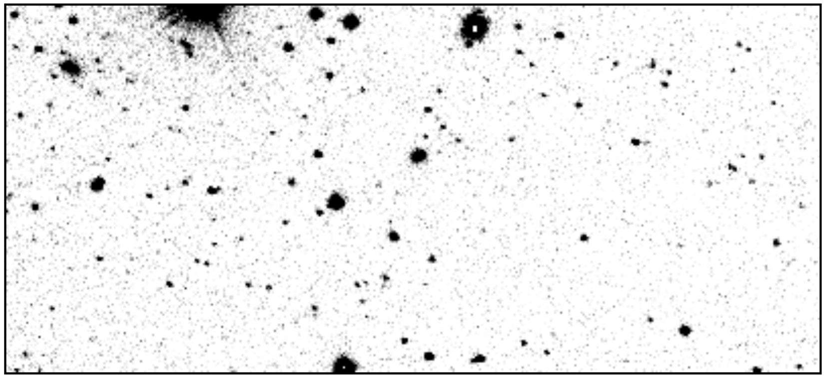


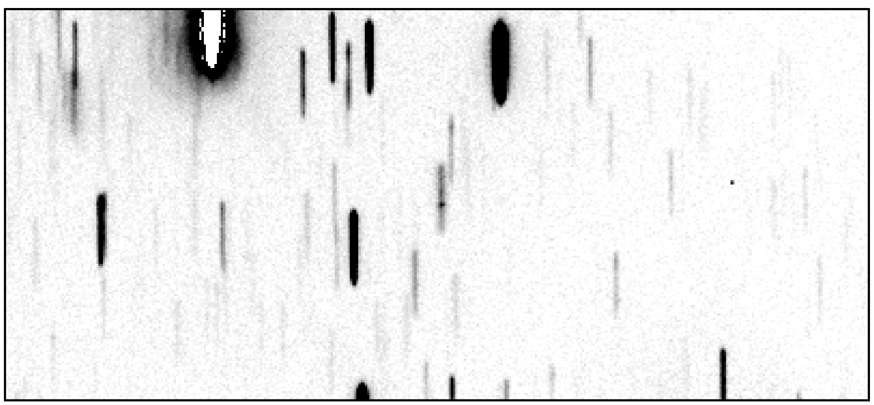
Telescope focal plane

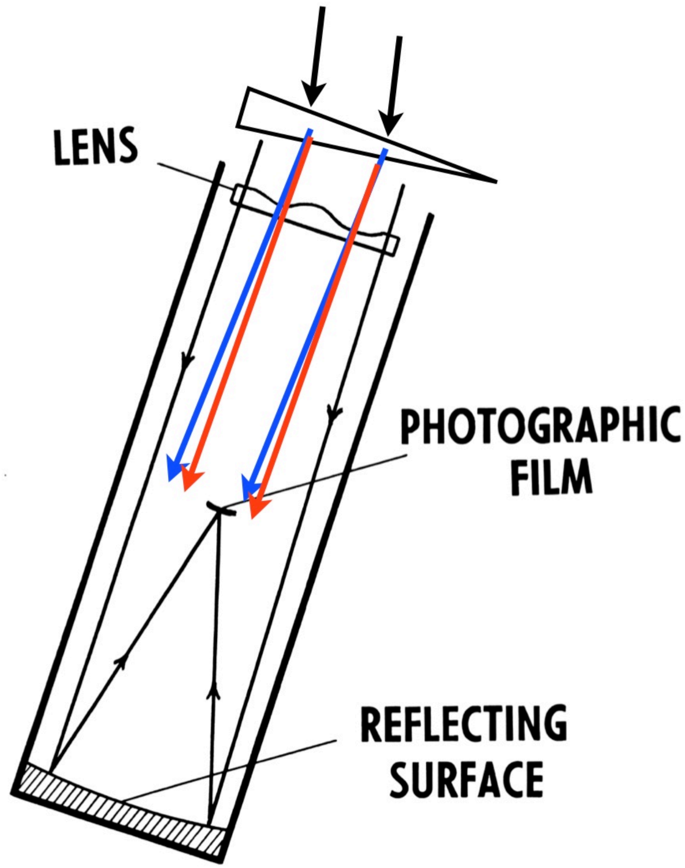
Spectrometer camera focal plane

“what position angle do you want?” Fixed PA

Objective Prism spectra

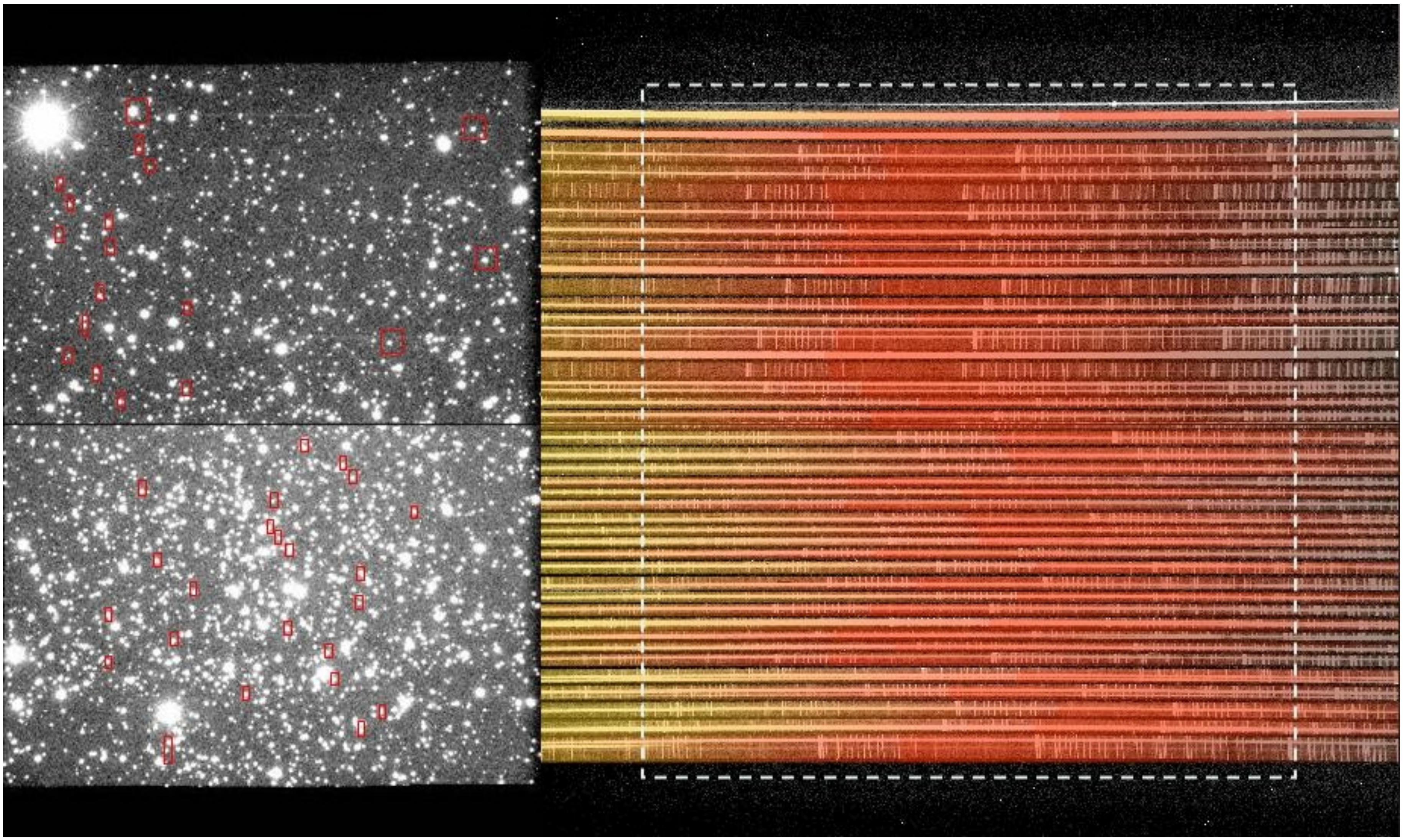




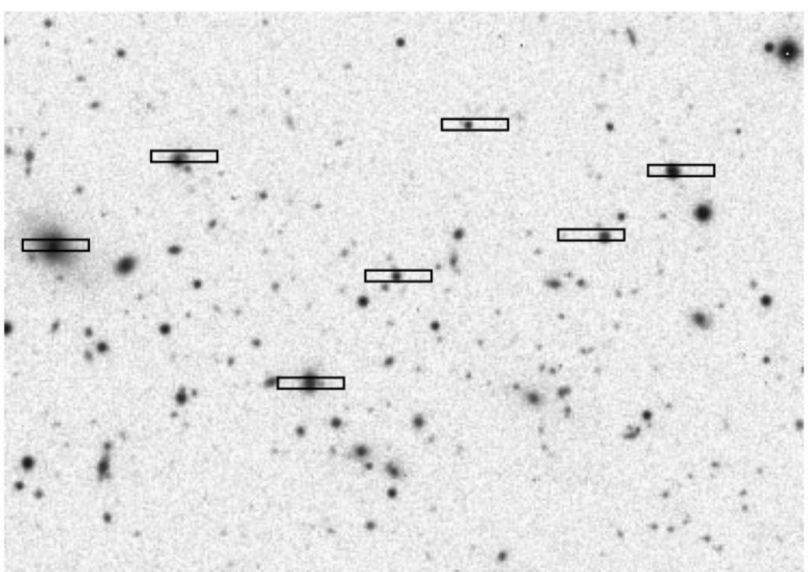


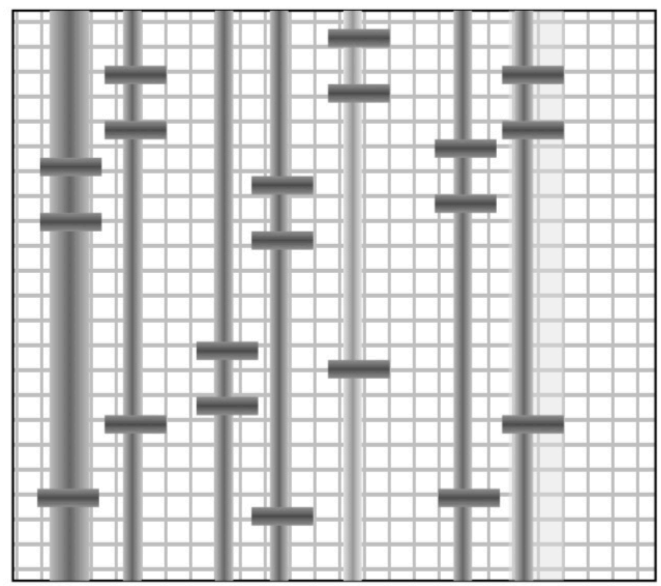
Imaging Spectrometer MOS

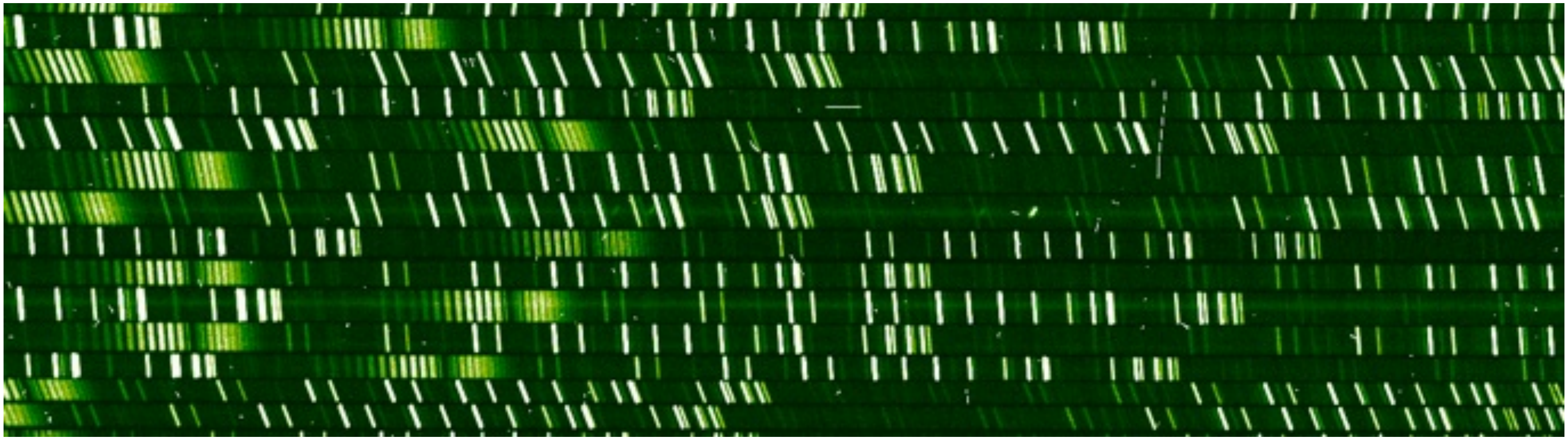
- Each slitlet generates a spectrum of the object and sky in the slit
- Each spectrum is spatially centered on a slit so the wavelength coverage is variable



- Variable wavelength coverage slitlet to slitlet.
- Have to avoid slitlet overlap which leads to detector real estate inefficiencies
- slitlets have high throughput
- need good astrometry and efficient alignment techniques at the telescope
- can change spectral resolution with slit sidth





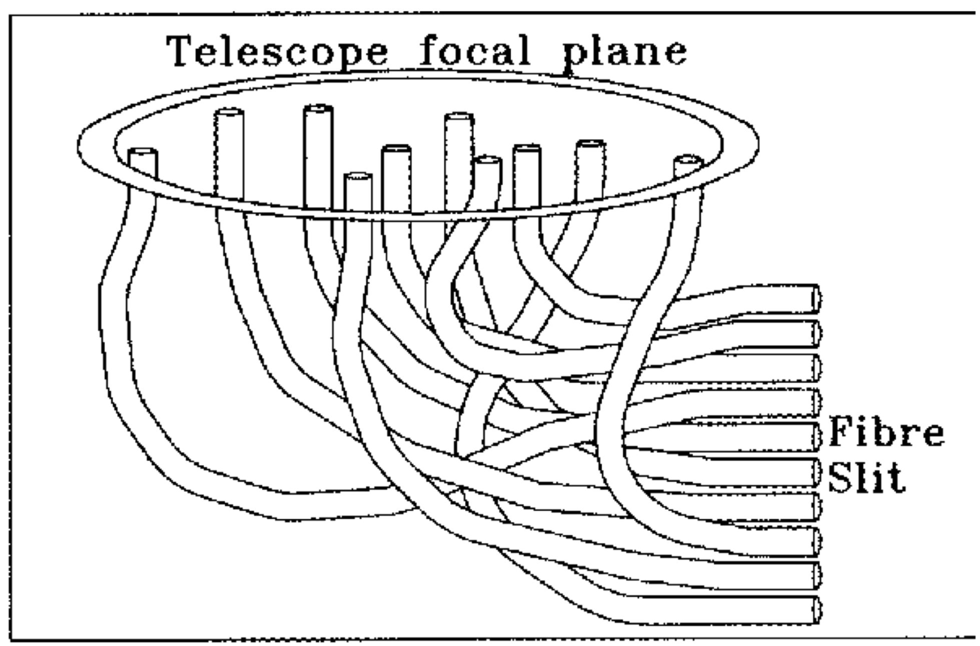


Slits can be cut at angles in order to measure rotation curves for galaxies.

Reduction is just like single-slit work, but have many apertures defined per mask

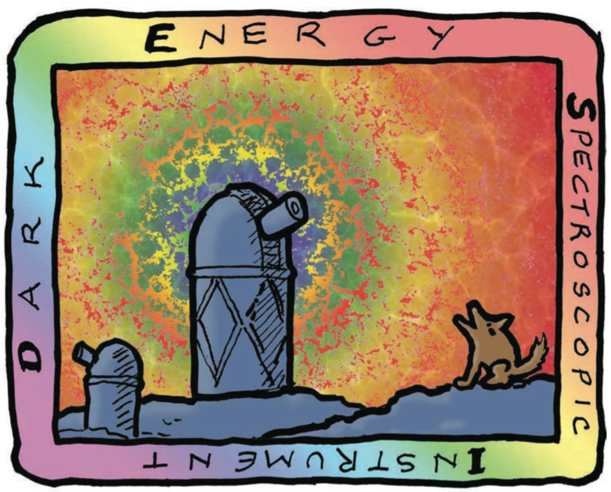
Fiber-fed systems

- Can put optical fibers at the location of objects and “sky” in the telescope focal plane and line the other end of the fibers to make a “pseudoslit”



Fibers

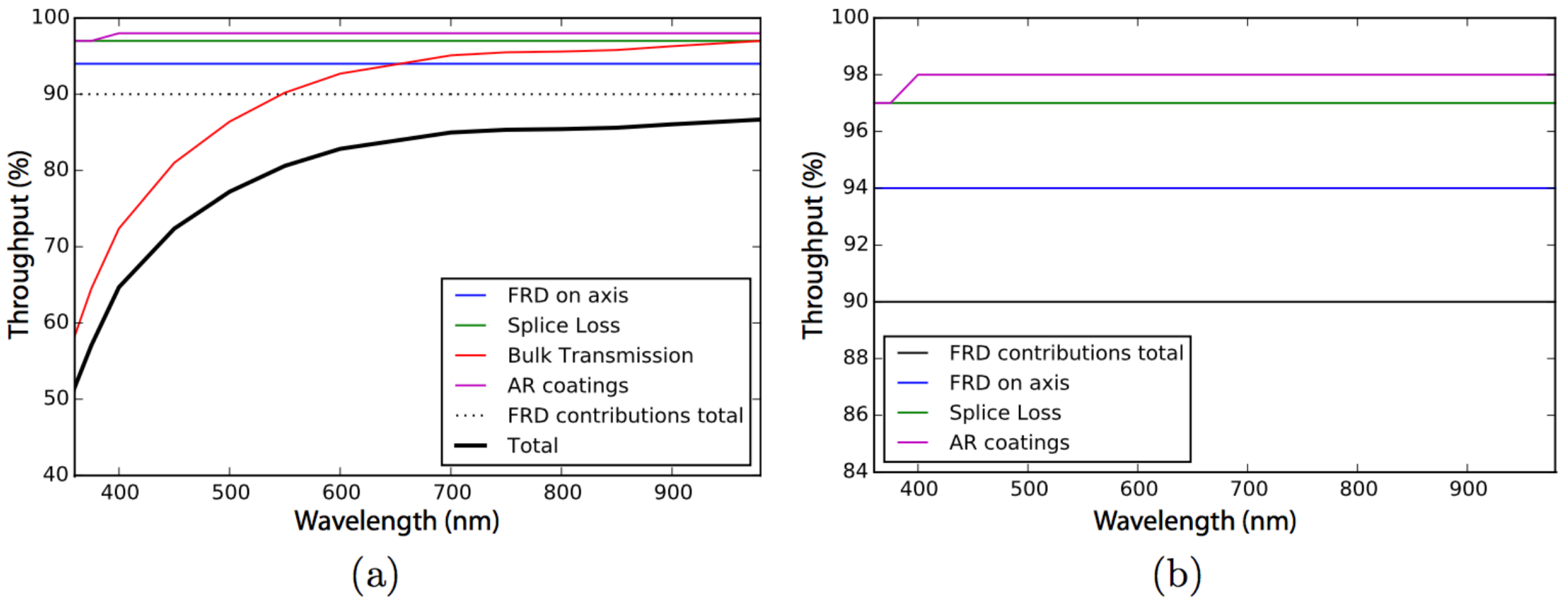
- Can efficiently pack the CCD and get uniform wavelength coverage for each spectrum
- Systems with 100’s and soon 1000’s of fibers are in use and planned, e.g.

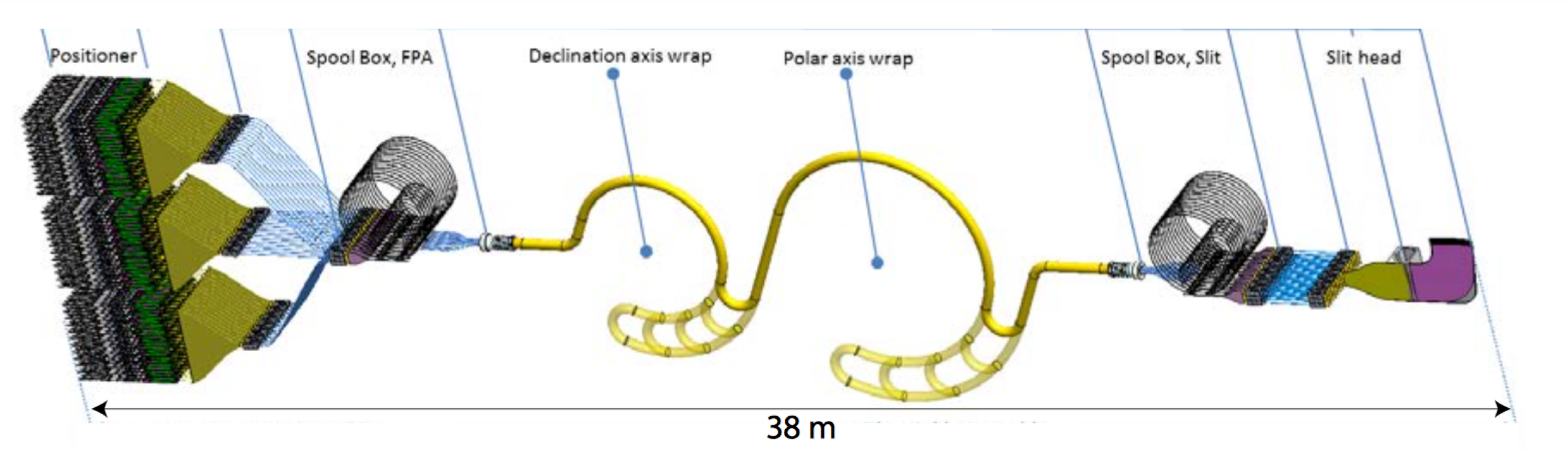


DESI: 5000 fibers
PFS @ Subaru 2500 fibers

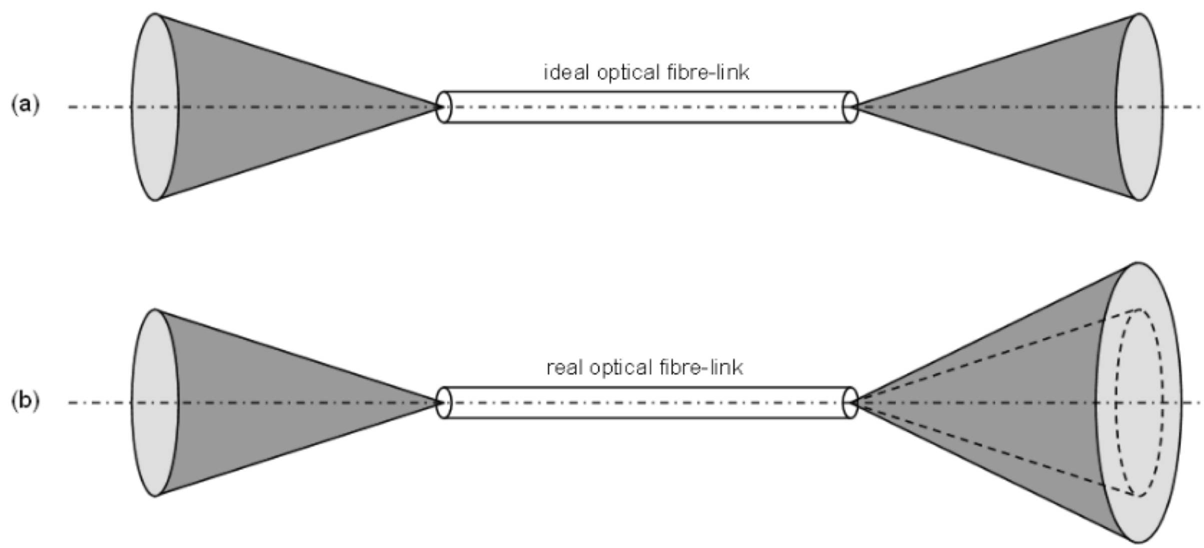
Fibers issues

- Throughput
- Sky subtraction
- Alignment and coupling

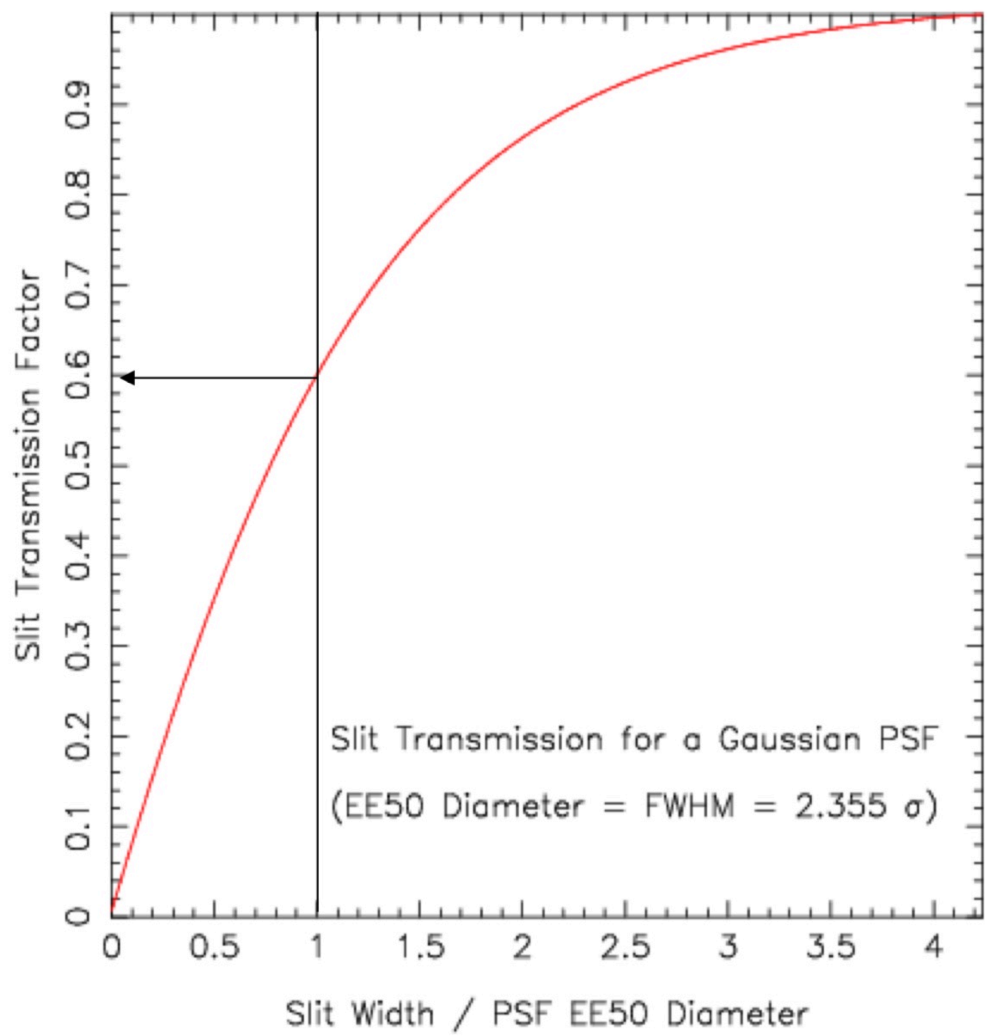




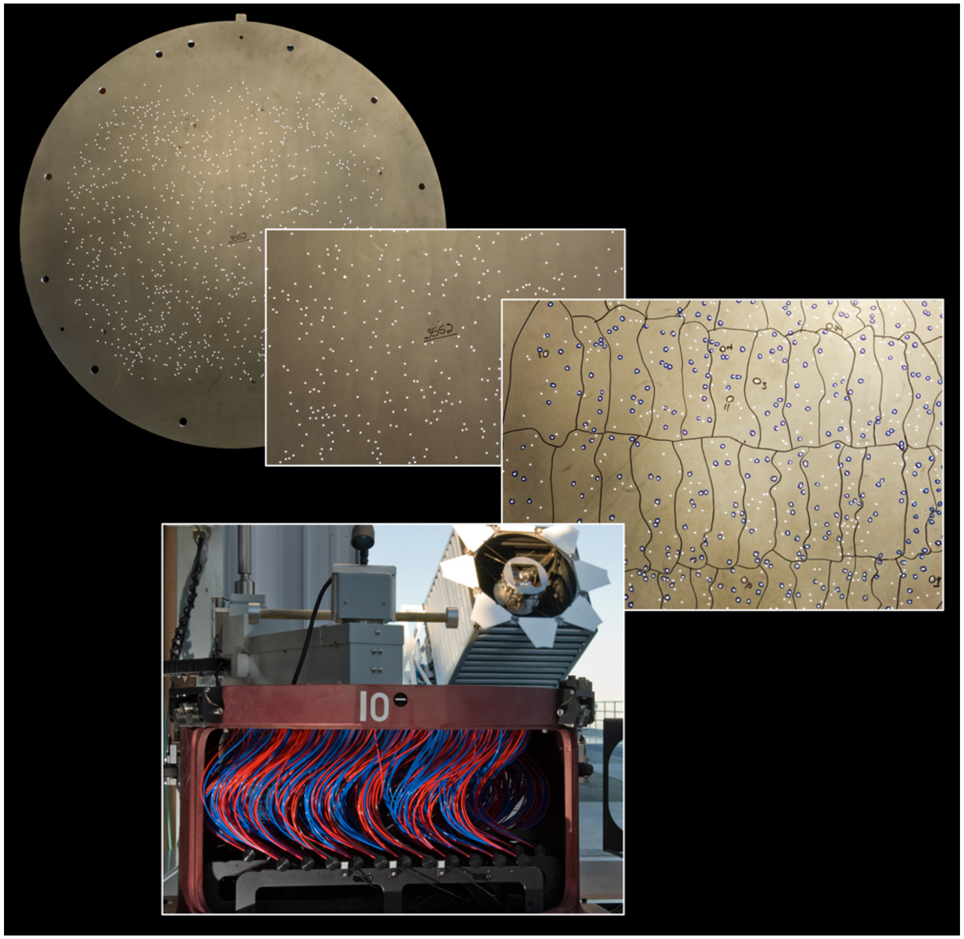
DESI FIBER ARRANGEMENT



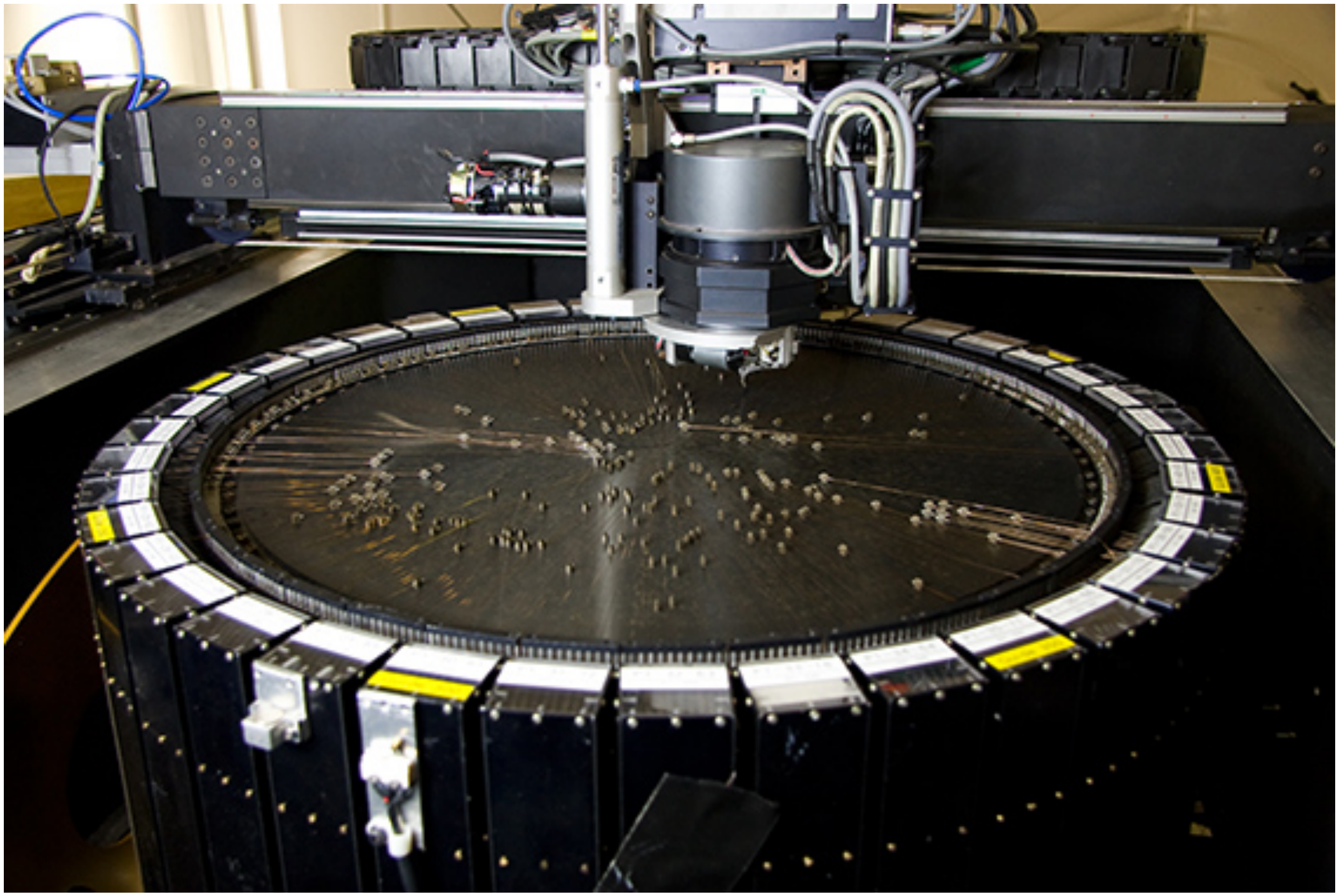
But, can gain back from fiber inefficiency by lack of slit losses

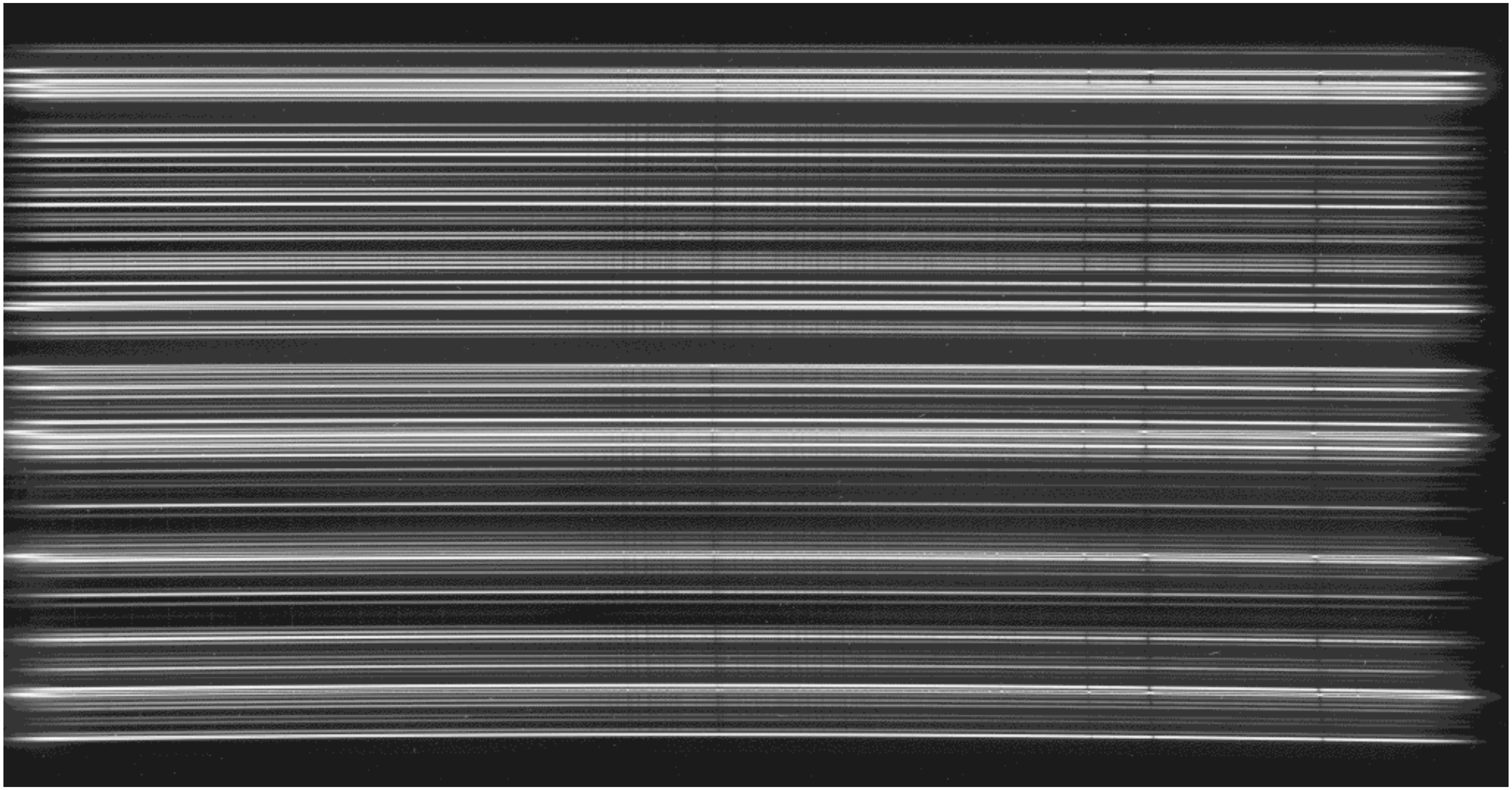


SDSS plugboards



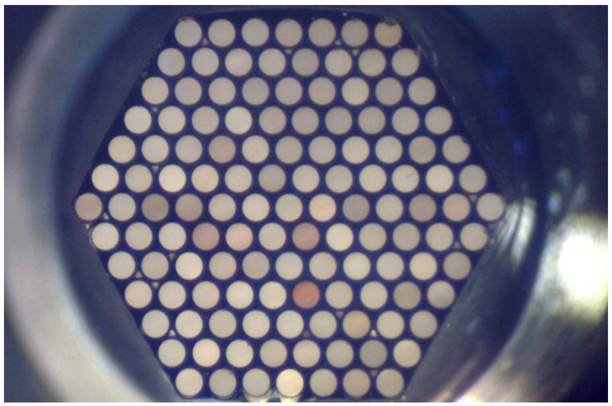
Fiber positioner robots

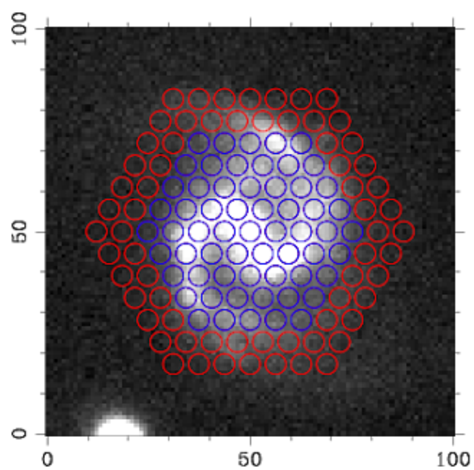


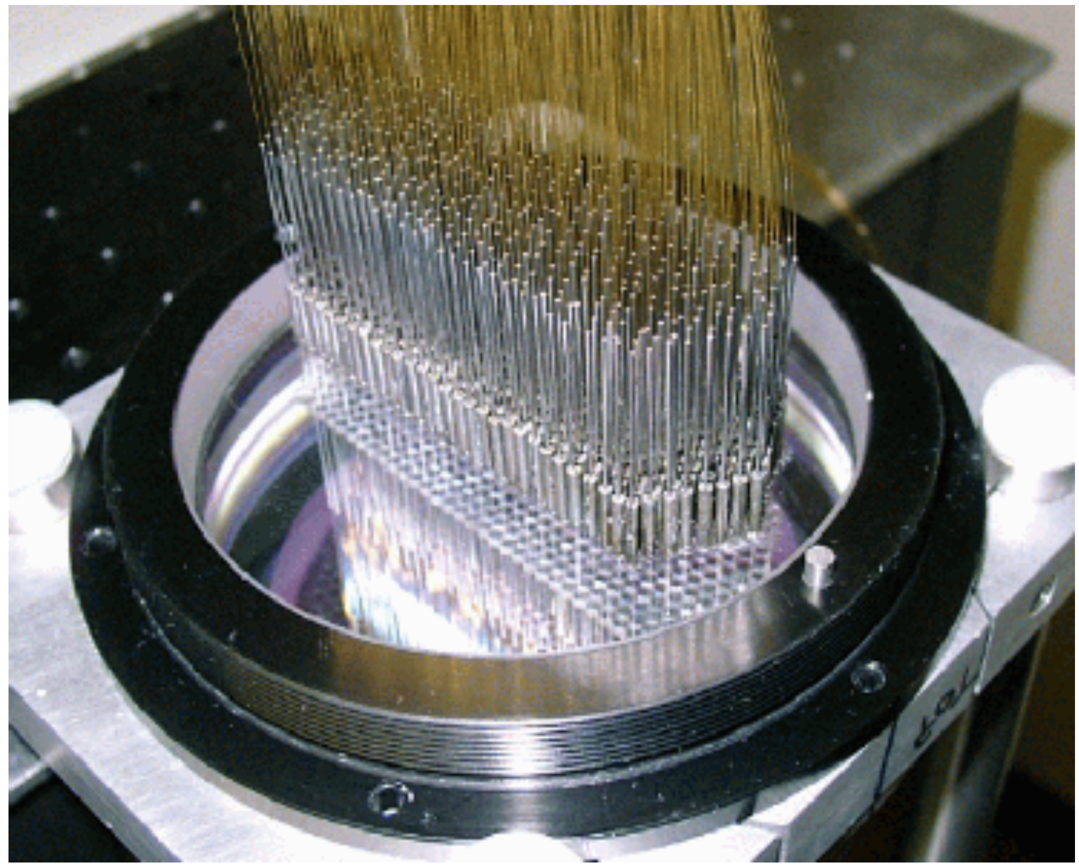


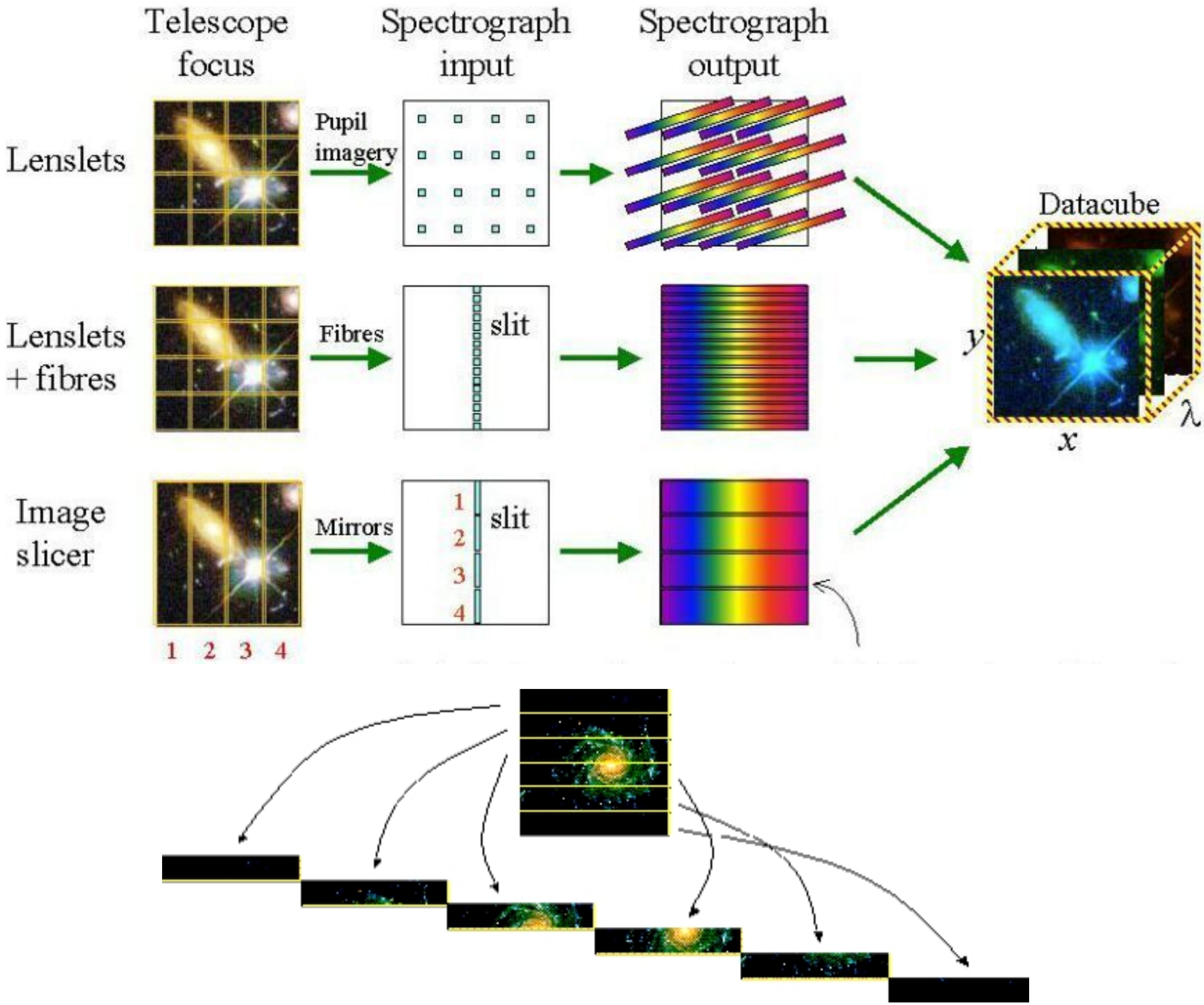
- Efficient use of detector
- Same wavelength coverage for each object
- Sky is tricky: nearby fiber or global fit
- Flat-fielding now includes fiber efficiency

Integral-Field Spectroscopy





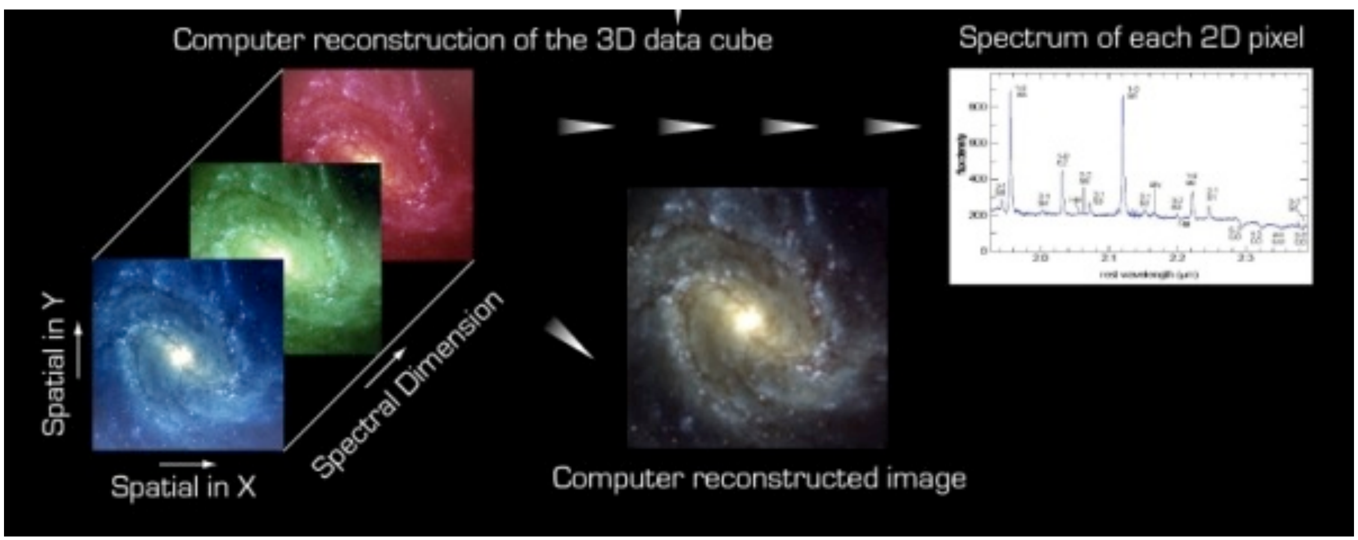


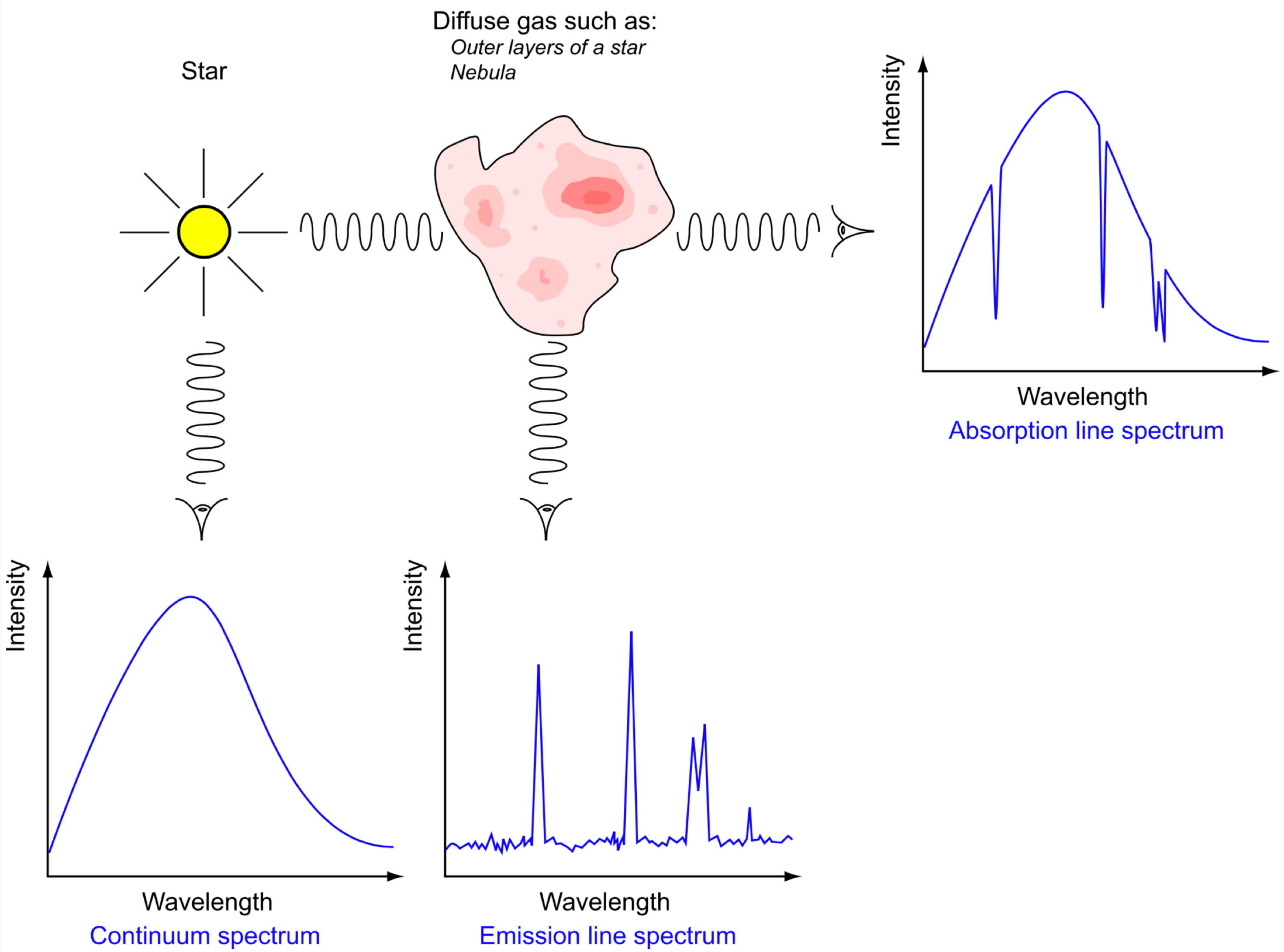


Telescope focus
Spectrograph input
Spectrograph output
Lenslets
Pupil imagery
Datacube
Lenslets + fibres
Fibres
slit
y
λ
x
Image slicer
Mirrors
1
2
3
4
slit
1 2 3 4

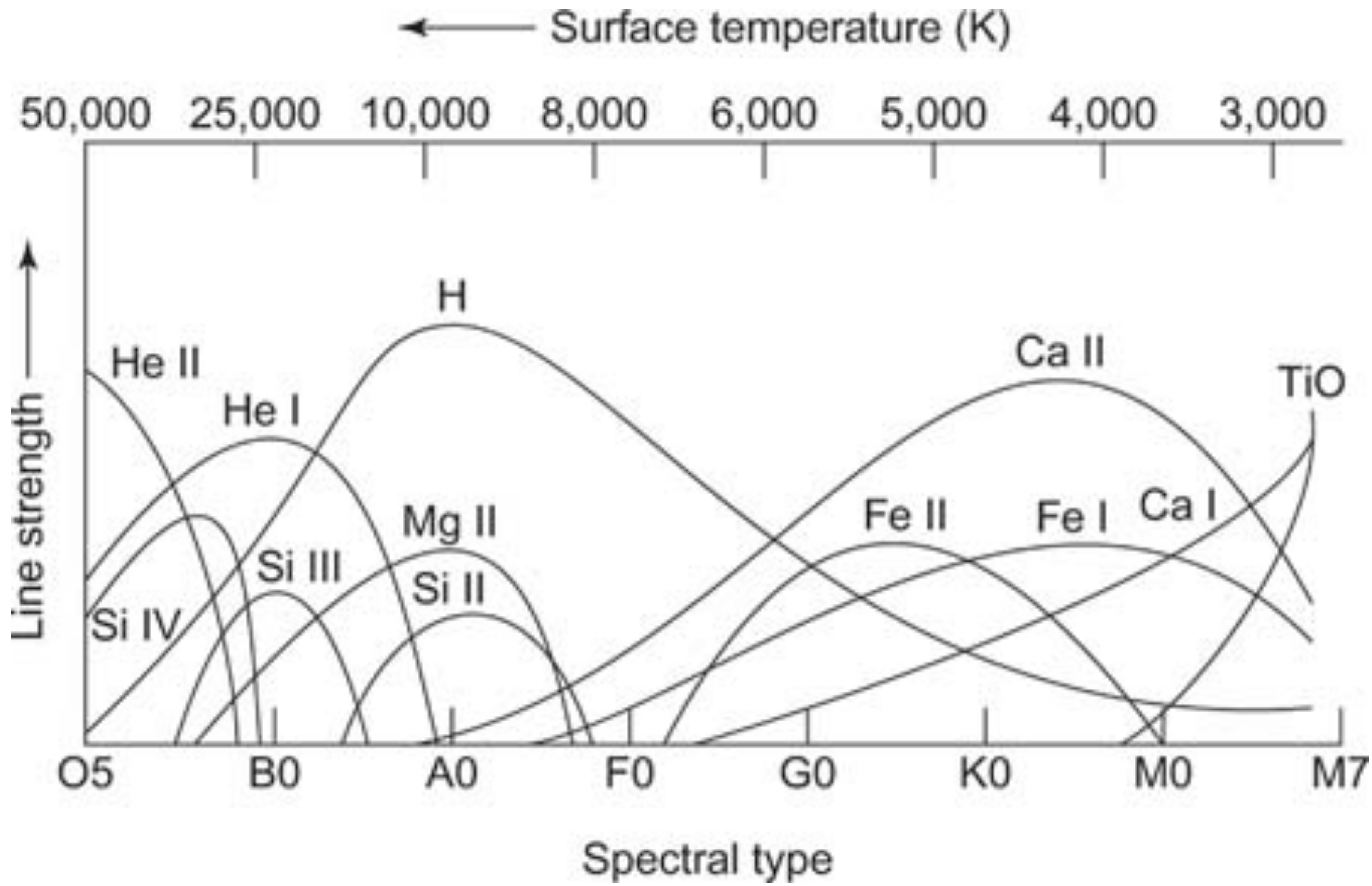
IFU data reduction

- Usually this is complicated to do the extraction of sources and then putting the spatial pieces back together properly
- Crosstalk between sources, background scattered light often complex
- Sometimes this is referred to as "3-D" spectroscopy





Diffuse gas such as:
Outer layers of a star
Nebula
Star
Intensity
Wavelength
Absorption line spectrum
Intensity
Wavelength
Continuum spectrum
Intensity
Wavelength
Emission line spectrum



For stellar spectra T_{eff} and Surface Gravity are most important for establishing the strength of absorption features.

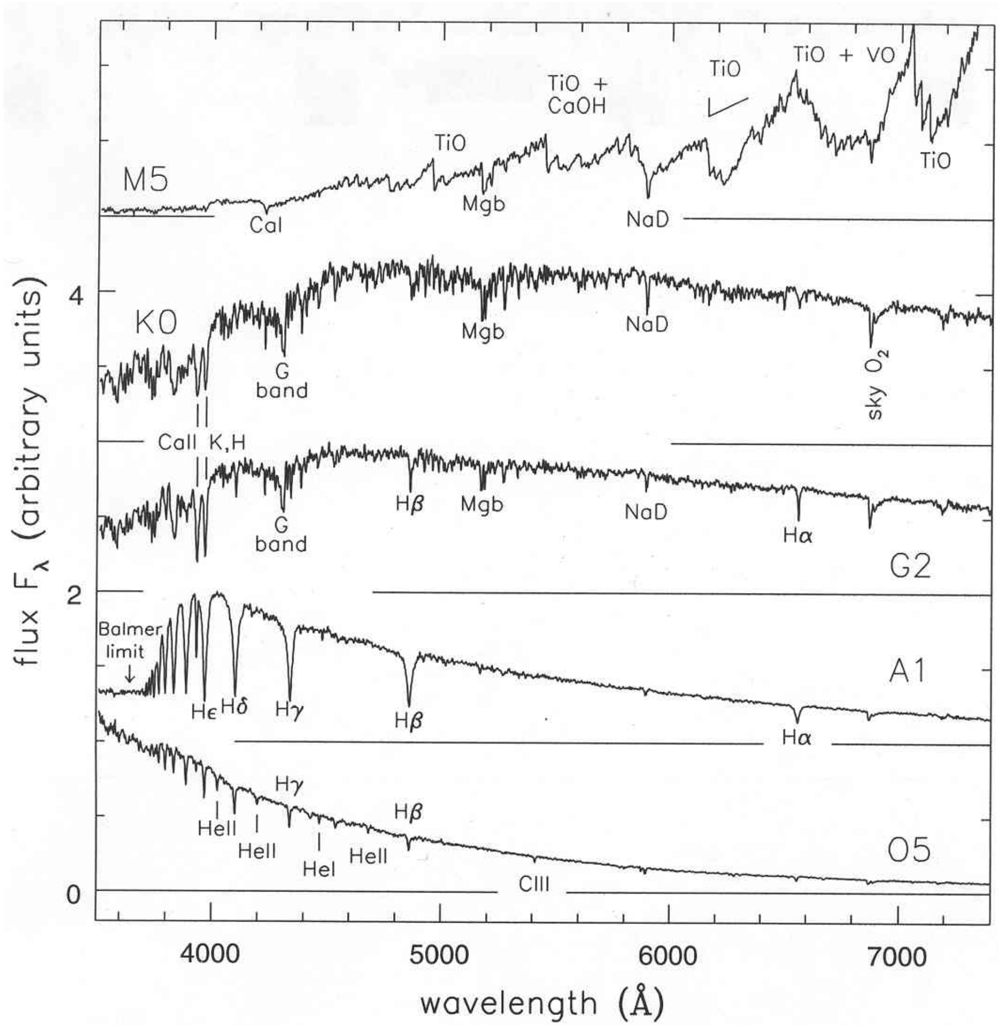
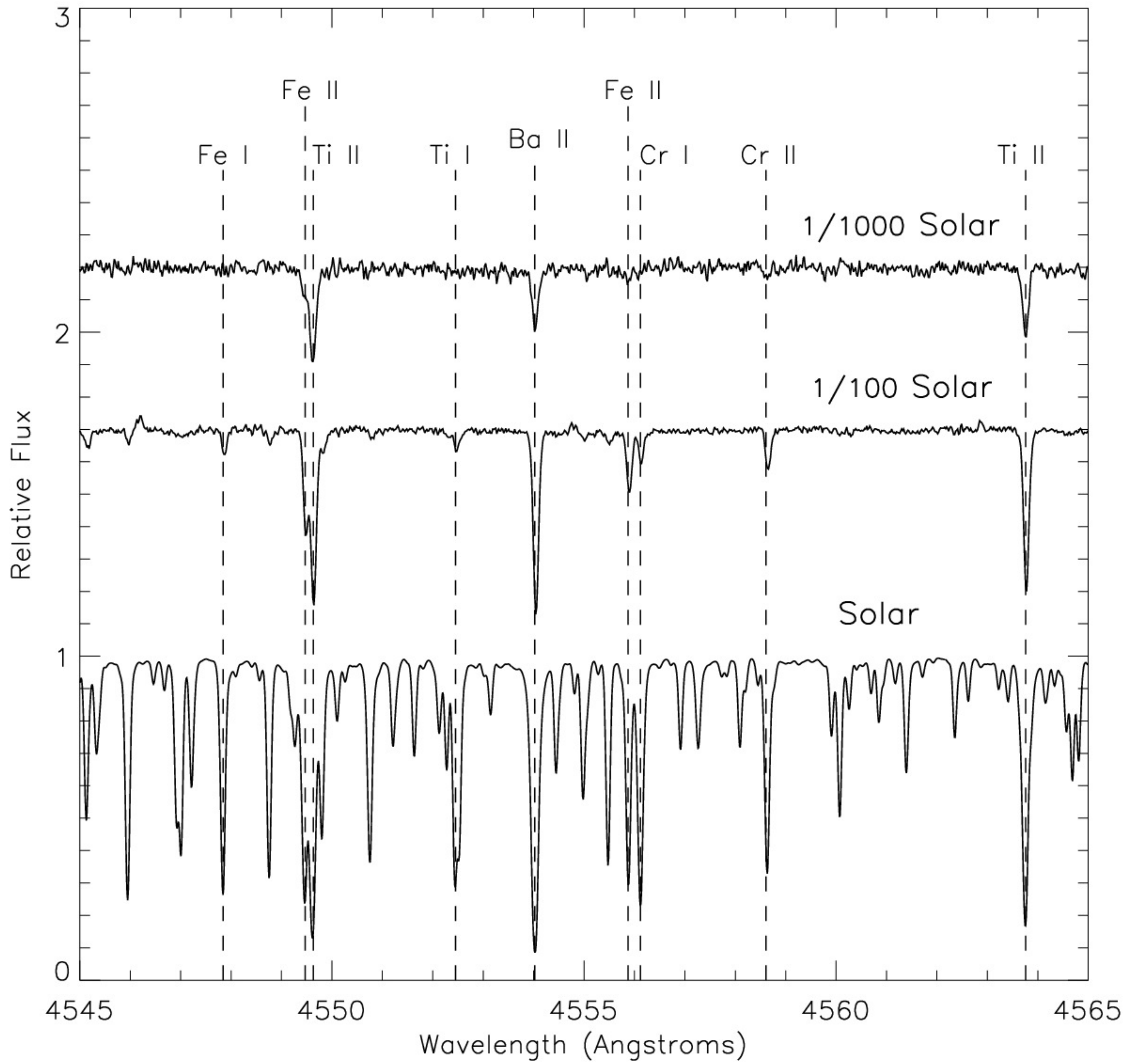
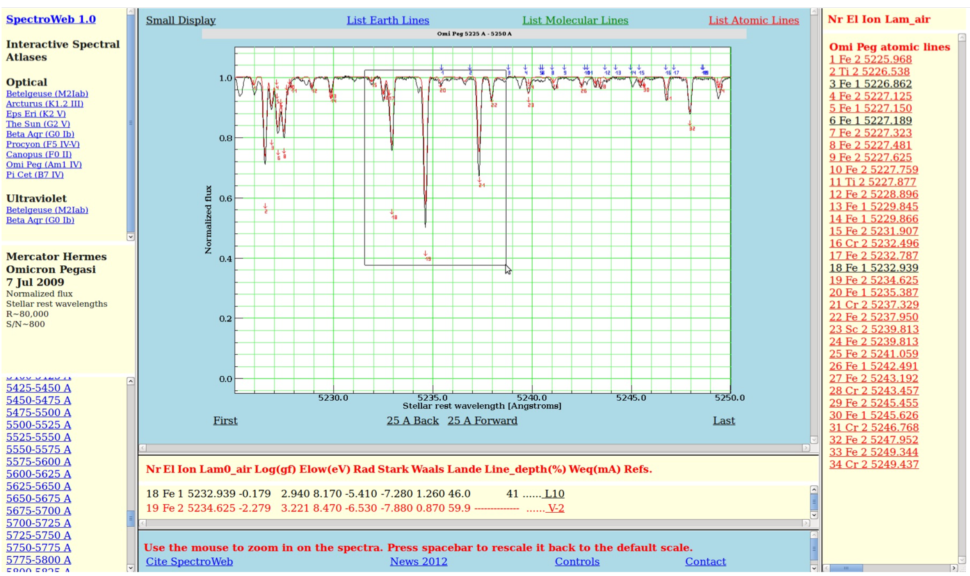


Figure 1.1 Optical spectra of main-sequence stars with roughly the solar chemical composition. From the top in order of increasing surface temperature, the stars have spectral classes M5, K0, G2, A1, and O5 – G. Jacoby *et al.*, spectral library.



Once T_{eff} and Log(g) are determined the strength of the Absorption lines gives a measurement of chemical abundances

What are those lines?

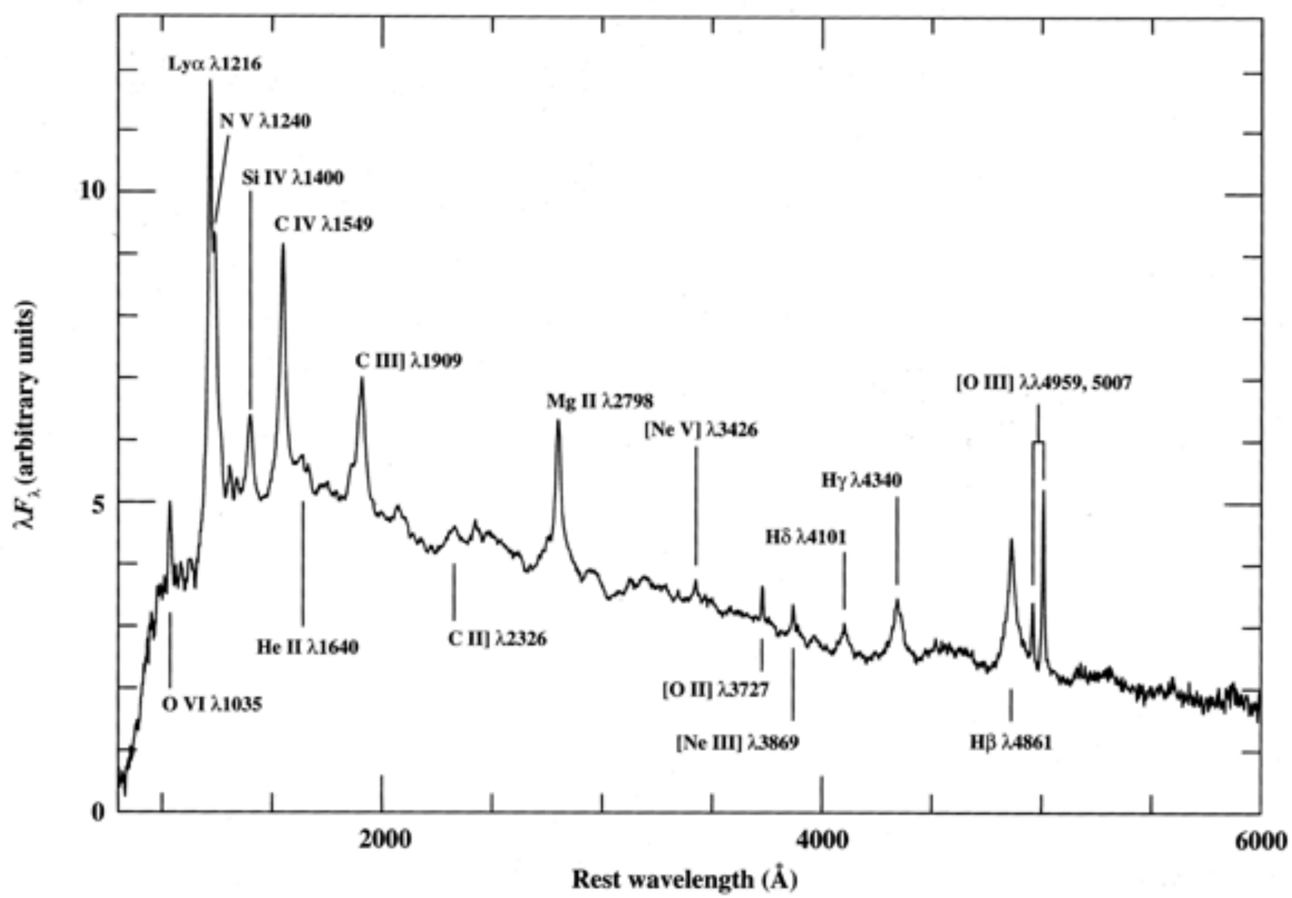


- Solar Atlas
- A revised version of the Identification List of Lines in Stellar Spectra (ILLSS) Catalogue by R. Coluzzi
- Look up papers
- http://spectra.freeshell.org/whyspectroweb.html

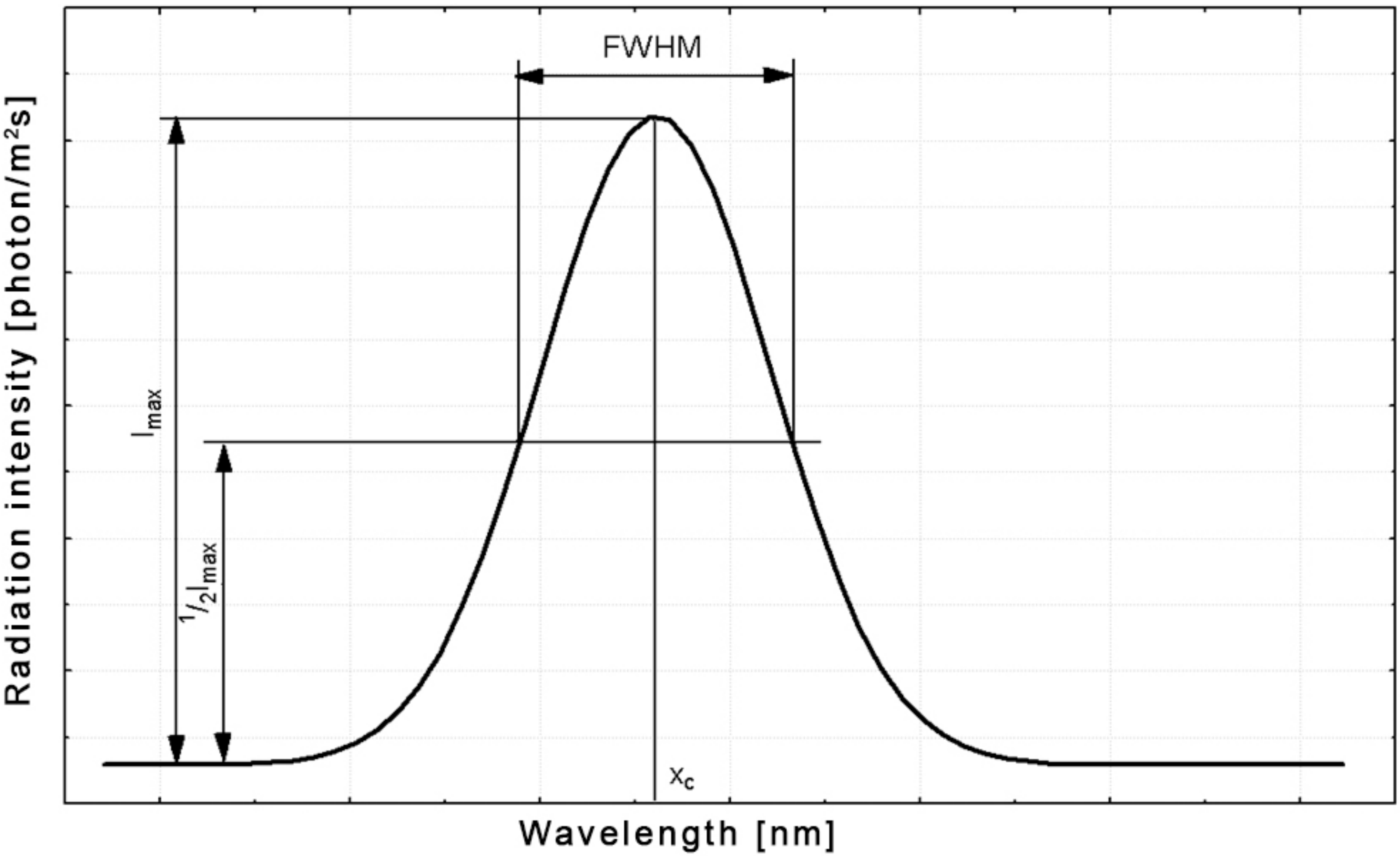
What Affects Absorption Lines?

- Temperature
- Pressure
- Radial motion
- Stellar rotation
- "Microturbulence"

- http://www.kcvs.ca/martin/astro/au/unit2/63/chp6_3.html



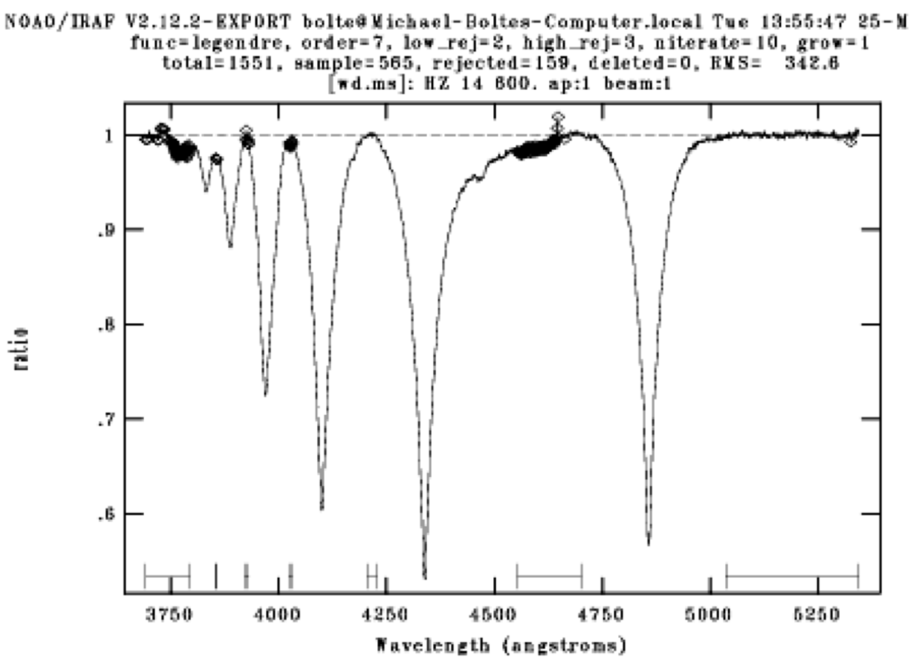
Lyα λ1216
N V λ1240
Si IV λ1400
C IV λ1549
C III] λ1909
Mg II λ2798
[Ne V] λ3426
[O III] λλ4959, 5007
Hγ λ4340
Hδ λ4101
He II λ1640
C II] λ2326
O VI λ1035
[O II] λ3727
[Ne III] λ3869
Hβ λ4861
λF_λ (arbitrary units)
0
5
10
2000
4000
6000
Rest wavelength (Å)



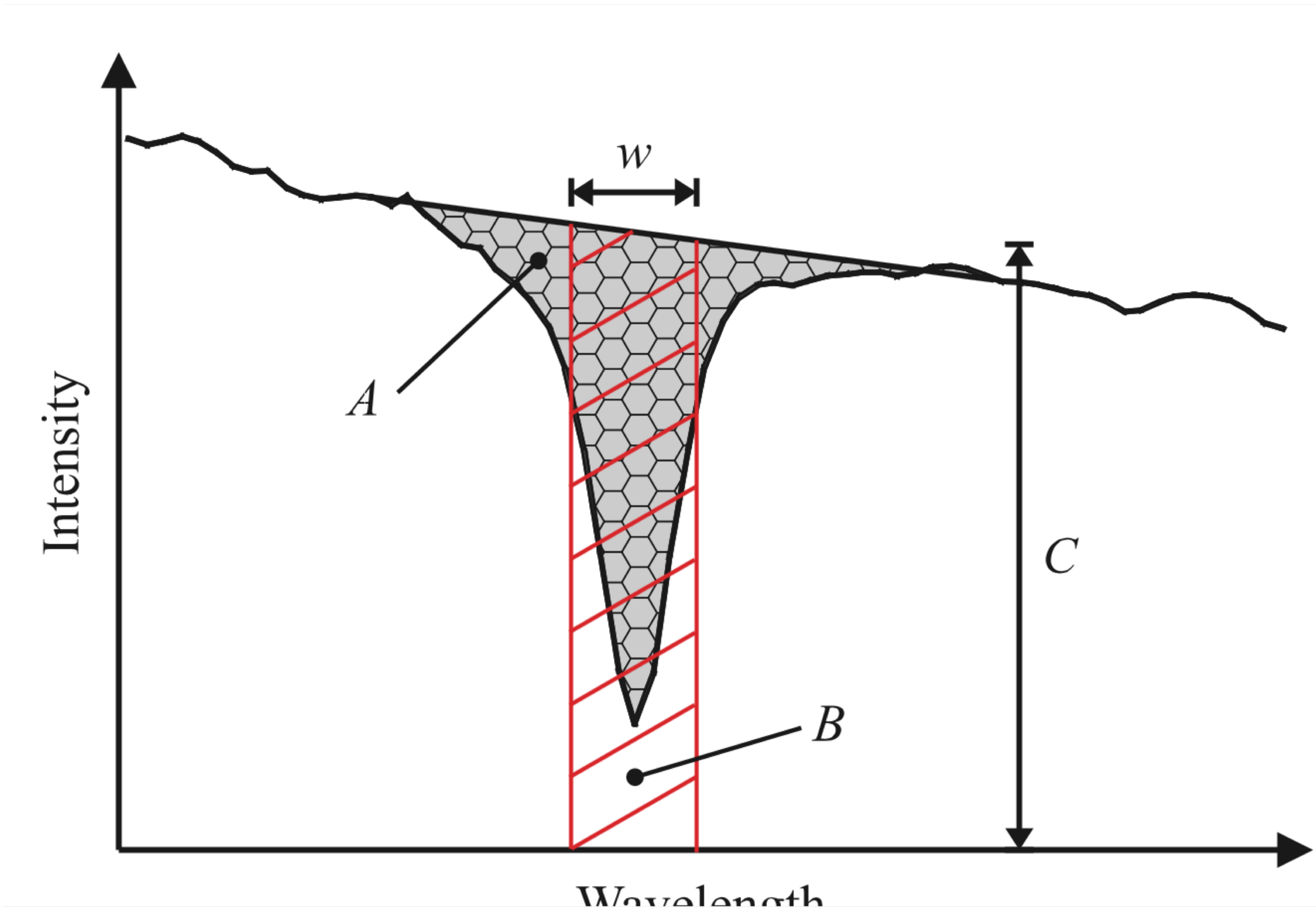
FWHM
I_max
1/2 I_max
x_c
Radiation intensity [photon/m²s]
Wavelength [nm]

Analysis procedures: Equivalent Width Measurements

- noao.oned task *splot* is a powerful measuring tool.
- Often start by normalizing a spectrum. In *splot*, the 't' option allows you to interactively do this



z- delete region
s- define region
:o n - switch fit to order n
f- refit
q- exit normalizing task

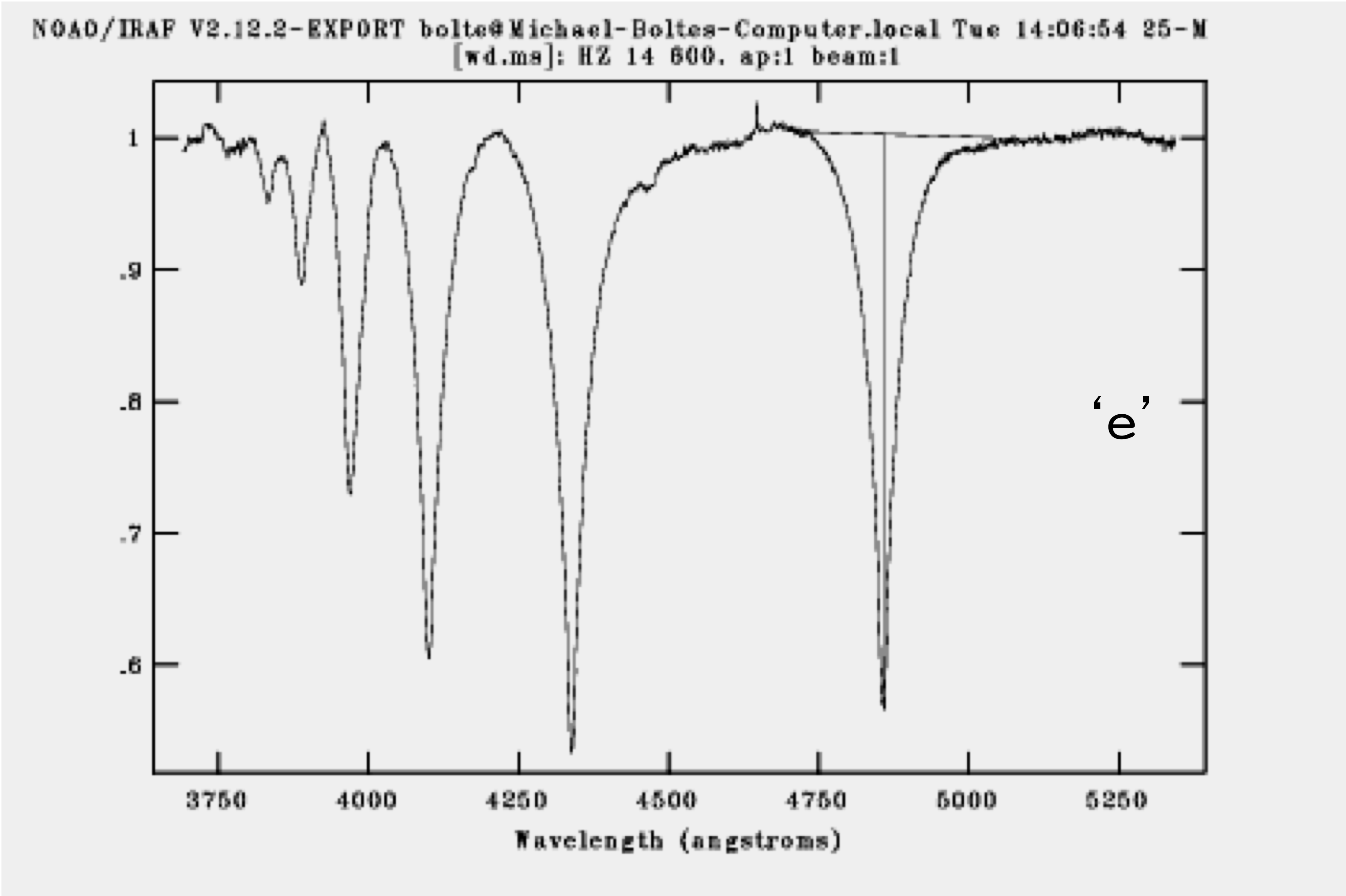


w
A
B
C
Intensity
Wavelength

splot help

? - This display
/ - Cycle thru short help on stat line
a - Autoexpand between cursors
b - Toggle base plot level to 0.0
c - Clear and redraw full spectrum
d - Deblend lines using profile mode
e - Equiv. width, integ flux, center
f - Arithmetic functions: log, sqrt...
g - Get new image and plot
h - Equivalent widths(*)
i - Write current image as new ima
j - Fudge a point to Y-cursor value
k - Profile fit to single line(*)
l - Convert to F-lambda
m - Mean, RMS, snr in marked region
n - Convert to F-nu
o - Toggle overplot of following plot
p - Convert to wavelength scale
q - Quit and exit

r - Redraw the current window
s - Smooth (boxcar)
t - Fit continuum(*)
u - Adjust coordinate scale(*)
v - Velocity scale (toggle)
w - Window the graph
x - Connects 2 cursor positions
y - Plot std star flux from calib file
z - Expand x range by factor of 2
) - Go to next spectrum in image
(- Go to previous spectrum in image
- Select new line/aperture
% - Select new band
$ - Toggle wavelength/pixel scale
- - Subtract deblended fit
, - Down slide spectrum
. - Up slide spectrum
I - Interrupt task immediately
<space> - Cursor position and flux



Center:4857.537 eqw: 26.0823

Other splot eqw options:

(*) For 'h' key: Measure equivalent widths

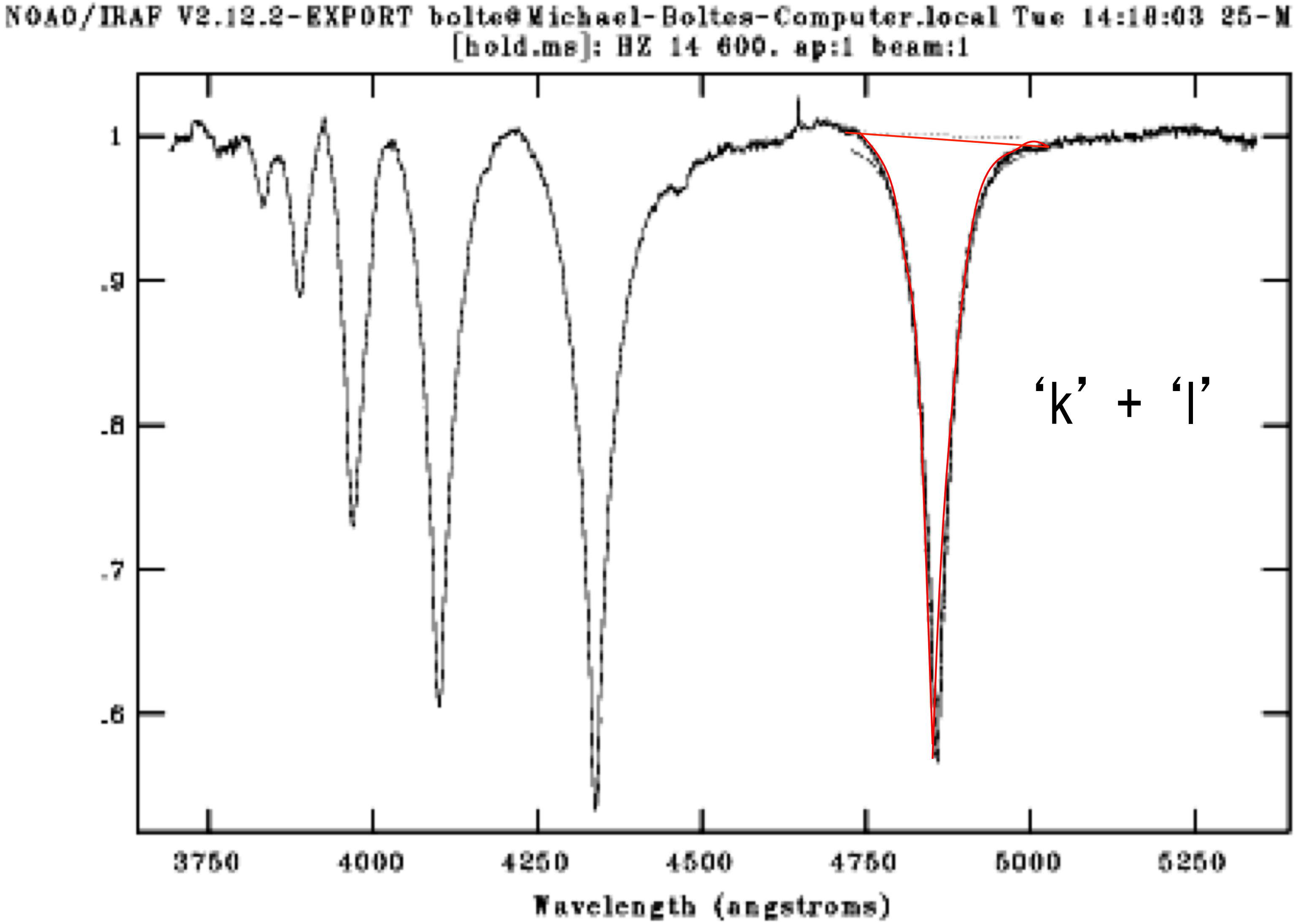
a - Left side for width at 1/2 flux   l - Left side for continuum = 1

b - Right side for width at 1/2 flux r - Right side for continuum = 1

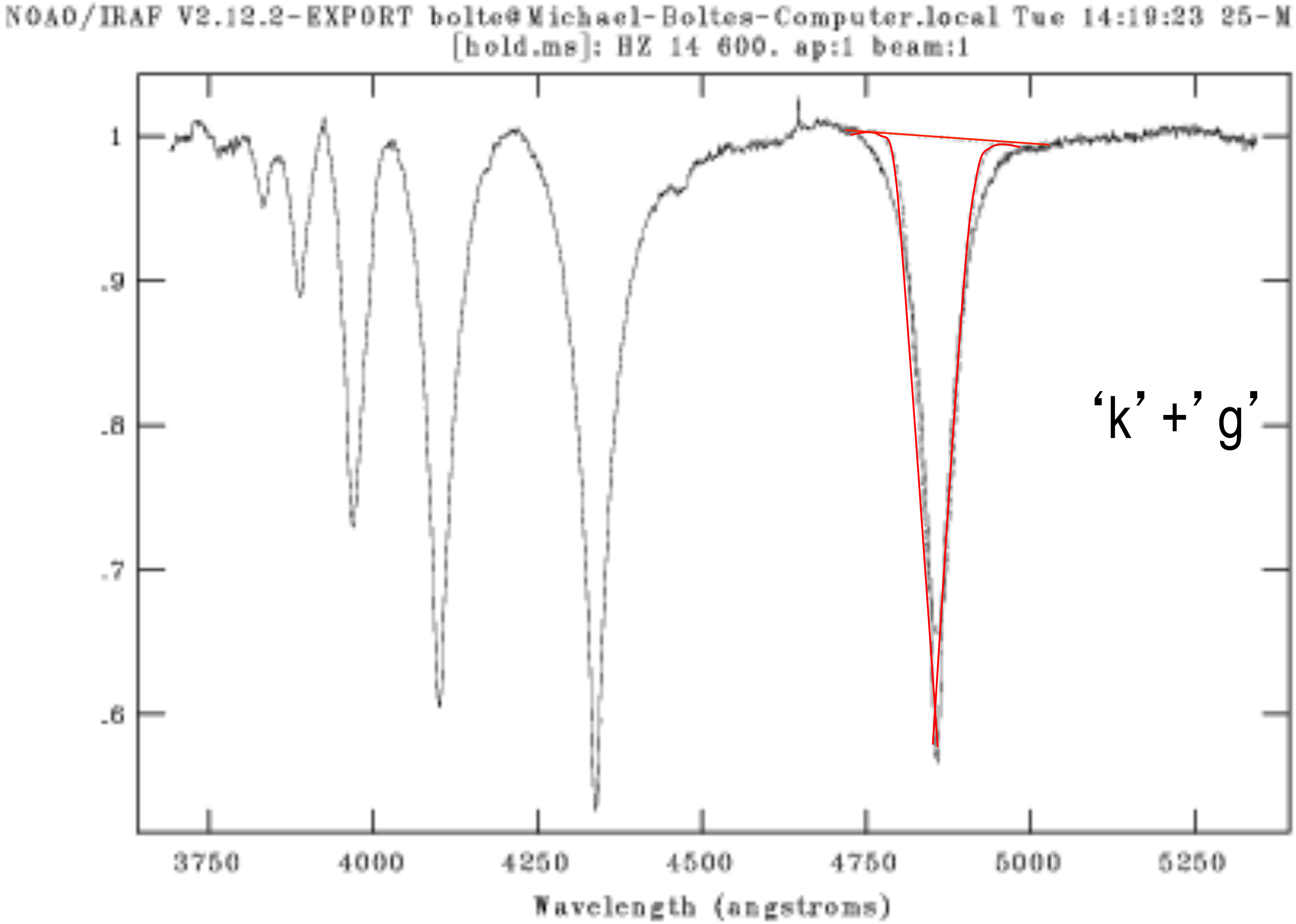
c - Both sides for width at 1/2 flux k - Both sides for continuum = 1

(*) For 'k' key: Second key may be used to select profile type

g - Gaussian, l - Lorentzian, v - Voigt, all others - Gaussiank



Center: 4857.31 eqw:29.49 lfwhm: 47.45



Center: 4857.38 eqw: 23.38 gfwhm:41.44

Note: can measure radial velocity and EW

Radial velocity measurements

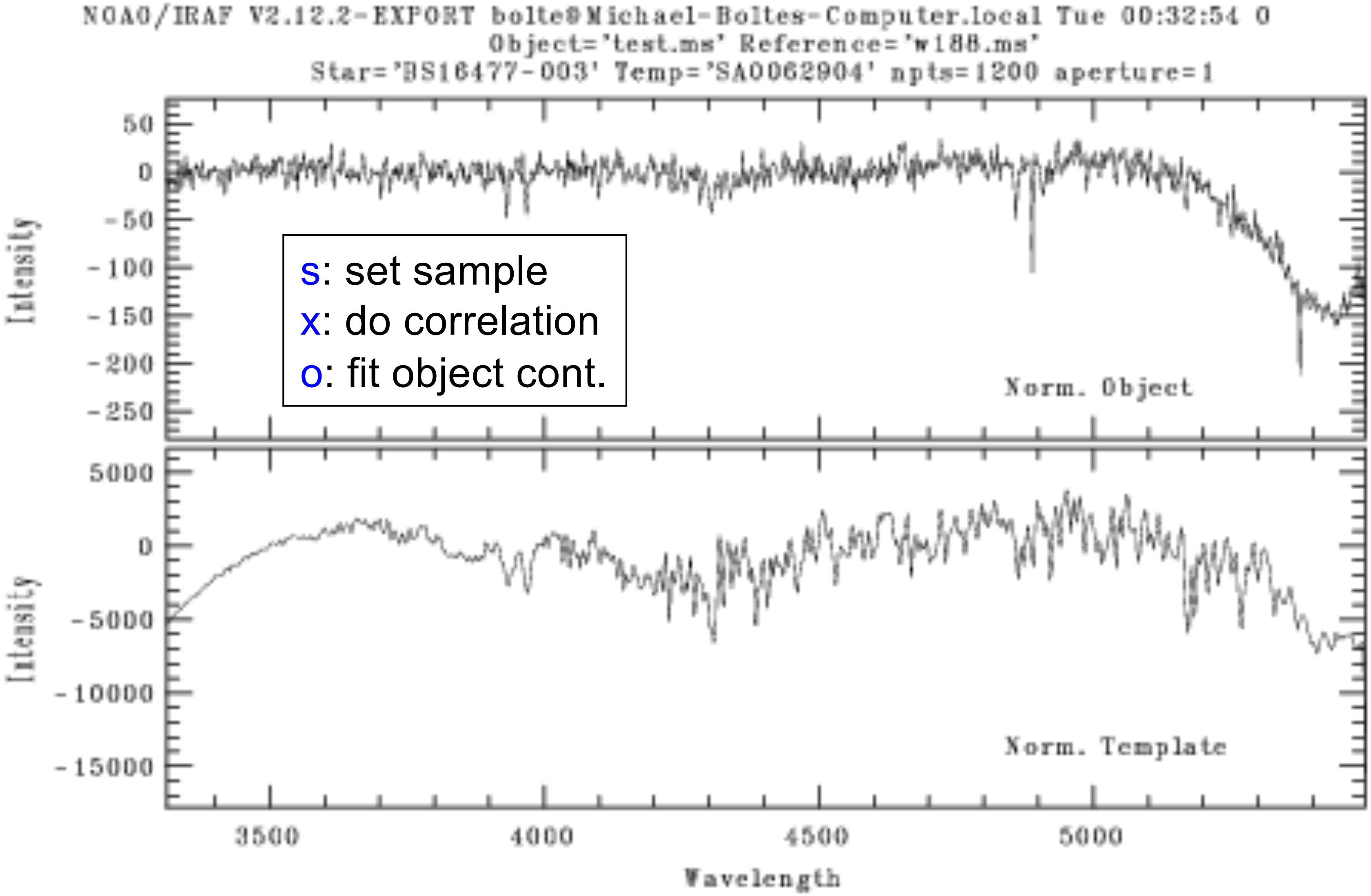
- Method 1 is to measure line centroids usually after making a zeropoint correction based on measuring a few night sky lines (in *splot* you can use the "u" and "z" keystroke command to accomplish this).
- Get line centers with "e" or one of the line fitting options, calculate doppler shift, apply the heliocentric correction.

Cross-correlation:FXCOR

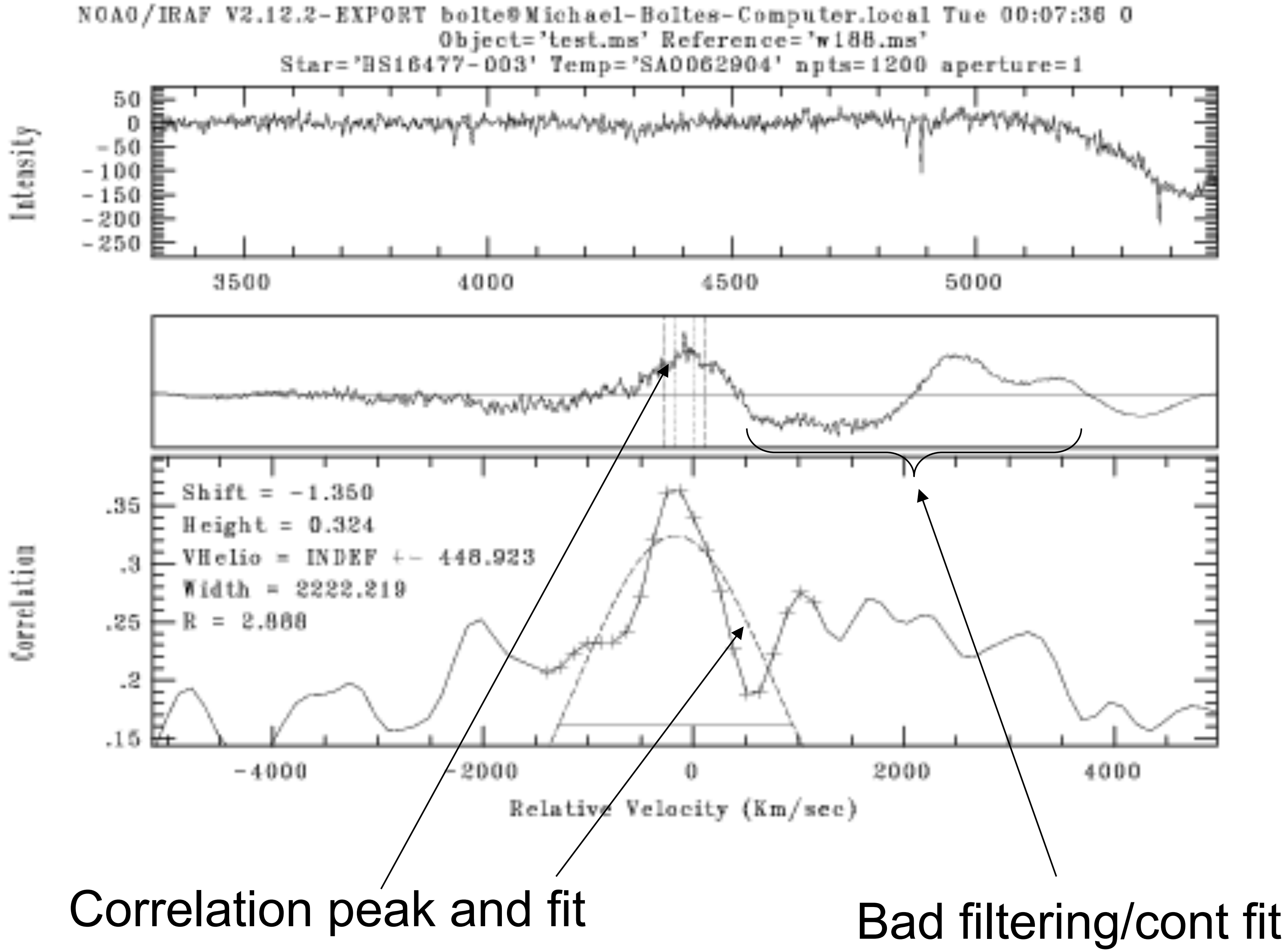
Tonry & Davis, 1979, A.J. 84, 1511.

noao.rv *fxcor* is a pretty good implementation.

- Need a template spectrum and an object spectrum.
- First, continuum is fitted and subtracted, then any filtering that is to be applied is applied, then a cross-correlation carried out, peak identified and fit.



Continuum fit object and template spectra



NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 00:07:36 0
Object='test.ms' Reference='w188.ms'
Star='BS16477-003' Temp='SA0062904' npts=1200 aperture=1
Intensity
Correlation
Shift = -1.350
Height = 0.324
VHelio = INDEF +- 448.923
Width = 2222.219
R = 2.888
Relative Velocity (Km/sec)
Correlation peak and fit
Bad filtering/cont fit

- Radial velocity precision/accuracy

$$R \equiv \frac{\lambda}{\Delta\lambda} = \frac{c}{\mathrm{v}}$$

$$\mathrm{v} = \frac{c}{R}$$

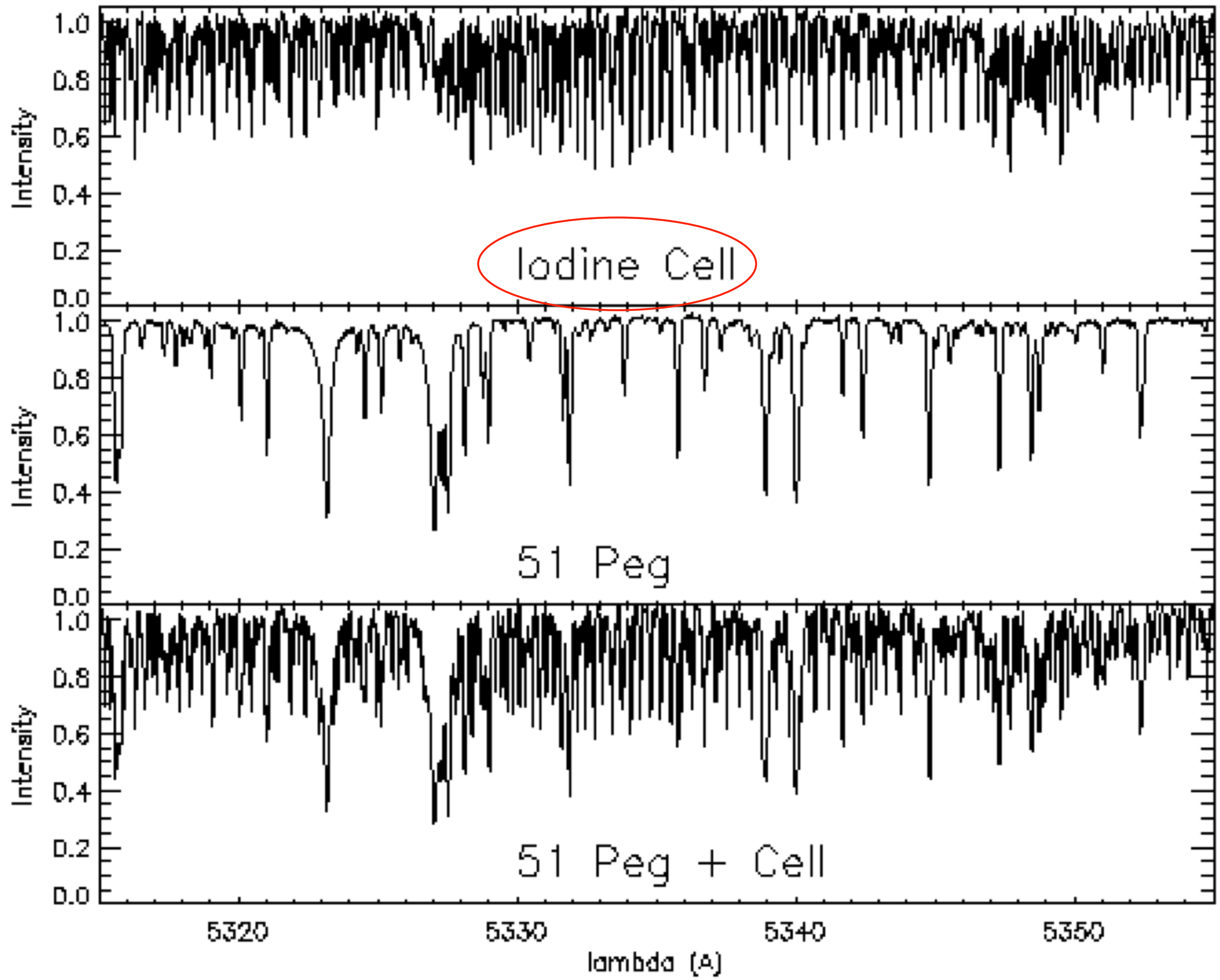
- R=2500 (LRIS/KAST): 120km/s
- Centroid to 1/20 resolution element gives a precision of 5 km/s (ignoring wavelength calibration uncertainties).
- HIRES@R=50000 and 1/20th: 0.3 km/sec

- For most spectrometers, systematic errors dominate by ~2km/sec. Flexure, illumination differences between sky and lamp paths, asymmetric line profiles due to detector and spectrometer optics shortcomings, spectrometer focal-plane scale shifts due to refocus/temperature changes, etc.
- Sun reflex motion due to Jupiter is 0.0124km/sec - planet searching is a new ballgame. At this level you even need to worry about the barycentric corrections: 1 m/sec corresponds to determining the mid-time of an observation to 30 seconds.

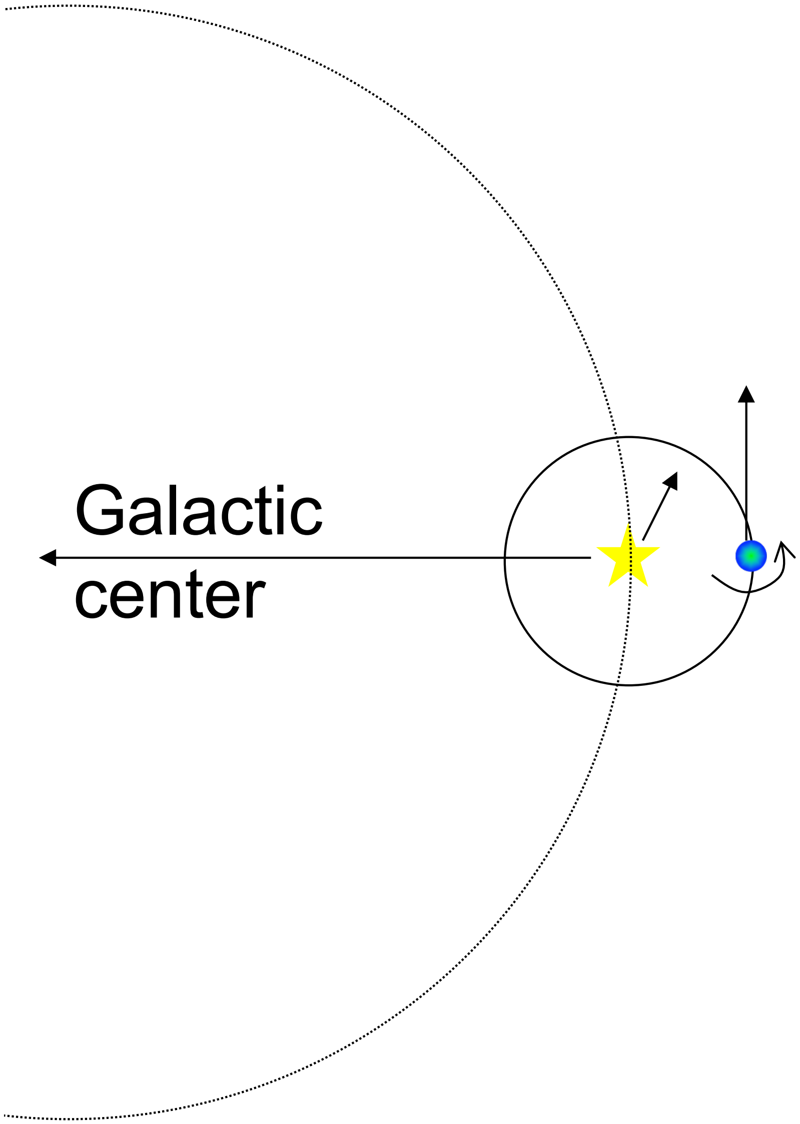
- Solutions for really high precision work are to environment control stationary spectrometers (coude or Nasmyth platform) and to use a stable, in-spectrum wavelength calibration source.
- Campbell & Walker (1979, PASP, 91, 540) proposed hydrogen-fluoride in a cell in front of the spectrometer slit to superpose narrow lines at zero velocity on the spectrum. Showed 15 m/sec precision was possible. HF was described as "obnoxious"

Marcy, & Butler, 1992, PASP, 104, 270

Butler, et al. 1996, PASP, 108, 500: 3m/s



rvcorrect



In noao.rv is *rvcorrect*

Based on date and time of the observation and the RA and DEC of the object it will return and write keywords into the header with the heliocentric correction to back out the motions of the Earth around the Sun and the Earth around its axis (the *diurnal velocity*), motion of the Earth around the Earth-moon barycenter and the Sun's peculiar motion wrt circular velocity at the mean distance from the Galactic center (LSR). You want the components of these motions in the direction of the object.

The help for this task has all the formulae required to make the calculations

- Usually need to set the keyword translation file to fit the headers of your particular frames using *keywpars*.
- *rvcorrect:*
- rv> rvcorrect

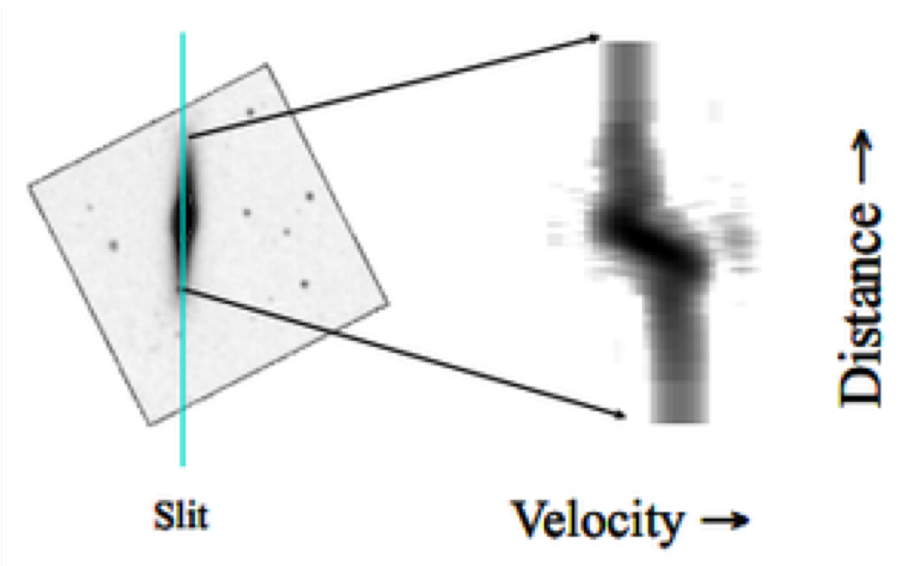
```
# RVCORRECT: Observatory parameters for Lick Observatory
#       latitude = 37:20.6
#       longitude = 121:38.2
#       altitude = 1290
##   HJD             VOBS   VHELIO   VLSR   VDIURNAL   VLUNAR   VANNUAL   VSOLAR
2452727.89086  0.00   -8.25    -2.18   -0.107     0.003    -8.143    6.070
```

Earth's spin (VDIURNAL) Earth's orbit (VANNUAL)

Julian date (HJD) heliocentric correction (VHELIO) correction to LSR (VLSR)

Earth-moon motion (VLUNAR)

Rotation curves

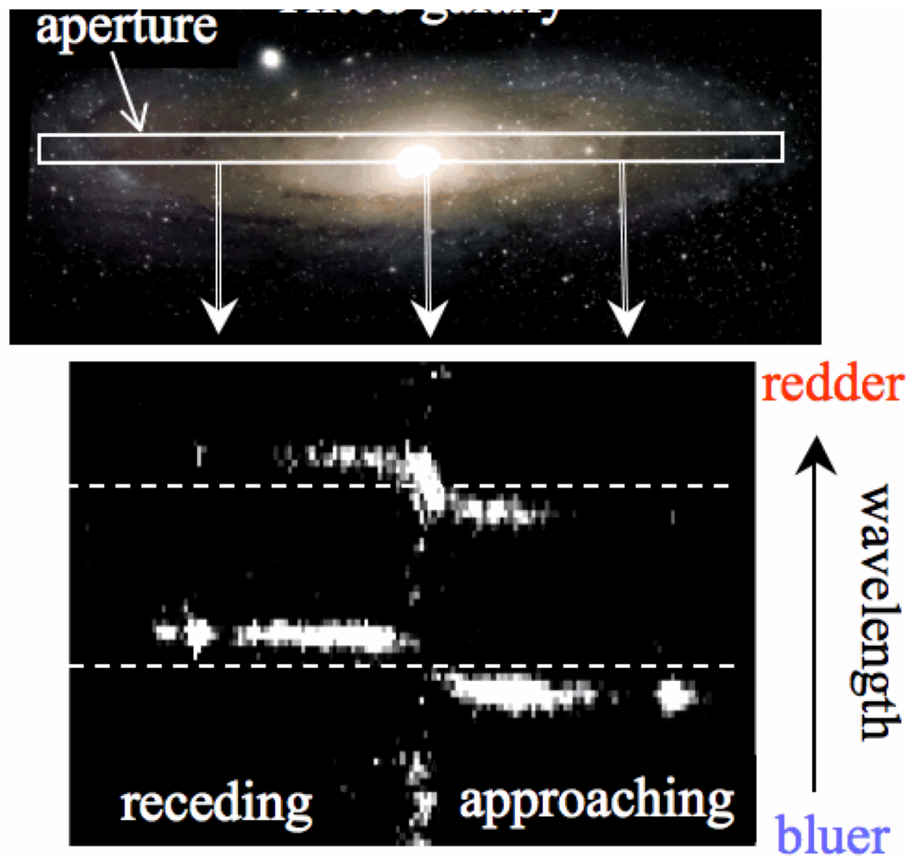


With a long slit or IFU you can extract spectra from different physical locations in a galaxy and derive mean radial velocity

Rotation curve, corrected for estimated inclination, can be used to measure enclosed mass as a function of distance from the center of the galaxy

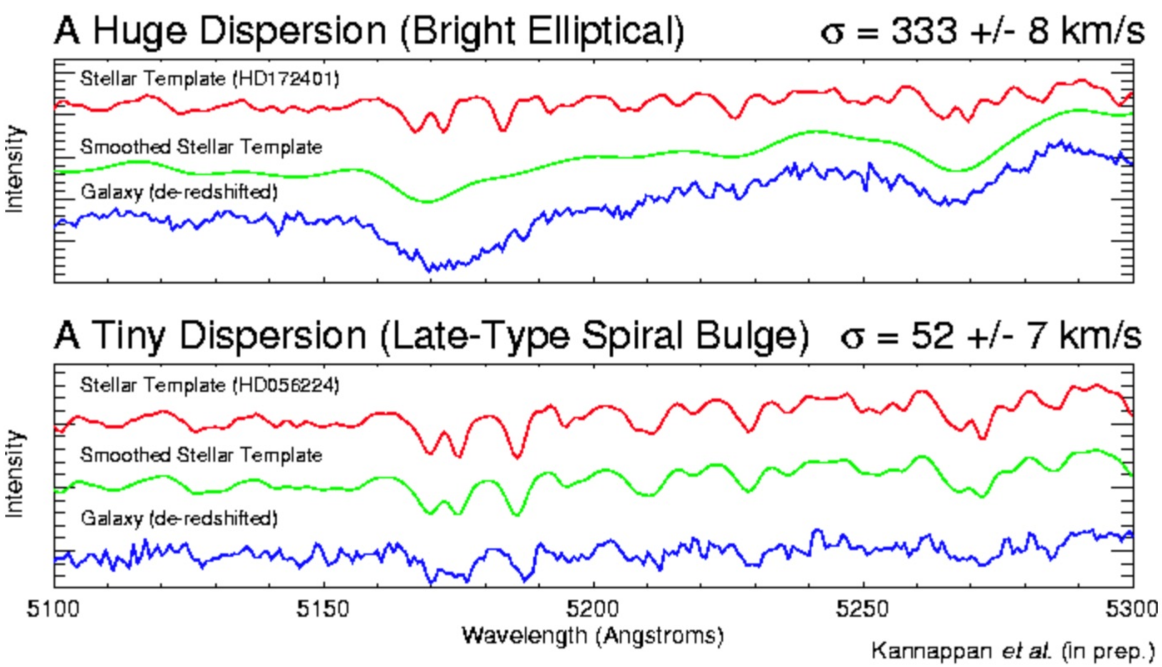
Rotation Curves

Vera Rubin measuring galaxy



Resulting spectrum of

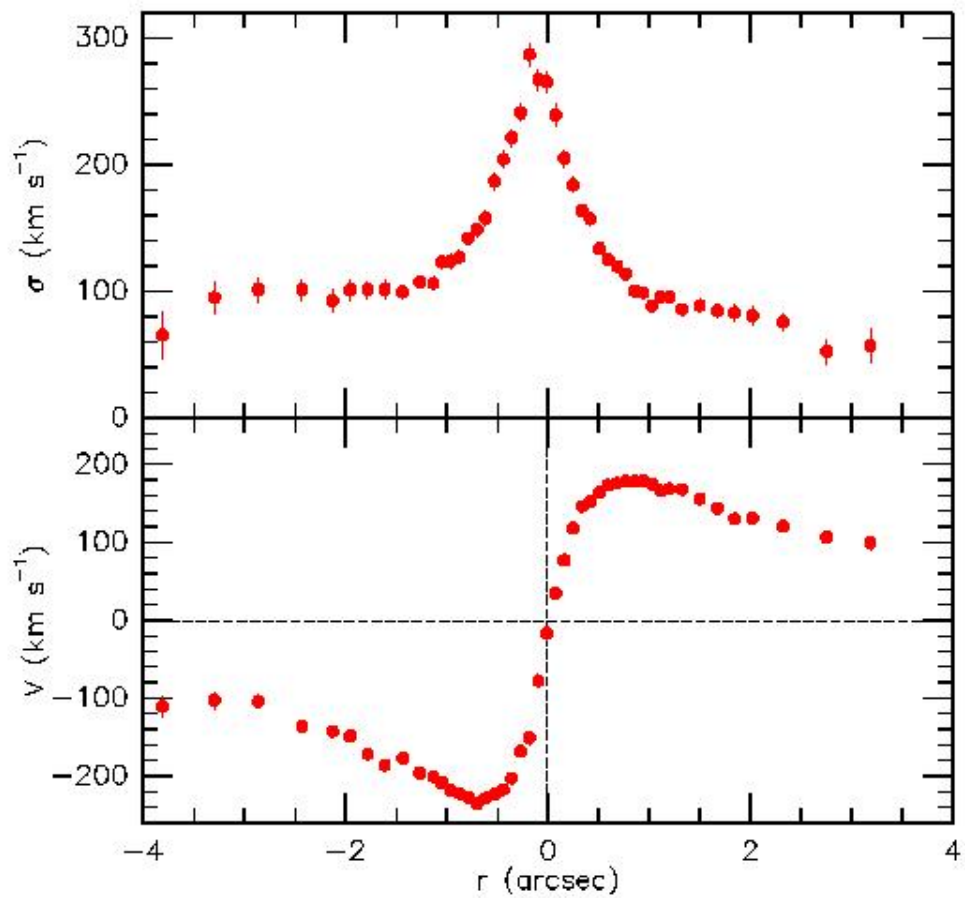
Velocity dispersions

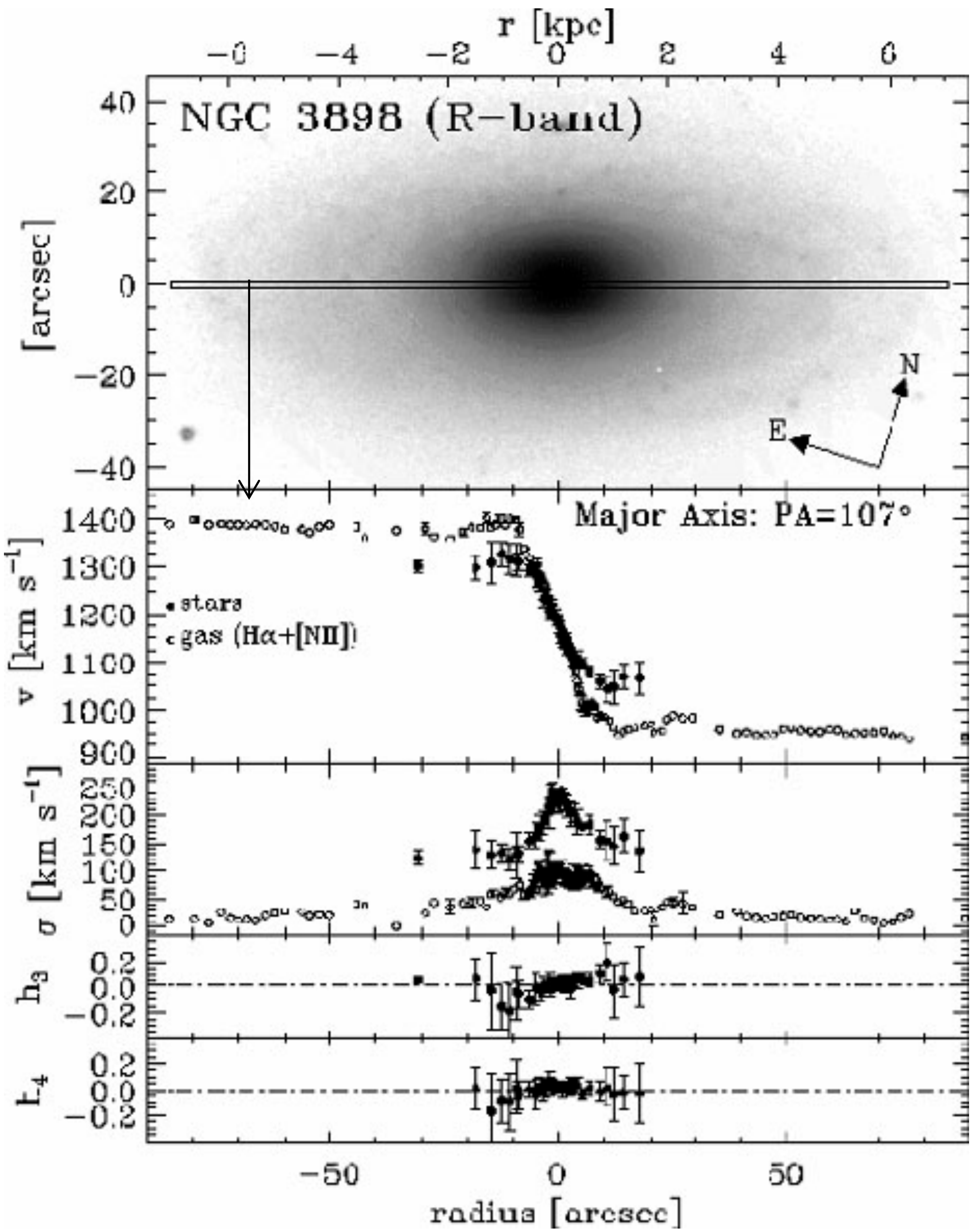


Random motions of stars and gas for a kinematically "hot" population also measure total mass

Usually measured by determining the broadening function compared to a star (FXCOR also does a Fourier decomposition)

Real life: rotation and dispersion





At each position along the slit, measure the mean doppler shift and broadening of absorption lines, do the same for emission lines and determine rotation curve and velocity dispersion profile