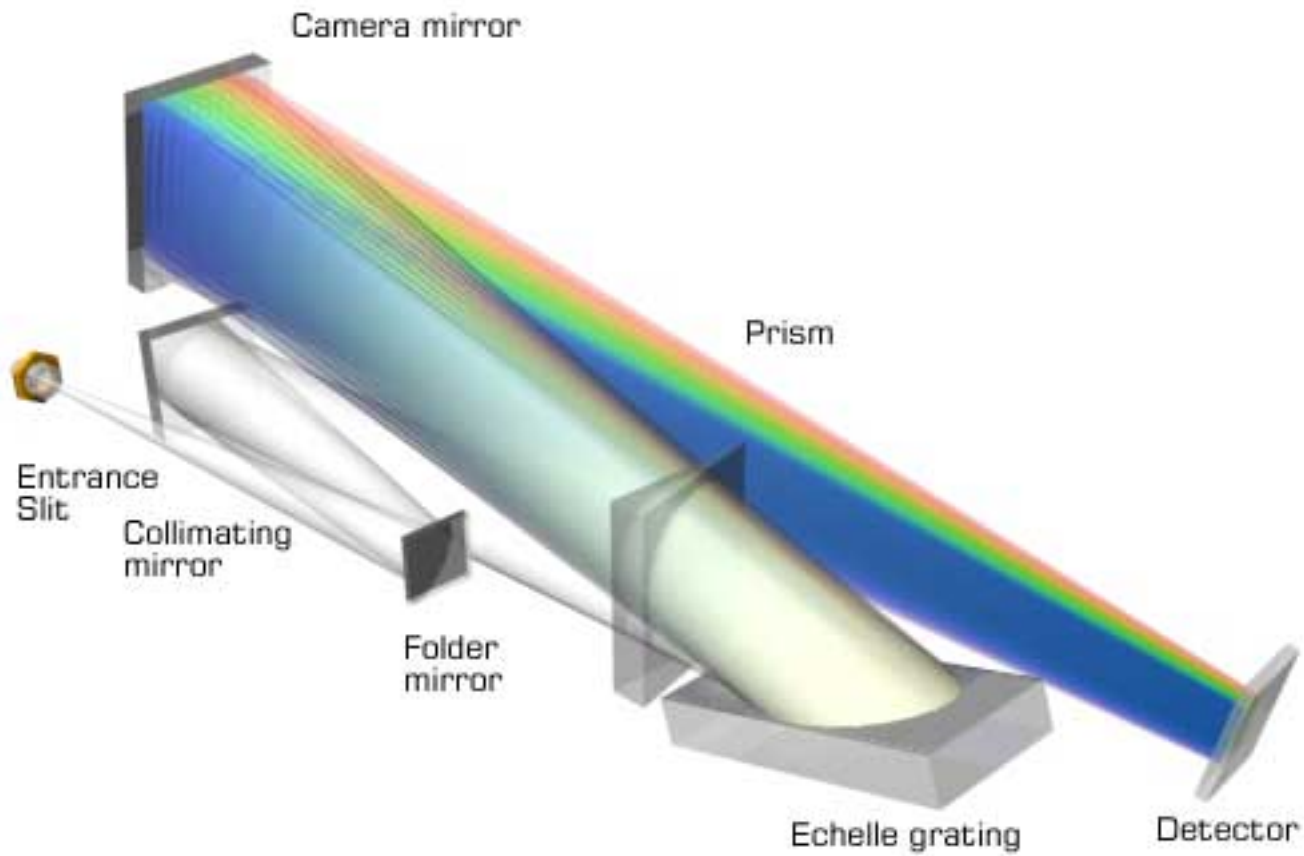
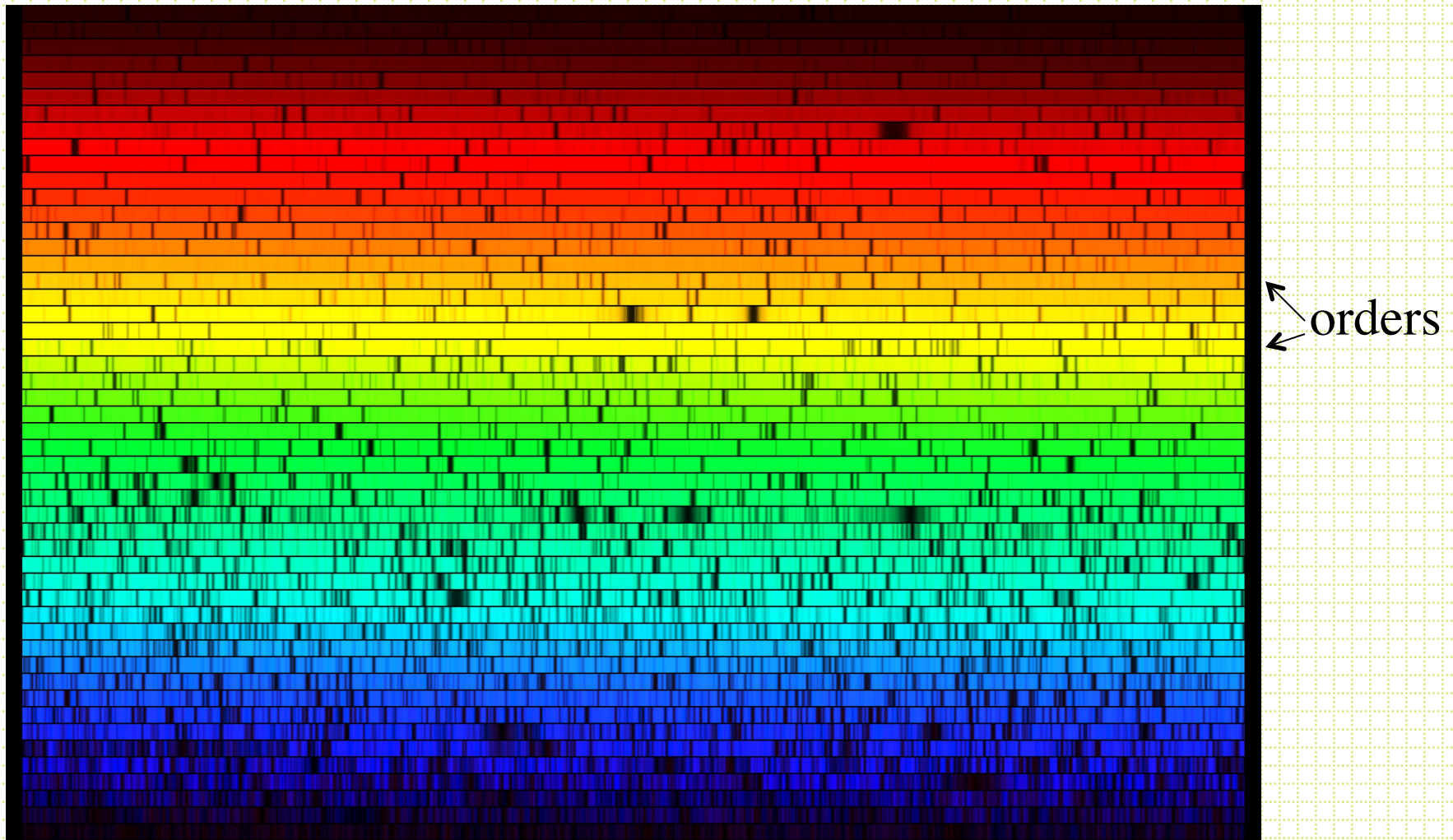
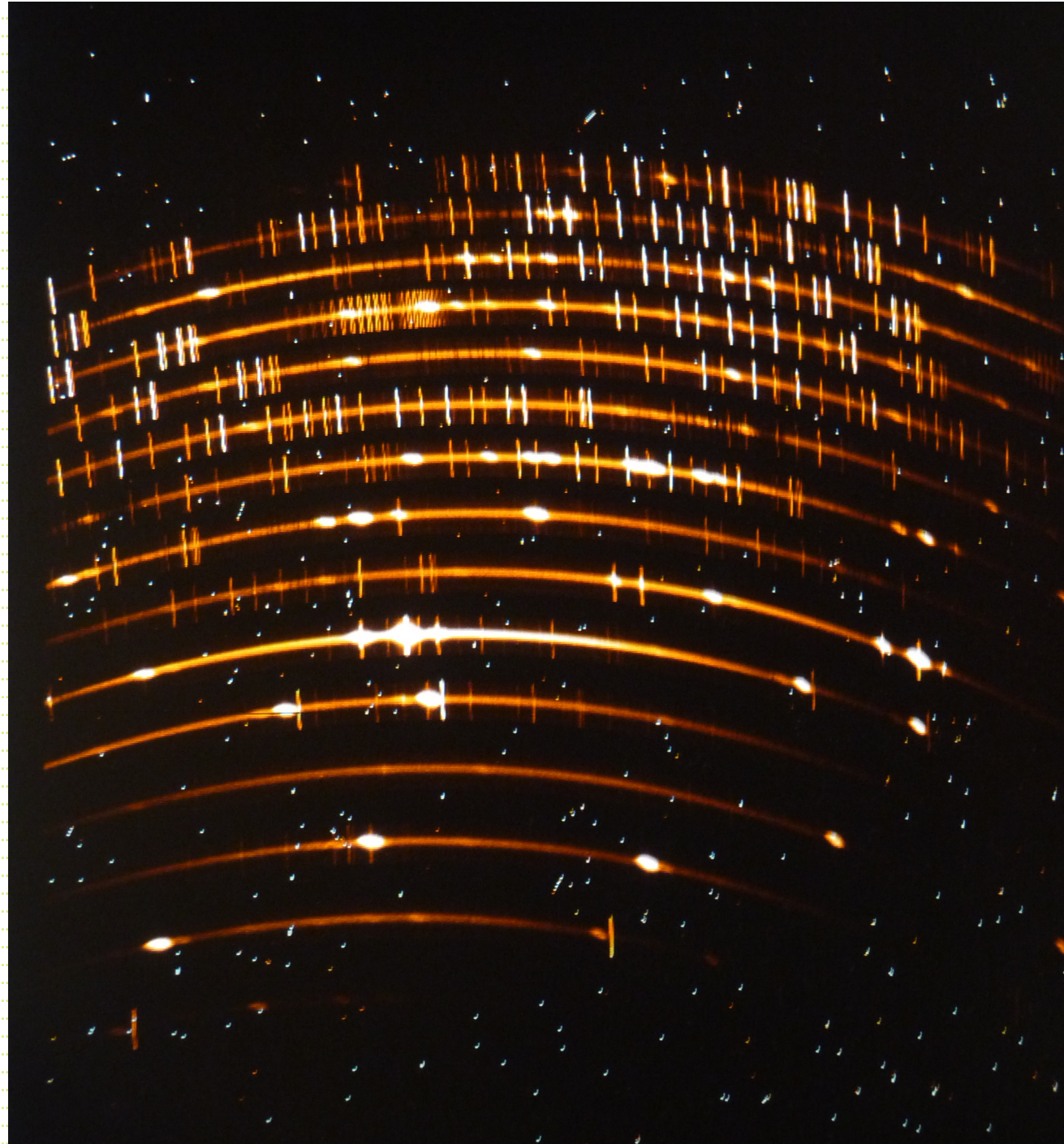


Cross-dispersed Spectra

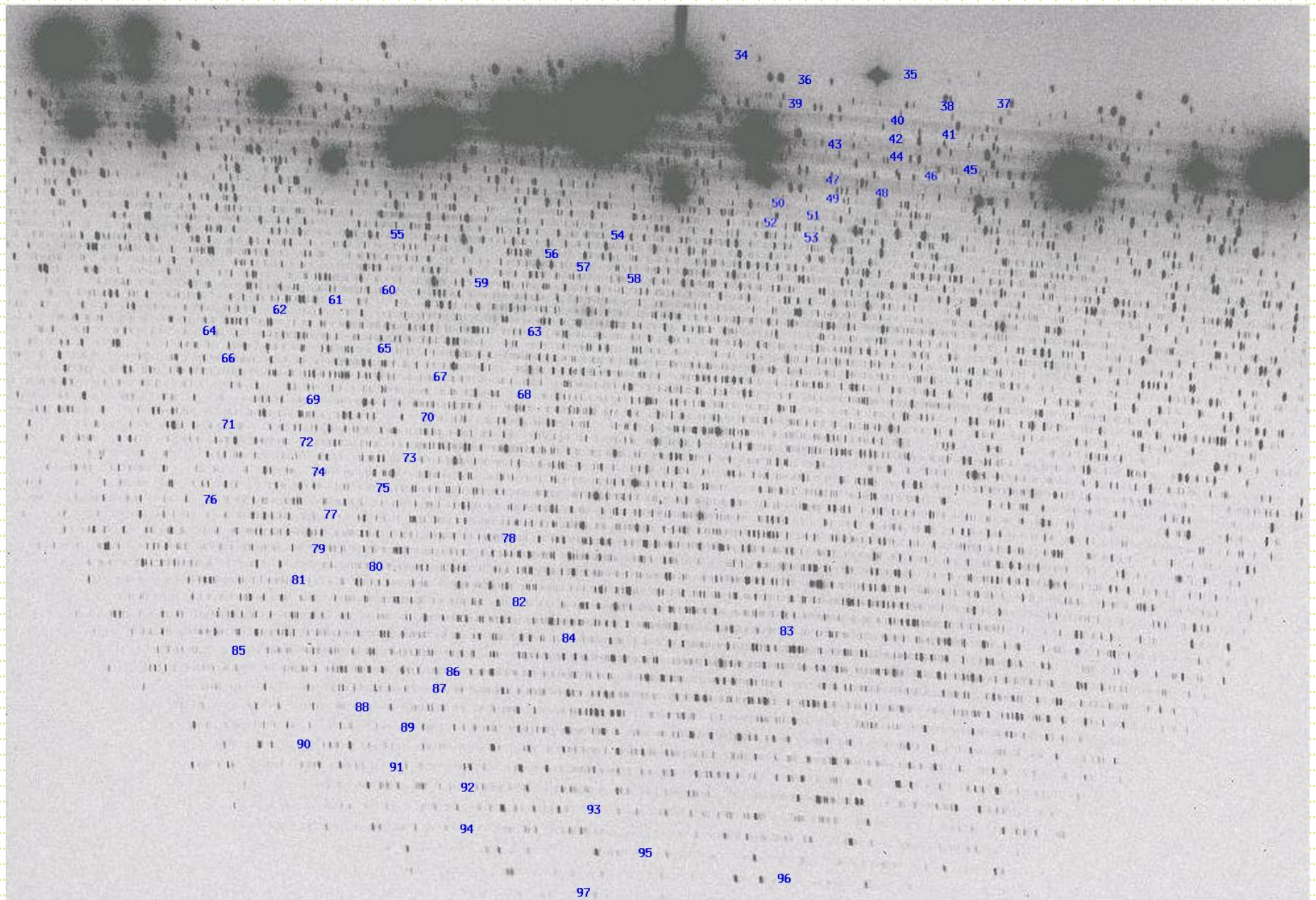


Typically have orders > 20 so spectral resolution is high.



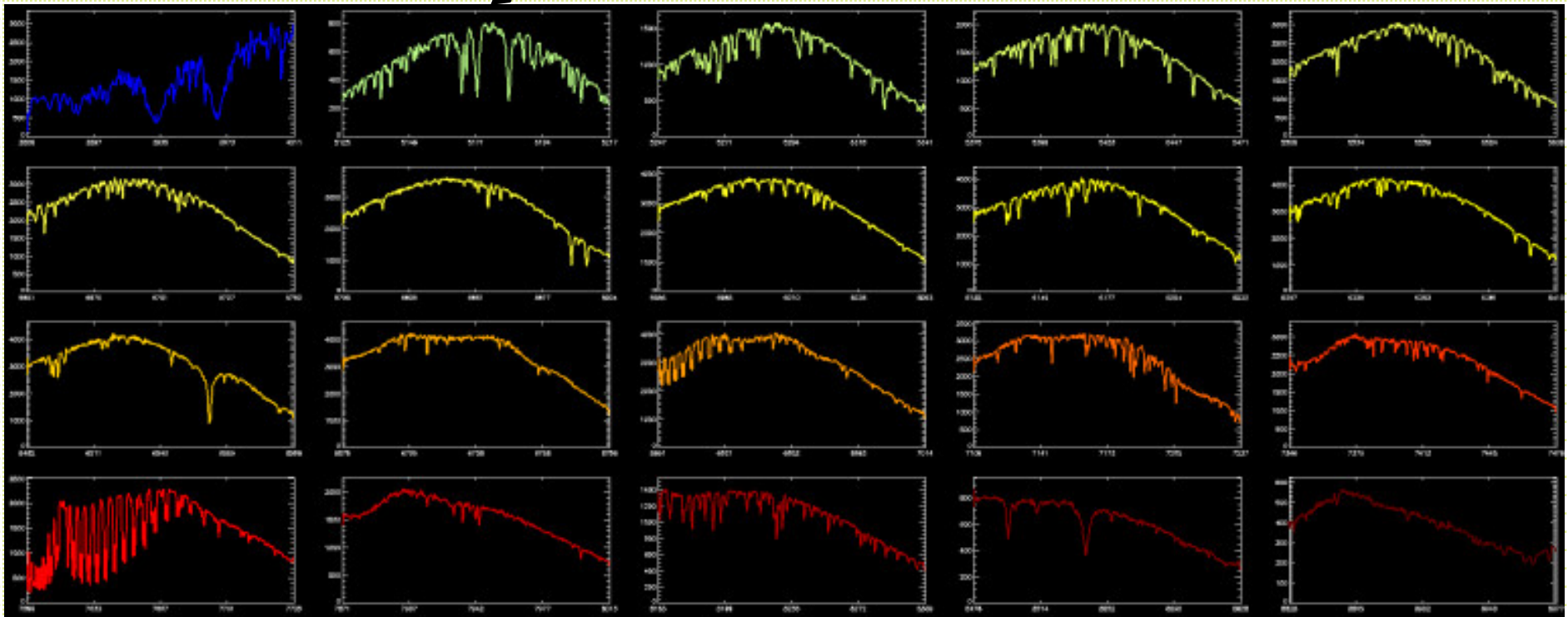
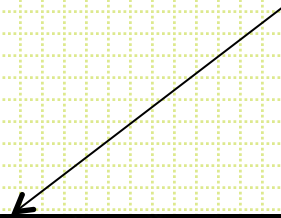


X-SHOOTER



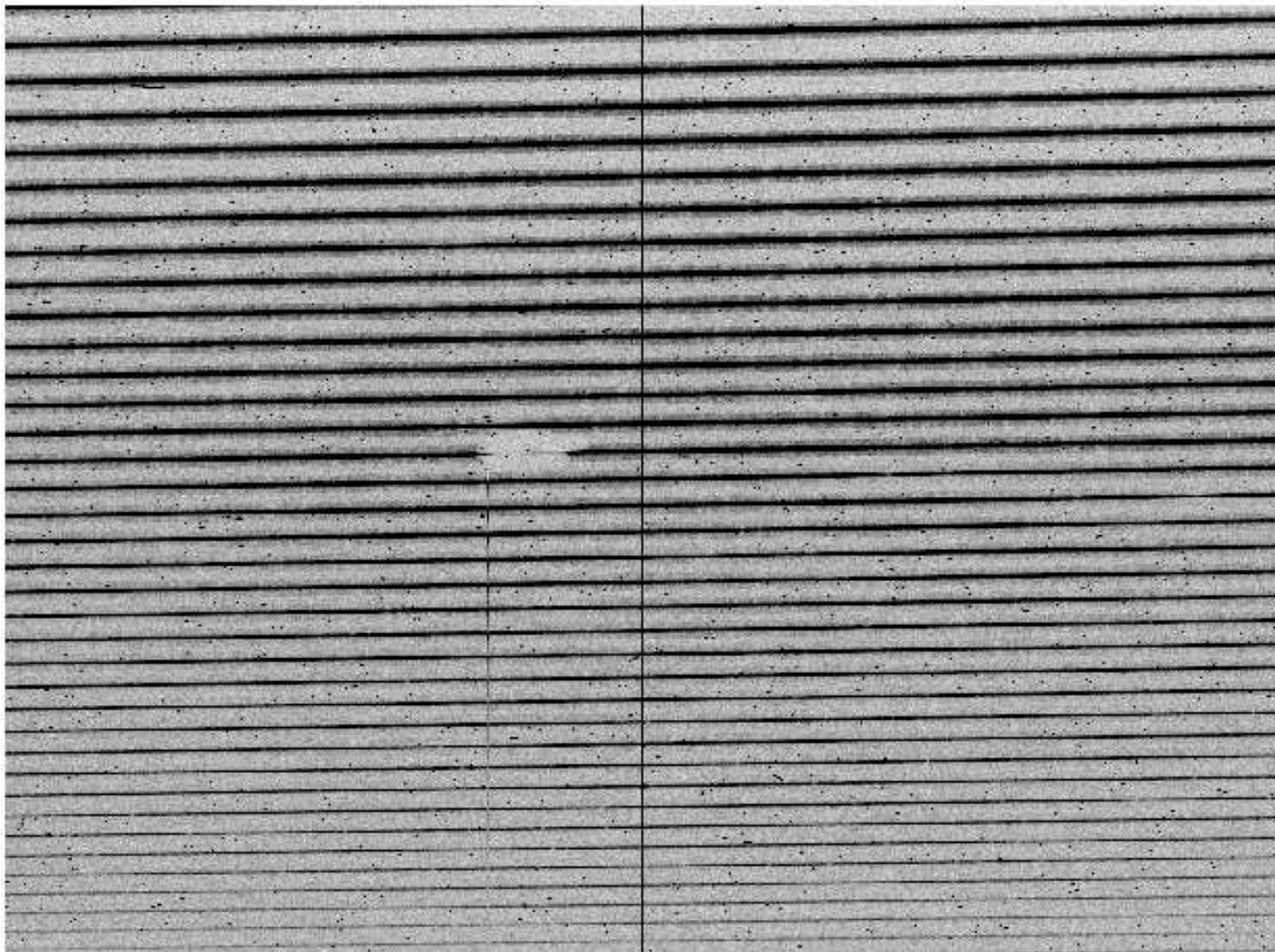
IMACS

Each order has a blaze function



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

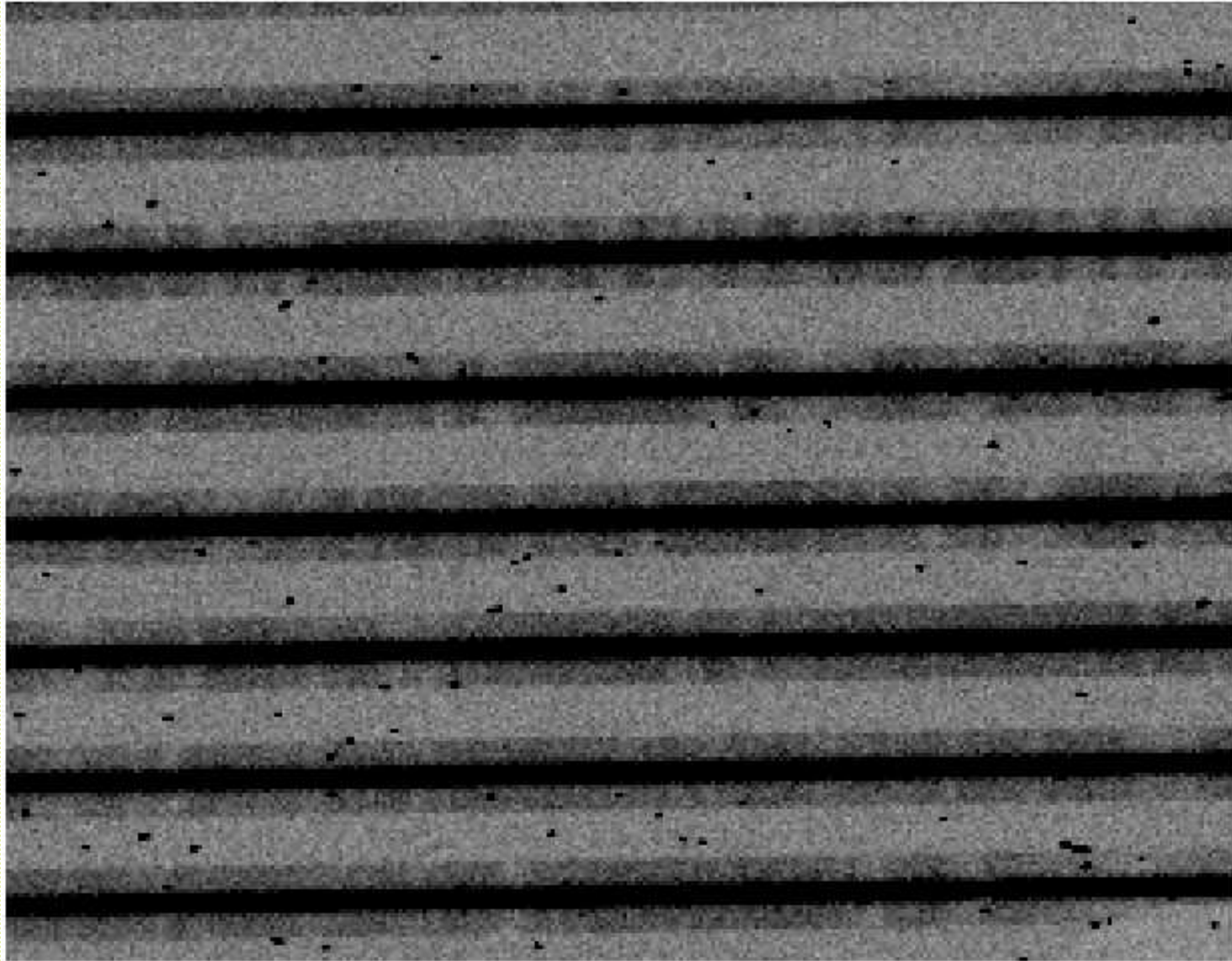
Echelle format spectra reduction



In apall, each order will be an aperture.

Each will have to be traced.

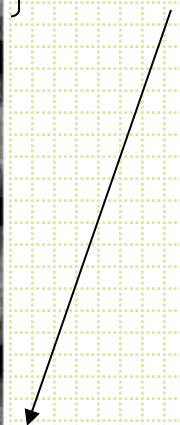
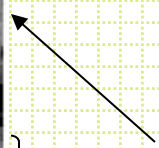
Often the background apertures need to be set for each order individually



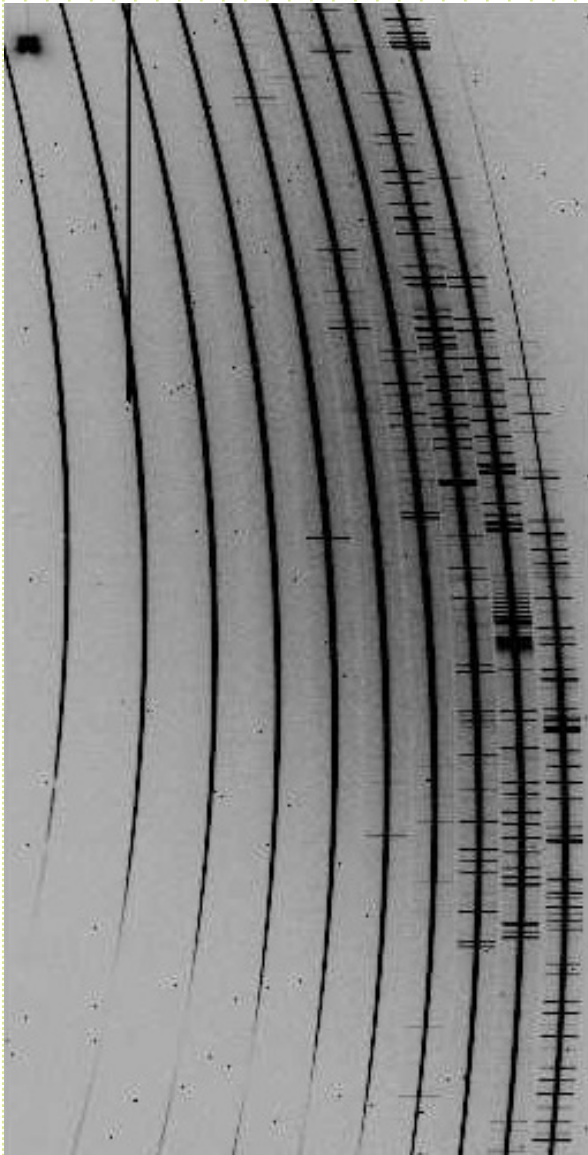
} Seeing disk

} Slit length

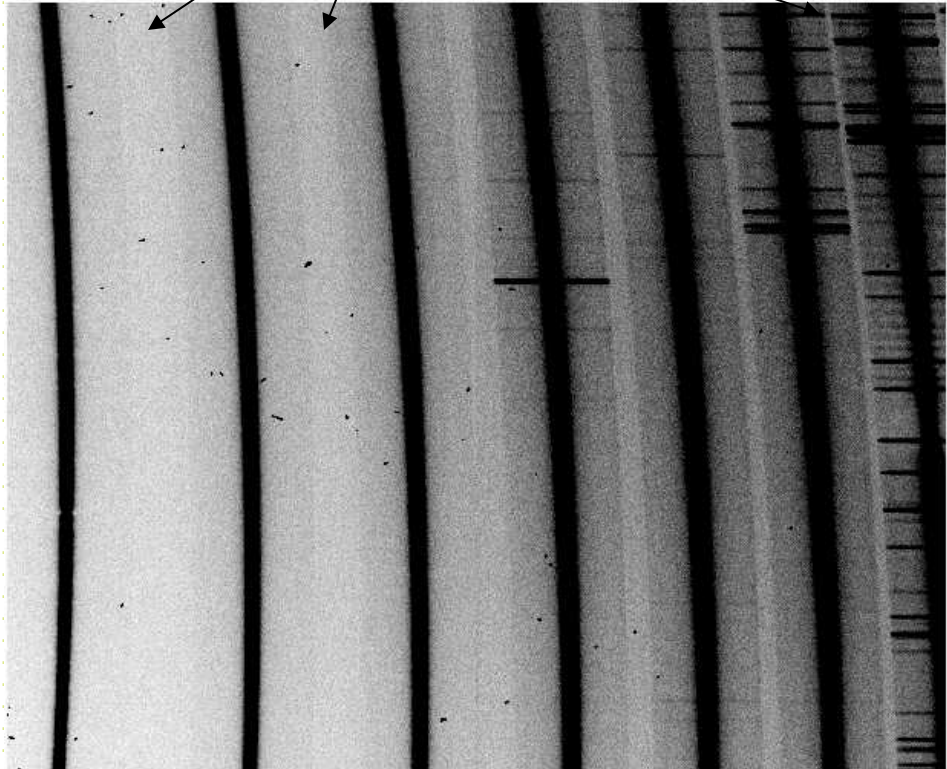
} Inter-order



ESI spectra

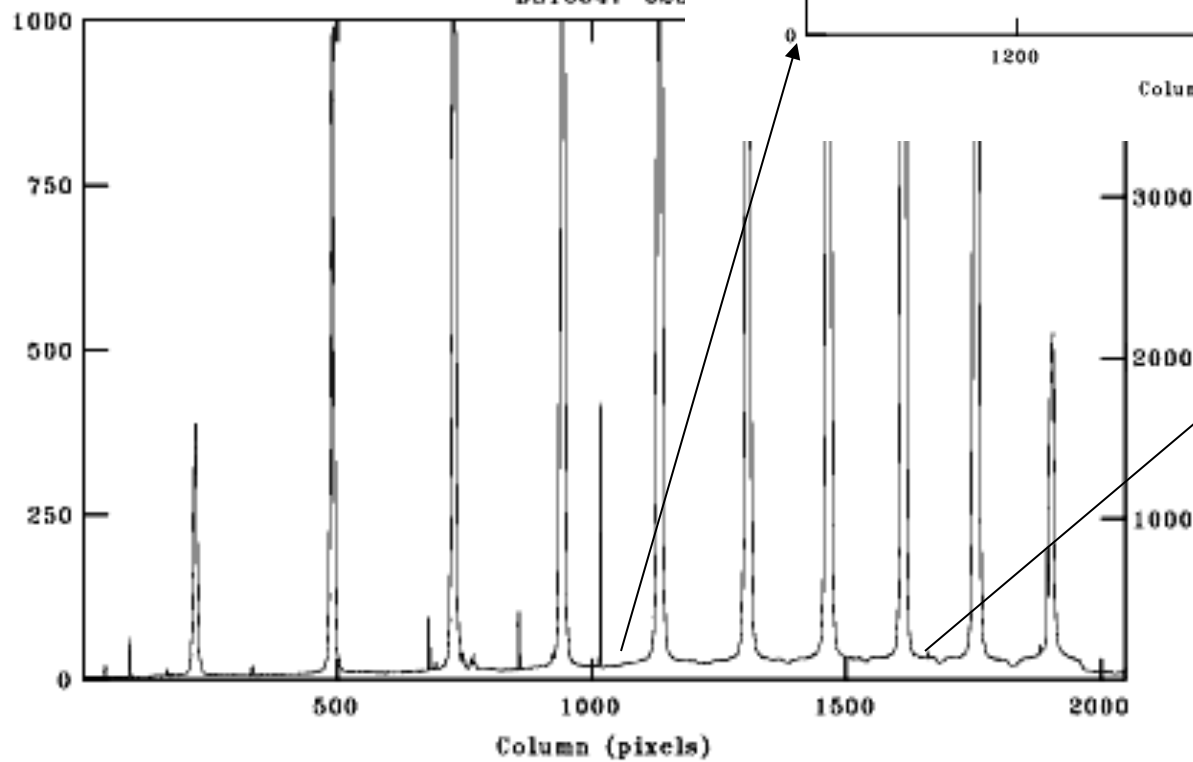


Inner order regions

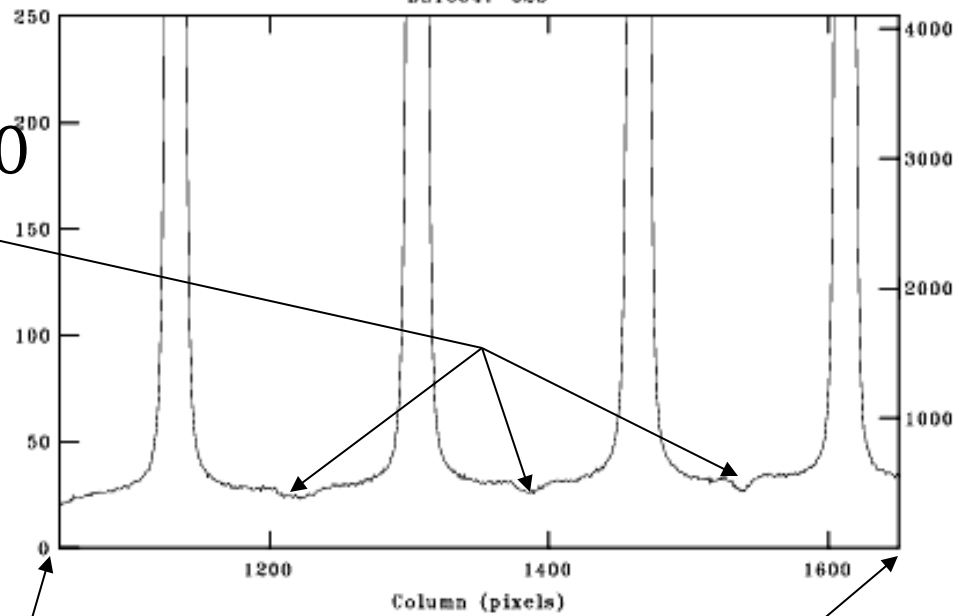


Inner order flux $\neq 0$

NOAO/IRAP V2.12.2-EXPORT bolte@sahara.ucolick.org
Average of lines 2000 to 2100 of b272
BS16547-025

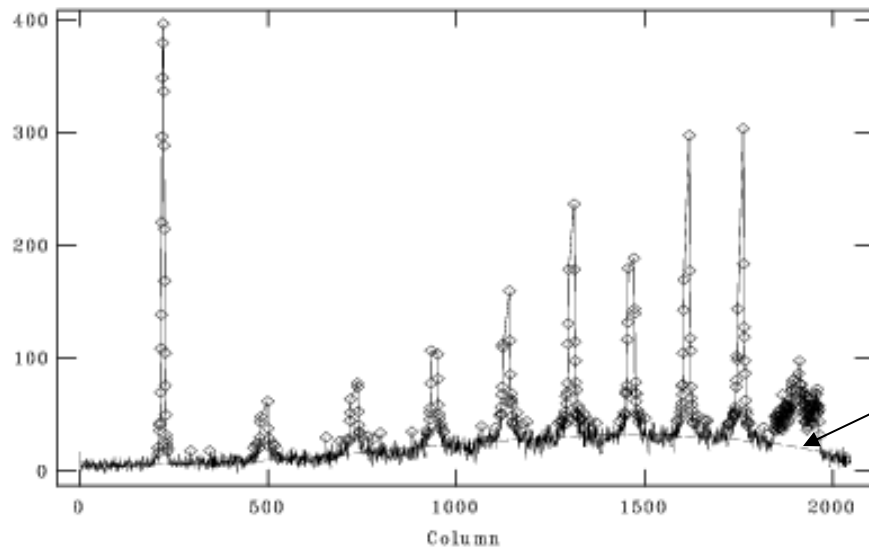


NOAO/IRAP V2.12.2-EXPORT bolte@sahara.ucolick.org Tue 12:48:46 25-May-200
Average of lines 2000 to 2100 of b272
BS16547-025



- 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.

```
NOAO/IRAF V2.12.2-EXPORT bolte@sahara.ucolick.org Tue 13:03:57 25-May-200  
func=spline3, order=1, low_rej=5, high_rej=2, niterate=5, grow=0  
total=1904, sample=1904, rejected=327, deleted=0, RMS= 5.128  
b272: Fit line 2048  
BS16547-025
```



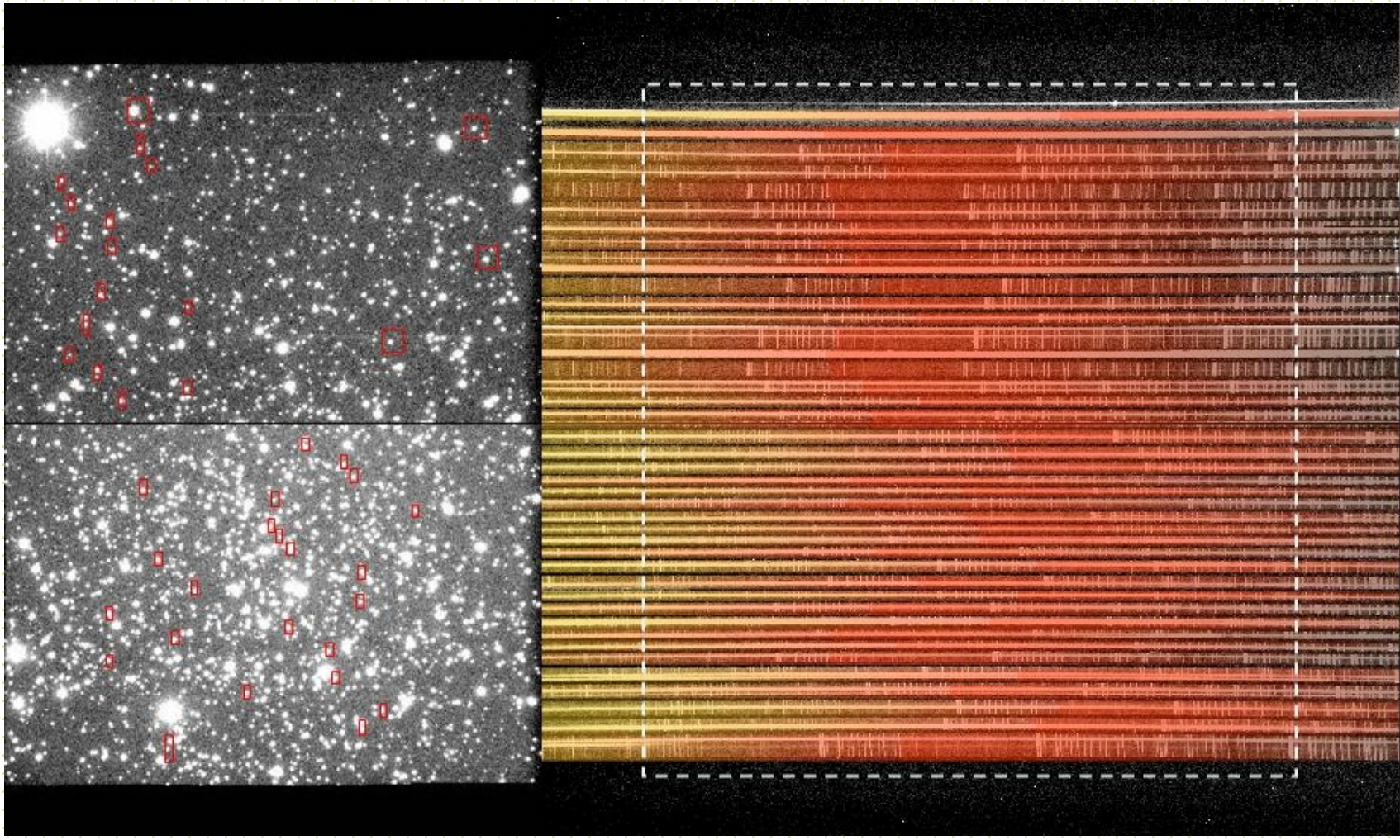
Need to identify and trace orders to identify the inner-order regions

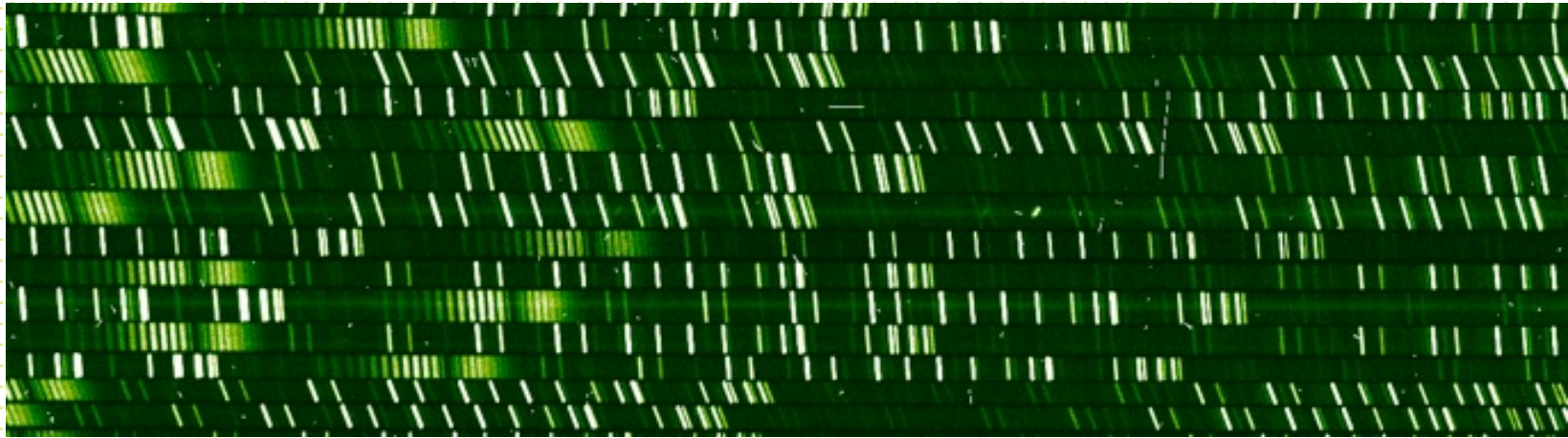
Scattered light fit

Multi-object spectra

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

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



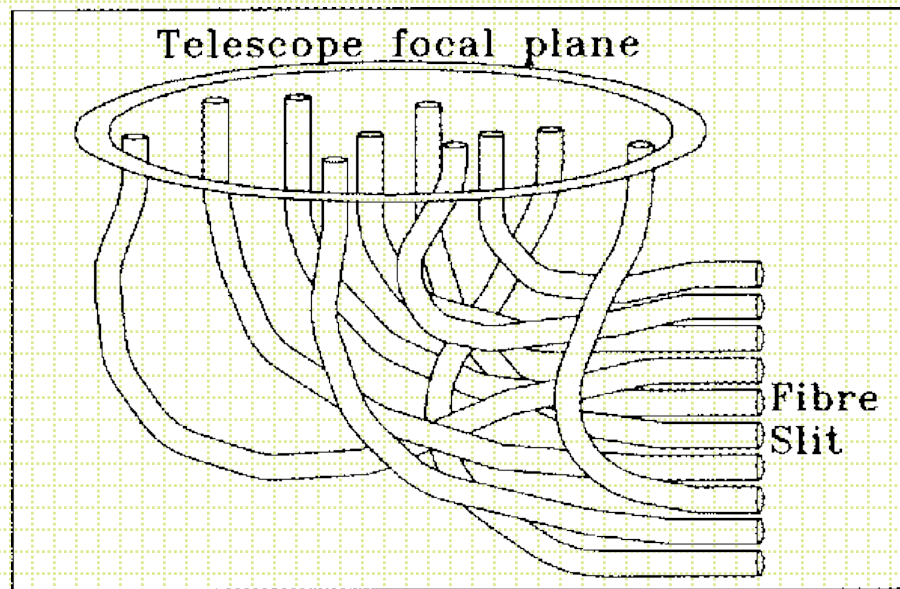


Slits can be cut at angles in order to measure rotation curves for galaxies.

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

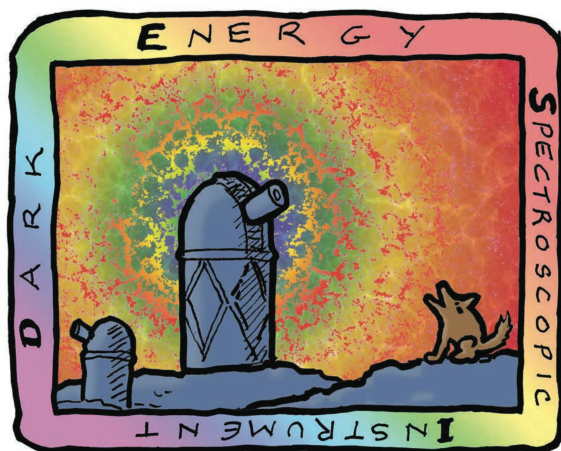
Fiber-fed systems

- 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.

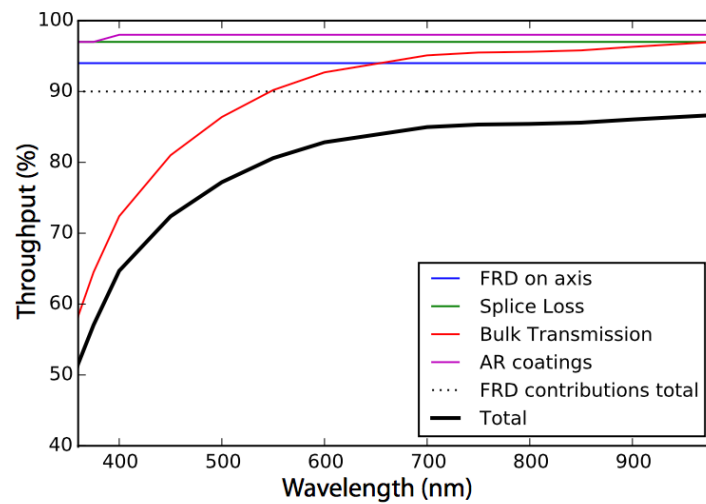


DESI: 5000 fibers

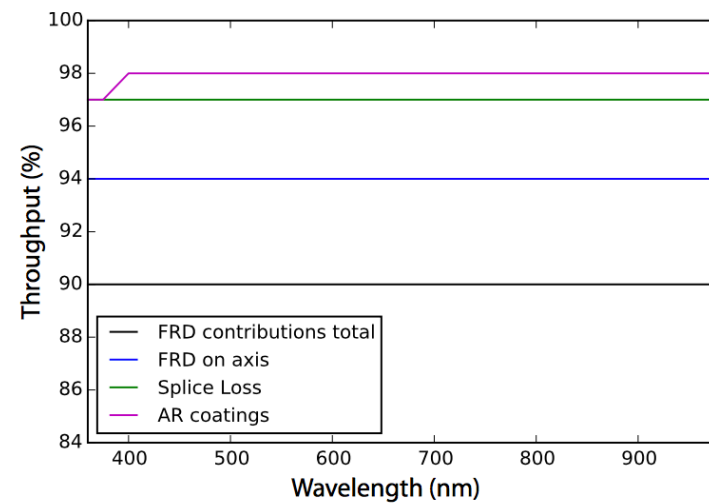
PSF @ Subaru 2500 fibers

Fibers issues

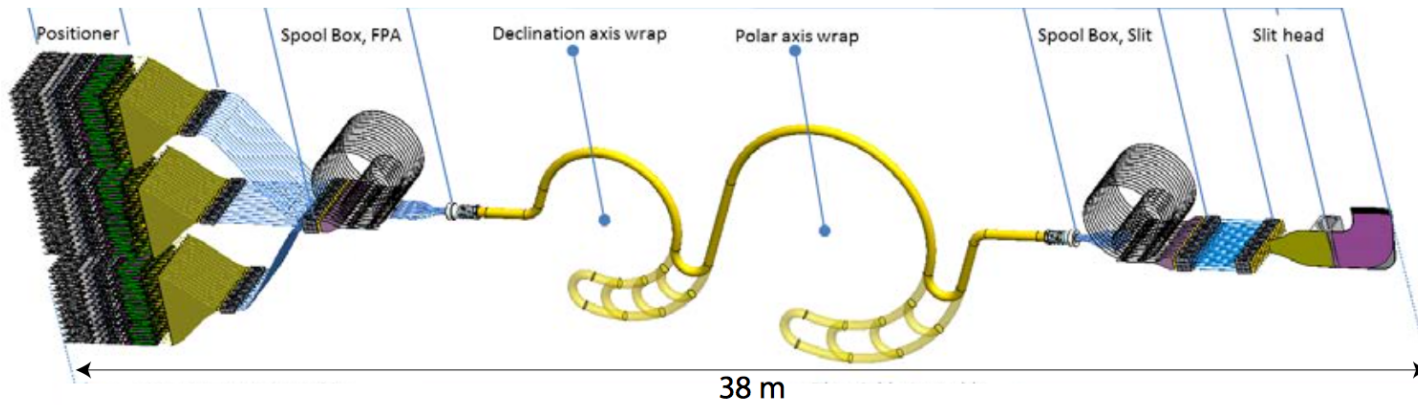
- Throughput
- Sky subtraction
- Alignment and coupling



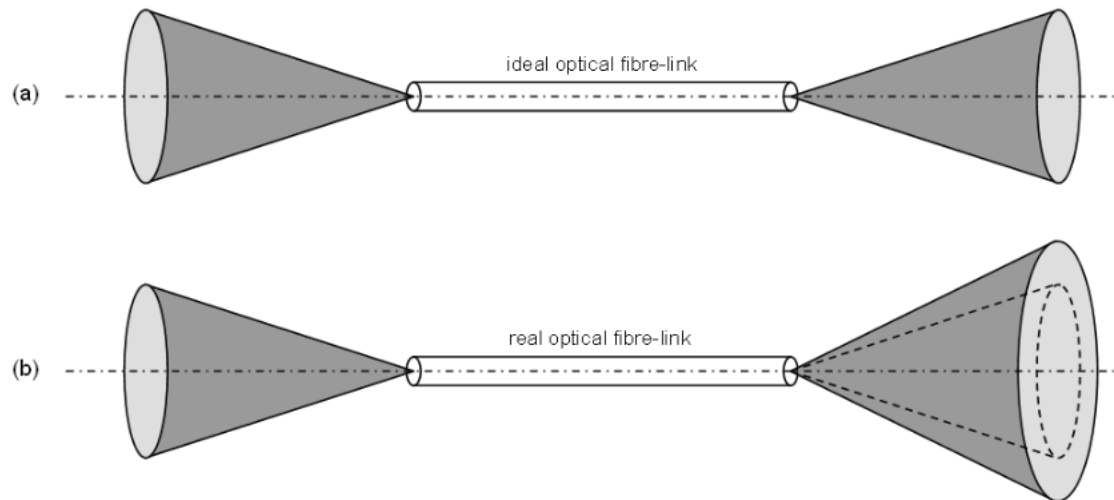
(a)



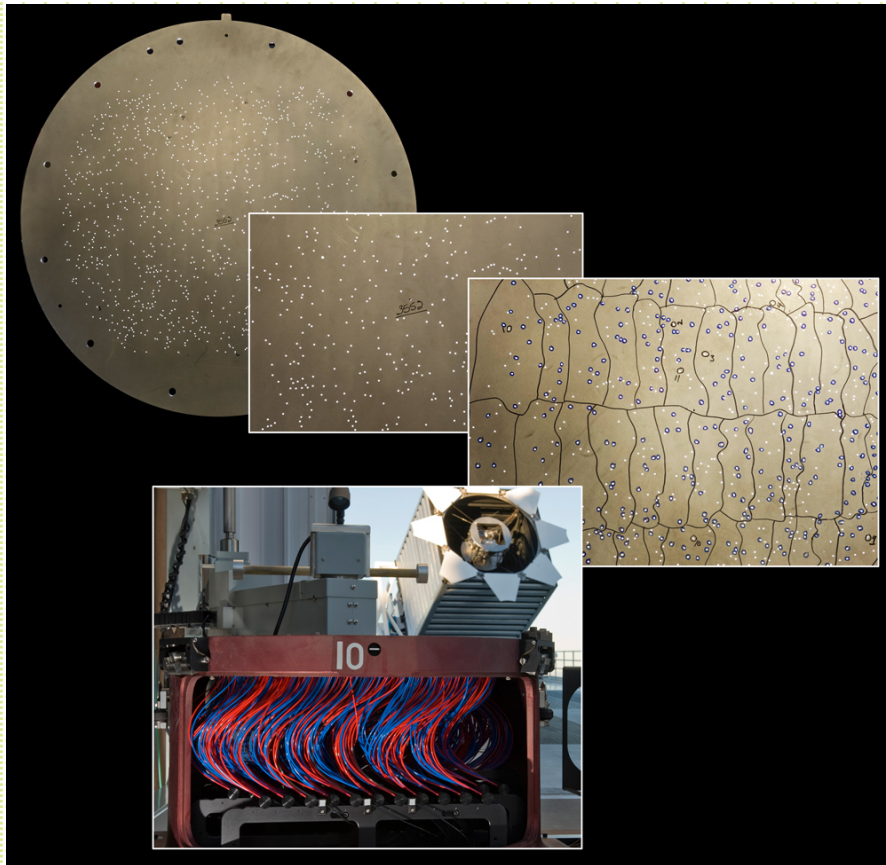
(b)



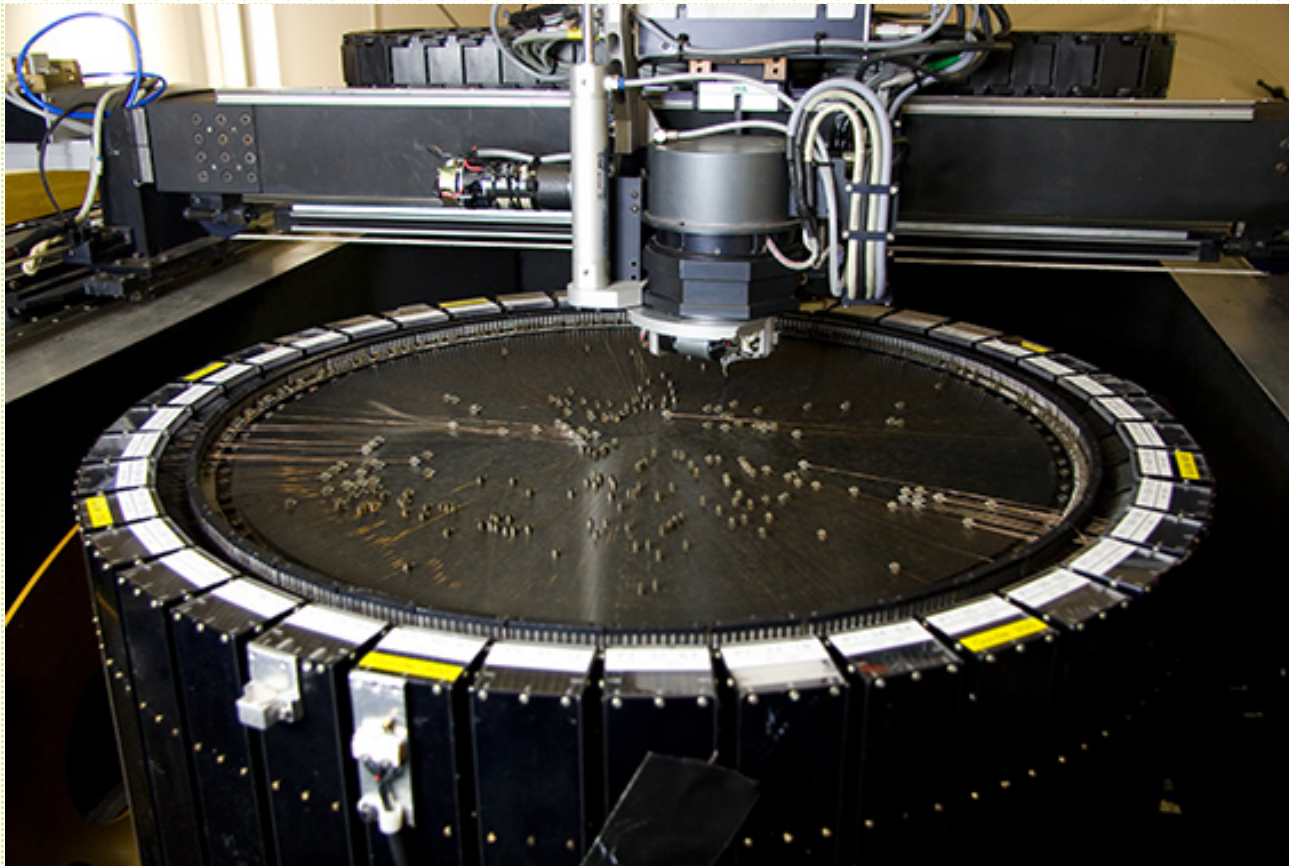
DESIGN FIBER ARRANGEMENT

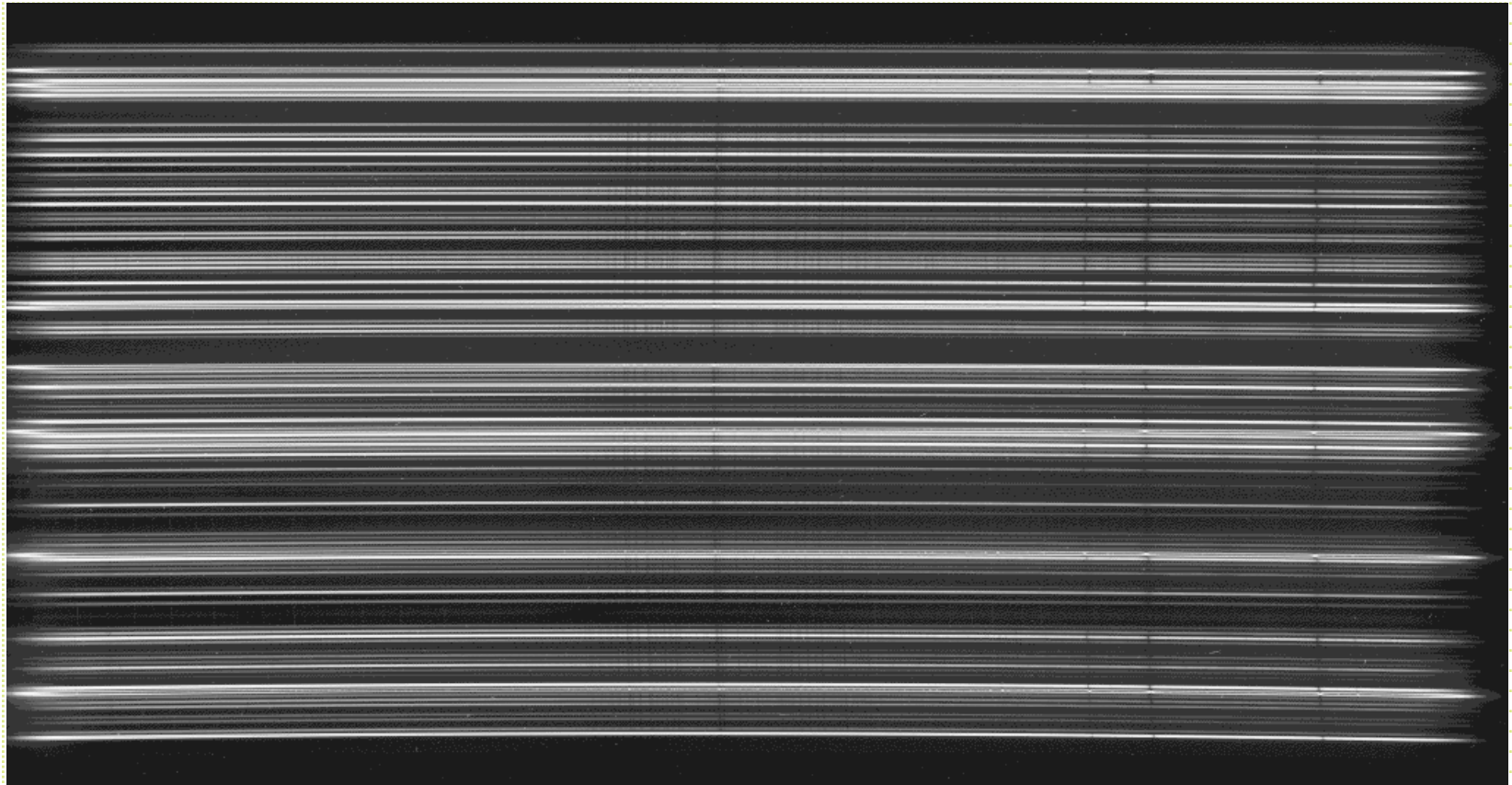


SDSS plugboards

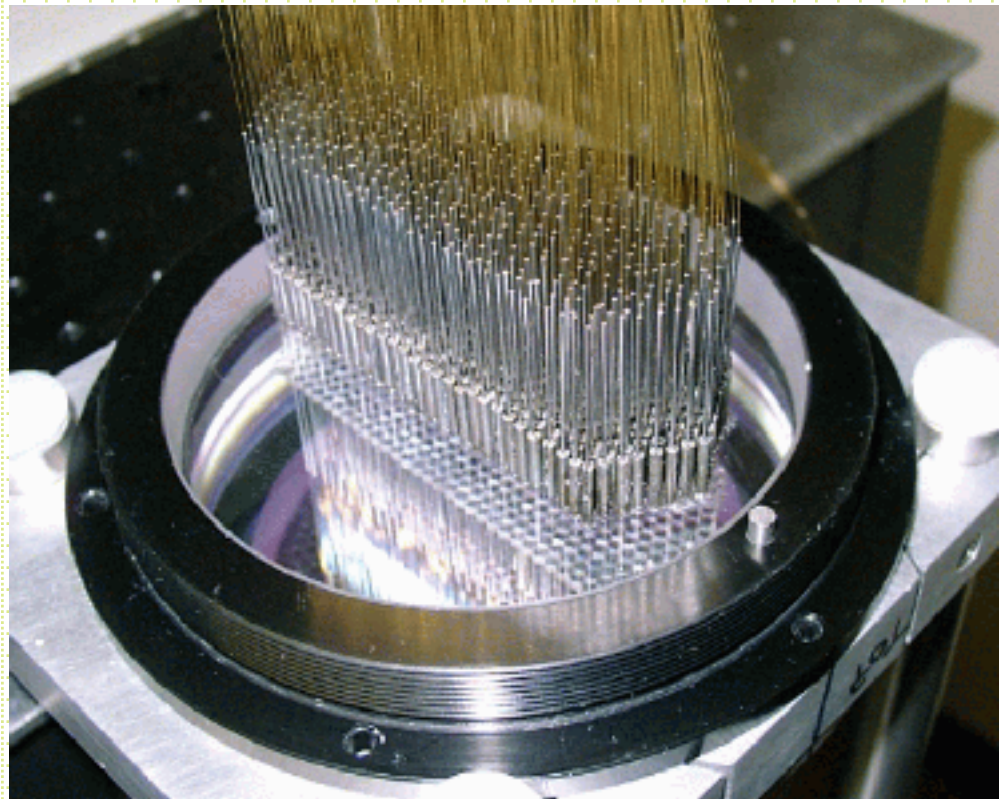
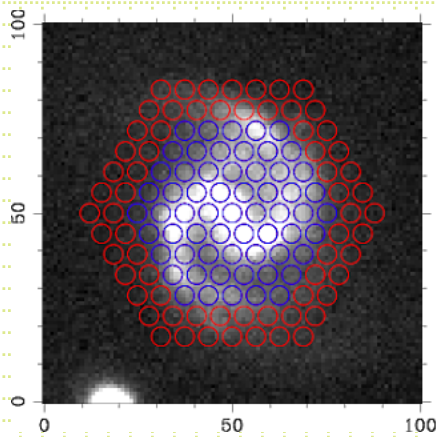
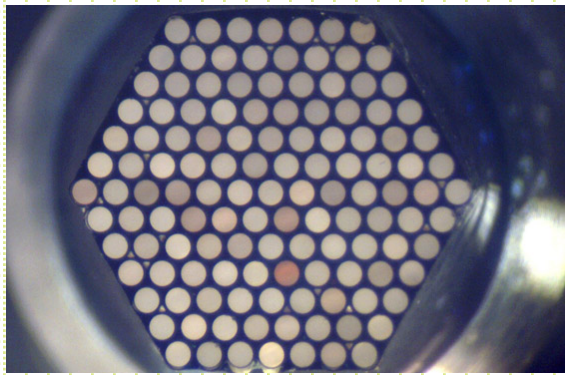


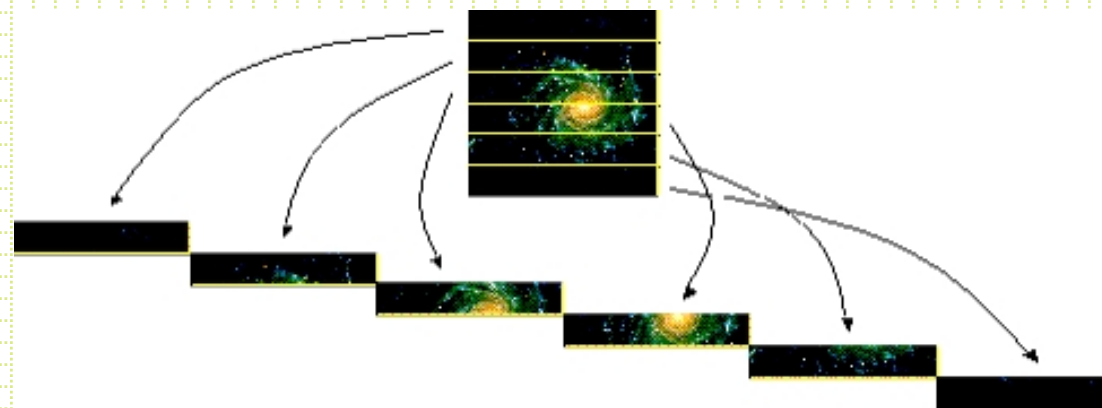
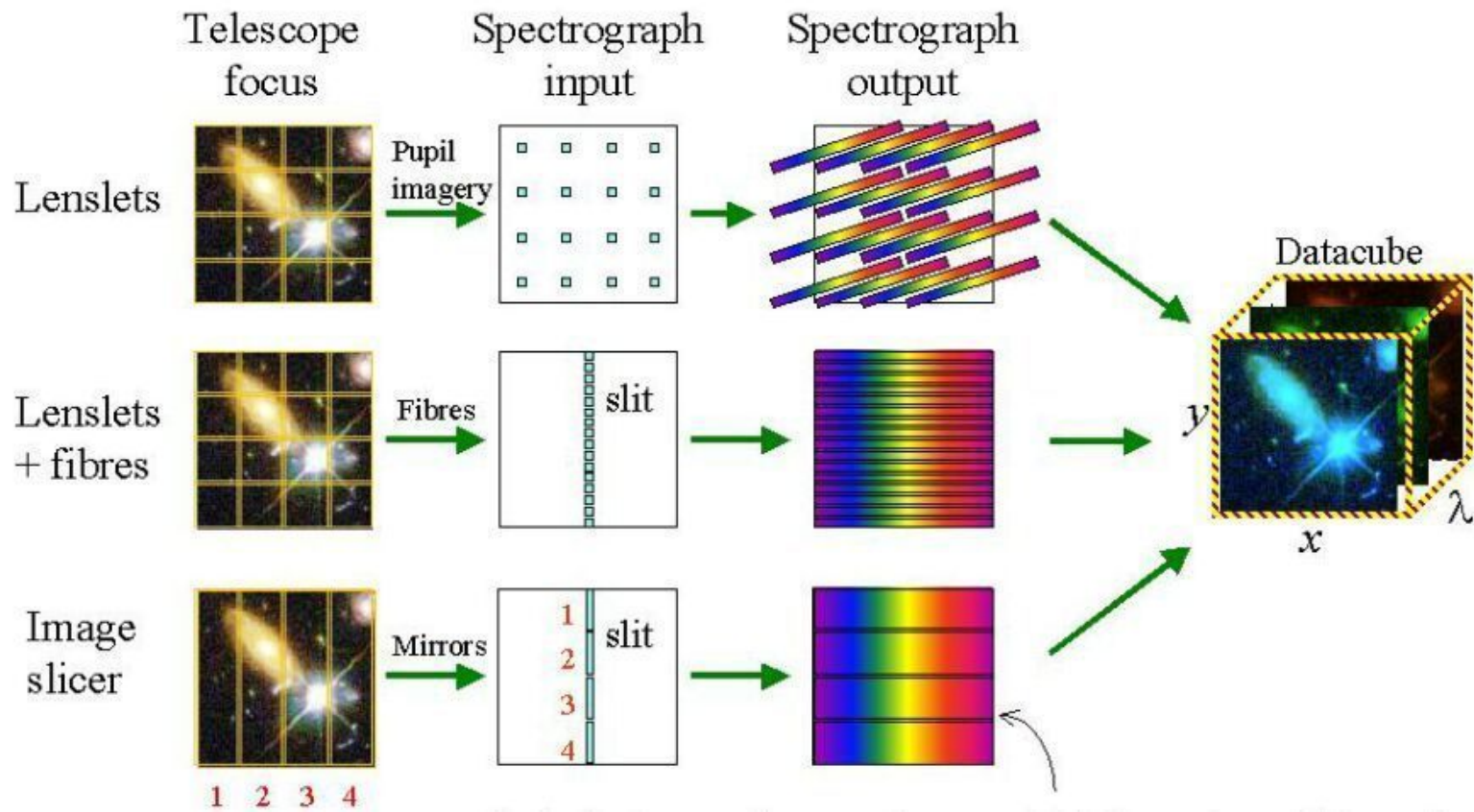
Fiber positioner robots





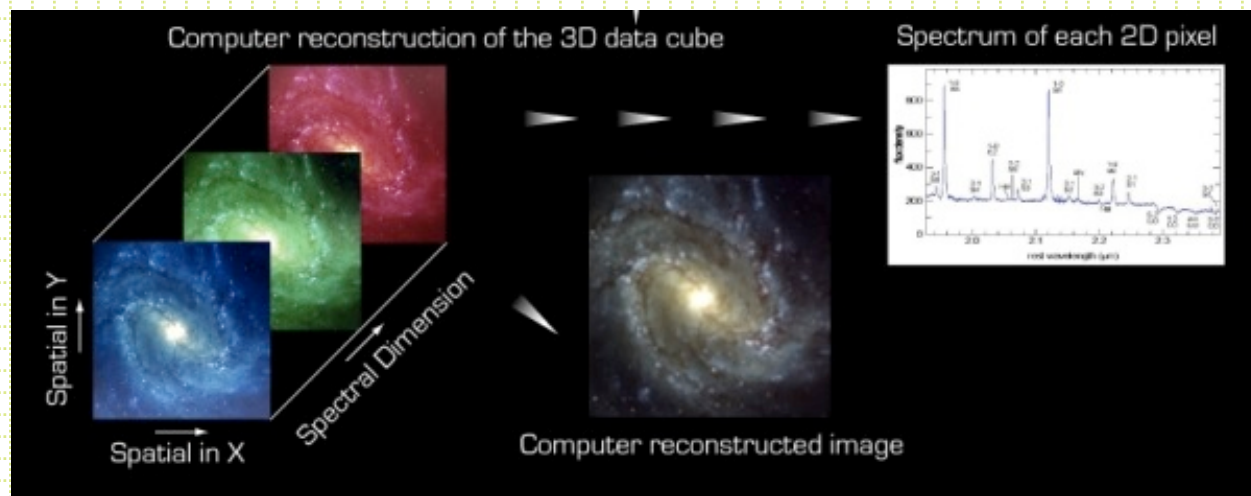
Integral-Field Spectroscopy

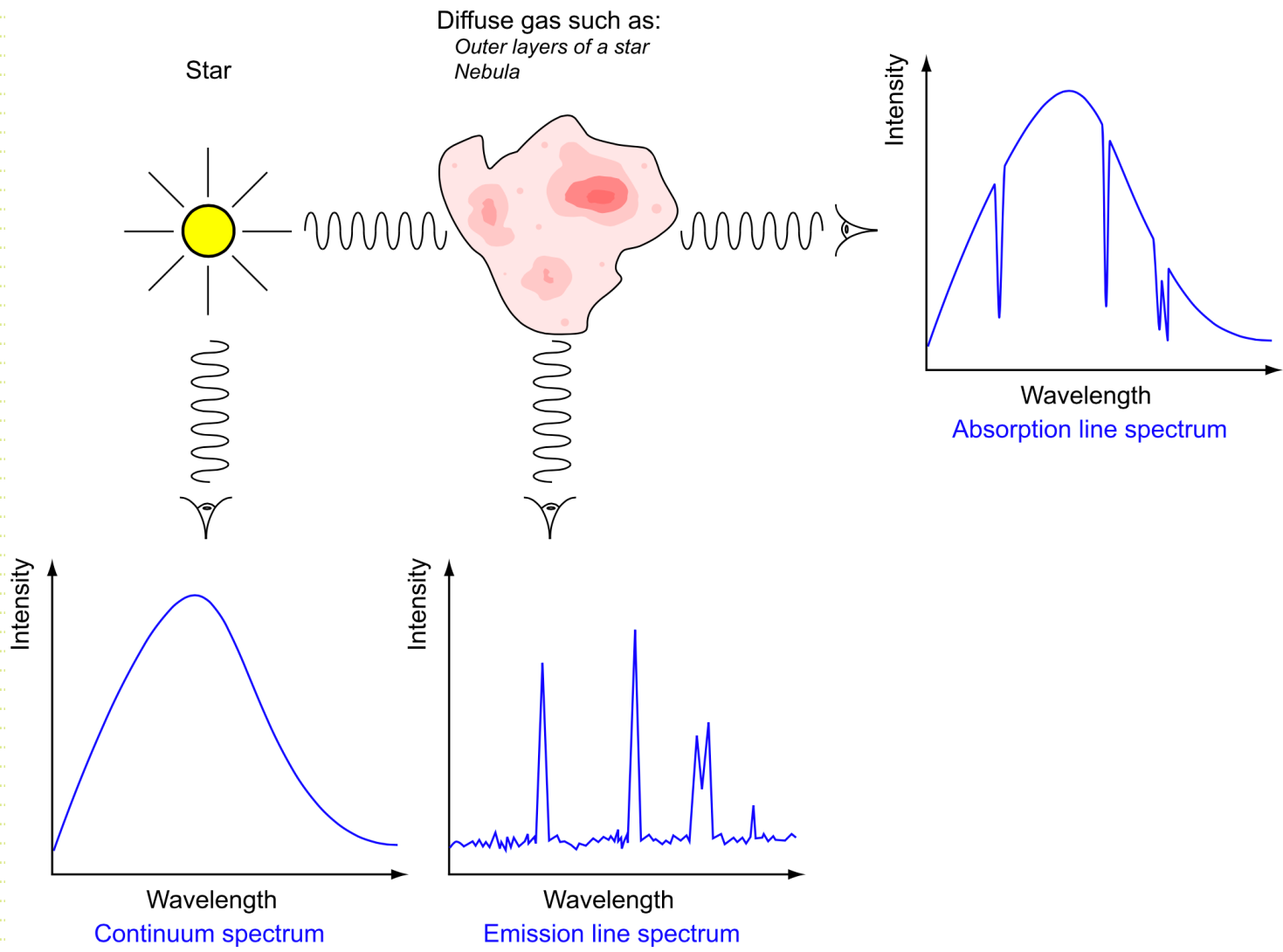


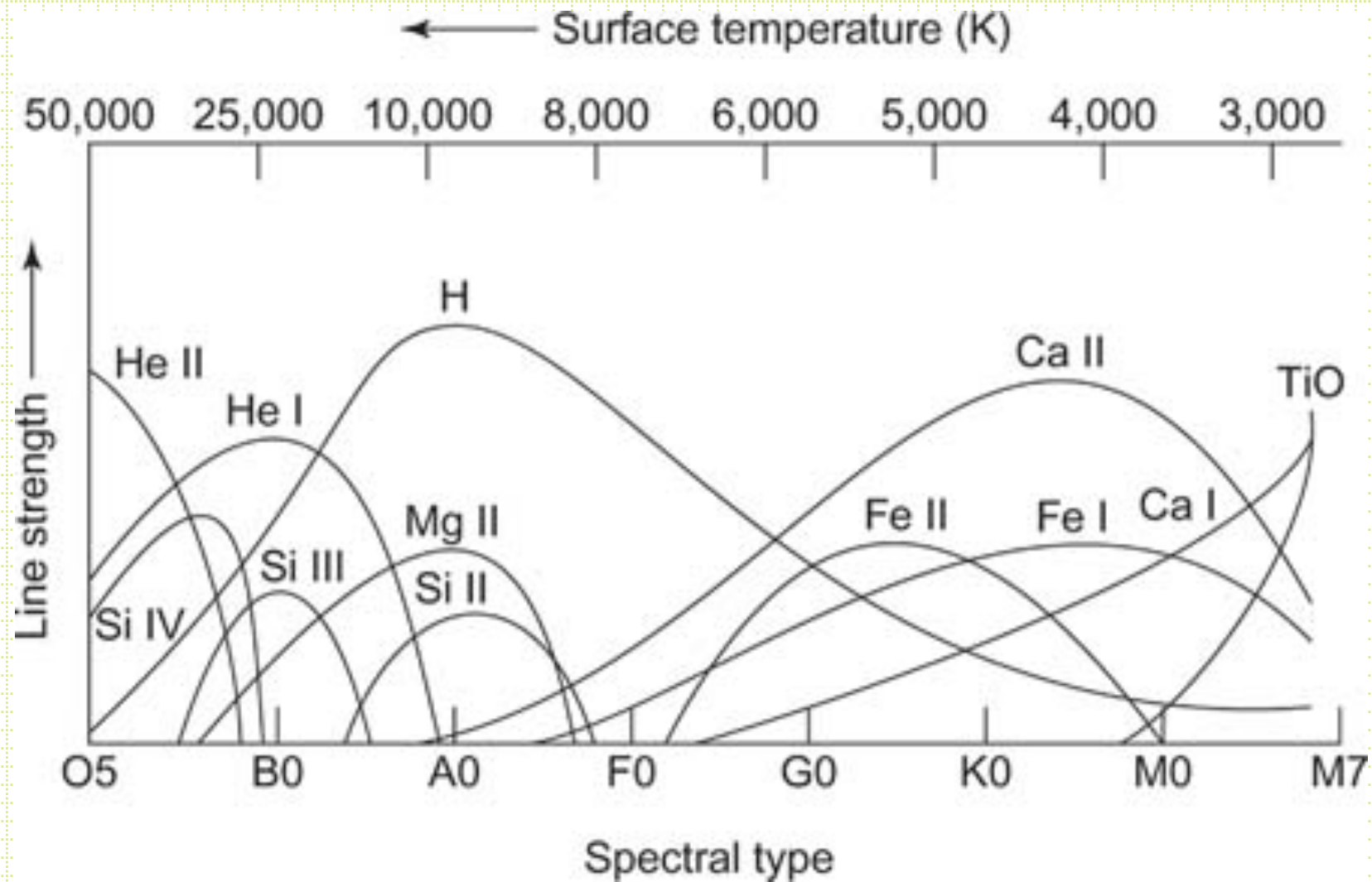


IFU data reduction

- Usually this is complicated. The usual 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







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

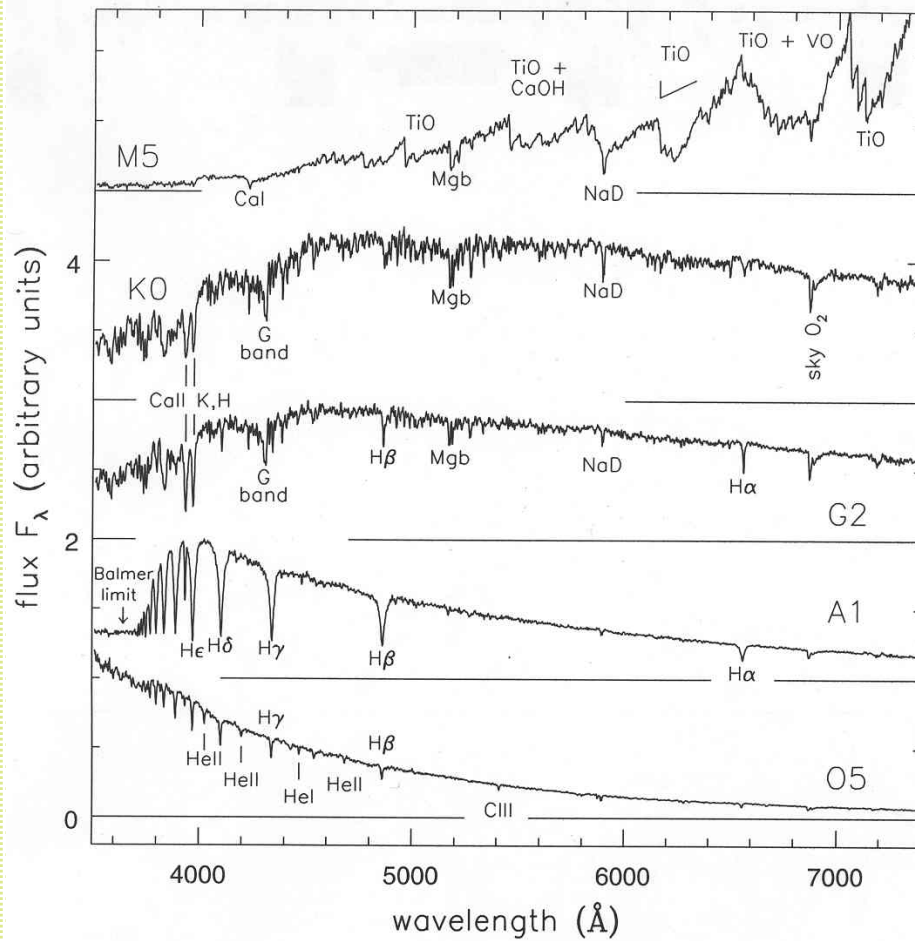
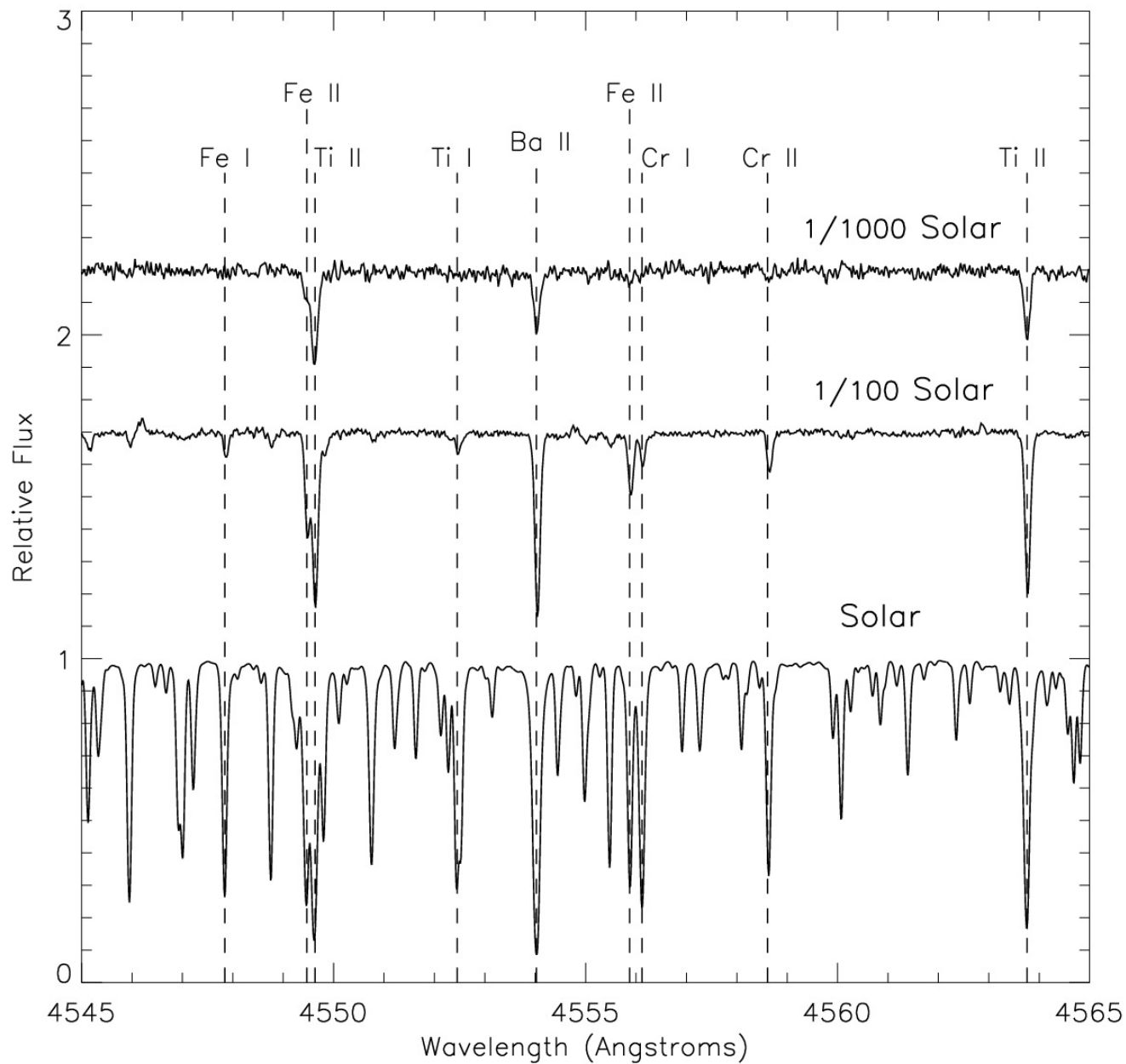


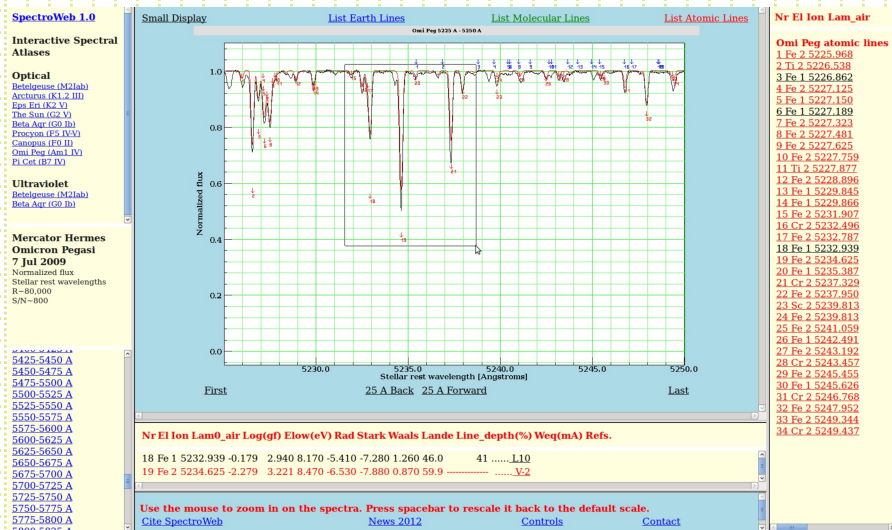
Figure 1.1 Optical spectra of main-sequence stars with roughly the solar chemical composition. From the top in order of increasing surface temperature, the stars have spectral classes M5, K0, G2, A1, and O5 – G. Jacoby *et al.*, spectral library.



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

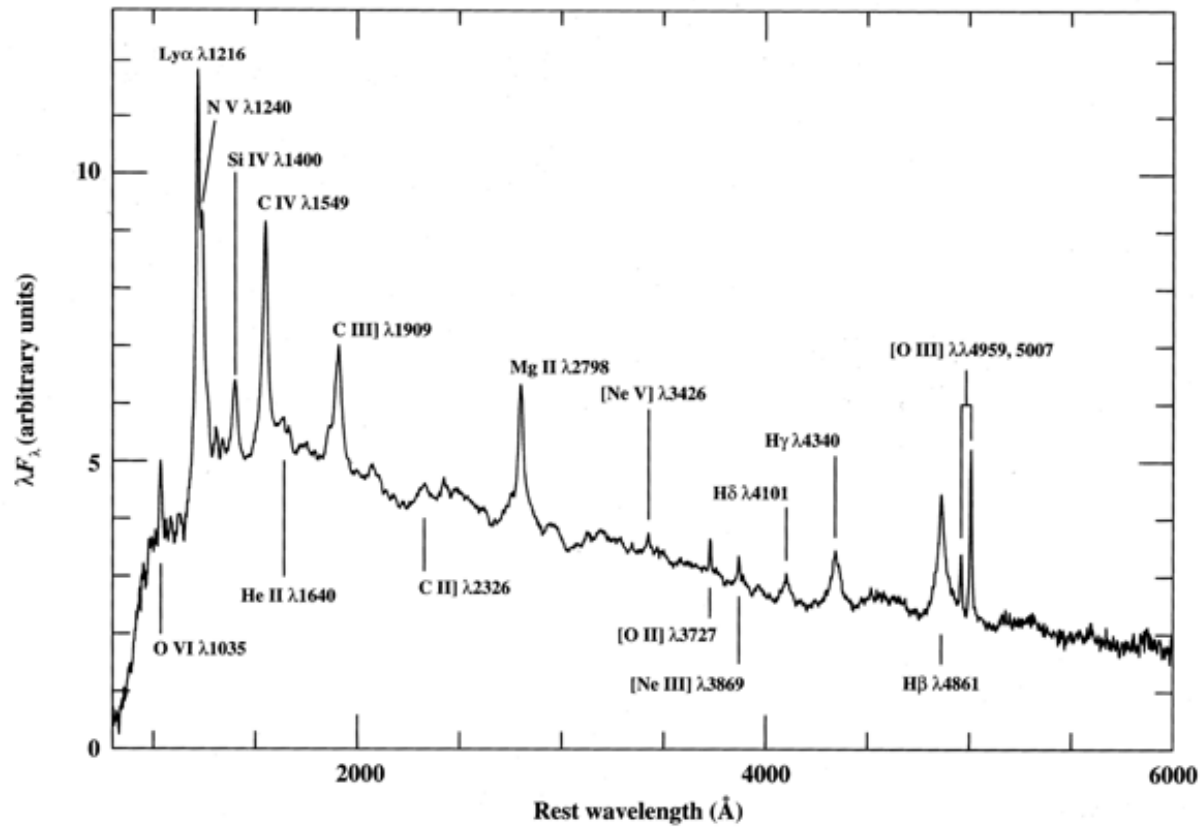
What are those lines?

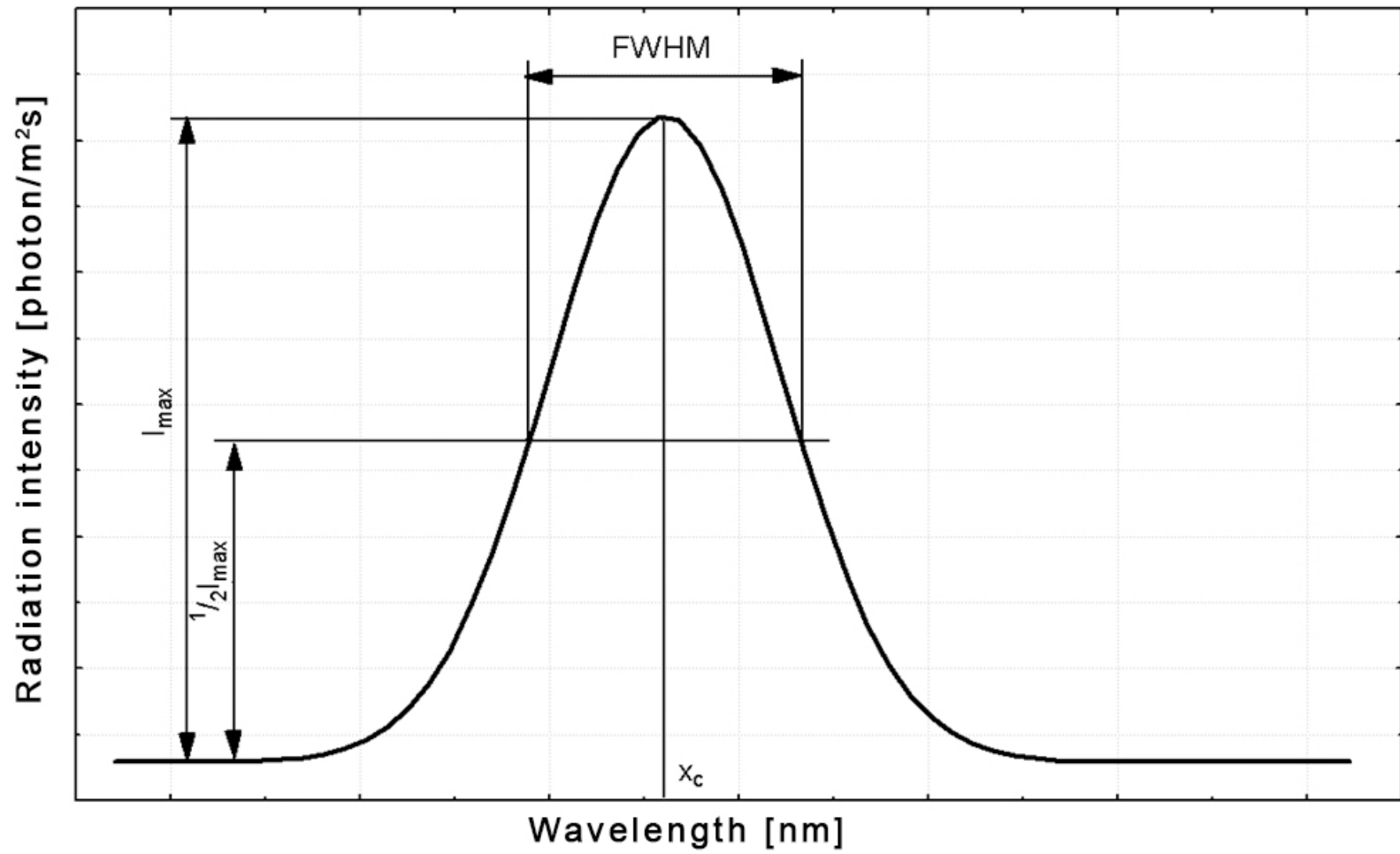
- Solar Atlas
- A revised version of the Identification List of Lines in Stellar Spectra (ILLSS) Catalogue by R. Coluzzi
- Look up papers



What Affects Absorption Lines?

- Temperature
- Pressure
- Radial motion
- Stellar rotation
- “Microturbulence”
- http://www.kcvs.ca/martin/astro/au/unit2/63/chp6_3.html

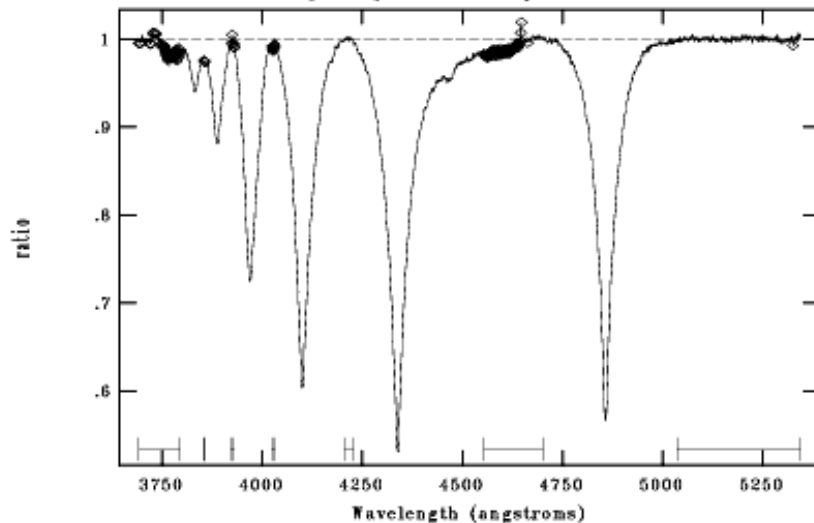




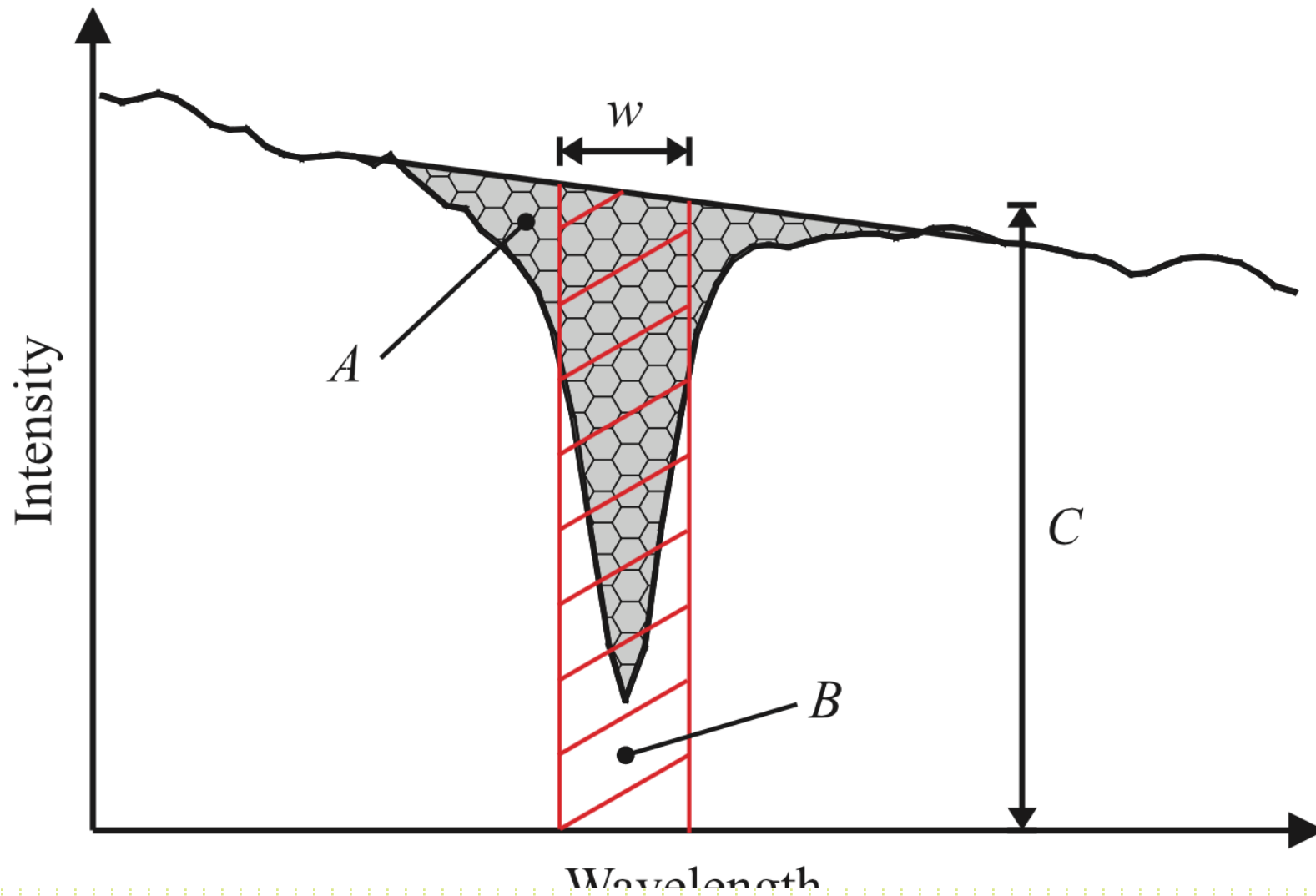
Analysis procedures: Equivalent Width Measurements

- 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

```
NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 13:55:47 25-M  
func=legendre, order=7, low_rej=2, high_rej=3, niterate=10, grow=1  
total=1551, sample=565, rejected=159, deleted=0, RMS= 342.6  
[wd.ms]: HZ 14 800. ap:1 beam:1
```



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

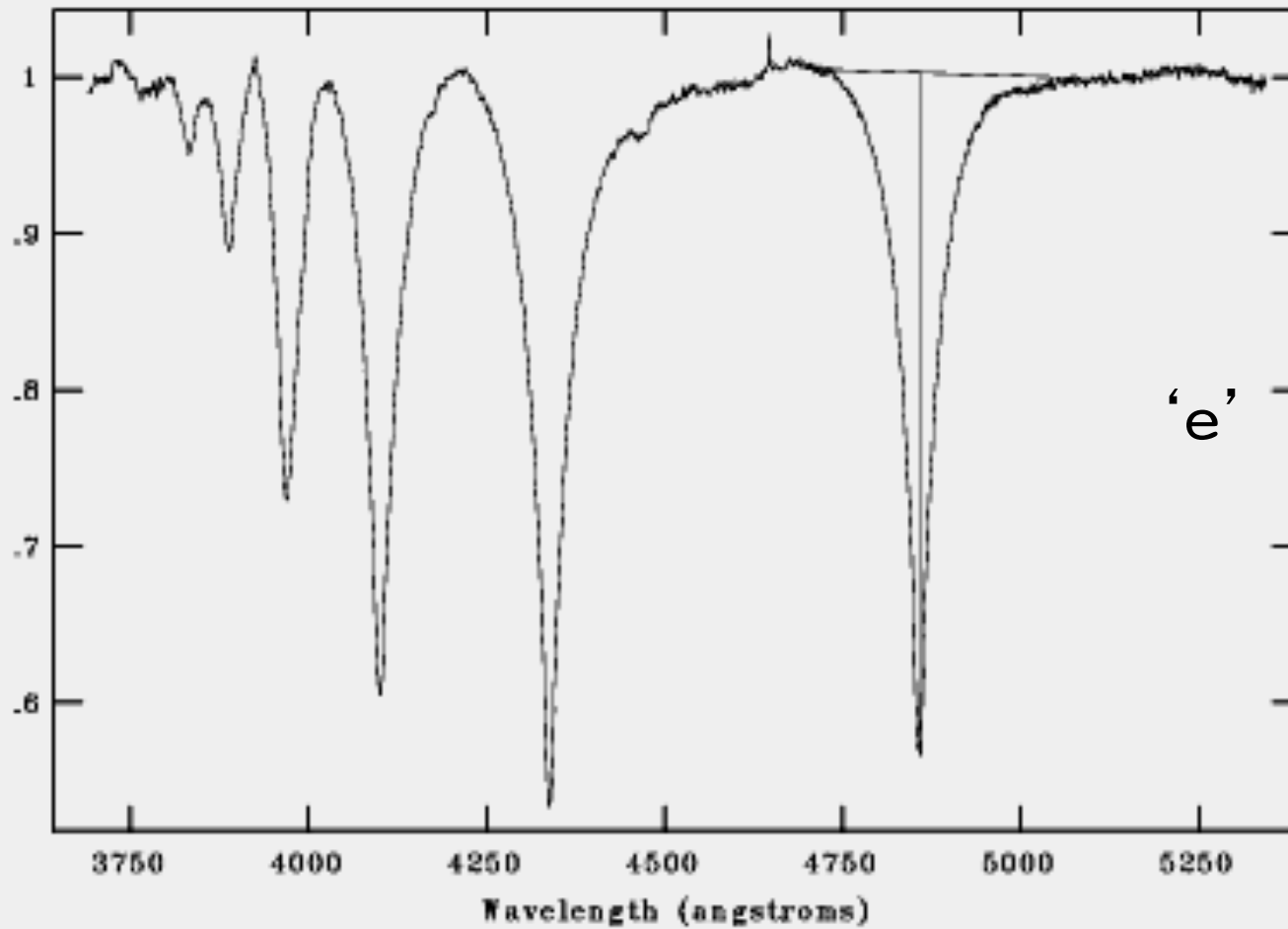


splot help

? - 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

NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 14:06:54 25-M
[wd.ms]: HZ 14 600. ap:1 beam:1



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

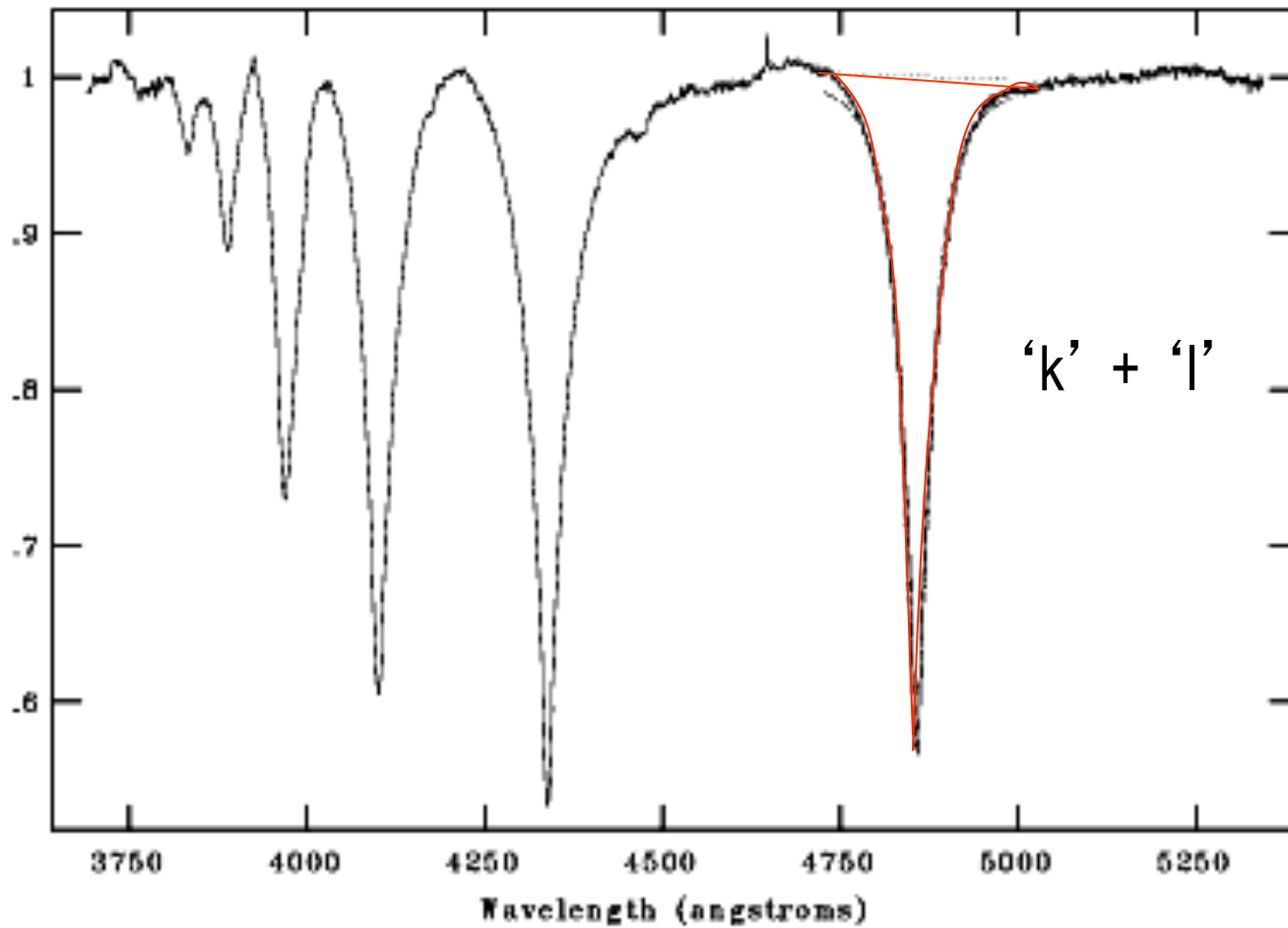
b - Right side for width at 1/2 flux r - Right side for continuum = 1

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

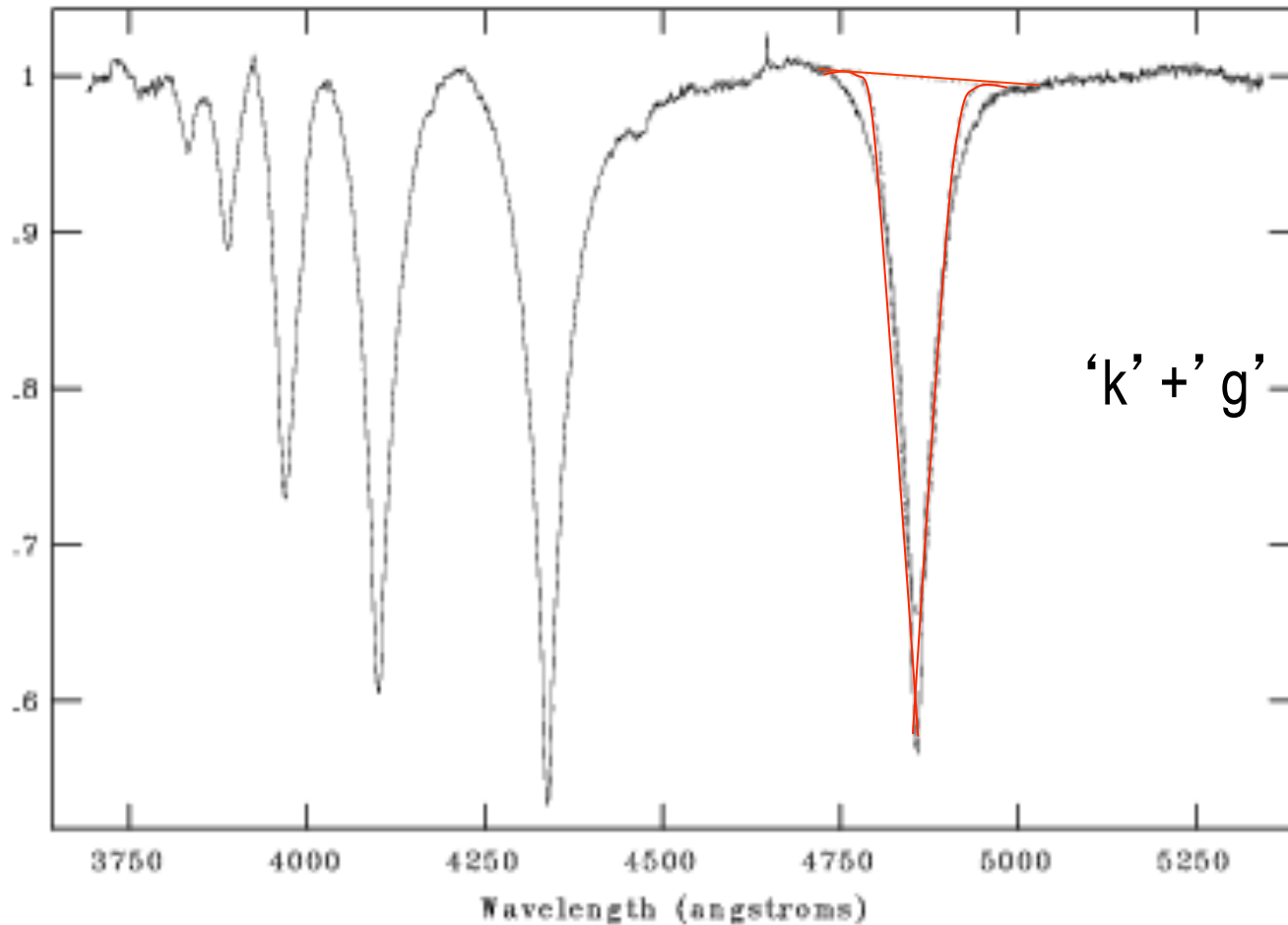
g - Gaussian, l - Lorentzian, v - Voigt, all others - Gaussiank

NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 14:18:03 25-M
[hold.ms]: HZ 14 600. ap:1 beam:1



Center: 4857.31 eqw:29.49 lwhm: 47.45

NOAO/IRAF V2.12.2-EXPORT bolte@Michael-Boltes-Computer.local Tue 14:19:23 25-M
[hold.ms]: HZ 14 600. ap:1 beam:1



Center: 4857.38 eqw: 23.38 gfwhm:41.44

Note: can measure radial velocity and EW

Radial velocity measurements

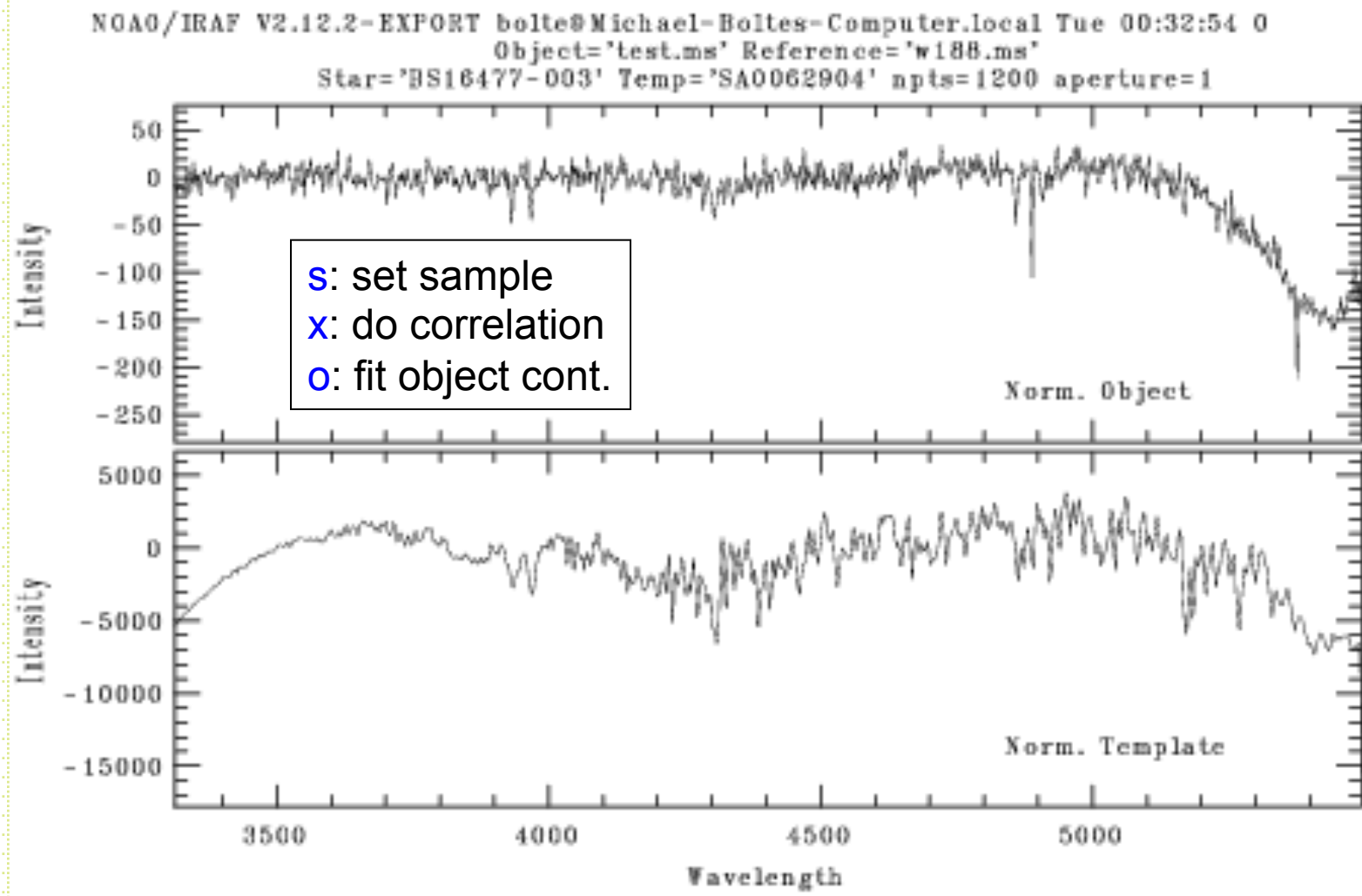
- Method 1 is to measure line centroids usually after making a zeropoint correction based on measuring a few night sky lines (in *splot* you can use the “u” and “z” keystroke command to accomplish this).
- Get line centers with “e” or one of the line fitting options, calculate doppler shift, apply the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

Cross-correlation:FXCOR

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

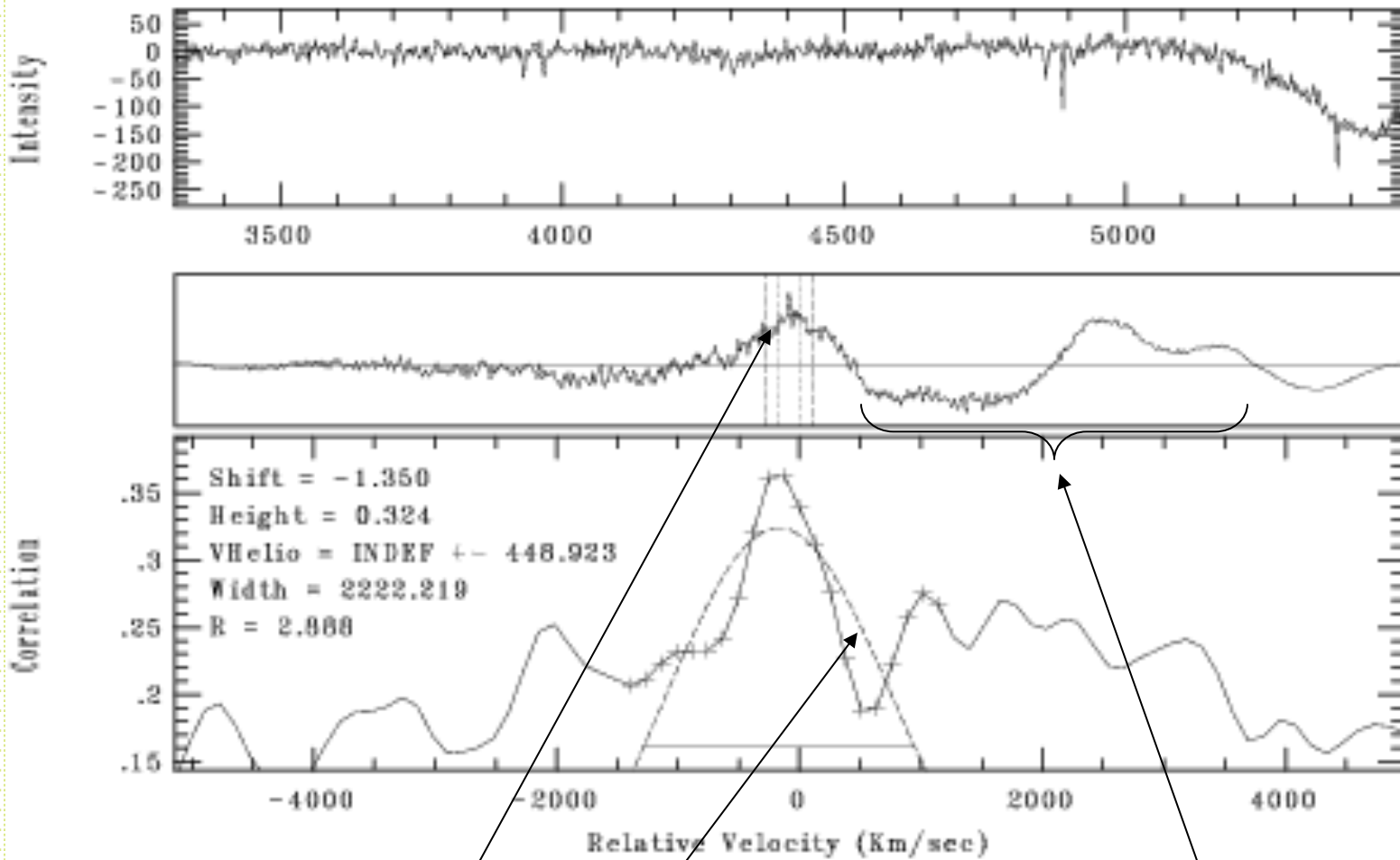
noao.rv *fxcor* is a pretty good implementation.

- 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='HS16477-003' Temp='SA0062904' npts=1200 aperture=1



Correlation peak and fit

Bad filtering/cont fit

- Radial velocity precision/accuracy

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

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

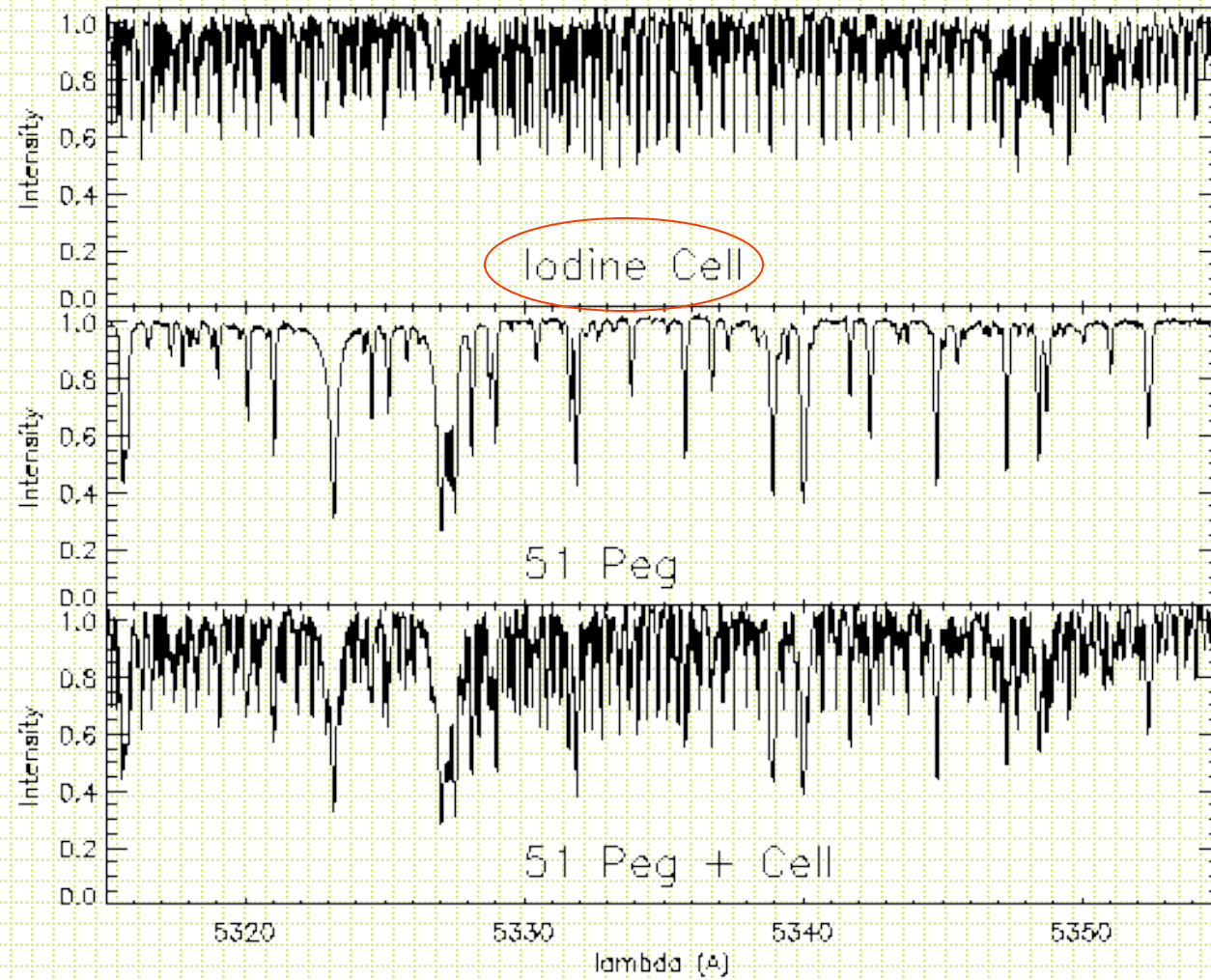
- R=2500 (LRIS/KAST): 120km/s
- Centroid to 1/20 resolution element gives a precision of 5 km/s (ignoring wavelength calibration uncertainties).
- HIRES@R=50000 and 1/20th: 0.3 km/sec

- For most spectrometers, systematic errors dominate by $\sim 2\text{km/sec}$. 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

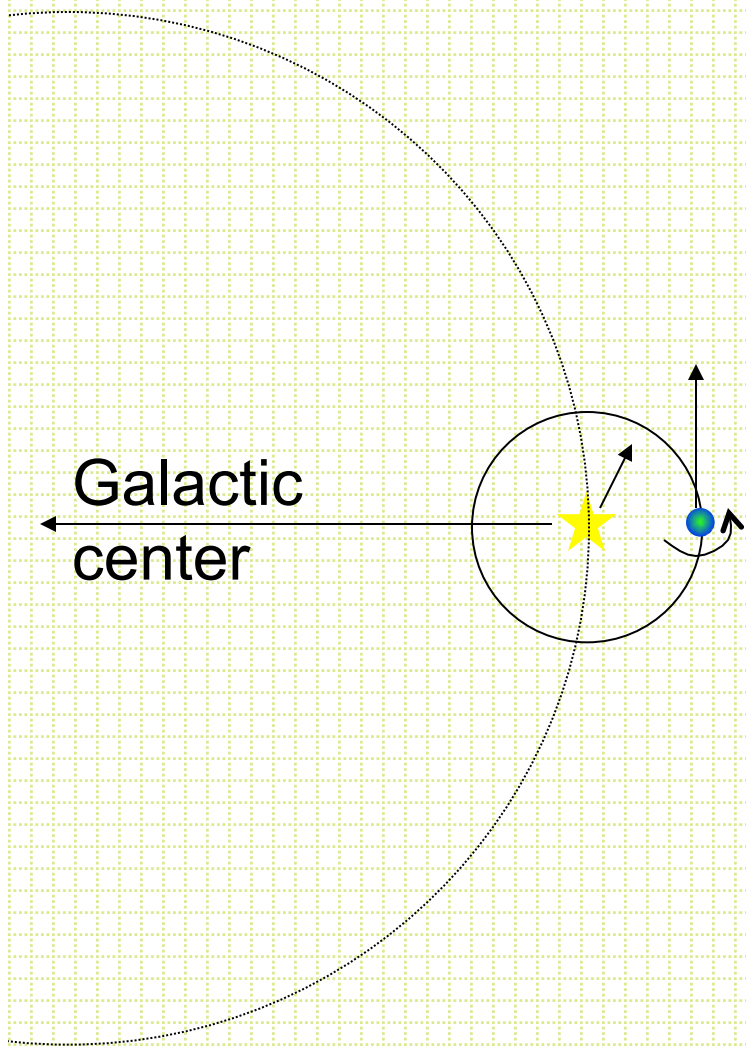


rvcorrect

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
```

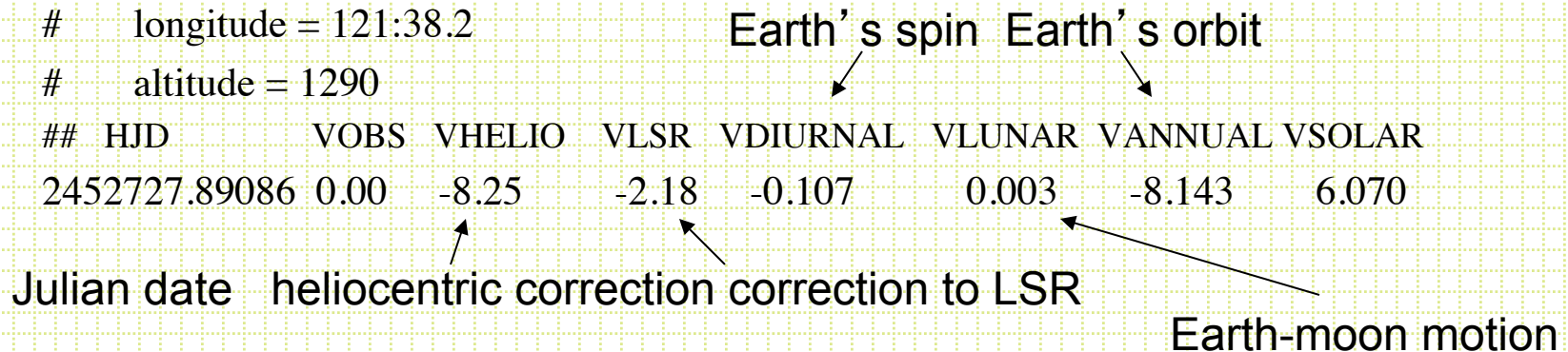
Julian date

heliocentric correction

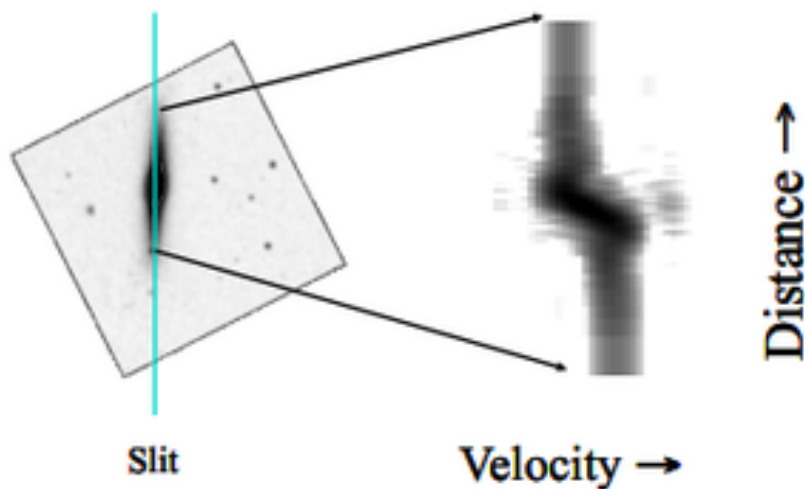
correction to LSR

Earth-moon motion

Earth's spin Earth's orbit



Rotation curves



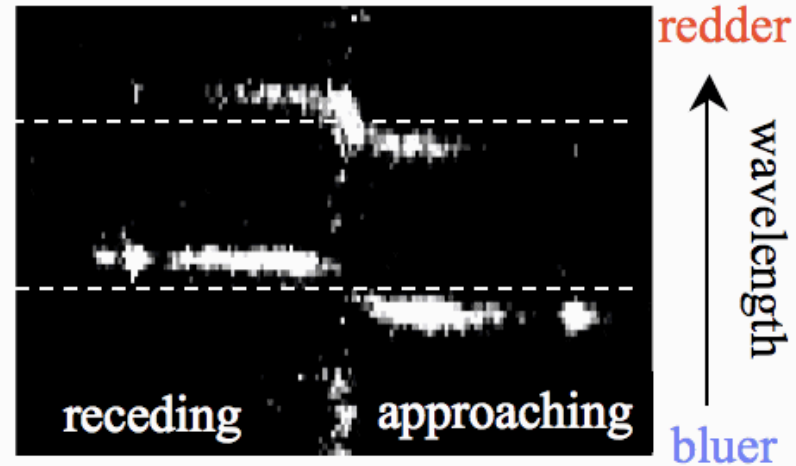
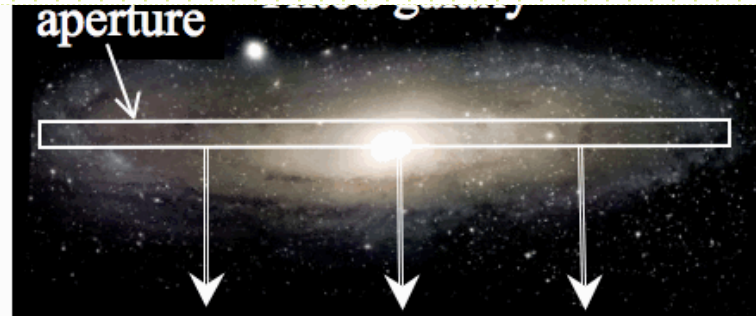
With a long slit or IFU you can extract spectra from different physical locations in a galaxy and derive mean radial velocity

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

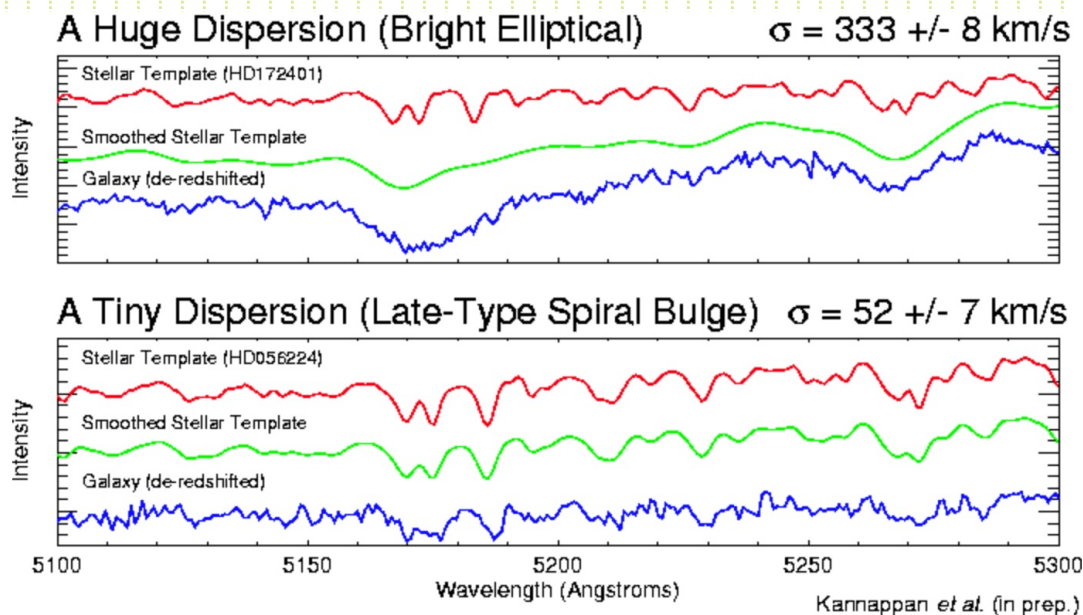


Vera Rubin measuring galaxy



Resulting spectrum of

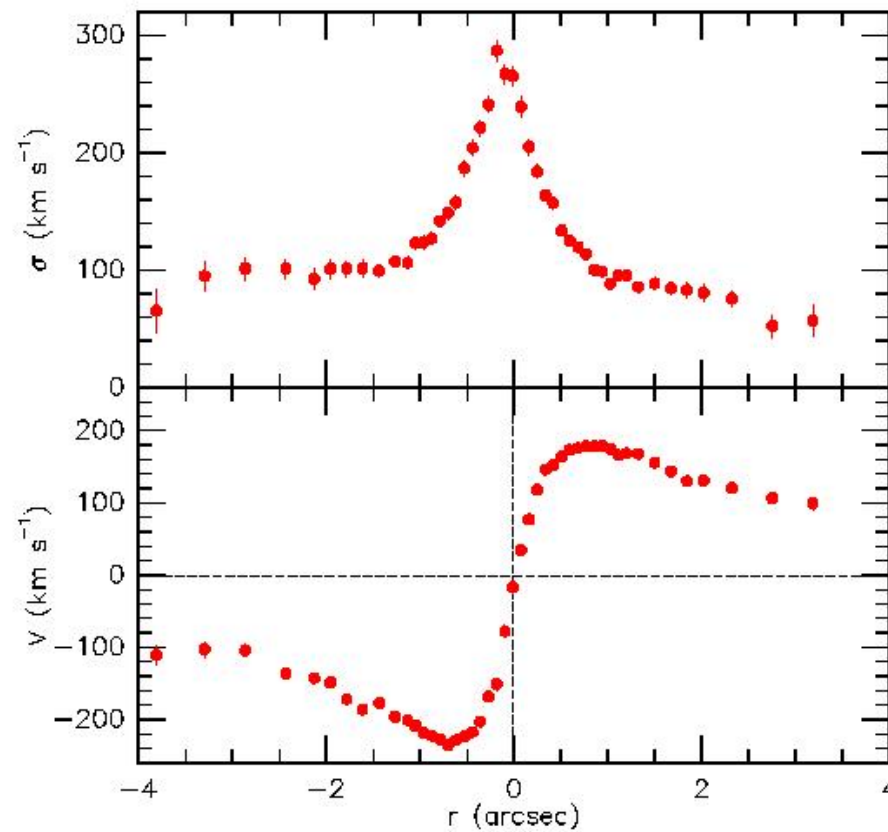
Velocity dispersions

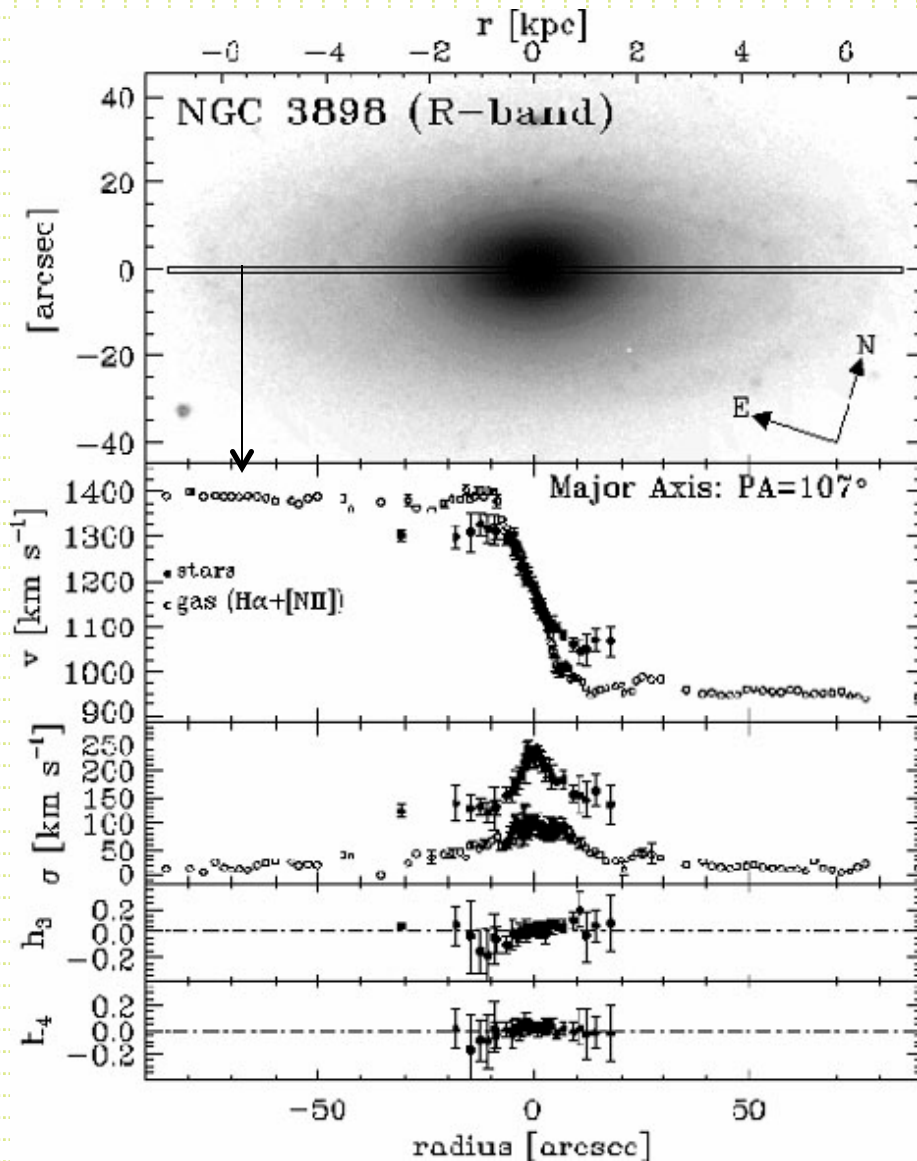


Random motions of stars and gas for a kinematically “hot” population also measure total mass

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

