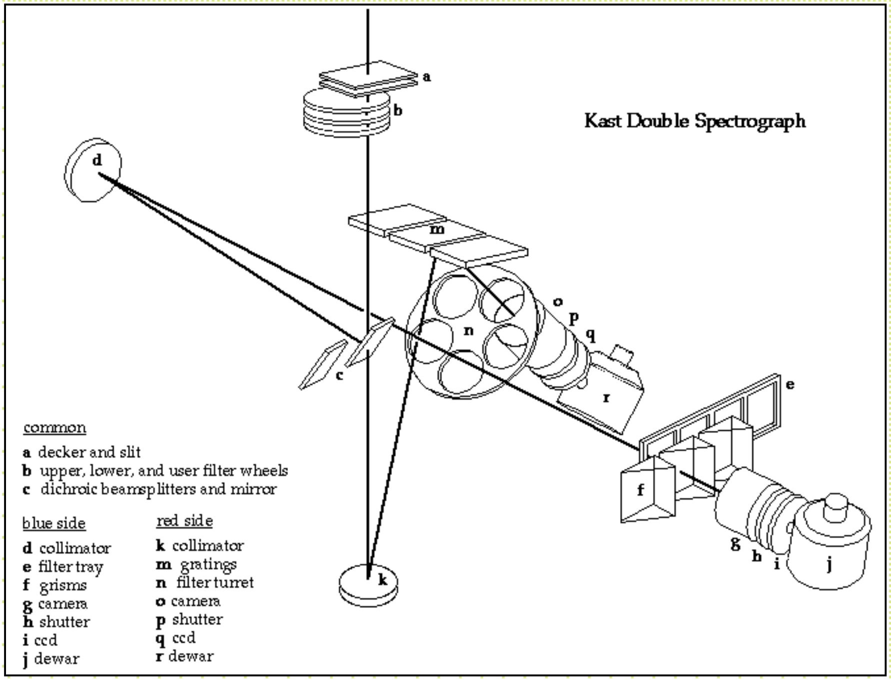
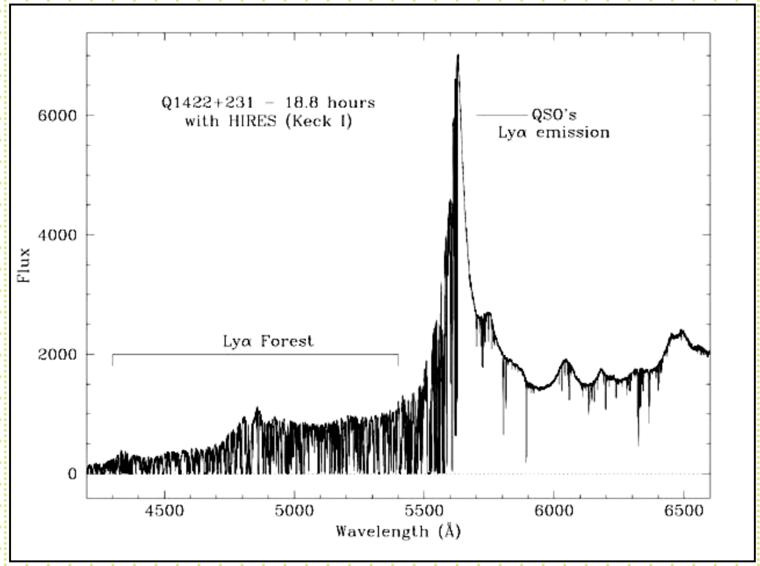
Spectra



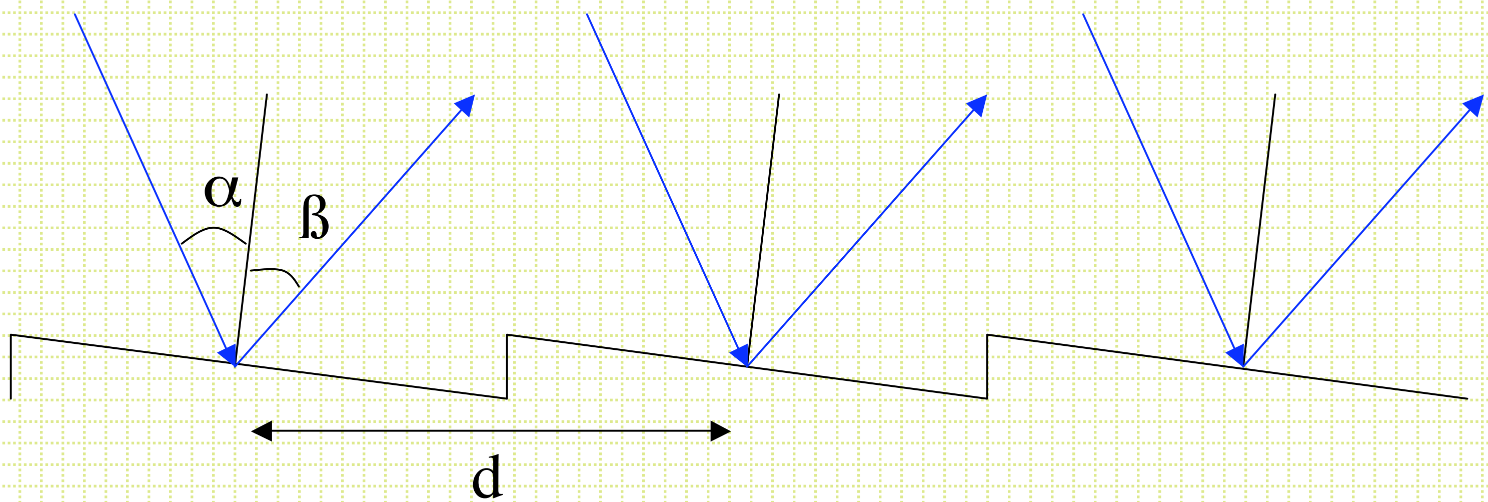


- Bowen, 1962, Astronomical Techniques, pg 34.
- Pogge, 1992, ASP Conf. Ser.#23, pg.160

Dispersing Elements

- Most common is probably the *reflecting diffraction grating*.
- Grating equation: $m\lambda = d[\sin(\alpha) + \sin(\beta)]$

order groove spacing



Grating dispersion

- Think of the Young Double-slit experiment with many slits very closely spaced together (100 - 10,000+ lines/mm) and for non-monochromatic light - same constructive/destructive interference phenomenon from *path-length differences*.
- Note: ruling gratings is not easy! Spacing tolerance is ~1nm. Richardson has a machine in a room kept a constant temperature to 0.01˚C

- Differentiate the grating equation wrt outgoing angle and get the *angular dispersion*

$$\frac{d\beta}{d\lambda} = \frac{m}{d\cos(\beta)}$$

- The *linear dispersion* is:

in camera focal plane

order

Å/mm α d/m

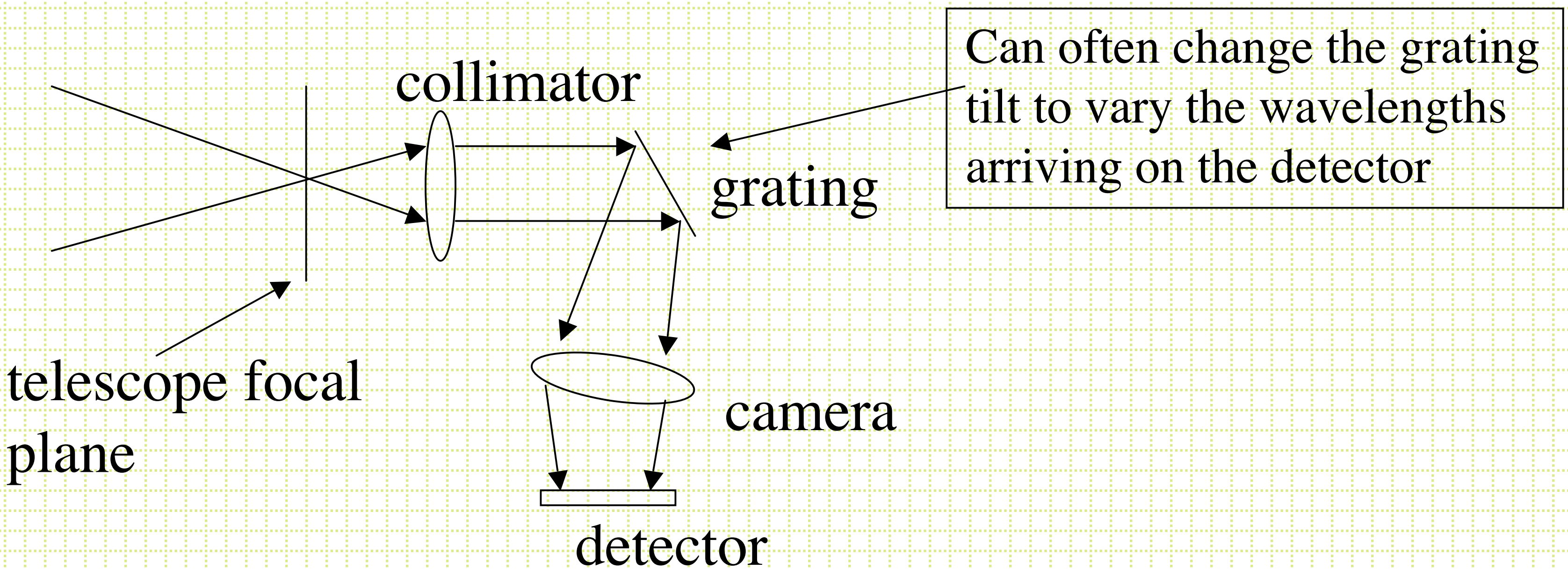
lines/mm

$$\frac{d\lambda}{dx} = \frac{d\lambda}{d\beta}\frac{d\beta}{dx} = \frac{\mathrm{d}\cos(\beta)}{\mathrm{m}F_{\mathrm{camera}}}$$

$$F_{\mathrm{camera}} = \frac{dx}{d\beta} \equiv \text{camera focal length}$$

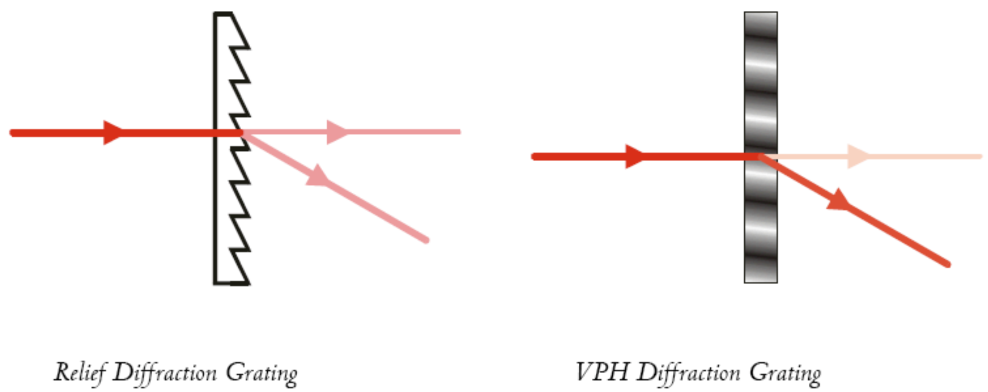
Spectrometers

- Gratings require collimated (parallel beam) light so the basic long-slit spectrometer:

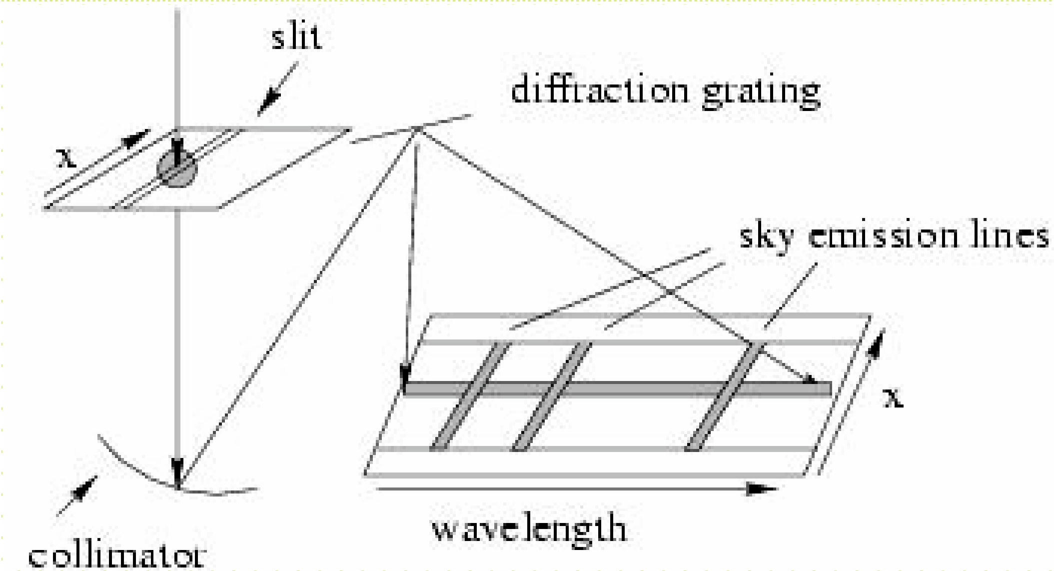


Transmission gratings

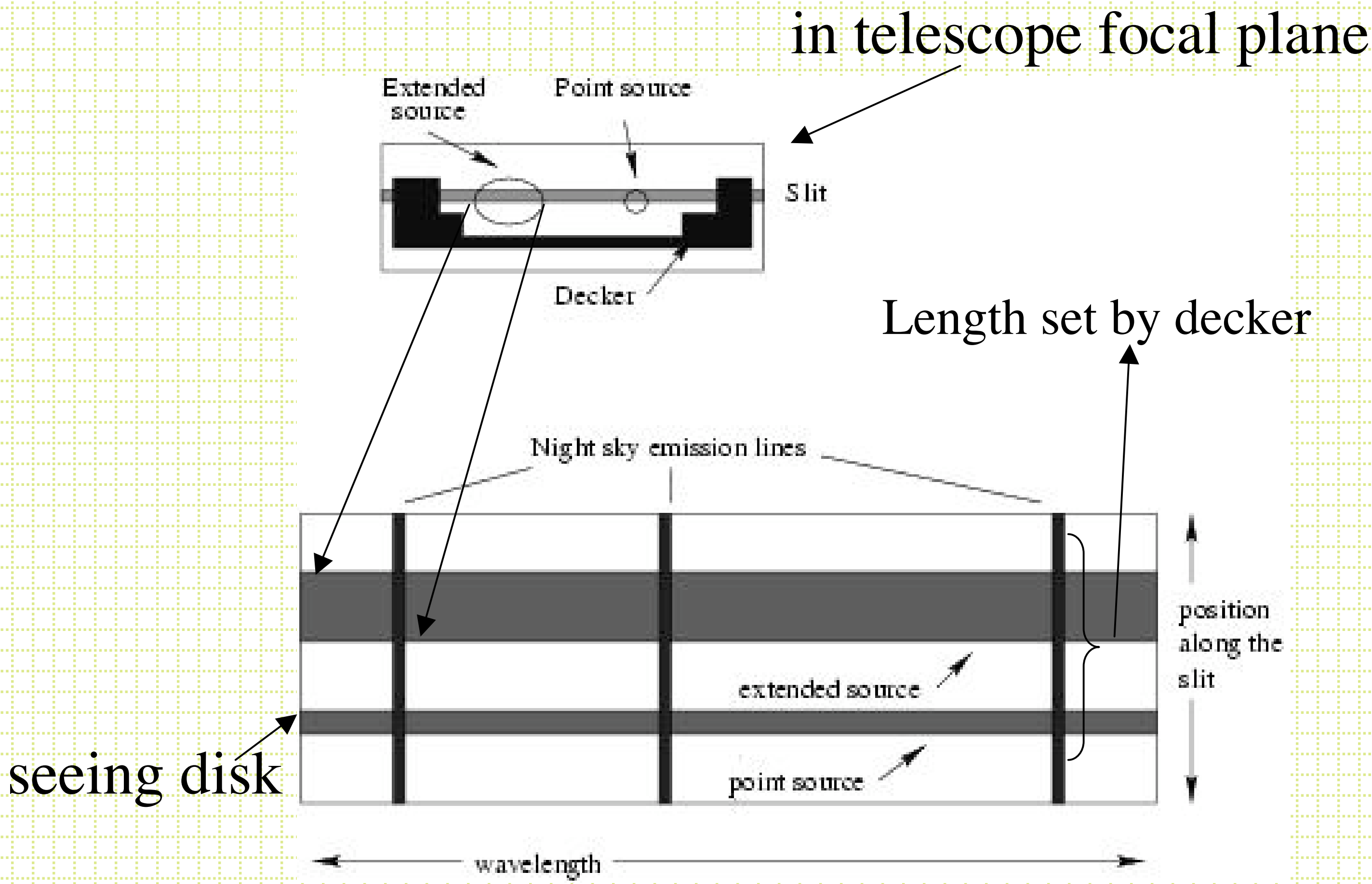
- There are also different versions of transmission gratings.
  - Transmission grating
  - *Grisms* - add a prism for *zero-deviation* transmission dispersion
  - *Volume Phase Holographic Gratings*: VPH - use modulations of the index of refraction rather than surface structures to produce dispersion. High efficiency.



Long-slit Spectra Geometry



In the *camera* focal plane there is the *dispersion direction* perpendicular to the slit and the *spatial direction* along the slit.


in telescope focal plane
Extended source
Point source
Slit
Decker
Length set by decker
Night sky emission lines
position along the slit
extended source
point source
seeing disk
wavelength

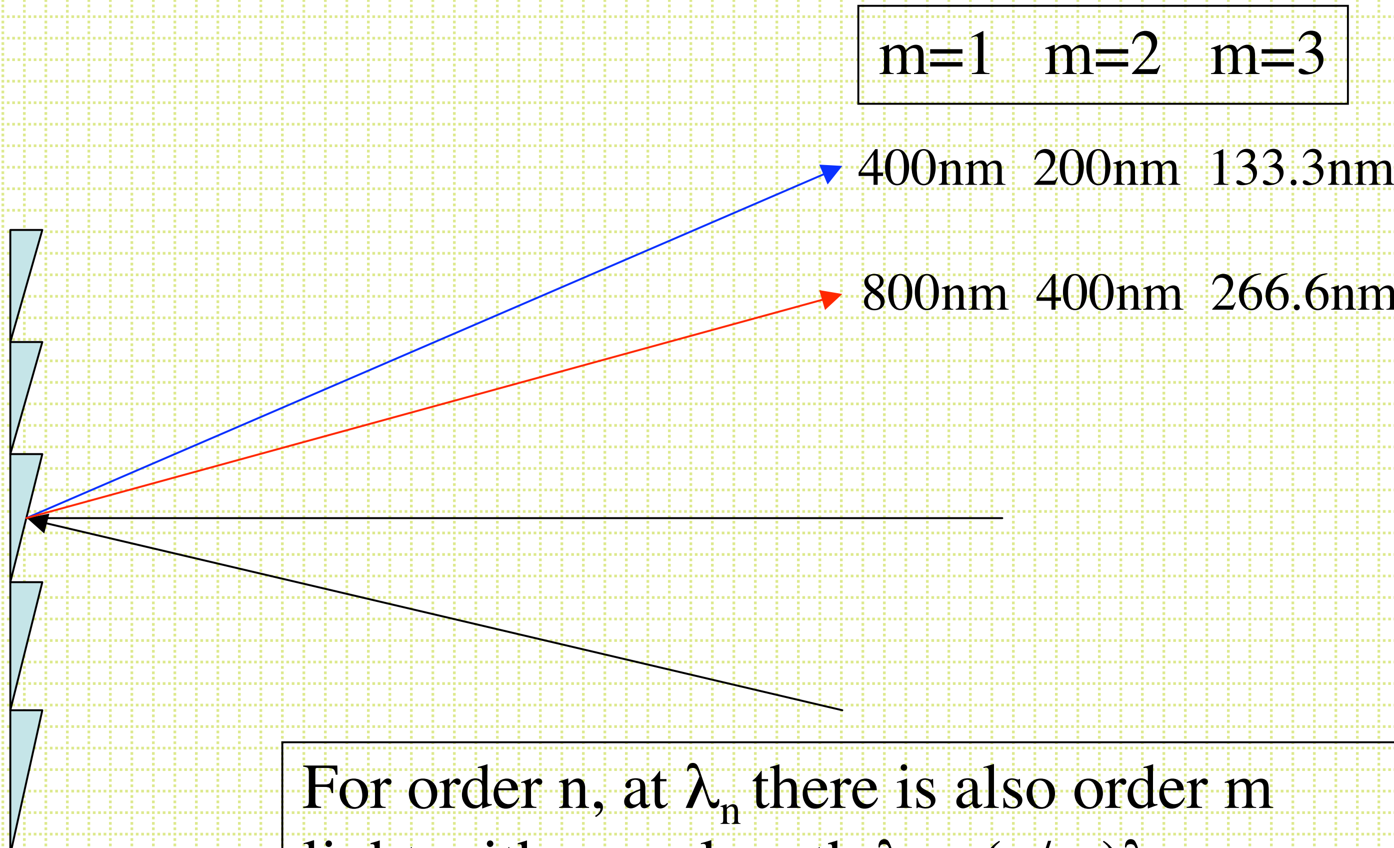
Spectral Resolution

- $R=\lambda/\Delta\lambda$
- For slit spectral, depends on slit width and grating choice.
- Examples:
  - V filter: 5500Å/1000Å=5.5
  - LRIS-R: 1″ ~4 pixels FWHM
    - 150 l/mm grating: R~6500/20 ~325
    - 600 l/mm grating: R~6500/5 ~1300
    - 1200 l/mm grating: R~6500/2.6 ~2600

LRIS (Keck Obs WWW page)

Grating Name	Grooves (l/mm)	Blaze Wave (Å)	Dispersion (Å/pix)	Spectral coverage (Å/2048 pix)
150/7500	150	7500	4.8	9830
300/5000	300	5000	2.55	5220
400/8500	400	8500	1.86	3810
600/5000	600	5000	1.28	2620
600/7500	600	7500	1.28	2620
600/10000	600	10000	1.28	2620
831/8200	831	8200	0.93	1900
900/5500	900	5500	0.85	1740
1200/7500	1200	7500	0.64	1310

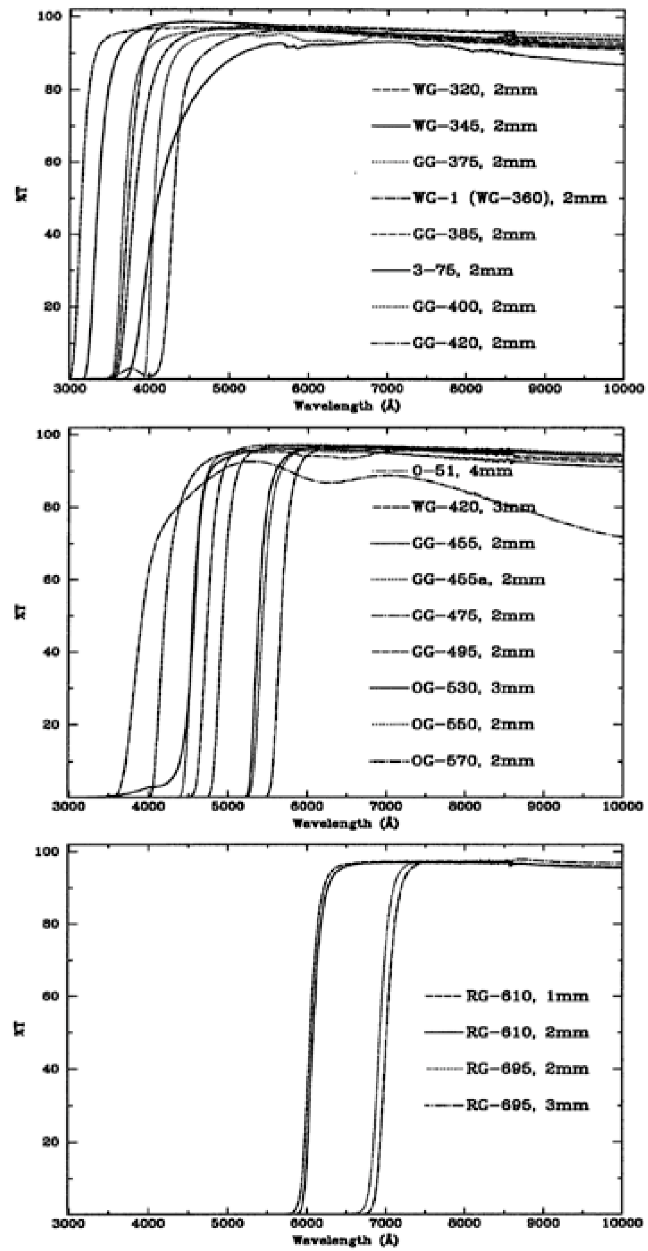
Orders and blocking filters



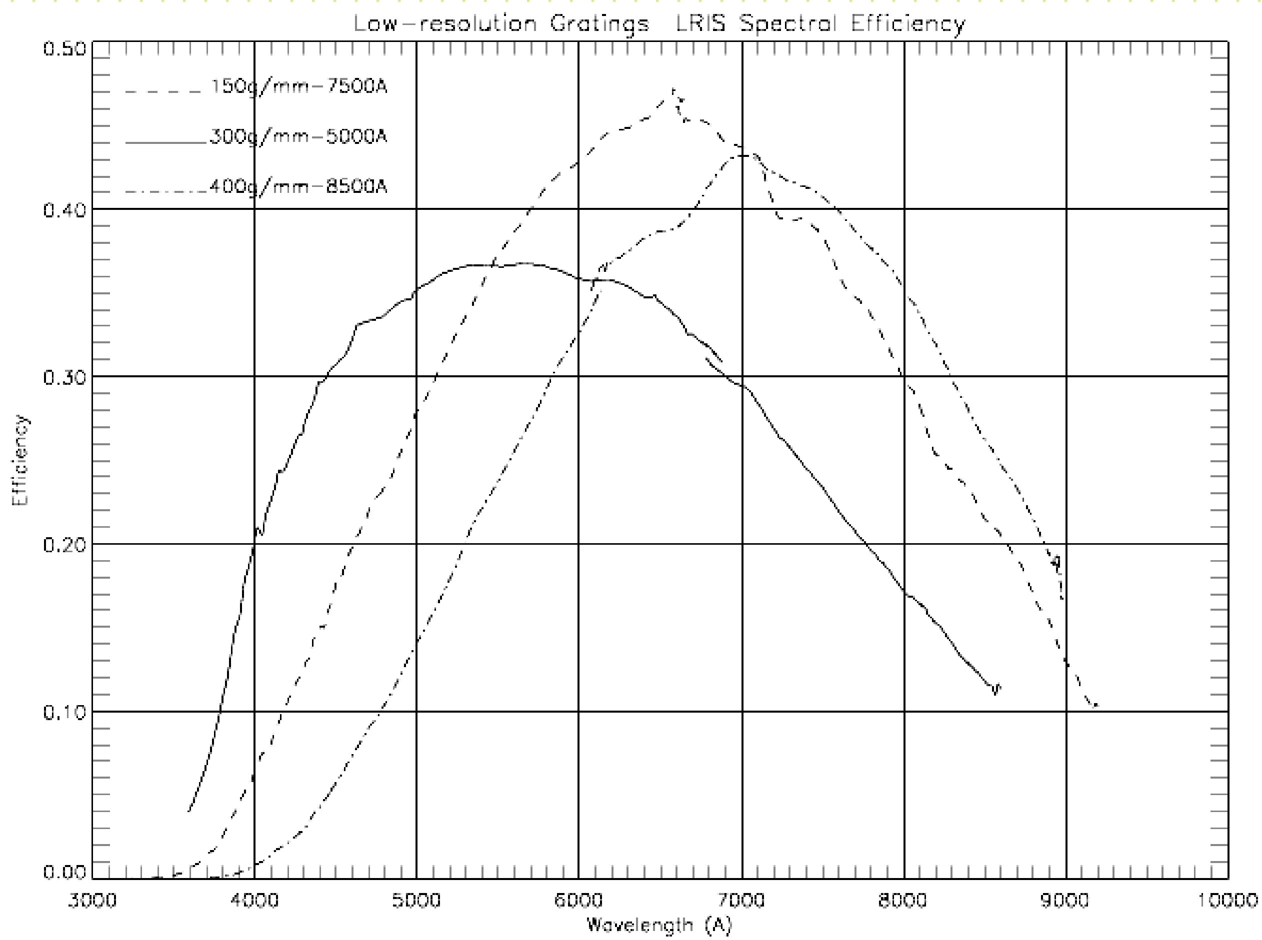
For order n, at λ_n there is also order m light with wavelength $\lambda_m=(n/m)\lambda_n$

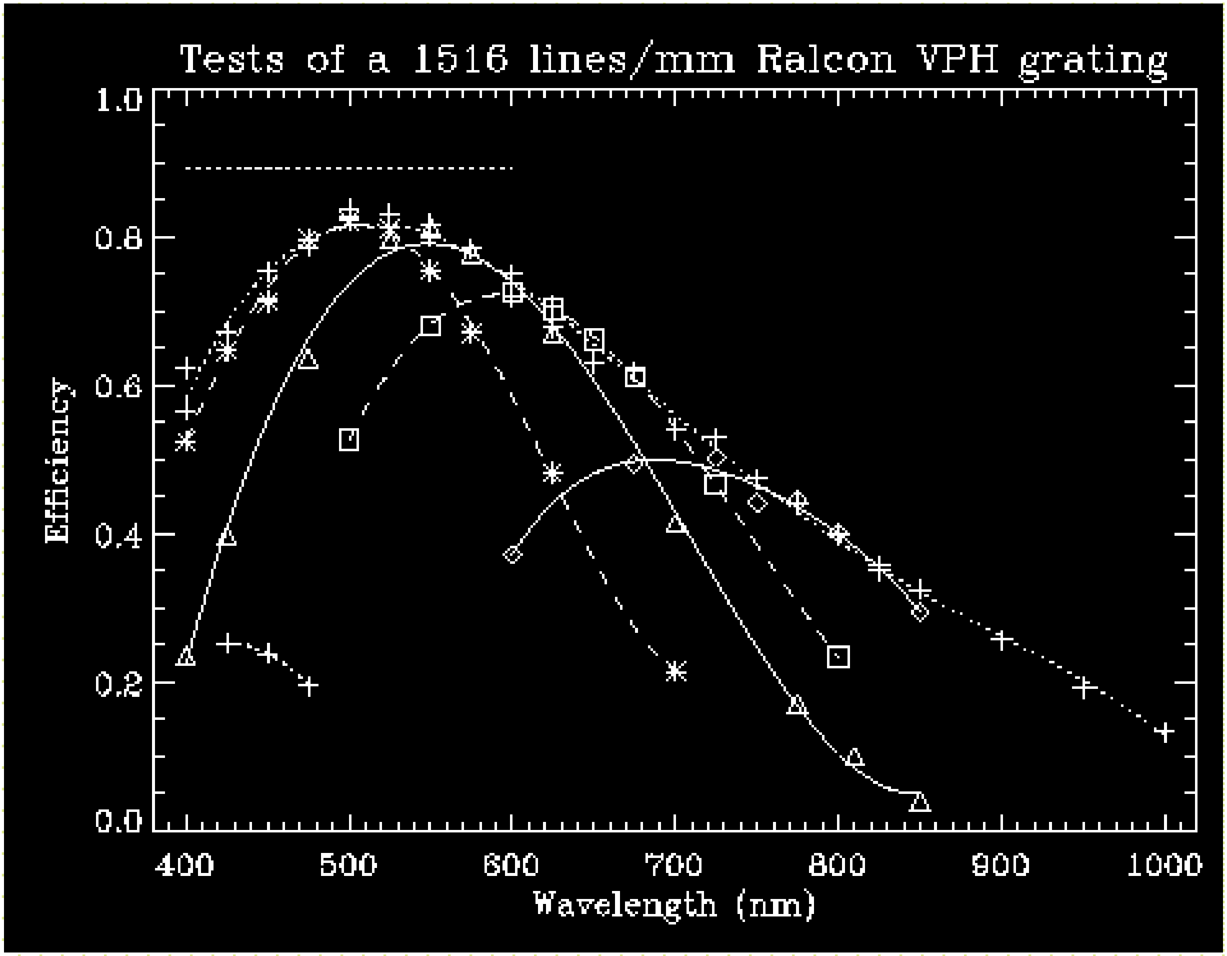
- For higher orders with λ<310nm it's not an issue as the atmosphere cuts out all the light (can still be an issue for calibration sources).
- But, if you are working in the red (>640nm) in 1st order, you need to block the 2nd order light.
- If you are working in a higher order, may need to block red light from lower orders.

KPNO 2.1m Goldcam blue blocking filters



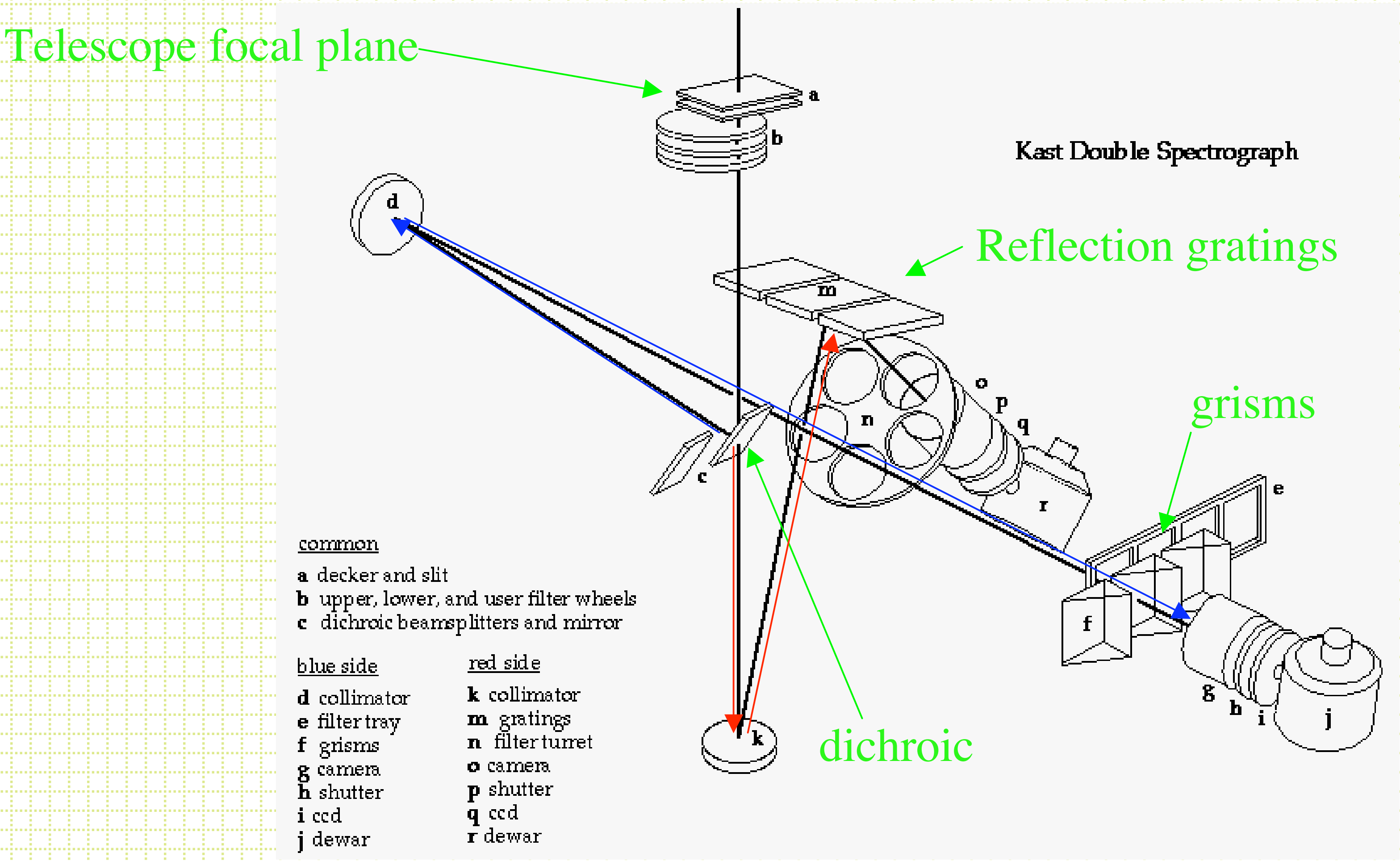
Grating Efficiencies





Tests of a 1516 lines/mm Ralcon VPH grating
Efficiency
Wavelength (nm)
0.0
0.2
0.4
0.6
0.8
1.0
400
500
600
700
800
900
1000

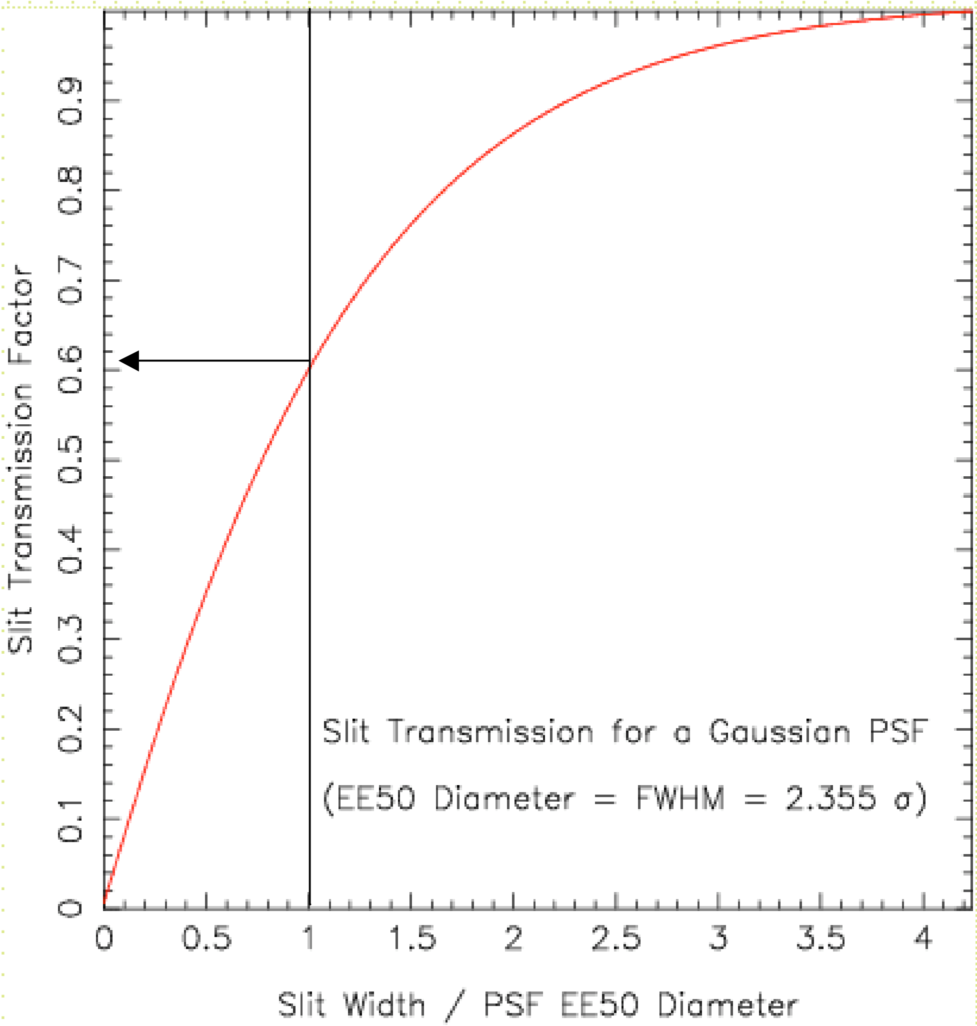
Dichroics and Double Spectrometers



Spectrometer Throughput

- Spectrometer throughput ranges from a few percent to ~50%. The losses accumulate fast. Dispersing elements are usually a big hit, then the losses at multiple surfaces go like $(\text{transmission})^n$ where n is the number of surfaces in the collimator and camera elements (n can be pretty big)
- $0.98^8=0.85*0.7*0.8=0.47$

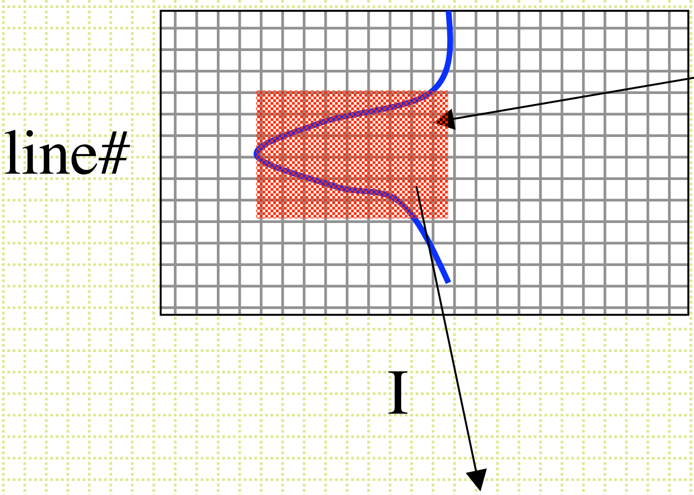
Camera/coll grating ccd

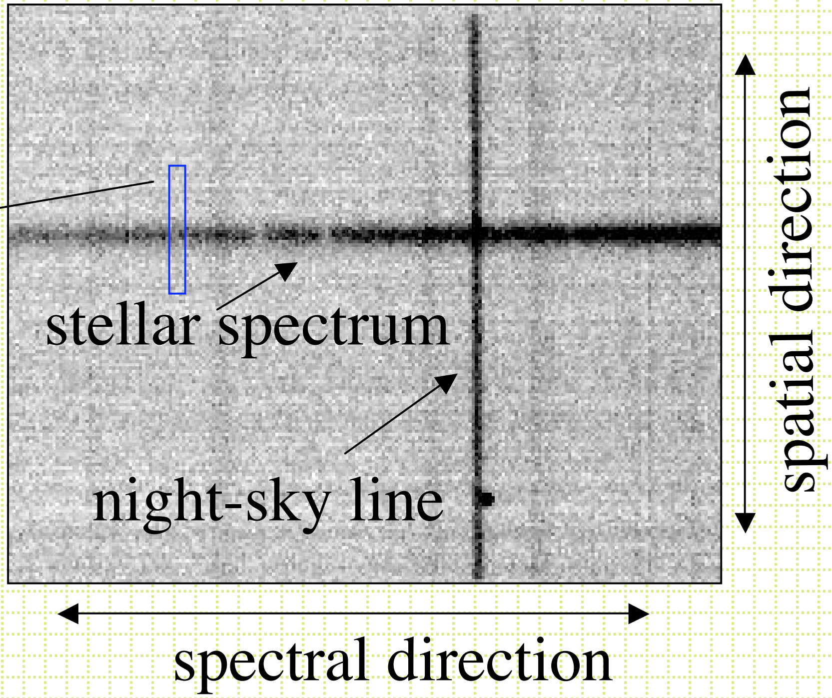


Another throughput issue: slit losses can be very significant!

Spectrometer Observing Considerations

- On-chip binning:





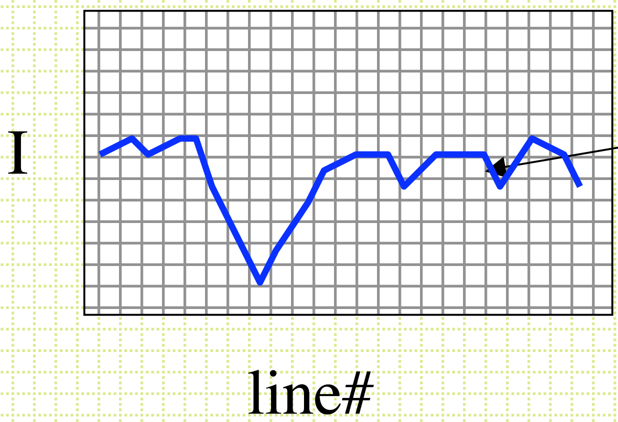
You are going to sum over these lines in the extraction anyway. On-chip binning will reduce RN x #pixels

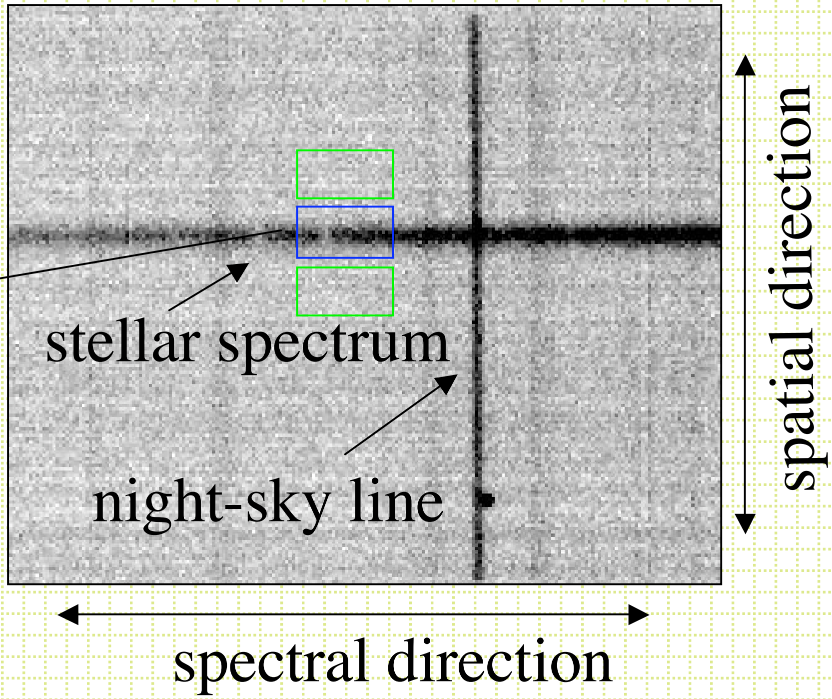
For LRIS-B, 0.15 arcsec/pixel in the spatial direction

- In the *spectral direction*, binning can reduce spectral resolution. If the FWHM of arclamp lines ≥ 5 pixels, you can start to think about binning. Lots of time you are interested in accurate line centers and higher moments of the spectral line profiles in which case, well sampled features are a good idea.

S/N for Spectral Observations

- On-chip binning:





$$S_{\text{spectral pixel}} = \sum_{\text{lines}} R_{\text{object}} \times t$$

$$N_{\text{spectral pixel}} = \sum_{\text{lines}} \left[(R_{\text{object}} \times t) + (R_{\text{sky}} \times t) + RN^2 \right]^{\frac{1}{2}}$$

S/N for Spectral Observations

- Often sum counts again in the spectral direction to determine $S/N_{\text{resolution element}}$.
- Note! Assumes sky noise is at the shot noise limit. Imperfectly modeled and subtracted sky lines are worse than this.
- For spectra the S/N usually varies considerably with wavelength:
  - Absorption, emission, continuum
  - Sky lines
  - System efficiency with wavelength

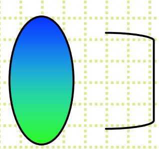
More Spectral Considerations

- Differential Atmospheric Dispersion (Filippenko, 1982, PASP, 94 715)
- Dispersion in the atmosphere causes chromatic distortion of images that gets larger at blue wavelengths at fixed airmass and larger with airmass at fixed central wavelength.

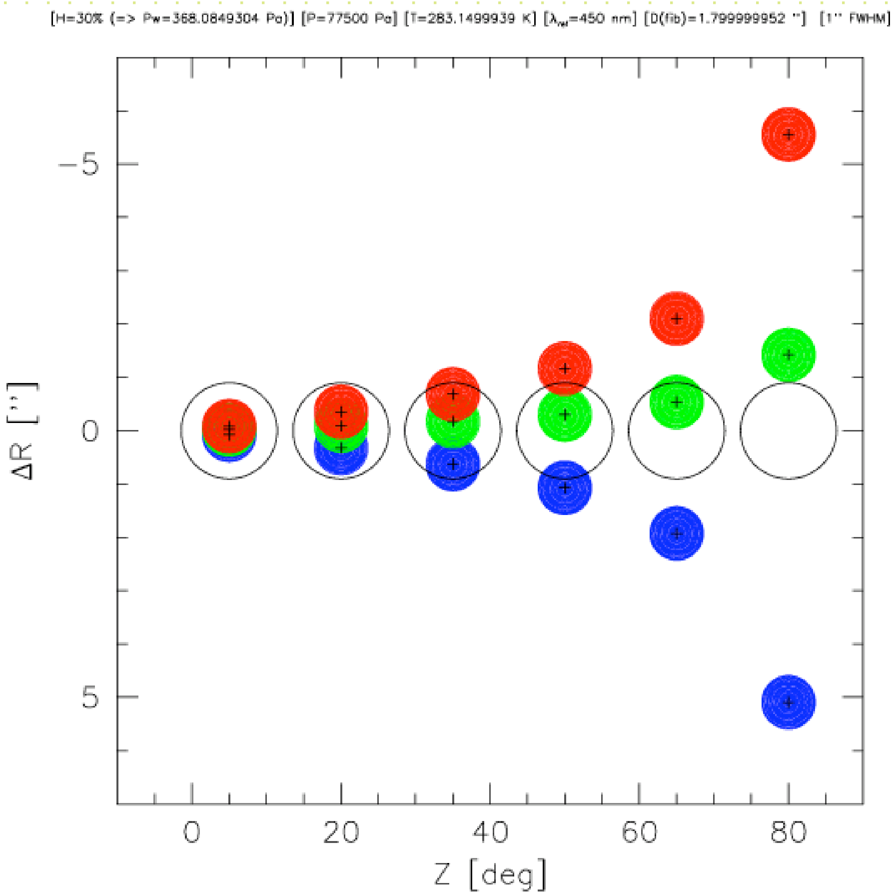
index of refraction

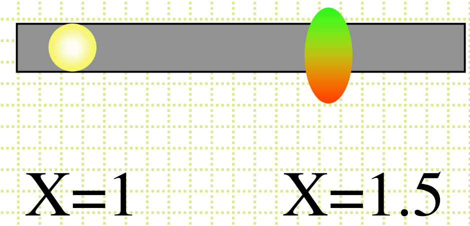
$$\Delta\theta = 206265 \times \left[(n_{\lambda 1} - 1) - (n_{\lambda 2} - 1)\right] \times \tan(ZD)$$

zenith distance



@X=1.5, 1.3″ separation between 350nm and 550nm



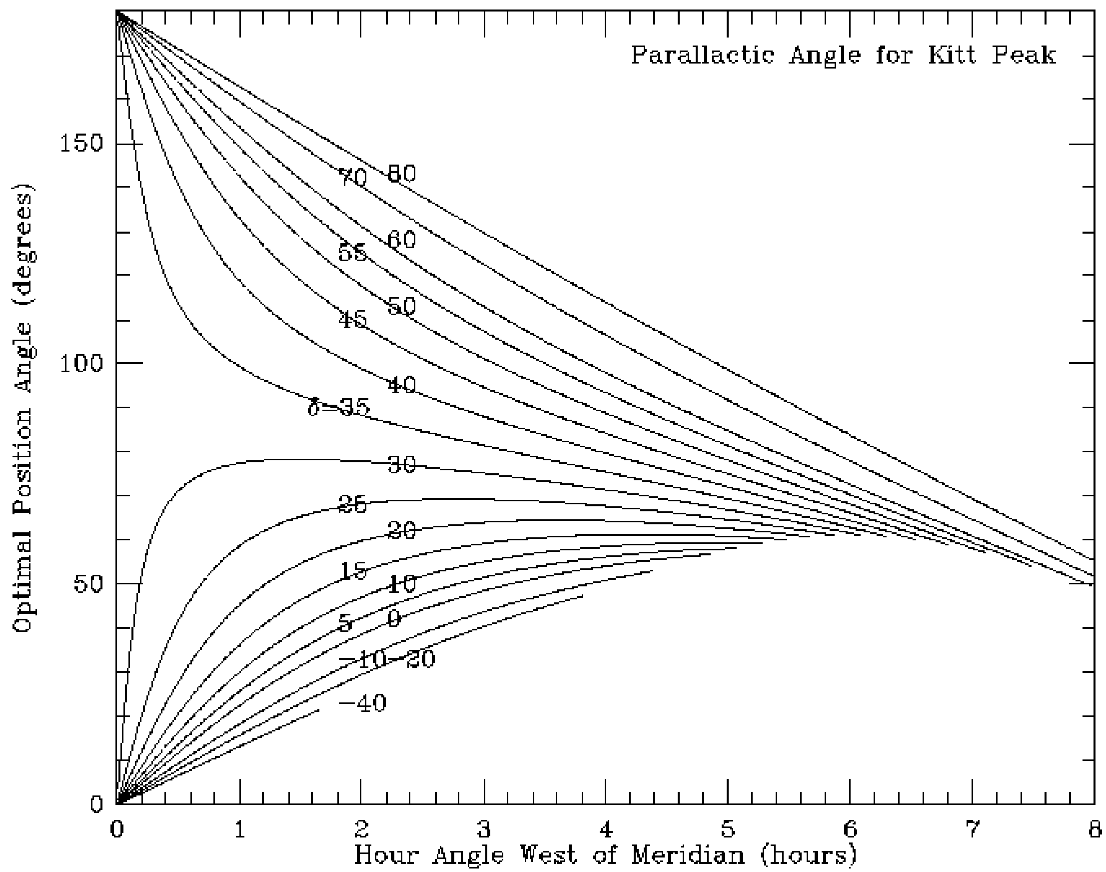


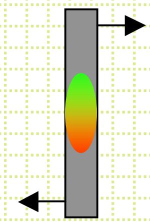
Two problems:

1) Preferentially lose red (or blue) light out of the slit.

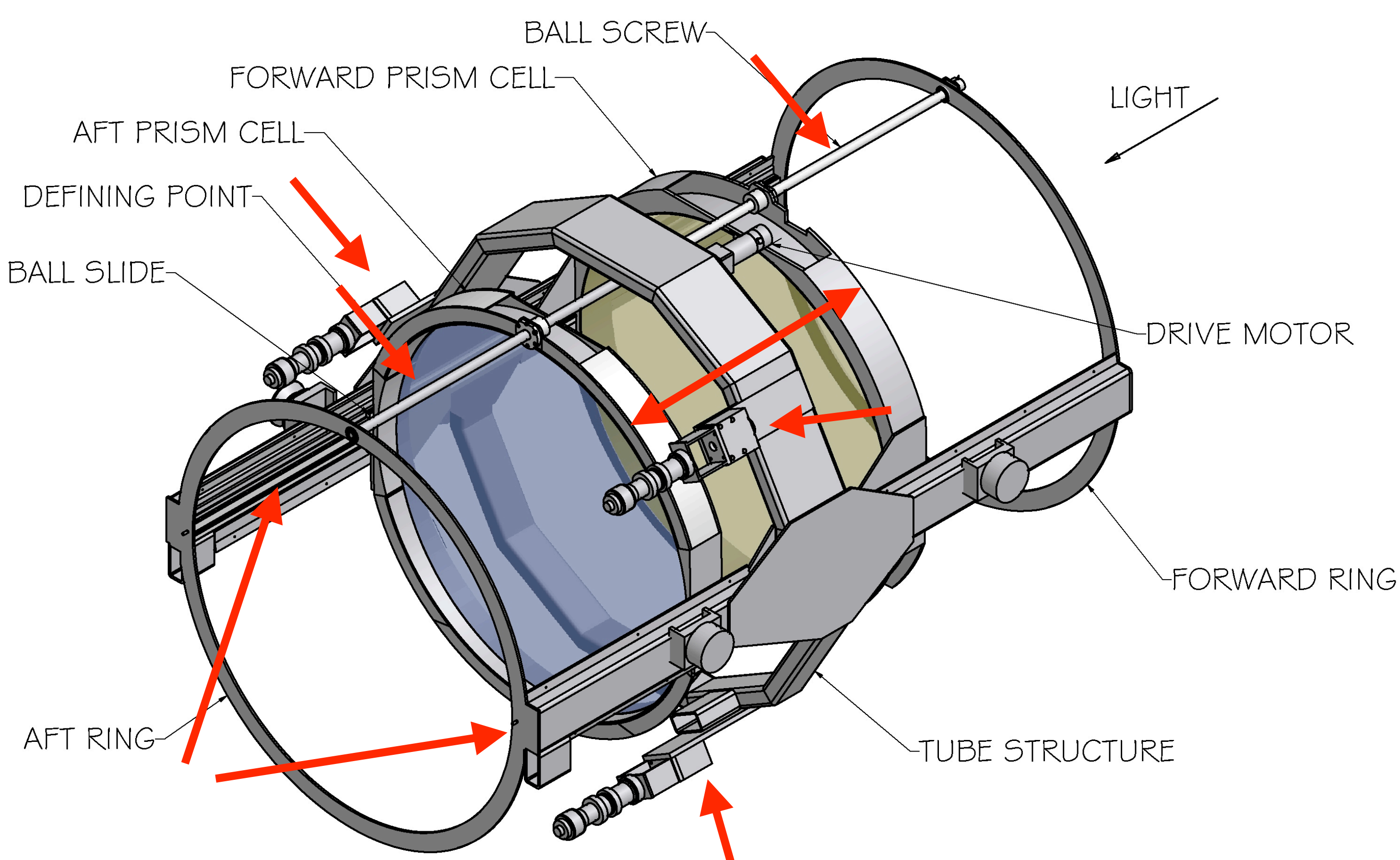
2) If guiding on a particular wavelength of light, the object at other wavelengths will move out of the slit.

- Two solutions:
  - Align slit along the *parallactic angle*



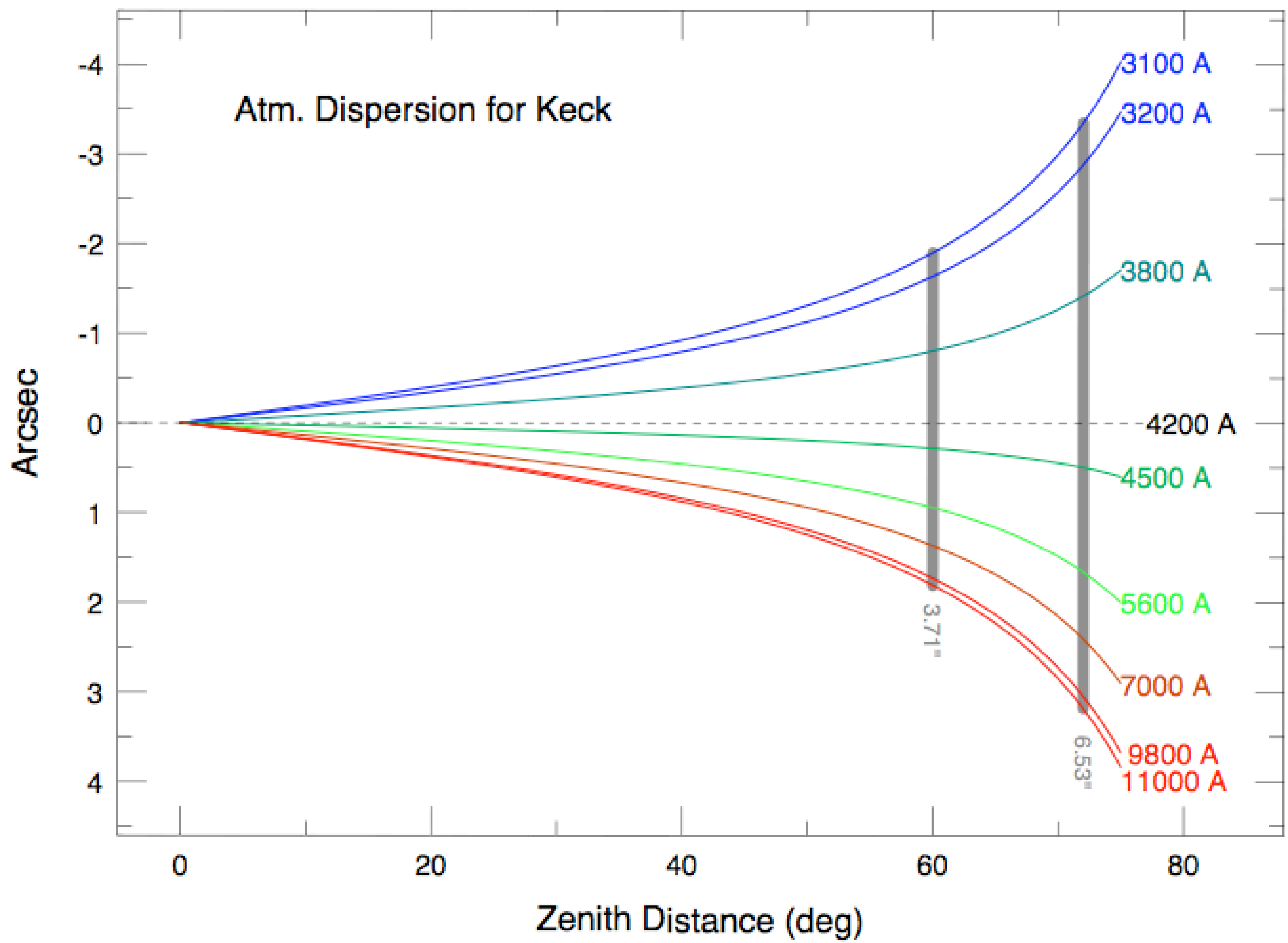


Build an ADC

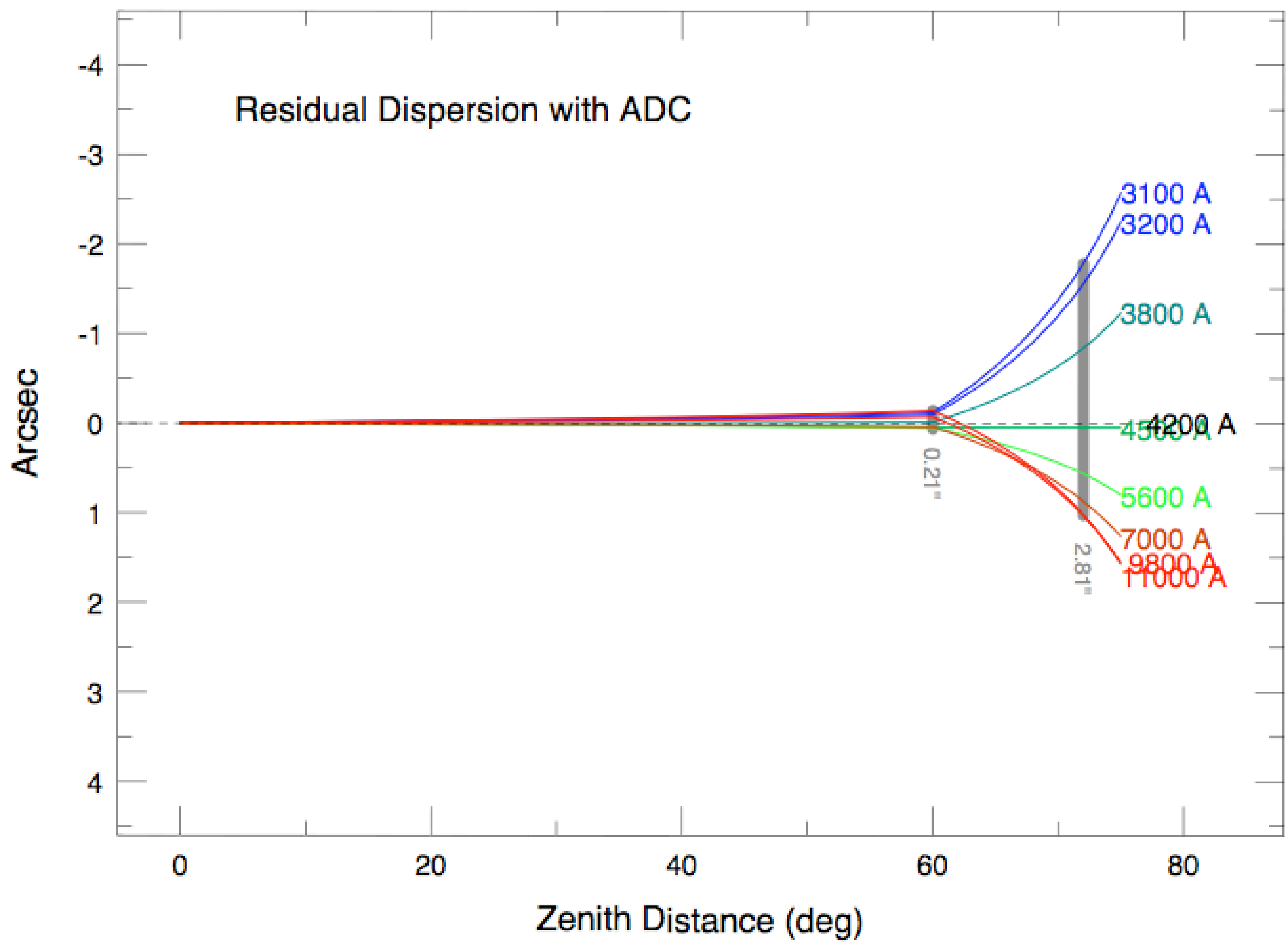


ADC WITHOUT CLADDING OR COVERS

Uncorrected



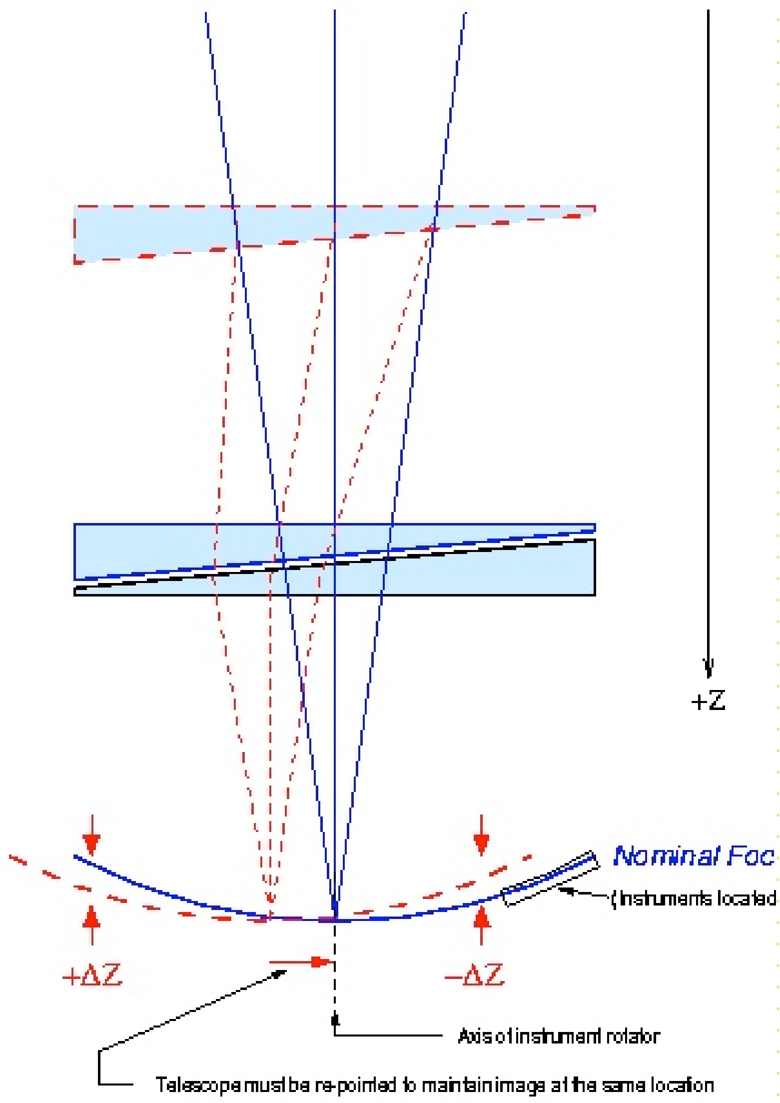
Corrected with ADC

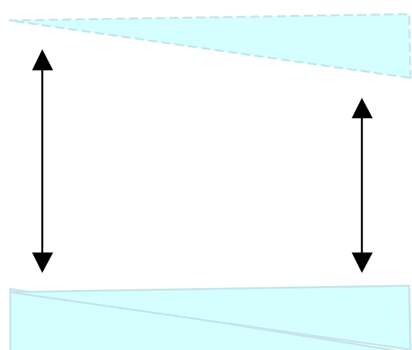


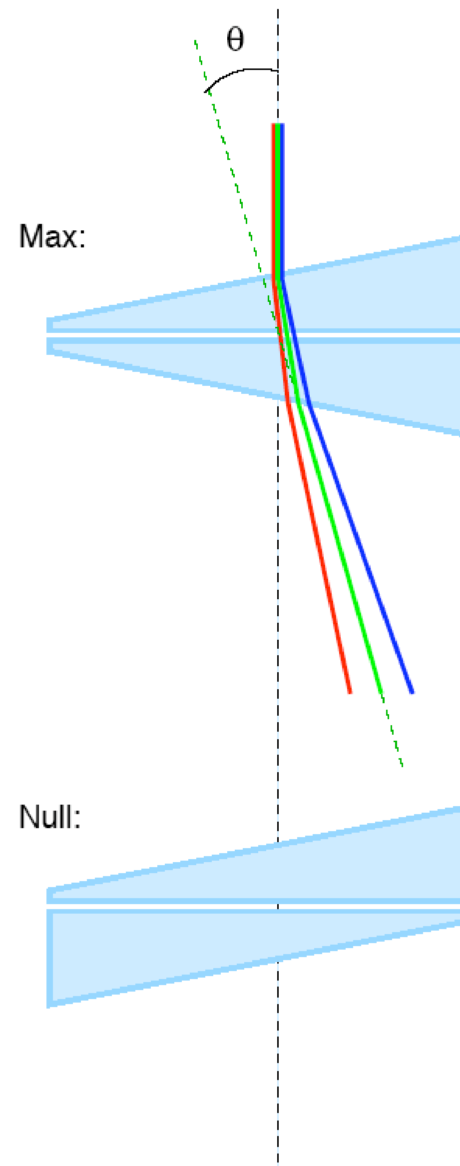
Linear ADC

LADC displaces focus:

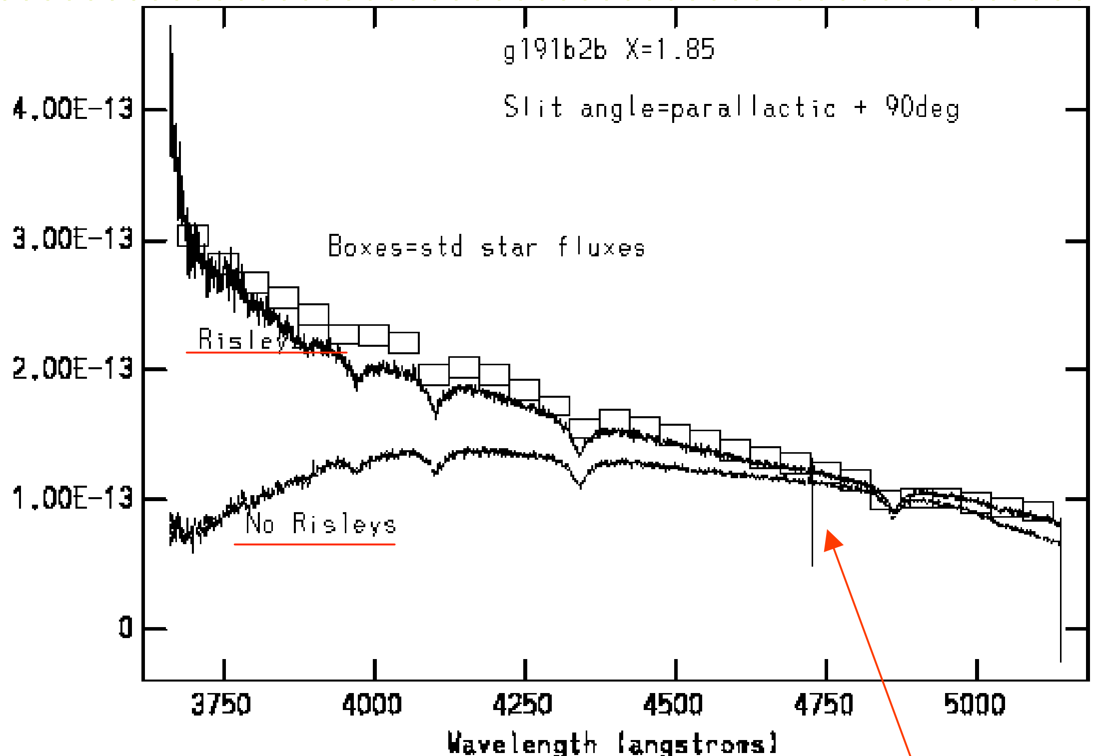
- Must repoint telescope
- Tilted focal surface -- must refocus telescope for prism separation and rotator angle
- Possible changes in vignetting
- Displaced pupil at grating (barely OK)
- Must oversize/displace prisms to minimize clear aperture






θ
Max:
Null:

Factor of 3+



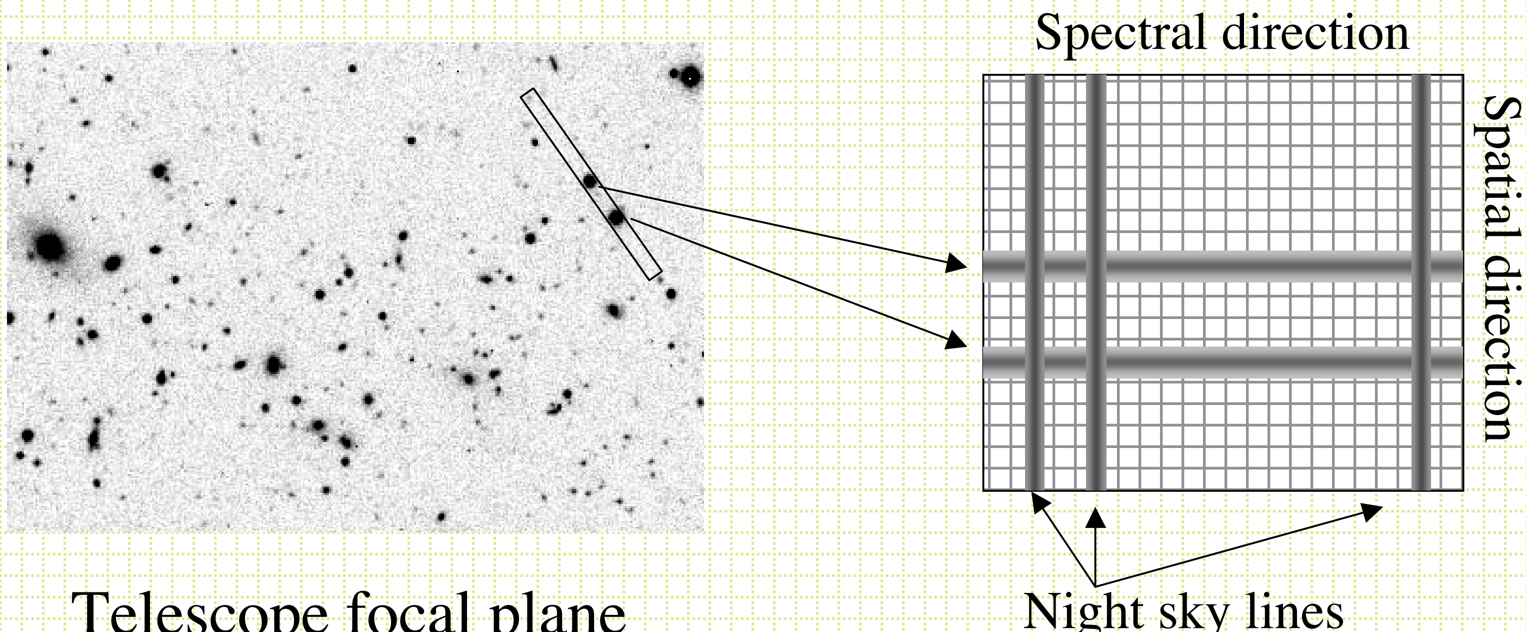
KPNO 4m rotating `Risley' prisms.

Central guider wavelength

Multiobject Spectroscopy

- Very popular option for the last decade or so.
  - Multislit
  - Fiber-fed
  - Fabry-Perot
  - IFU

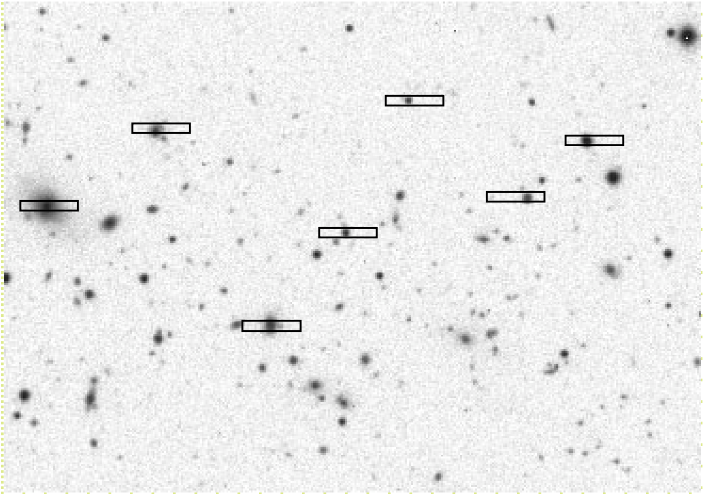
- Remember the simple case: carefully rotated long slit. Note: better have an ADC.

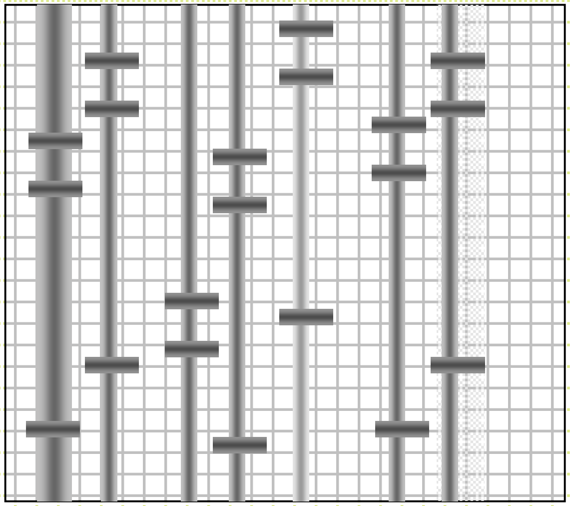


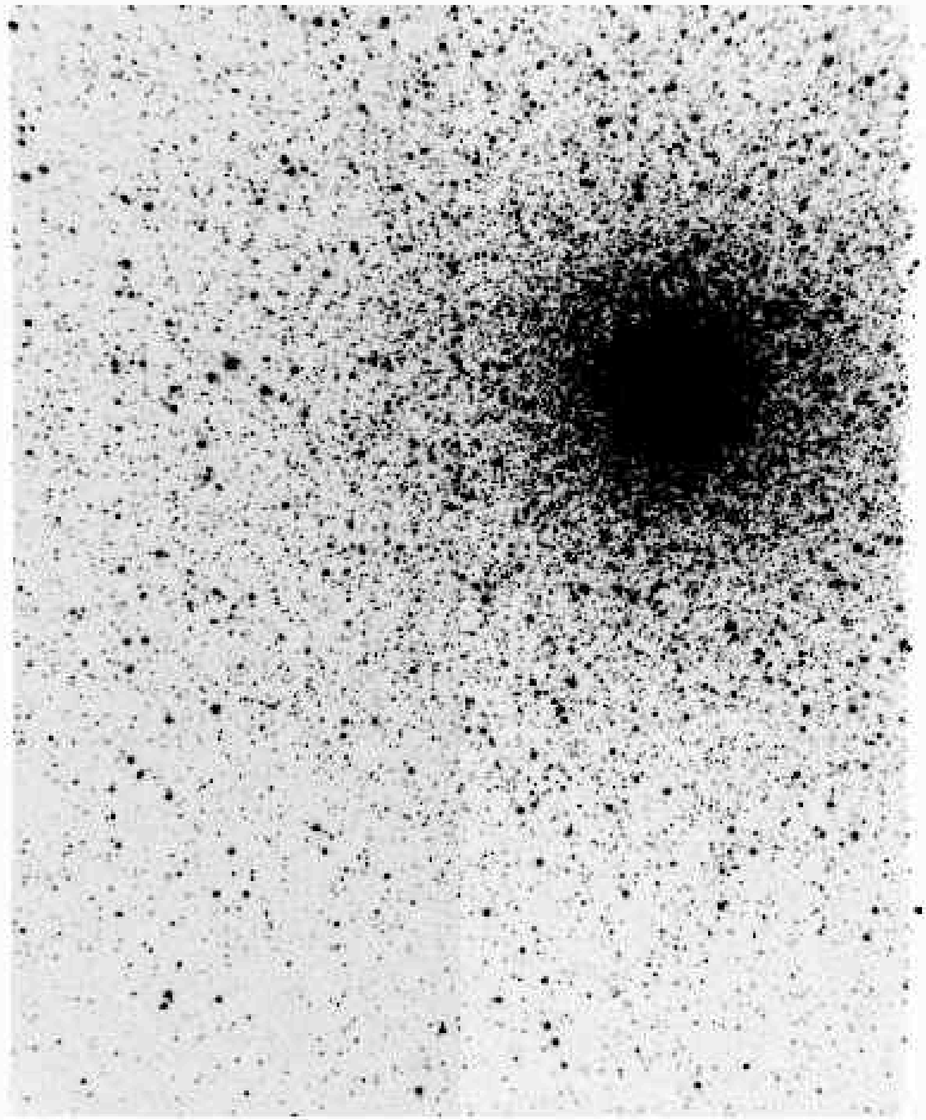
Telescope focal plane

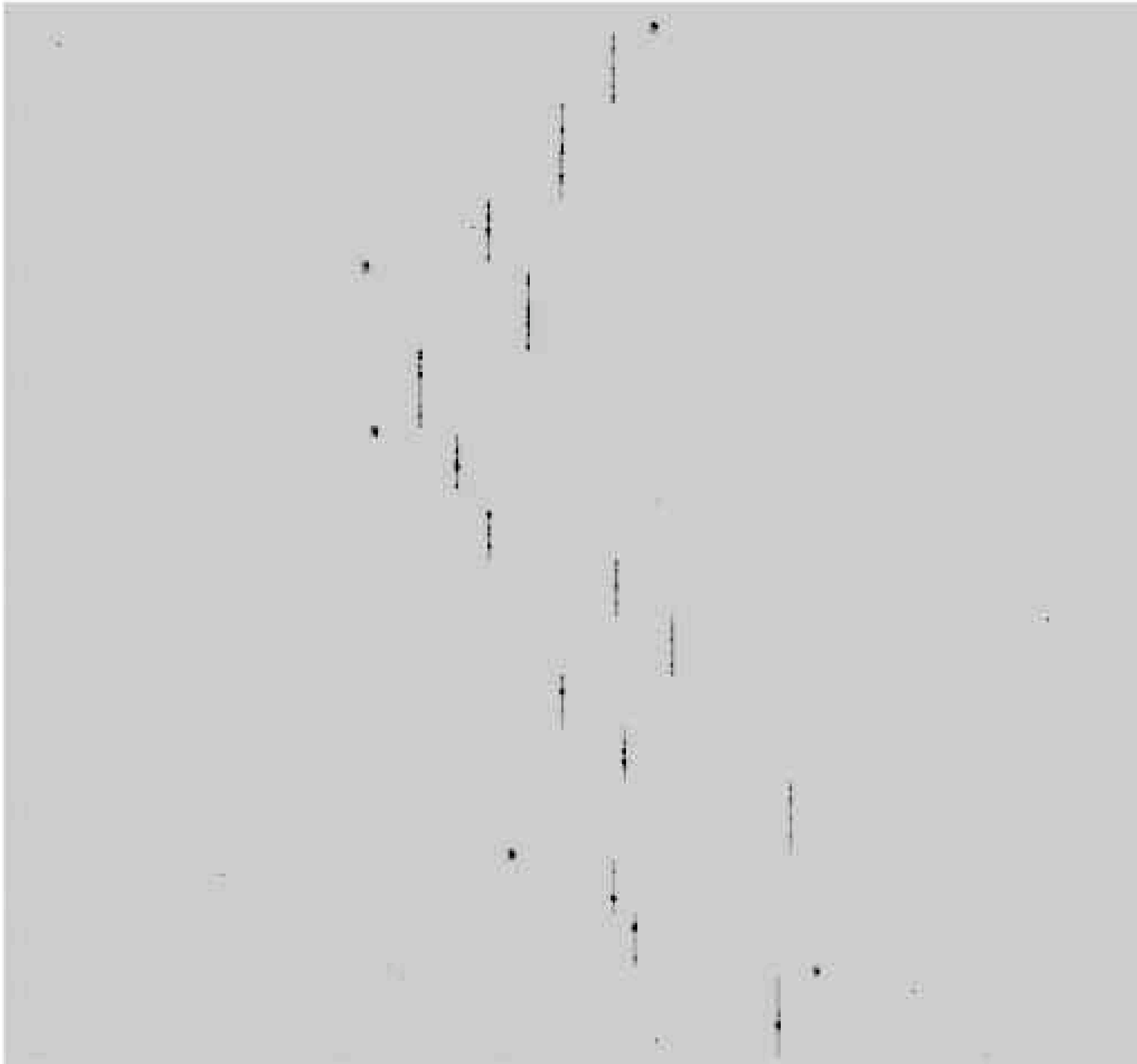
Spectrometer camera focal plane

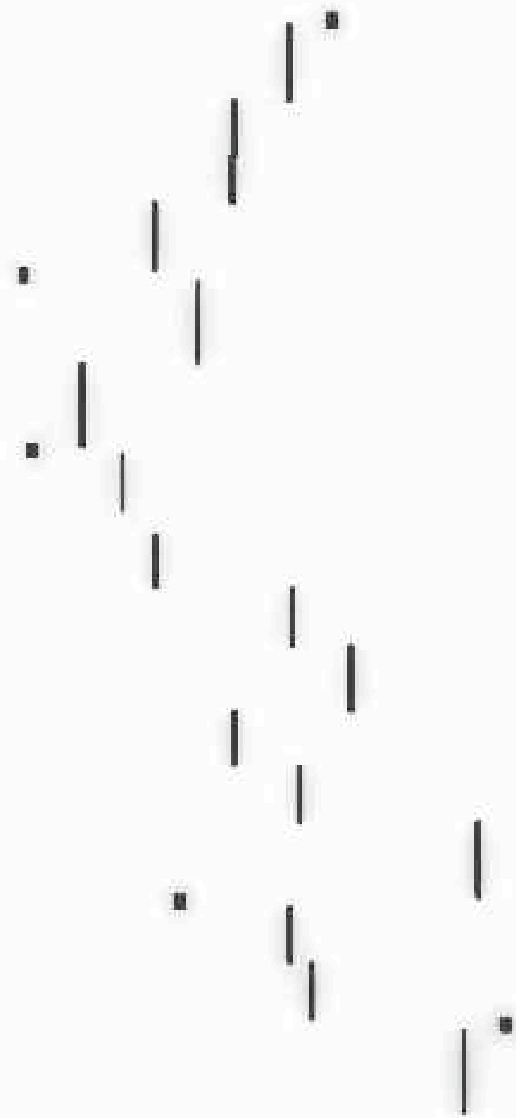
Multislit spectroscopy

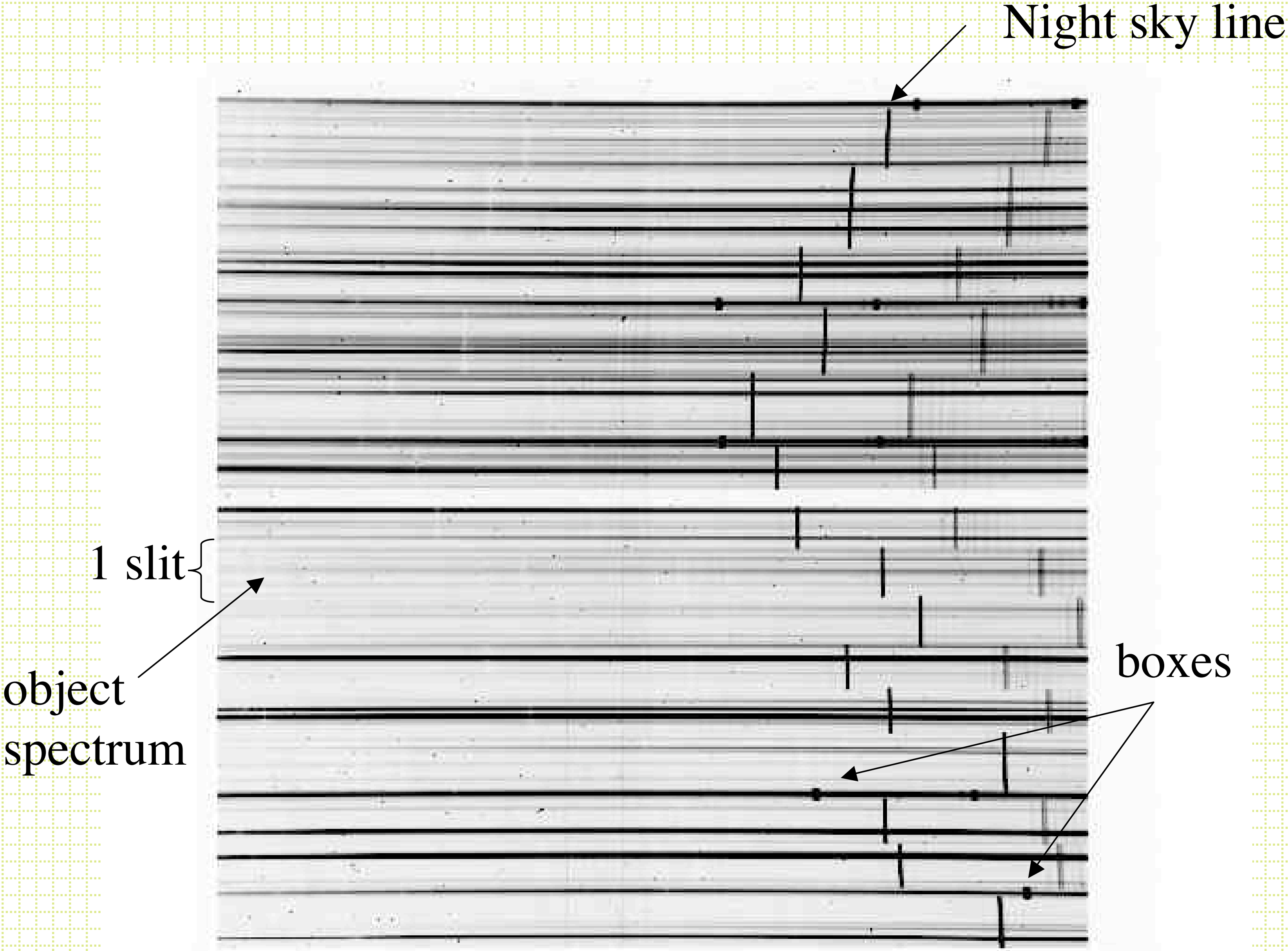


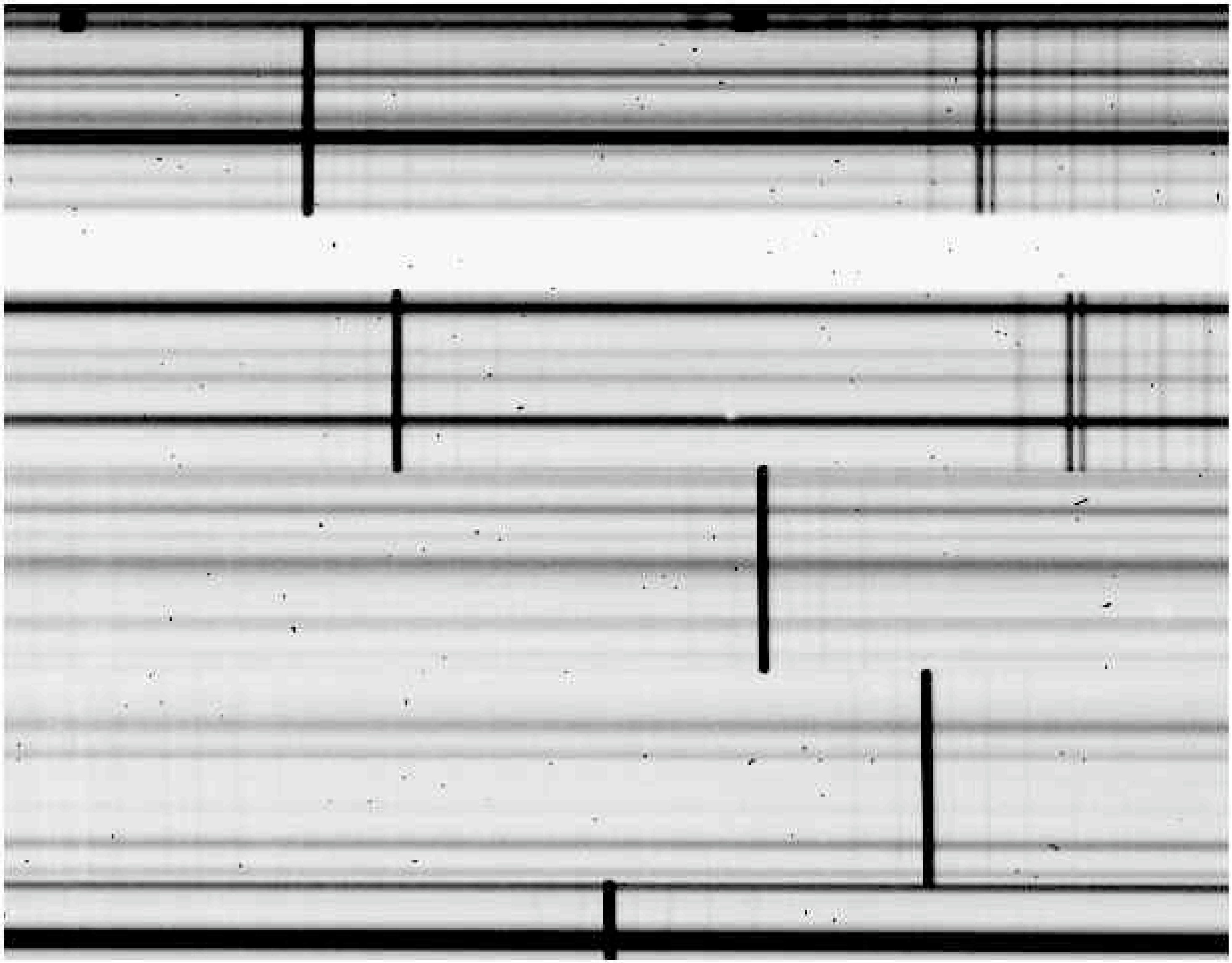









Night sky line
1 slit
object
spectrum
boxes

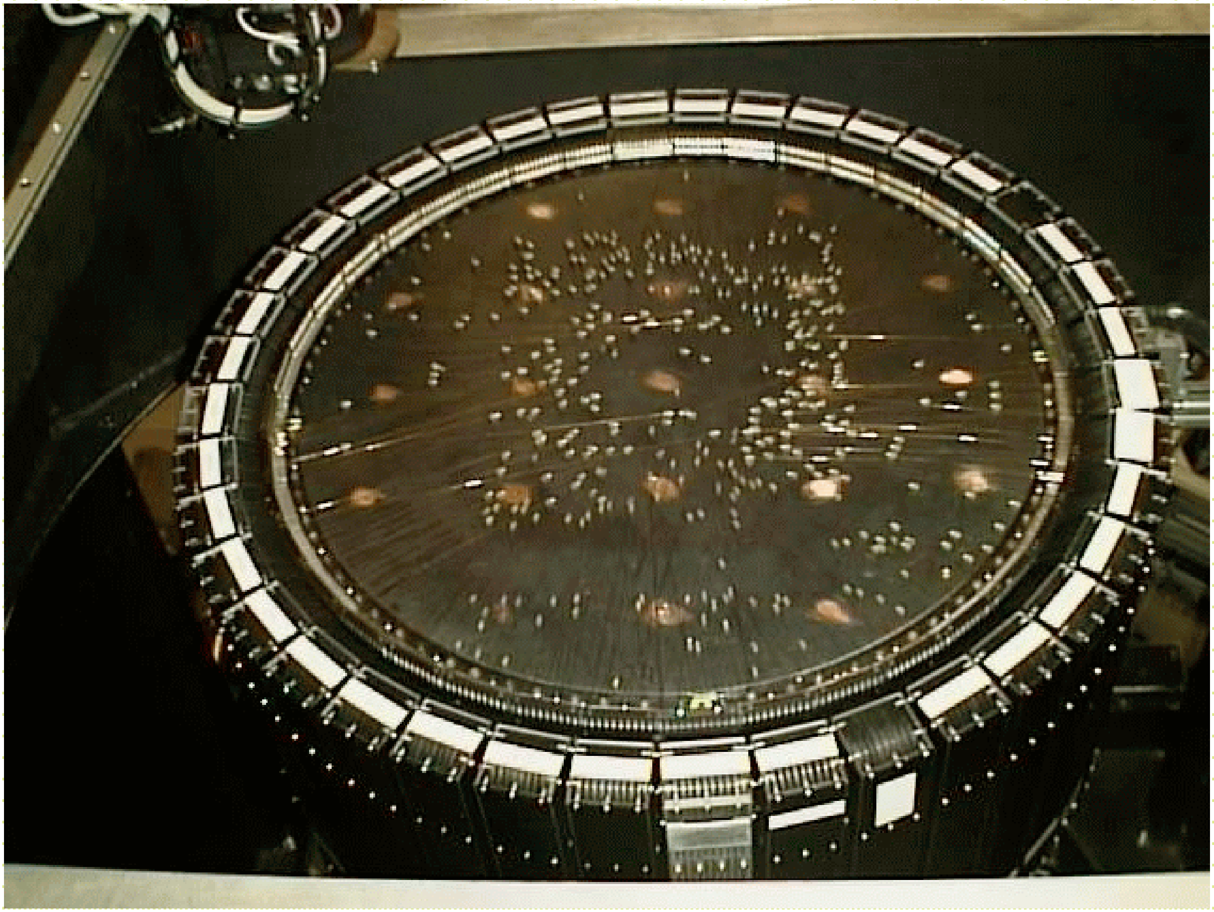


- Advantages of multislits:
  - High throughput
  - Can choose slit width and length
  - Good sky subtraction
  - Can place slits close together in telescope focal plane
- Disadvantages of multislits:
  - wavelength coverage varies with the slit position
  - do not always use the detector area efficiently.

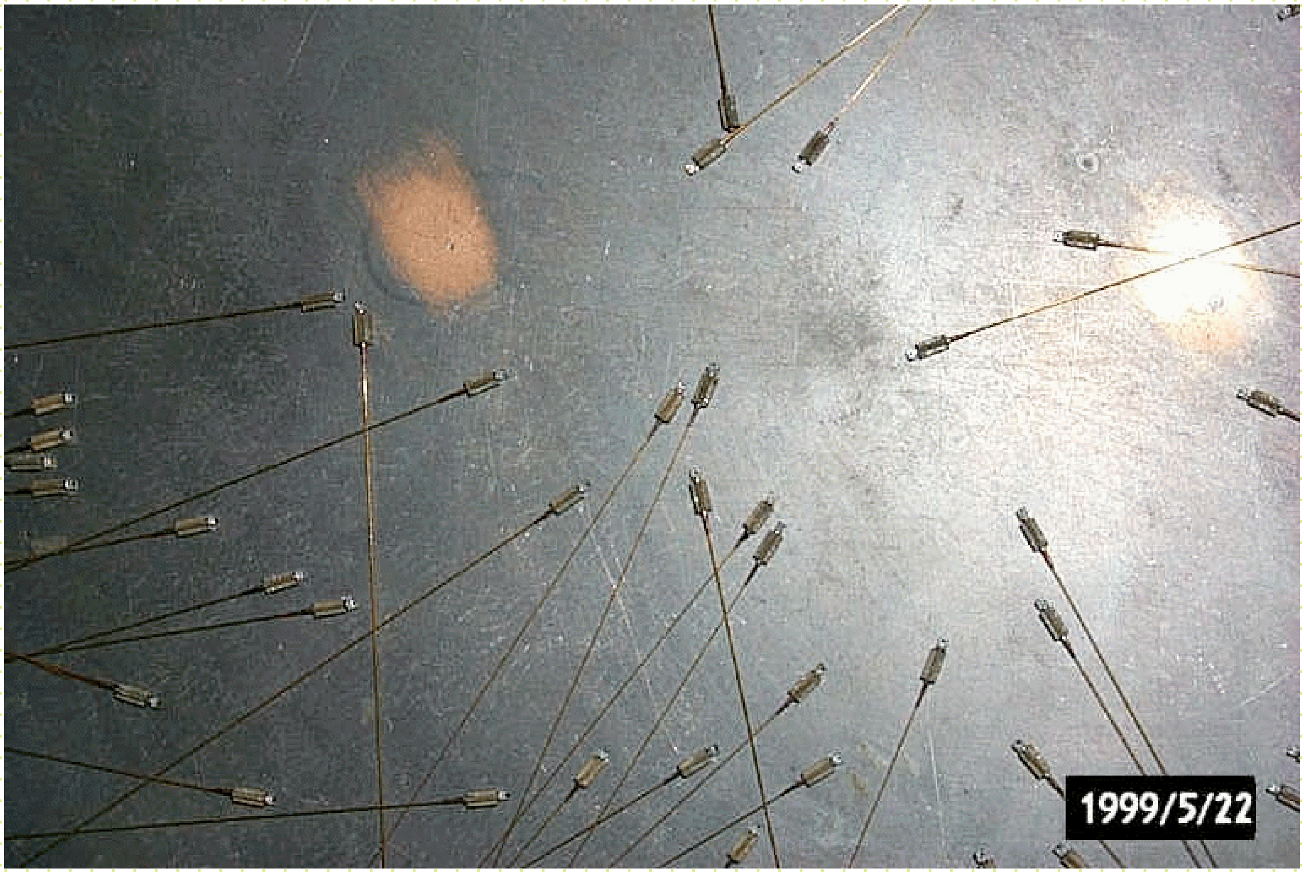
Fiber-fed MOS

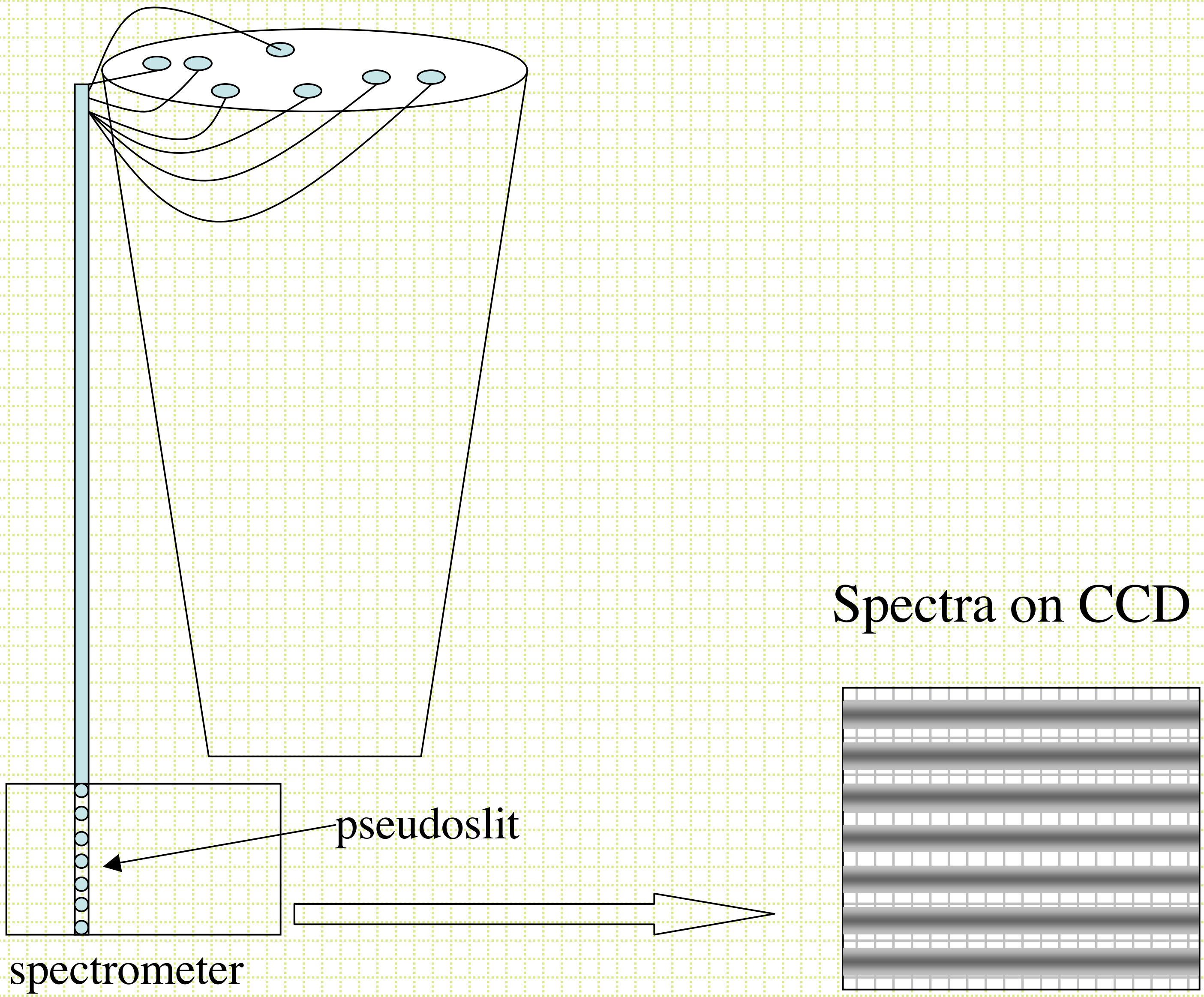
- ASP Conf Series #37, 1997
- Examples:
  - Lick 3m MOS (80 fibers/1° field)
  - HYDRA@ WIYN (200+ fibers/1° field)
  - 2DF@ AAT (400 fibers/2° field)

2DF focal plane

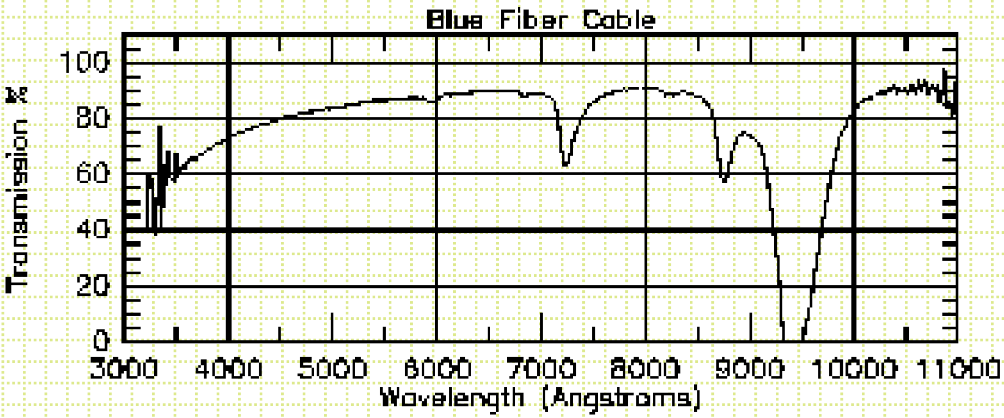


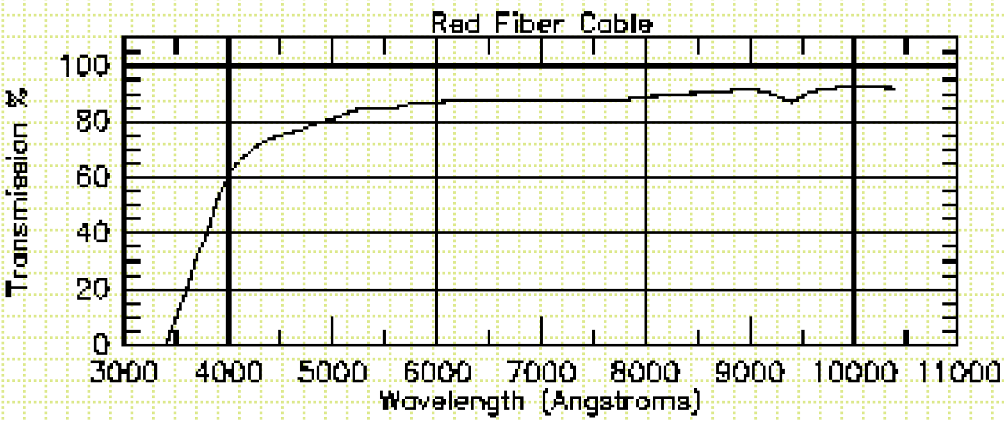
2DF buttons+fibers




Spectra on CCD
pseudoslit
spectrometer

- Advantages of multi-fiber systems
  - Large fields
  - Uniform wavelength coverage
  - Efficient use of detector area
- Disadvantages
  - Minimum separation is between a few and 10+ arcseconds
  - Fiber losses are significant and grow with time (fiber are delivate)
  - Sky subtraction difficulties
  - Setup times can be long

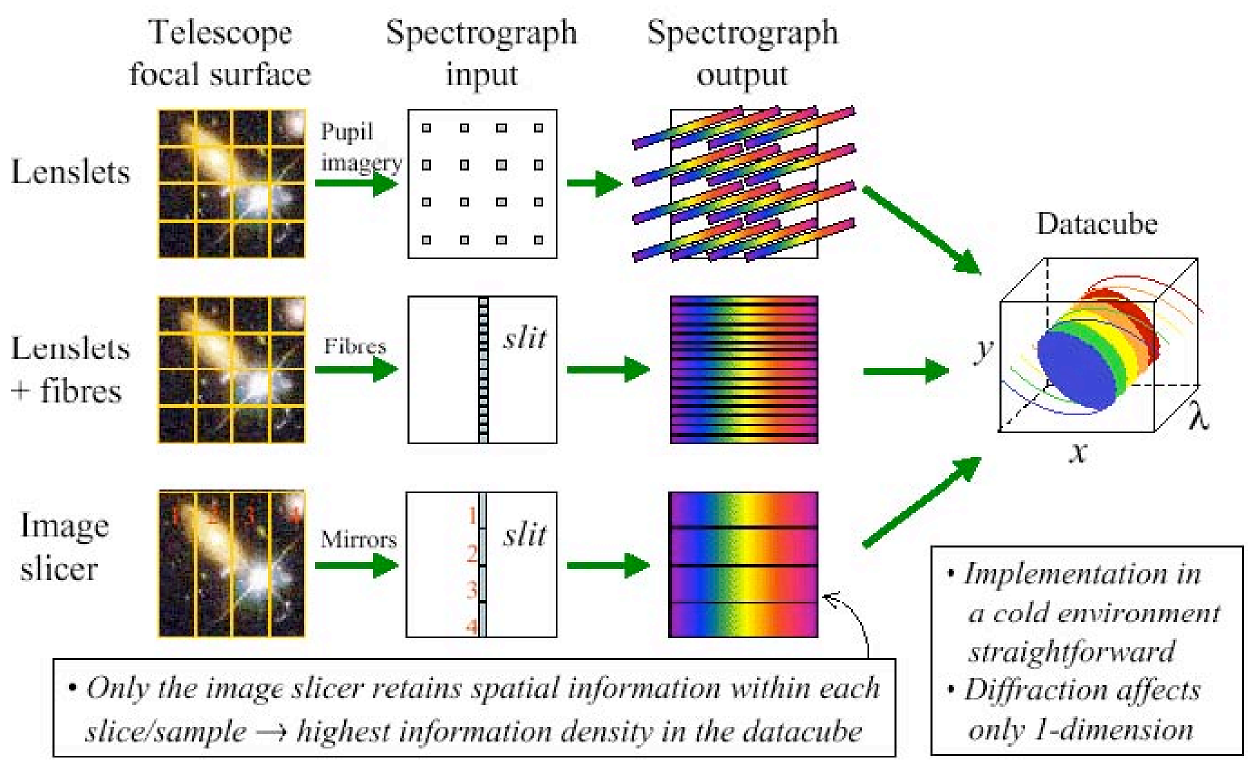




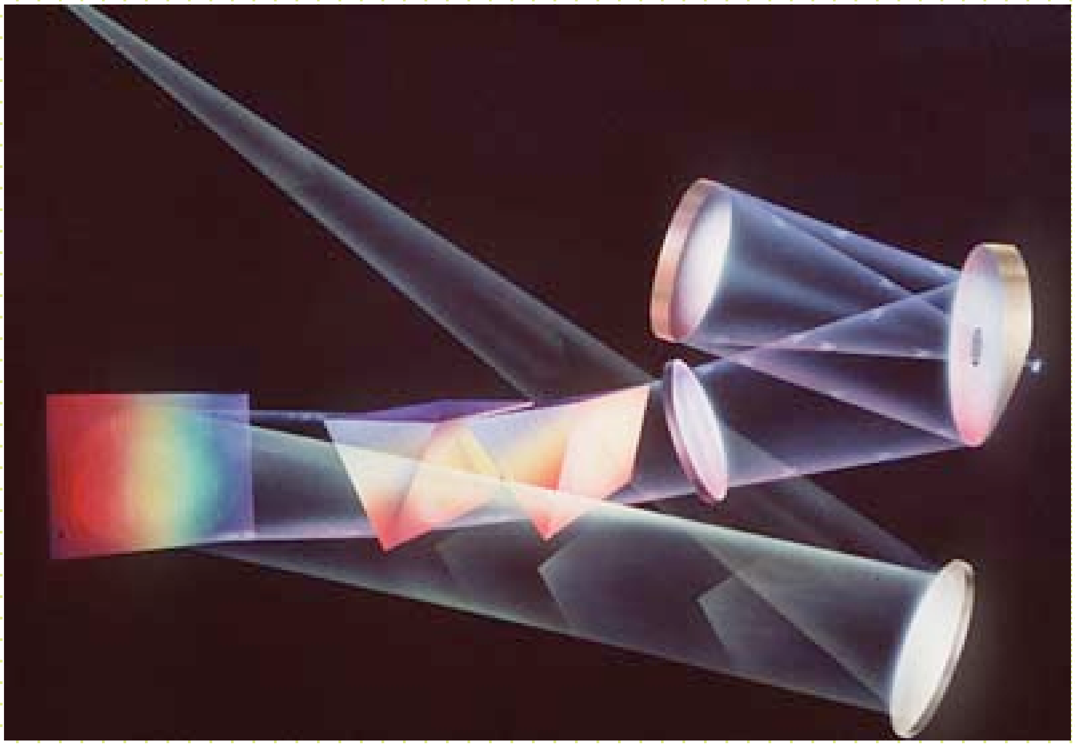
Add in `button' losses and focal-ratio degredation.

Fiber loss is per unit length

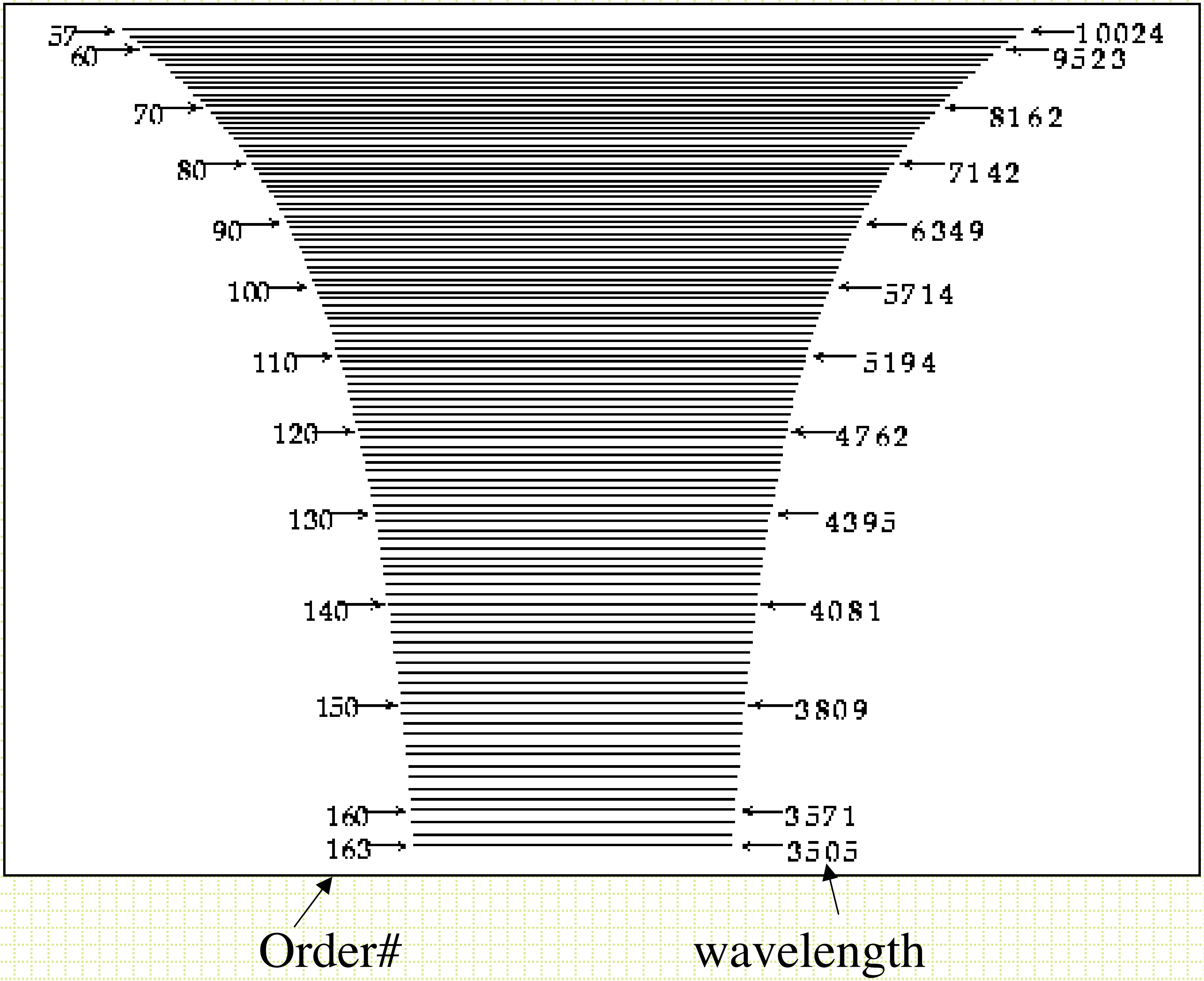
IFUs

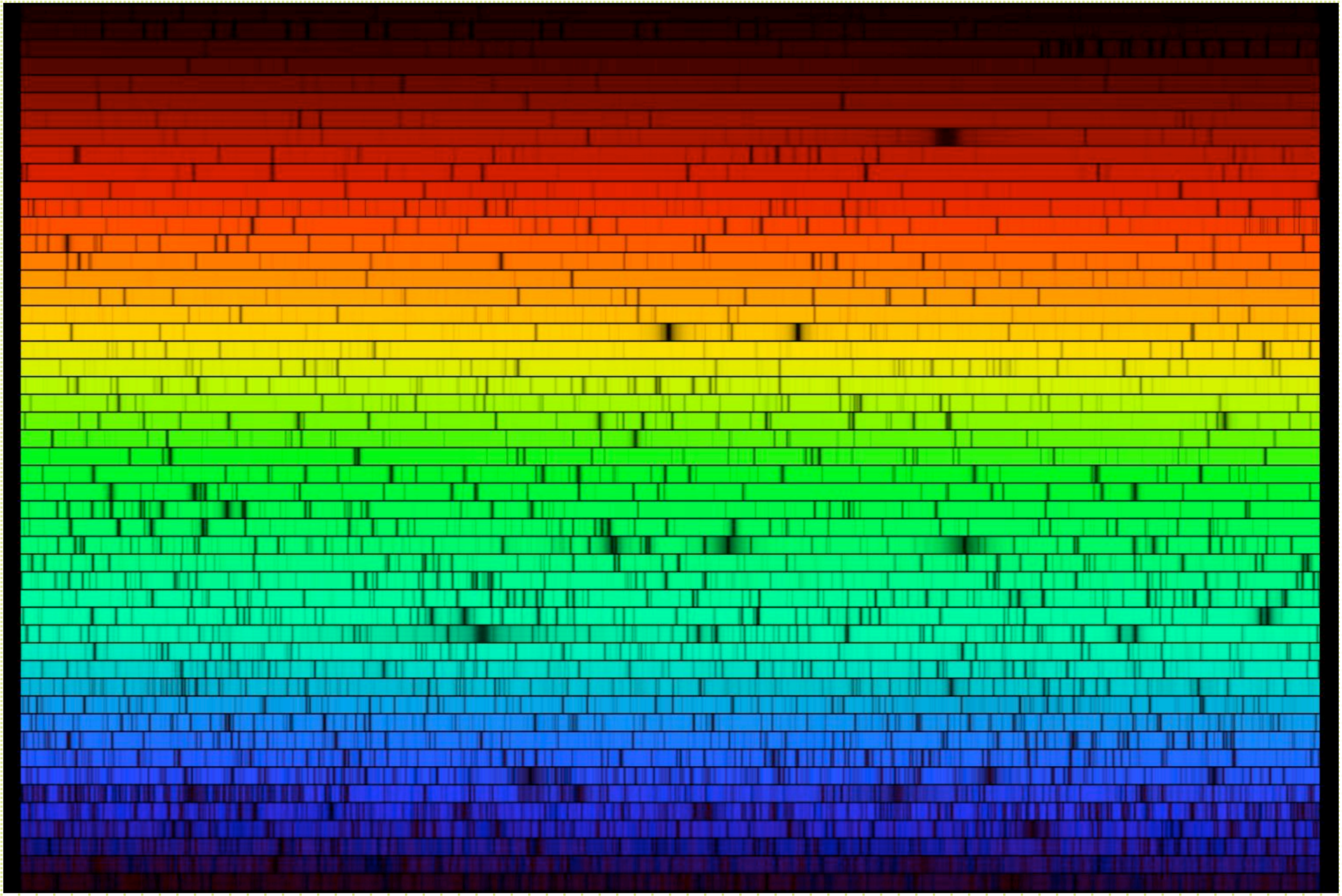

Telescope focal surface
Spectrograph input
Spectrograph output
Lenslets
Pupil imagery
Datacube
Lenslets + fibres
Fibres
slit
y
x
λ
Image slicer
Mirrors
slit
1
2
3
4
• Only the image slicer retains spatial information within each slice/sample → highest information density in the datacube
• Implementation in a cold environment straightforward
• Diffraction affects only 1-dimension

Echelle Spectrometers



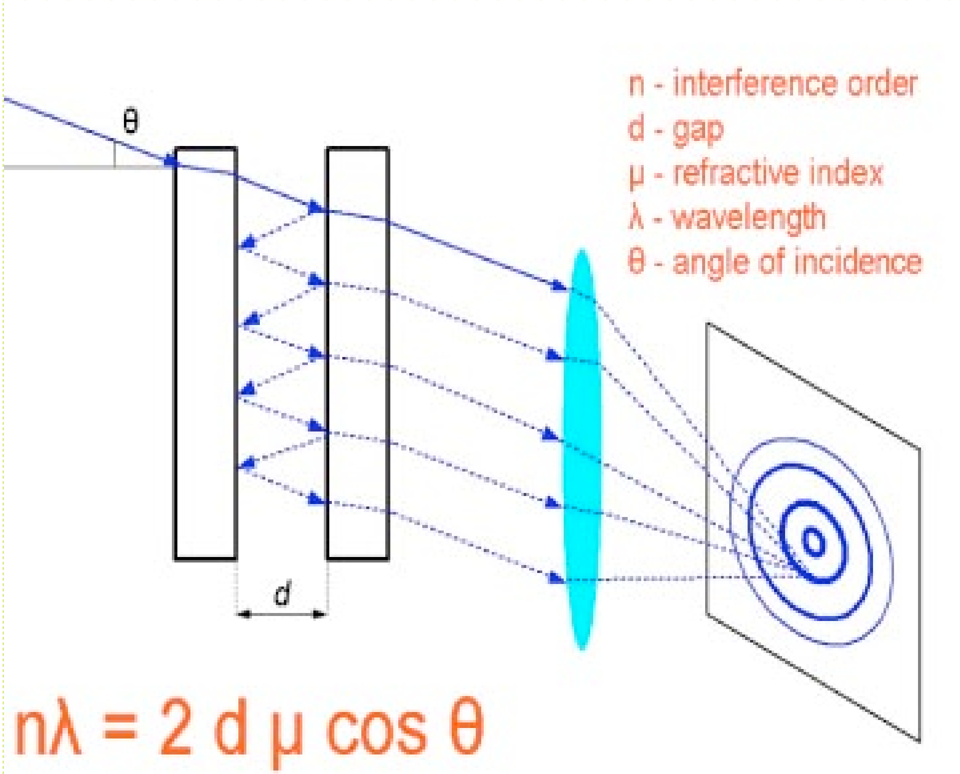
- If after grating dispersion you `cross disperse’ the spatially coincident orders you can separate the orders in the camera focal plane.
- This is an echelle spectrometer. Usually do the initial dispersion with a fine ruled grating and the cross dispersiing with a prism.
- Local examples are the Lick Hamilton Spectrometer and Keck HIRES

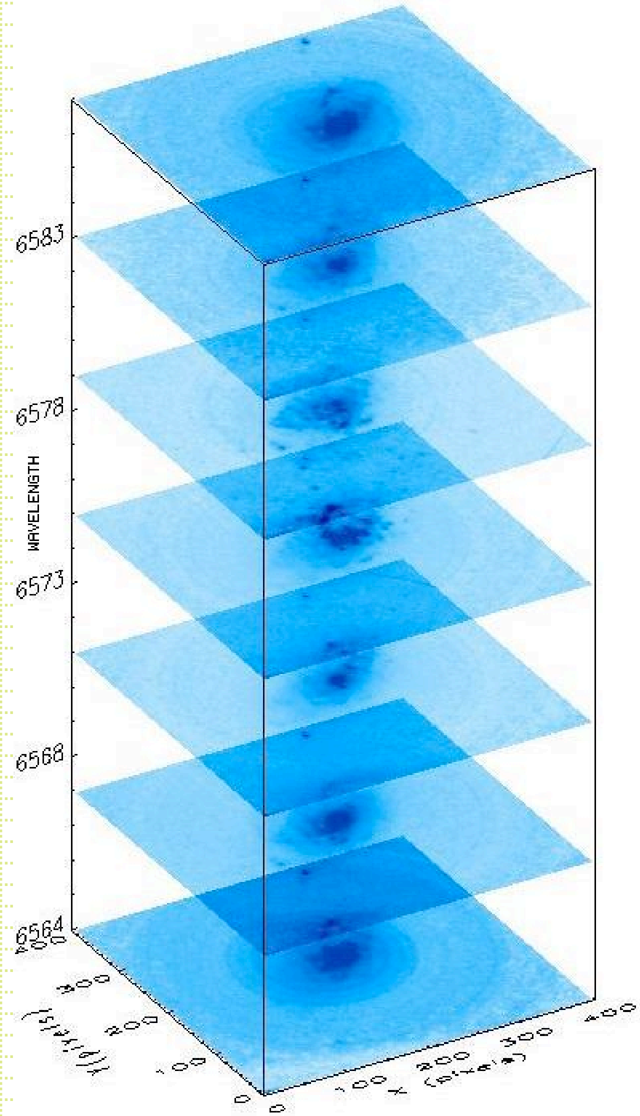

57
60
70
80
90
100
110
120
130
140
150
160
163
10024
9523
8162
7142
6349
5714
5194
4762
4395
4081
3809
3571
3505
Order#
wavelength



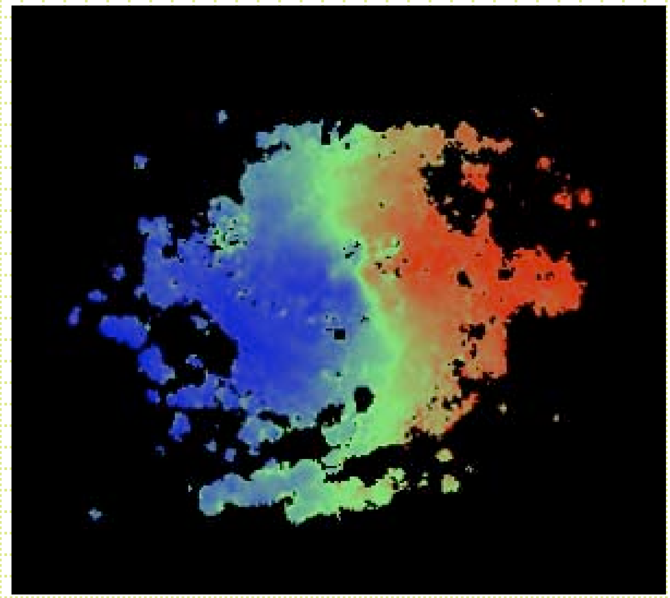
Fabry-Perot

- A final type of spectrometer is a F-P system





F-P data cube



Color-coded velocity map