Astro 500

Techniques of Modern *Observational* Astrophysics

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Lecture Outline

Spectroscopy from a 3D Perspective

- ✓ Basics of spectroscopy and spectrographs
- ✓ Fundamental challenges of sampling the data cube
- Approaches and example of available instruments
  - ➢ I: Grating-dispersed spectrographs ⟵ a lot of material
  - ➢ II: Fabry-Perot interferometry
  - ➢ III: Spatial heterodyne spectroscopy

Approaches

Examples of available instruments

- ✓ Grating-dispersed spectrographs
  - ✓ basic spectrograph design
  - ✓ dispersive elements
  - ➢ Long-slit spectrographs
    - o General Observing Considerations
  - ➢ Double spectrographs + ADC's
  - ➢ Multi-objects spectrographs: slitlets vs fibers
  - ➢ Echelle spectrographs
  - ➢ 3D spectroscopy: coupling formats and methods
    - o Fiber
    - o Fiber+lenslet
    - o Slicer
    - o Lenslet
    - o Filtered multi-slit
  - ➢ summary of considerations
  - ➢ sky subtraction

Grating-dispersed spectrographs
dispersive elements - *recap*

- **Implications for resolution, band-pass, efficiency, in instrument design**
  - transmission vs reflection:
    - VPH transmission gratings preferred because of higher throughput, large size, customization, and resulting compact spectrograph geometry (minimize vignetting, maximize throughput).
      - Novel, efficient modes possible: grism, double-gratings, notch gratings.
    - requires articulating camera - not always possible or practical.
    - VPH grisms an improvement if no articulation.
  - For the highest resolutions, high density VPH gratings may compete with echelles; double VPH gratings certainly will.
  - Echelle gratings get best combination of high dispersion and large anamorphic factors: better at packing spectral resolution elements on the detector, at the cost of less-compact (lossy) geometry and/or the need for larger optics.
    - white pupil designs ameliorate some of these problems.
    - *No free lunch!*

Grating-dispersed spectrographs

basic spectrograph design

- **Grating equation**

  $m \lambda = \sigma (\sin \beta + \sin \alpha)$

  (reflection)

  σ is groove separation (nm)

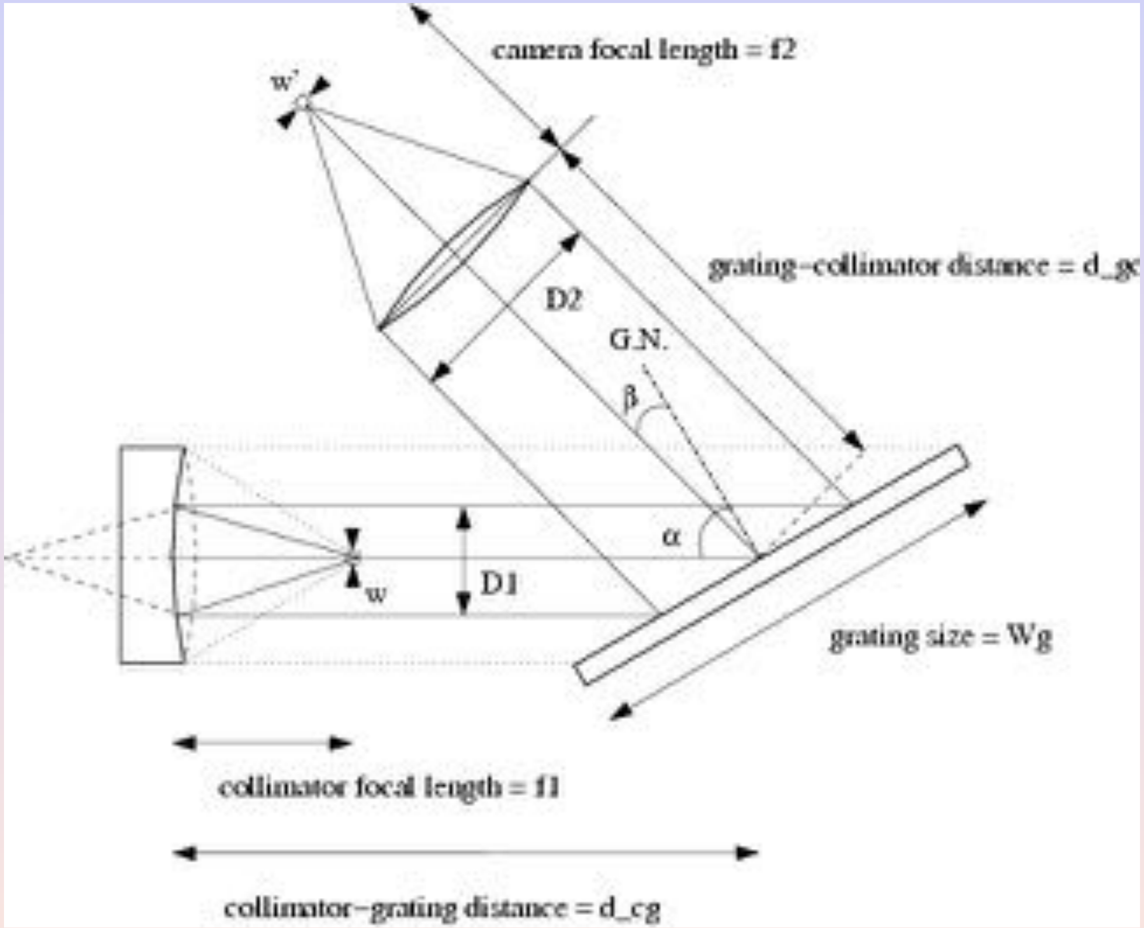
- **Angular dispersion**

  $\gamma = d\beta/d\lambda = m / \sigma \cos \beta$

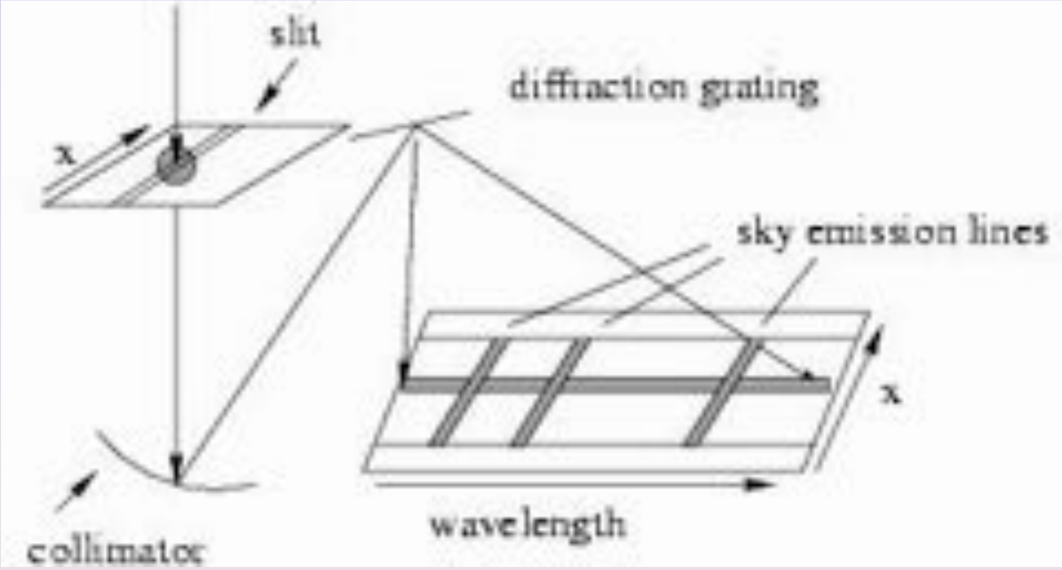
  $= (\sin \beta + \sin \alpha) / \lambda \cos \beta$

- **Linear dispersion**

  $dx/d\lambda = f_2 \gamma$

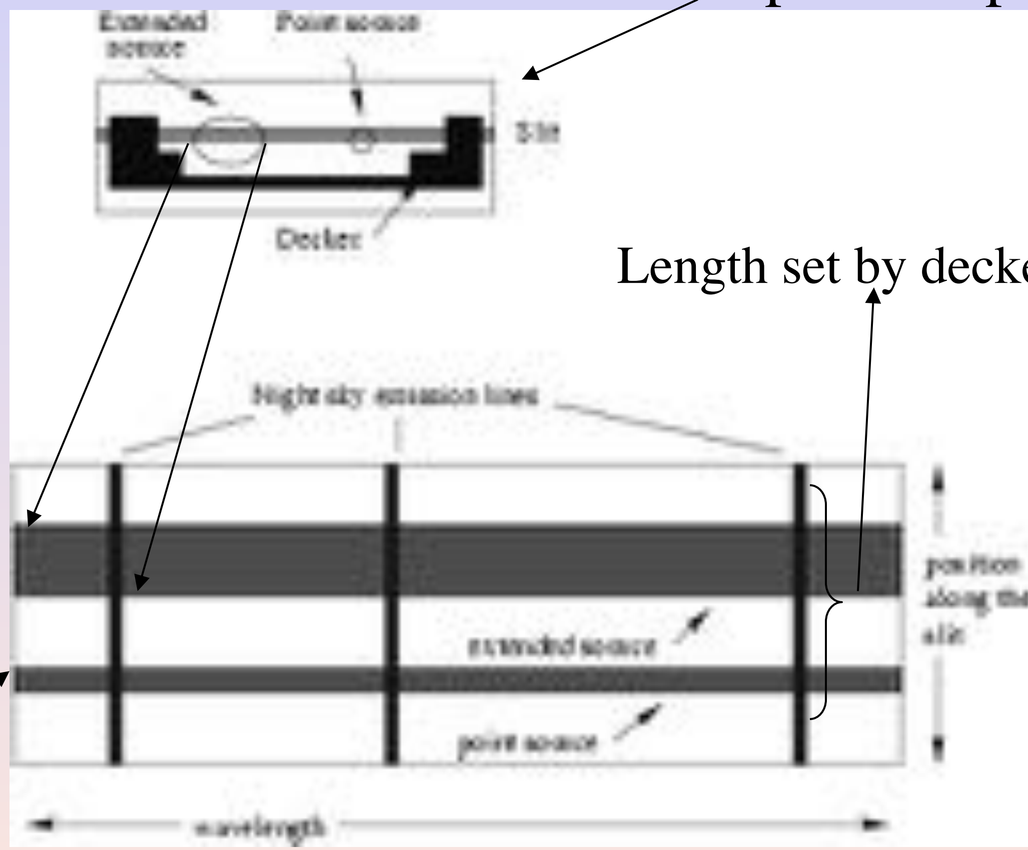


Long-slit Spectra Geometry



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



Length set by decker

seeing disk

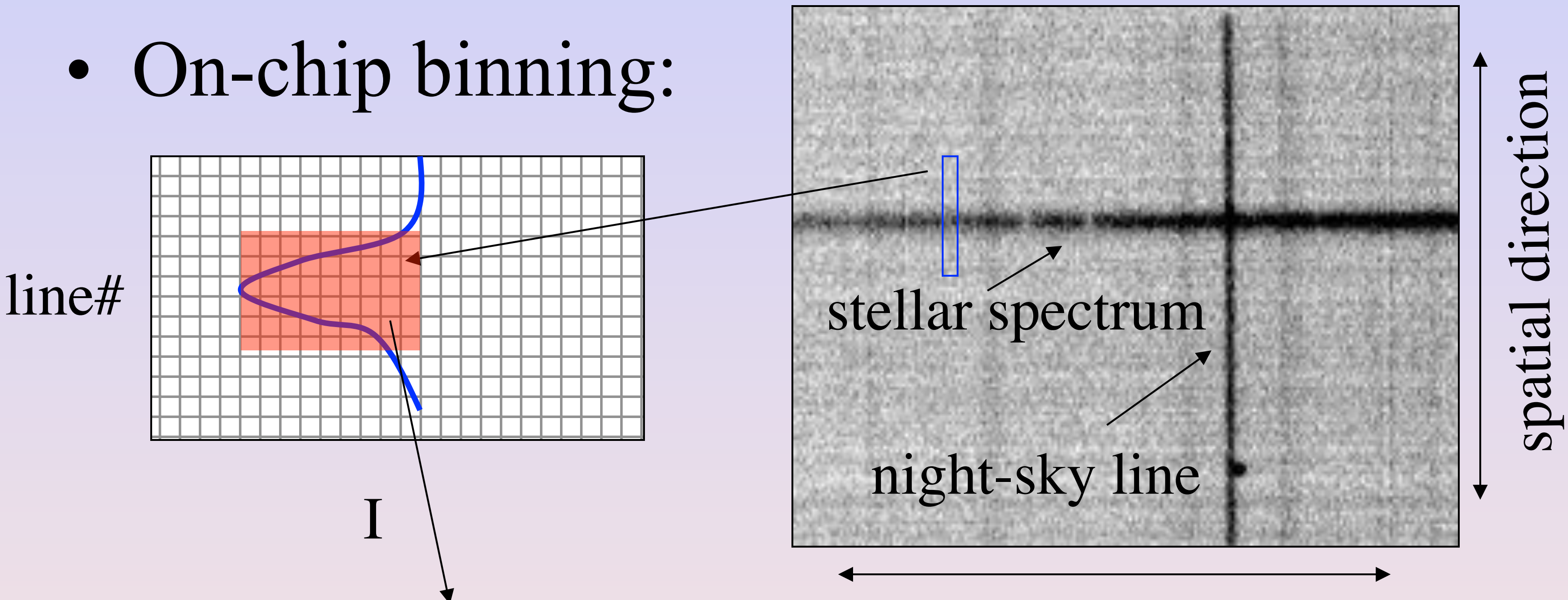
General Spectrometer

Observing Considerations

- On-chip binning
- S/N
- Order-blocking
- Atmospheric dispersion
- Resolution and slit-width

On-chip Binning

- On-chip binning:

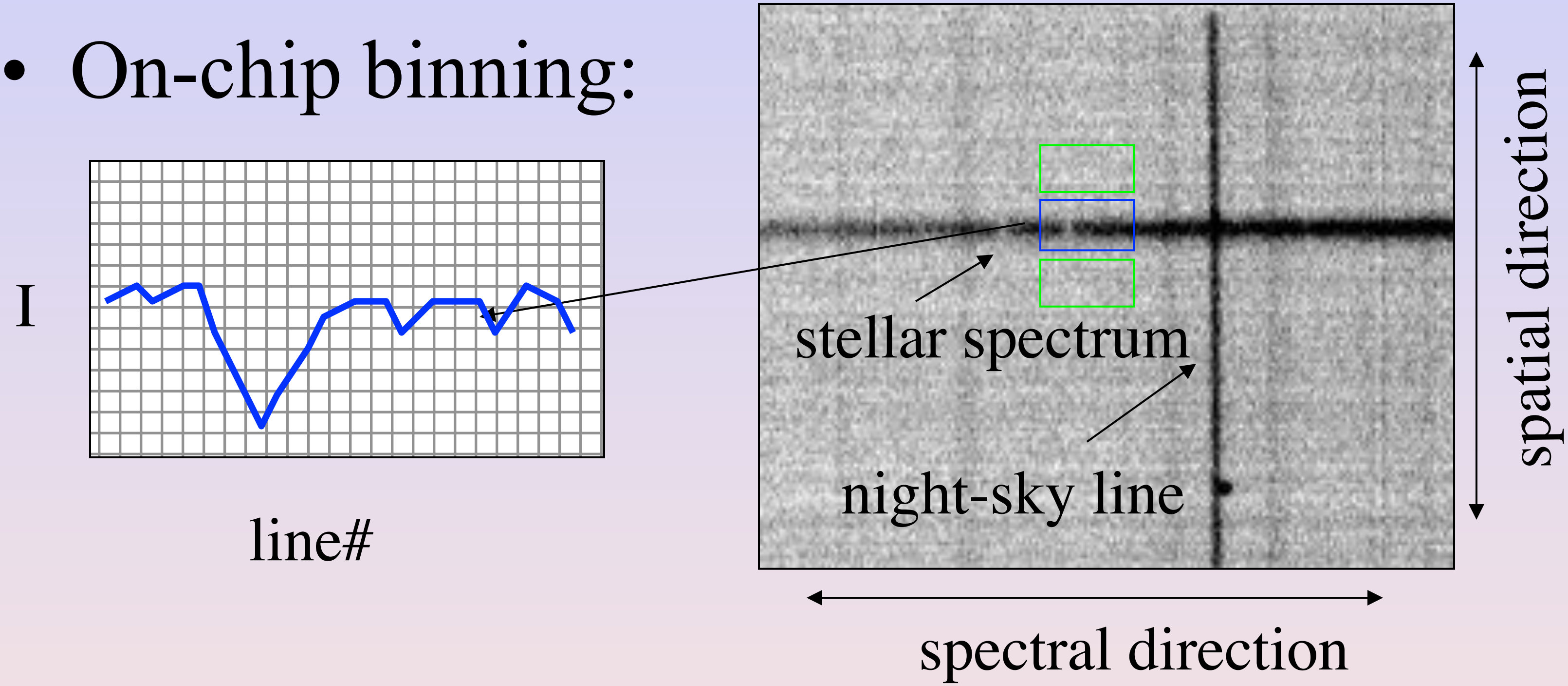


You are going to sum over these lines in the extraction anyway. On-chip binning will reduce RN x #pixels

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

S/N for Spectral Observations

- On-chip binning:



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

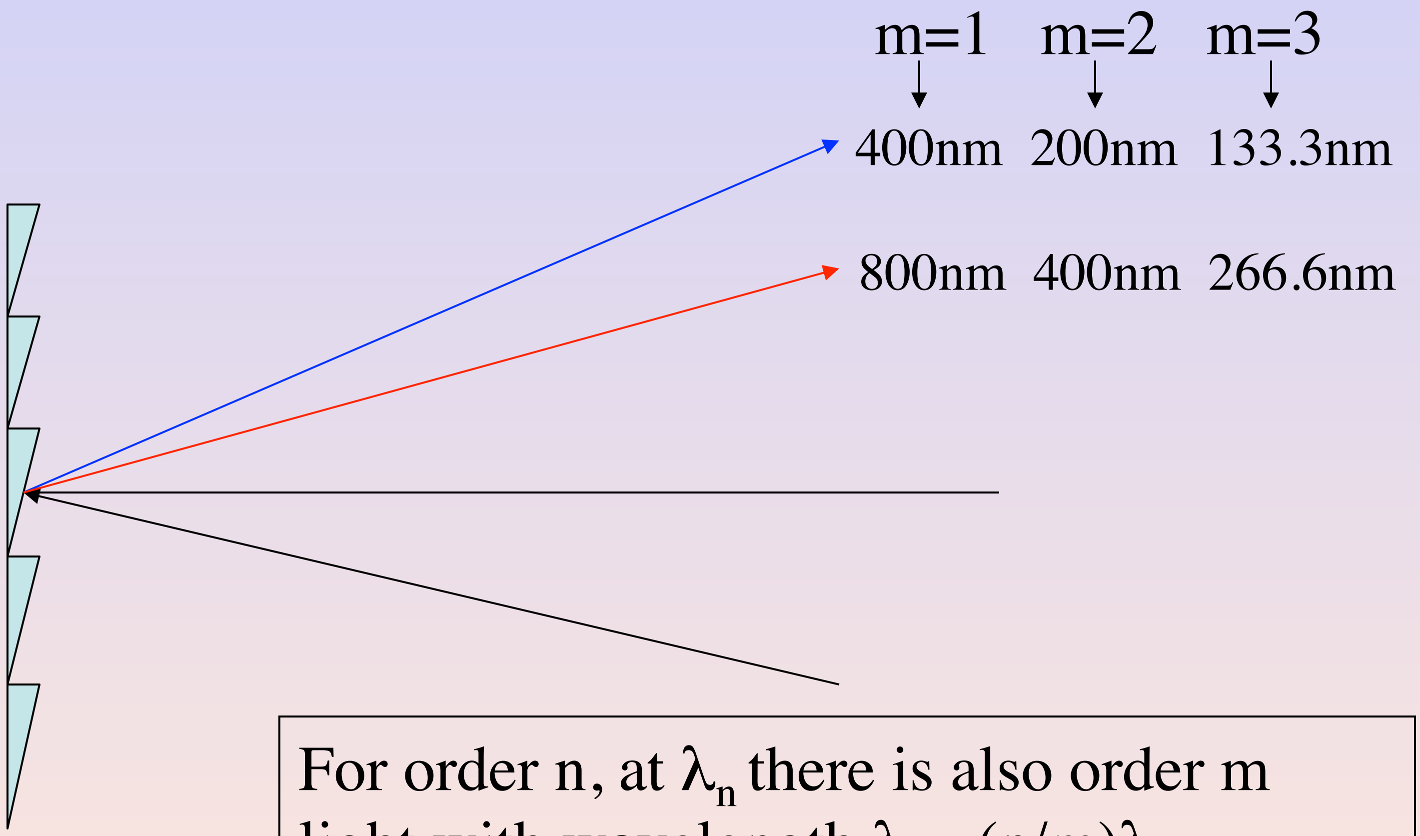
$$N_{\text{spectral pixel}} = \sum_{\text{lines}} \left[(R_{\text{object}} \times t) + (R_{\text{sky}} \times t) + RN^2 \right]^{\frac{1}{2}}$$

- In the *spectral direction,* binning can reduce spectral resolution. If the FWHM of arc-lamp lines ≥ 5 pixels, you can start to think about binning. *But* ...
- 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

- 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

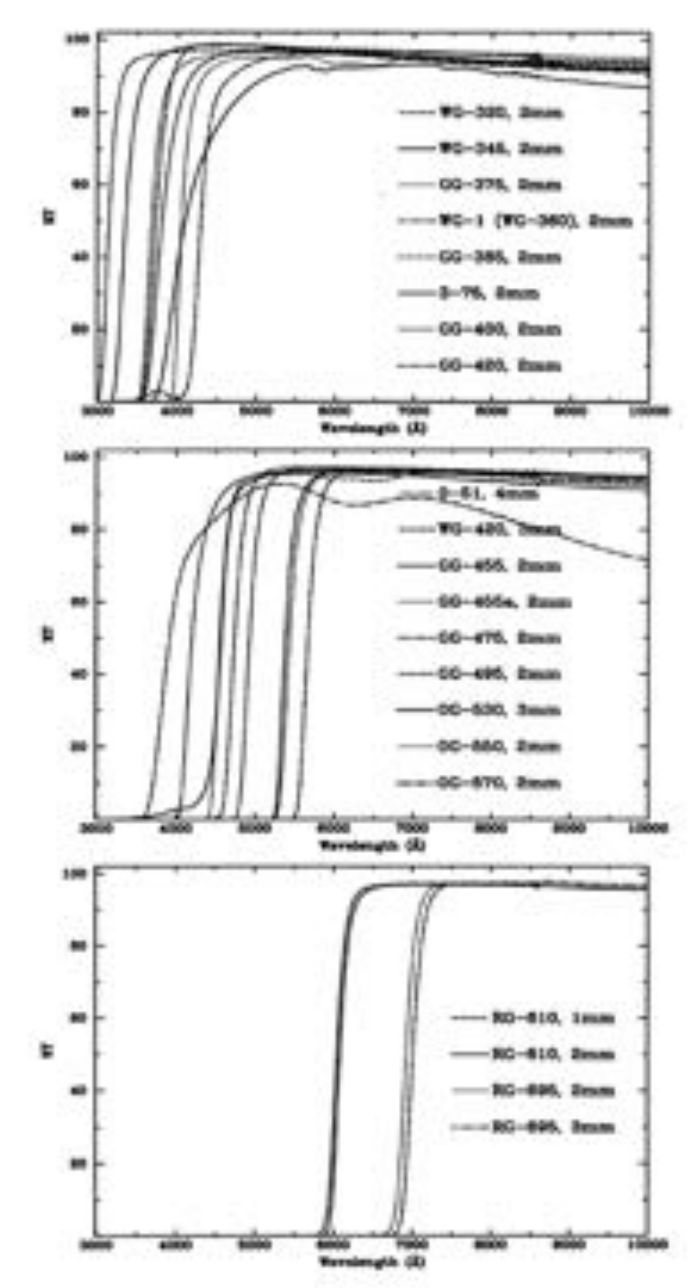
Orders and blocking filters



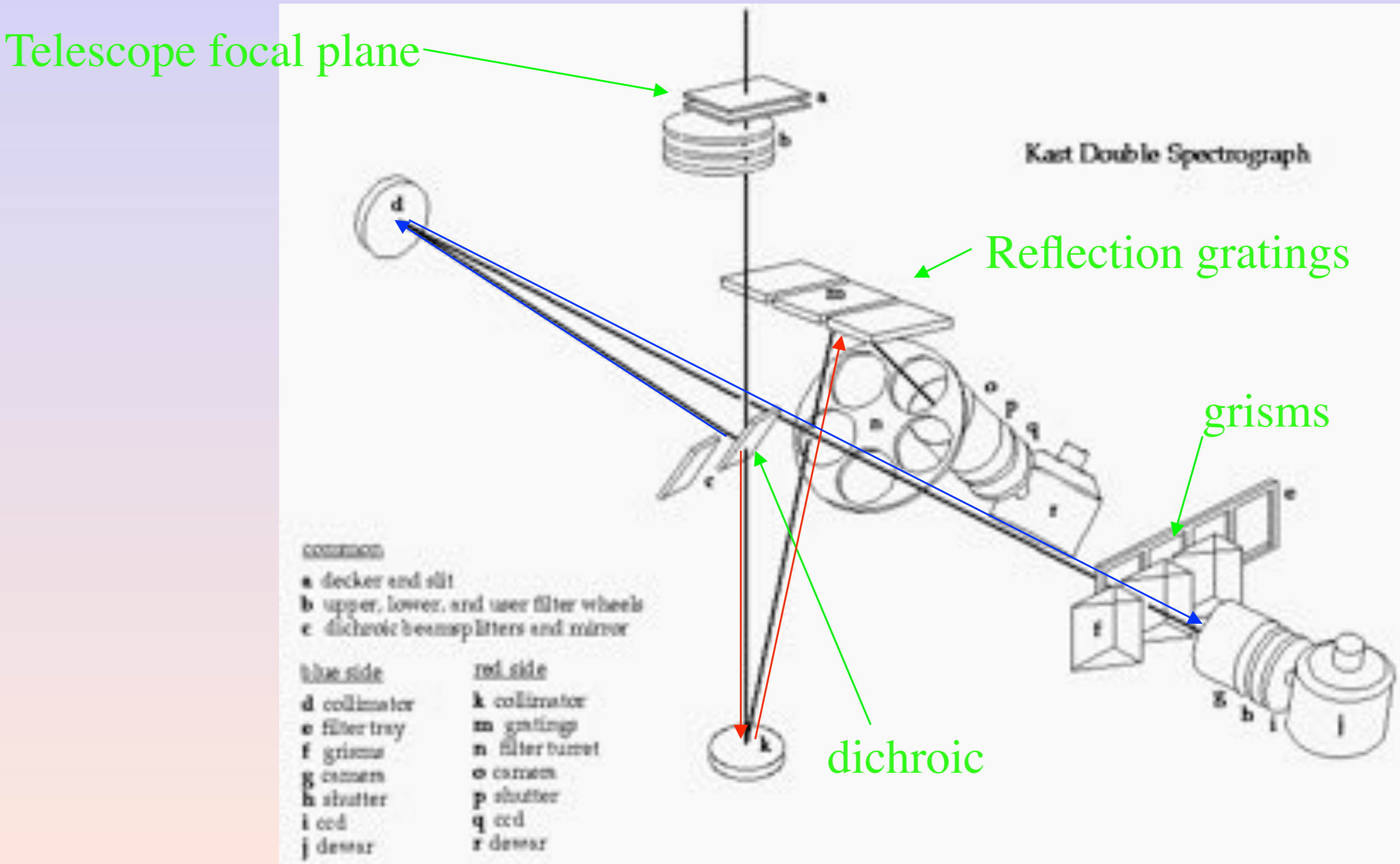
For order n, at λ_n there is also order m light with wavelength $\lambda_m=(n/m)\lambda_n$

- For higher orders with $\lambda<310$nm 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



Dichroics and Double Spectrometers



Spectral Resolution

- $R = \lambda / \Delta\lambda$
- For slit spectra, depends on slit width and grating choice.

What is the effective slit-width of a circular fiber?

What is the effective slit-width of a tilted slit?

LRIS (Keck Obs WWW page)

Typical information provided:

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

What order?

What else do you need to know in order to calculate resolution?

Spectral Resolution

- Examples:
  - V filter: 5500Å/1000Å = 5.5
  - LRIS-R: 1″ ~4 pixels FWHM
    - o 150 l/mm grating: $R \sim 6500/20 \sim 325$
    - o 600 l/mm grating: $R \sim 6500/5 \sim 1300$
    - o 1200 l/mm grating: $R \sim 6500/2.6 \sim 2600$

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 (transmission)^n where n is the number of surfaces in the collimator and camera elements (n can be pretty big).

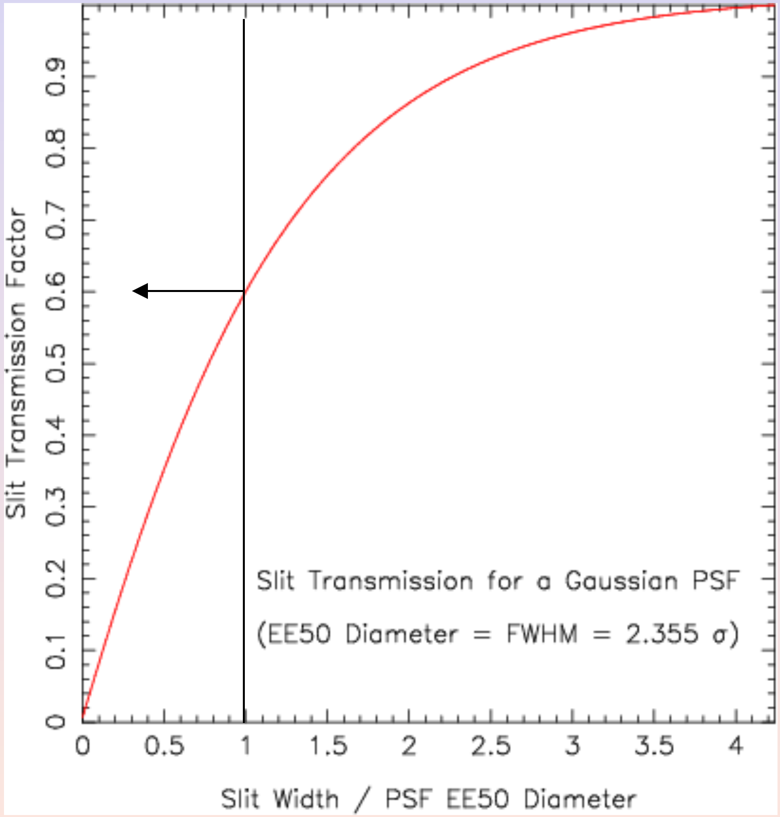
$$0.98^8 * 0.7 * 0.8 = 0.47$$

Camera/coll with 8 surfaces (often more) → 0.98^8; grating → 0.7; ccd → 0.8

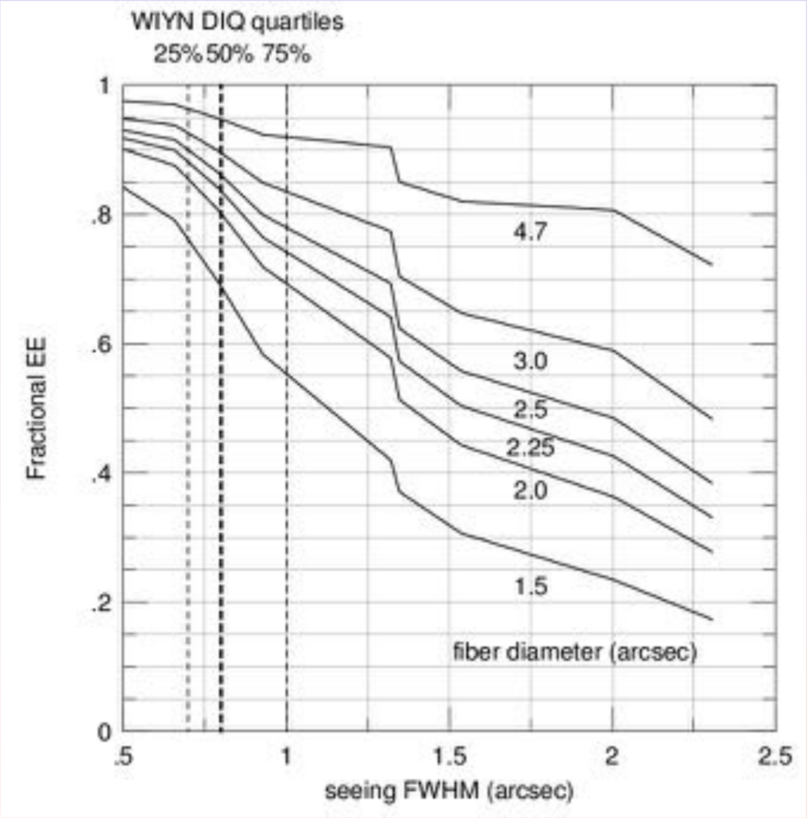
What's missing?

Slit Losses

Another throughput issue: slit losses can be very significant!



Applies to fibers too.



Other Losses

- Lens absorption (particularly in blue/NUV)
- Beam over-fill or blockage (vignetting)
- Fiber losses (transmission and surfaces)
- Slicer losses (optical surfaces)
- Telescope losses (mirrors)
- ADC losses
- Atmospheric absorption

Other???

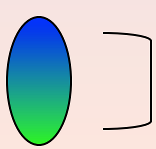
Atmospheric dispersion

- 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.

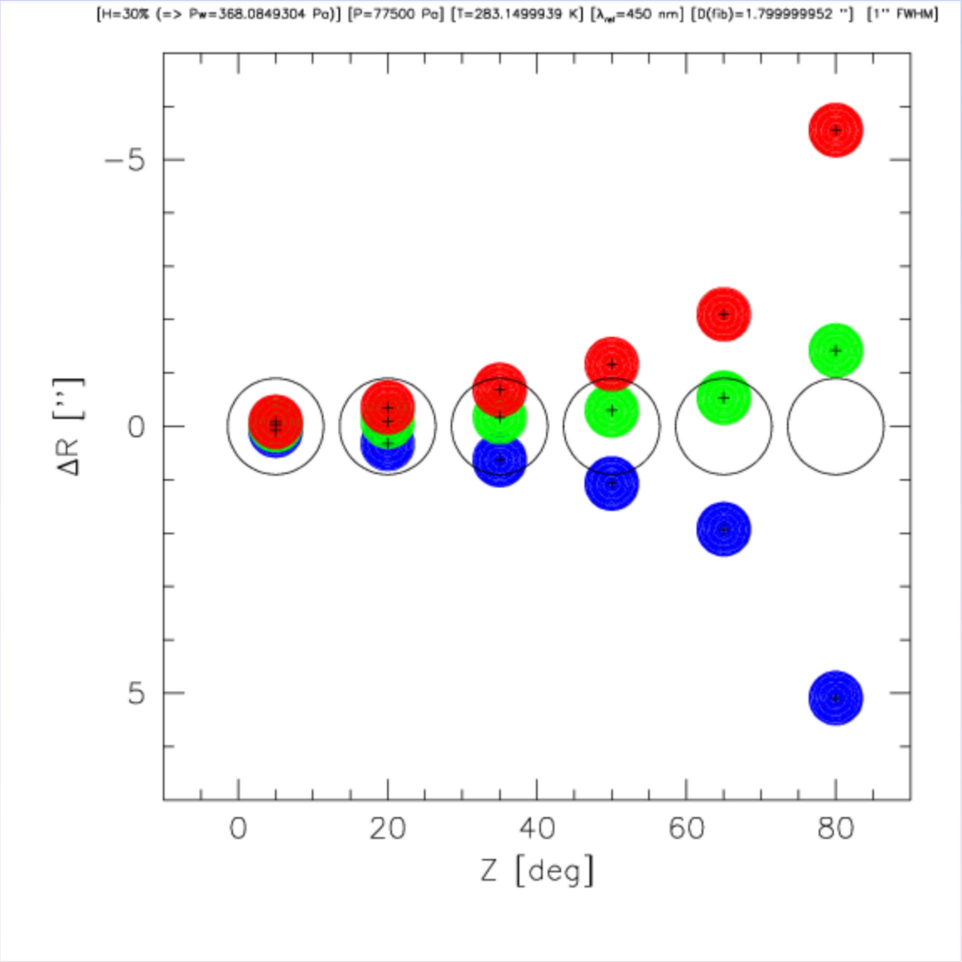
index of refraction

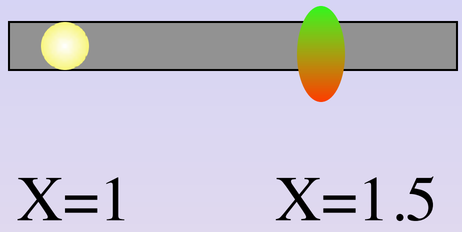
$$\Delta\theta = 206265 \times \left[(n_{\lambda 1} - 1) - (n_{\lambda 2} - 1)\right] \times \tan(ZD)$$

zenith distance



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

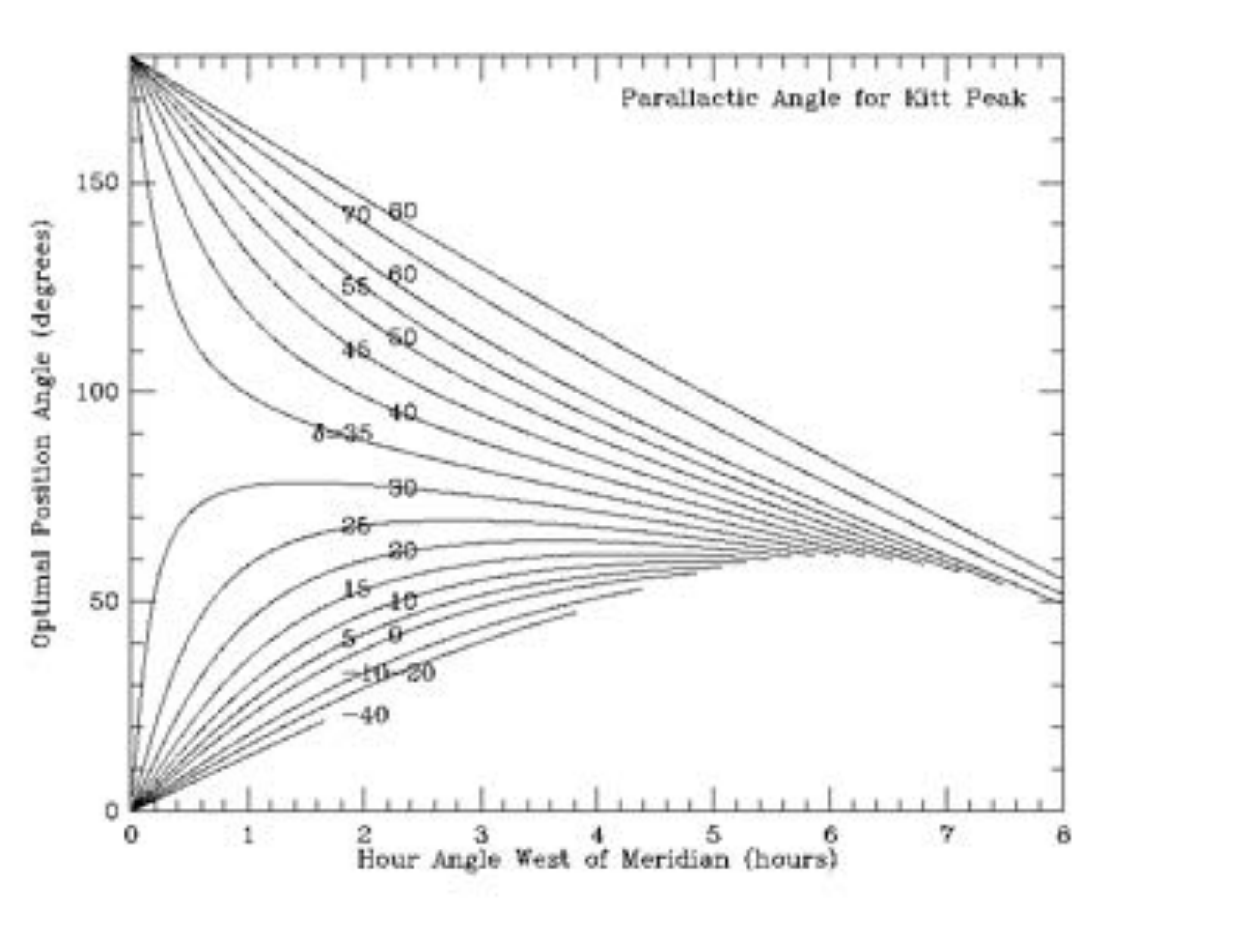


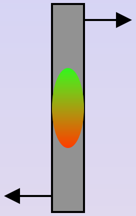


Two problems:
1) Preferentially lose red (or blue) light out of the slit.

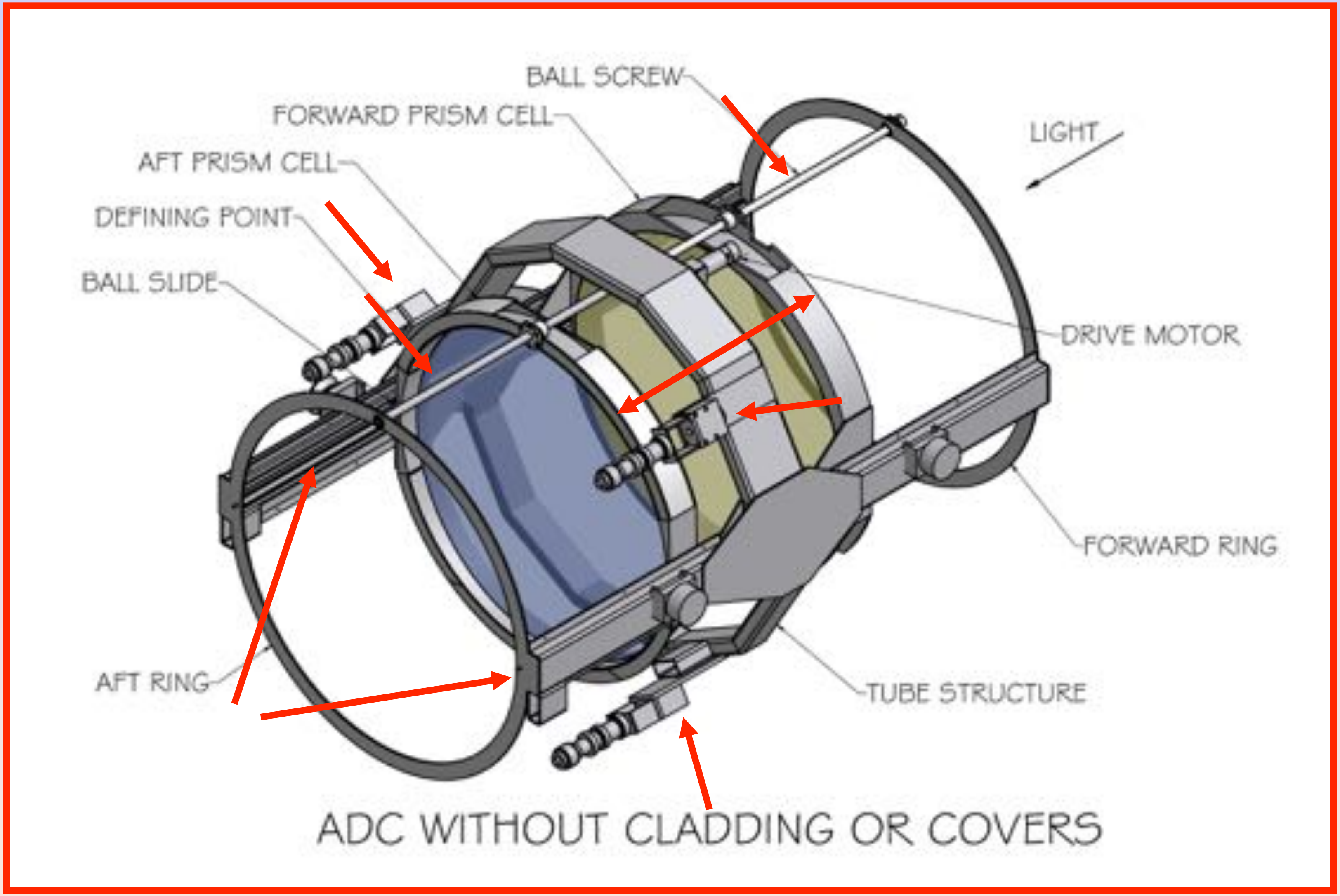
2) If guiding on a particular wavelength of light, the object at other wavelengths will move out of the slit.

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

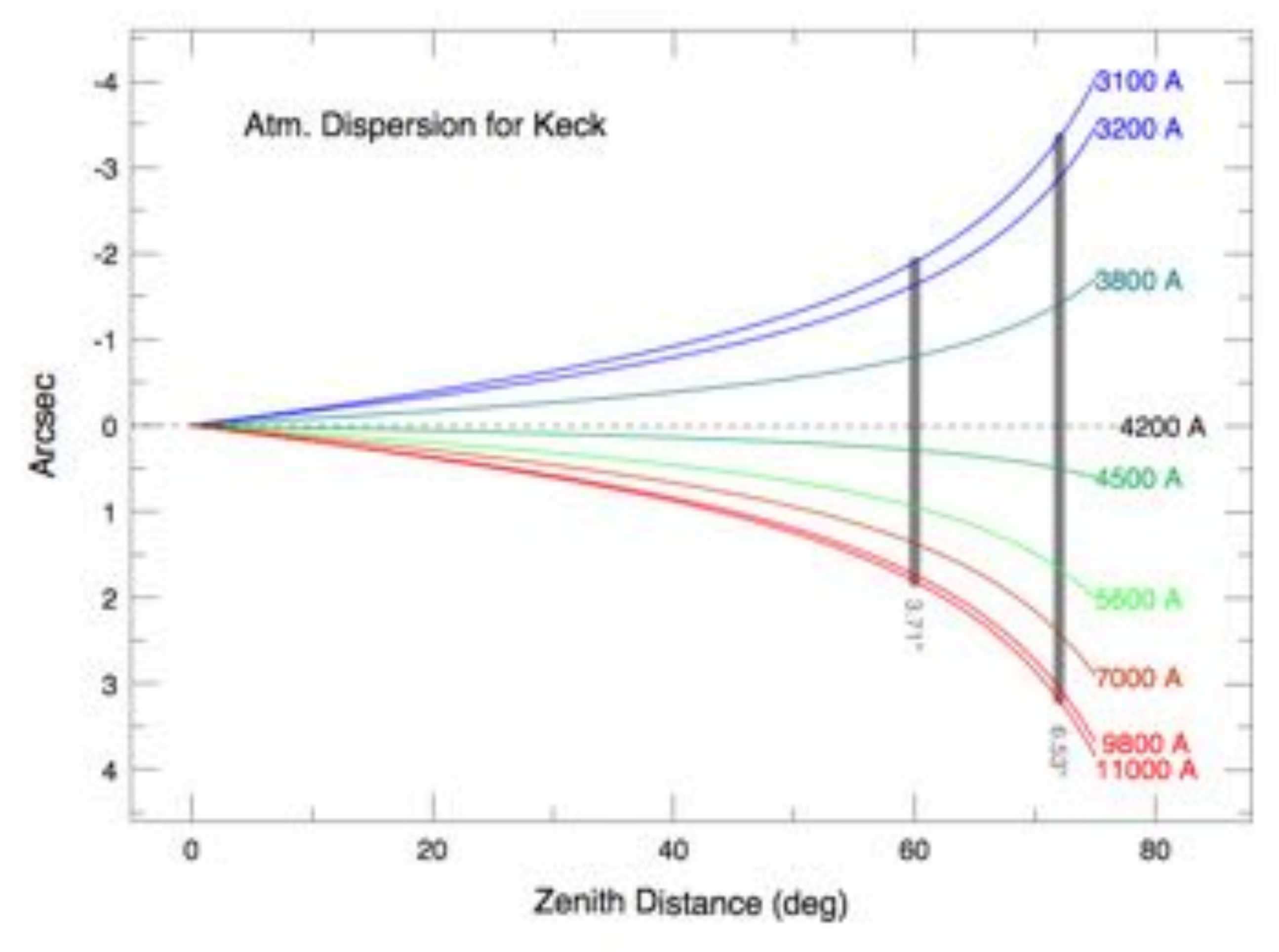




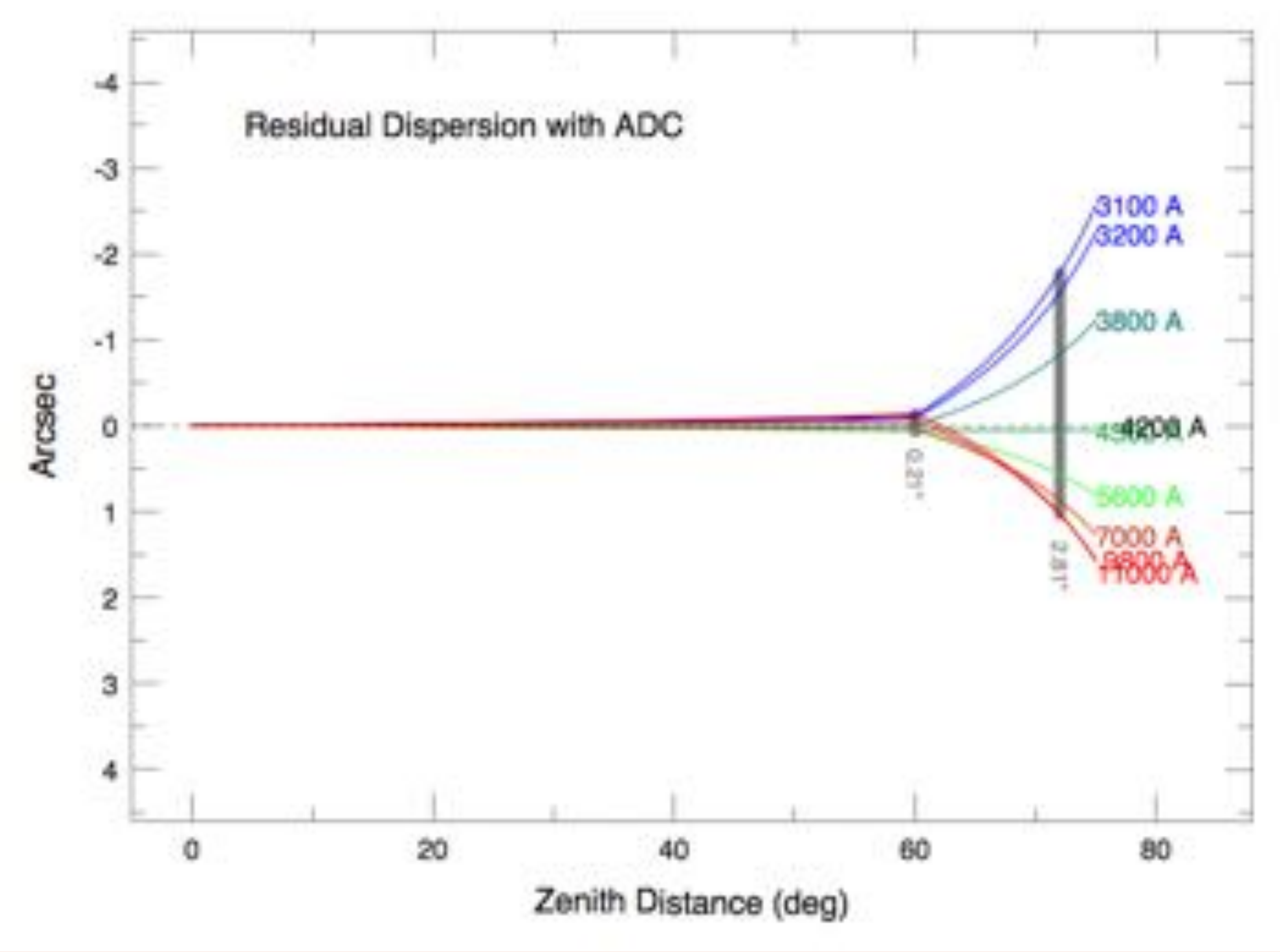
Build an ADC


BALL SCREW
FORWARD PRISM CELL
AFT PRISM CELL
DEFINING POINT
BALL SLIDE
LIGHT
DRIVE MOTOR
FORWARD RING
AFT RING
TUBE STRUCTURE
ADC WITHOUT CLADDING OR COVERS

Uncorrected



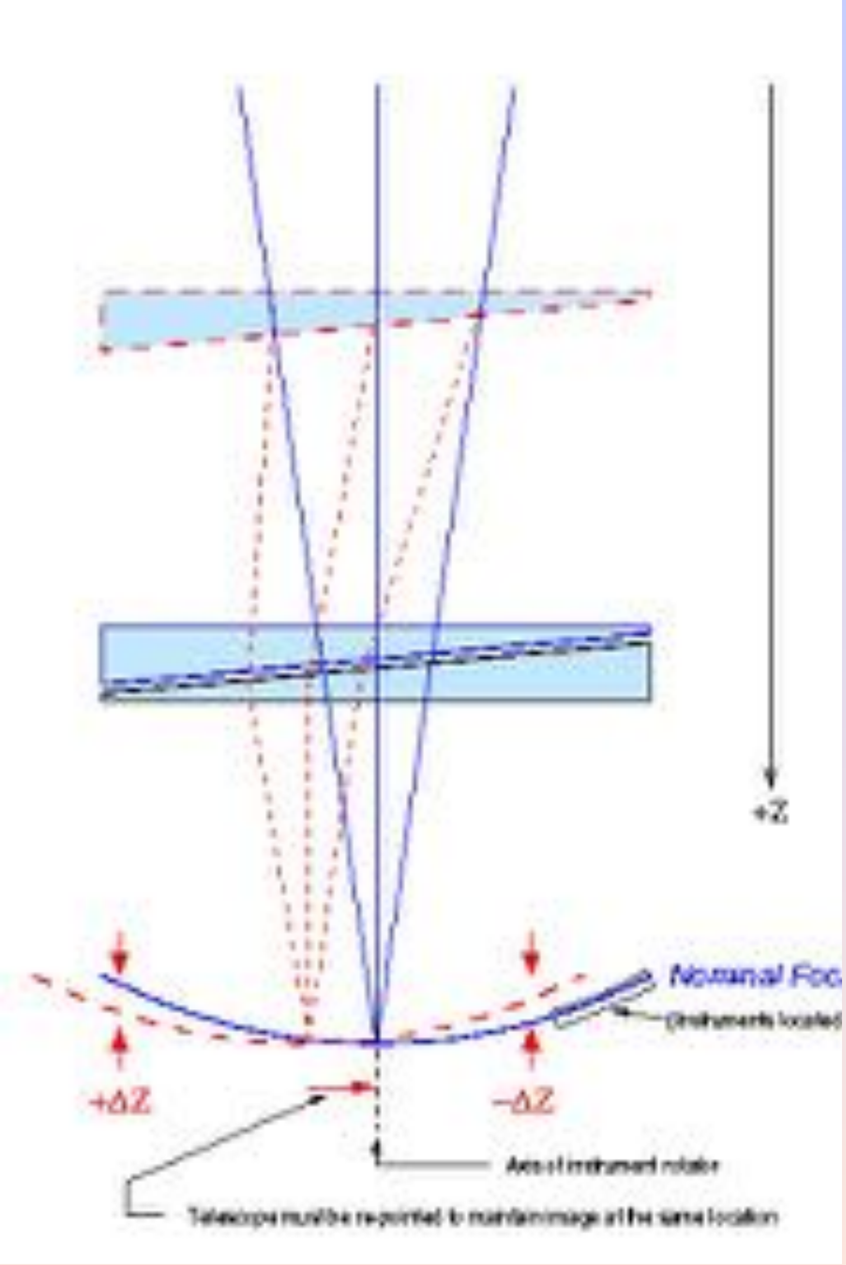
Corrected with ADC

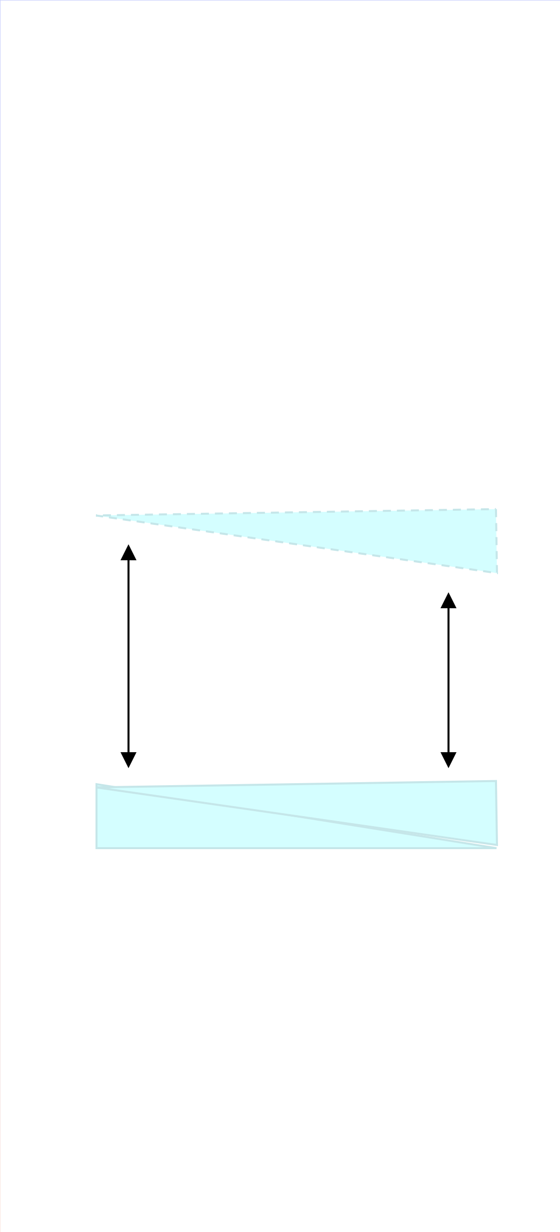


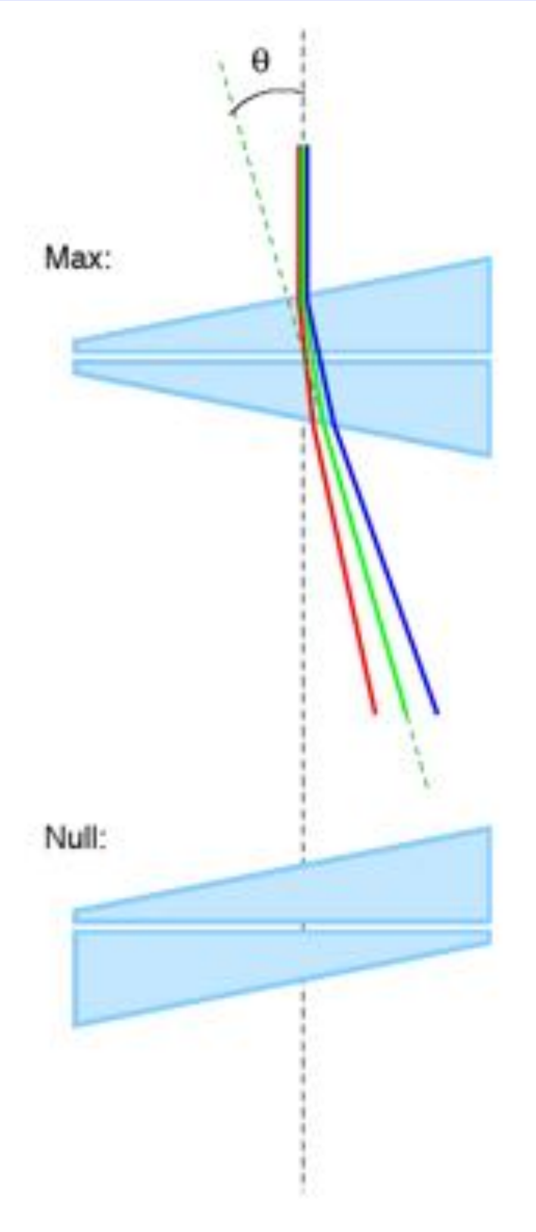
Linear ADC

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



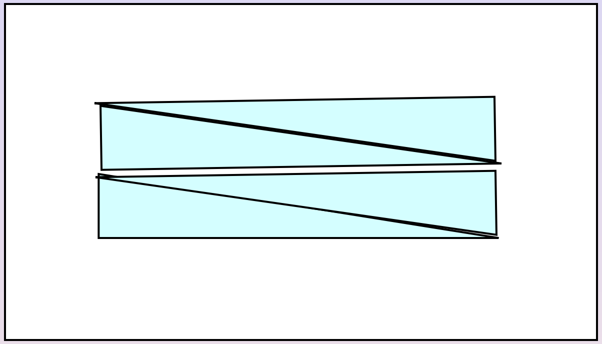


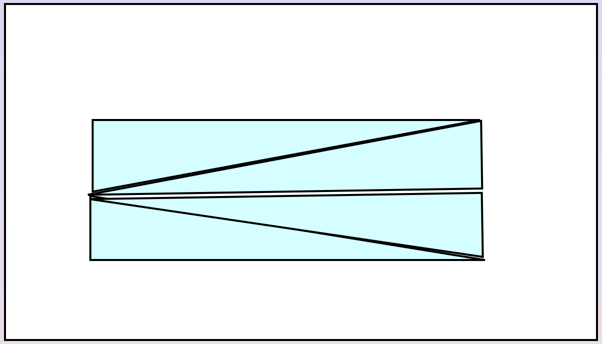

θ
Max:
Null:

Risely and Amici style ADC's

Maximum dispersion

Zero dispersion

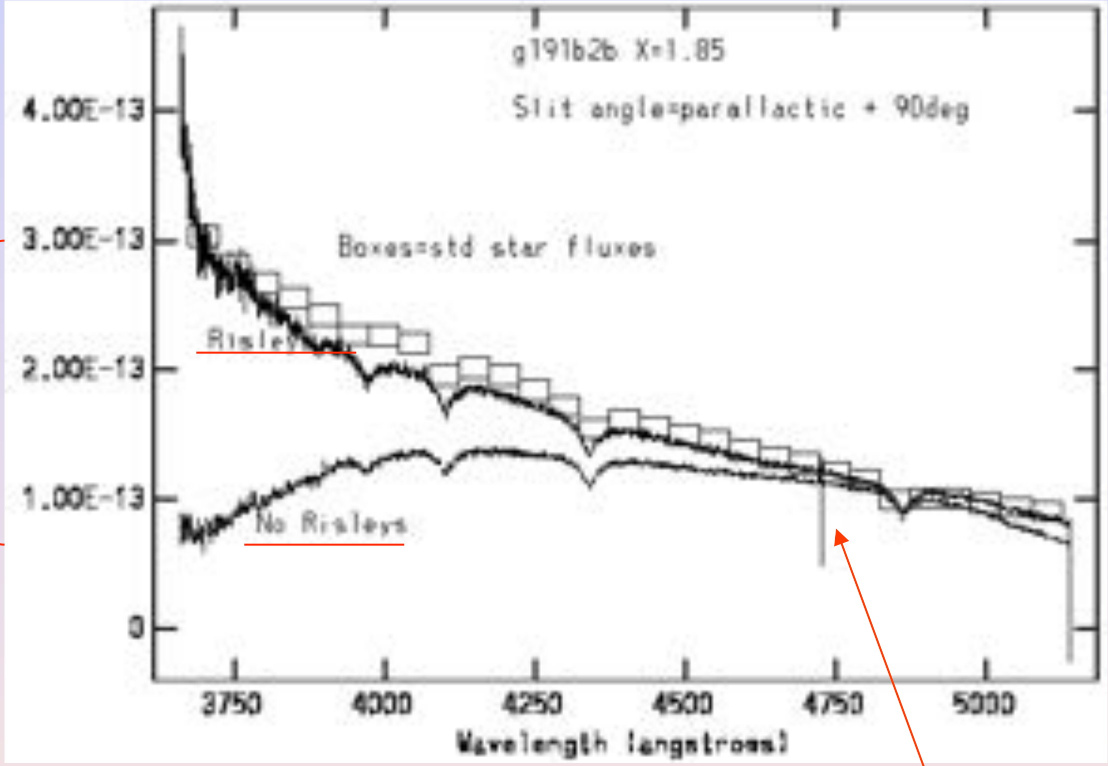




Pairs rotate depending on ZD

What's needed for SALT?

Factor of 3+



KPNO 4m rotating `Risley' prisms.

Central guider wavelength