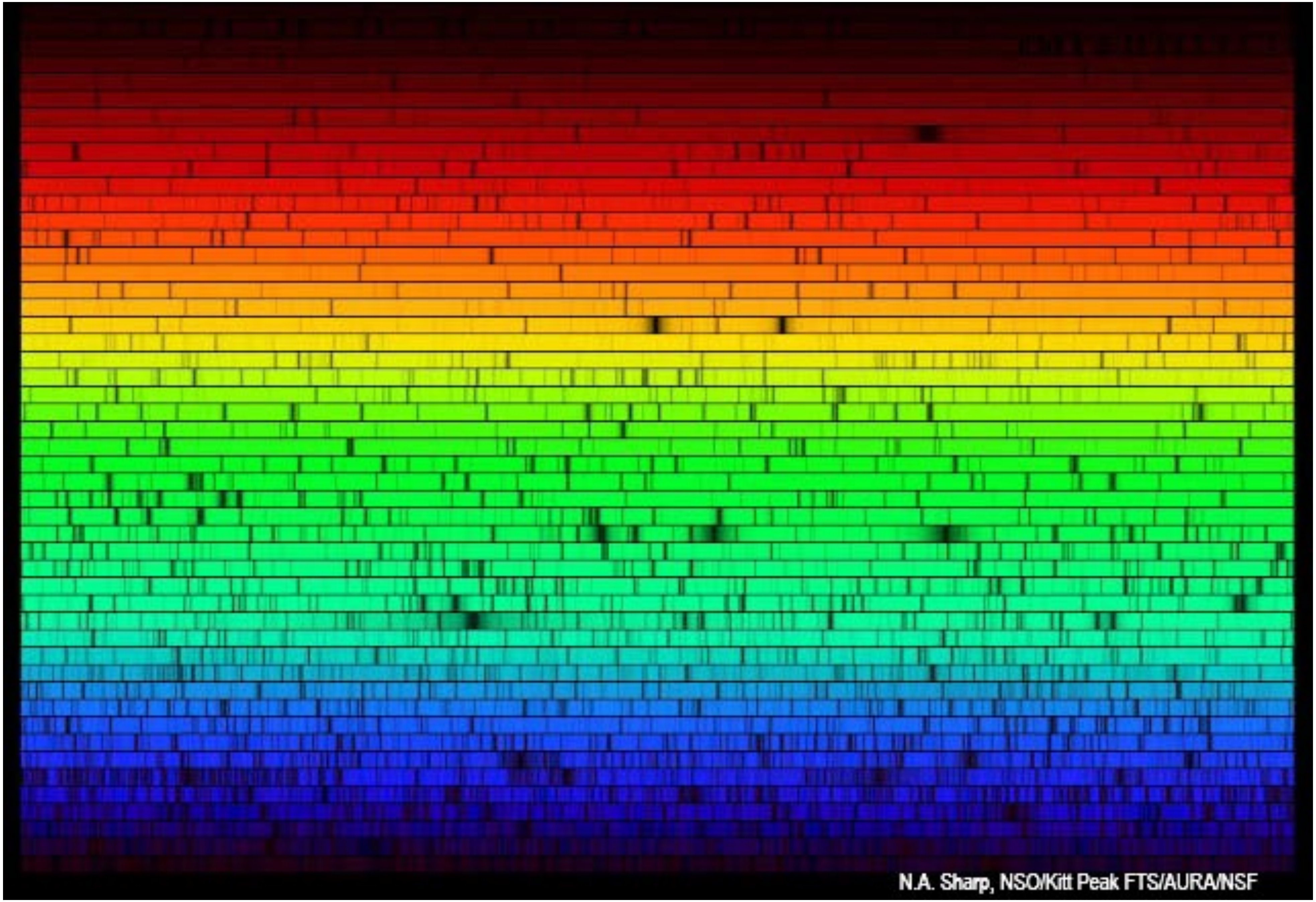
Spectrographs Part 1

ATI 2014 Lecture 10

Kenworthy and Keller

The Solar Spectrum



Design drivers for spectrographs

What spectral resolution do you need?

Spectral resolution $R = \frac{\lambda}{\Delta\lambda}$

What bandwidth (wavelength range) do you need?

Spectrograph is sensitive from λ_{blue} **to** λ_{red}

Maximising throughput for best efficiency

Etendue, limiting magnitude, throughput, multiplexing

Science drivers for spectrographs

R

10^1 Spectral typing of stars

10^2 Rotation curves of galaxies

10^3 RV of stars in globular clusters

10^4 Chemical abundances of stars

Radial Velocity exoplanets

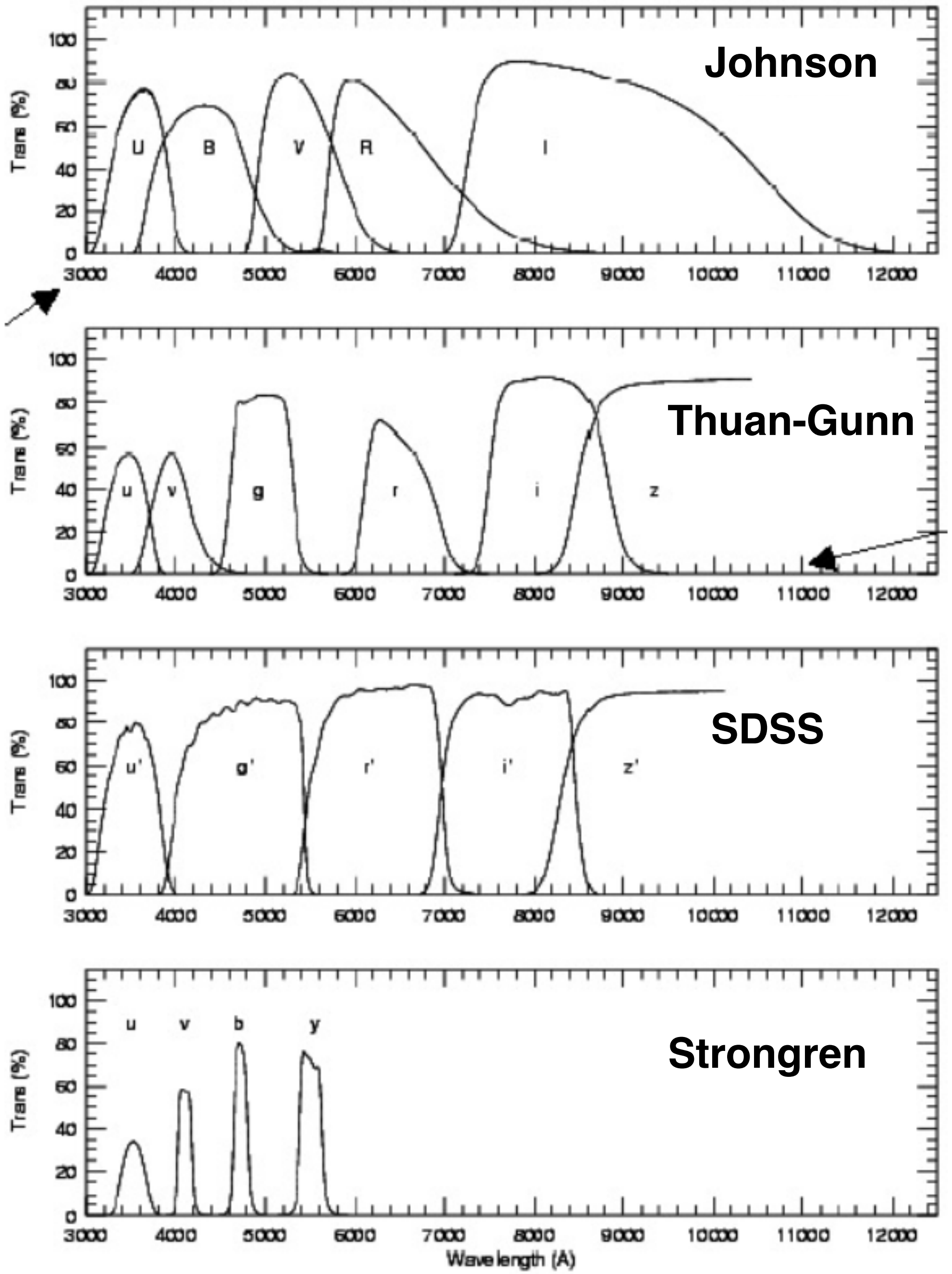
10^5

ISM studies

Isotope abundances

10^6 exoplanet rotation curves

Basic spectroscopy: colour filters



Take multiple images with different bandpass filters

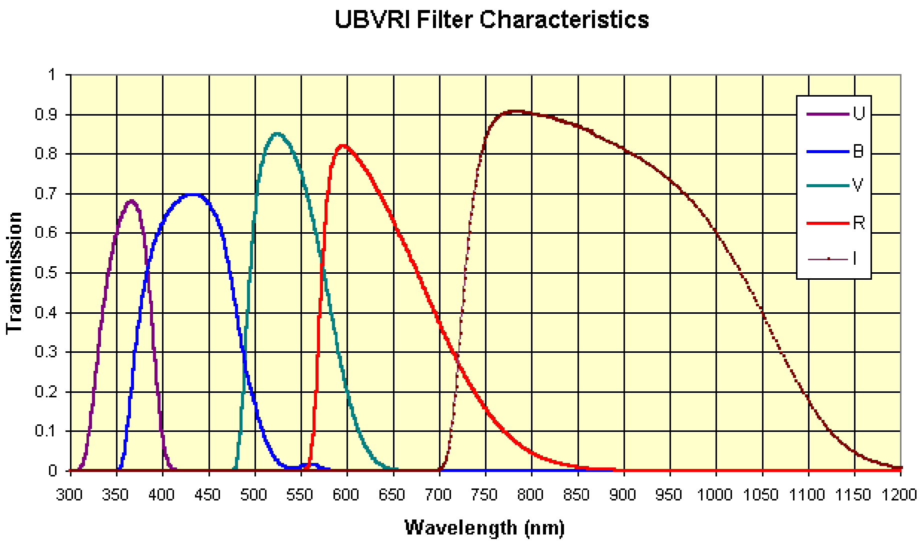
Johnson system designed to measure properties of stars

Thuan-Gunn filters for faint galaxy observations

Stromgren has better sensitivity to stellar properties (metallicity, temperature, surface gravity)

Sloan Digital Sky Survey (SDSS) for faint galaxy classification

Basic spectroscopy: colour filters



www.sbig.com/products/filters.htm

VRIJKLMNQ by Johnson (1960)

UBV by Johnson and Morgan (1953)

Classifying stars with photomultipliers

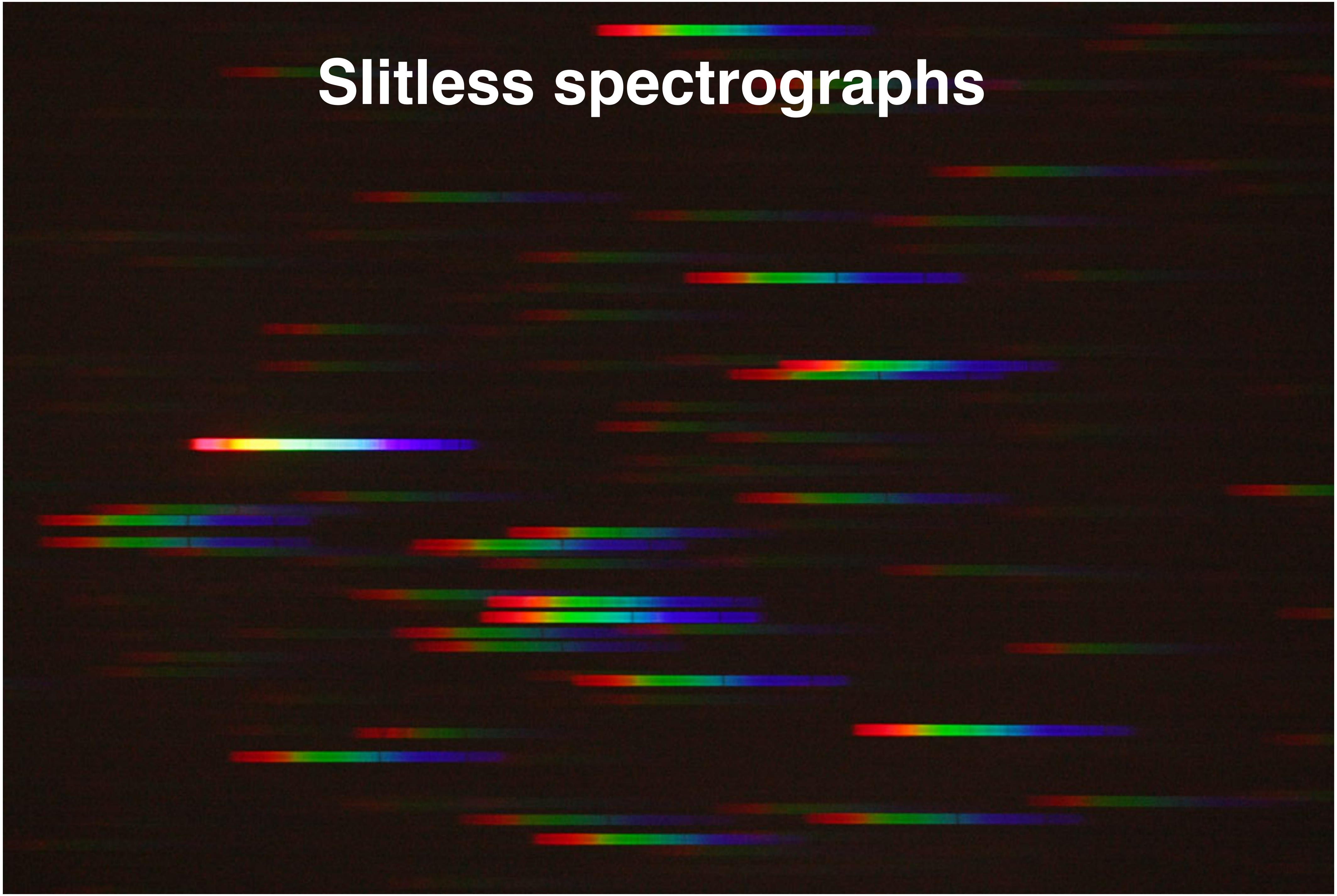
Zero points of (B-V) and (U-B) color indices defined to be zero for A0 V stars

Slitless spectrographs

Put a dispersing element in front of the telescope aperture

http://www.lpl.arizona.edu/~rhill/

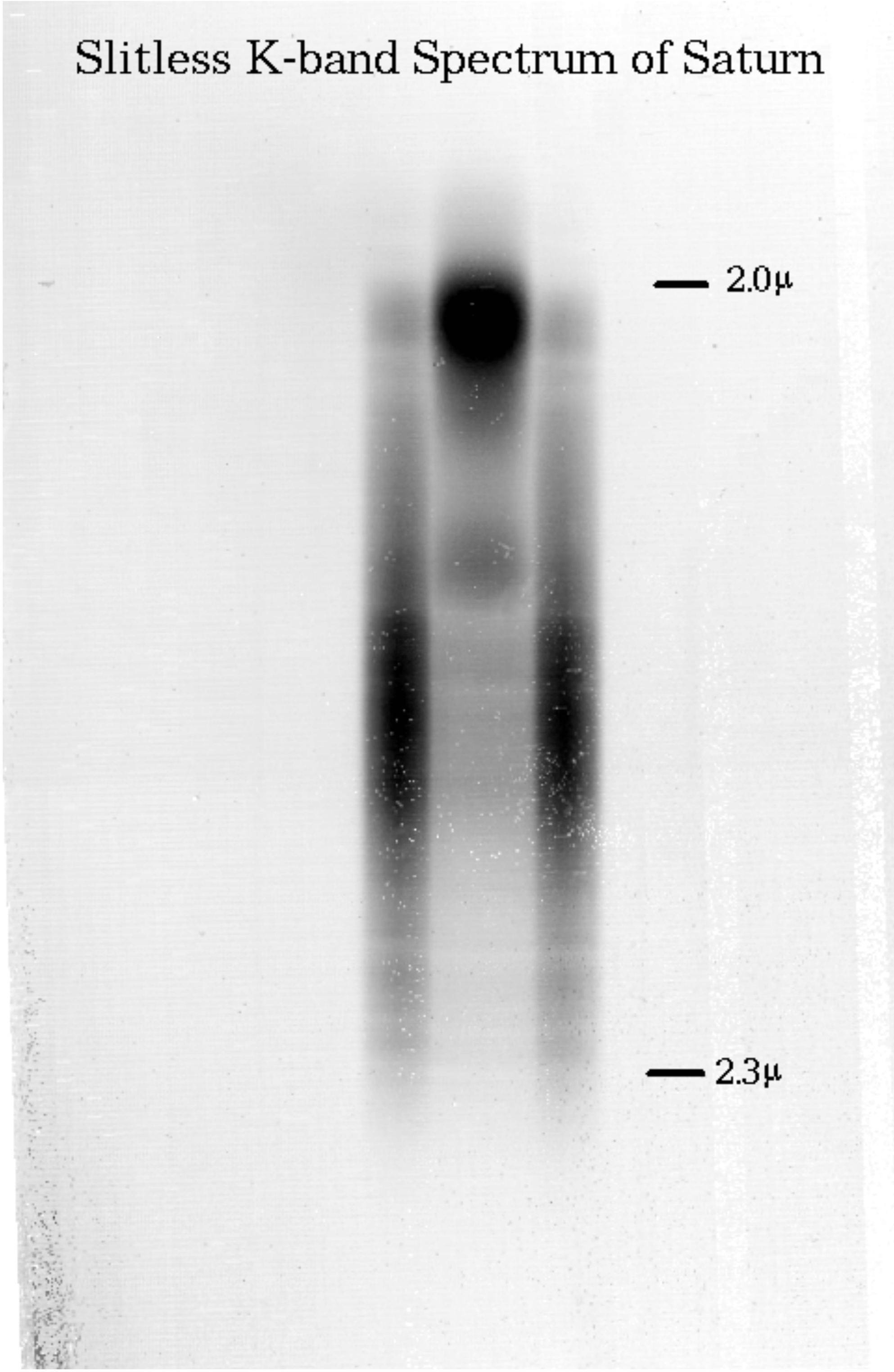
Slitless spectrographs



http://theketelsens.blogspot.nl/2011/01/seeing-light.html

Slitless spectrographs

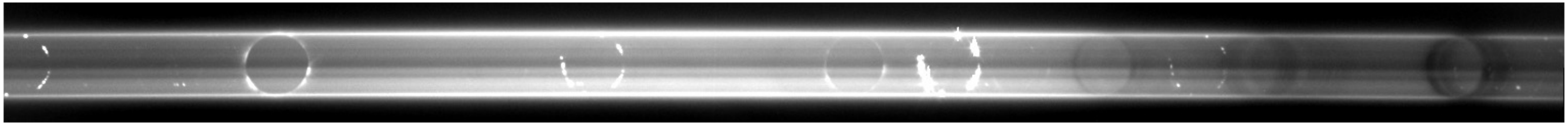
Dispersed



R. Pogge (OSU) with NOAO 2.1m Telescope

Slitless spectrographs

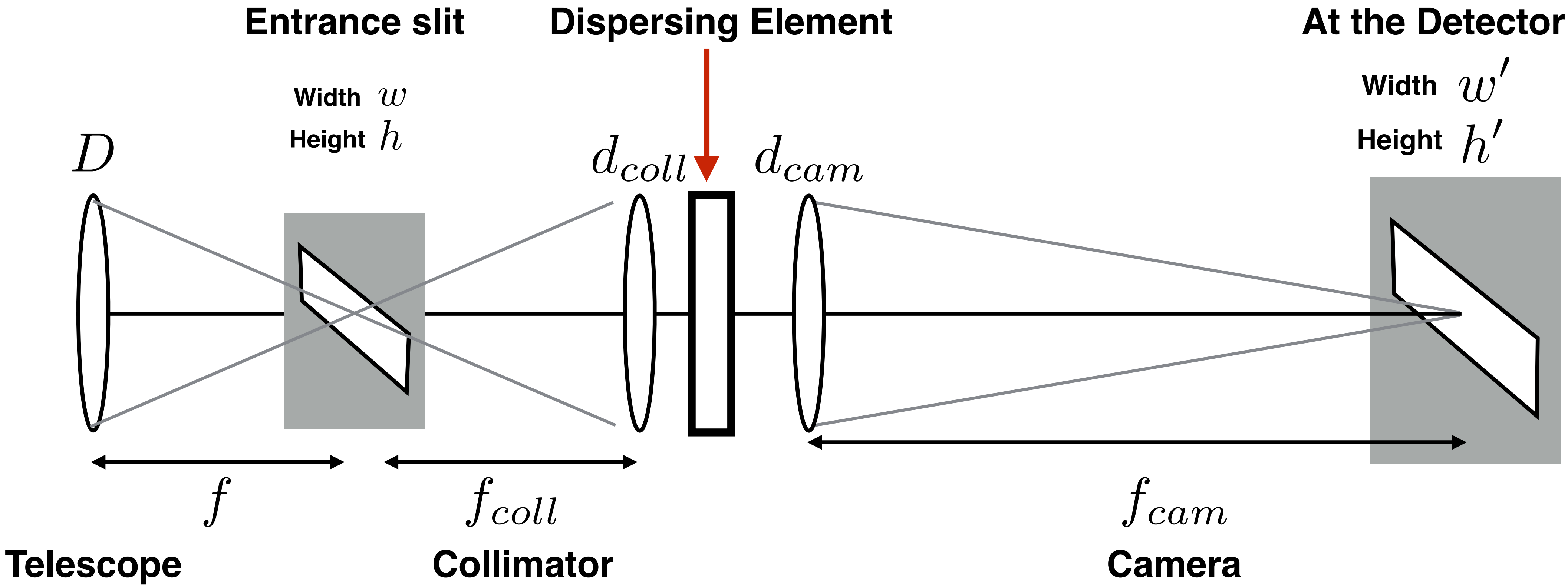
The solar corona
(solar disk is blocked by a coronagraph)



Wavelength

http://www.astro.virginia.edu/class/majewski/astr313/lectures/spectroscopy/spectrographs.html

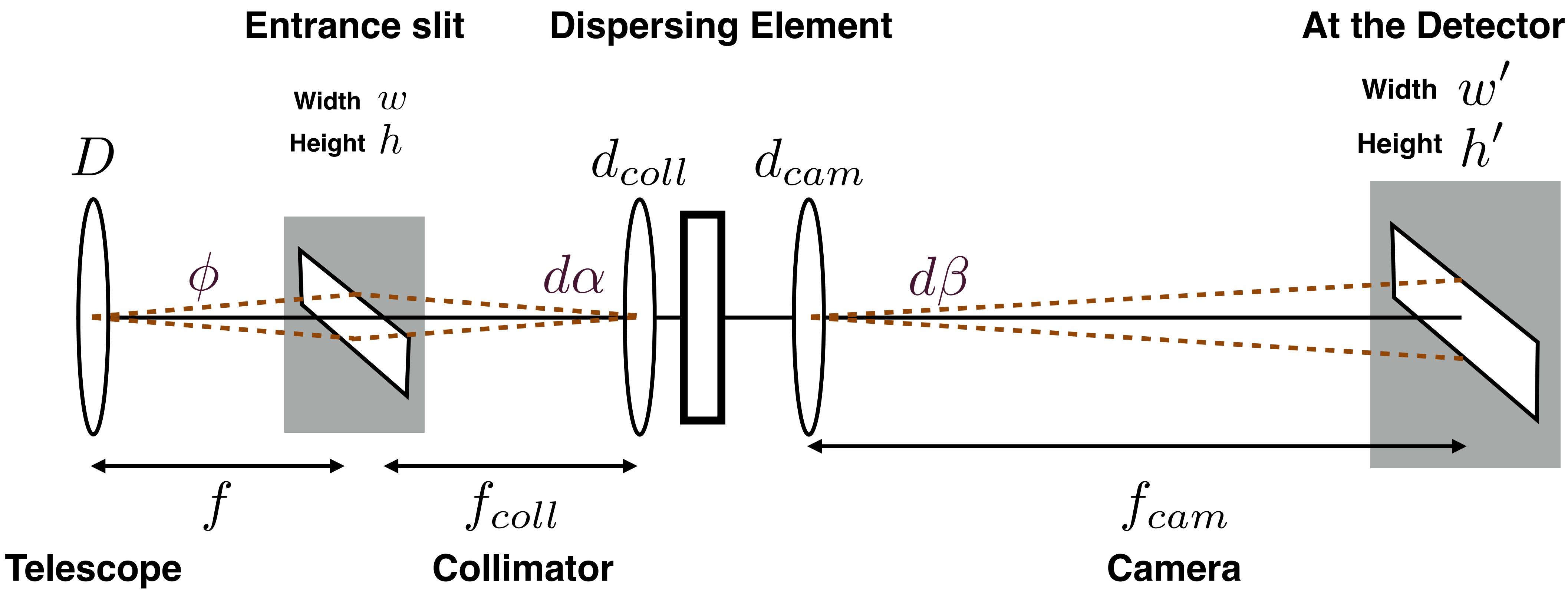
Layout of a spectrograph



$$f/D = f_{coll}/d_{coll}$$

IMPORTANT! d_{coll} **and** d_{cam} **may not be the same!**

Layout of a spectrograph



Anamorphic magnification

Resolution Element

The resolution element is the minimum resolution of the spectrograph. This will depend of the spectral size of the image, which is a factor of image size, spectral magnification and the linear dispersion

Typically the central wavelength

$$R = \frac{\lambda}{\Delta\lambda}$$

Resolution element

Resolution Element

The resolution element is the minimum resolution of the spectrograph. This will depend of the spectral size of the image, which is a factor of image size, spectral magnification and the linear dispersion

$$\Delta\lambda = w' \frac{d\lambda}{dl}$$

Slitwidth in mm corrected for anamorphic magnification and spectral magnification

Linear dispersion measured in $\mathrm{\AA/mm}$.

The Slit

We cannot record three dimensions of data (x,y, wavelength) onto a two dimensional detector, so we need to choose how we fill up our detector area:

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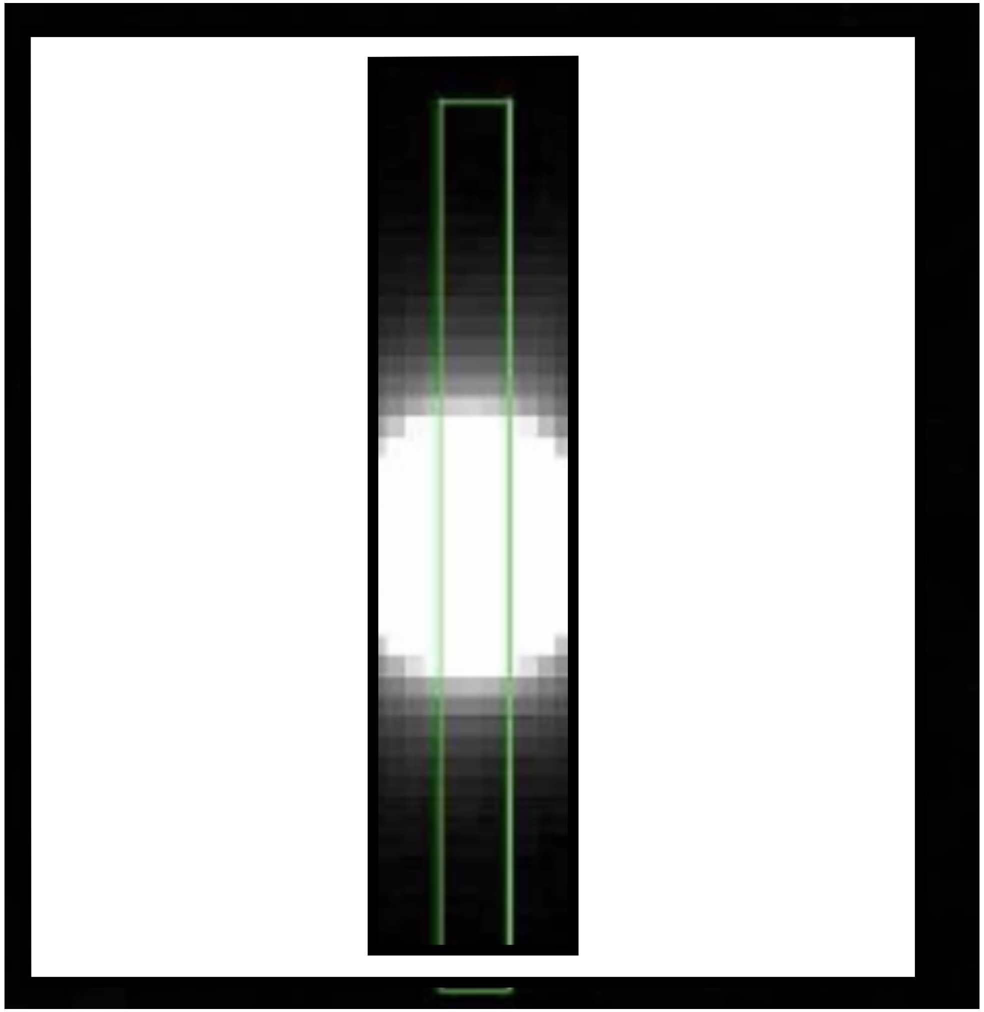
Setting the slit width

For a seeing limited object, such as a star, varying the slit width is a balance between spectral resolution and throughput

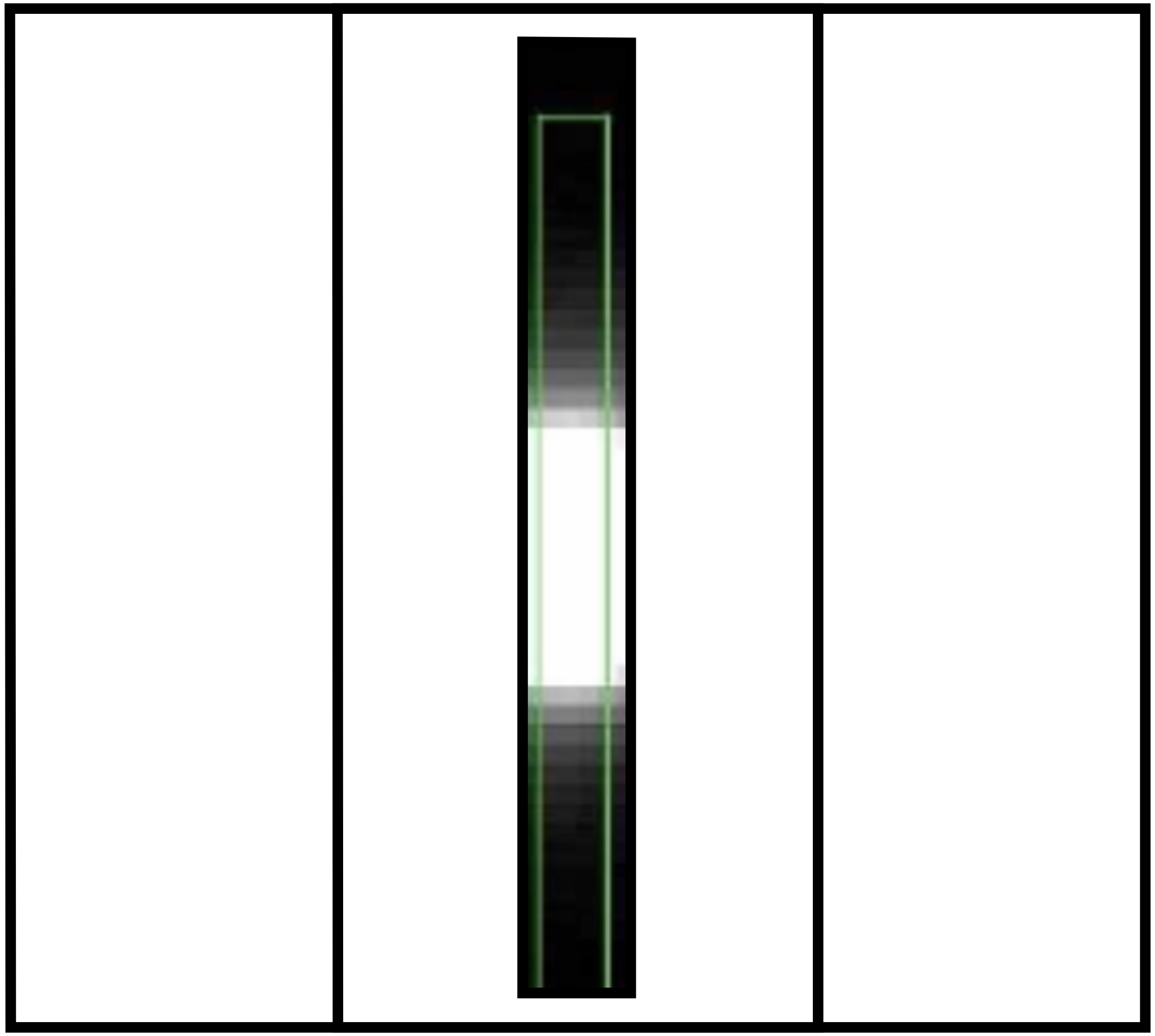


Slit too wide, spectral resolution goes down

Slit too narrow, flux from seeing limited object is lost

Setting the slit width

For a seeing limited object, such as a star, varying the slit width is a balance between spectral resolution and throughput



Slit too wide, spectral resolution goes down

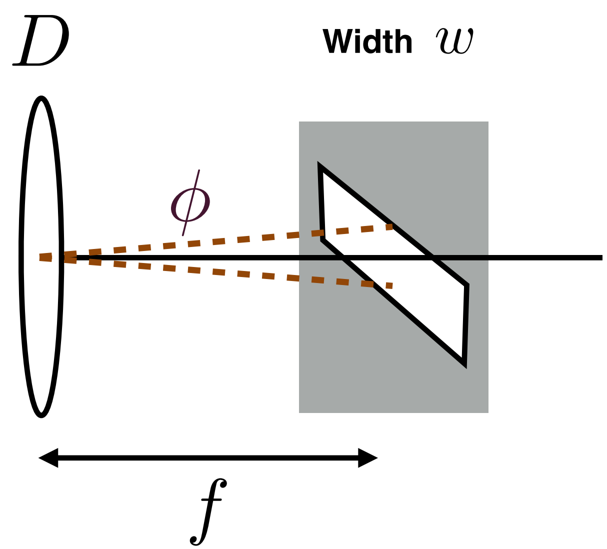
Slit too narrow, flux from seeing limited object is lost

The Slit

Spectrographic slits are given in terms of their angular size on the sky, either in arc seconds or in radians.

$$\phi = w/f$$

where f is the focal length of the telescope and w is the size of the slit in mm. The angle ϕ is given in radians.



Two types of magnification

Anamorphic magnification arises because the diffracting element may send light off at a large angle from the camera normal, and is defined as r.

$$r = \frac{d_{coll}}{d_{cam}} = \frac{d\beta}{d\alpha}$$

$$w' = rw\frac{f_{cam}}{f_{coll}}$$

Spatial (de)magnification occurs because of the different focal lengths of the camera and collimator so that detector pixels are Nyquist sampled

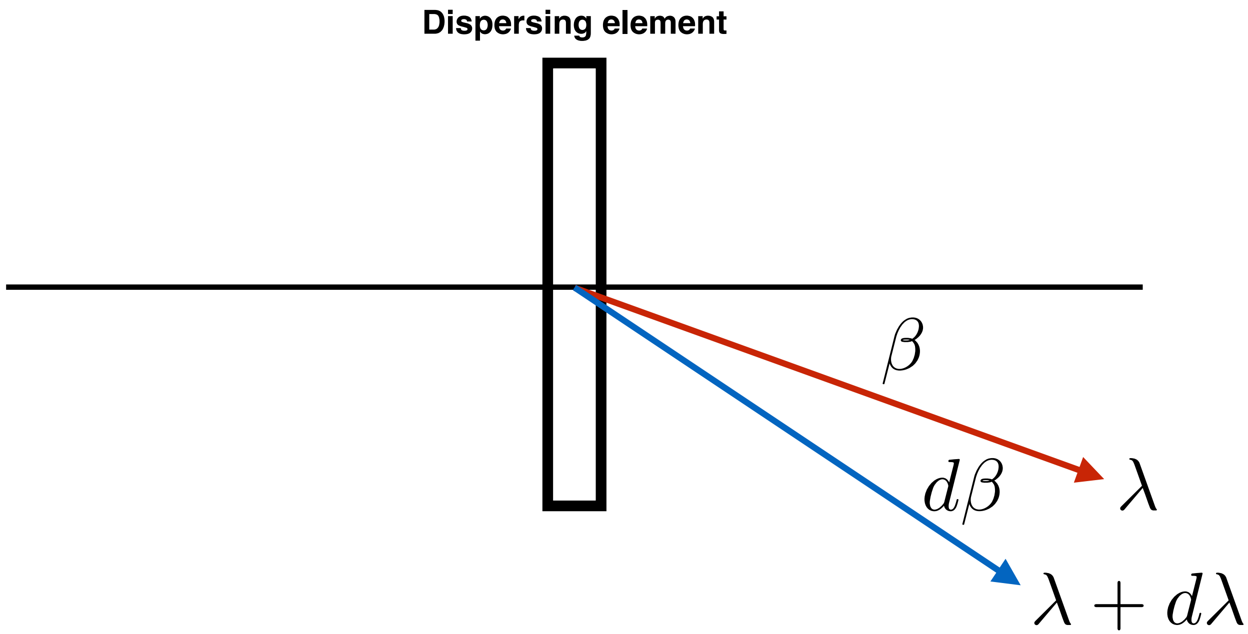
Two types of magnification

The size of the slit that the detector sees for the slit is therefore given by:

$$w' = rw\frac{f_{cam}}{f_{coll}} = r\phi f\frac{f_{cam}}{f_{coll}}$$

Definition of Dispersion

The angular dispersion is given by: $$A = \frac{d\beta}{d\lambda}$$

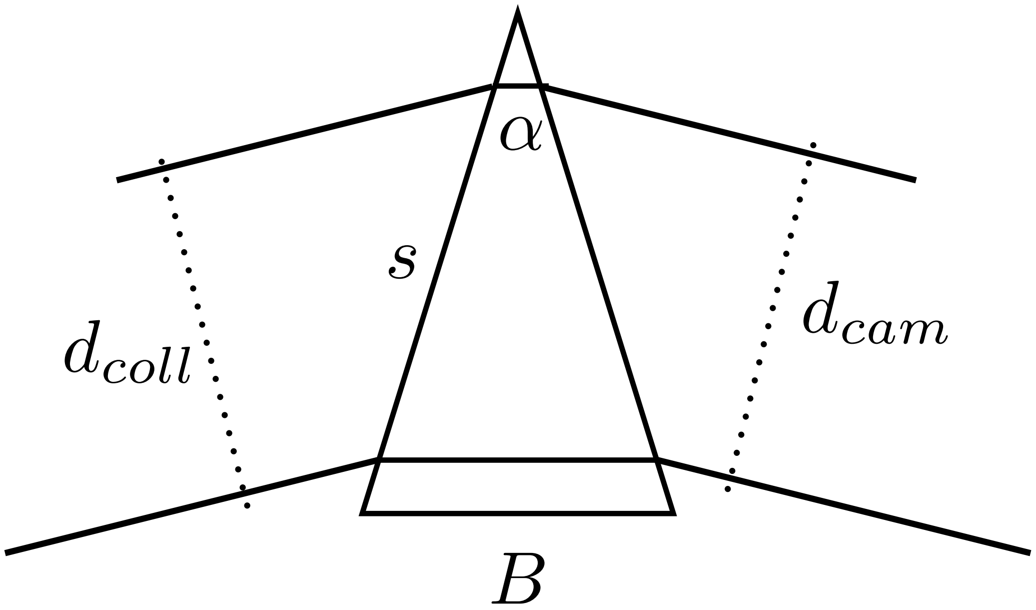


The linear dispersion is then: $$\frac{dl}{d\lambda} = f_{cam} A$$

Dispersion of Glass Prisms

Prisms are used near minimum deviations so that rays inside the prism are parallel to the base. The input and output beams are the same size.

$$A = \frac{d\beta}{d\lambda} = \frac{B}{d_{cam}} \frac{dn}{d\lambda}$$



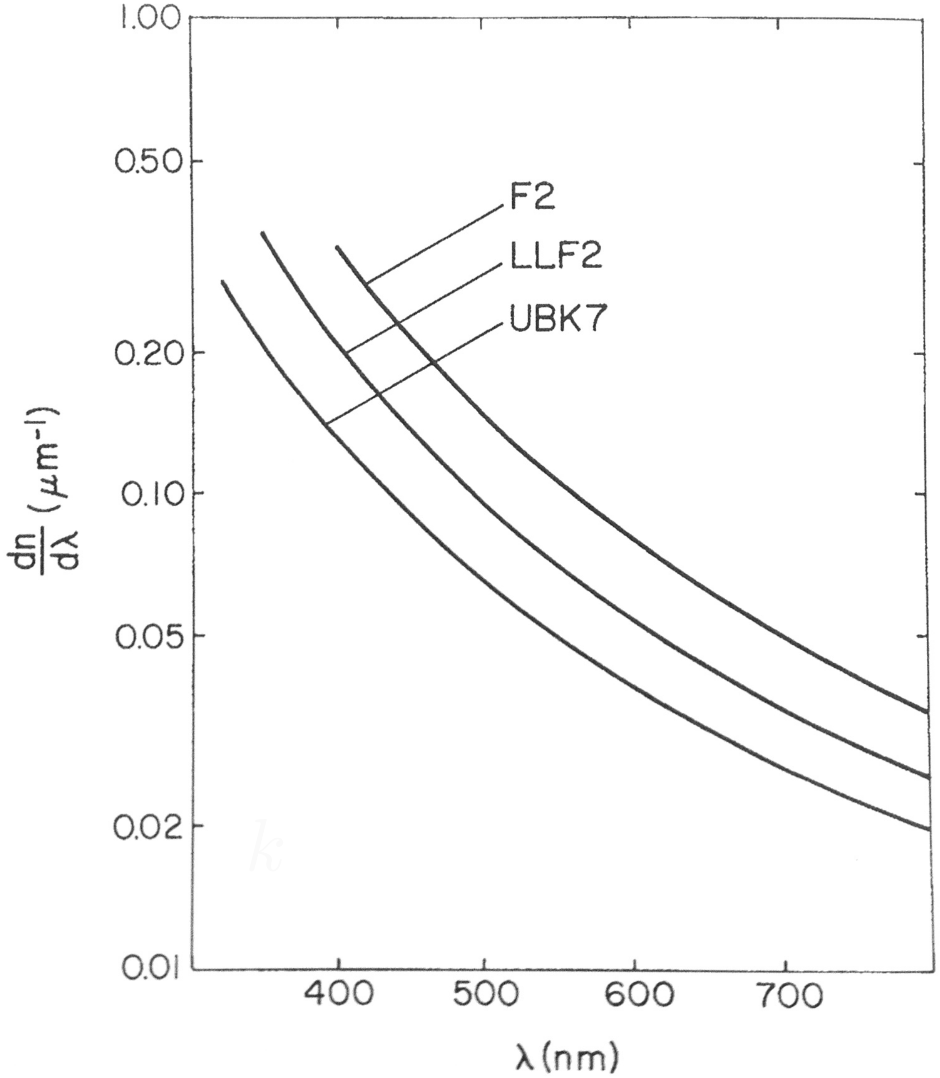
Angular dispersion changes with wavelength

For k identical prisms in a row, dispersion is multiplied by k

Dispersion of Glass Prisms

Dispersion is not constant with wavelength, and very high resolution is not possible.

$$A = \frac{d\beta}{d\lambda} = \frac{B}{d_{cam}} \frac{dn}{d\lambda}$$



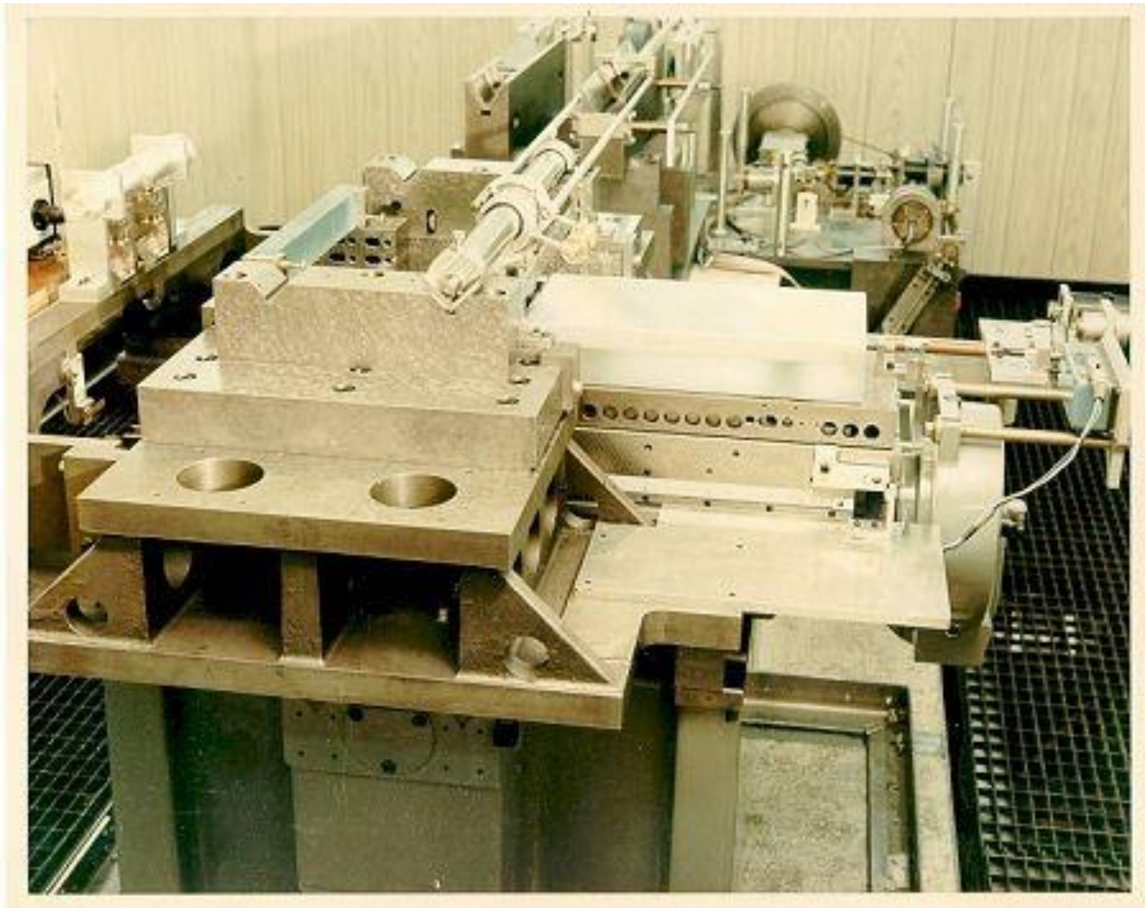
Diffraction grating

Can be transmissive or reflective, and consist of thousands of periodic features on an optically flat surface.

Manufactured using ruling engines in temperature controlled rooms

Made by David Rittenhouse in 1785

Reinvented by Frauenhofer in 1821



Diffraction grating

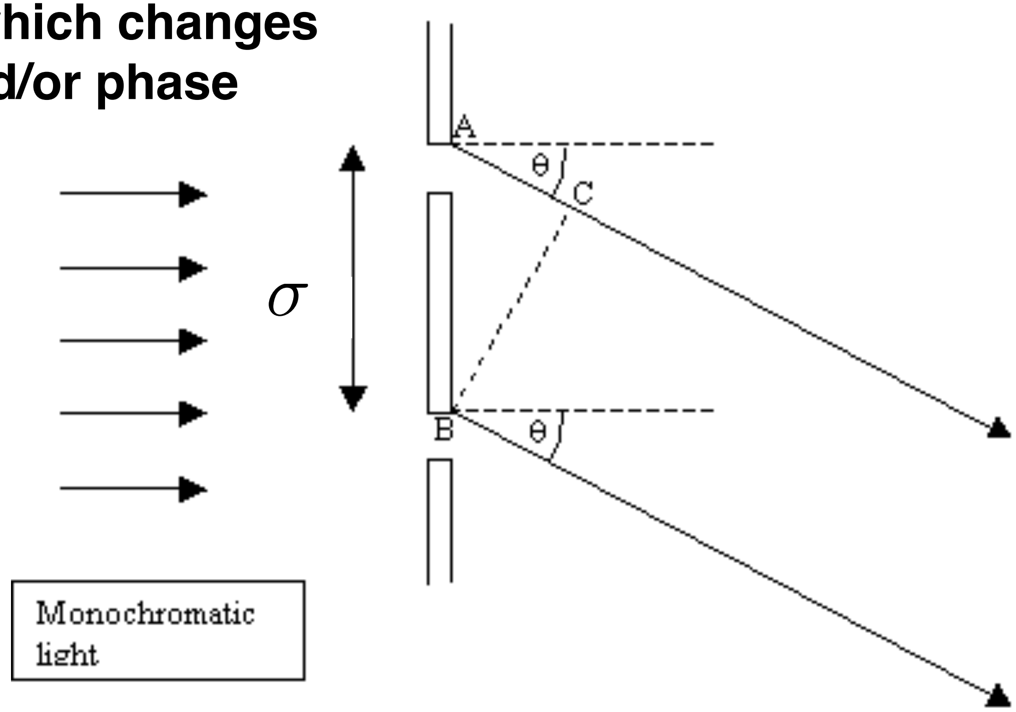
Frauenhofer gratings resolved Solar absorption spectrum, and labelled the absorption lines with letters (A,B,C,D…)

Diffraction grating

HARPS grating

Diffraction grating

Flat wavefront passes through periodic structure, which changes the amplitude and/or phase

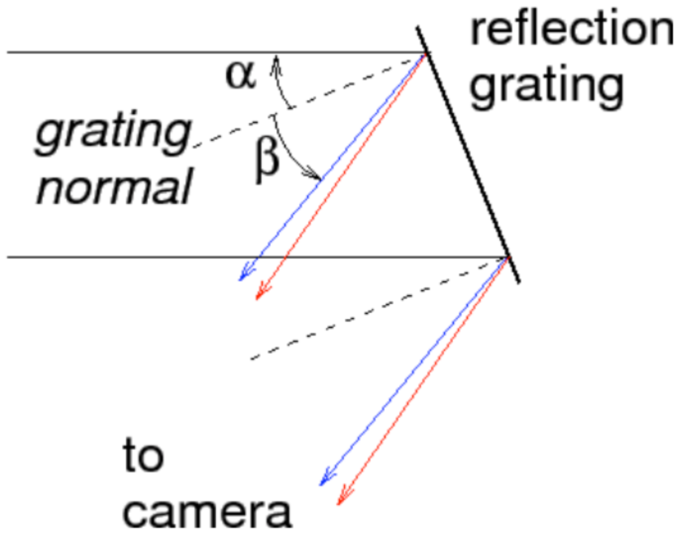


Direction of constructive interference is wavelength dependent

Dispersion of Diffraction Gratings

From diffraction theory, the grating equation relates the order m, the groove spacing σ (the number of mm between each ruled line)

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



… where the sign is positive for reflection, negative for transmission

Angular dispersion $$A = \frac{d\beta}{d\alpha} = \frac{m}{\sigma \cos\beta}$$

Typically 600 lines per mm and used at 60 degrees incidence

Increasing spectral resolution

Increasing σ is difficult, and $\cos\beta$ cannot be greater than unity

Angular dispersion $$A = \frac{d\beta}{d\alpha} = \frac{m}{\sigma\cos\beta}$$

Look at large values of m to get high spectral resolution

$$R = nm$$

where n is the total number of illuminated grooves

Higher spectral orders

Higher order dispersion from the grating will result in overlapping spectra:

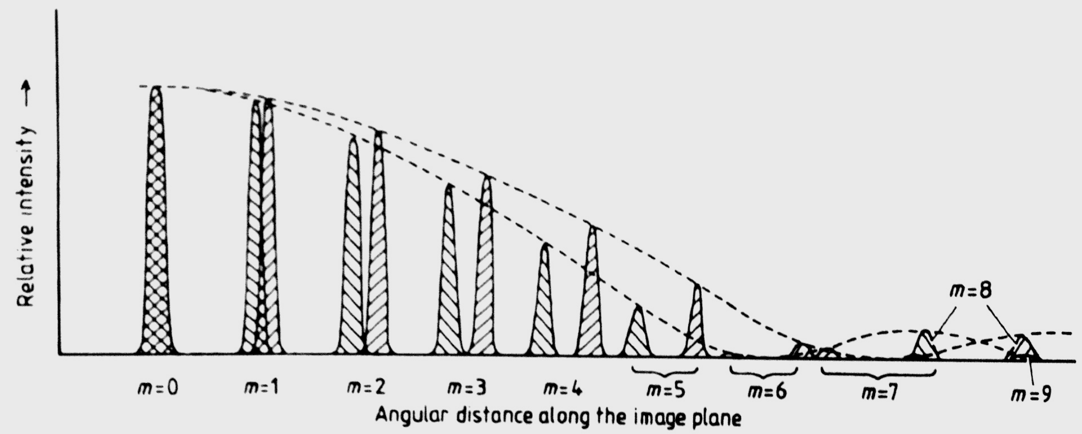


Figure 4.1.10. A portion of the image structure for a single bichromatic point source viewed through several apertures.

The free spectral range of a spectrograph is given by:

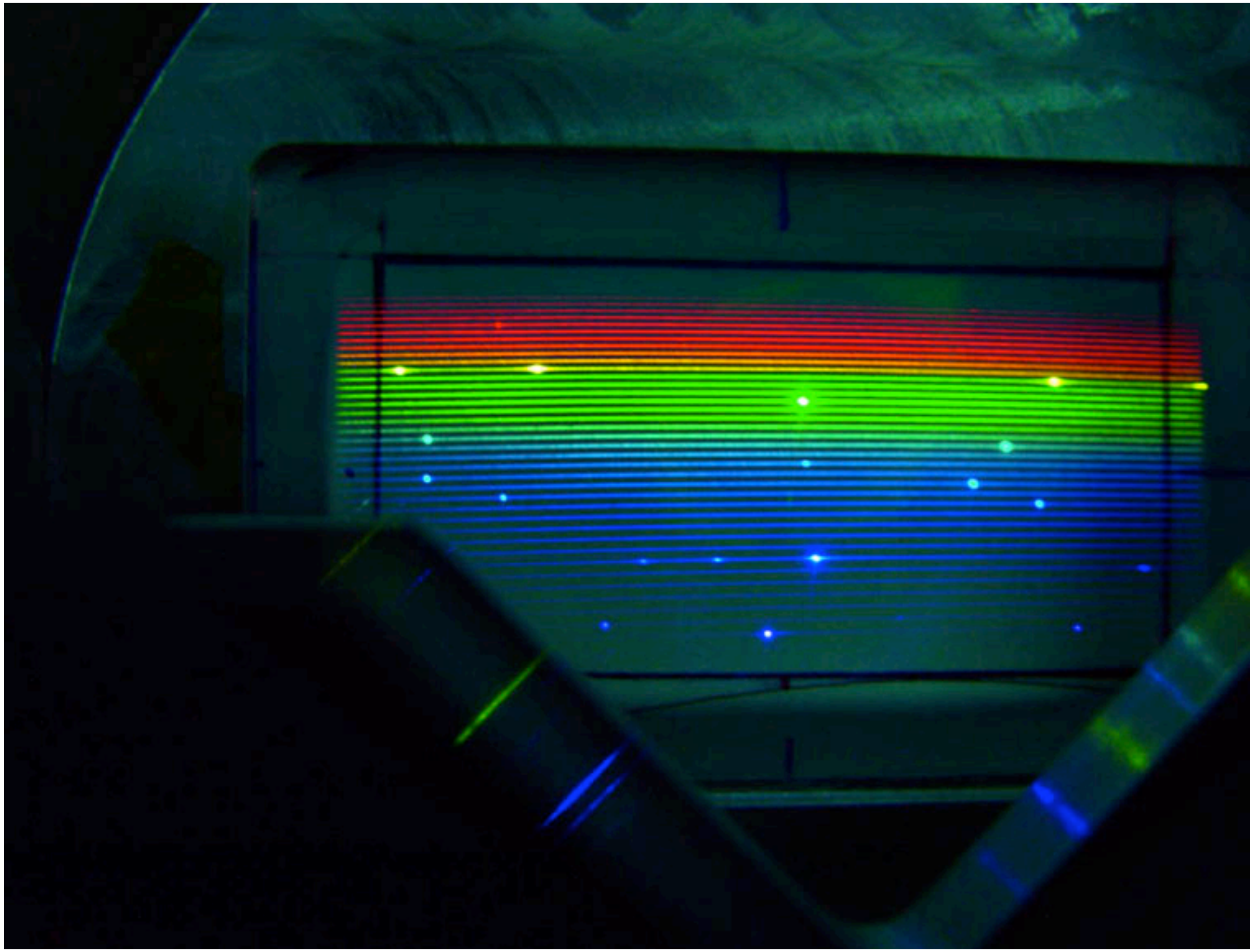
$$\lambda' - \lambda = \lambda/m$$

$$m\lambda' = (m+1)\lambda$$

We can either use an ORDER BLOCKING FILTER or a CROSS disperser to split out the different spectral orders

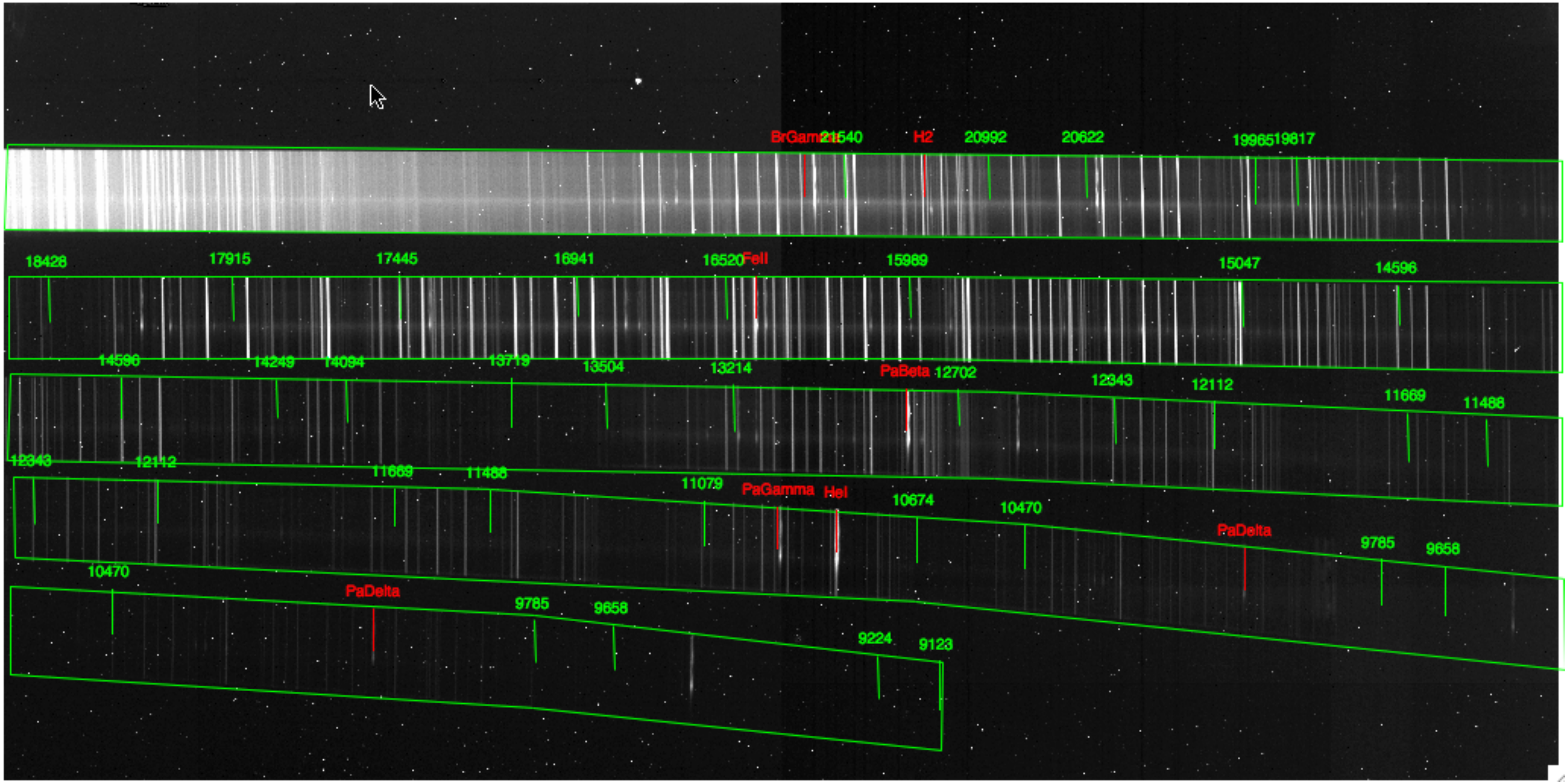
Higher spectral orders

CROSS disperser to split out the different spectral orders



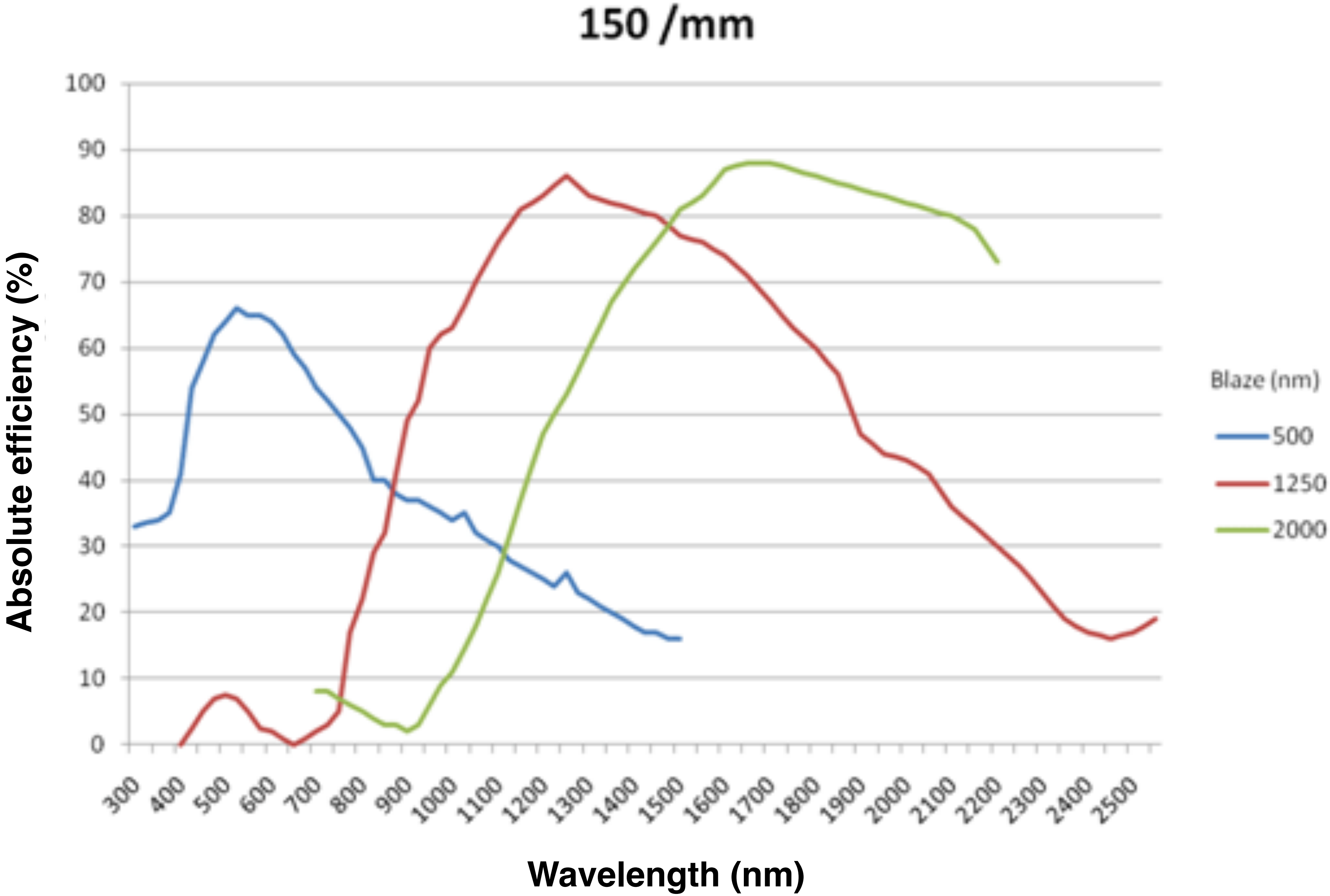
Higher spectral orders

CROSS disperser to split out the different spectral orders

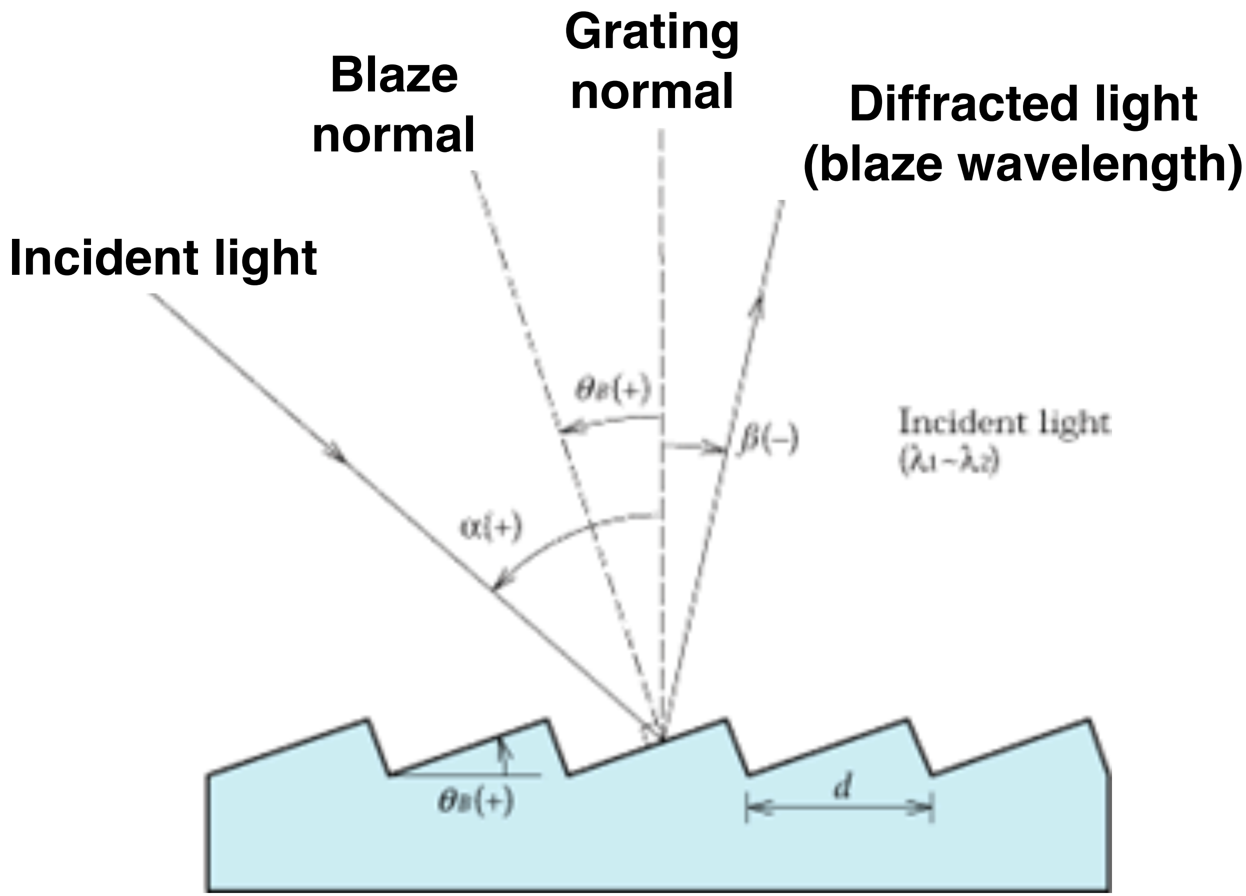


Trispec

Diffraction grating efficiency

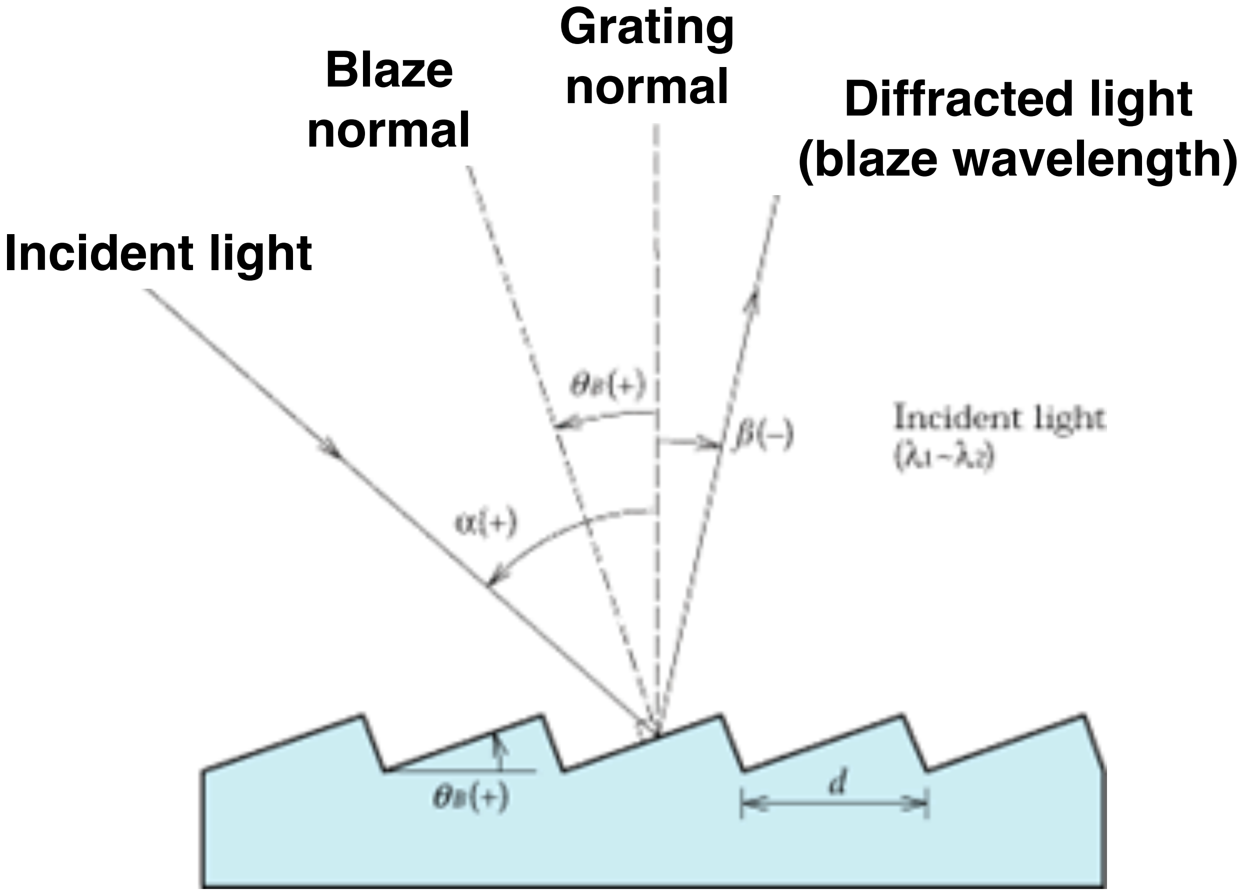


Optimising the grating efficiency



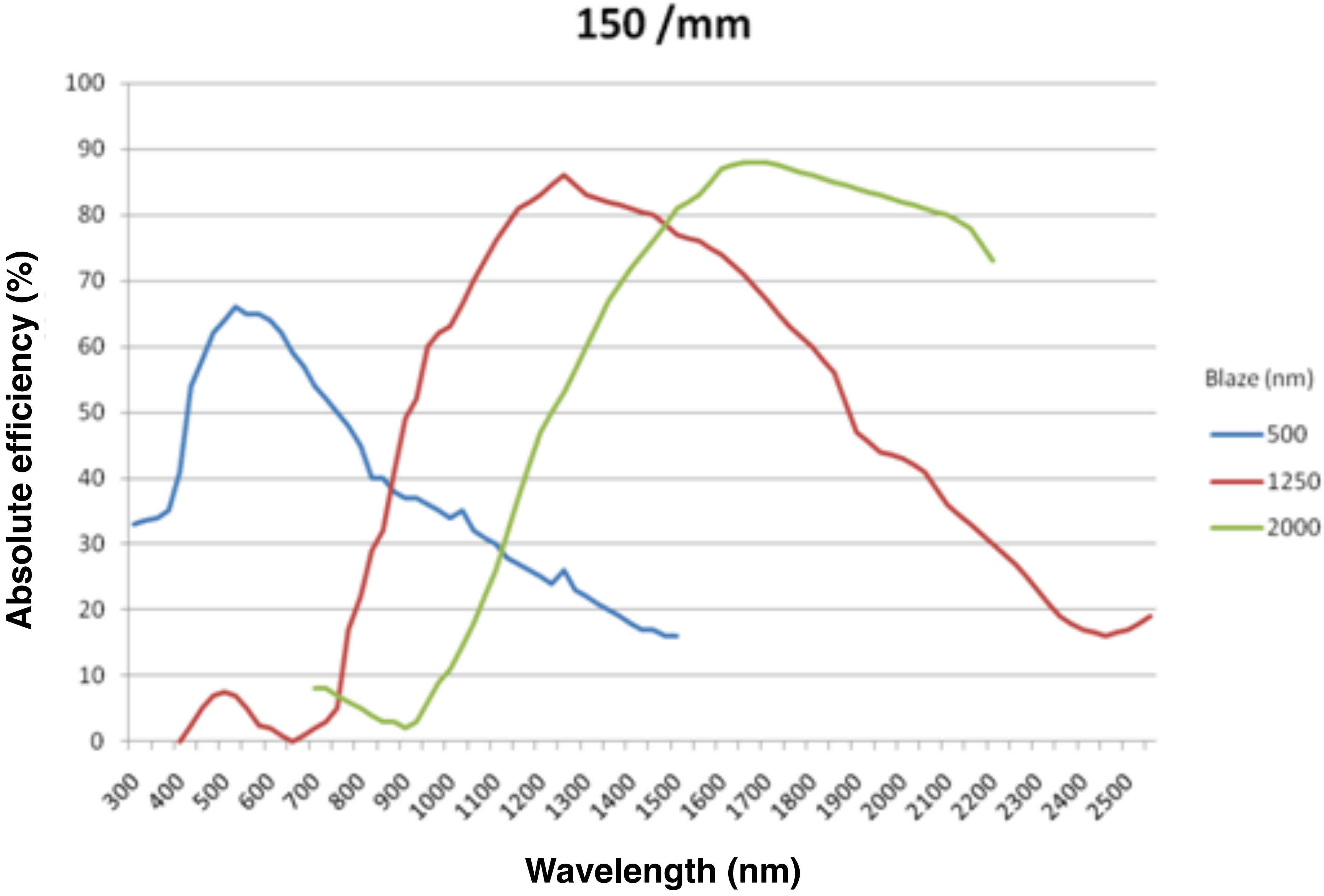
Making the facets of the diffraction grating tilt over so that the diffracted light also goes out along the science wavelength

Optimising the grating efficiency

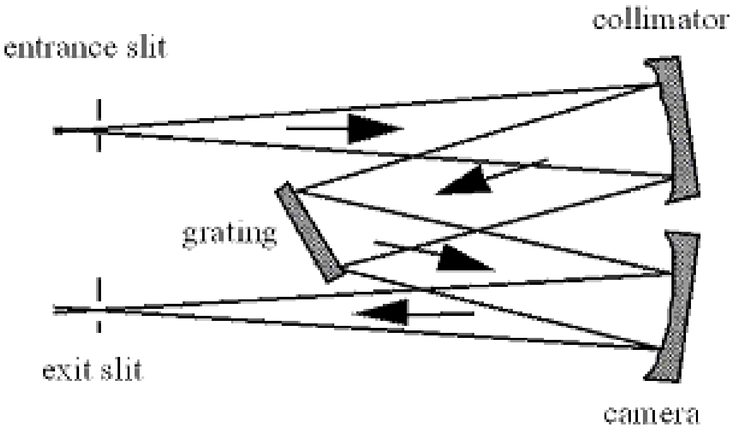


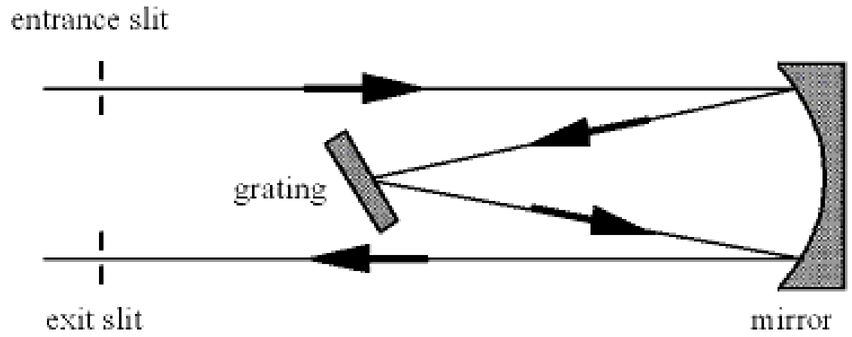
$$\theta_B = \frac{\alpha + \beta}{2} \quad \lambda_B = \frac{2}{nm} \sin\theta_B \cos(\alpha - \theta_B)$$

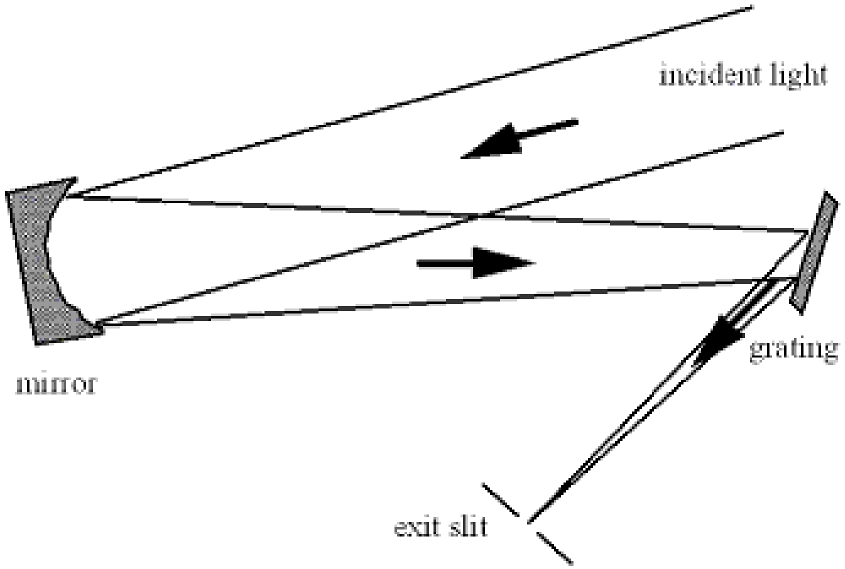
Peak efficiencies at blaze wavelengths

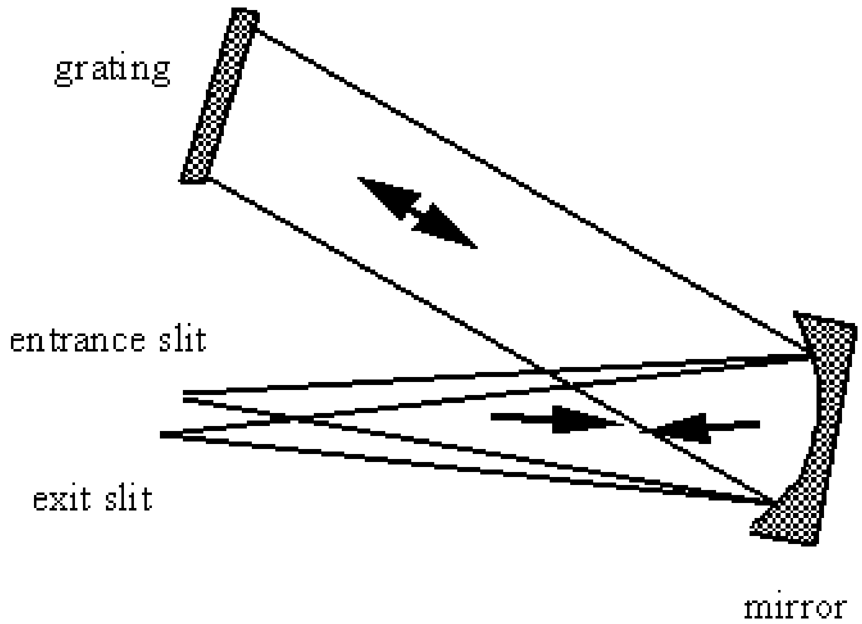


Common spectrograph configurations

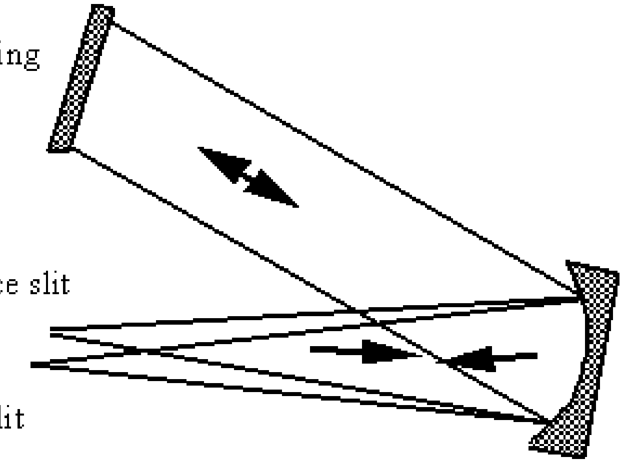








The Littrow spectrograph



Incident angle equals diffracted angle:

$$\alpha = \beta$$

So for Littrow:

$$\lambda = \frac{2\sigma \sin \alpha}{m}$$

Simplifies the grating design, setting the blaze angle so that optimum efficiency is for α

Detector

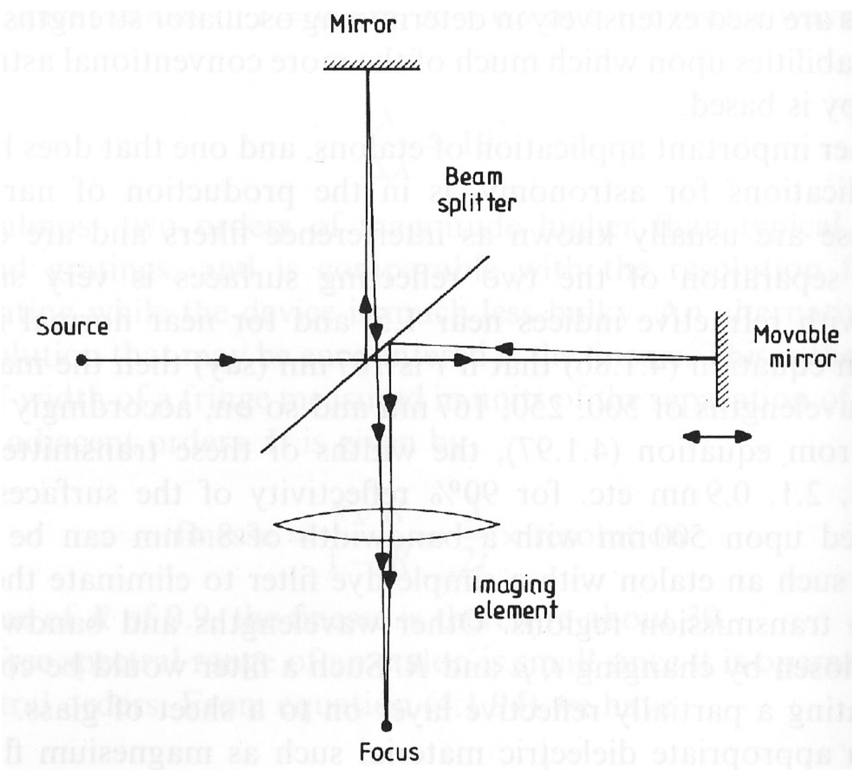
The smallest resolution for the spectrograph should be sampled at the minimum of the Nyquist frequency, which is 2 pixels per resolution element.

Spectral dispersion per pixel is:

$$\mu \frac{d\lambda}{dl}$$

where μ **is the pixel size in mm.**

Fourier Transform Spectrographs



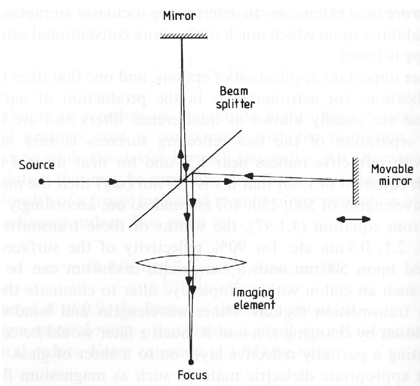
A Michelson interferometer with one moving arm

Consider a monochromatic wave with:

$$k = 2\pi/\lambda$$

Electric field is then: $e^{i(\omega t - kx)}$

Fourier Transform Spectrographs



At output of interferometer, the amplitude A is:

$$A = \frac{1}{2} e^{i\omega t} (e^{-ikx_1} + e^{-ikx_2})$$

Intensity output is: $$AA^* = \frac{1}{2}(1 + \cos k(x_2 - x_1))$$

Adding up all the incoherent intensities from a star with spectral distribution $B(k)$ and taking $x = x_2 - x_1$ and I_0 as a constant, you can rewrite it as:

$$I(x) = I_0 + \frac{1}{2} \int_0^\infty B(k) \cos kx \, \mathrm{d}k$$

Fourier Transform Spectrographs

$$I(x) = I_0 + \frac{1}{2}\int_0^\infty B(k)\cos kx\,\mathrm{d}k$$

You can measure $I(x)$ and get the spectral distribution back with a cosine fourier transform of $I(x) - I_0$

Spectral resolution is given by largest path length difference L:

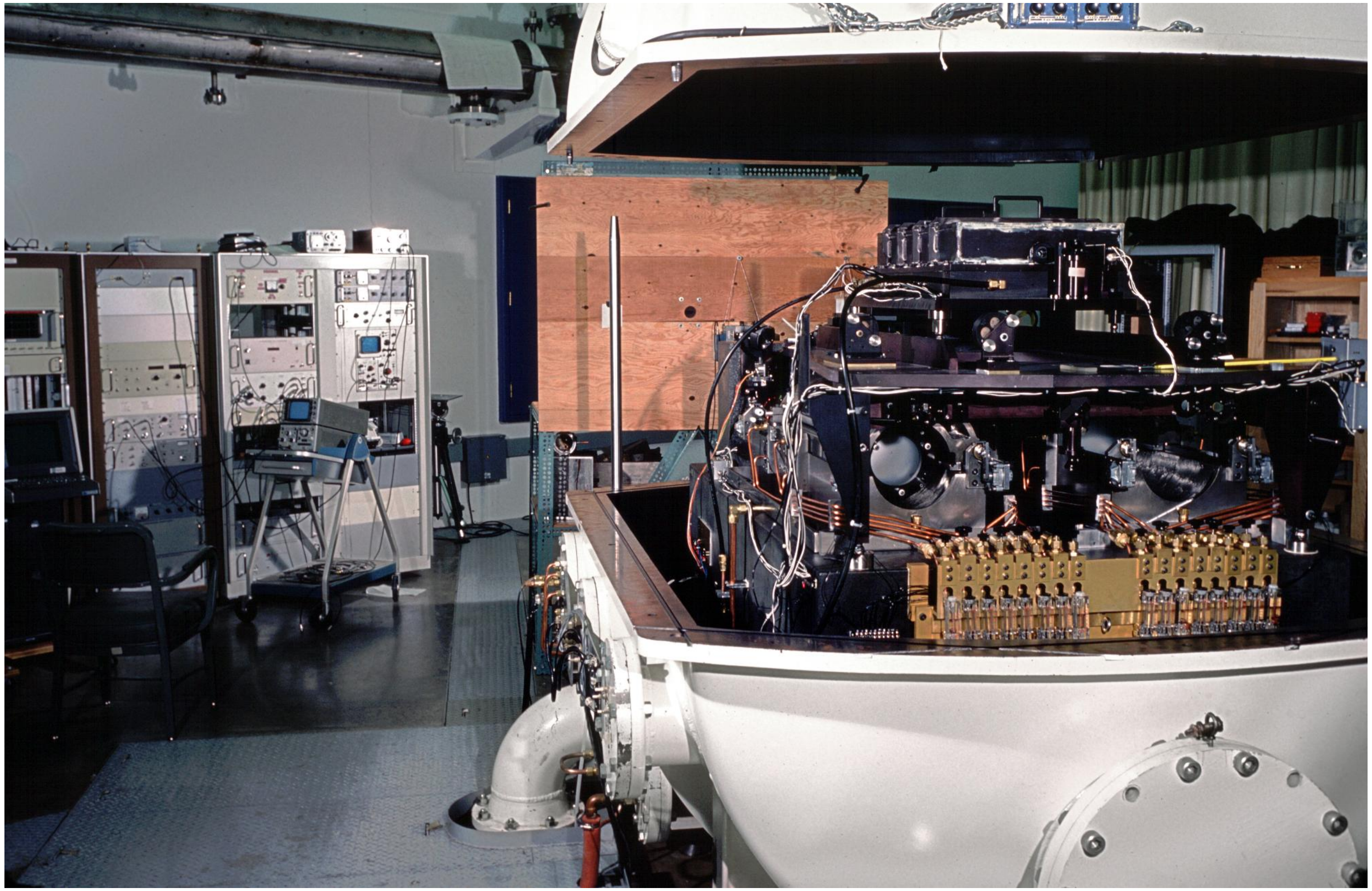
$$\Delta k = 2\pi/L$$

$$\lambda/\delta\lambda = 2 \times 10^6$$

PROS: Simple, compact, absolute calibration of spectral lines possible

CONS: very susceptible to any change in background flux

Fourier Transform Spectrographs



1m Kitt Peak FTS - Eglin, Hanna, NOAO/AURA/NSF