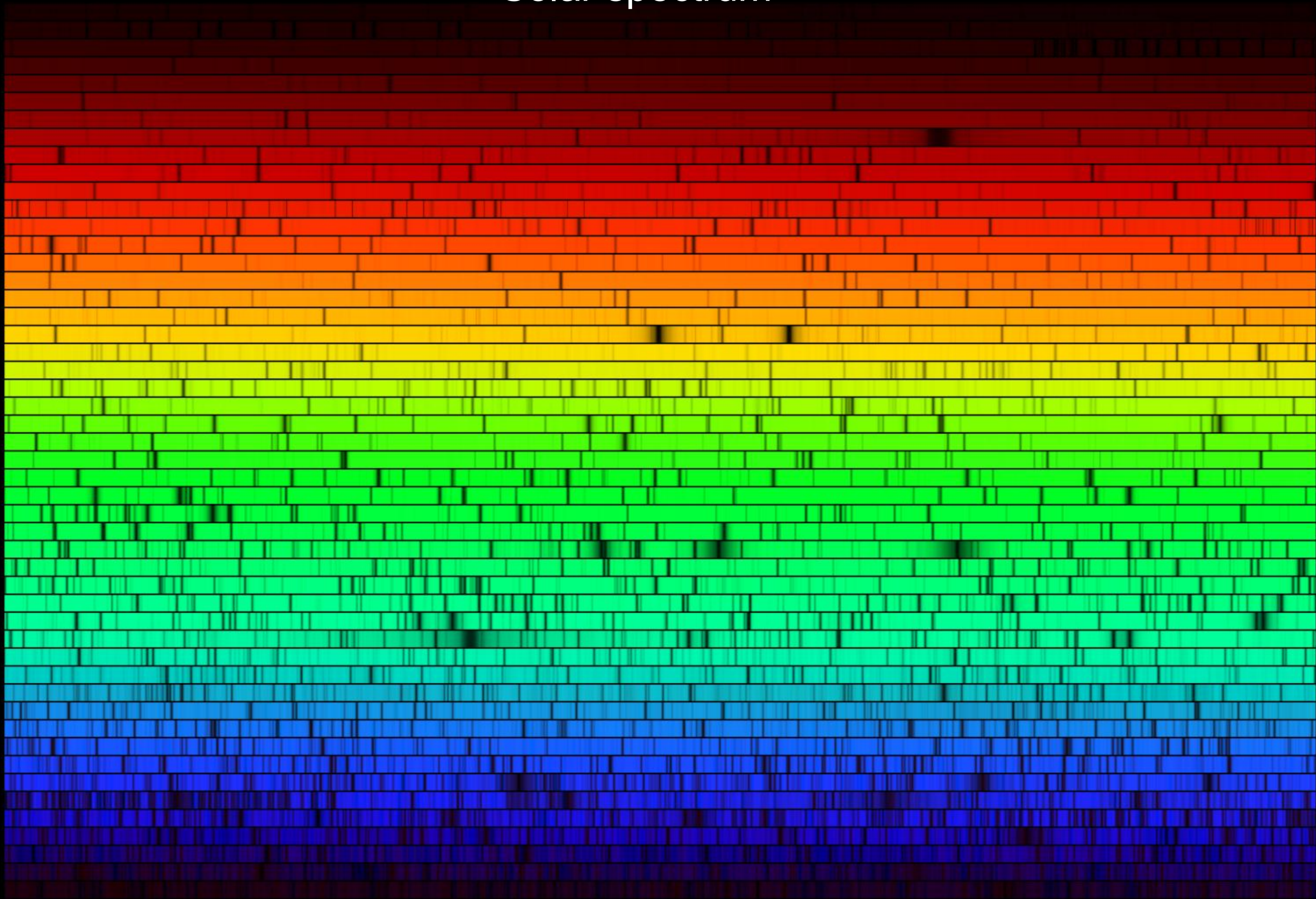
Astronomical Observing Techniques 2019

Lecture 11:
How to Fingerprint a Star

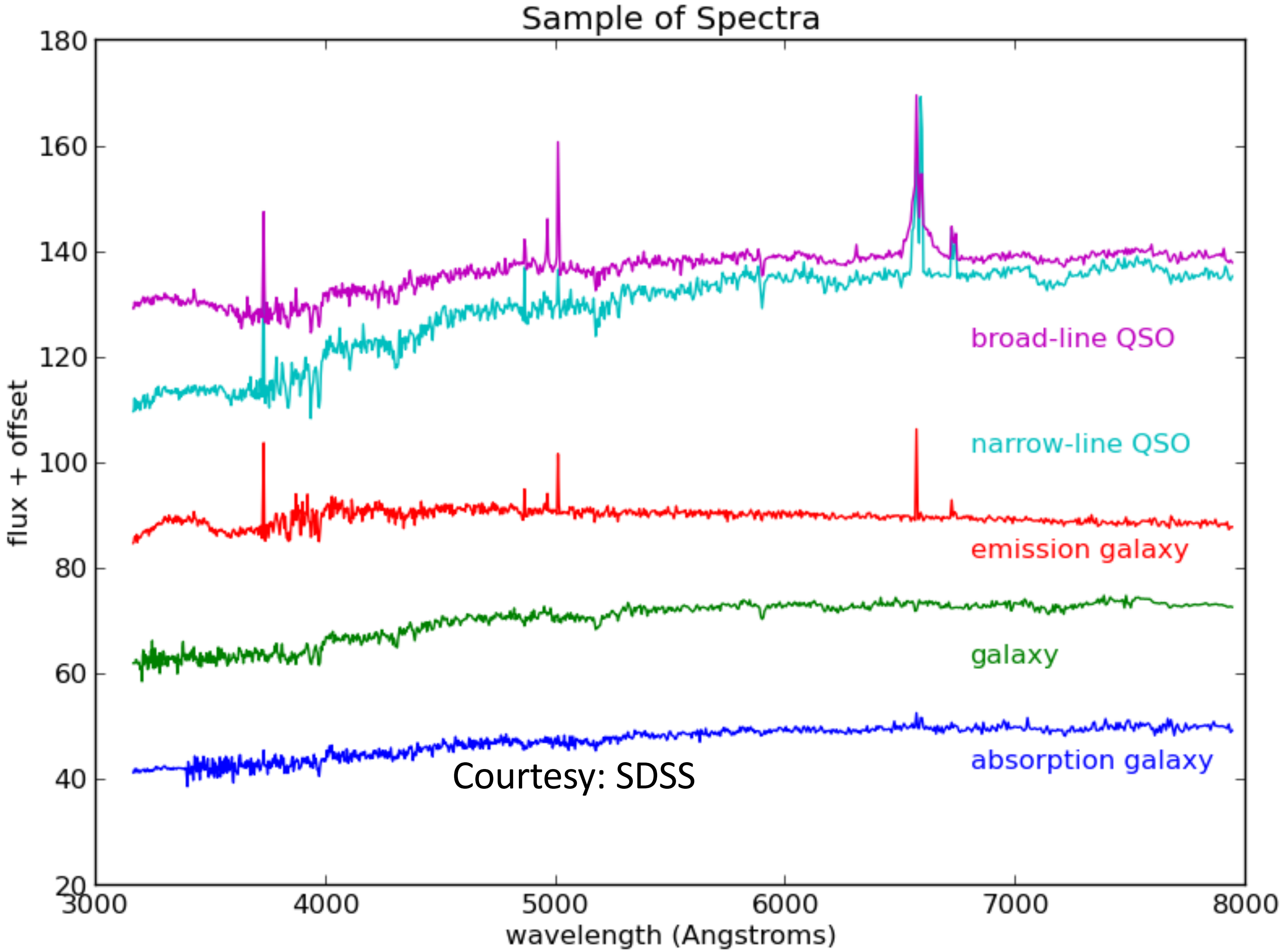
Huub Rottgering
rottgering@strw.leidenuniv.nl

Content

Solar spectrum



Sloan Digital Sky Survey Spectra



Spectroscopy of Extended Objects

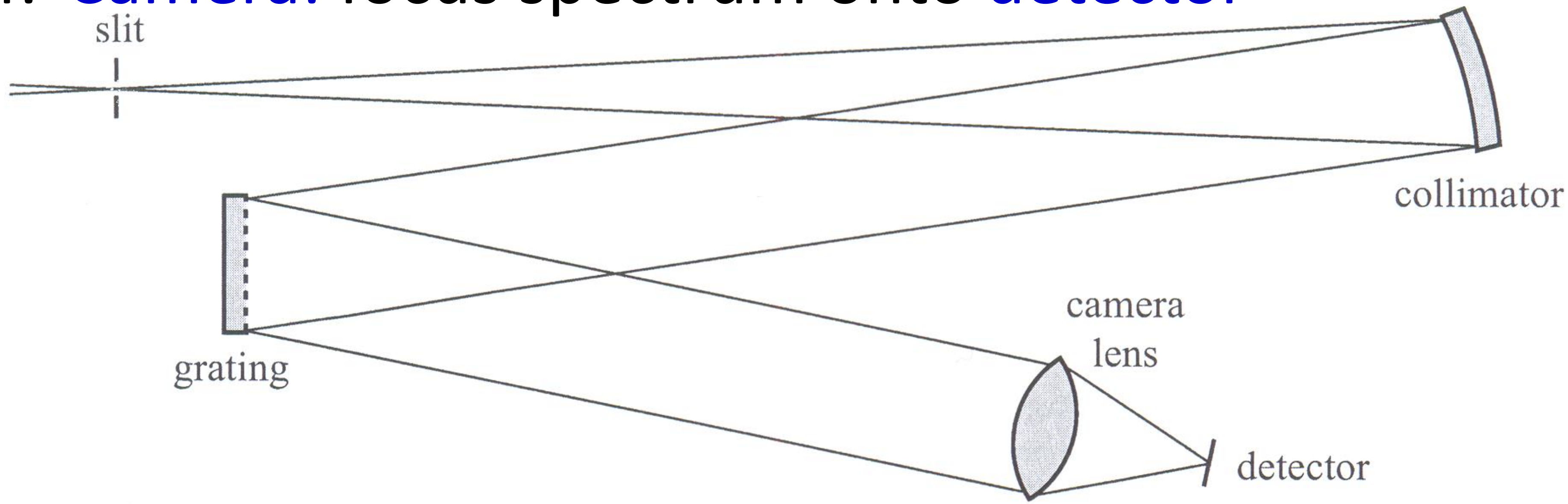
- 3 dimensions to measure
  - two spatial/angular dimensions, one wavelength dimension

  while in general detectors are 2D

- Slicing the 3D data cube
  - (narrow-band) filters: scan in wavelength
  - slit spectrograph: spectra along one spatial dimension
  - multi-object spectroscopy, integral field units (IFU)

Slit spectrography: Components

1. Slit: sample one dimension of telescope image
2. Collimator: collimate (make parallel) diverging light
3. Disperser: spectrally disperses the light
4. Camera: focus spectrum onto detector



Spectrograph Characteristics

- Spectral range
- Spectral resolution element: $\Delta\lambda$
  - smallest spectral feature that can be resolved
  - FWHM of line that is not resolved
  - not the same as pixel size
- Spectral resolution (or resolving power) R:

$$R=\lambda/\Delta\lambda$$

  - $R < 100$: low spectral resolution
  - $R \approx 100$-10000: medium spectral resolution
  - $R > 10000$: high spectral resolution

Spectrograph Characteristics

- Instrumental profile P(λ) broadens infinitely narrow line: $I_0(\lambda) = \delta(\lambda - \lambda_0)$
- to observed line width:

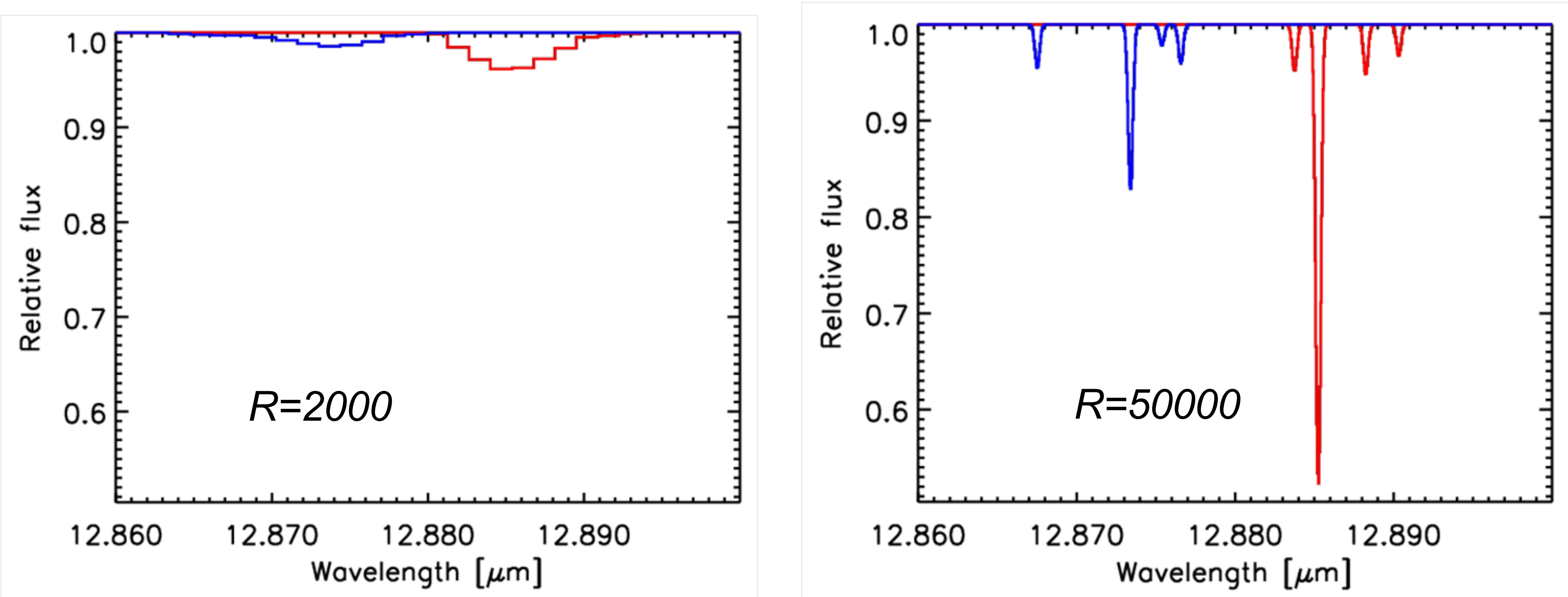
$$I(\lambda) = P(\lambda) * I_0(\lambda)$$

- Instrumental profile often determines spectral resolution element, which should be Nyquist-sampled
- Transmission determines throughput

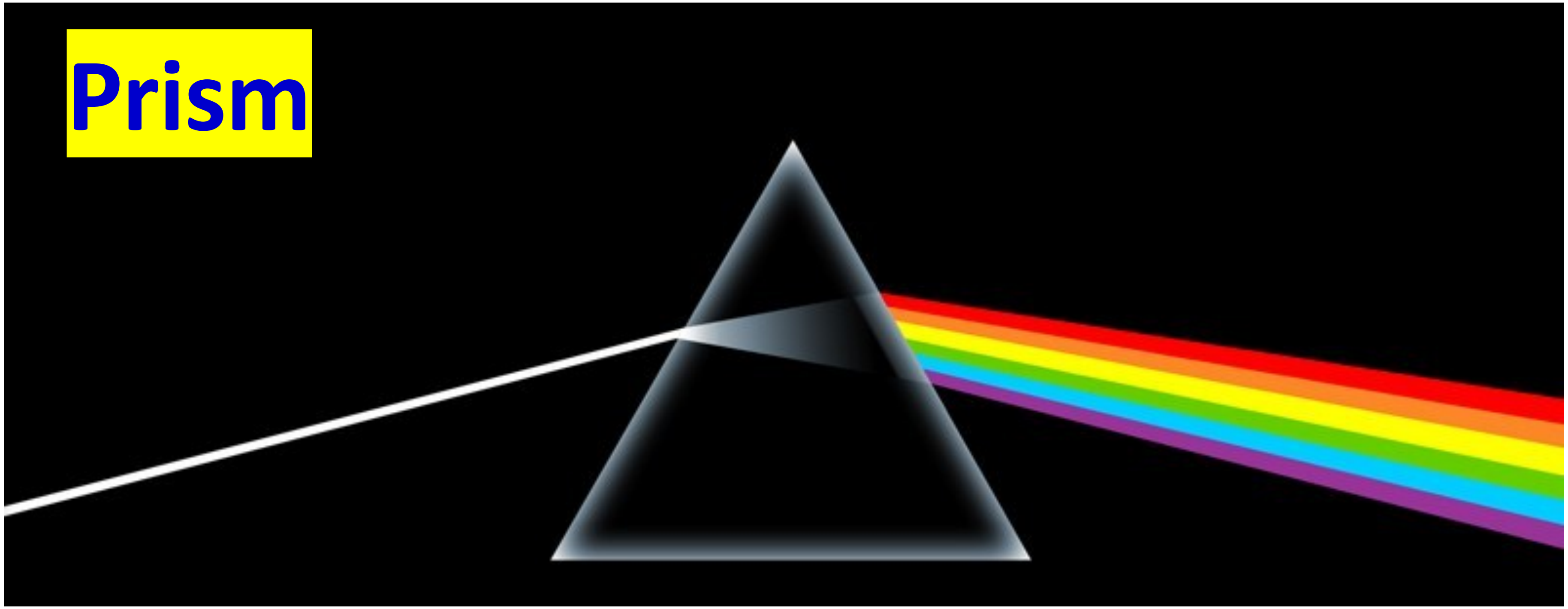
$$\eta(\lambda) = \frac{I_{out}(\lambda)}{I_{in}(\lambda)}$$

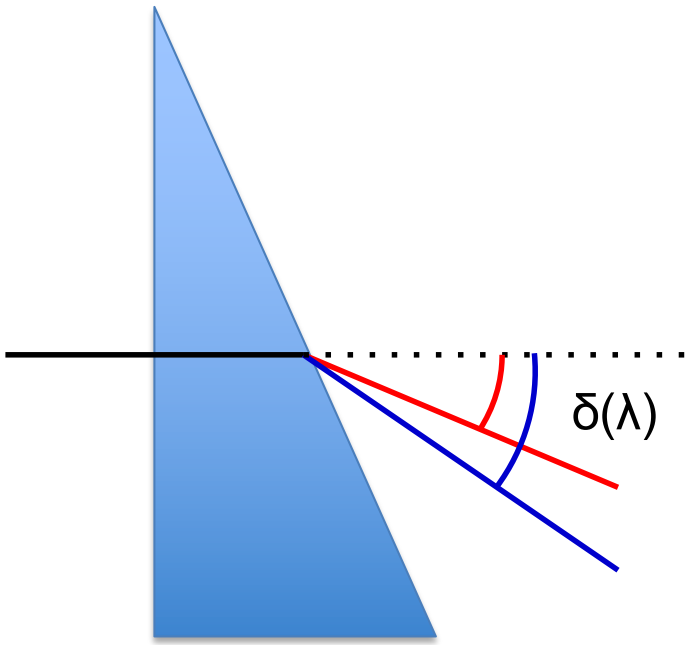
Spectral Resolution and S/N

For *unresolved* spectral lines, both the S/N and the line/continuum contrast increase with increasing resolution

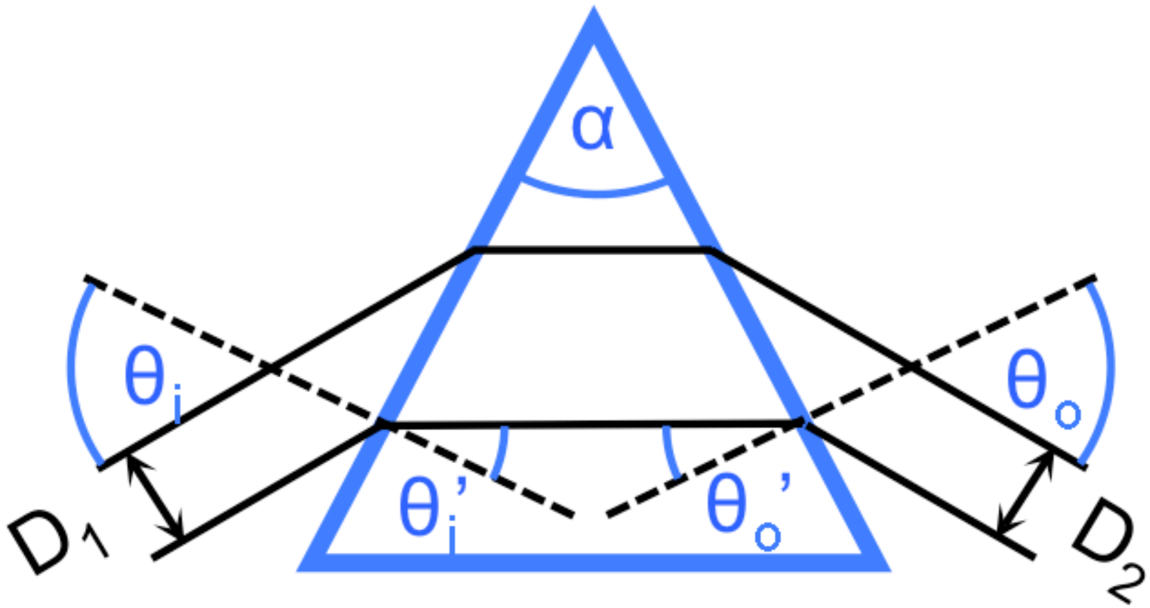


Model spectra of C_2H_2 at 900K and HCN at 600K (assumed Doppler broadening ~4 km/s) at different spectrograph resolutions (figure provided by F. Lahuis).





- good for low-resolution spectroscopy
- no order overlap
- angular dispersion $d\delta/d\lambda$ depends on wavelength

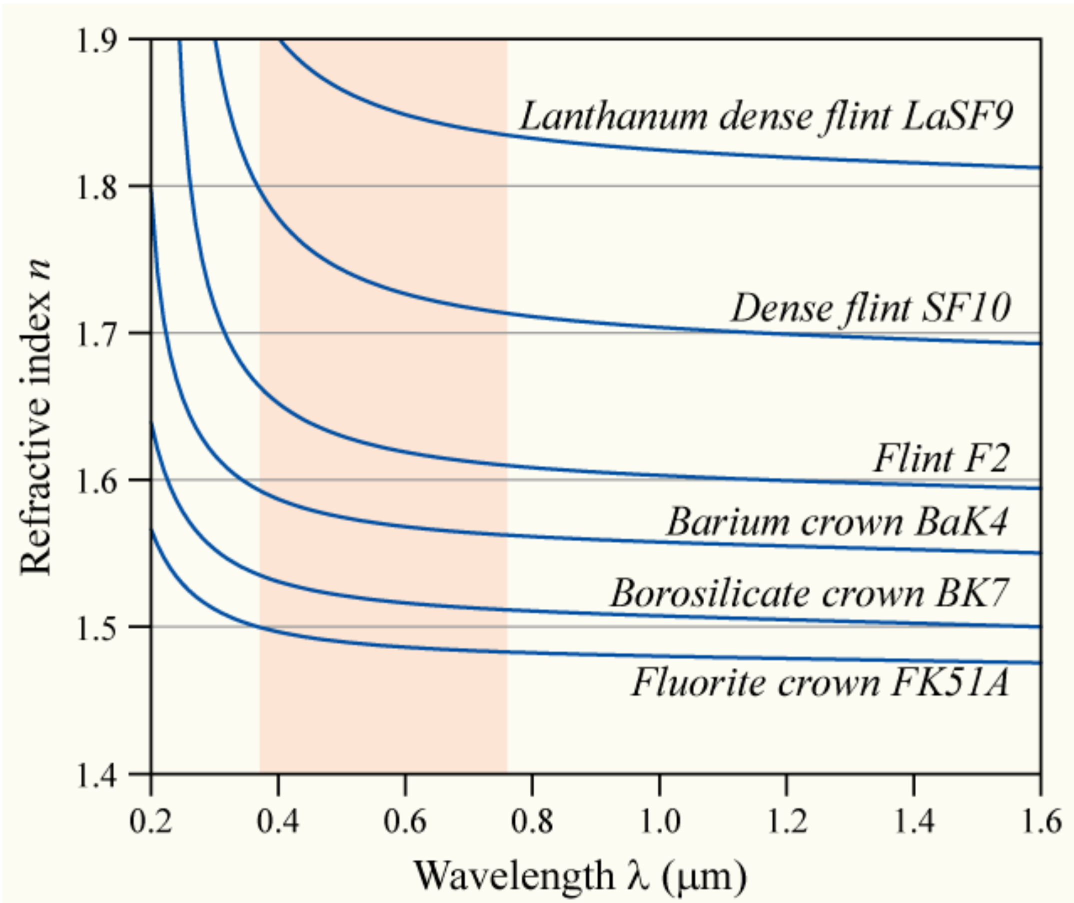


$$\frac{\partial \delta}{\partial \lambda} = \frac{\sin \alpha}{\cos \theta_o \cos \theta_i'} \cdot \frac{\partial n}{\partial \lambda} \qquad \sin \theta_i' = \frac{\sin \theta_i}{n} \qquad \sin \theta_o = n \sin\left(\alpha - \theta_i'\right)$$

See Kitchen on Prisms, Chapter 4

Angular Dispersion

- angular dispersion dδ/dλ maximized with high-dispersion dn/dλ glass



Diffraction Grating

Grating introduces optical path difference as function of angle to surface normal

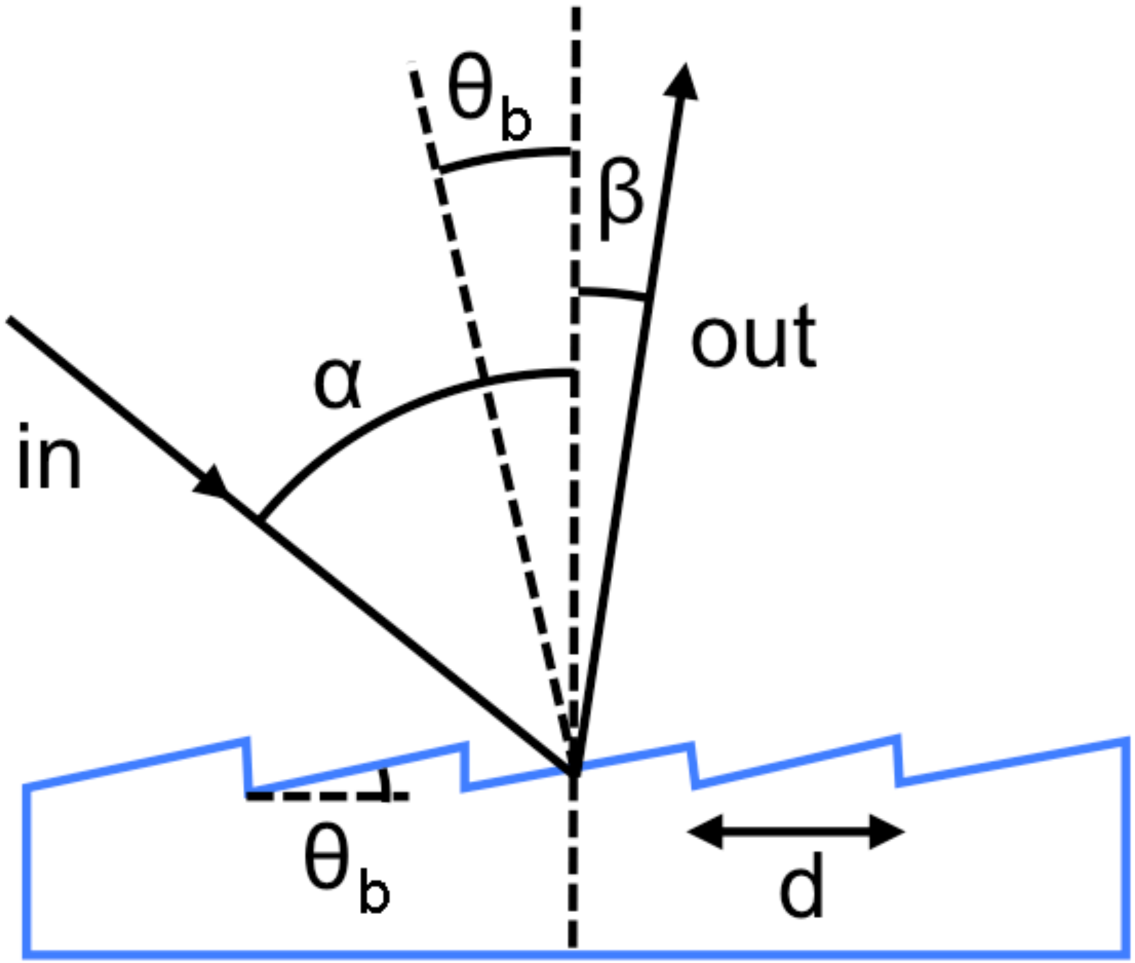
λ = wavelength

d = distance between equally spaced grooves

α = angle of incoming beam

β = angle of reflected beam

θ_B = Blaze angle



Grating Spectral Resolution

Condition for constructive interference given by grating equation:

$$m\lambda = d\cdot(\sin\alpha \pm \sin\beta)$$

m = order of diffraction

- Maximum spectral resolution *R* given by *R=mN* *

  N = number of grooves

  m = diffraction order

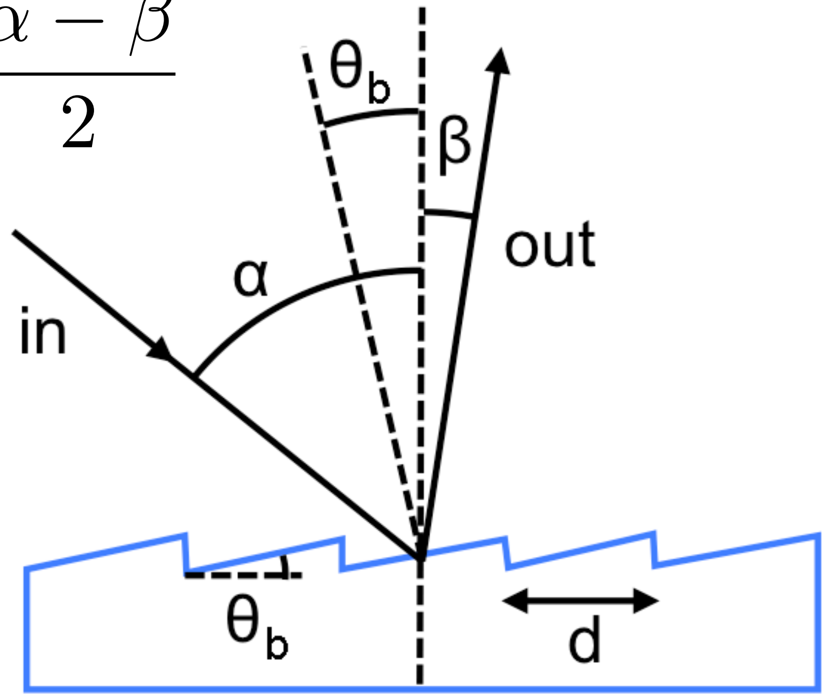
- Angular dispersion: $d\beta/d\lambda = \dfrac{m}{d\cos\beta}$ *

* A non-trivial derivation: this is the limiting case of considering imaging by a linear ensemble of equidistant small apertures illuminated by a plane wave. For derivations see Kitchin: Astrophysical Techniques.

Blaze Angle

- Periodic structure distributes energy over many orders
- Observing only one arbitrary order is inefficient
- For blazed gratings the *directions of constructive interference and specular reflection coincide*:

$$\alpha - \theta_b = \theta_b + \beta \quad \Rightarrow \quad \theta_b = \frac{\alpha - \beta}{2}$$



Advantage:

- High efficiency

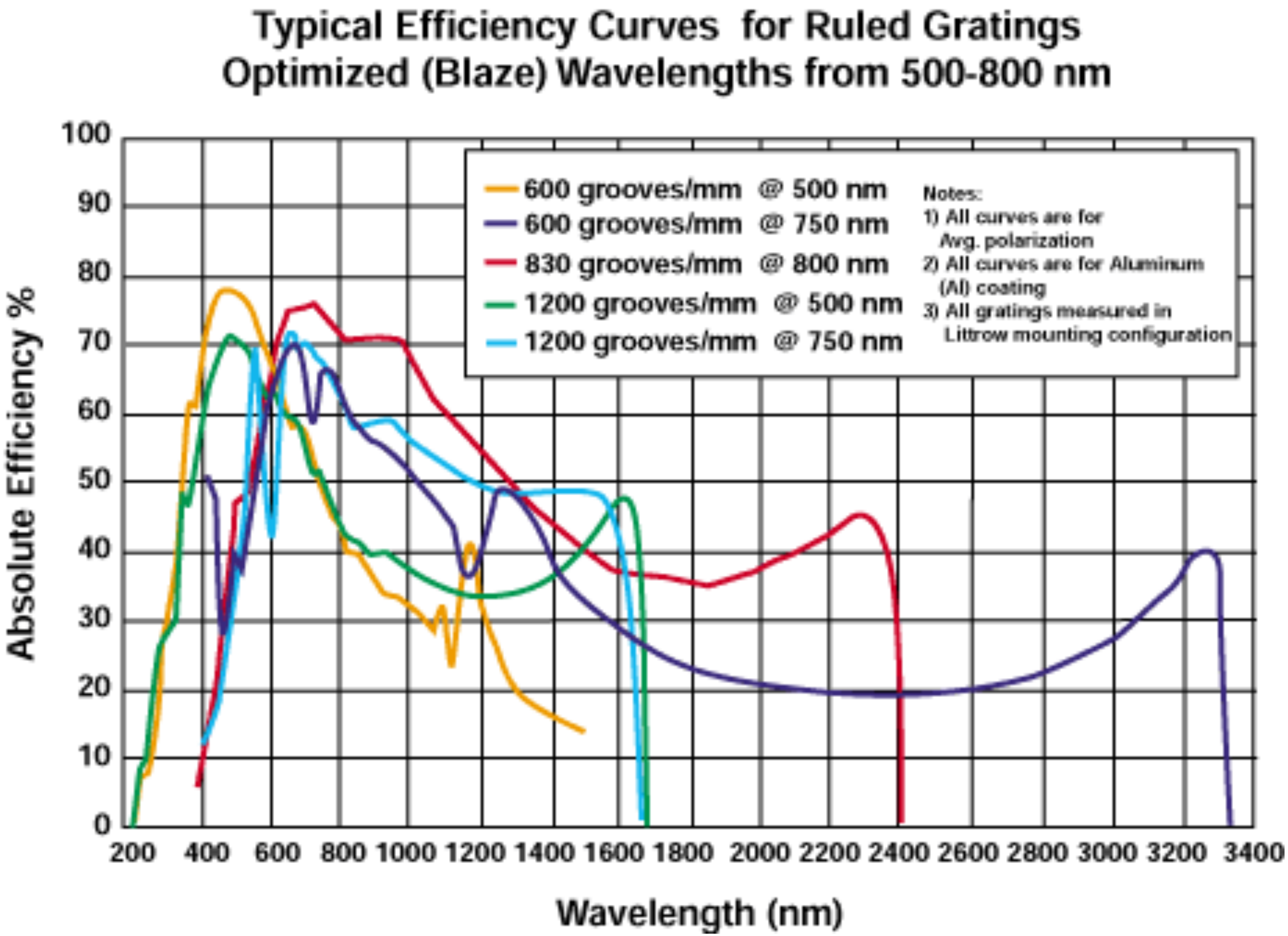
Disadvantage:

- Blaze angle ϑ_B (and blaze wavelength λ_B) fixed by construction

Blaze angle

A blazed grating has grating lines lines that possess a triangular, sawtooth-shaped cross section, forming a step structure. The steps are tilted at the so-called blaze angle θ_B with respect to the grating surface. Accordingly, the angle between step normal and grating normal is θ_B. The blaze angle is optimized to maximize efficiency for the wavelength of the used light. Descriptively, this means θ_B is chosen such that the beam diffracted at the grating and the beam reflected at the steps are both deflected into the same direction. Commonly blazed gratings are manufactured in the so-called Littrow configuration.

https://en.wikipedia.org/wiki/Blazed_grating

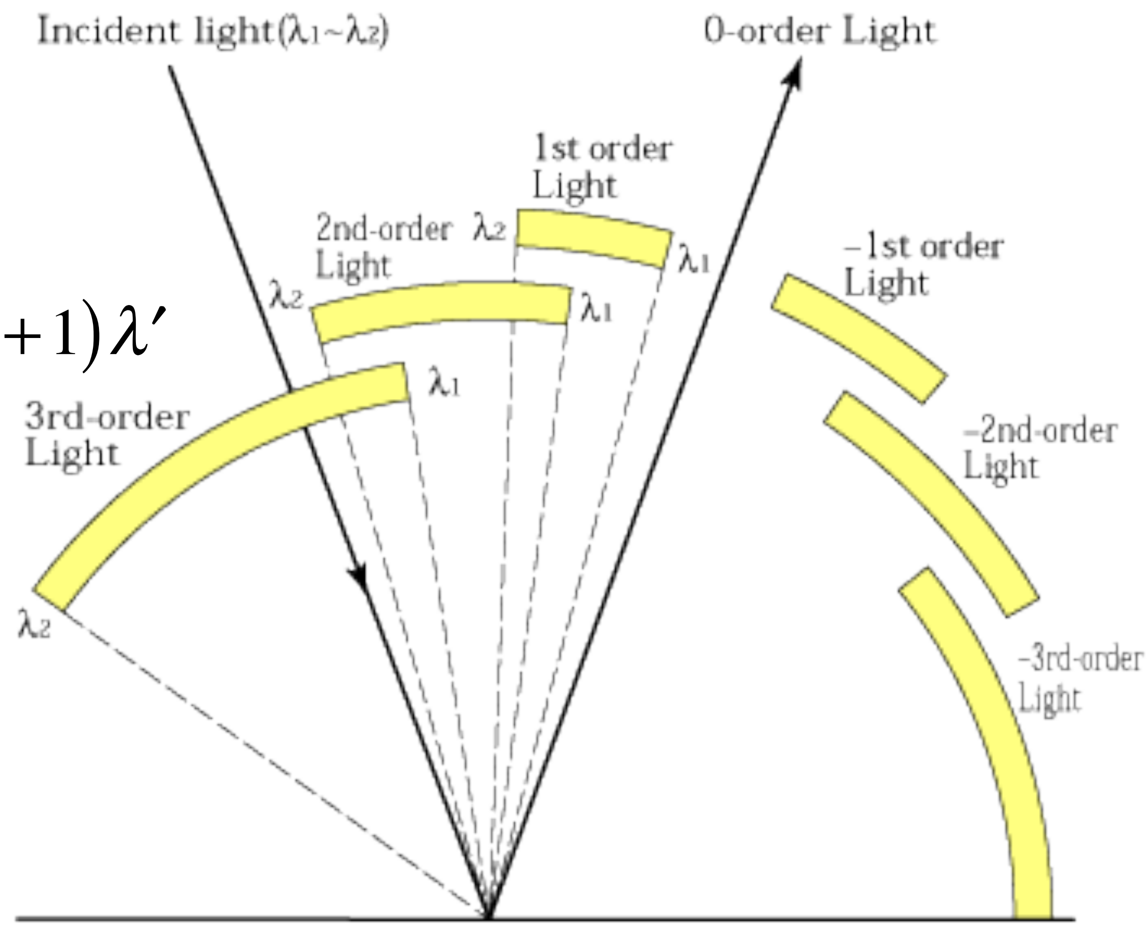


www.edmundoptics.eu/globalassets/commerce/products/6425.gif

Free Spectral Range

Different diffraction orders overlap with each other:

$$m\lambda = d(\sin\alpha + \sin\beta) = (m+1)\lambda'$$



Free spectral range is largest wavelength range for a given order that does not overlap with an adjacent order

$$\Delta\lambda_{free} = \lambda - \lambda' = \frac{\lambda'}{m}$$

Overlapping Grating Orders

www.stargazing.net/david/spectroscopy/SpectraL200F4T5Dorders.html

Echelle Gratings

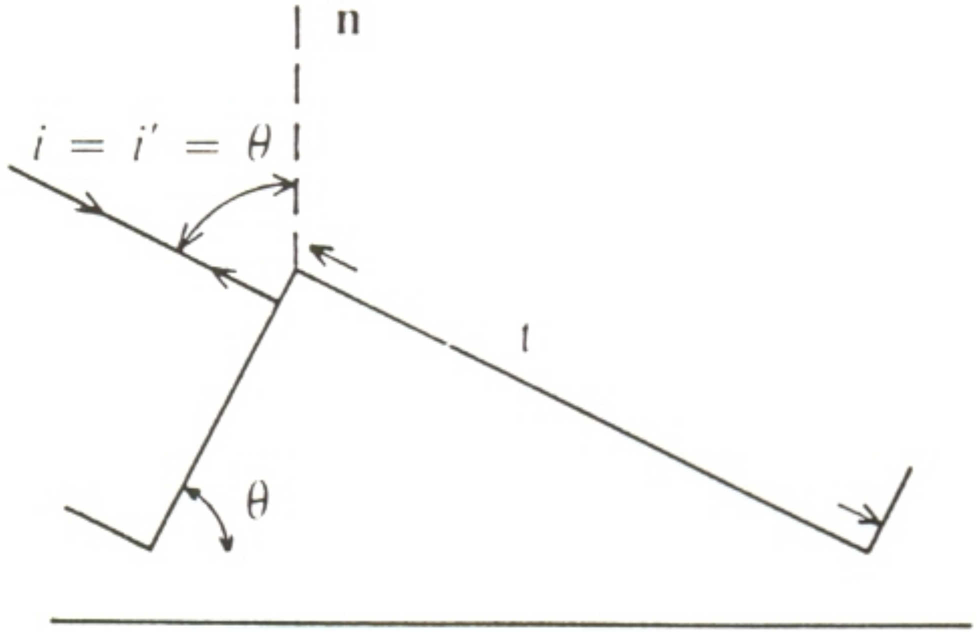
Want high dispersion

$$\frac{d\beta}{d\lambda} = \frac{m}{d\cos\beta} = \frac{\sin\alpha + \sin\beta}{\lambda\cos\beta}$$

and high spectral resolution

$$R = Nm$$

α and β large, high order m (≈ 50): grating is strongly tilted



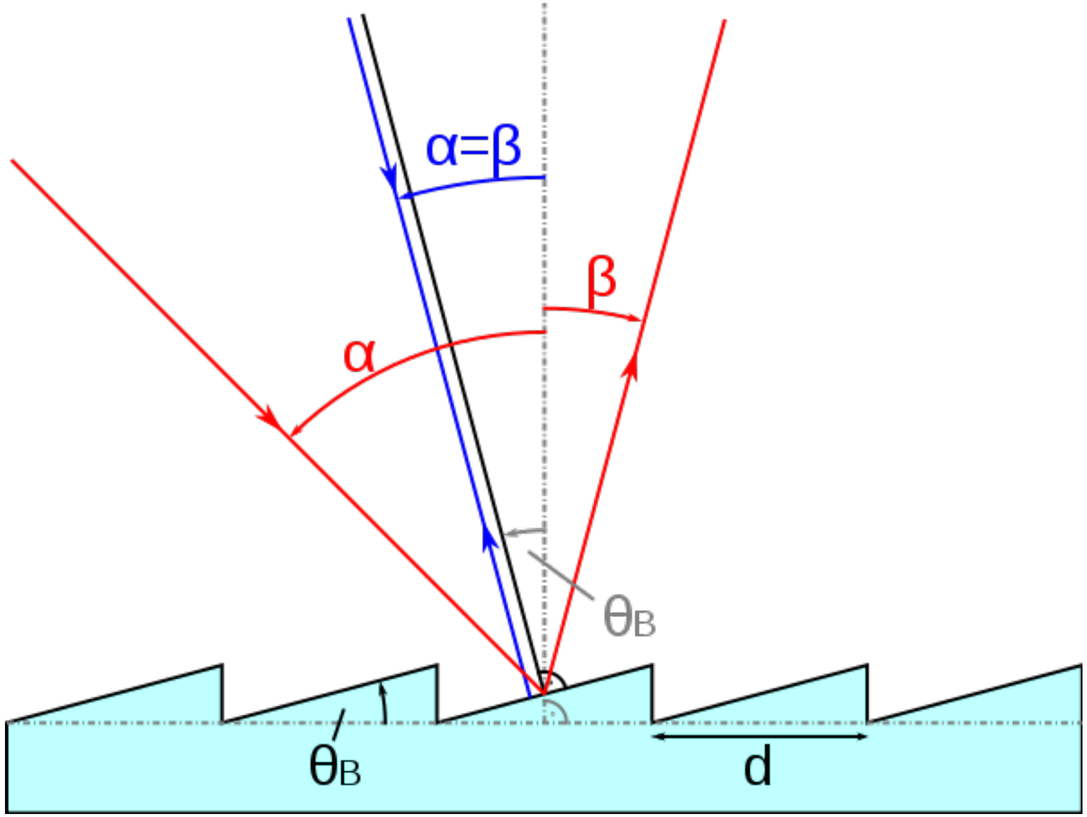
Linear dispersion in length *L* on detector per wavelength, often in mm/nm:

$$\frac{\partial L}{\partial \lambda} = f \cdot \frac{\partial \beta}{\partial \lambda}$$

with *f* the focal length of the camera lens/mirror

Grating equation in Littrow configuration (α=β): $m\lambda_B = 2d \sin\beta$

Littrow configuration



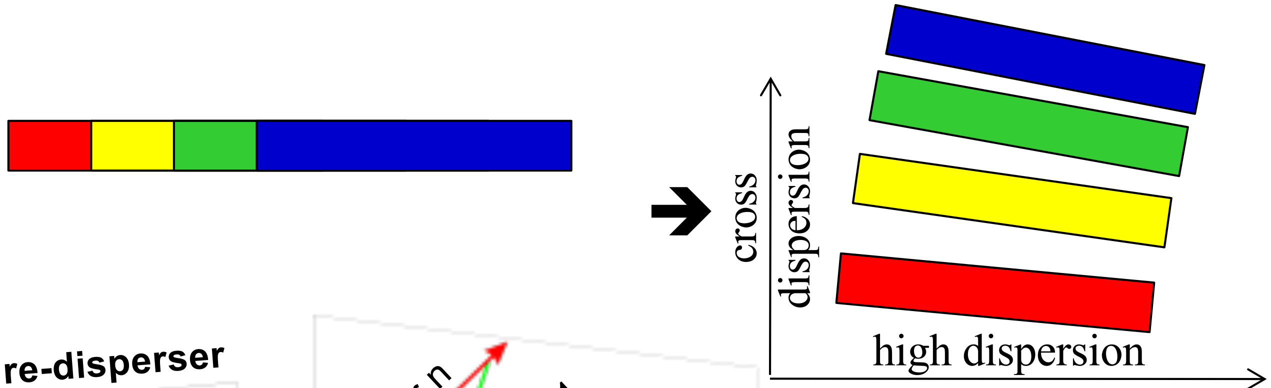
Diffraction at a blazed grating. The general case is shown with red rays; the Littrow configuration is shown with blue rays

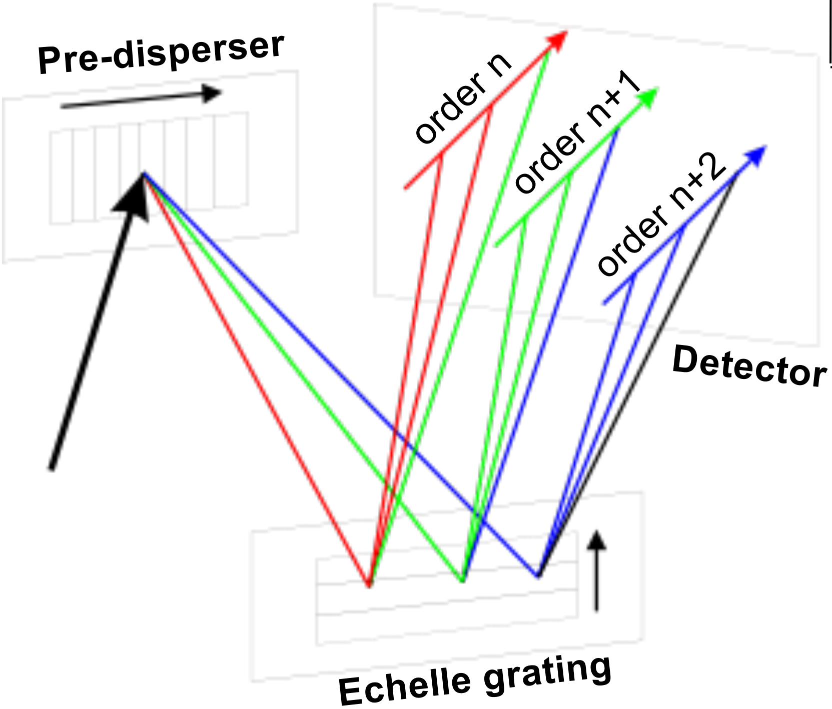
The Littrow configuration is a special geometry in which the blaze angle is chosen such that diffraction angle and incidence angle are identical. For a reflection grating, this means that the diffracted beam is back-reflected into the direction of the incident beam (blue beam in picture). The beams are perpendicular to the step and therefore parallel to the step normal. Hence it holds in Littrow configuration $\alpha = \beta = \theta_B$.

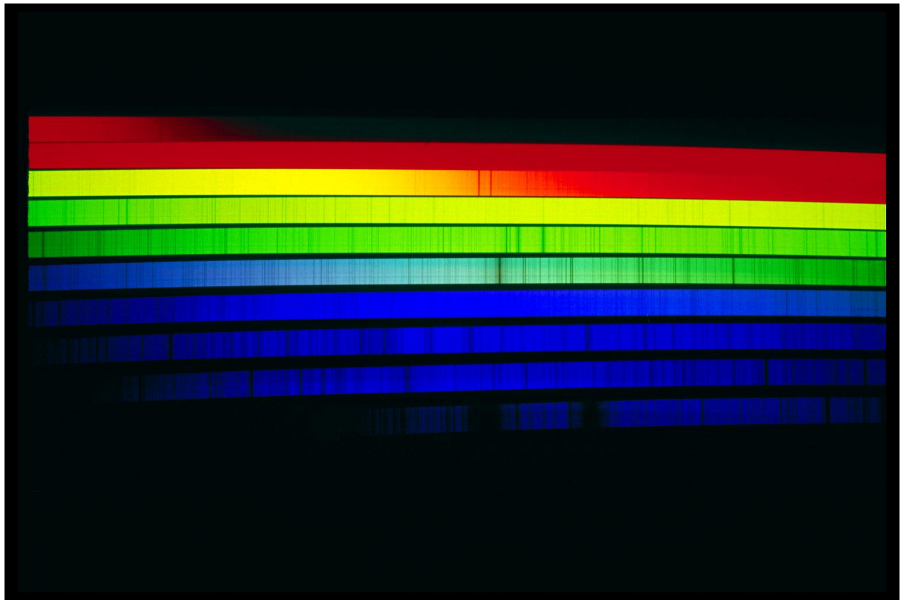
https://en.wikipedia.org/wiki/Blazed_grating

Cross-Dispersion

Spatially separate orders with an additional dispersive element such as low-dispersion prism/grating with dispersion direction perpendicular to that of high-dispersion grating

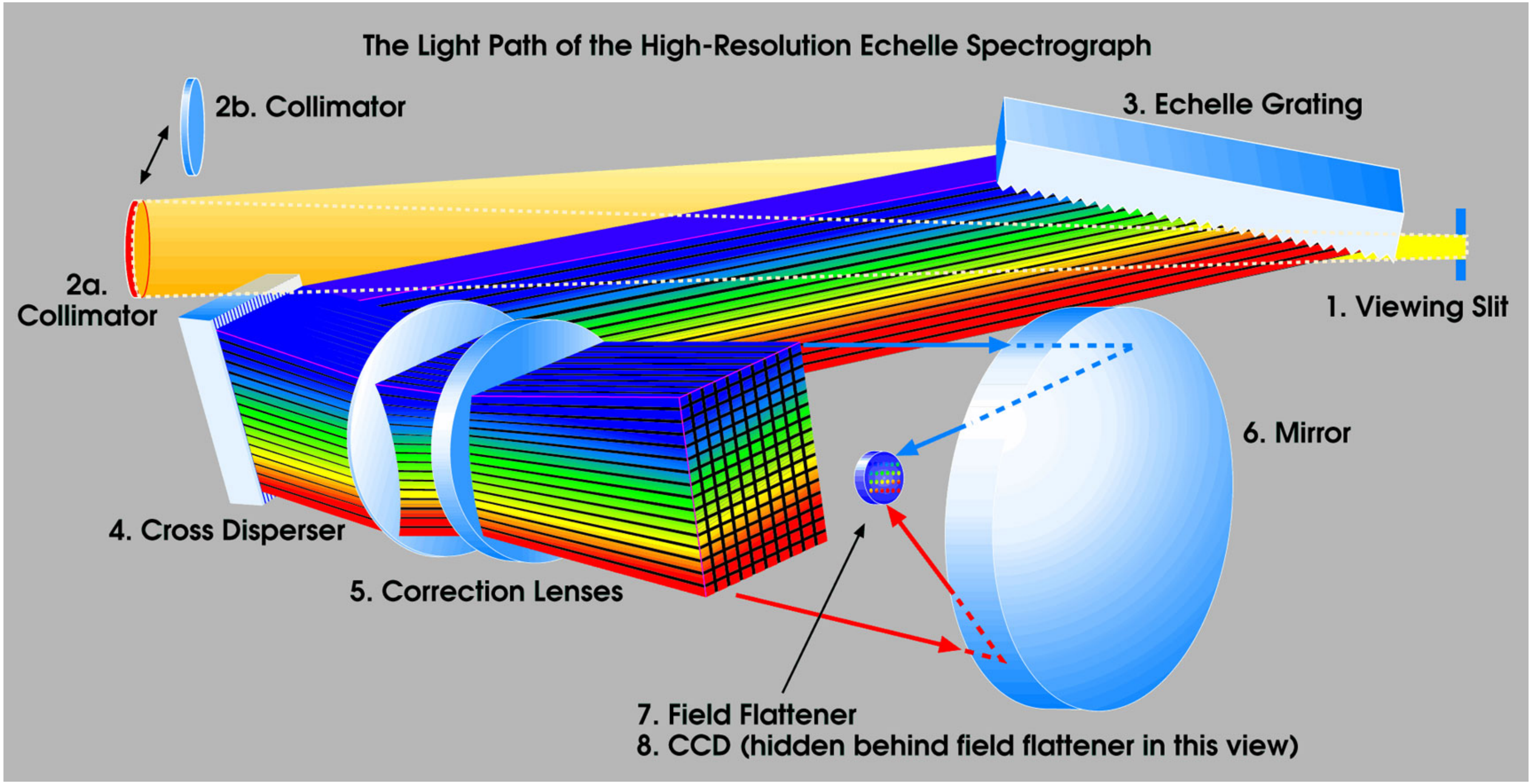






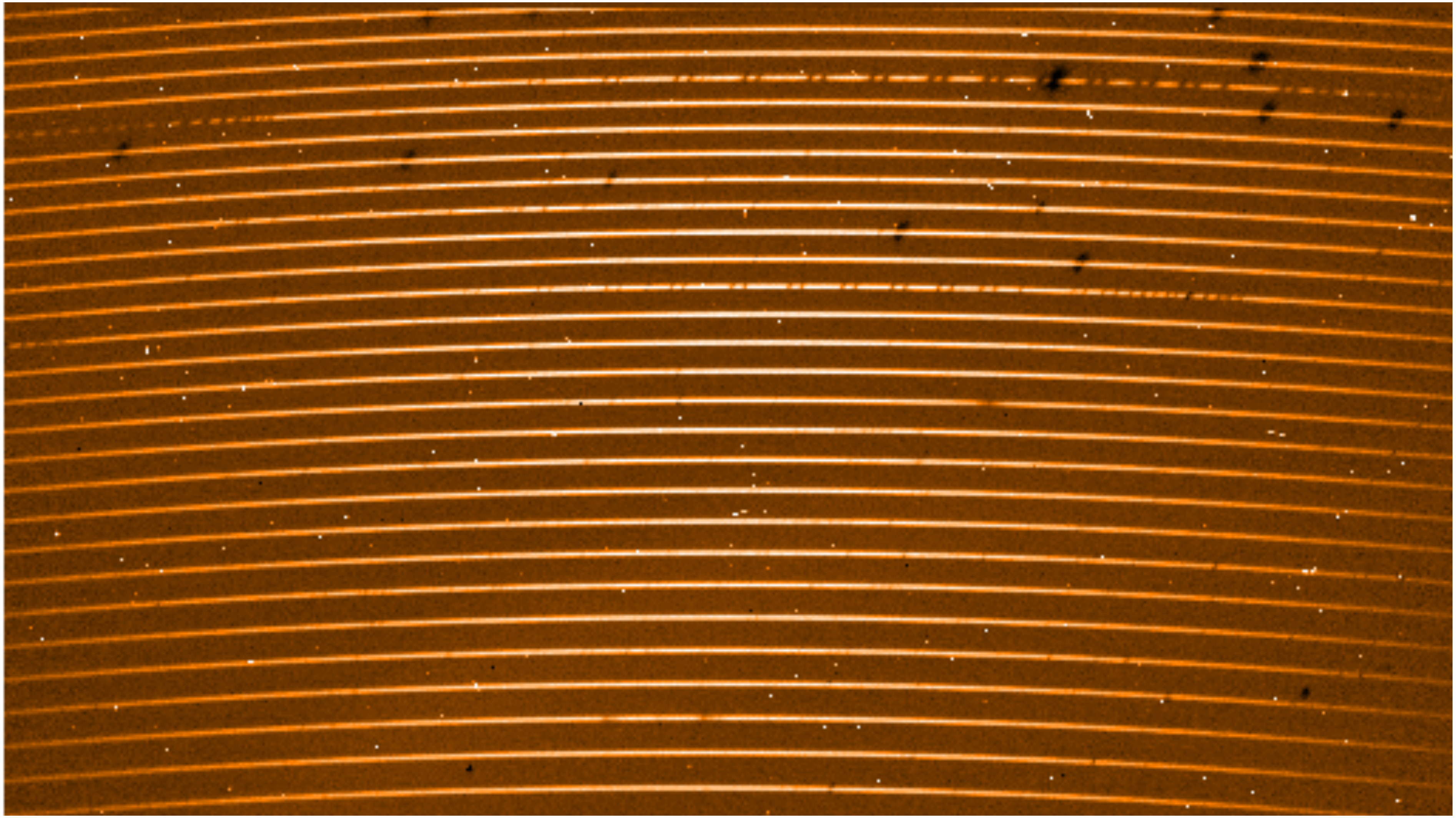
Echelle Spectrograph

Operation in high order → cross-disperser is essential



McMath-Pierce Spectrograph

Cross-Dispersed Echelle Spectrum

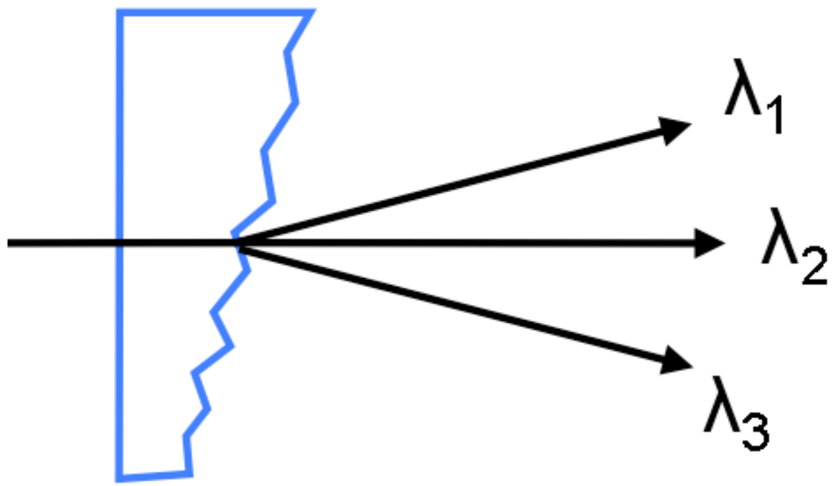


echelle spectrum of V454 Aur

Grisms

Grism = transmission GRating + prISM

For one wavelength and diffraction order, refraction of grating and prism may compensate and optical axis remains (almost) unchanged.



Advantage:

- ideal to bring in and out of a collimated beam ("filter wheel")

Disadvantages:

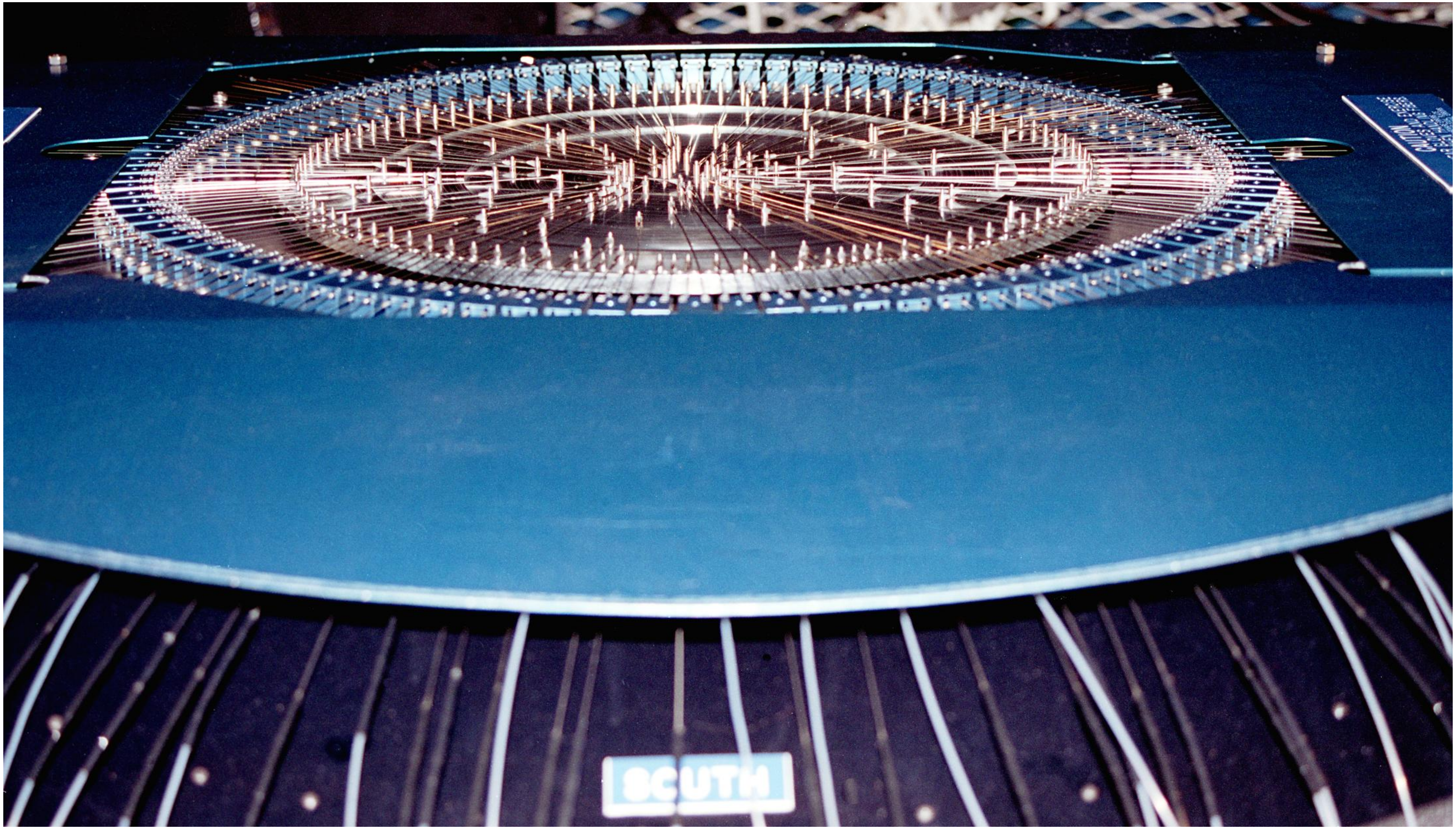
- difficult to manufacture (replication and gluing or by direct ruling).
- can be quite "bulky" (← filter wheel)

Multi-Object Spectrographs

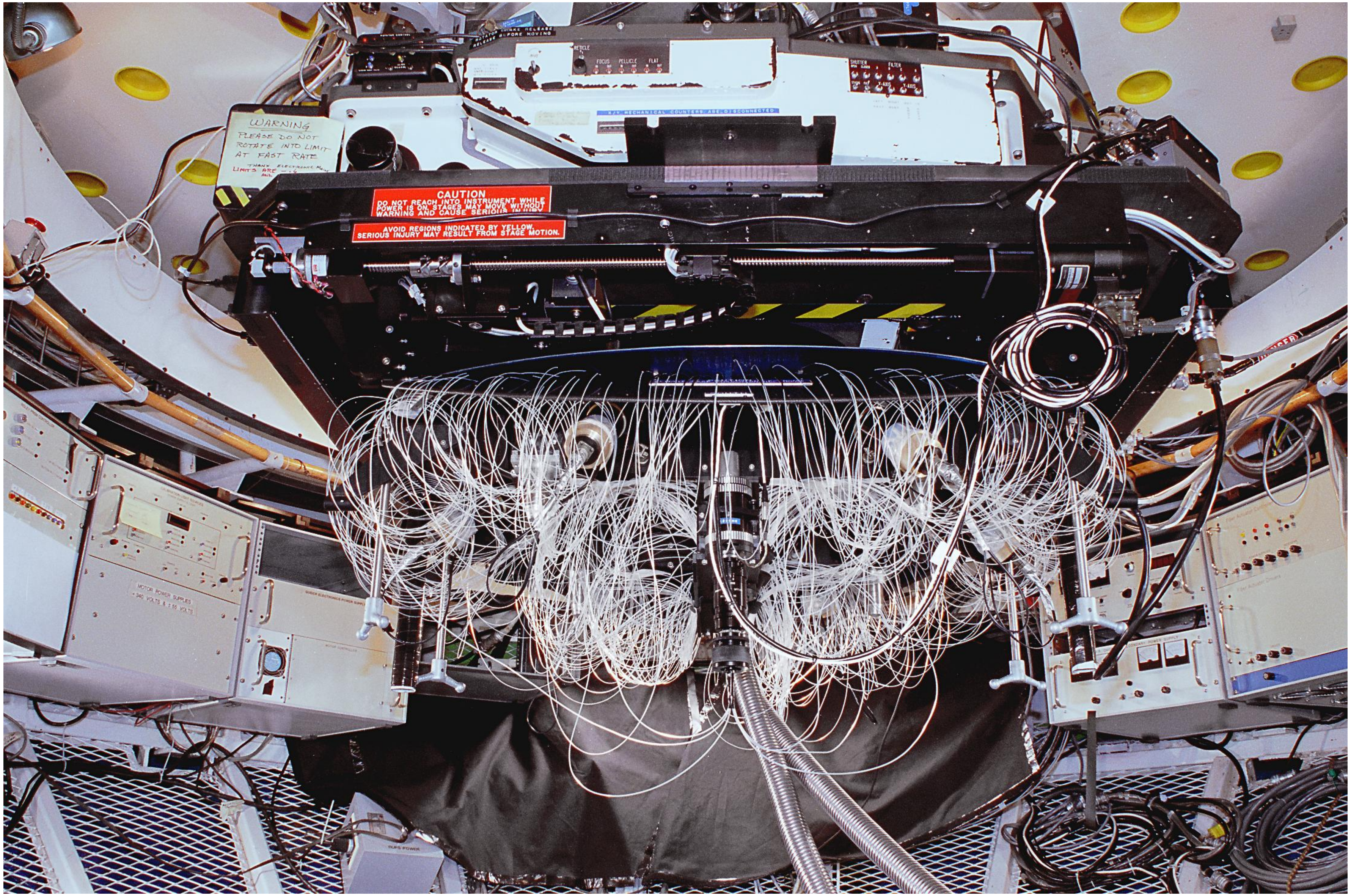
Use numerous “slits” in the focal plane simultaneously → multiple source pick-ups using fibers or mirrors.

Needs different slit masks for different fields.

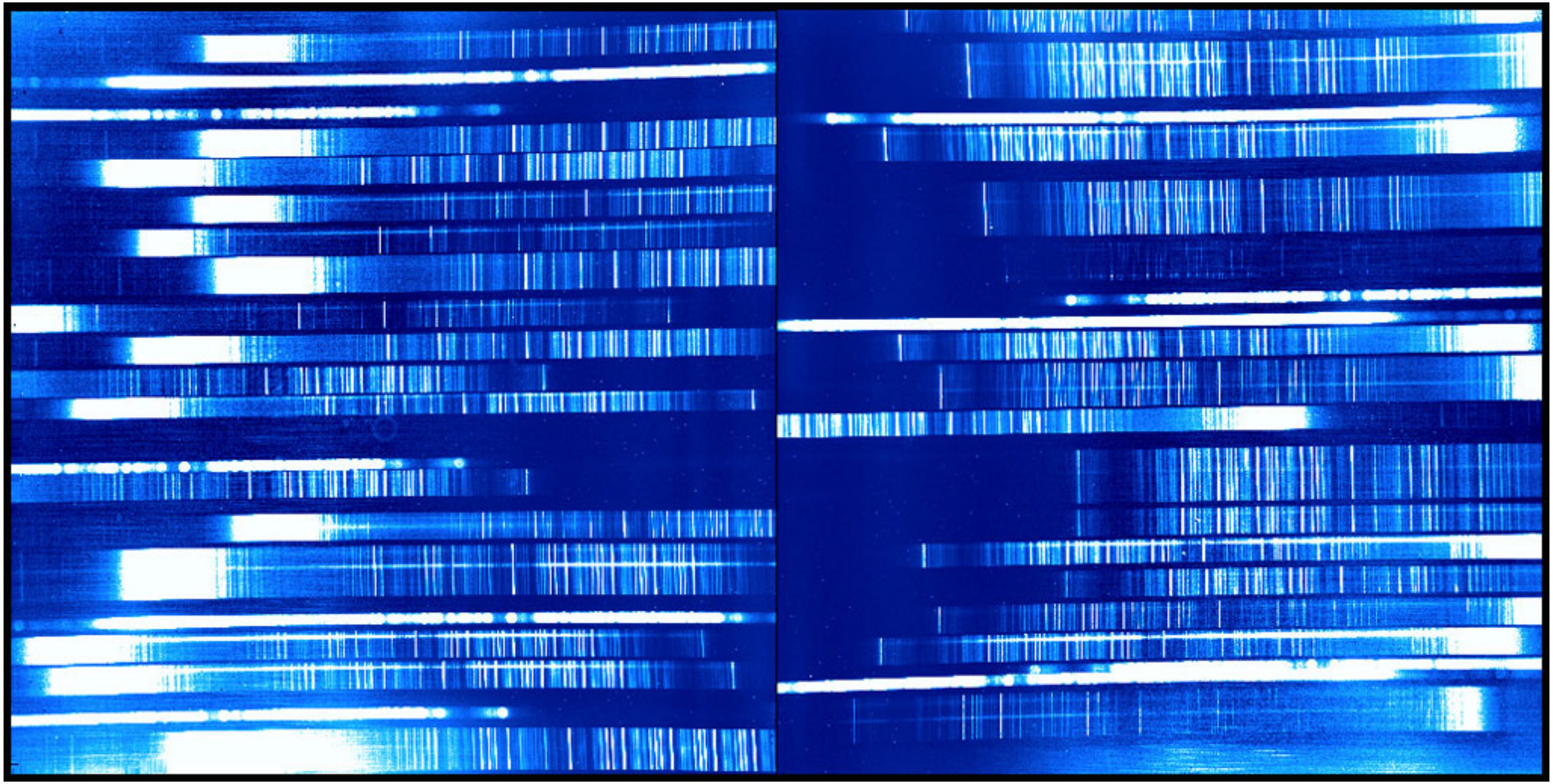
Hydra Arbitrary Fiber Positioning



Hydra Arbitrary Fiber Positioning

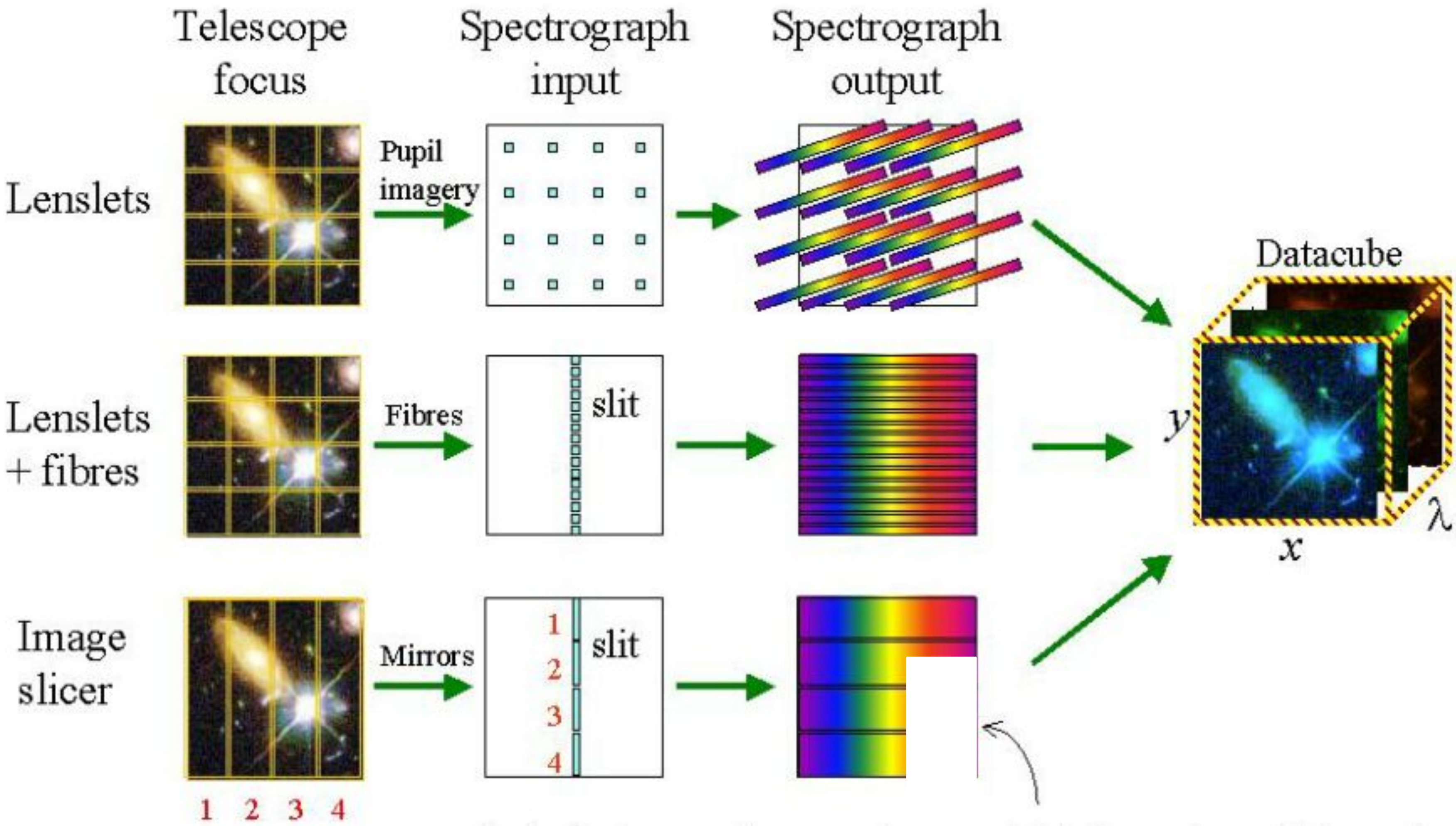


Multi-Object Spectrograph Spectra

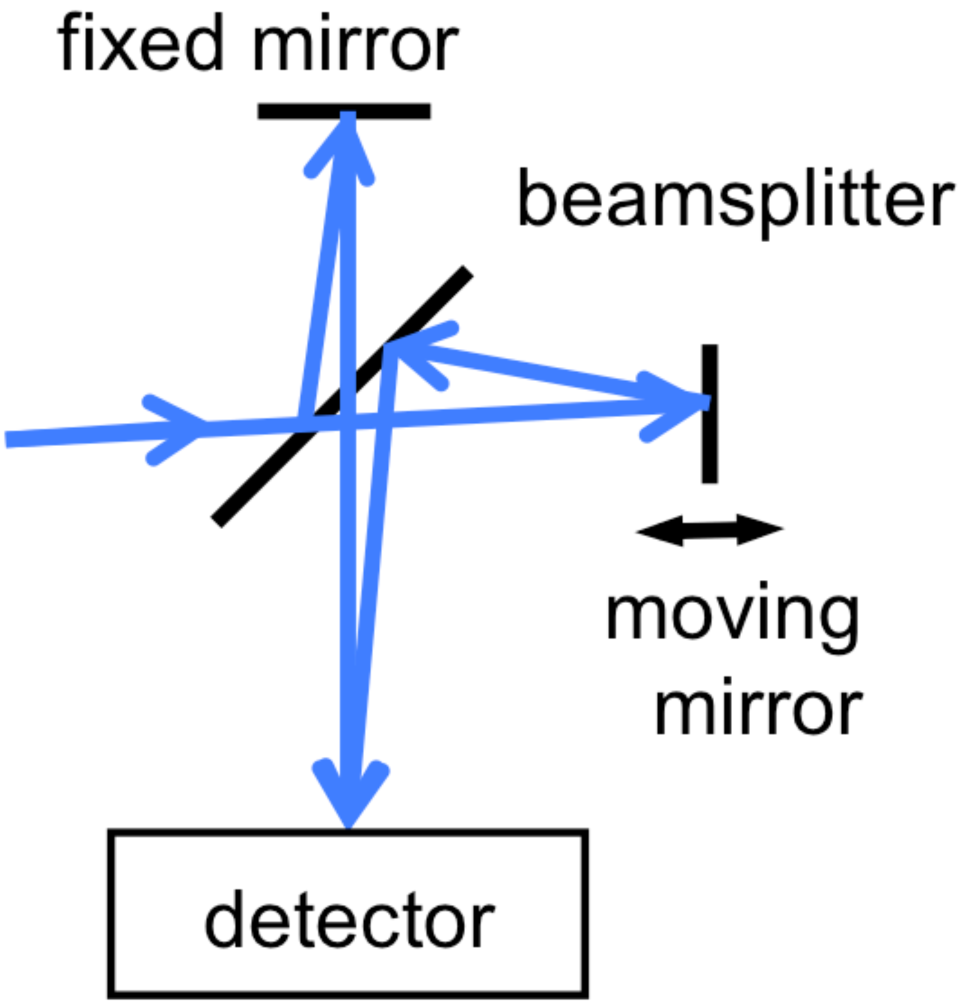


Integral Field Spectrographs

Cut area on sky into adjacent slices or sub-portions, realign them optically into one long slice and treat it as a long slit spectrograph.



Fourier Transform Spectrometer (FTS)



- Michelson interferometer with one moving arm to change optical pathlength
- Mostly single pixel as detector

FTS – Measured Intensity

- Output intensity $I(x)$ for a monochromatic input intensity I_0 (with wave number $k=2\pi/\lambda$ and path length difference x) is:

$$I(x)=\frac{I_0}{2}(1+\cos kx)$$

- Source with spectrum $I_0(k)$ in range $[k_1,k_2]$ produces signal

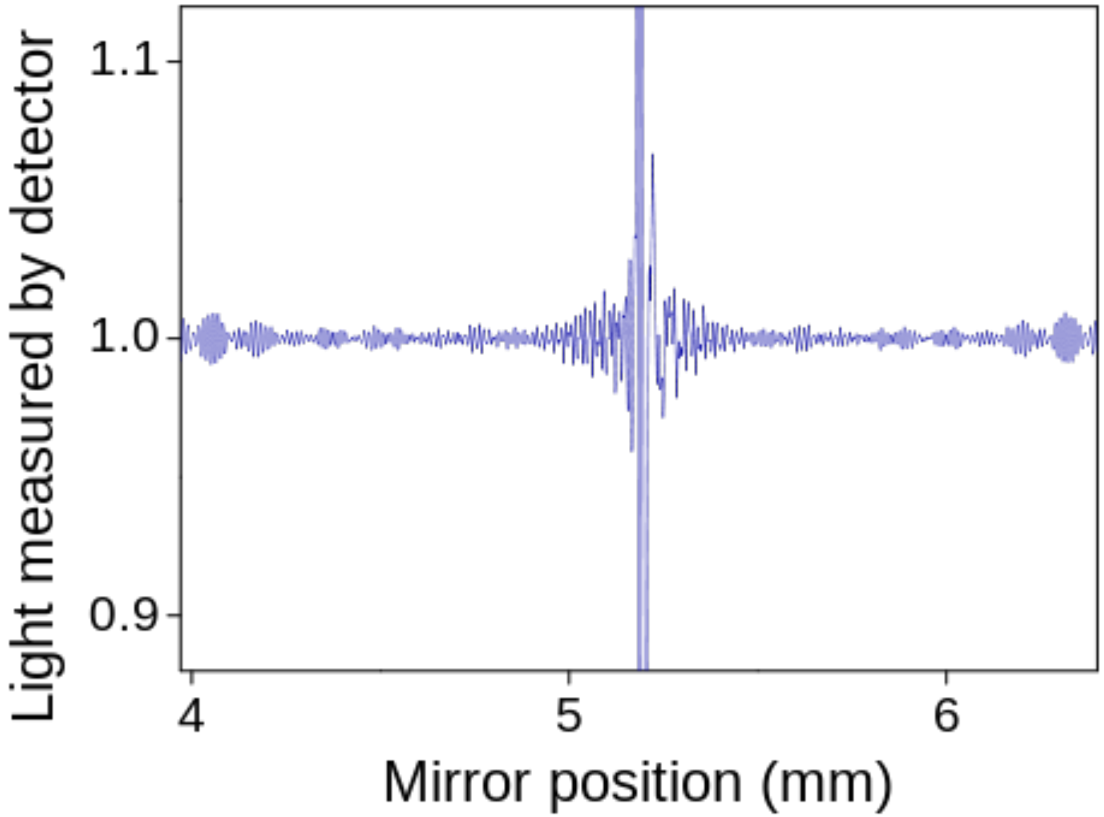
$$I(x)=\frac{1}{2}\int_{k_1}^{k_2} I_0(k)(1+\cos kx)\,dk$$

- Constant term plus real part of Fourier transform of spectrum

FTS – Measured Intensity

- For each path-length difference *x*, all spectral elements of incident spectrum contribute to signal
- Only one Fourier component is measured at any given path-length difference *x*
- Spectral resolution with maximum path length difference x_{max} is $R=2x_{max}/\lambda$

FTS – Output Signal



- For each moving mirror position, broadband (integrated over wavelength) intensity is measured
- Measured signal is an interferogram
- Interferogram is Fourier transform of object spectrum

Pros & Cons of Different Spectrographs

Spectrometer	Advantages	Disadvantages
Long-slit	• relatively simple → high throughput • easy to calibrate and to remove skylines	• only one object at a time • inefficient use of detector space
Echelle	• high spectral resolution • efficient use of detector	• challenging grating/optics • limited instantaneous λ range
Integral field	• instantaneous 2D info • ideal for resolved objects	• complex optics • single objects only
Multi-object	• up to thousands of spectra • ideal for spectral surveys	• complex mechanisms to select fields • fibre transmission limits λ
Fourier-transform (FTS)	• very high resolution • imaging FTS possible	• less gain with high background • high resolution ⇔ wide interval • difficult in cryo instruments