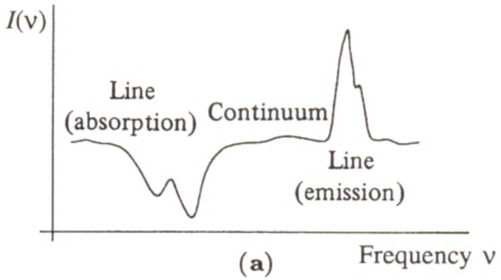
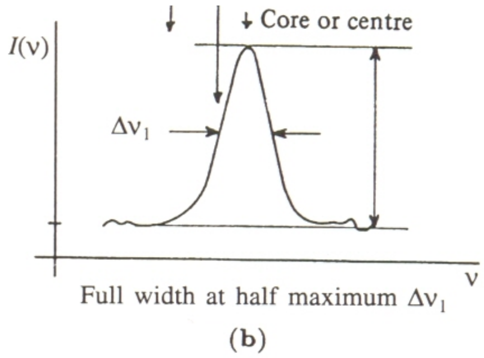
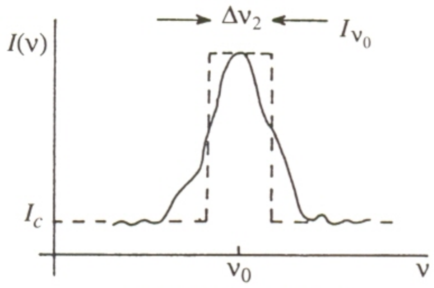
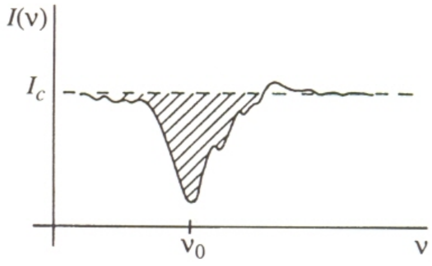
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

Based on lectures by Bernhard Brandl



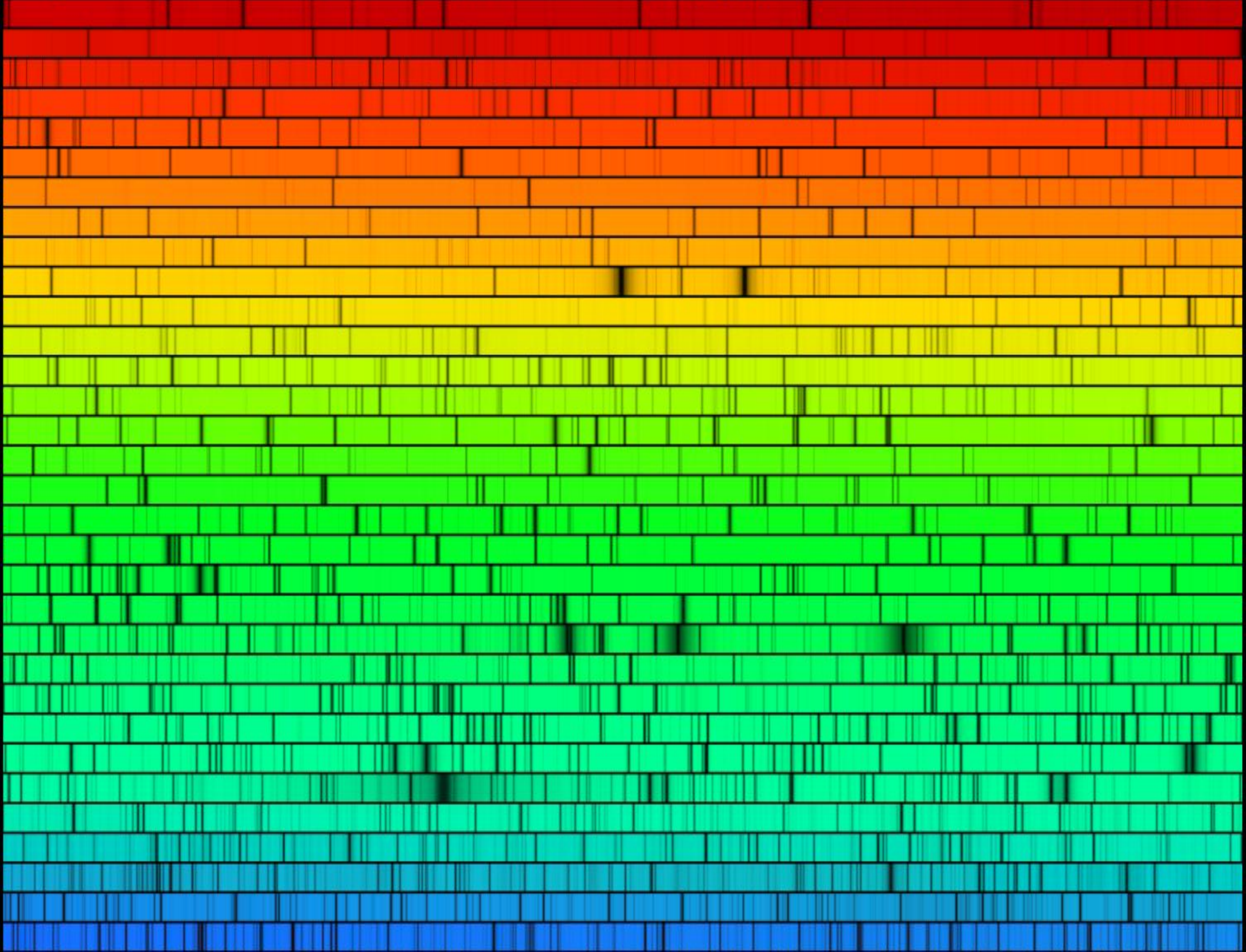






Lecture 11: Spectrographs

1. Spectral Lines
2. Optical Spectrograph
3. Gratings and Filters
4. Advanced Spectrometers
5. Spectral Line Analysis



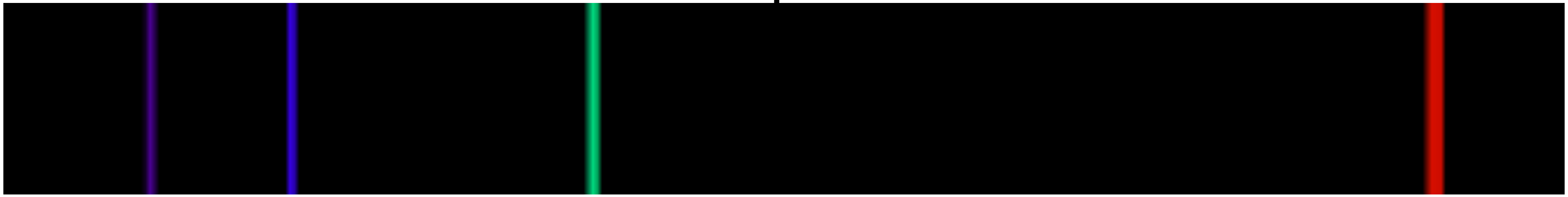
Origins of Spectral Lines

- Electronic transitions due to electron orbit changes (→ *visible, near-infrared*).
- Electronic fine structure transitions due to coupling of electron spin and orbital angular momentum (→ *far-IR, radio*).
- Electronic hyperfine structure transitions due to interaction of nuclear and electron spins (→ *radio, 21-cm line*).
- Molecular transitions such as rotational and vibrational transitions (→ *near-far-IR*).
- Nuclear lines due to nuclear excitations or electron-positron annihilation (→ *MeV range*)
- Transitions in solids (ices) due to vibrations → phonons (→ *near-far-IR*).

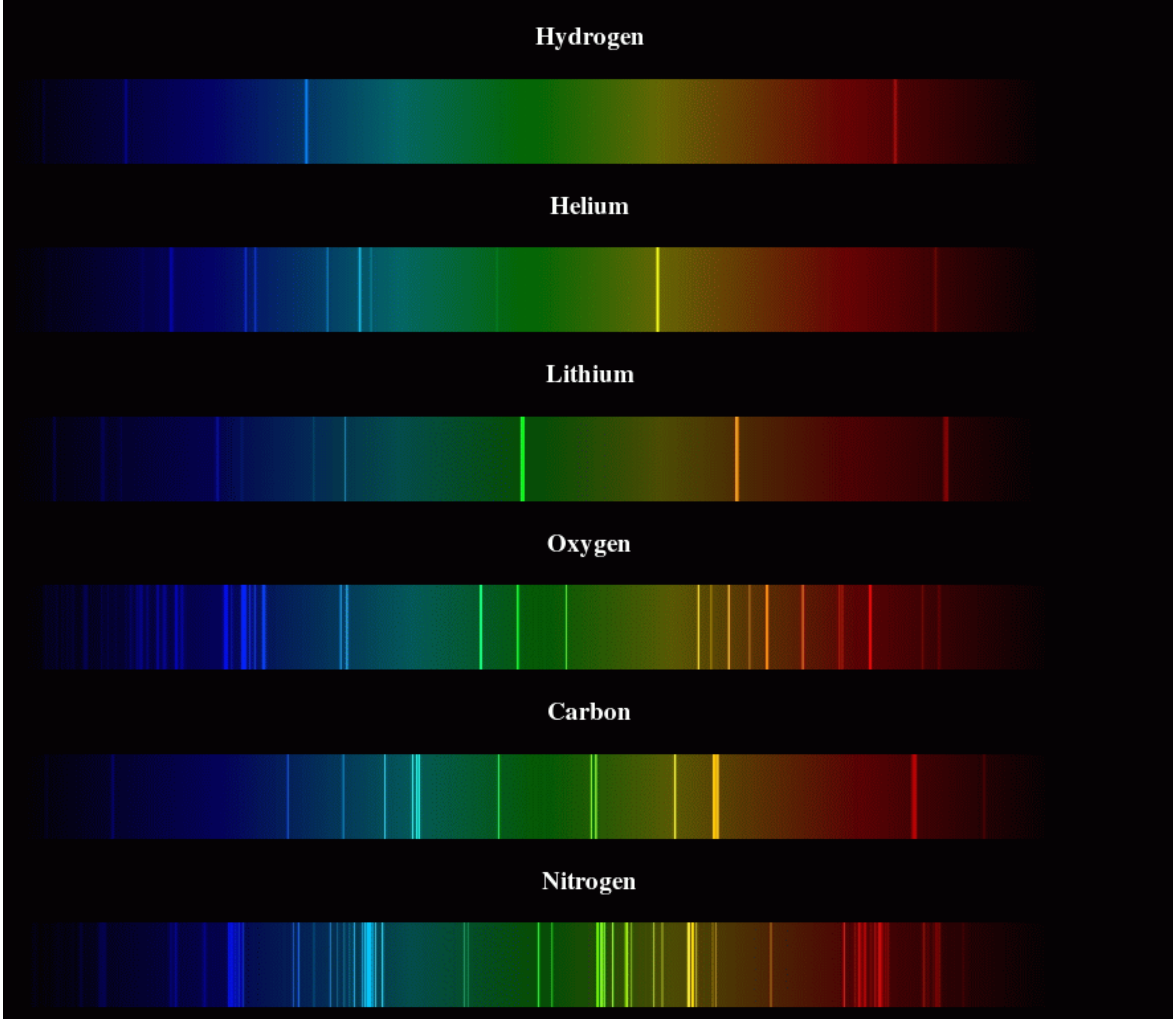
Continuous, Emission and Absorption Spectra

Continuous spectrum

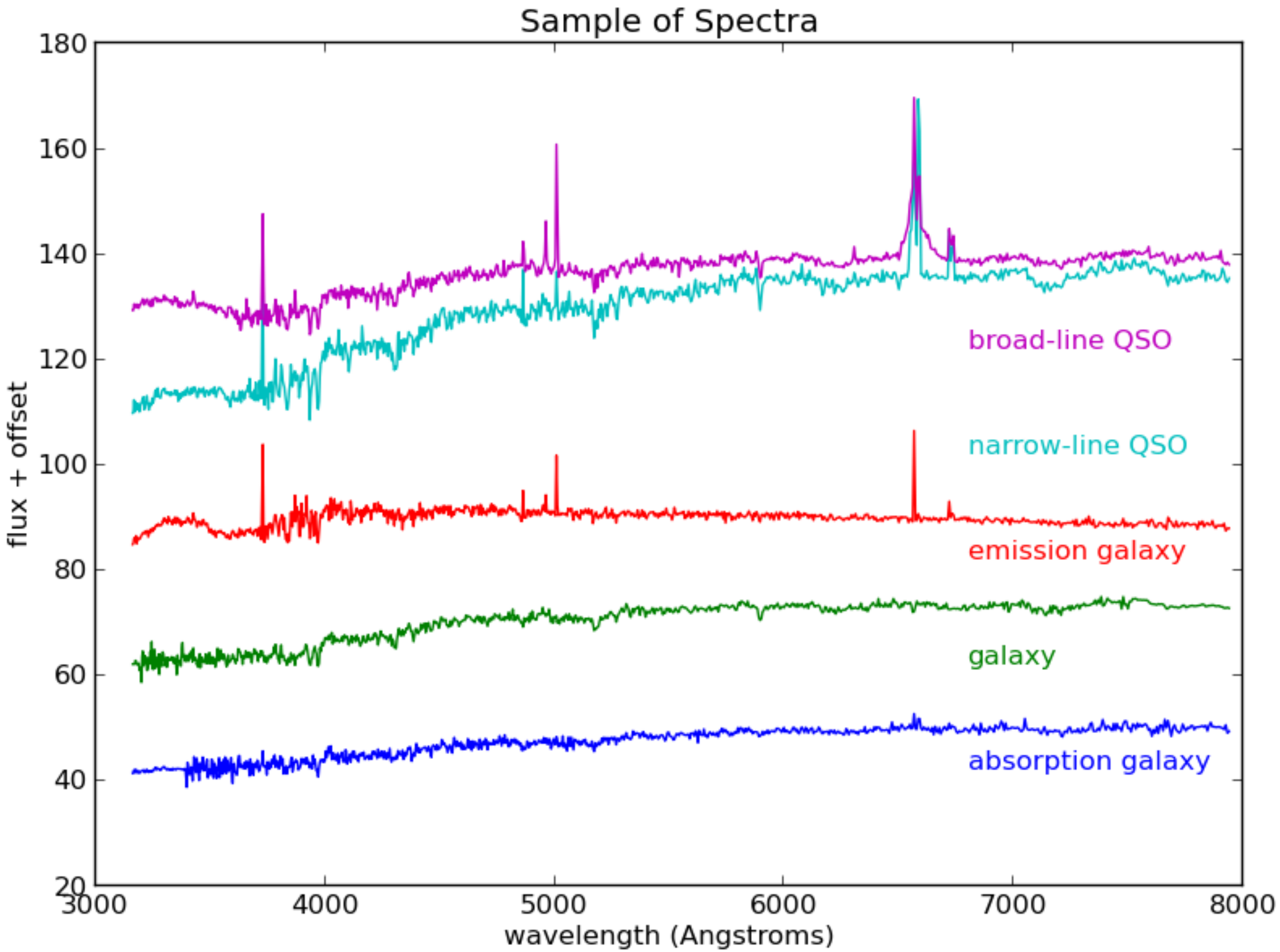
Emission line spectrum



Absorption line spectrum

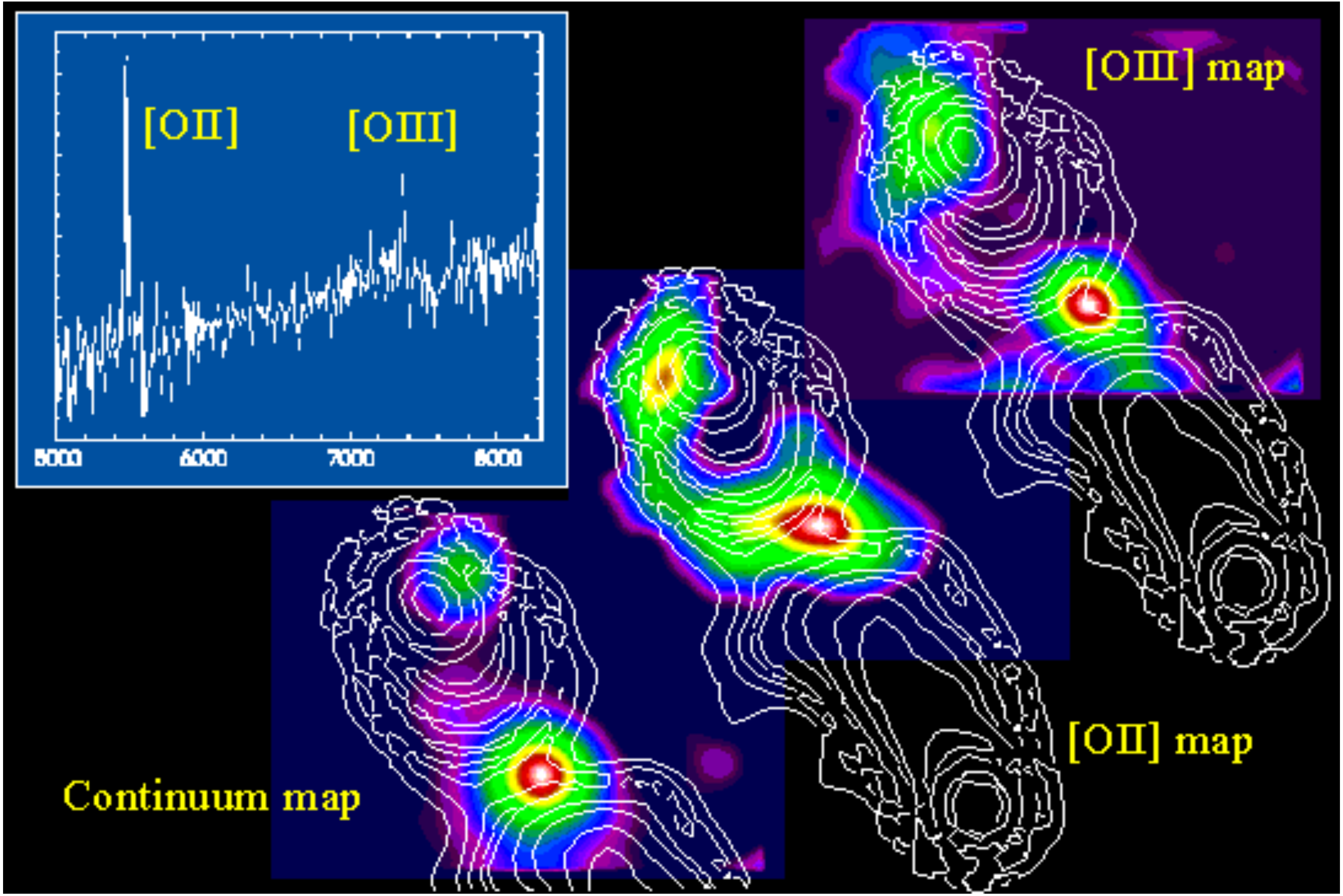


Courtesy:
http://home.achilles.net/~ypvsj/data/elements/index.html



Plot courtesy: SDSS

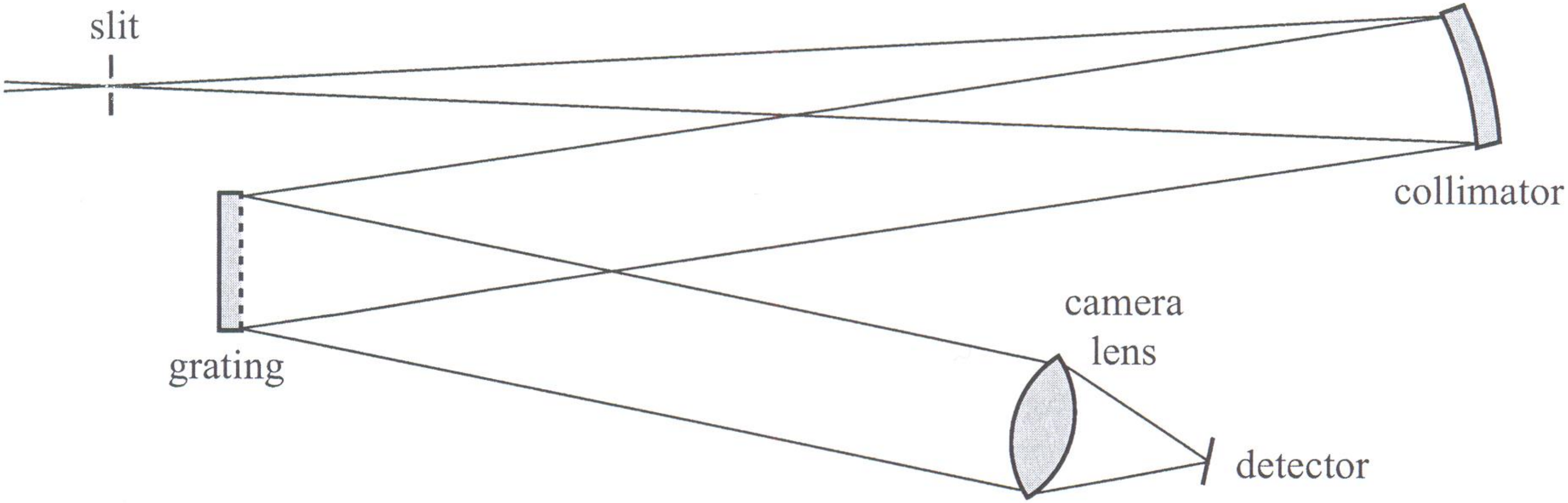
Spectral Line Maps



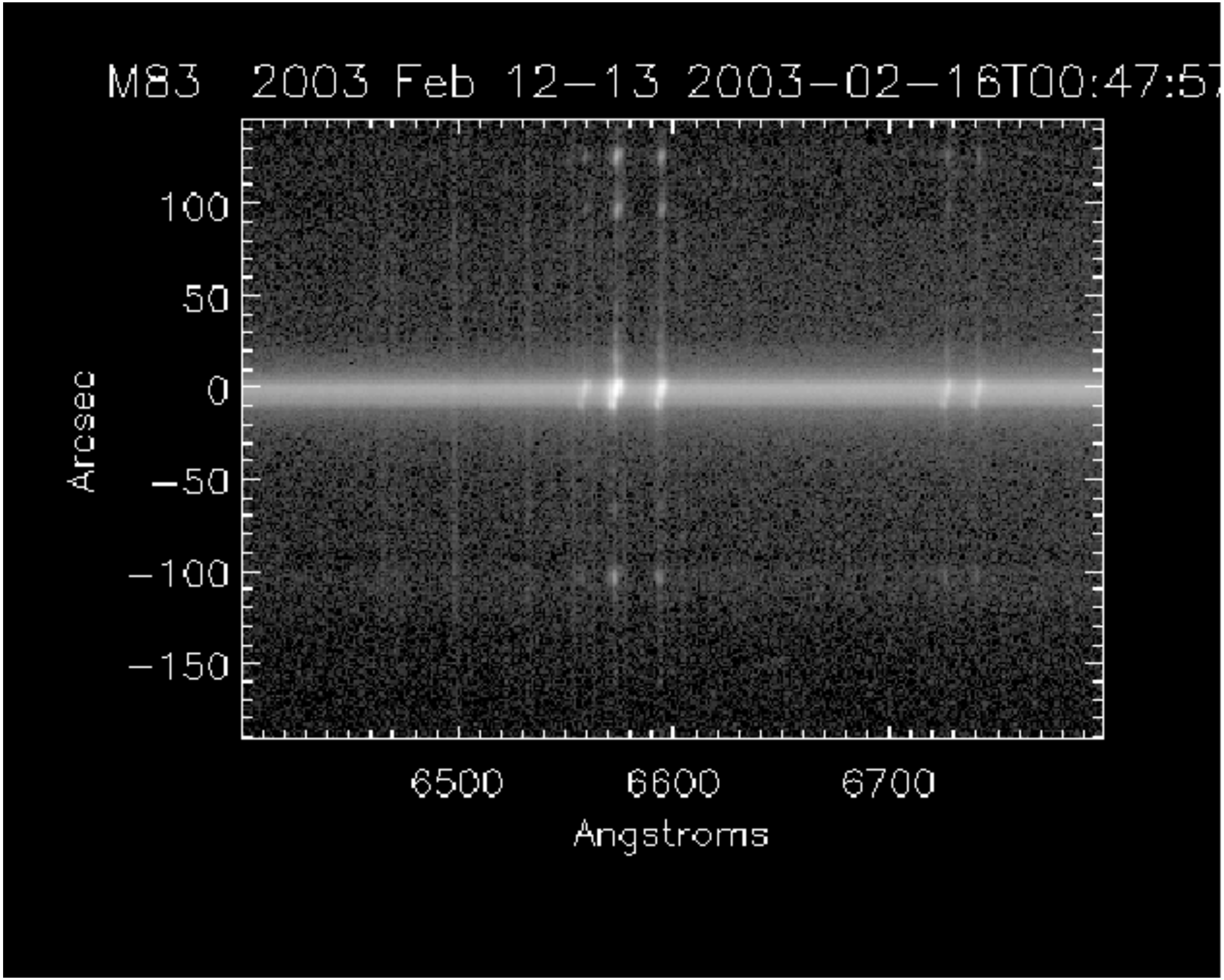
Radiogalaxy 3C435A radiogalaxy 3C435A
Plot courtesy: Universite de Lyon, Recent TIGER Scientific Results

Ingredients of an Optical Spectrograph

1. A Slit (onto which the light of the telescope is focused)
2. A Collimator (diverging → parallel/collimated light)
3. A Disperser (to spectrally disperse the light)
4. A Camera (to focus the spectrum onto the detector)



Long Slit Spectra



Main Characteristics of a Spectrograph

- Spectral resolution element Δλ
- Spectral resolution (or resolving power): R=λ/Δλ
- Instrumental profile P(λ) broadens a theoretically infinitely narrow line to the observed line width:

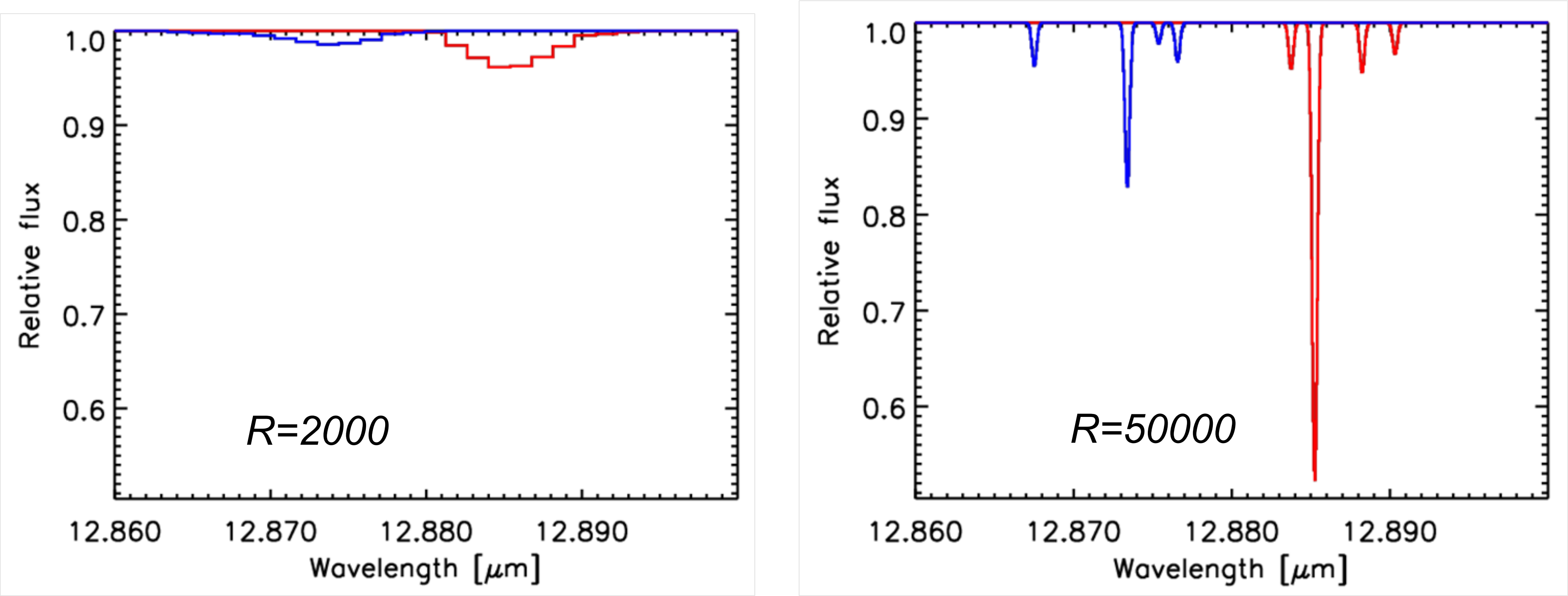
$$I_0(\lambda) = \delta(\lambda - \lambda_0) \qquad I(\lambda) = P(\lambda) * I_0(\lambda)$$

- *Usually the instrumental profile determines the spectral resolution element, which is typically Nyquist-sampled*
- Transmission determines the throughput η(λ)

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

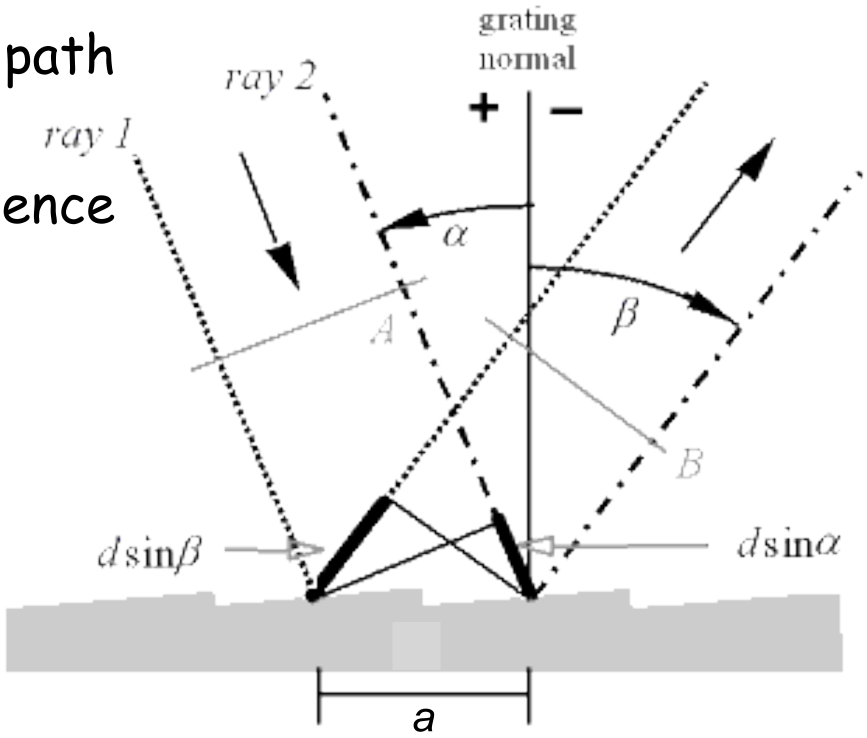
Spectral Resolution and S/N

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).

Diffraction Grating



Use a device that introduces an optical path difference = f{angle to the surface}

The condition for constructive interference is given by the grating equation:

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

m = order of diffraction
λ = wavelength
a = distance between equally spaced grooves
α = angle of incoming beam
β = angle of reflected beam

- Gratings usually in collimated beam close to pupil
- Maximum spectral resolution: R=mN
  N = number of (illuminated) grooves
- Angular dispersion

$$d\beta / d\lambda = \frac{m}{a\cos\beta}$$

Blaze Angle

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

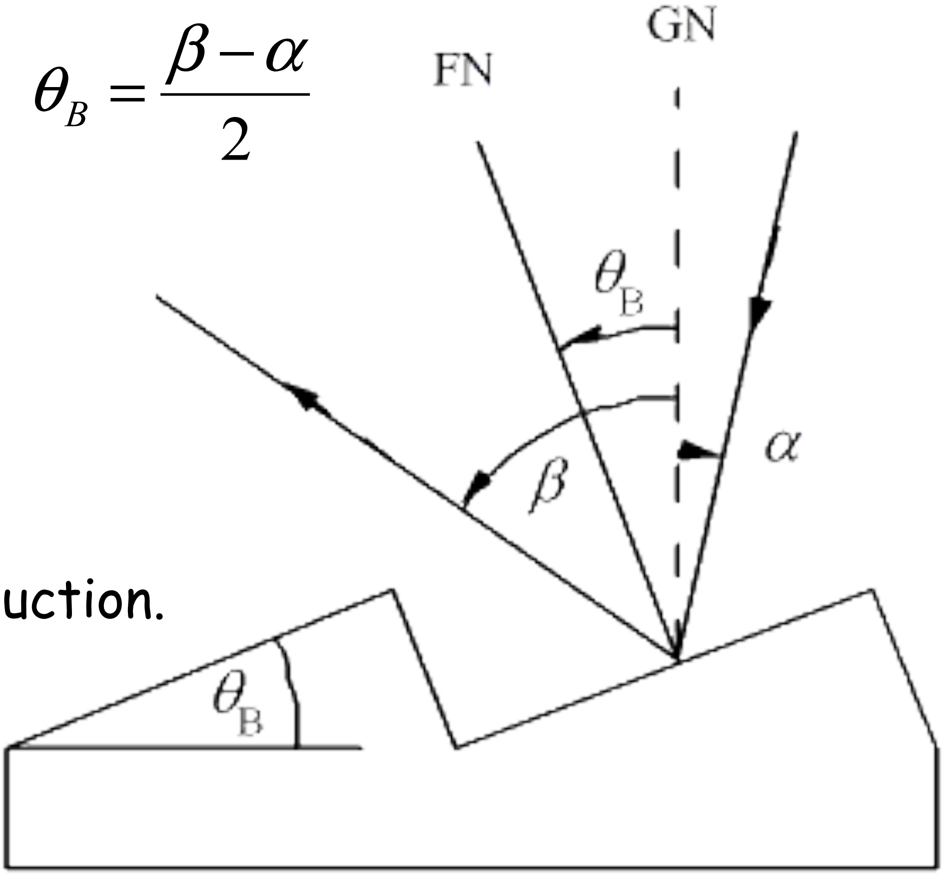
$$\alpha + \beta = 2(\alpha + \theta_B) \;\Rightarrow\; \theta_B = \frac{\beta - \alpha}{2}$$

Advantage:

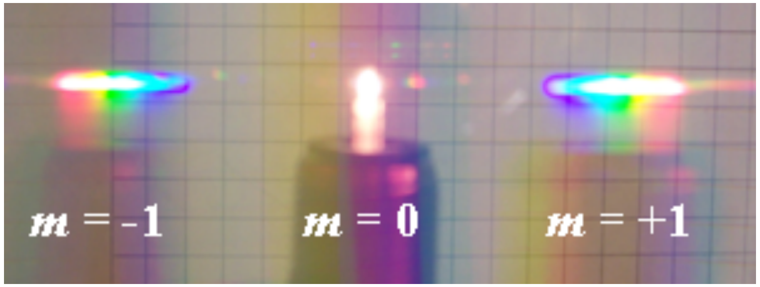
- High efficiency

Disadvantage:

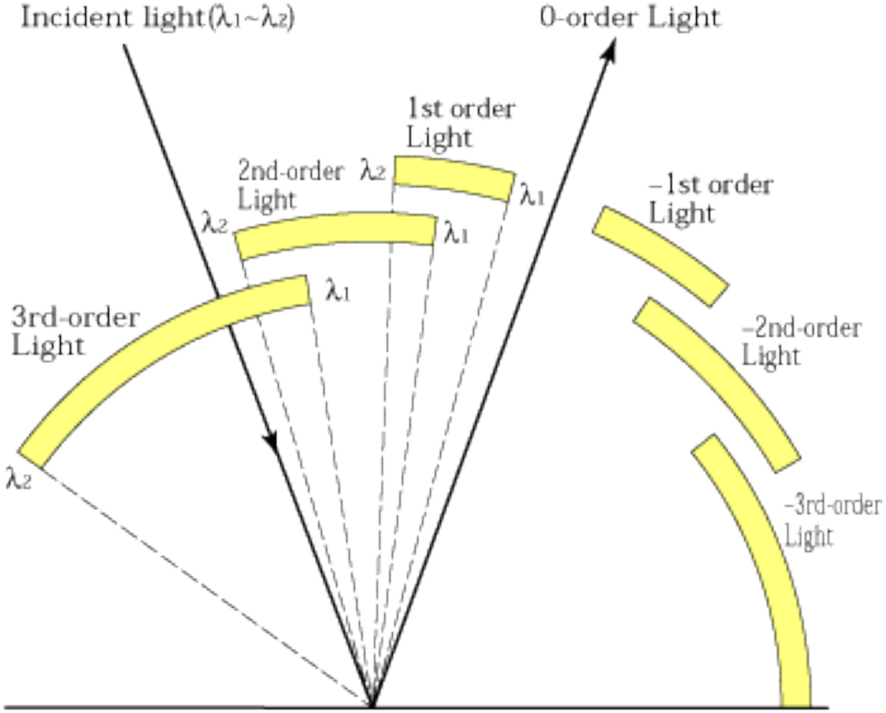
- Blaze angle θ_B (and hence blaze wavelength Λ_B) are fixed by construction.



Free Spectral Range …



A light bulb seen through a transmissive grating, showing three diffracted orders. m = 0 corresponds to direct transmission; colors with increasing wavelengths (from blue to red) are diffracted at increasing angles. Source: Wikipedia



Different diffraction orders overlap with each other:

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

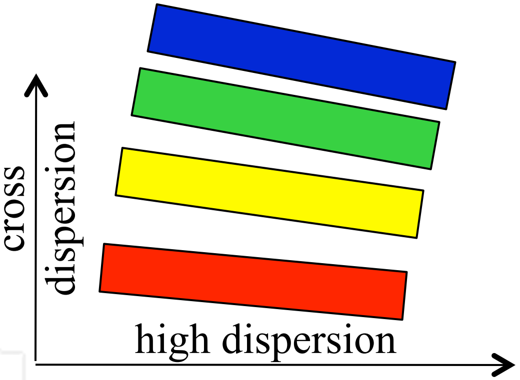
The free spectral range is the largest wavelength range for a given order that does not overlap the same range in an adjacent order.

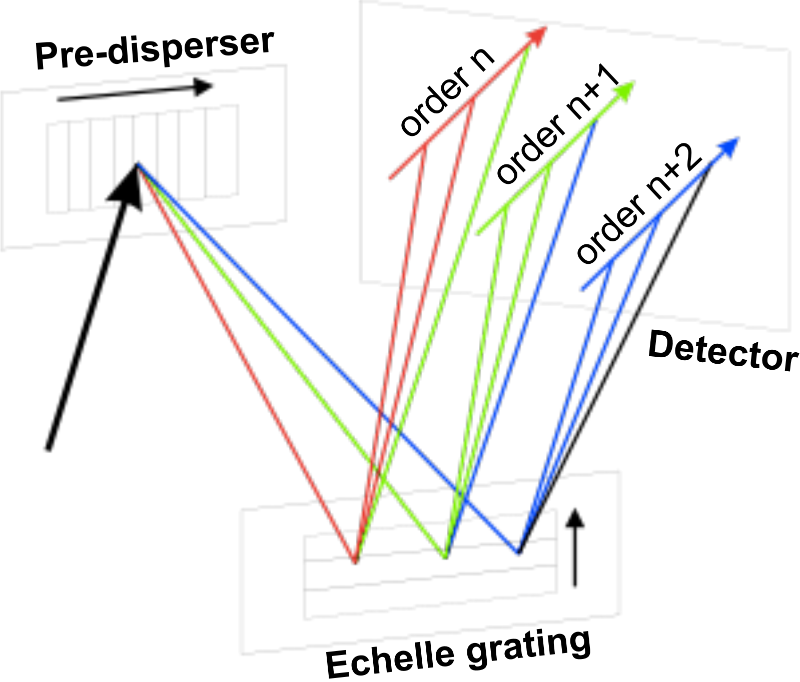
$$\Delta\lambda_{free} = \lambda - \lambda' = \frac{\lambda'}{m}$$

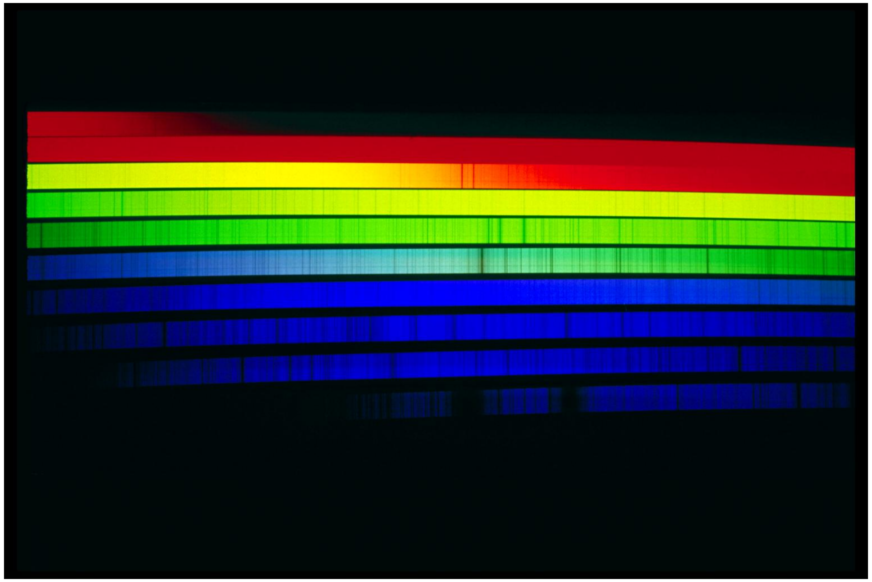
…and Cross-Dispersion

To spatially separate the orders and avoid overlap, an additional optical element will be needed:

A low-dispersion prism/grating with a dispersion direction perpendicular to that of the high-dispersion grating





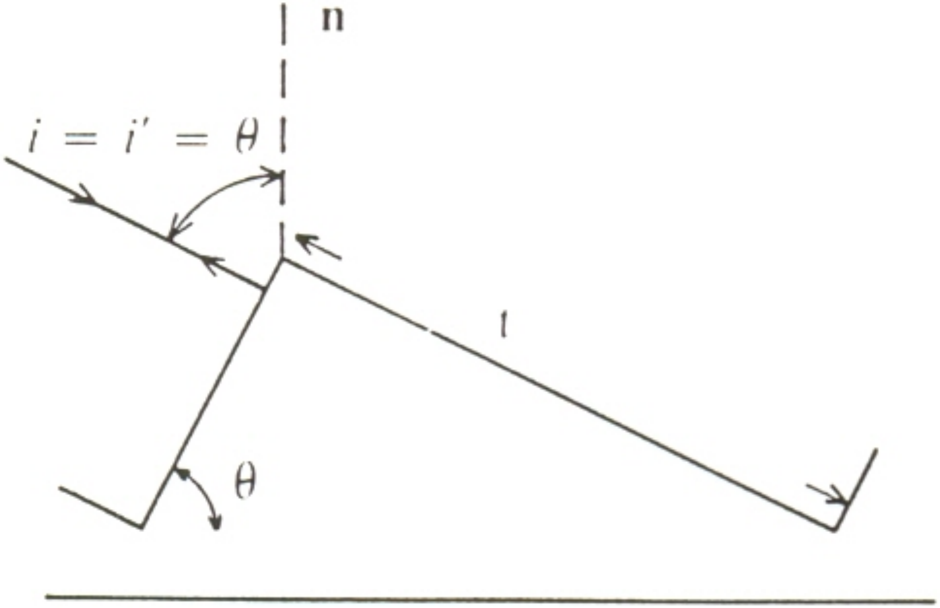


Echelle Gratings

Want high dispersion $$\frac{d\beta}{d\lambda} = \frac{m}{a\cos\beta} = \frac{\sin\alpha + \sin\beta}{\lambda\cos\beta}$$

and high spectral resolution $$R = Nm$$

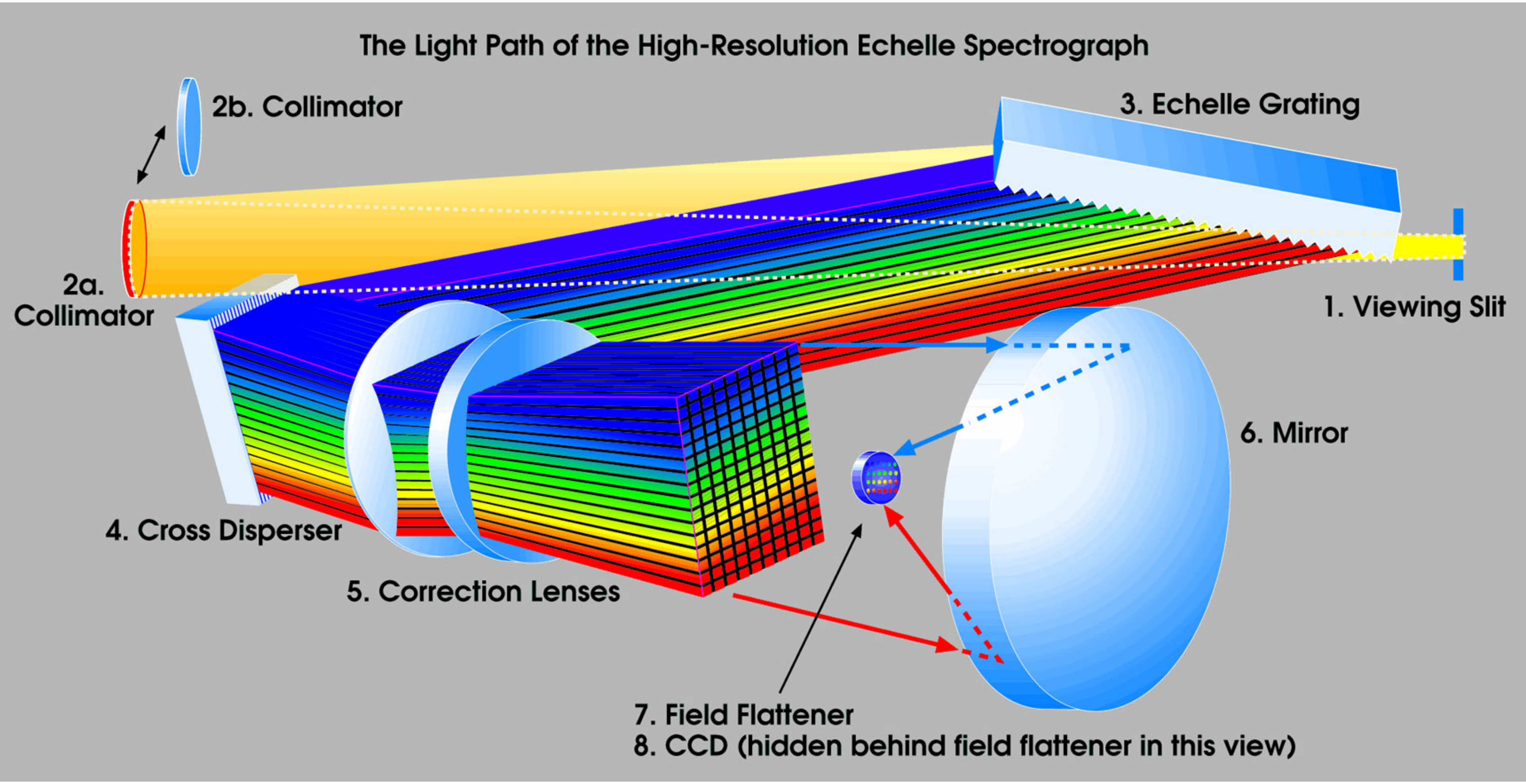
α and β large, high order m (≈ 50), and therefore large a



Grating equation in Littrow configuration ($\alpha=\beta$): $m\lambda_B = 2a\sin\beta$

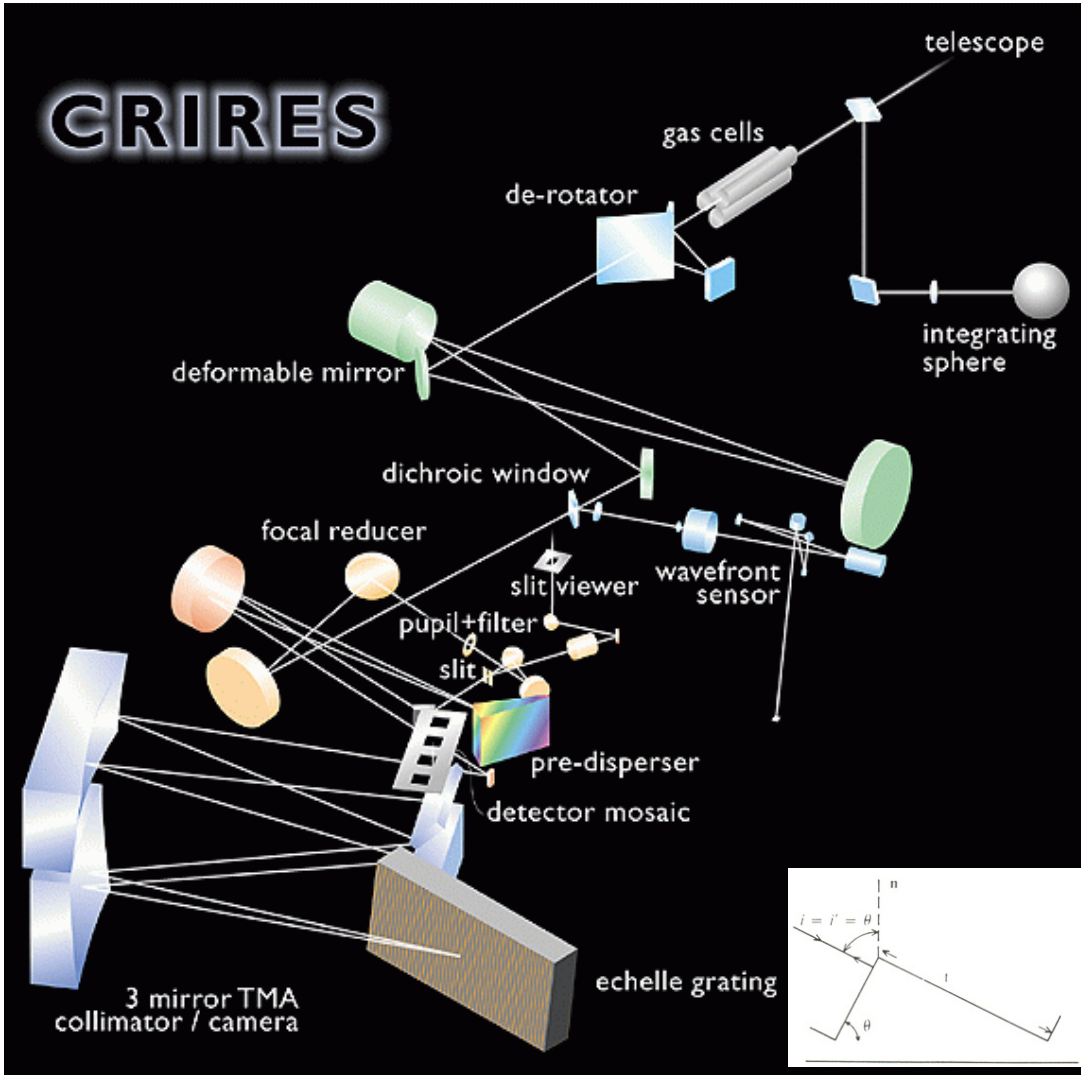
Echelle Spectrograph

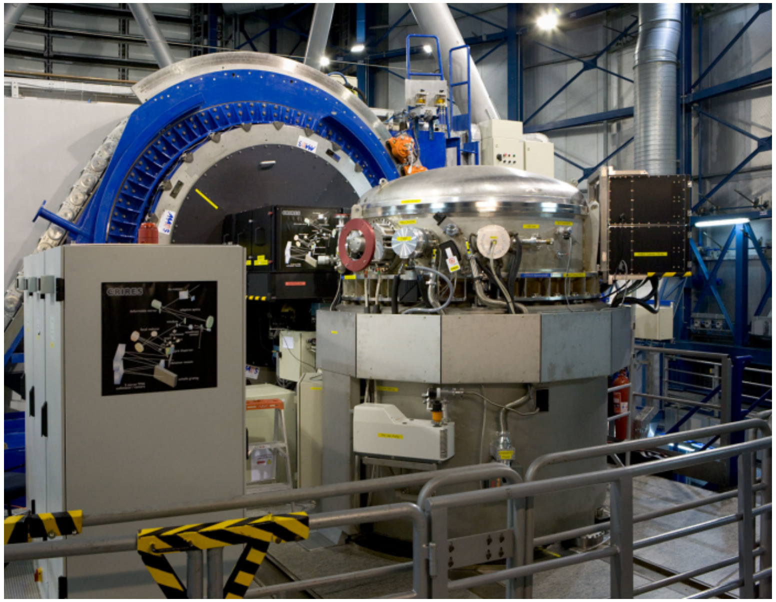
Operation in high order → pre-disperser essential



Echelle Spectrographs

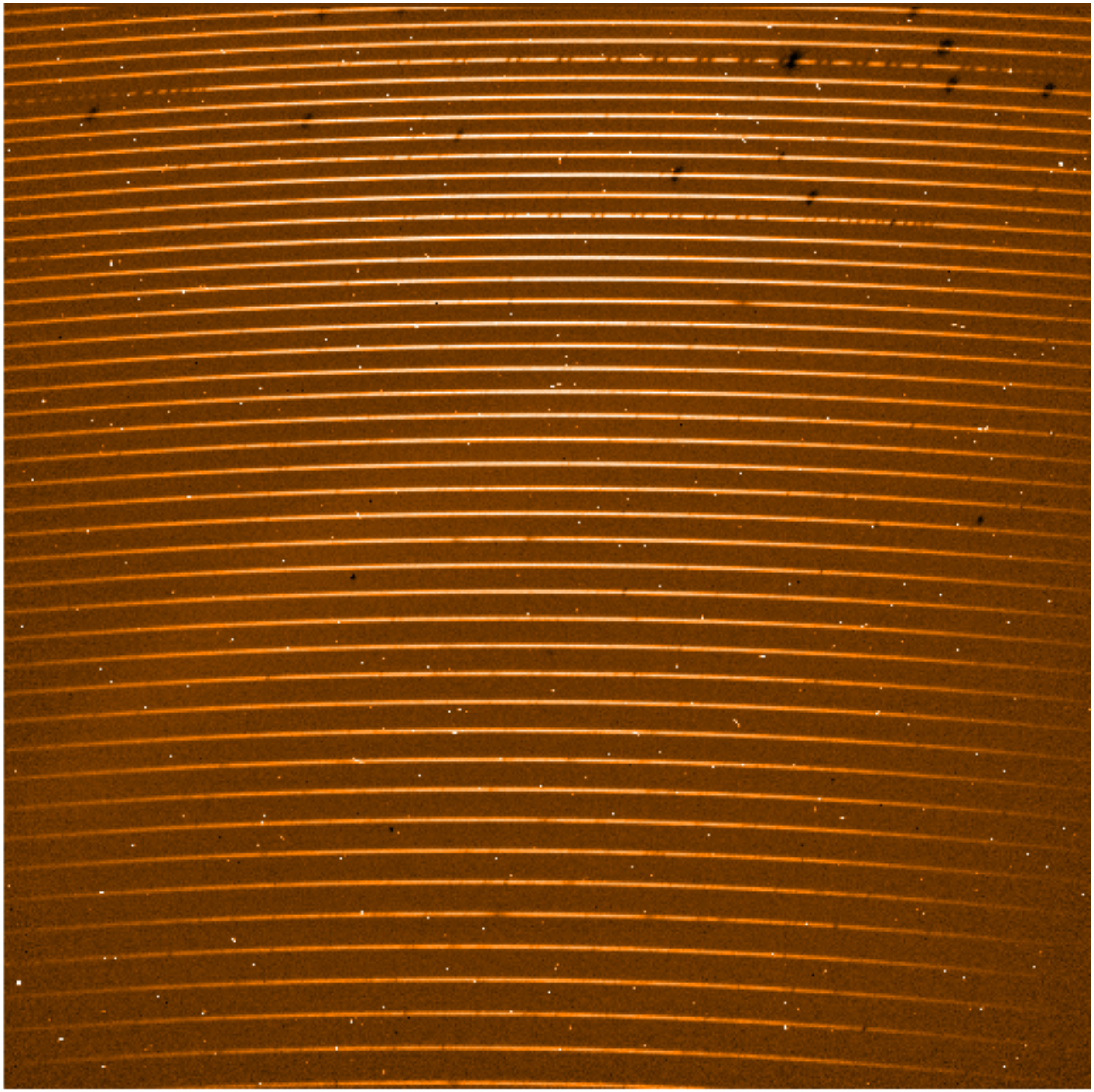
Example: ESO's VLT instrument CRIRES:





The ruled echelle grating of the SOFIA Facility Spectrometer AIRES. Two images of the engineer are seen reflected from the facets of the grooves that are at angles of 90 degrees from each other.

Echelle Spectra

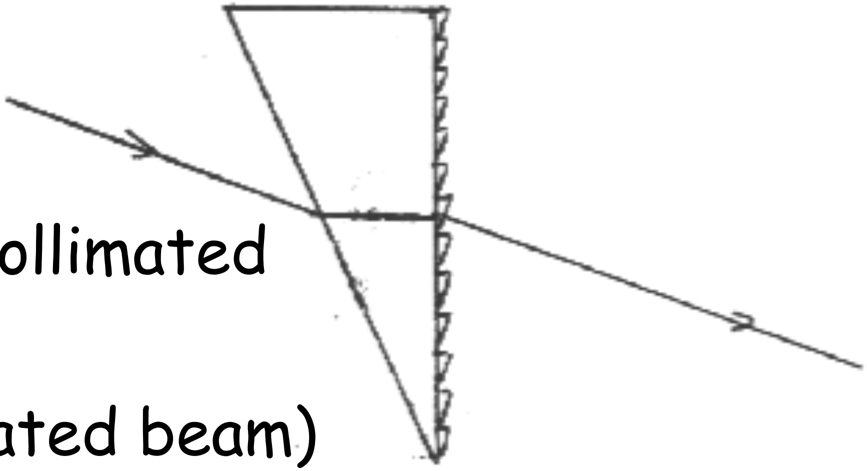


echelle spectrum of V454 Aur

Grisms

Grism = transmission GRating + prISM

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



Advantages:

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

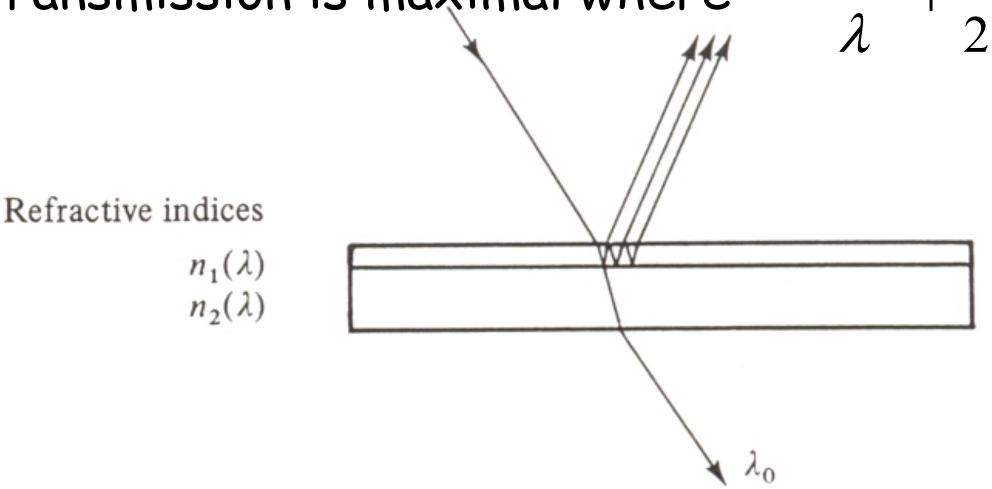
Disadvantages:

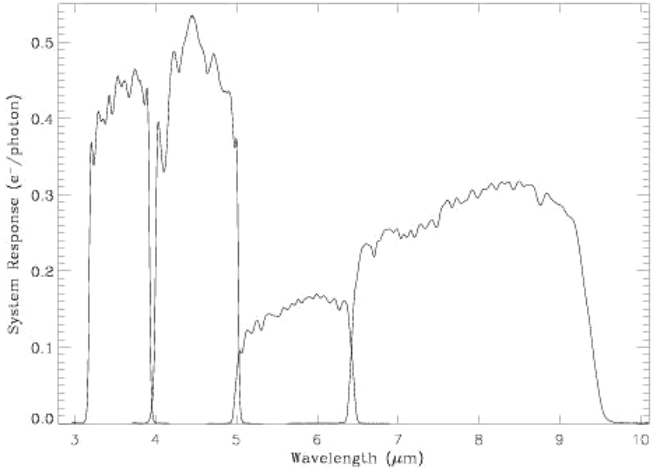
- difficult to manufacture (either by replication and gluing or by direct ruling.
- can be quite "bulky" (← filter wheel)

Interference (Transmission) Filters

Principle: layers with thickness of ~λ with different indices of refraction deposited on a substrate.

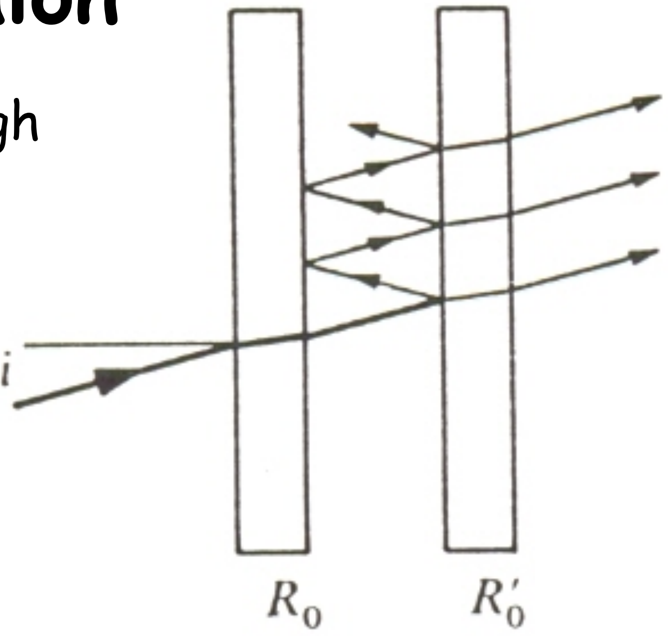
The transmission is maximal where $\frac{2n_1 d}{\lambda} + \frac{\pi}{2} = 2k\pi$





- spectral resolution typically R ~ 3 - 1000
- typically many interference layers
- filters are often tilted with respect to the optical axis to avoid reflections → shift of λ_0
- wavelengths farther from λ_0 (for which the above equation is also satisfied) need a blocking or absorbing filter.

Fabry-Perot Etalon



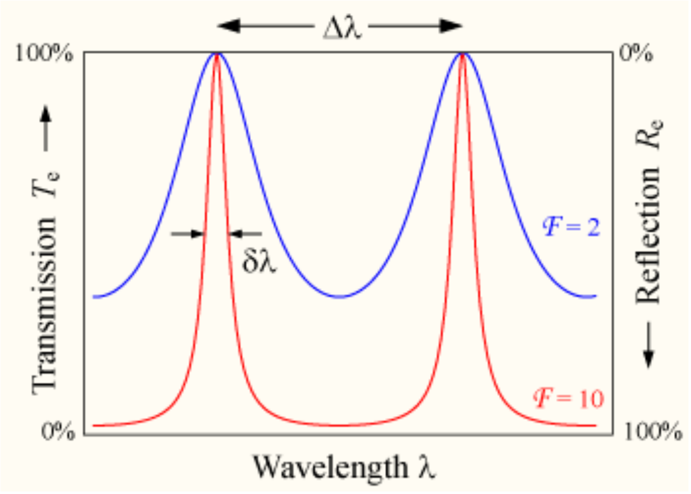
Two parallel plates (Fabry-Perot etalon) of high reflectivity *r* and transmission *t* = 1-*r*.

The transmission is:

$$I = I_0\left(\frac{r}{1-r}\right)^2\left[1+\frac{4r}{(1-r)^2}\sin^2(2\pi dk\cos i)\right]^{-1}$$

and has transmission peaks where $k = \frac{m}{2d}$

Here, *m* is the order of the interferometer, *d* is the separation of the plates, and Δ*k* = 1/2*d* the free spectral range.

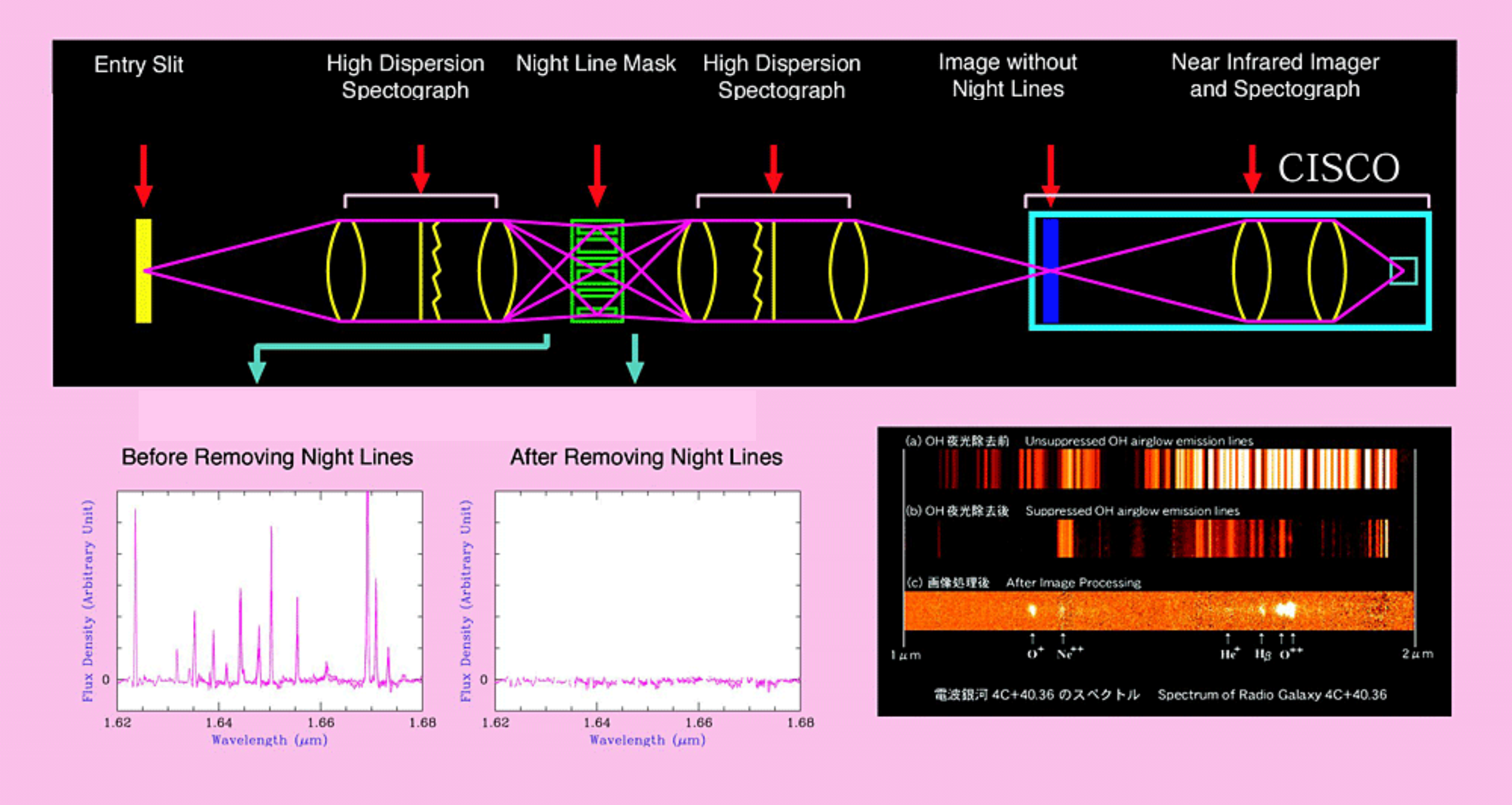


The spectral resolution is given by

1. The finesse $F = \frac{\pi\sqrt{r}}{1-r}$,
2. The resolution $R = \frac{k}{\Delta k} = mF$

OH Suppression Spectrographs

OHS filter out the wavelengths of atmospheric OH lines, which contribute the major part of the near-IR background.

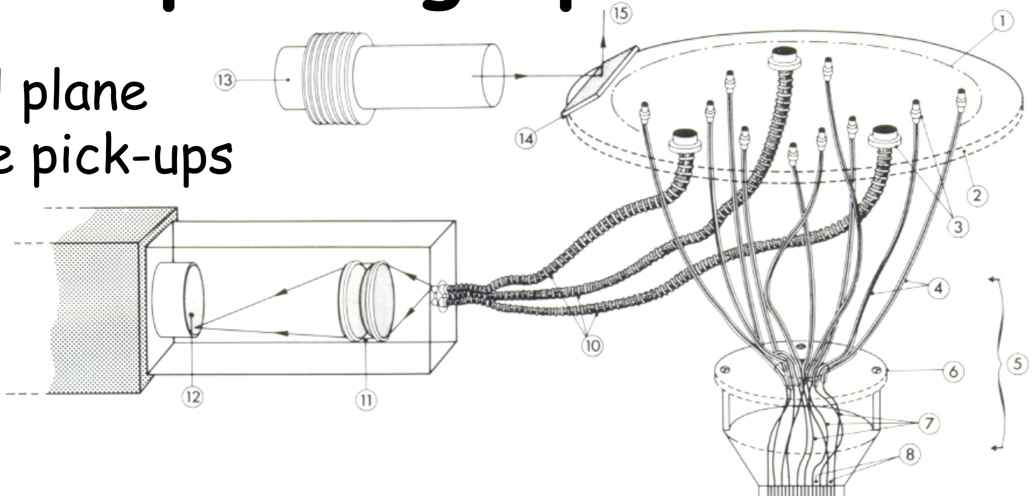


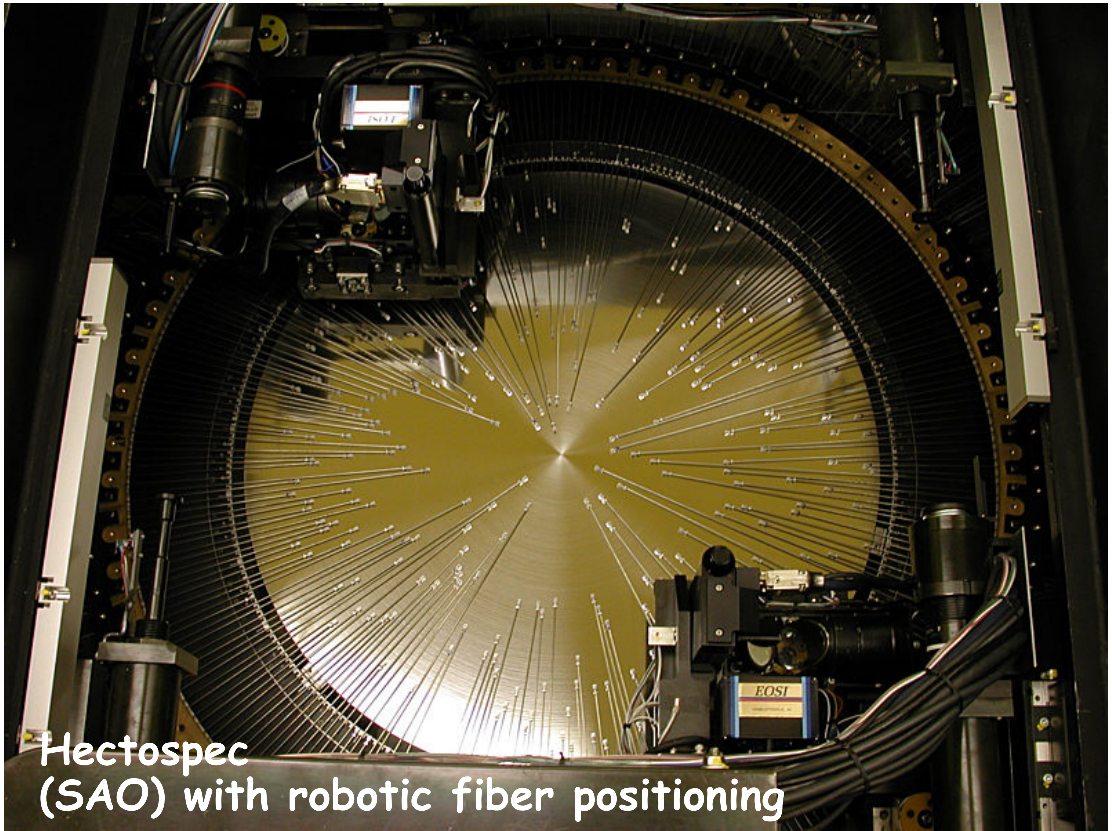
http://subarutelescope.org/Introduction/instrument/img/OHS_concept.gif

Multi-Object Spectrographs

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

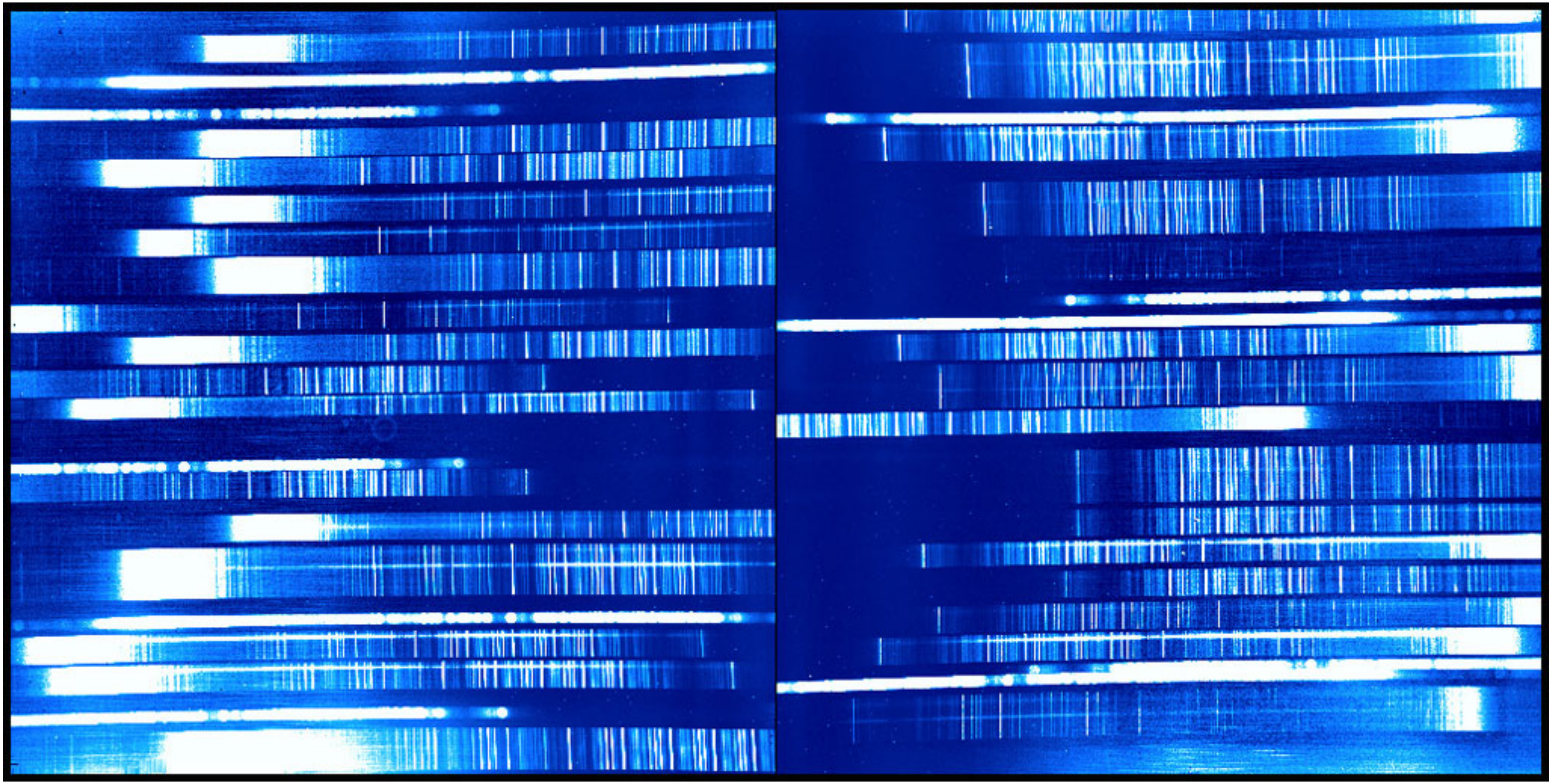
Needs different slit masks for different fields.





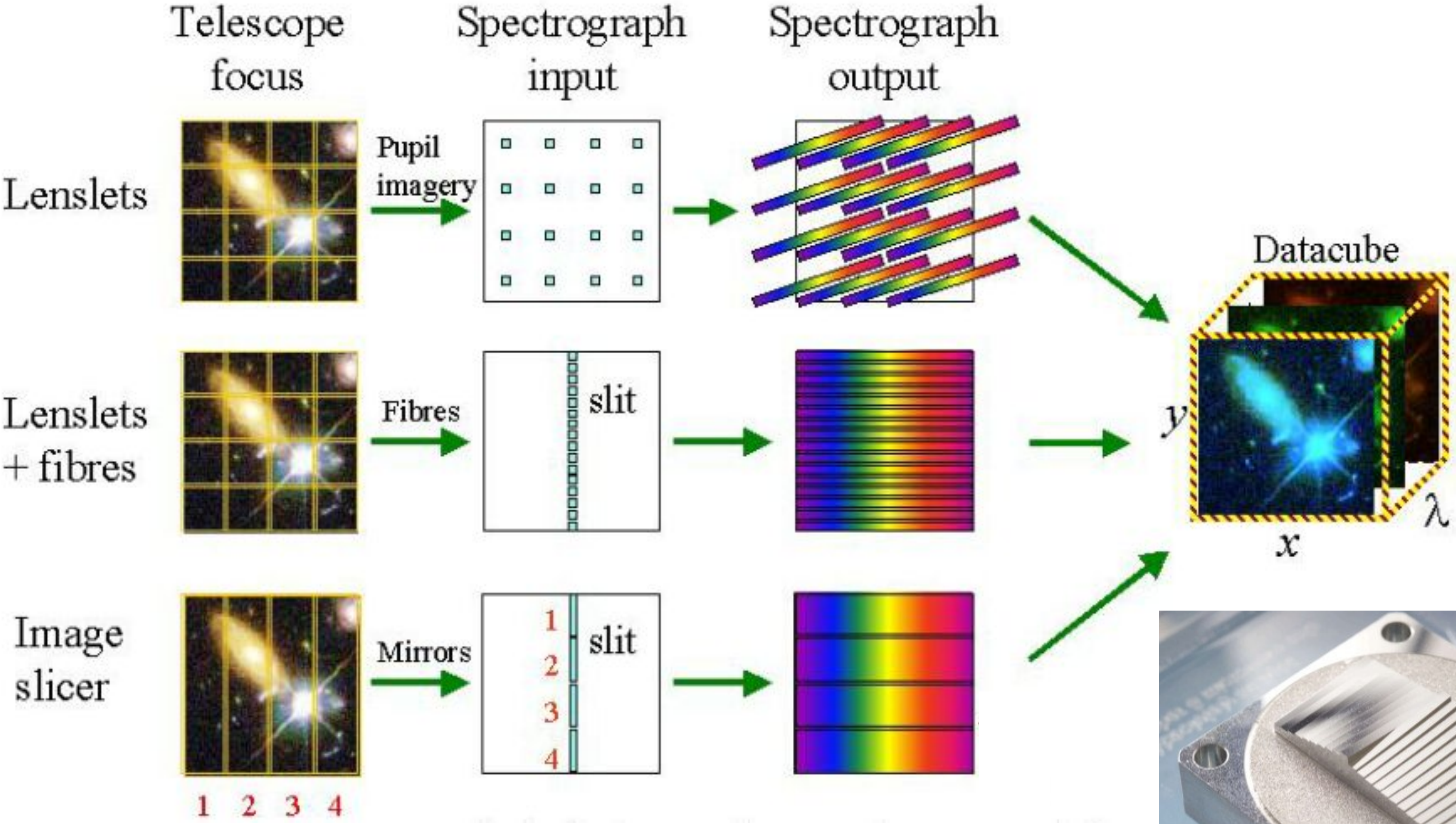
Hectospec (SAO) with robotic fiber positioning

Data Products (2): MOS Spectra

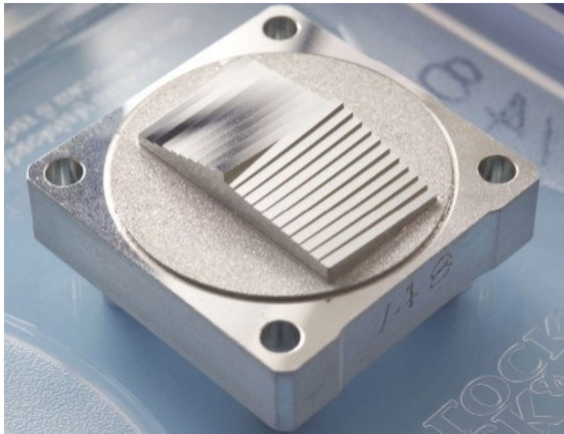


Integral Field Spectrographs

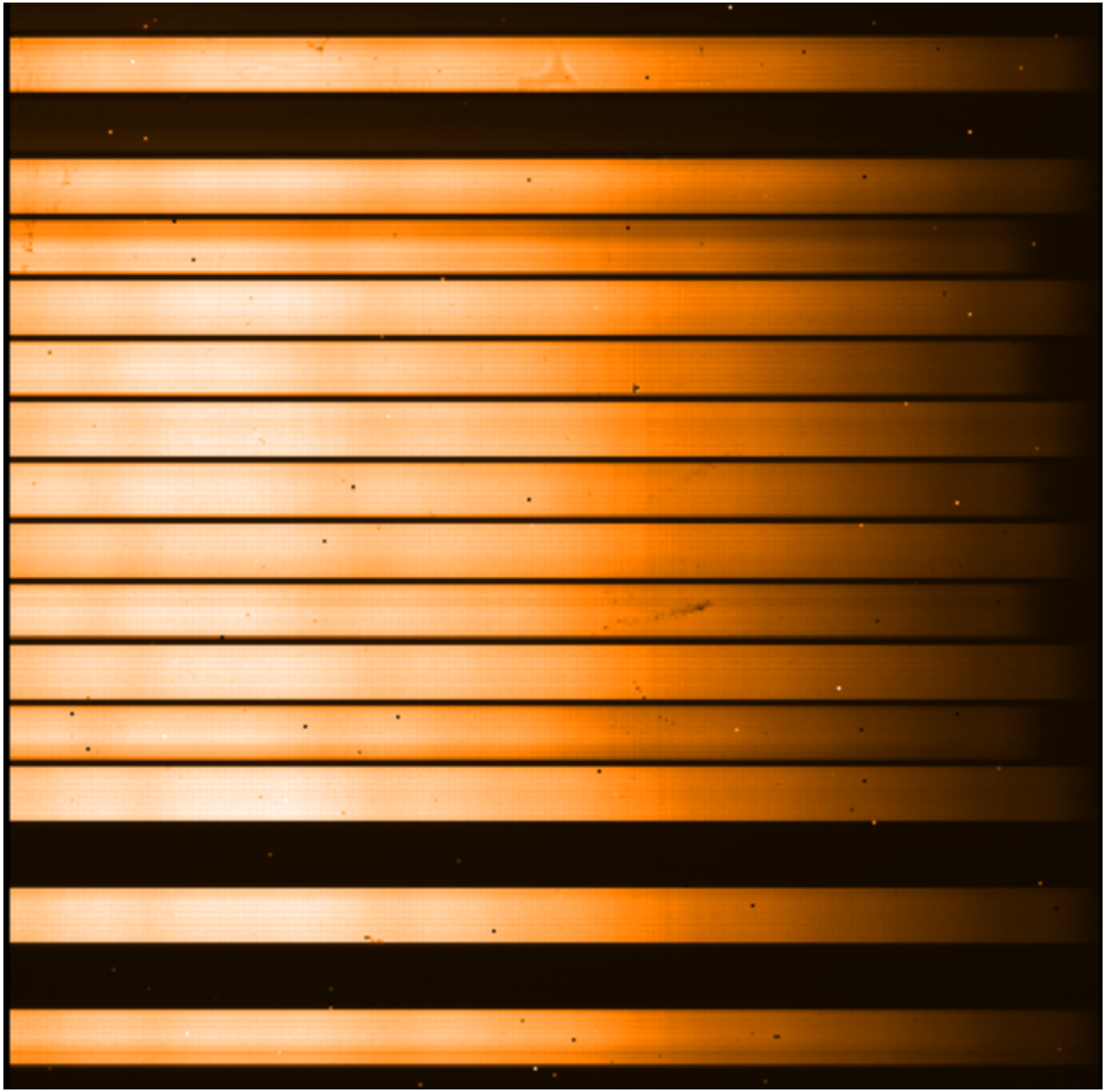
Cut an area on the sky in several adjacent slices or sub-portions, realign them optically into one long slice and treat it as a long slit spectrograph.



JWST-MIRI image slicer:

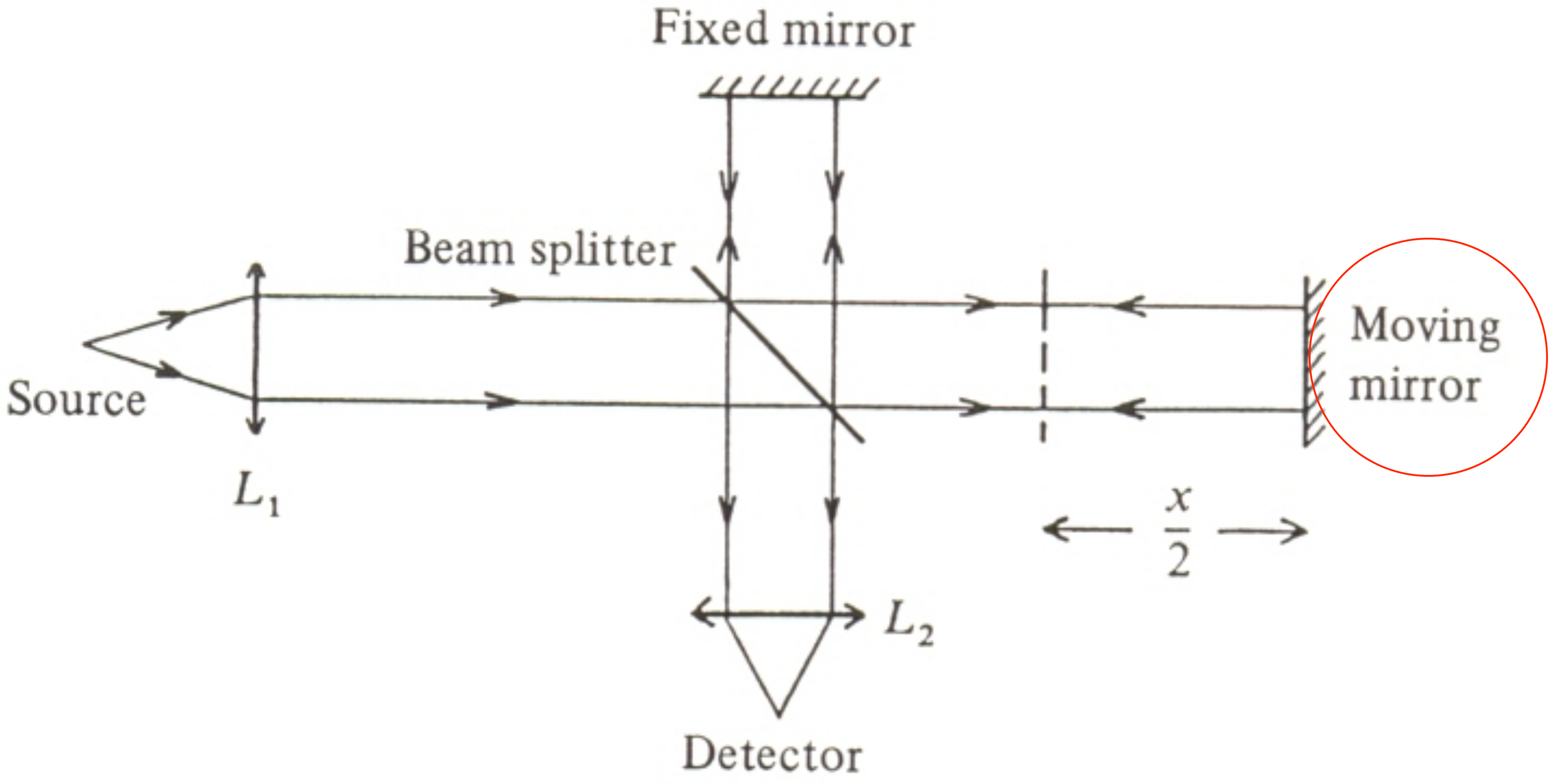


IFU Spectra



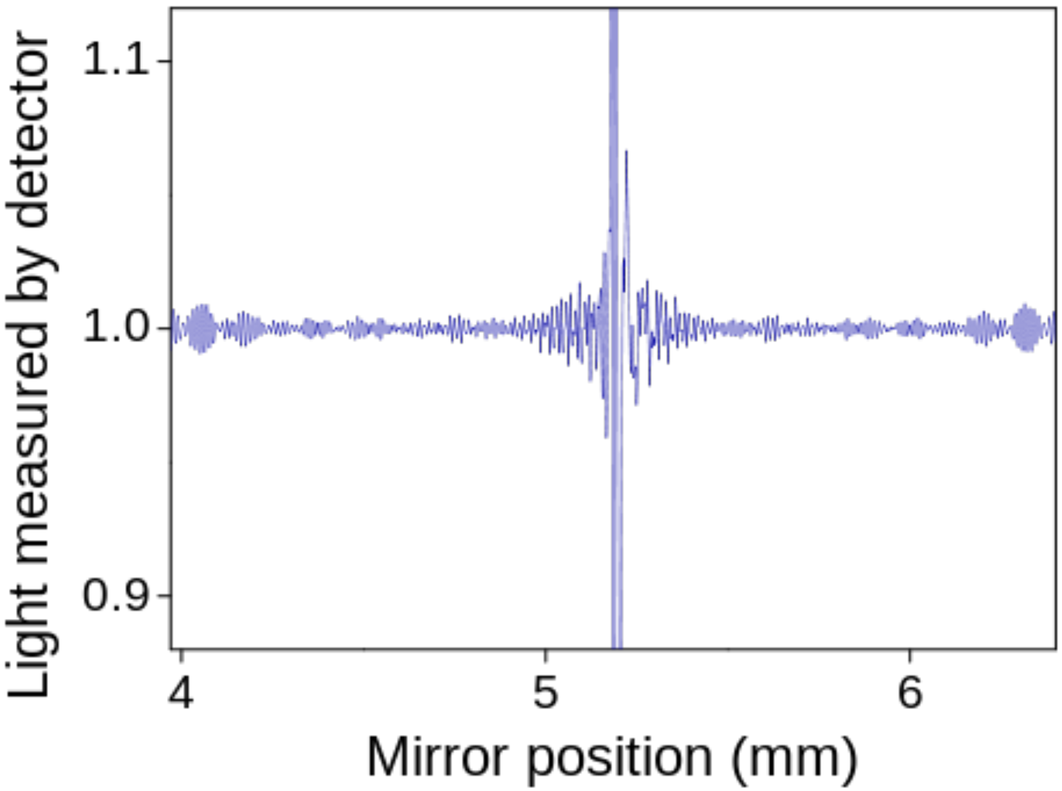
Fourier Transform Spectrometer

First, let's *assume* we only have a single pixel detector



FTS or Michelson interferometer is a <u>two-wave</u> interferometer (note: grating has *N* waves from *N* grooves).

FTS – Output Signal



- For each moving mirror position, broadband intensity is measured.

- The signal is an interferogram. It is the Fourier transform of the spectrum of the object.

FTS – Measured Intensity

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

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

A source with a spectrum $I_0(k)$ in the range $[k_1,k_2]$ produces a signal of:

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

Note that for each value of x, all spectral elements of the incident spectrum contribute to the signal, but only one Fourier component is measured at any given point.

Spectral resolution with maximum path length difference x_{max} is $R=2x_{max}/\lambda$

Pros and Cons of the Different Types

Spectrometer	Advantages	Disadvantages
Long-slit	• relatively simple → high throughput • easy to calibrate	• 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
Fabry-Perot	• ideal for large objects • high spectral resolution • more compact than FTS	• not practical for large λ range • line and continuum observed at different times → calibration • needs pre-disperser
Fourier-transform (FTS)	• very high resolution • absolute wavelengths • imaging FTS possible	• less gain with high background • high resolution ⇔ wide interval • difficult in cryo instruments