Astronomical Observing Techniques

Lecture 11:
How to Fingerprint a Star

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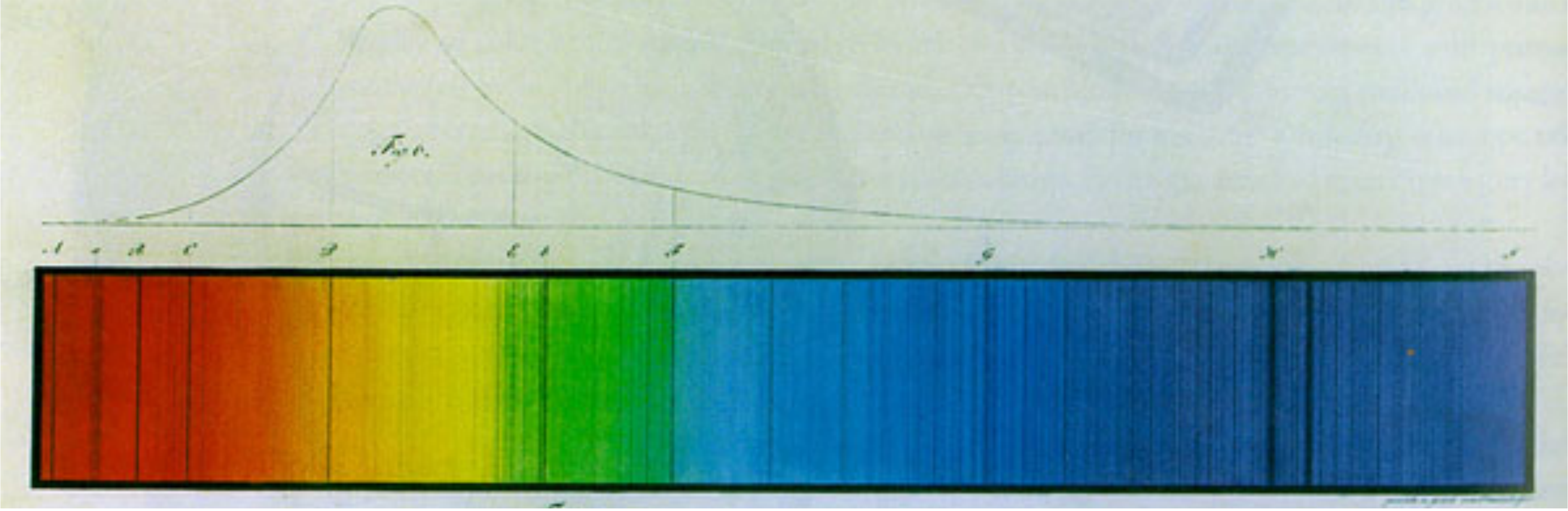
Overview

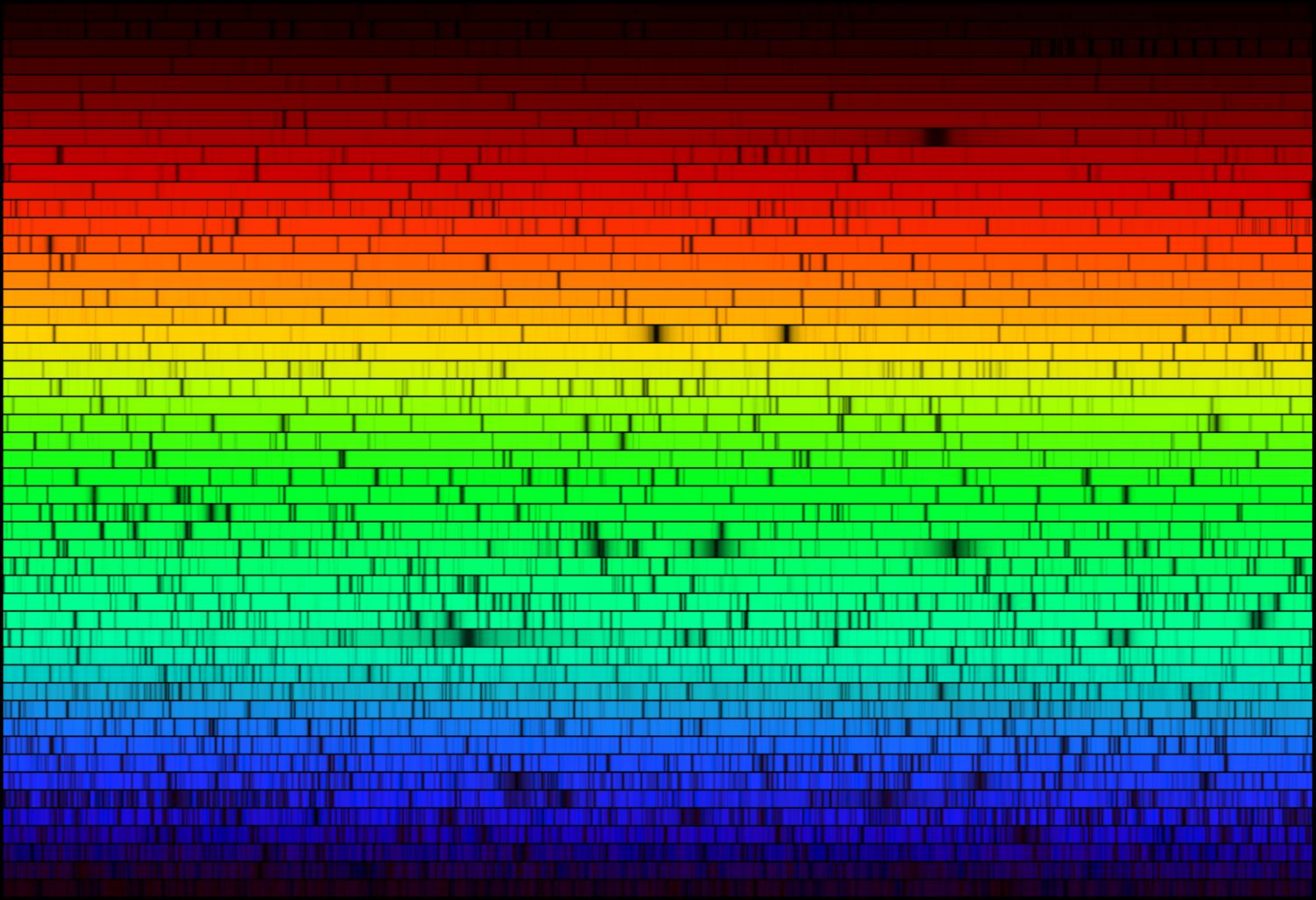
1. Spectral Lines
2. Spectrograph Concept
3. Grating Spectrograph
4. Grisms
5. Filters and Fabry-Perots
6. OH Suppression Spectrographs
7. Multi-Object Spectrographs
8. Fourier Transform Spectrometer

Fraunhofer's Solar Spectrum



A: telluric O_2
B: telluric O_2
C: Hα
D: Na I D_1, D_2, He I D_3

E: Fe I
F: Hβ
G: CN band
H: Ca II
K: Ca II

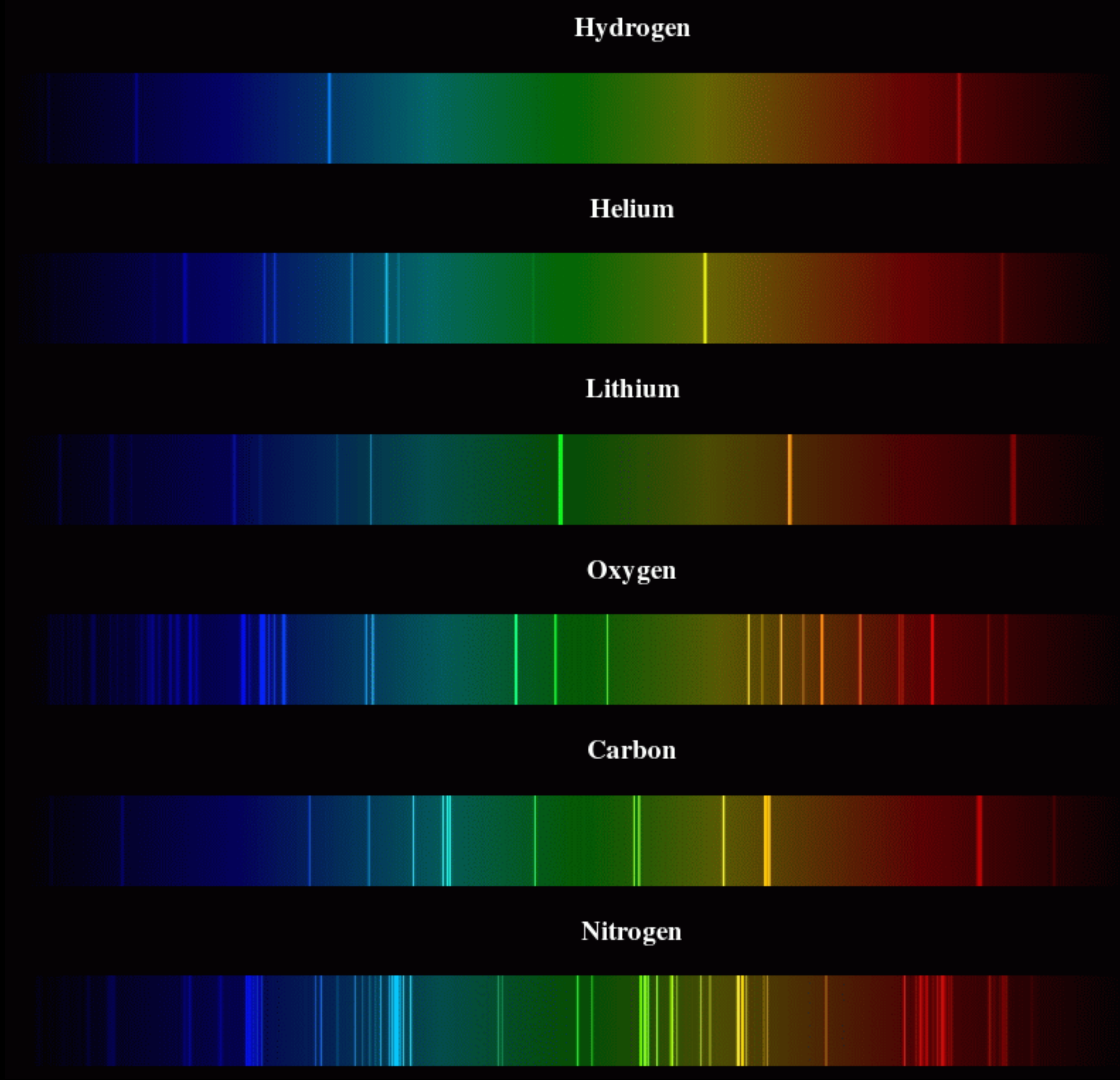


Continuous, Emission, Absorption Spectra

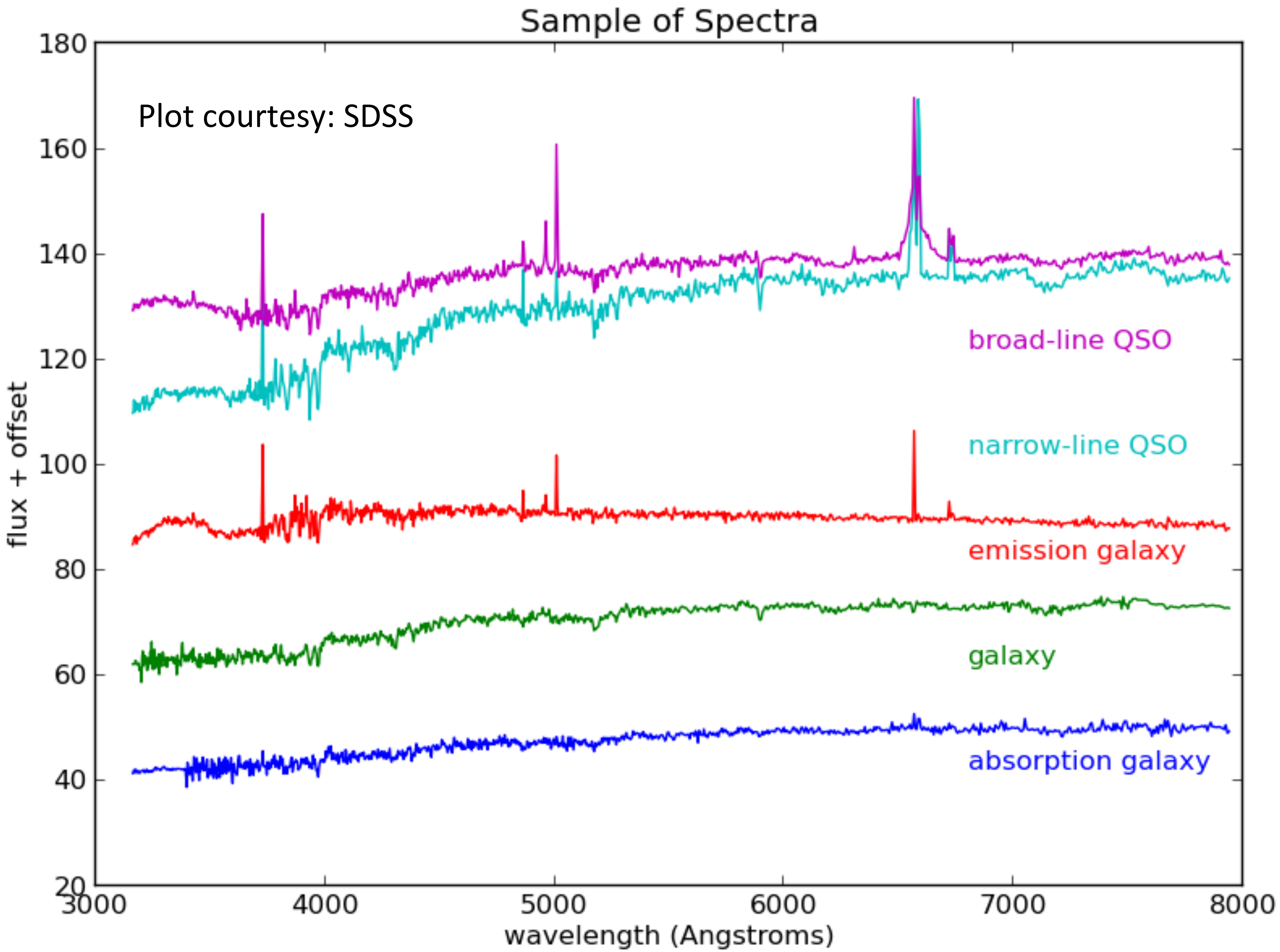
Continuous spectrum

Emission line spectrum

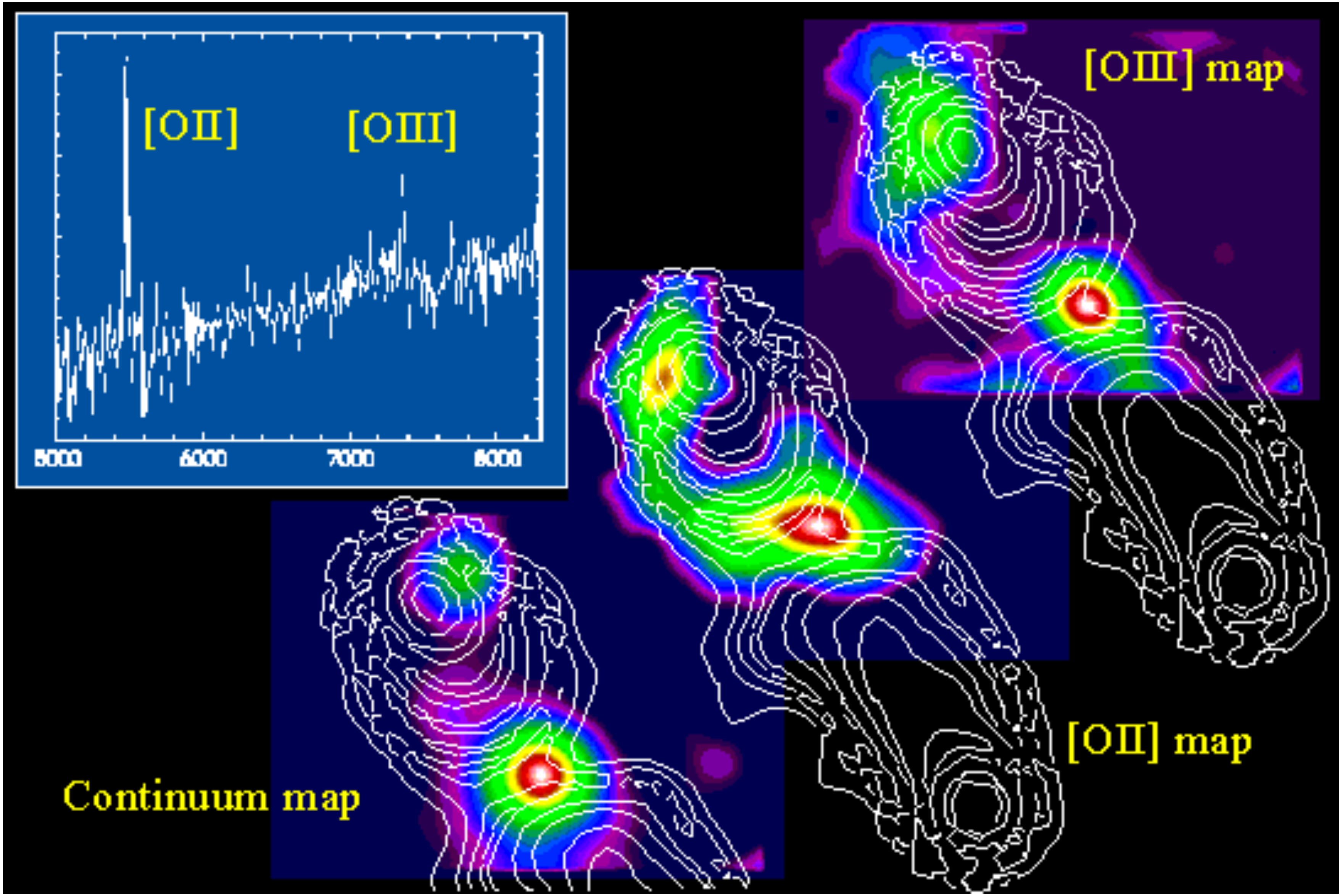
Absorption line spectrum



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

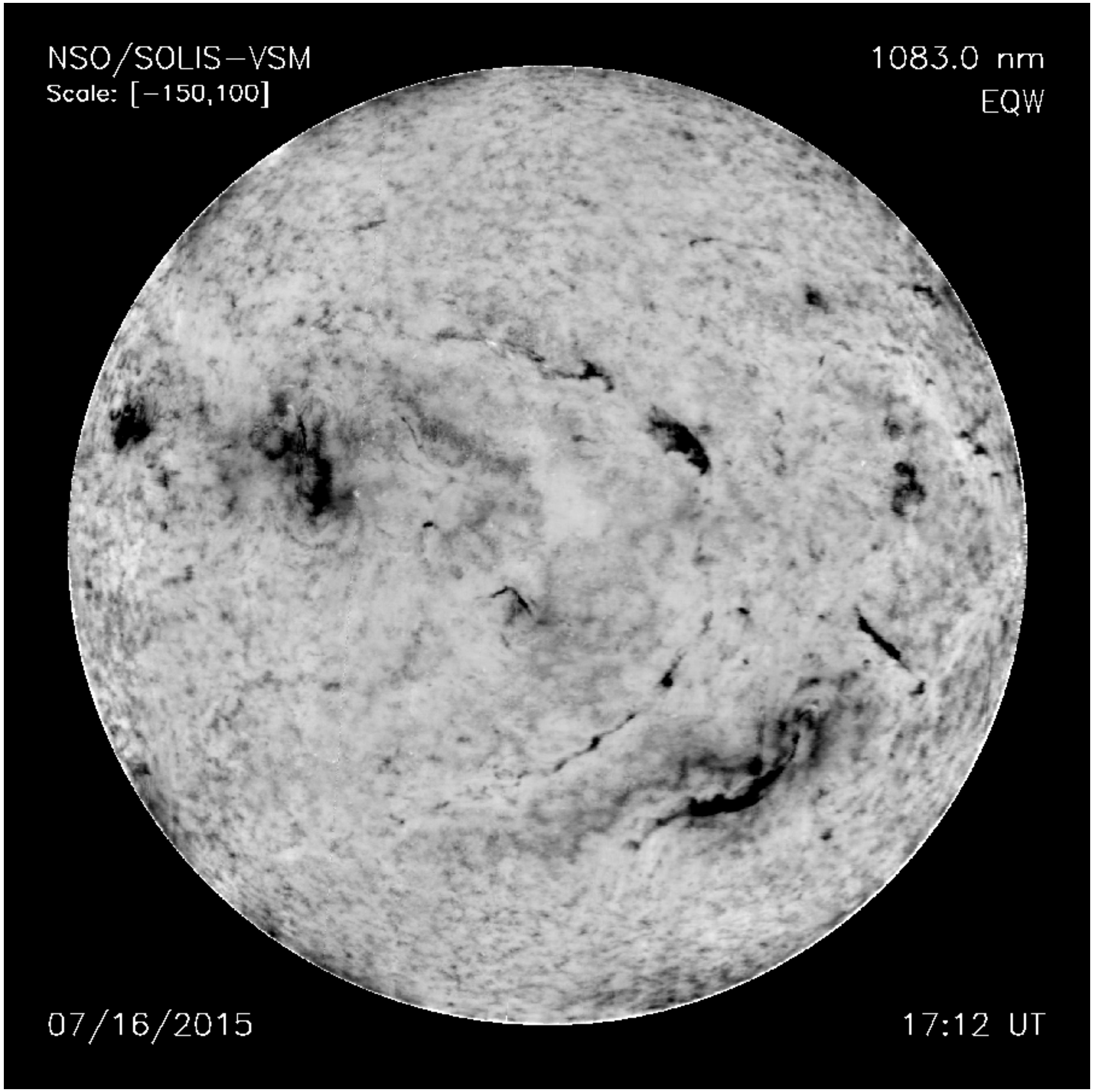

Sample of Spectra
Plot courtesy: SDSS
broad-line QSO
narrow-line QSO
emission galaxy
galaxy
absorption galaxy
flux + offset
wavelength (Angstroms)
180
160
140
120
100
80
60
40
20
3000
4000
5000
6000
7000
8000

Oxygen in Radio Galaxies



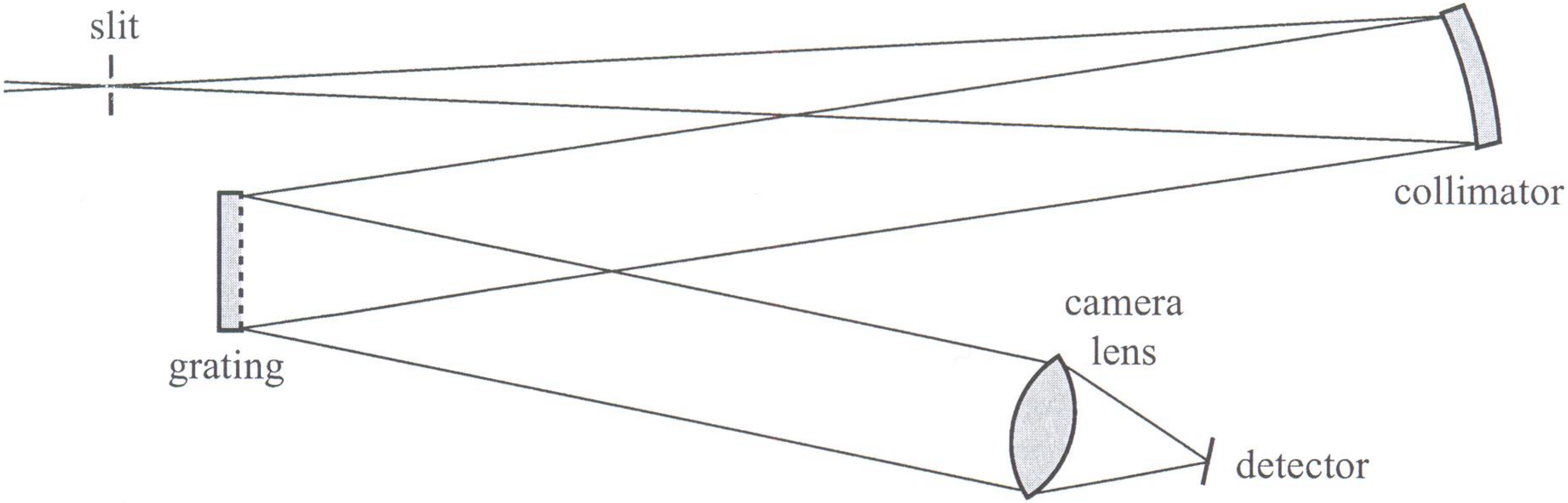
Radio galaxy 3C435A, Plot courtesy: Université de Lyon, TIGER Scientific Results

The Sun in Helium I

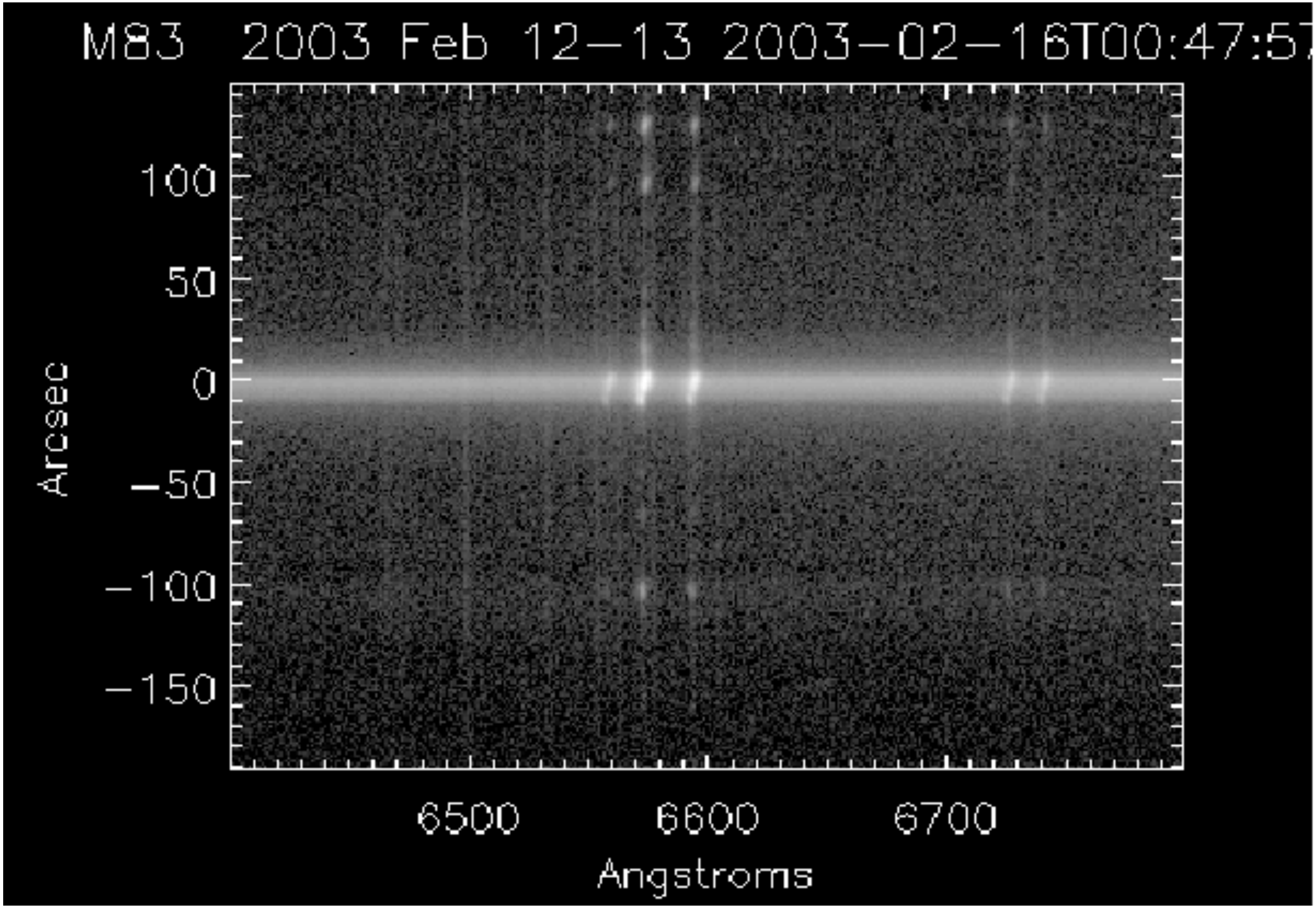


Spectrograph Components

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



Long Slit Spectrum



Spectrograph Characteristics

- 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
  - $R \approx 100$-10’000: medium spectral resolution
  - $R > 10$’000: high spectral resolution

Spectrograph Characteristics

- Instrumental profile P(λ) broadens theoretically infinitely narrow line to observed line width:

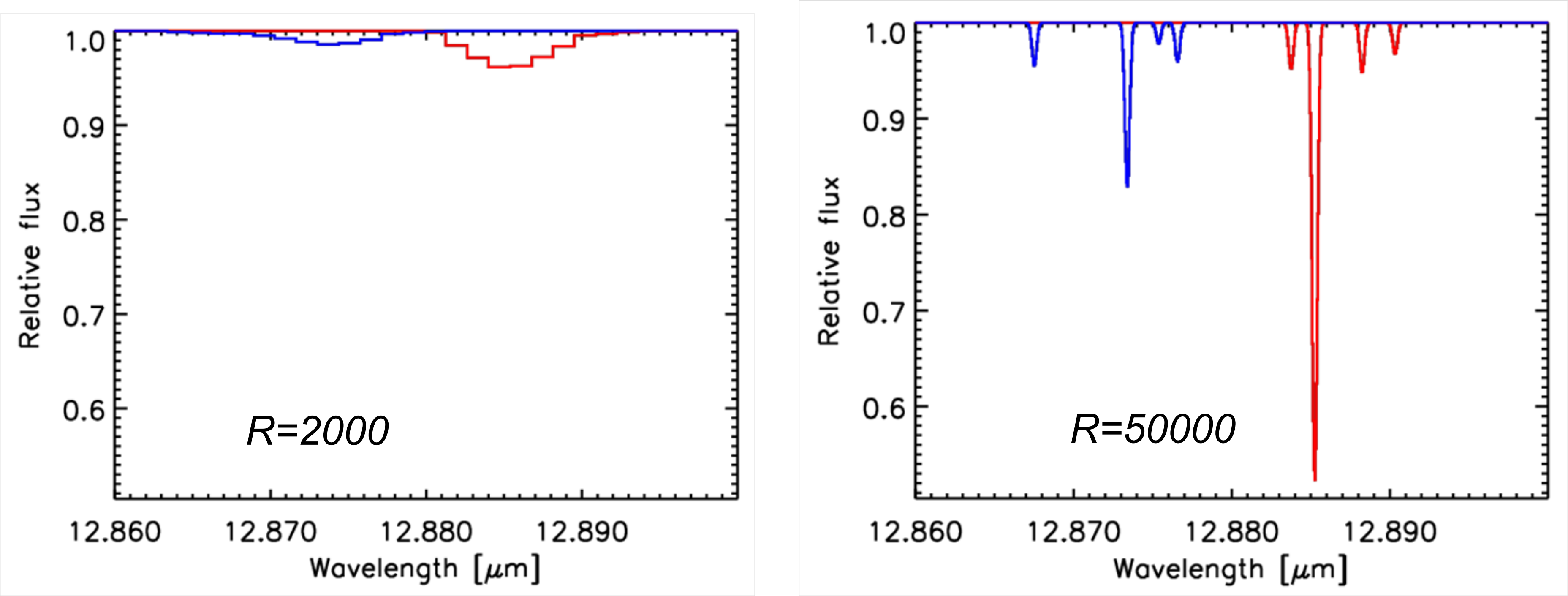
$$I_0(\lambda) = \delta(\lambda - \lambda_0) \quad I(\lambda) = P(\lambda) * I_0(\lambda)$$

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

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

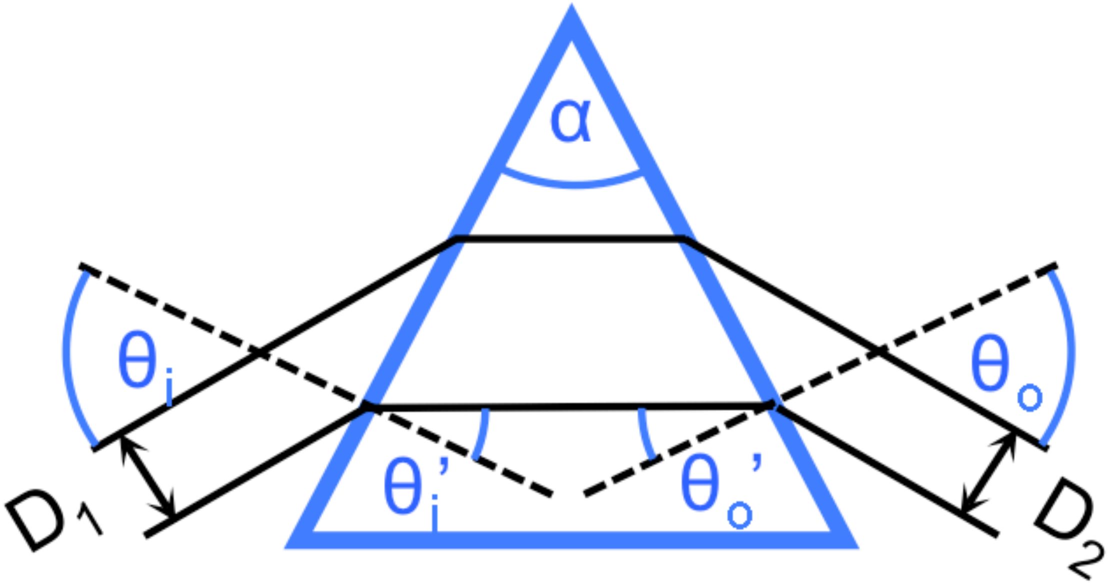
Spectral Resolution and S/N

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).

Prism



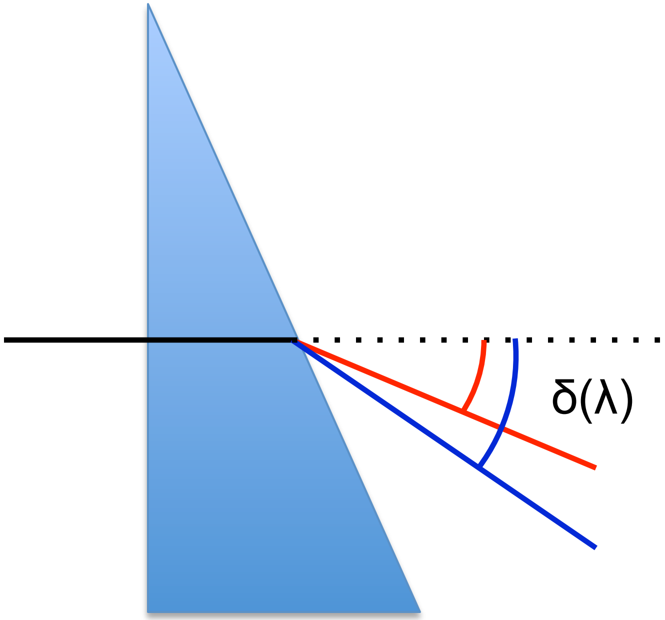
$$\frac{\partial \delta}{\partial \lambda} = \frac{\sin \alpha}{\cos \theta_o \cos \theta_i'} \cdot \frac{\partial n}{\partial \lambda} \qquad \sin \theta_i' = \frac{\sin \theta_i}{n} \qquad \sin \theta_o = n \sin\left(\alpha - \theta_i'\right)$$

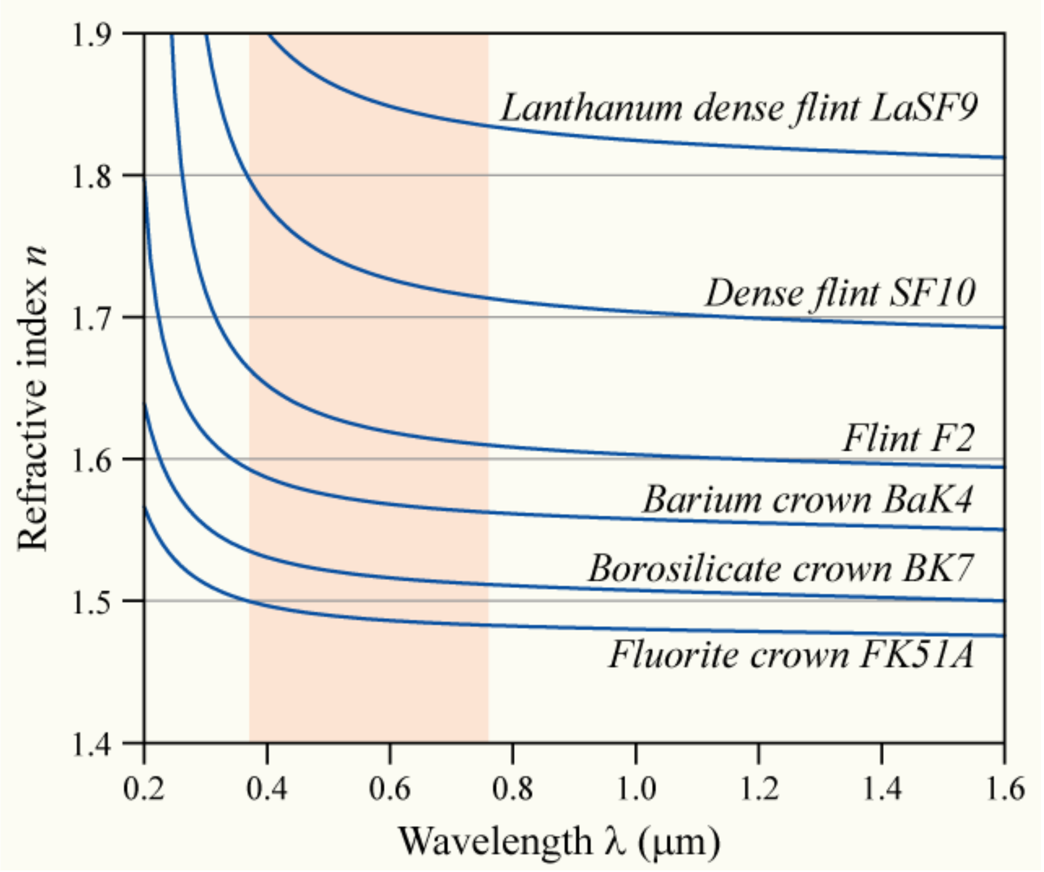
- good for low-resolution spectroscopy
- no order overlap
- dispersion depends on wavelength

Angular Dispersion

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

$$\frac{\partial \delta}{\partial \lambda} = \frac{\sin \alpha}{\cos \theta_o \cos \theta_i'} \cdot \frac{\partial n}{\partial \lambda}$$



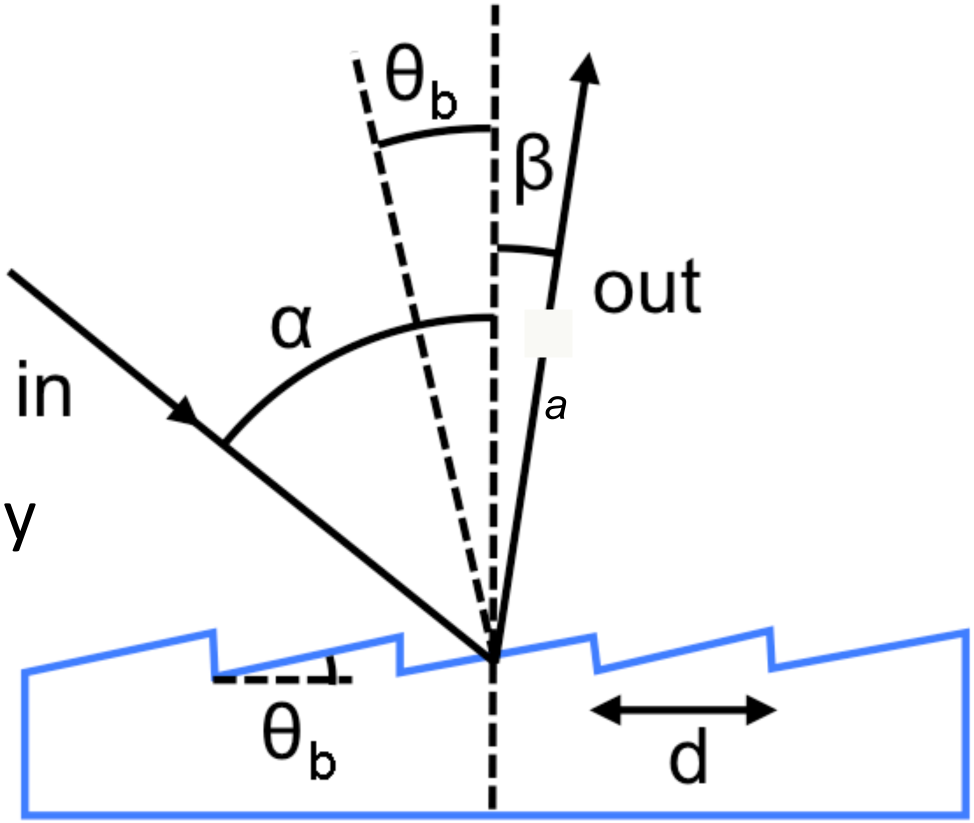


Diffraction Grating

Grating introduces optical path difference = f(angle to surface normal)

Condition for constructive interference given by grating equation:

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



m = order of diffraction

λ = wavelength

d = distance between equally spaced grooves

α = angle of incoming beam

β = angle of reflected beam

Grating Spectral Resolution

- Grating equation $m\lambda = d \cdot (\sin\alpha \pm \sin\beta)$
- Gratings usually in collimated beam close to pupil image
- Maximum spectral resolution R given by *R=mN*

  N = number of (illuminated) grooves

  m = diffraction order
- Angular dispersion $d\beta / d\lambda = \dfrac{m}{d\cos\beta}$

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*:

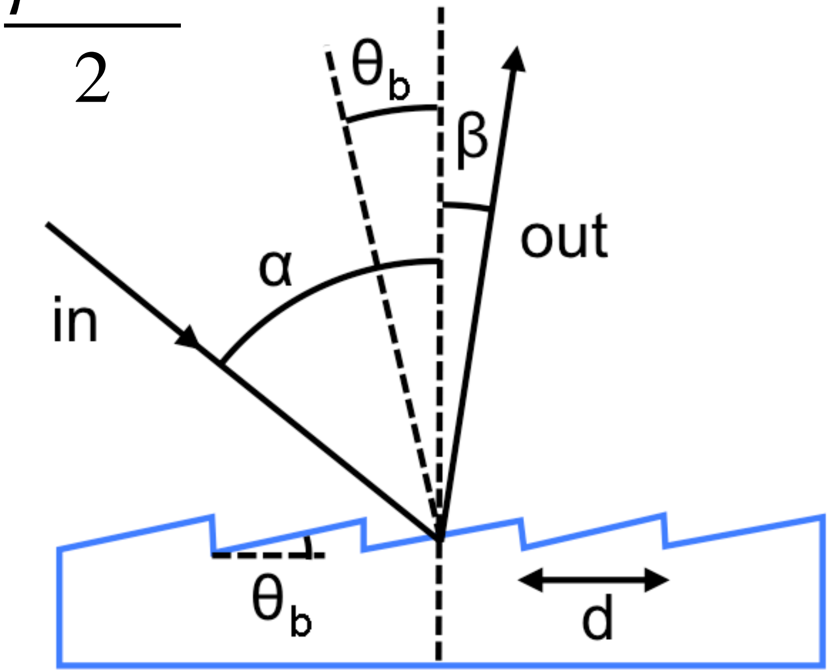
$$\alpha + \beta = 2(\alpha + \theta_B) \quad \Rightarrow \quad \theta_B = \frac{\beta - \alpha}{2}$$

Advantage:

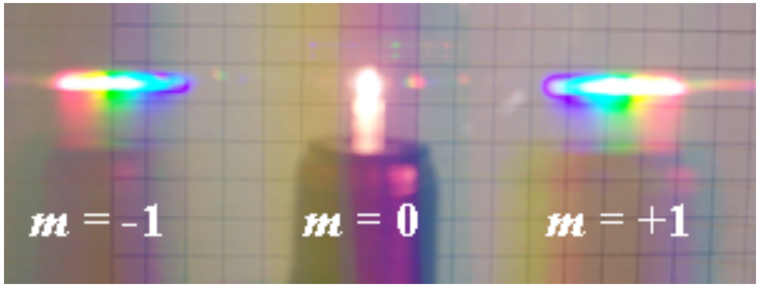
- High efficiency

Disadvantage:

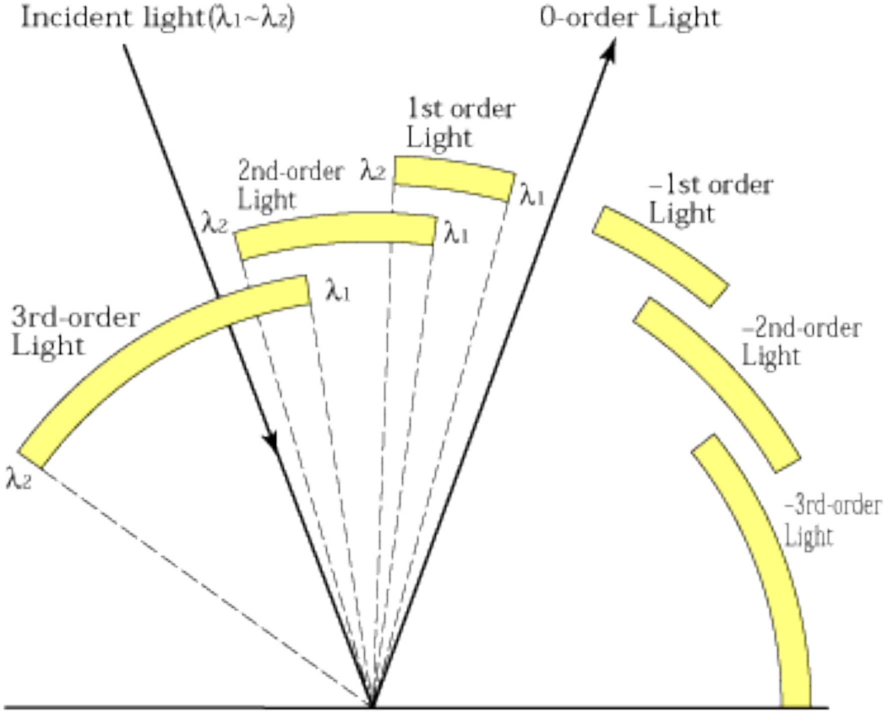
- Blaze angle θ_B (and blaze wavelength λ_B) fixed by construction



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:

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

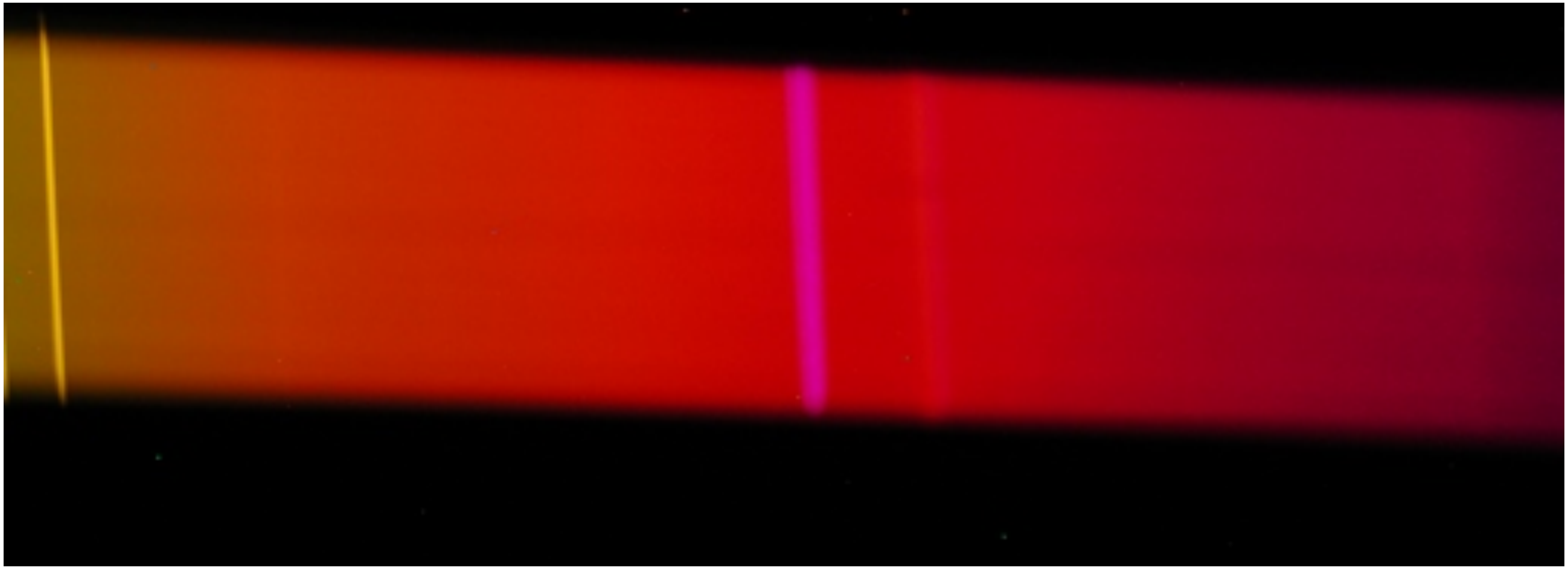
The free spectral range is the largest wavelength range for a given order that does not overlap the same range in an adjacent order.

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

Overlapping Grating Orders

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

Overlapping Orders



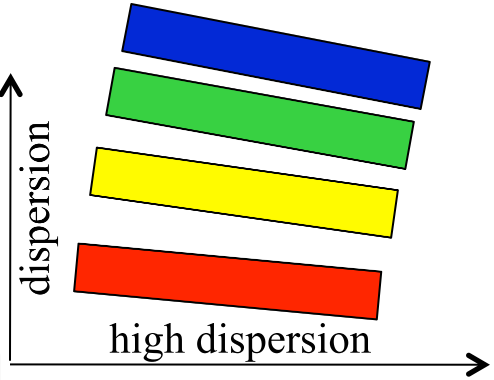
www.stargazing.net/david/spectroscopy/SpectraL200F4T5Dorders.html

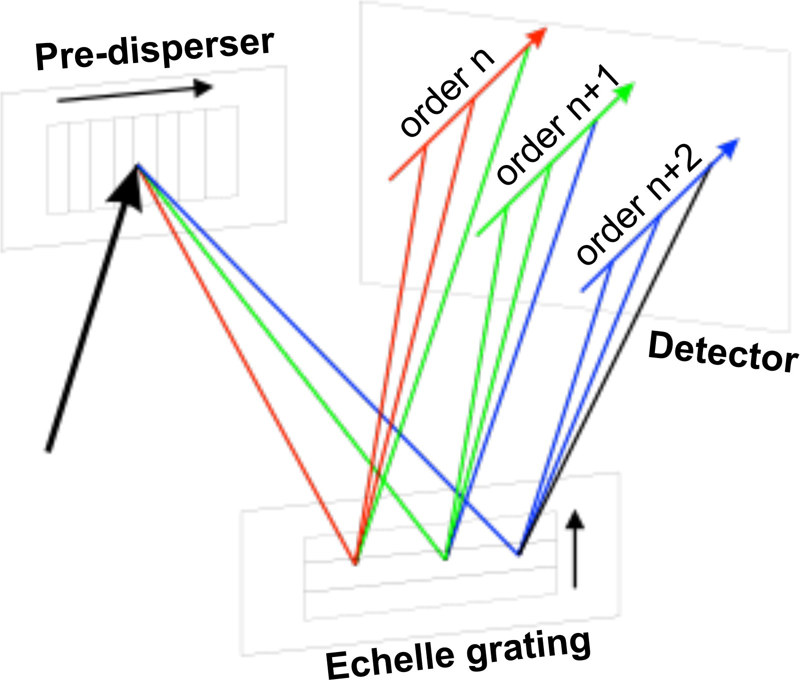
- blue emission line in 3rd order overlaps red continuum in 2nd order

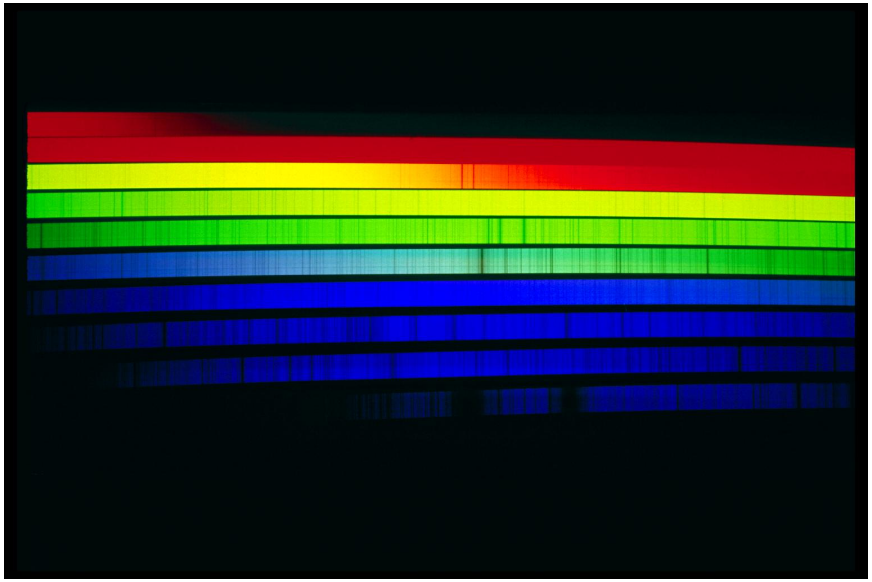
Cross-Dispersion

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

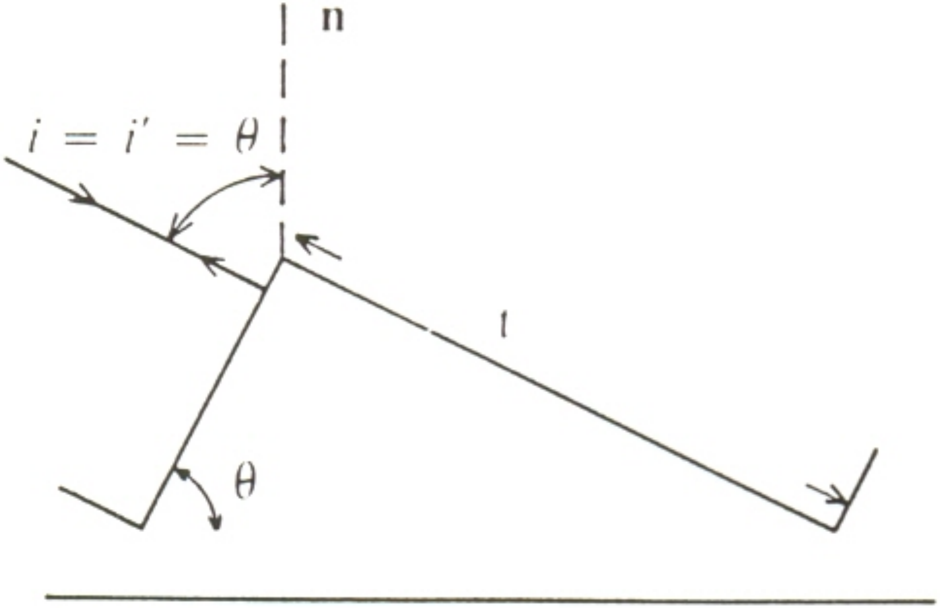
Want high dispersion

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

and high spectral resolution

$$R = Nm$$

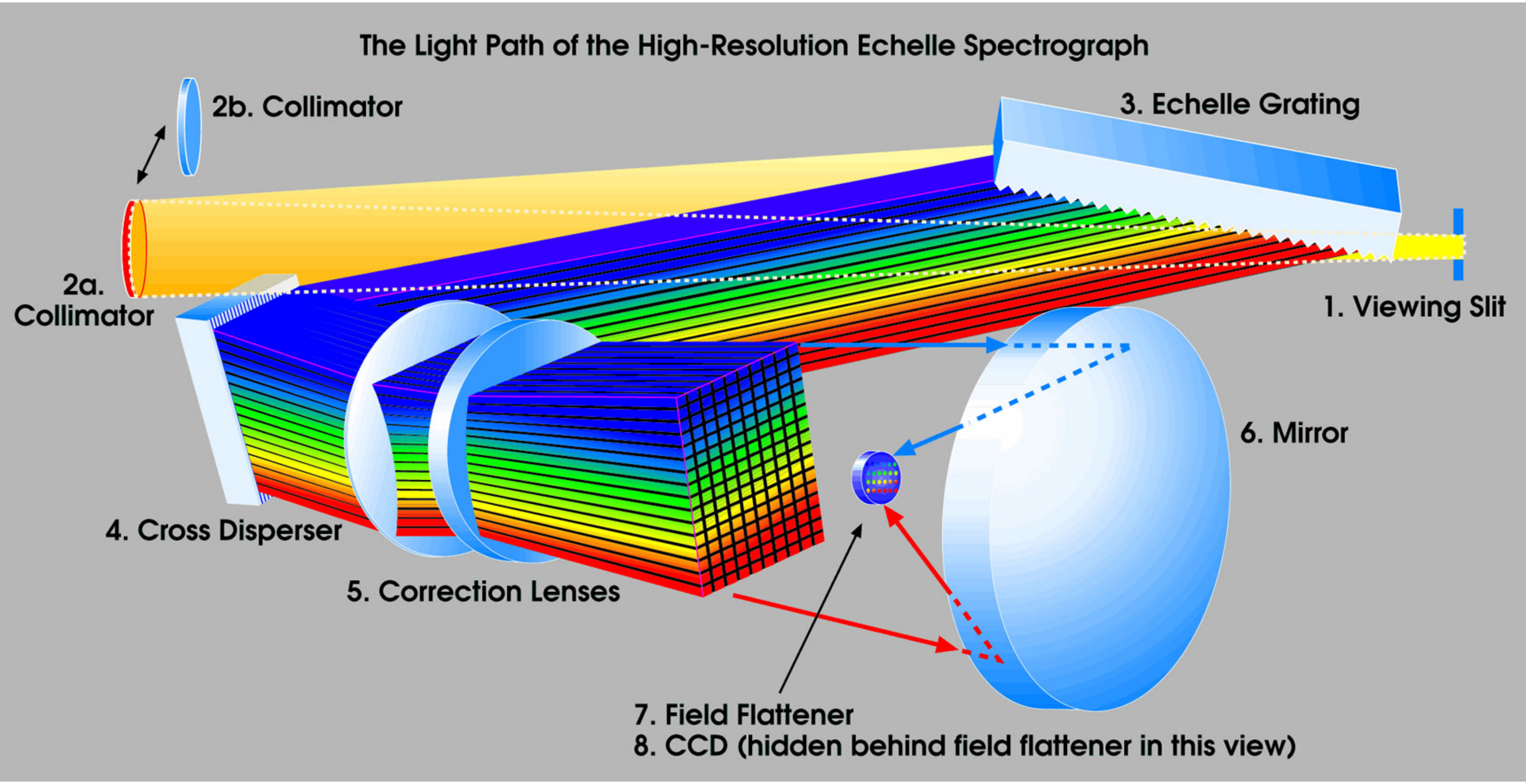
α and β large, high order m (≈ 50), and therefore large a



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

Echelle Spectrograph

Operation in high order → cross-disperser essential

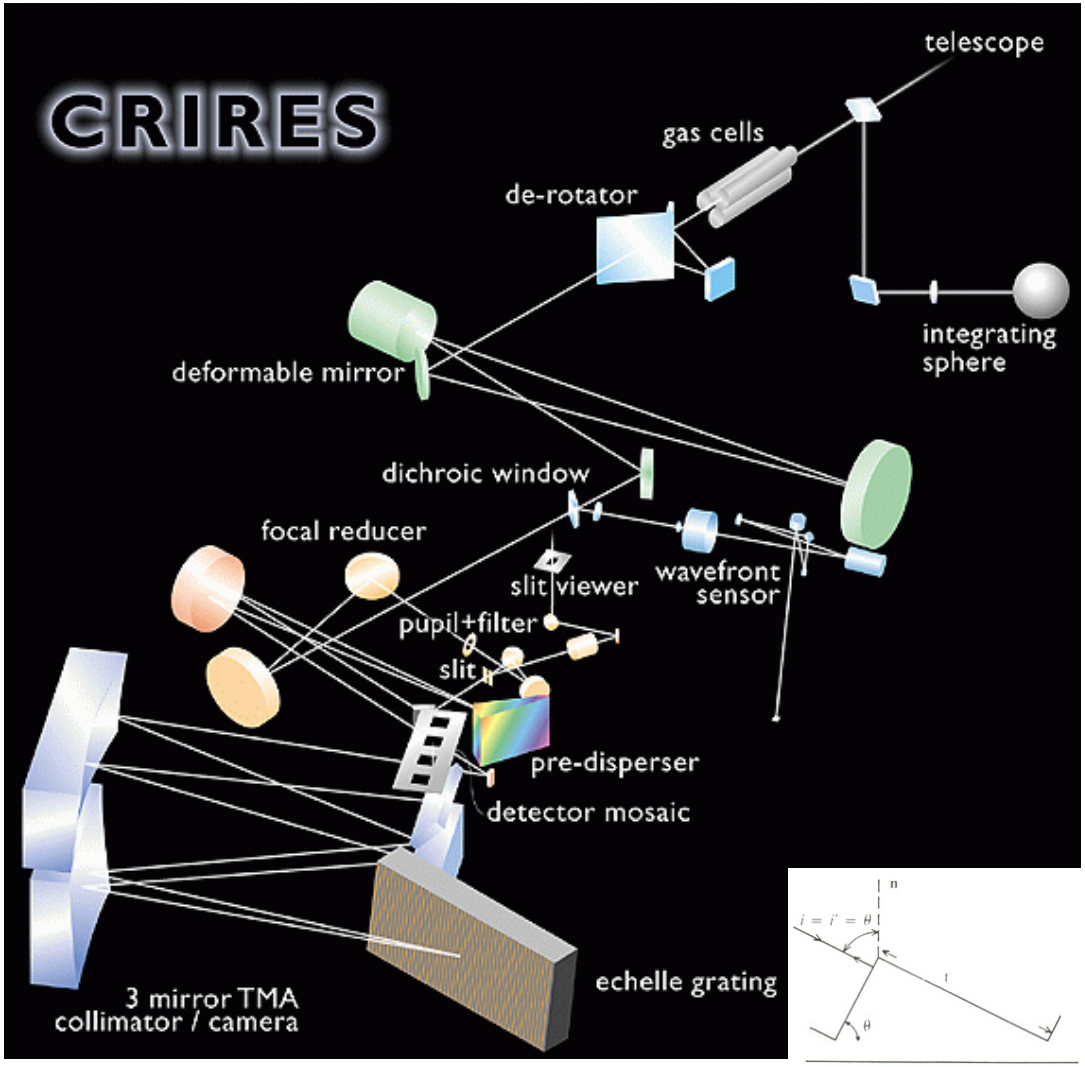


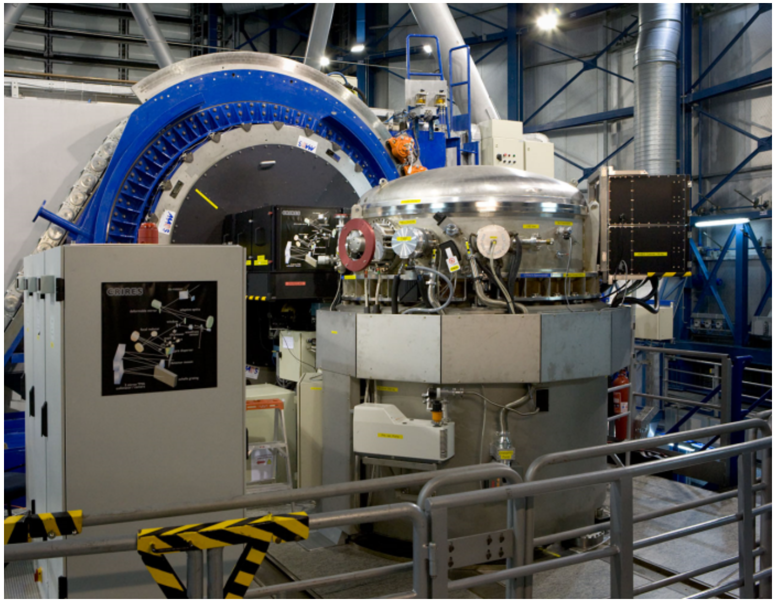
McMath-Pierce Spectrograph

Smaller Pixels

Echelle Spectrographs

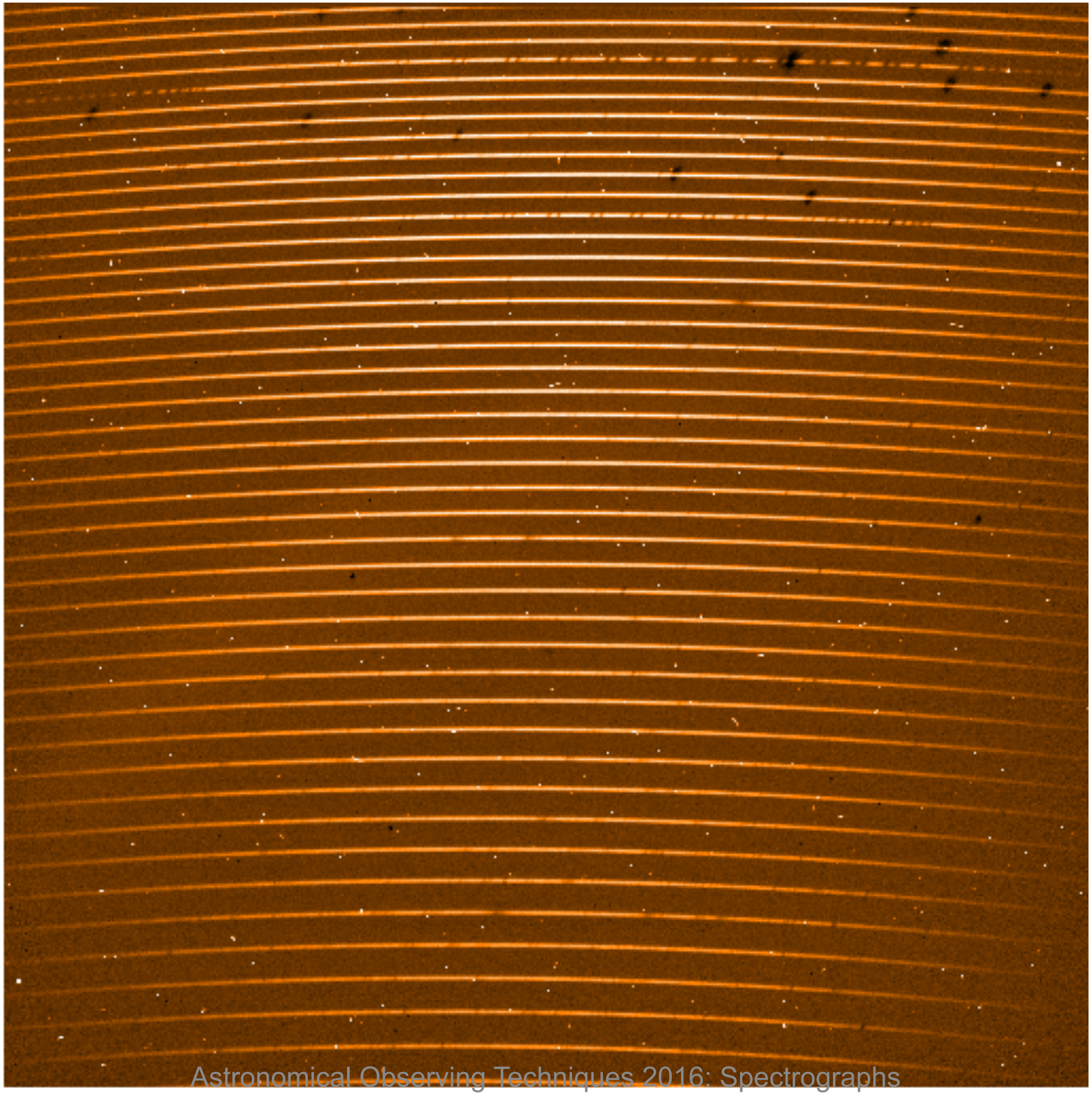
Example: ESO's VLT instrument CRIRES:





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

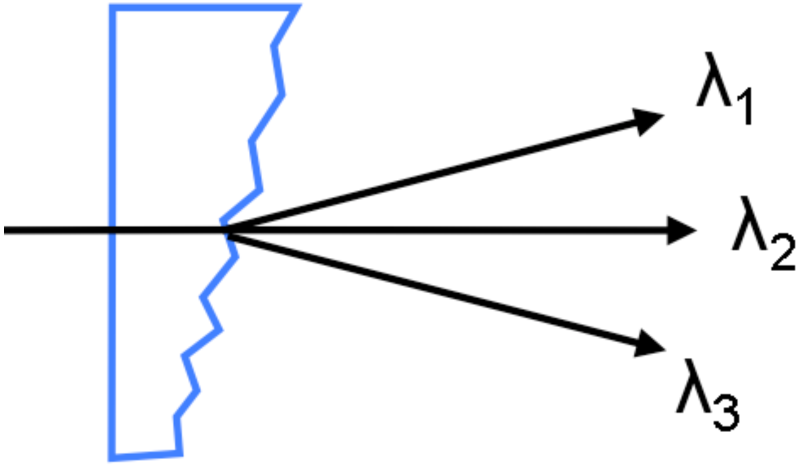


echelle spectrum of V454 Aur

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)

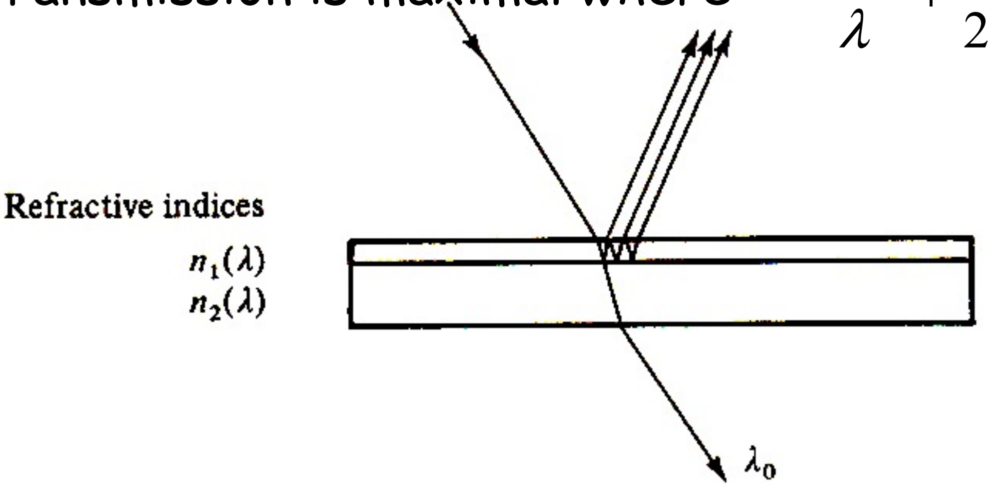
Disadvantages:

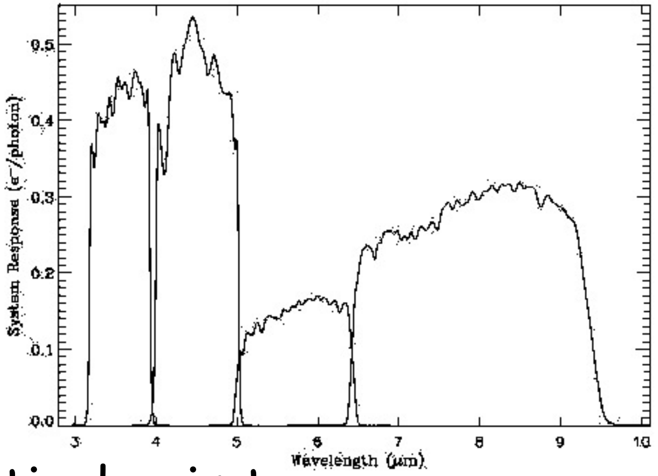
- difficult to manufacture (replication and gluing or by direct ruling.
- can be quite "bulky" (← filter wheel)

Interference (Transmission) Filters

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

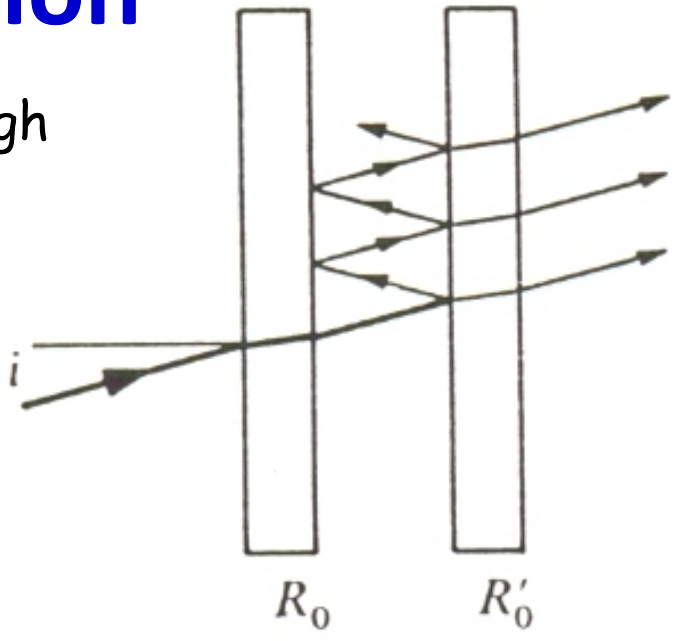
The transmission is maximal where $$\frac{2n_1 d}{\lambda}+\frac{\pi}{2}=2k\pi$$





- 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:

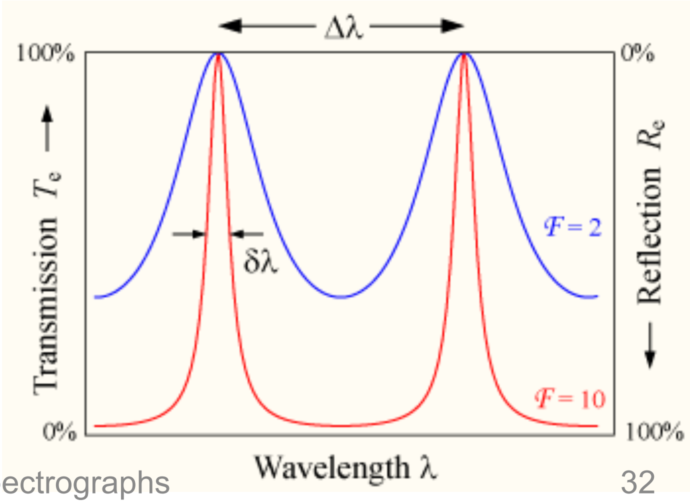
$$I = I_0\left(\frac{r}{1-r}\right)^2\left[1+\frac{4r}{(1-r)^2}\sin^2(2\pi dk\cos i)\right]^{-1}$$

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.

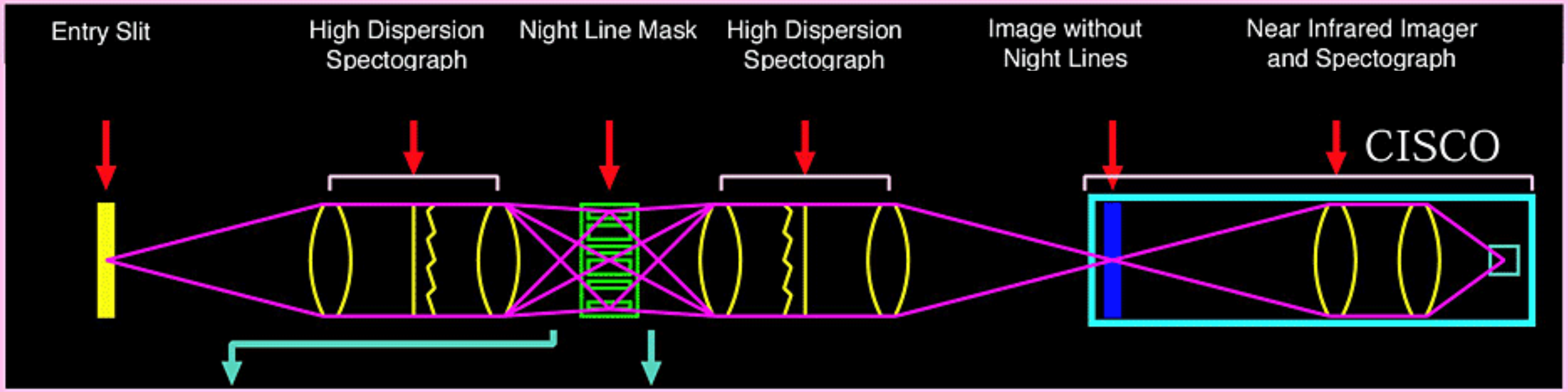
The spectral resolution is given by

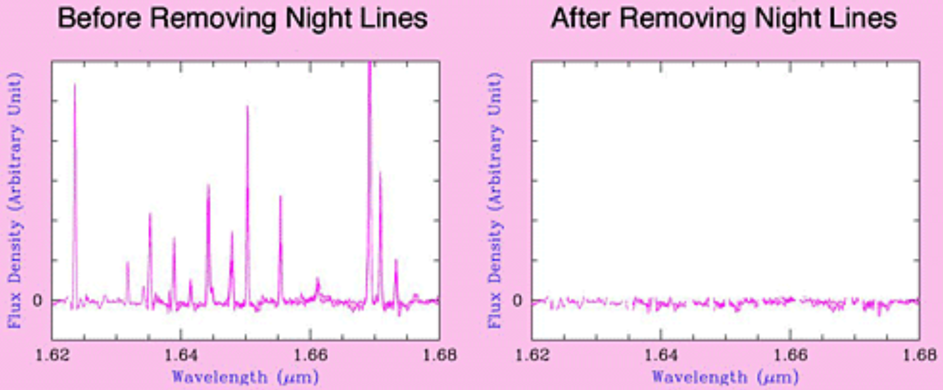
1. The finesse $F = \frac{\pi\sqrt{r}}{1-r}$,
2. The resolution $R = \frac{k}{\Delta k} = mF$

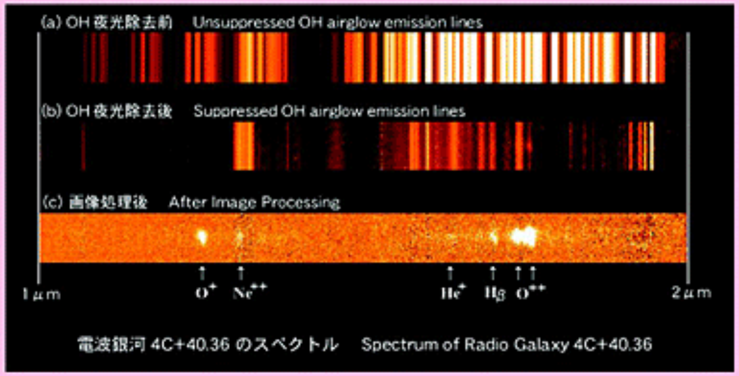


OH Suppression Spectrographs

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





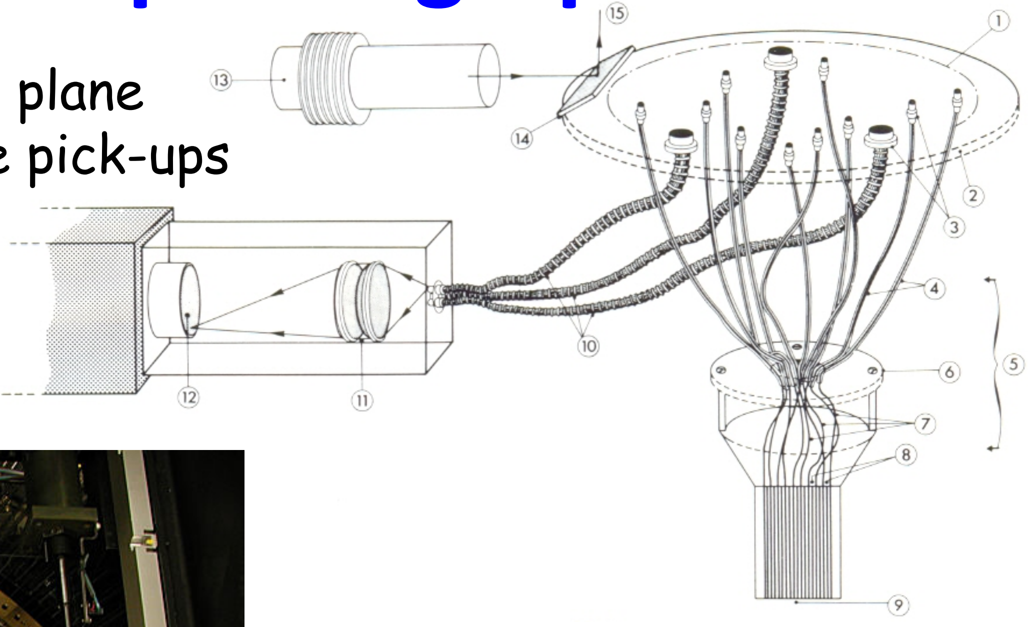


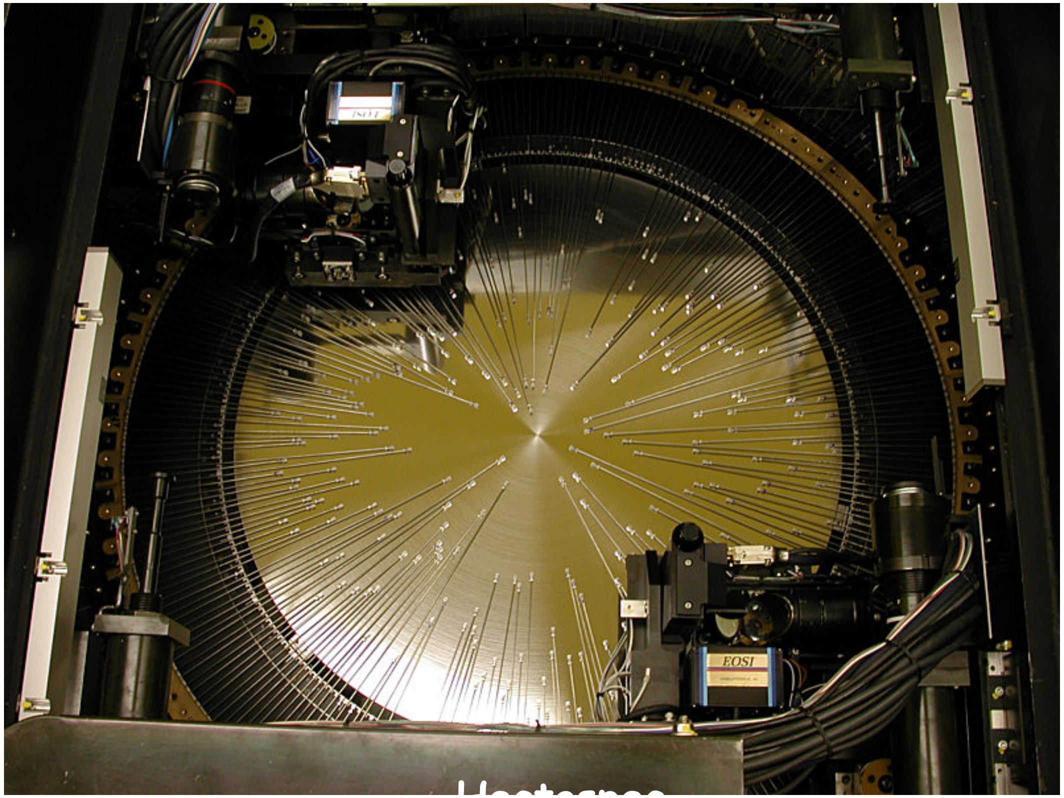
http://subarutelescope.org/Introduction/instrument/img/OHS_concept.gif

Multi-Object Spectrographs

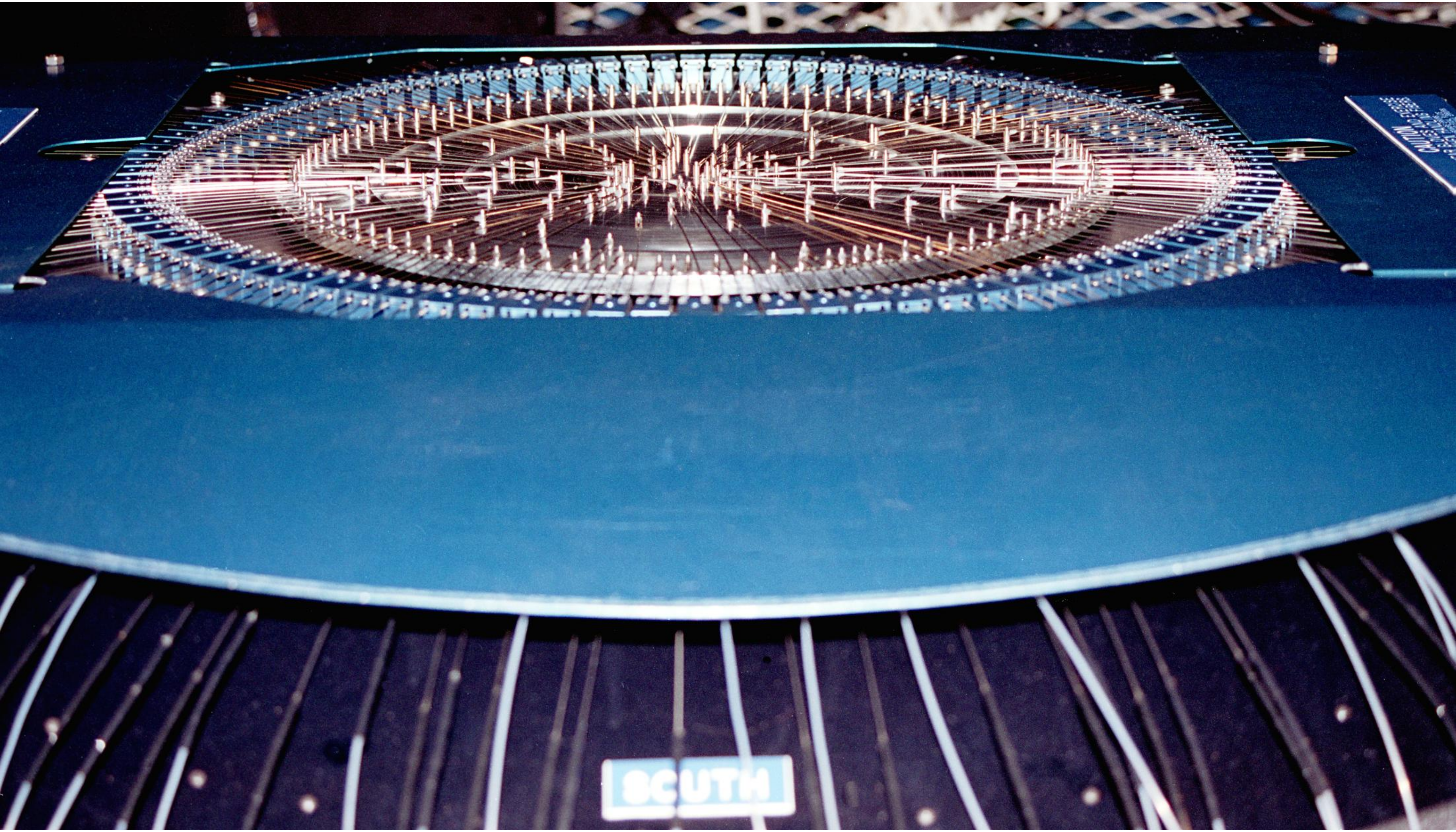
Use numerous “slits” in the focal plane simultaneously → multiple source pick-ups using fibers or mirrors.

Needs different slit masks for different fields.

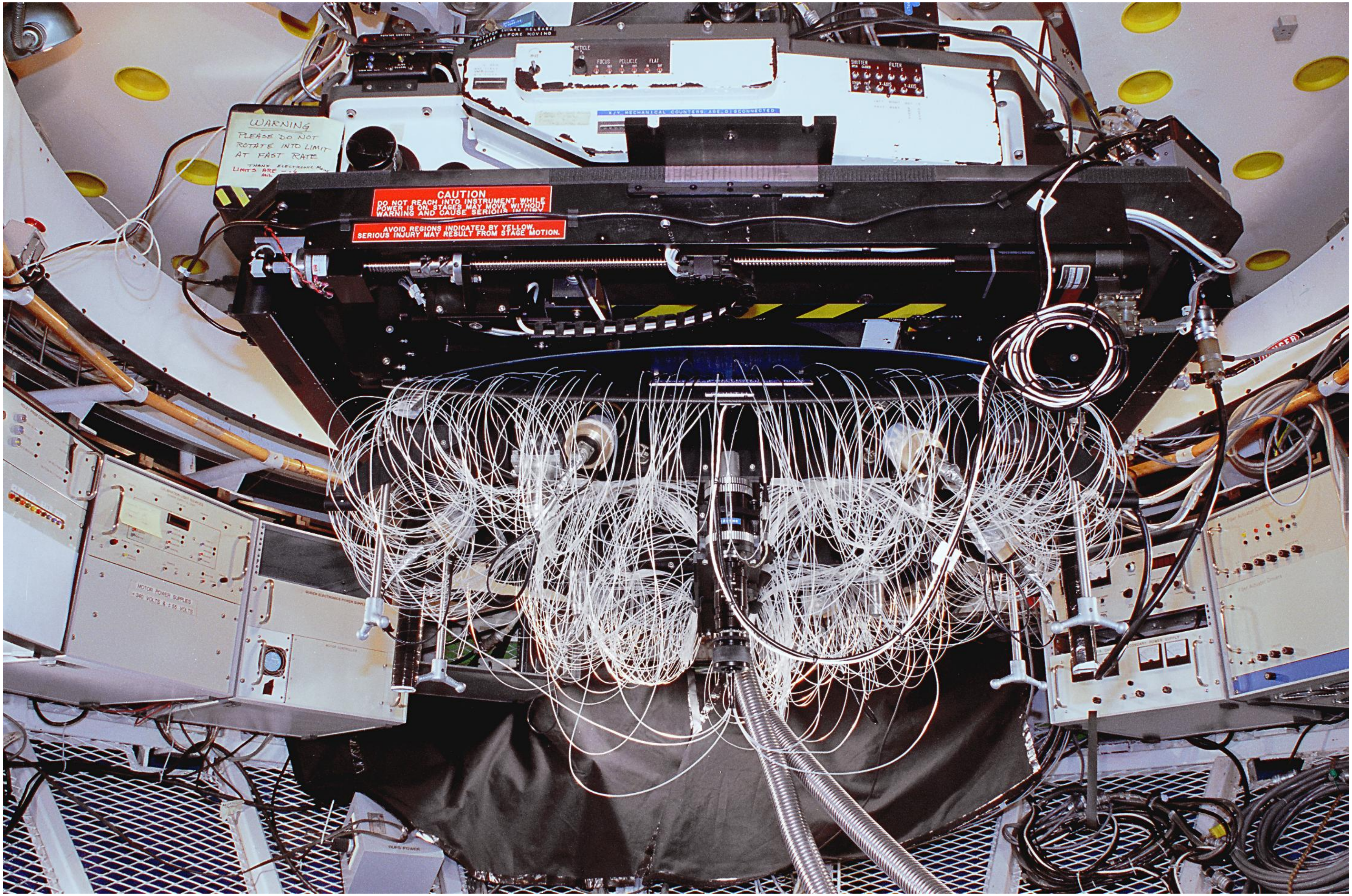




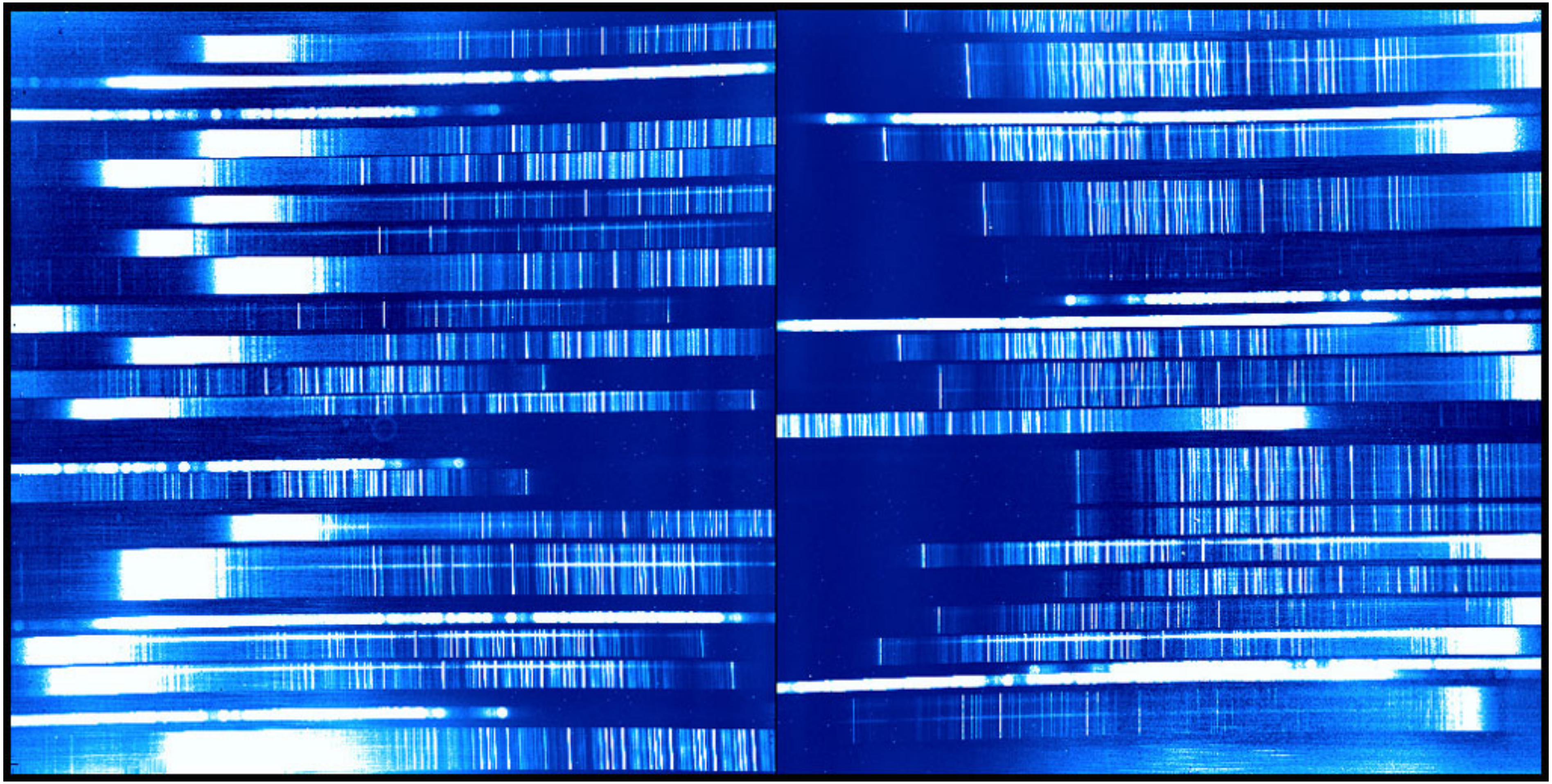
Hydra Arbitrary Fiber Positioning



Hydra Arbitrary Fiber Positioning

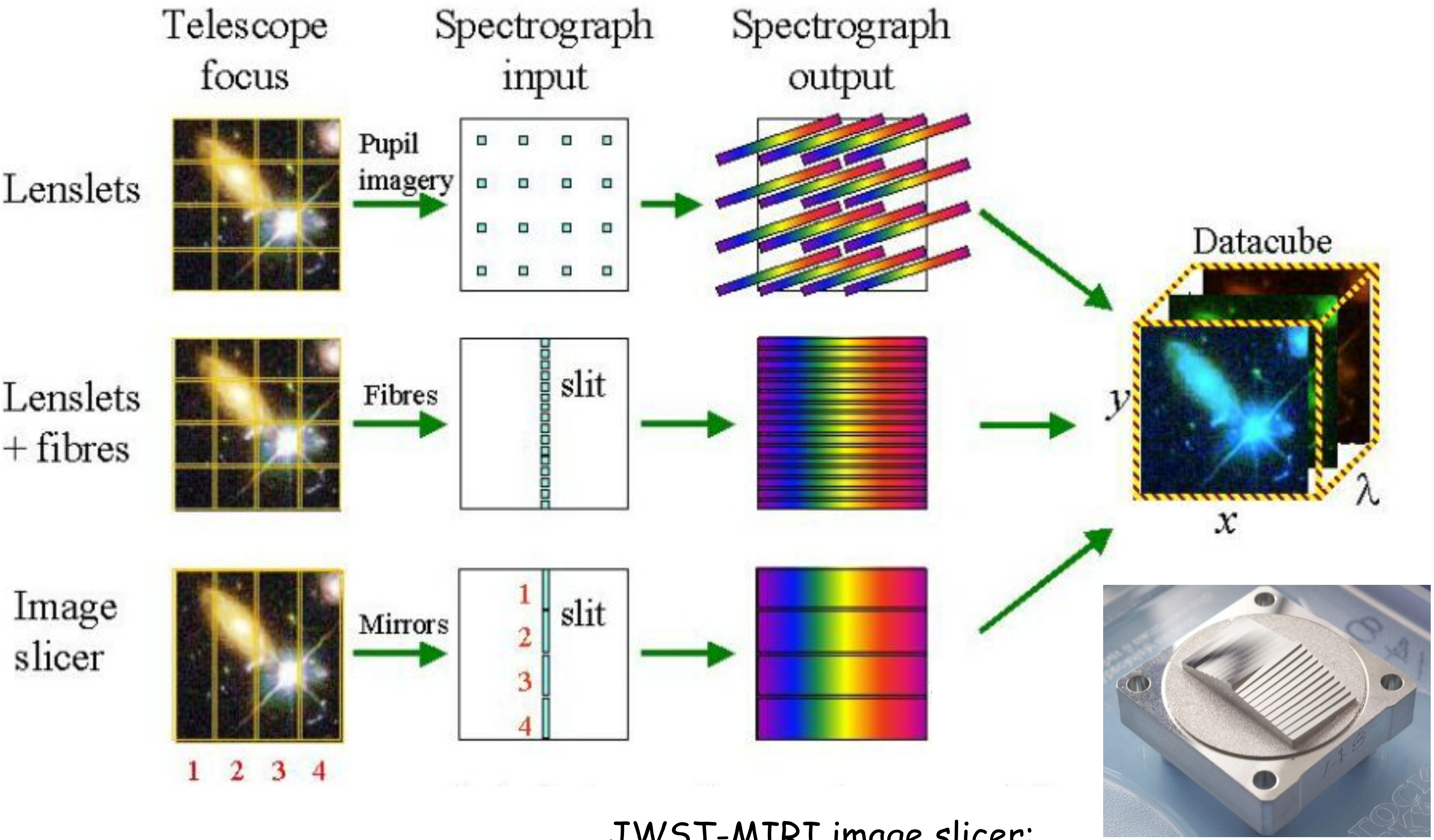


Multi-Object Spectrograph Spectra



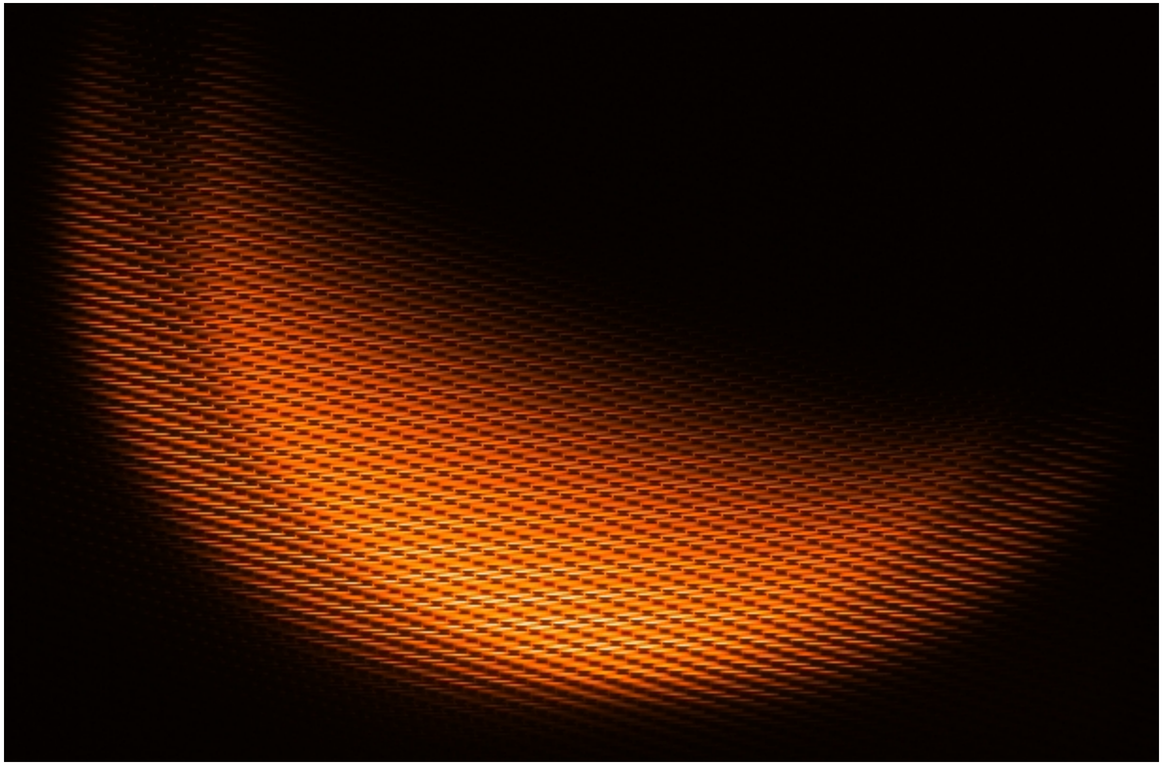
Integral Field Spectrographs

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.



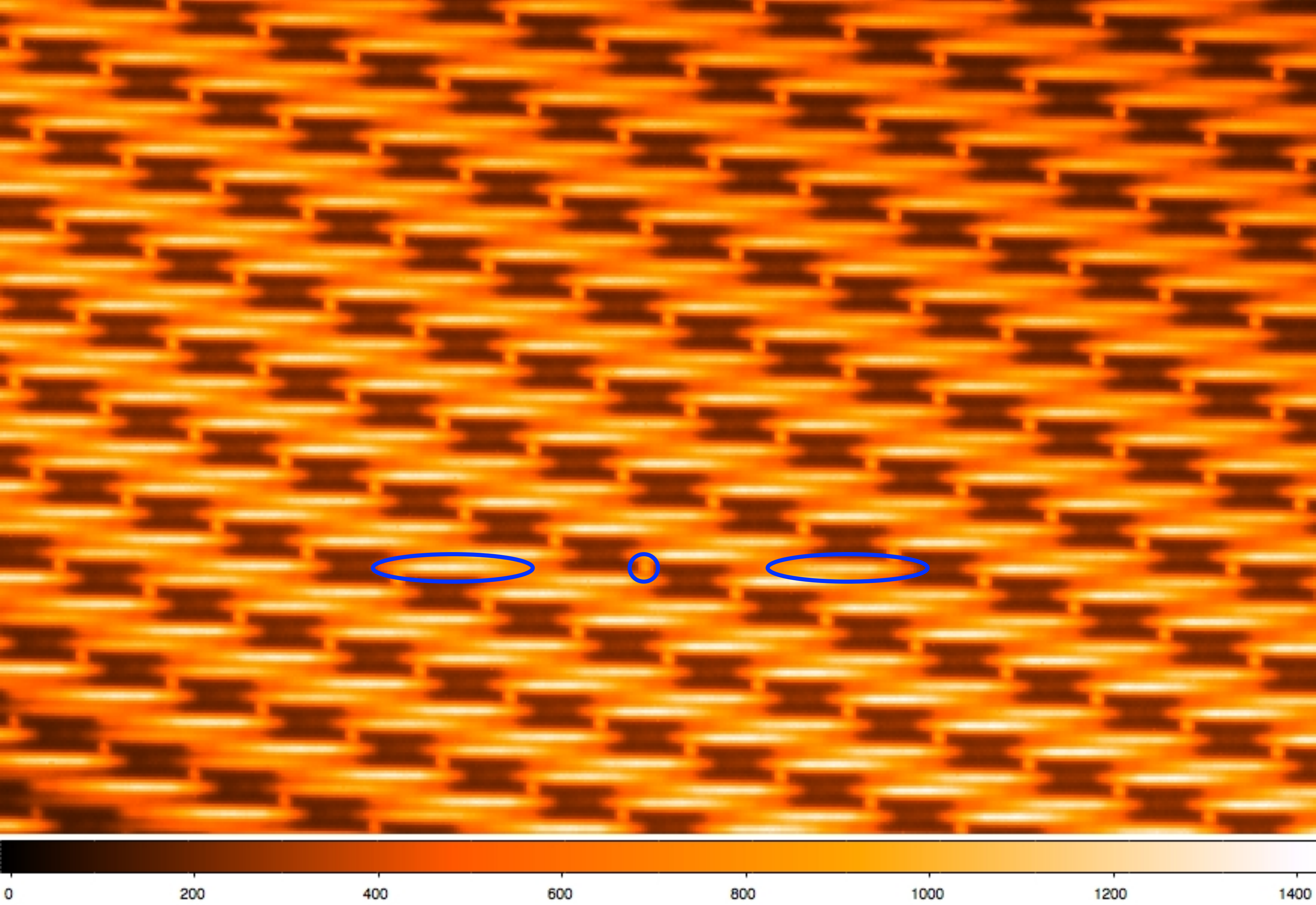
JWST-MIRI image slicer:

Leiden Observatory pIFU



Venus
 (Rodenhuis
2013)

- 450-900 nm, R~25
- polarization grating: polarizing beamsplitter and transmission grating


0
200
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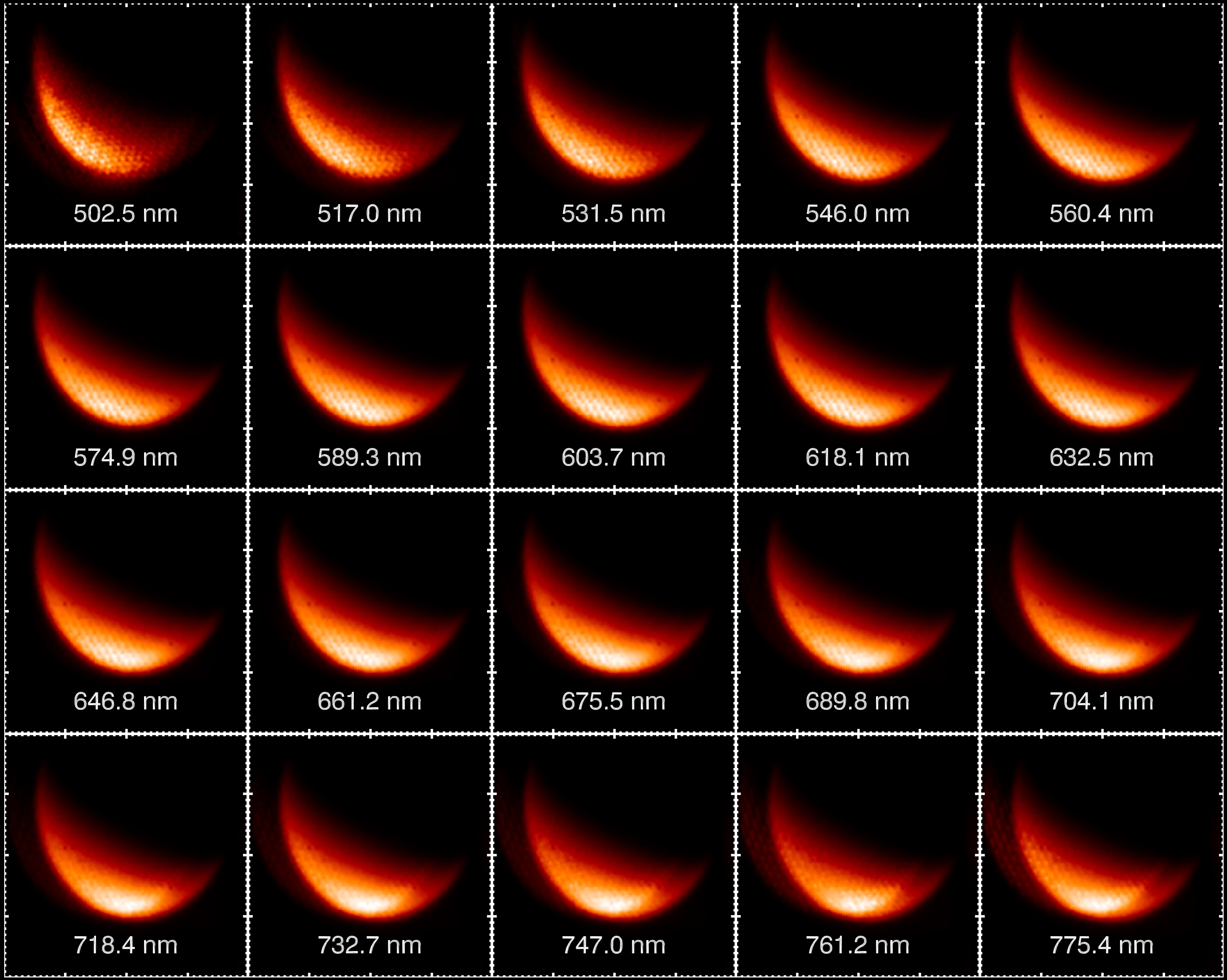
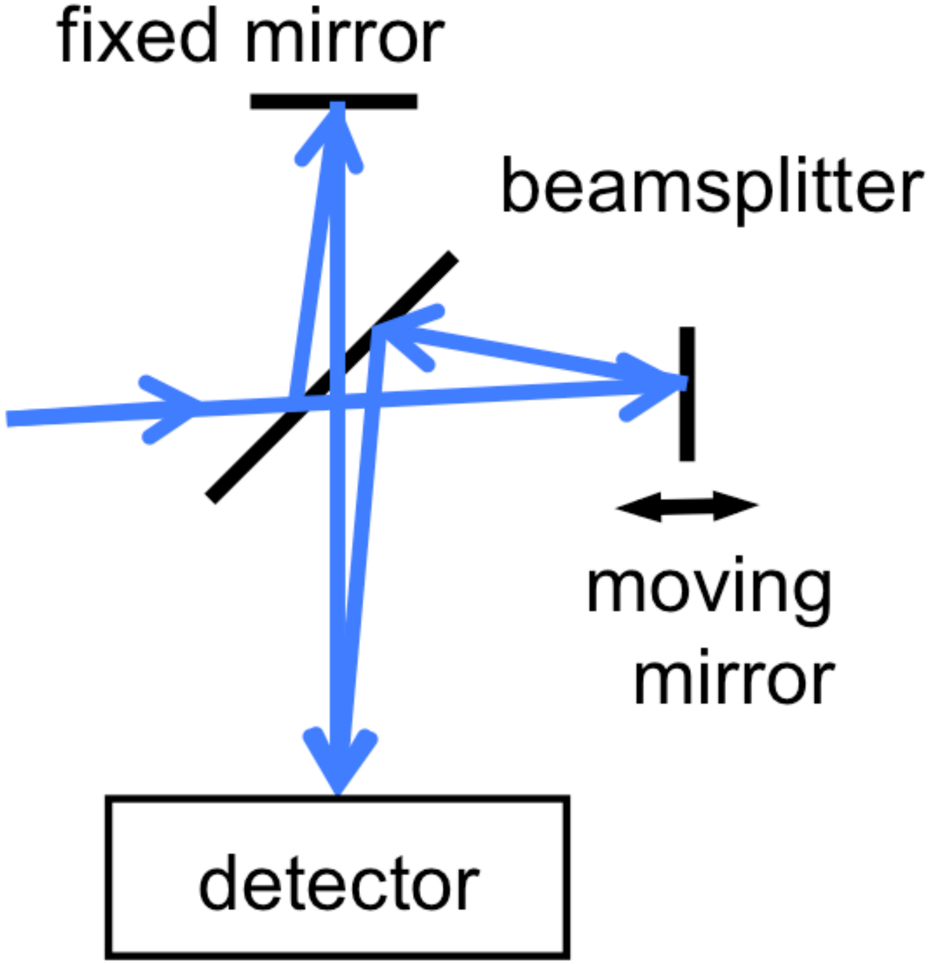
Simultaneous Multi-Wavelength Images of Venus



Fourier Transform Spectrometer (FTS)



- *Assume* a single pixel detector

- FTS or Michelson interferometer is a two-wave interferometer (grating has *N* waves from *N* grooves)

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

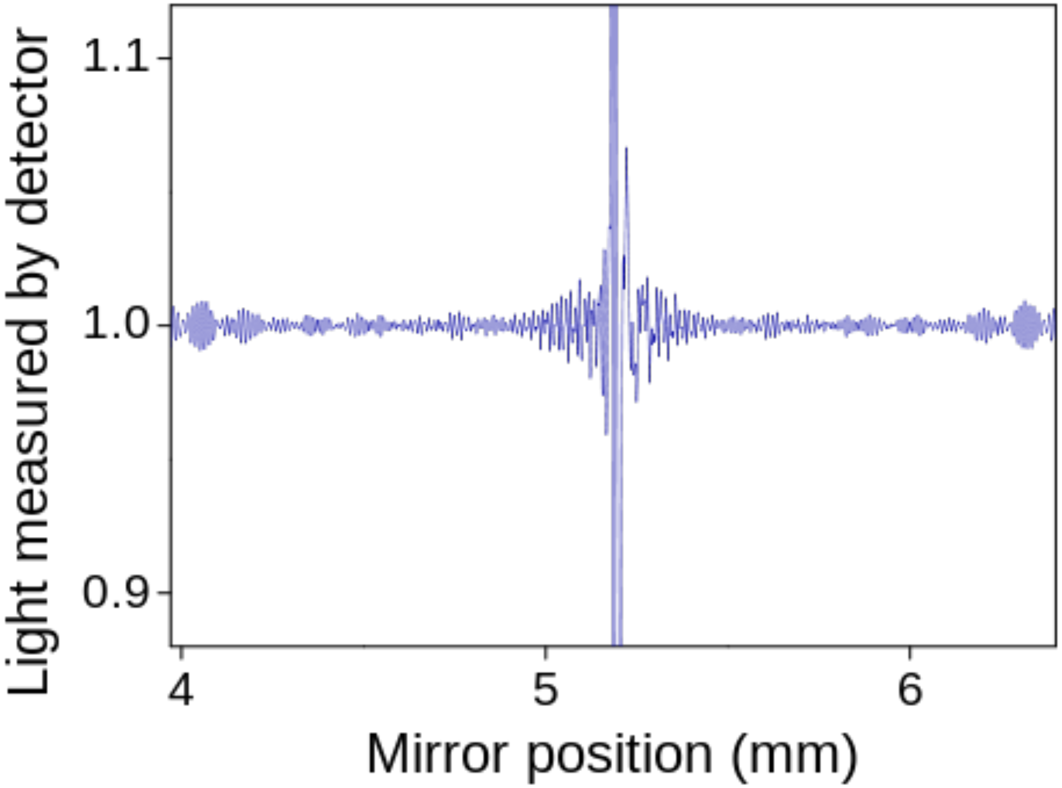
$$I(x)=\frac{1}{2}\int_{k_1}^{k_2} I_0(k)(1+\cos kx)\,dk$$

- Constant term plus real part of Fourier transform of spectrum

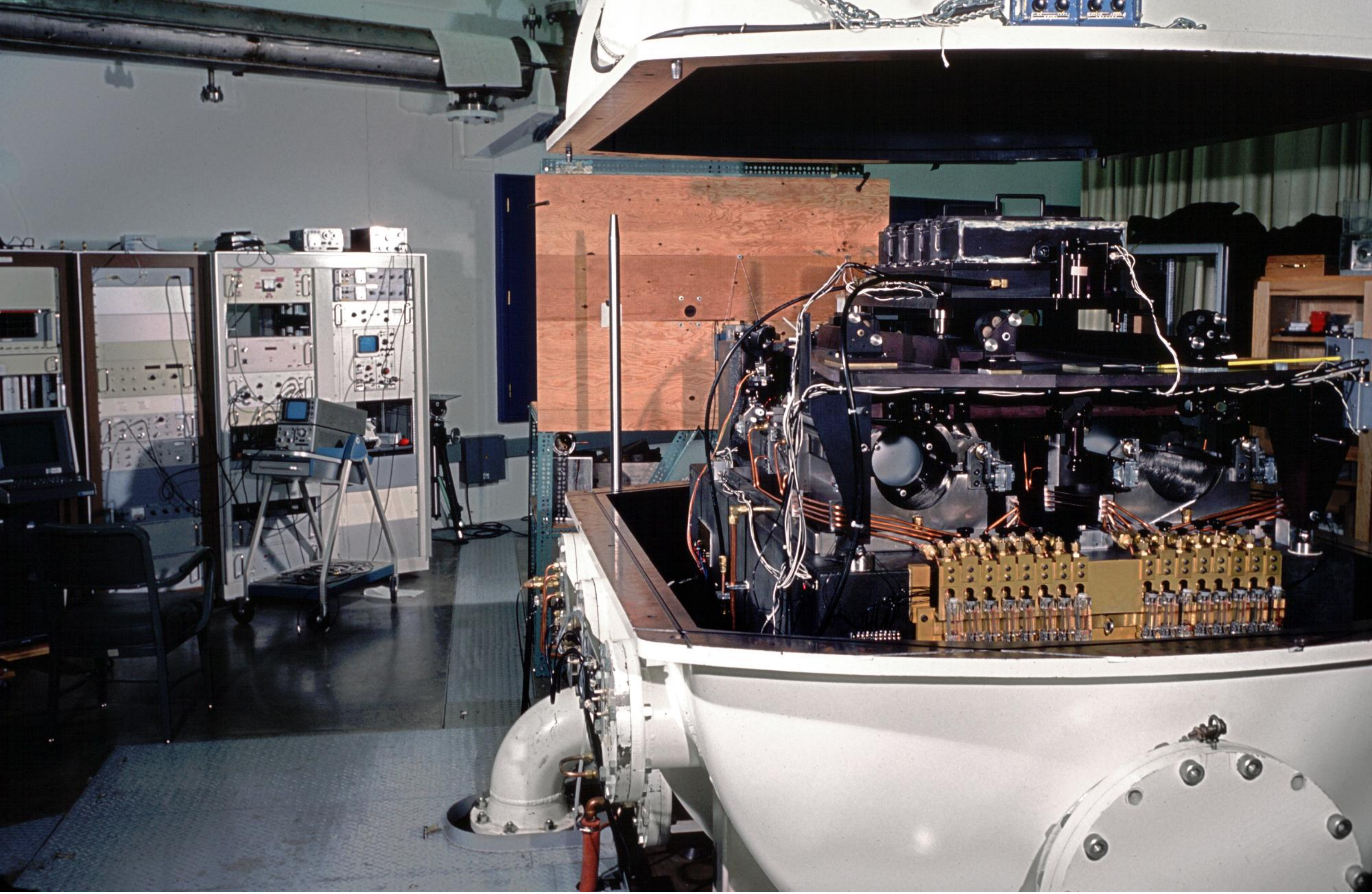
FTS – Measured Intensity

- 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	• 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