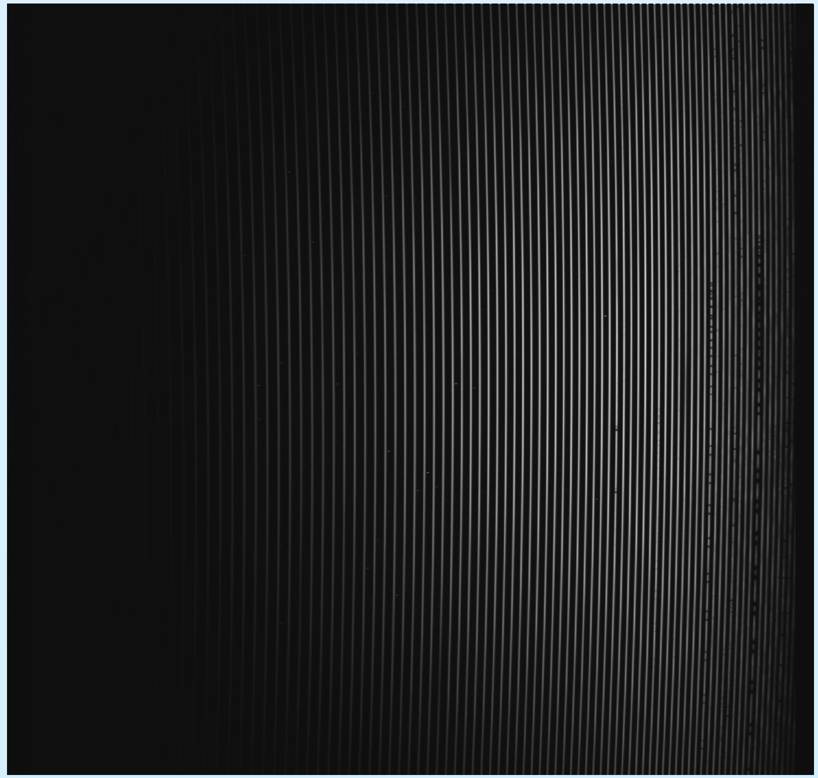
Fundamentals of Echelle Spectroscopy



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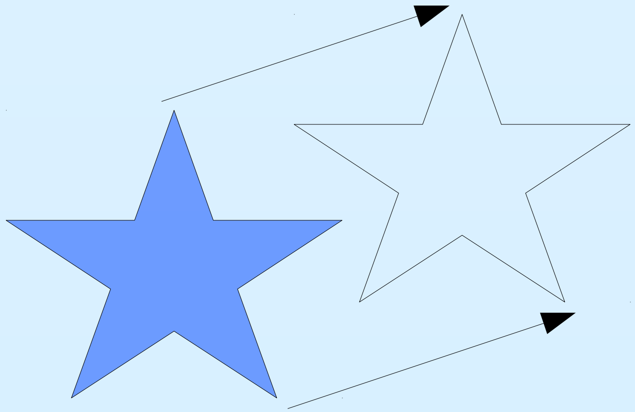
Moletai Summer School - August 2012

UPPSALA UNIVERSITET

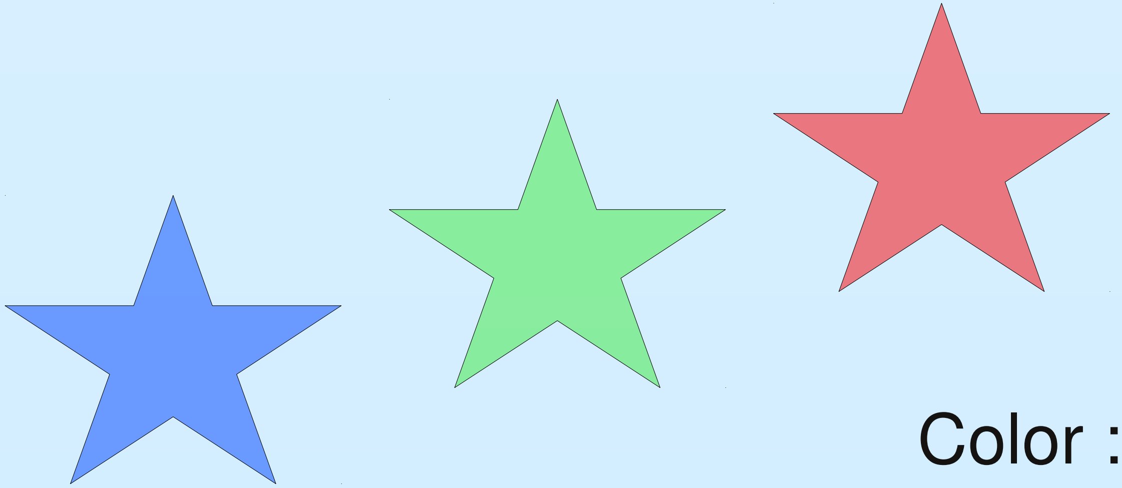
Overview

- A different introduction to optics?
- Dispersive elements
- Making a spectrograph
- Improving a spectrograph

Astronomical observables



Position : astrometry



Color : spectroscopy
(photometry)

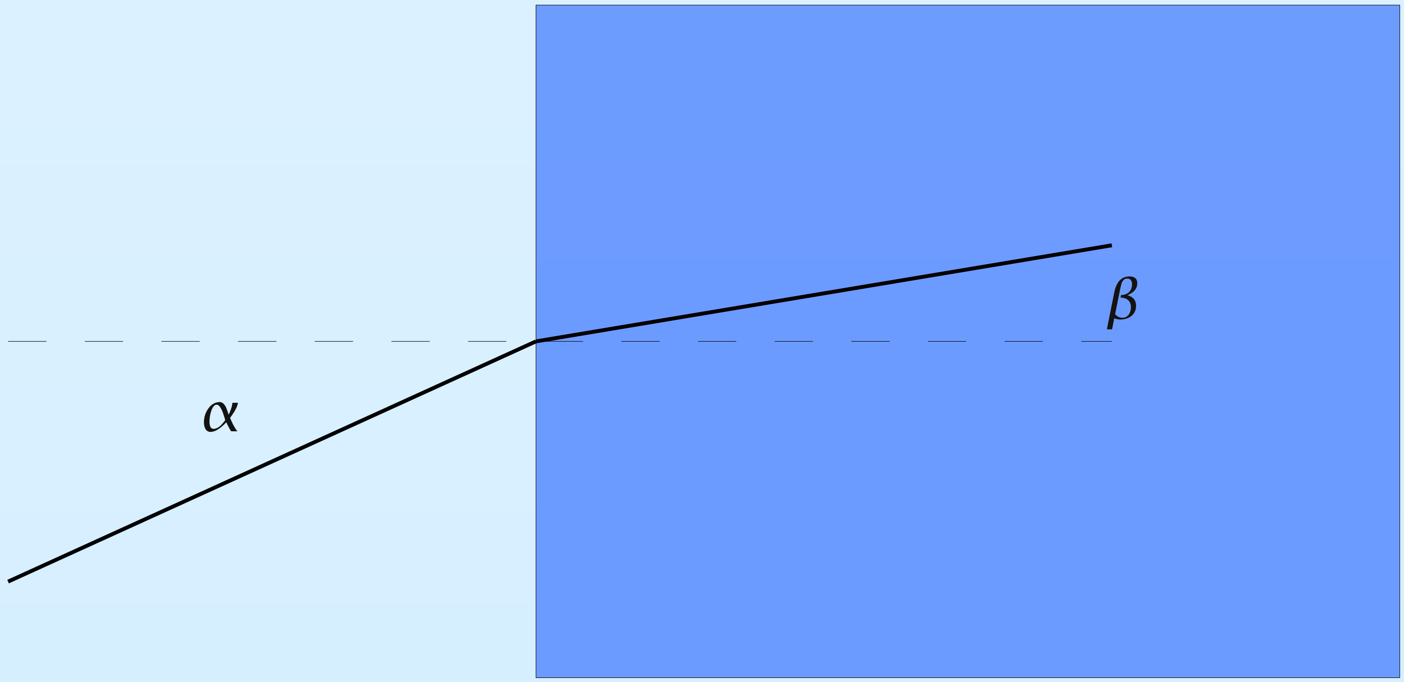
Spectroscopy

Detectors cannot measure the wavelength of light!

with filters = photometry
(simple, efficient, but very low resolution)

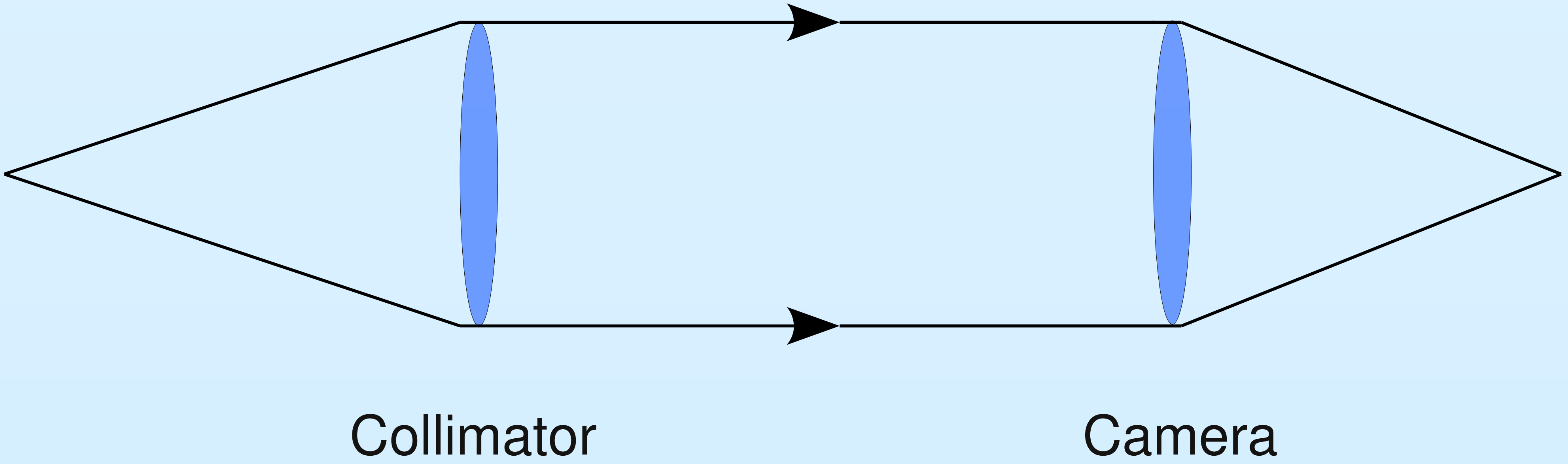
with dispersive element = spectroscopy
(technically more demanding, but gives high resolution)

Simple refraction

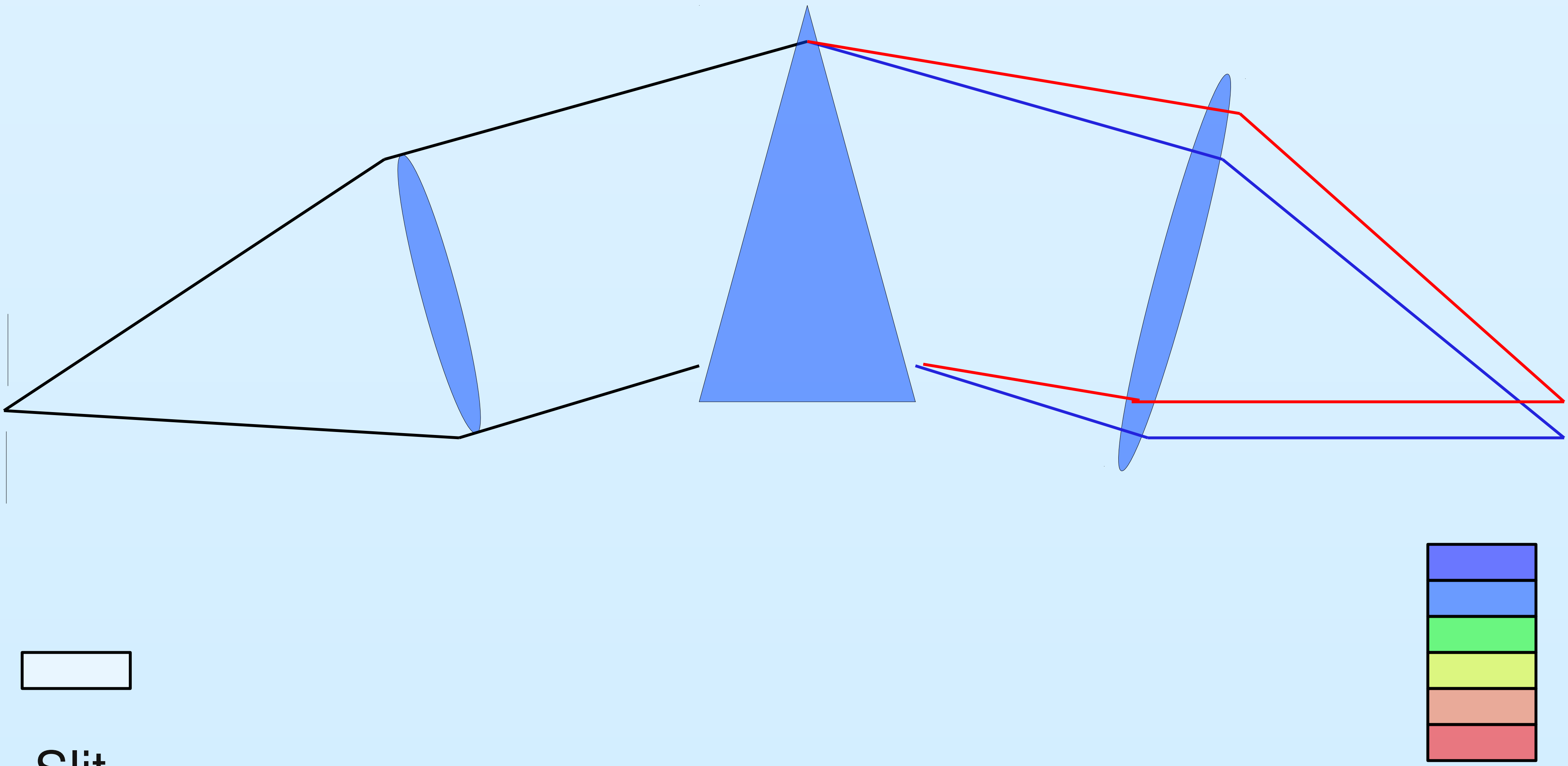


- Speed of light in medium is c/n
- Refraction is actually light taking the *quickest* path

Simple imager



Simple spectrograph

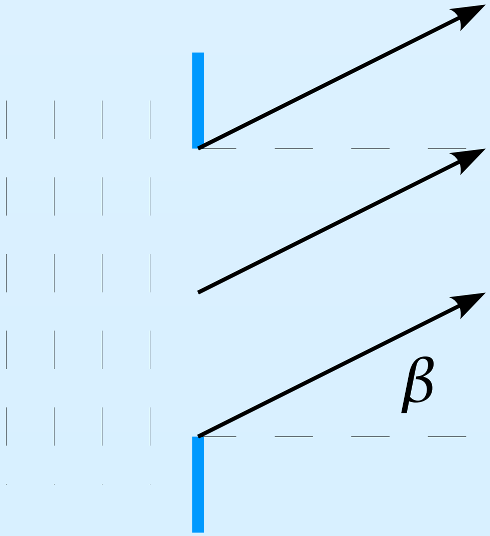


Slit

Fourier perspective of optics

First, for a single, wide slit :

$$G(\beta) = \int F(x,t) G(x) e^{2\pi i (x \sin\beta)/\lambda} dx$$



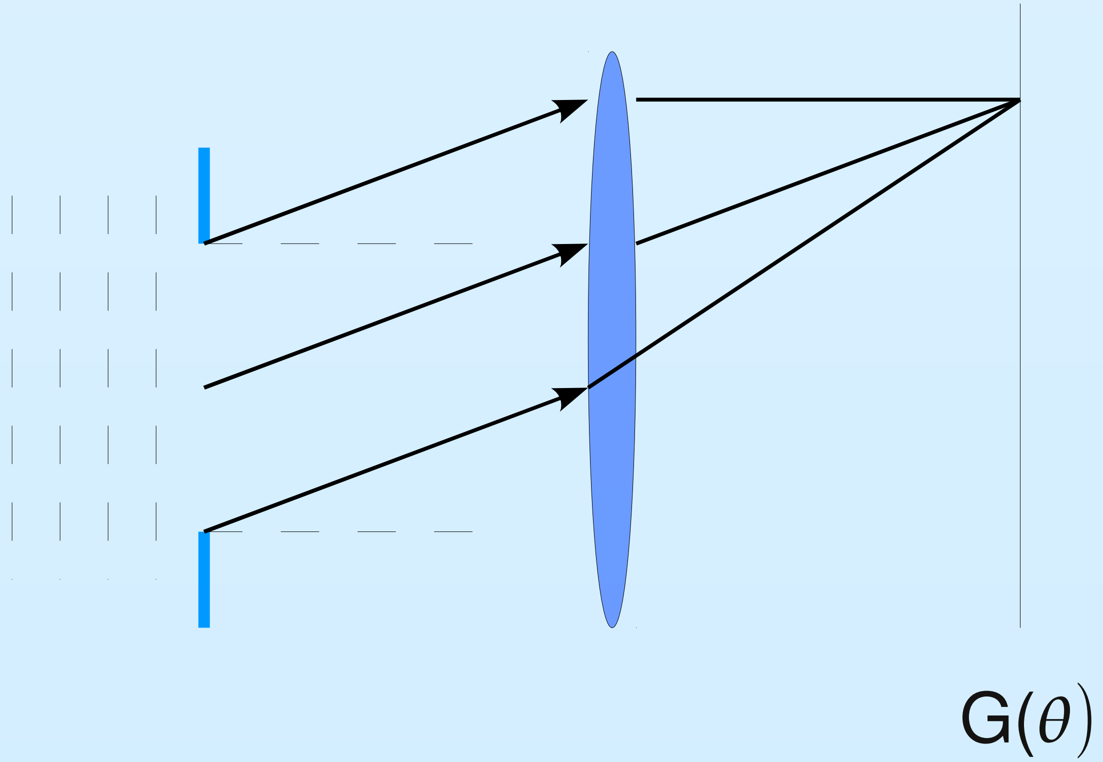
Switch variables : $\theta = x \sin\beta / \lambda$

$$G(\theta) = F_0 \int G(x) e^{2\pi i x \theta} dx$$

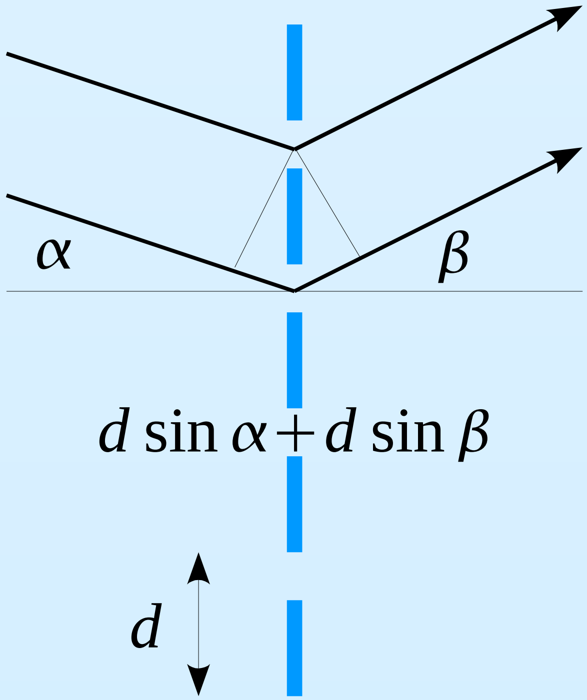
which is a *Fourier transformation* and holds for *all* G(x)

Fourier perspective of optics

With a lens we can determine G(θ) :



Transmission grating

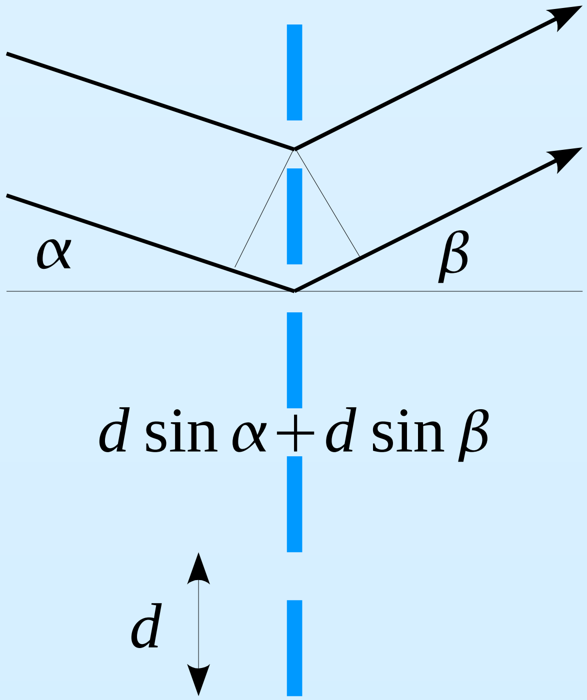


$$\sin\alpha + \sin\beta = \theta = \frac{n\lambda}{d}$$

High dispersion can be obtained by :

- High order number (n)
- Small distance between grooves (d)

Transmission grating - efficiency

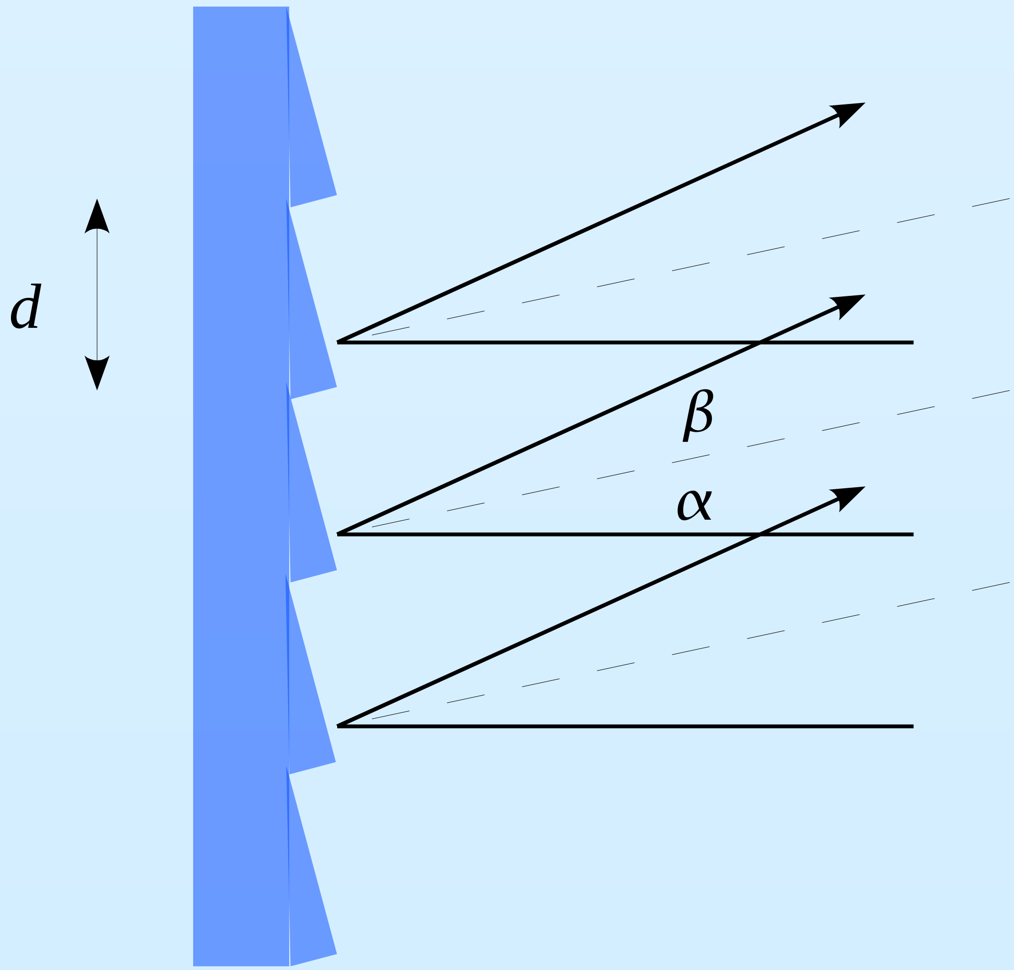


At high orders, efficiency becomes an issue

Directing light towards higher orders not a solution, because it introduces phase shifts

Solution : blazed reflection grating

Blazed grating

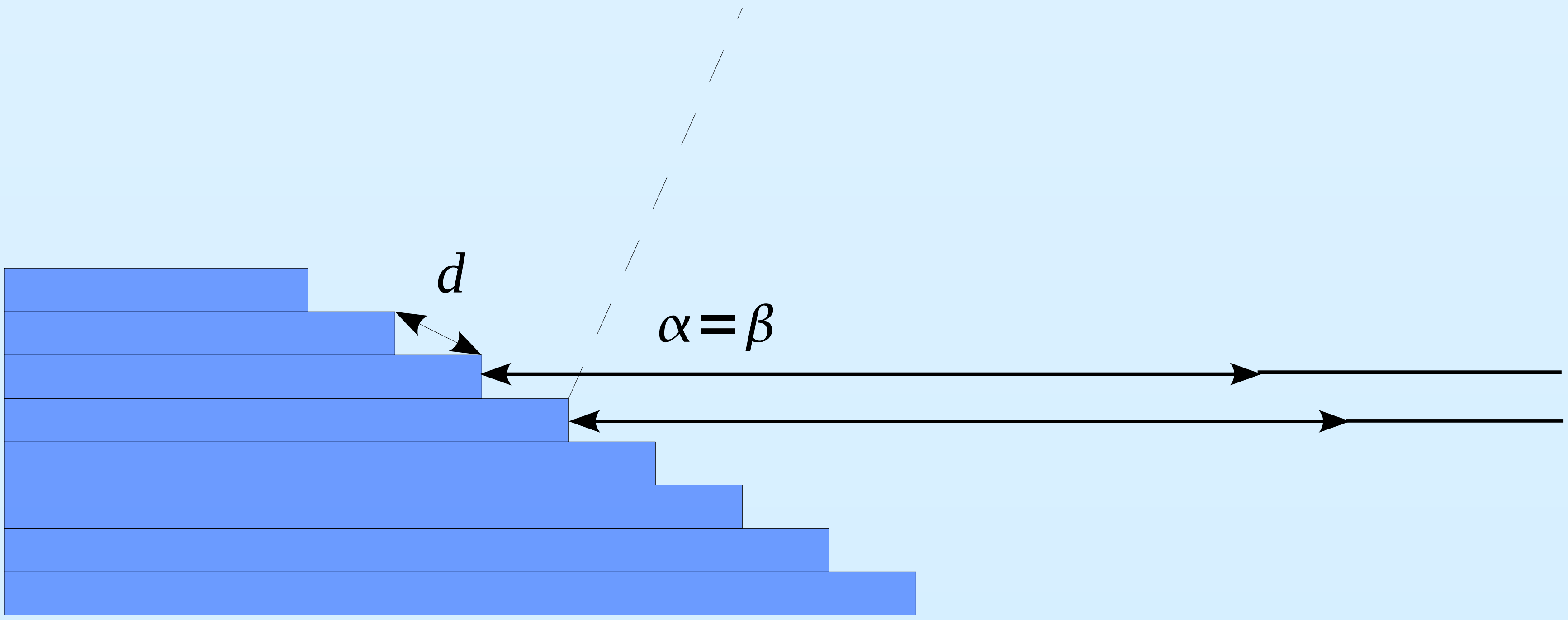


$$\sin\alpha + \sin\beta = \theta = \frac{n\lambda}{d}$$

Central blaze directed to higher orders

Best performance if : $\alpha = \beta$
(no shadowing)

Echelle



Easy to work in very high orders

$$\sin\alpha + \sin\beta = \theta = \frac{n\lambda}{d}$$

Resolution of an echelle

$$\sin\alpha + \sin\beta = \theta = \frac{n\lambda}{d}$$

$$\frac{d\lambda}{d\beta} = \frac{d\cos\beta}{n}$$

and thus :

$$\Delta\lambda = \Delta\beta\,\frac{d\cos\beta}{n}$$

This can be used to calculate the resolution that can be achieved for a given echelle and slit width

Spectral resolution

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

- Low-resolution spectroscopy

  $R < 10\,000$

- High-resolution spectroscopy

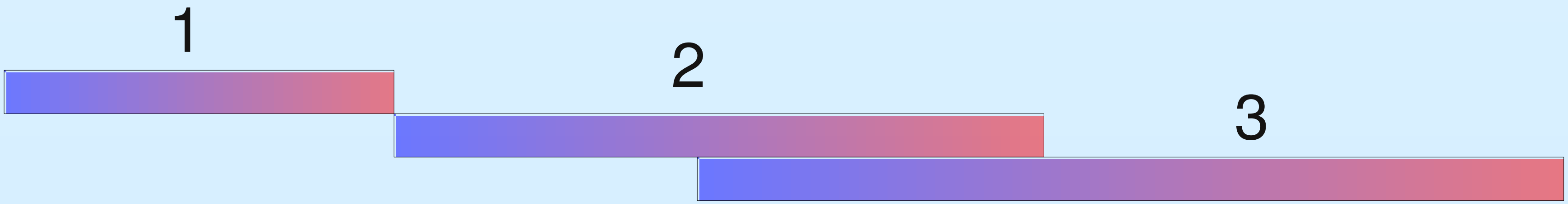
  $10\,000 < R < 100\,000$

- Ultra-high resolution spectroscopy

  $R > 100\,000$

Grating and echelle : order overlap

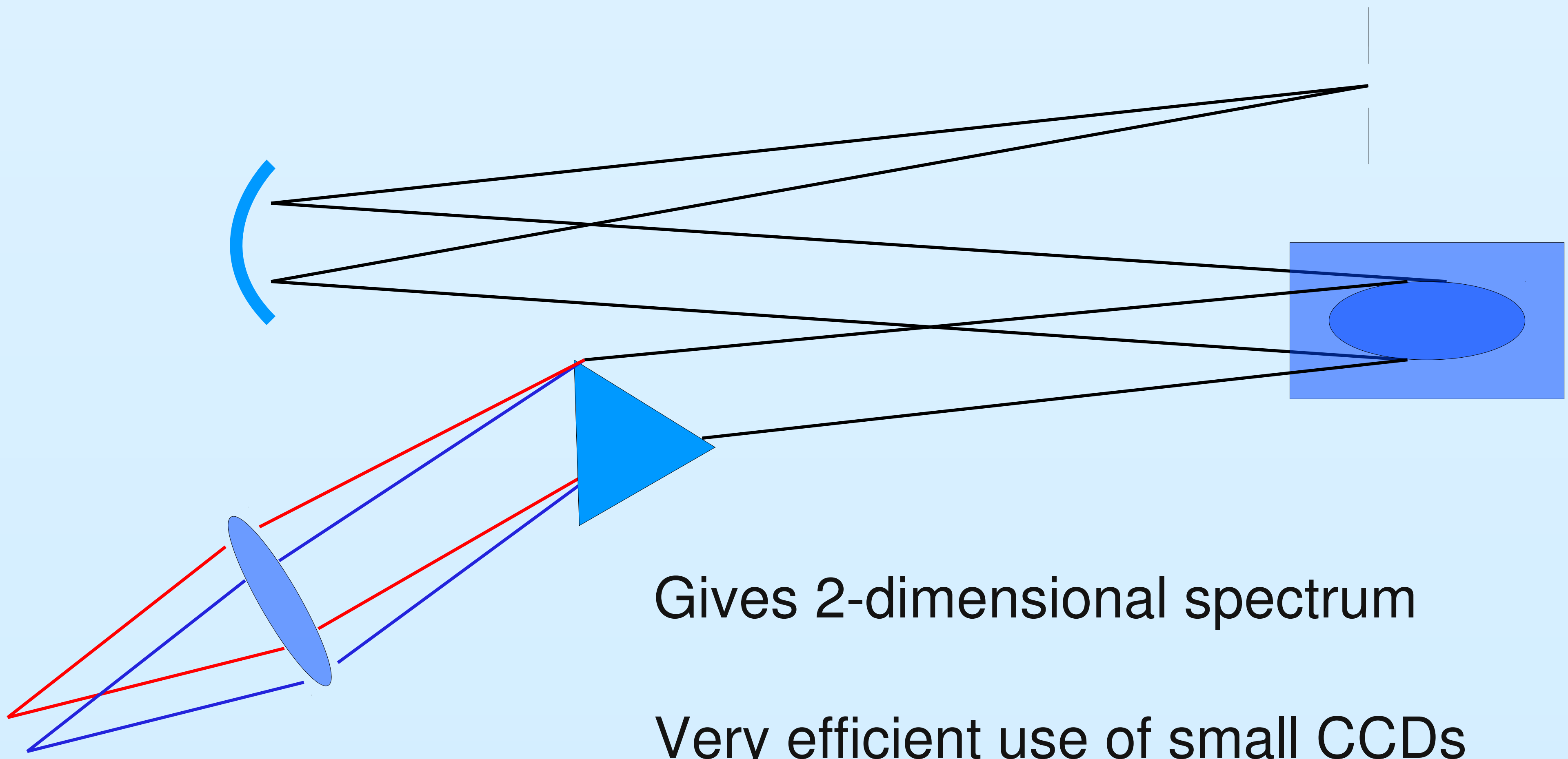
For n > 1



Order sorting filter or cross-disperser

Now we can make a very efficient high-resolution spectrograph

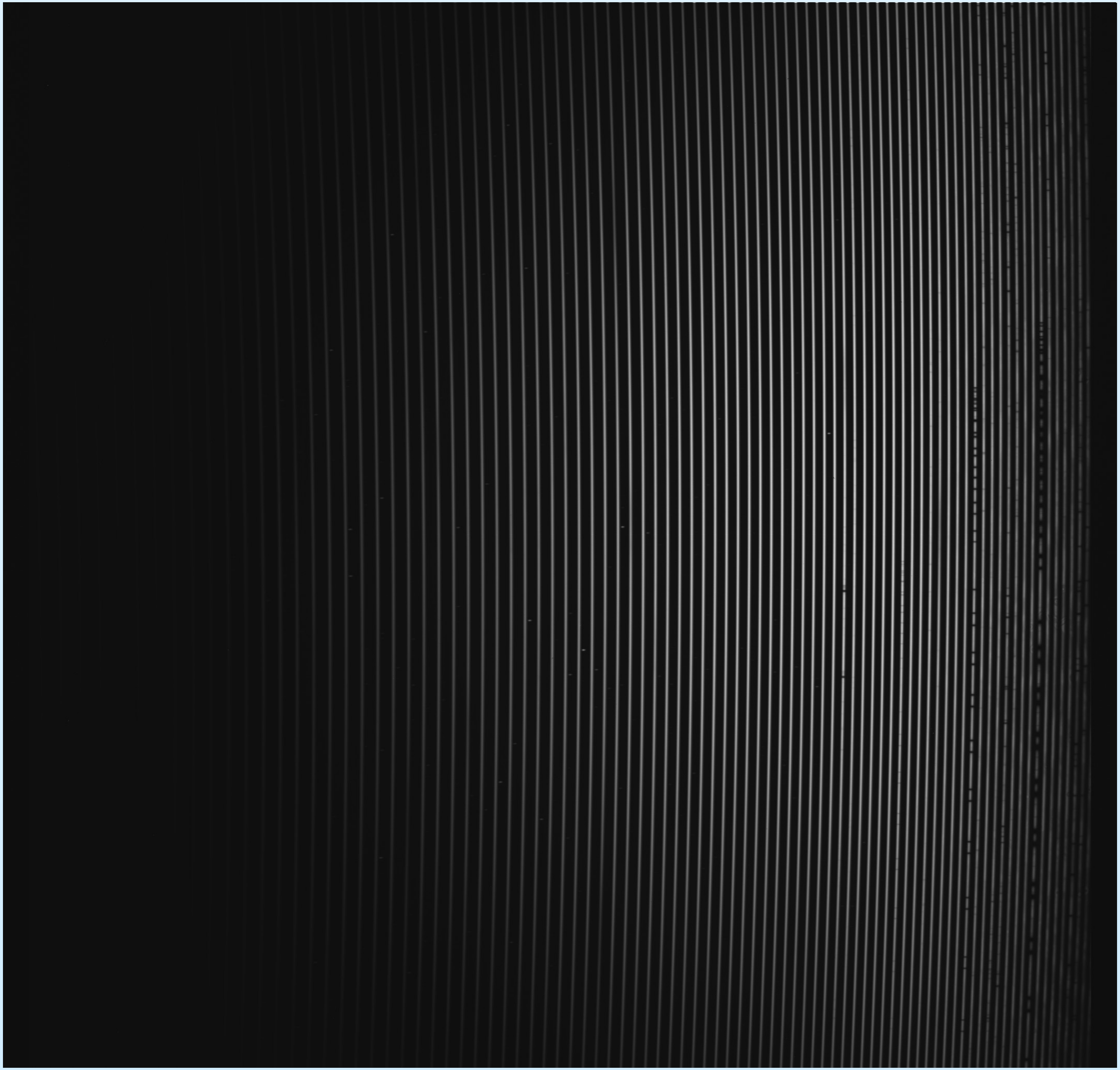
Simple cross-dispersed spectrograph



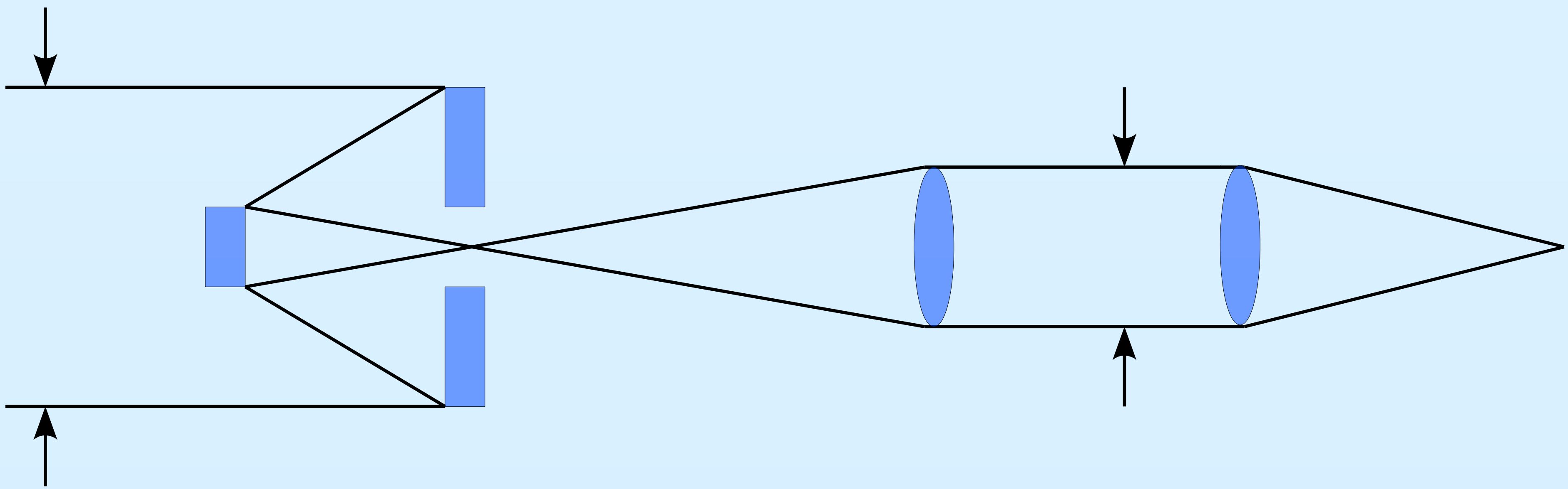
Gives 2-dimensional spectrum

Very efficient use of small CCDs

Disadvantage - limited slit length



Telescope + Spectrograph



Ratio of diameters determines magnification

Cannot have small PSF (=high resolution) and have small beam

Very expensive to have a high-resolution spectrograph on a large telescope

Example - possible resolution for FIES

$$\sin\alpha + \sin\beta = \theta = \frac{n\lambda}{d}$$

$$\Delta\lambda = \Delta\beta \frac{d\cos\beta}{n}$$

FIES has an echelle with 31.6 grooves/mm and a blaze angle of 63.5 degrees.

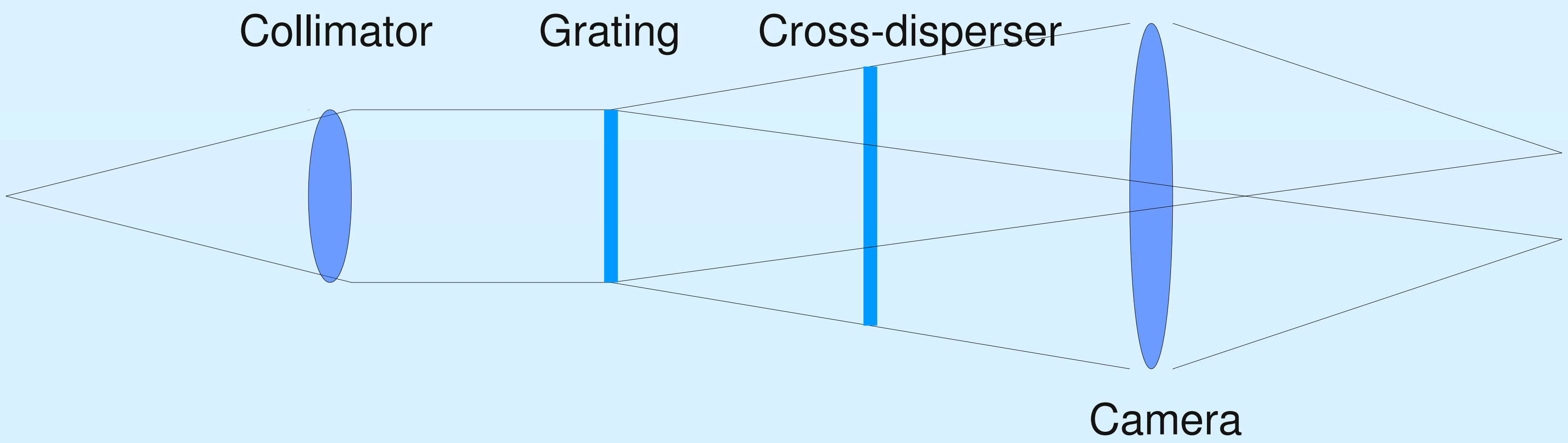
The FIES beam has a diameter of 15 cm
The NOT mirror has a diameter of 250 cm

The fiber diameter is 1 arcsecond on the sky

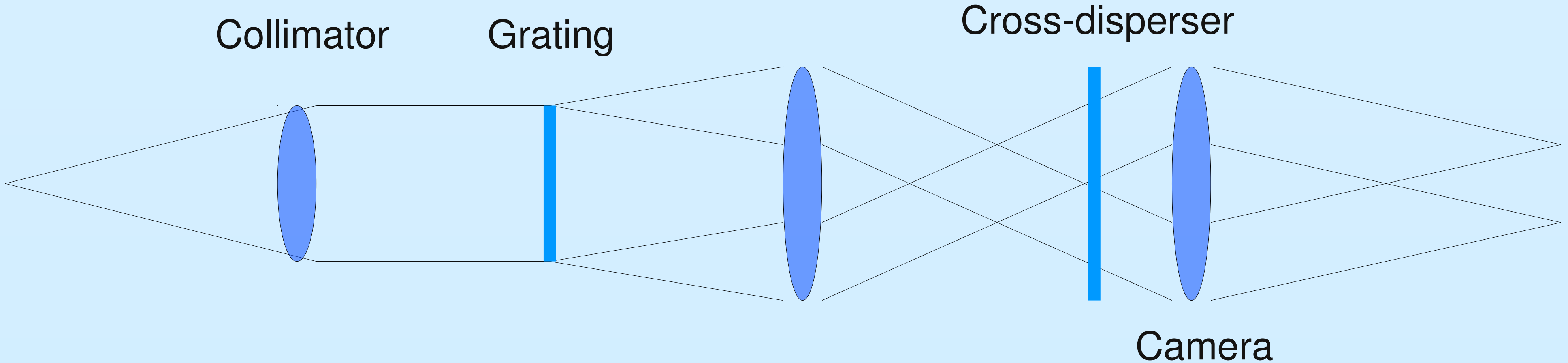
Further improvements to the spectrograph

- White pupil
- Temperature stabilization
- Fibers
- Image slicer

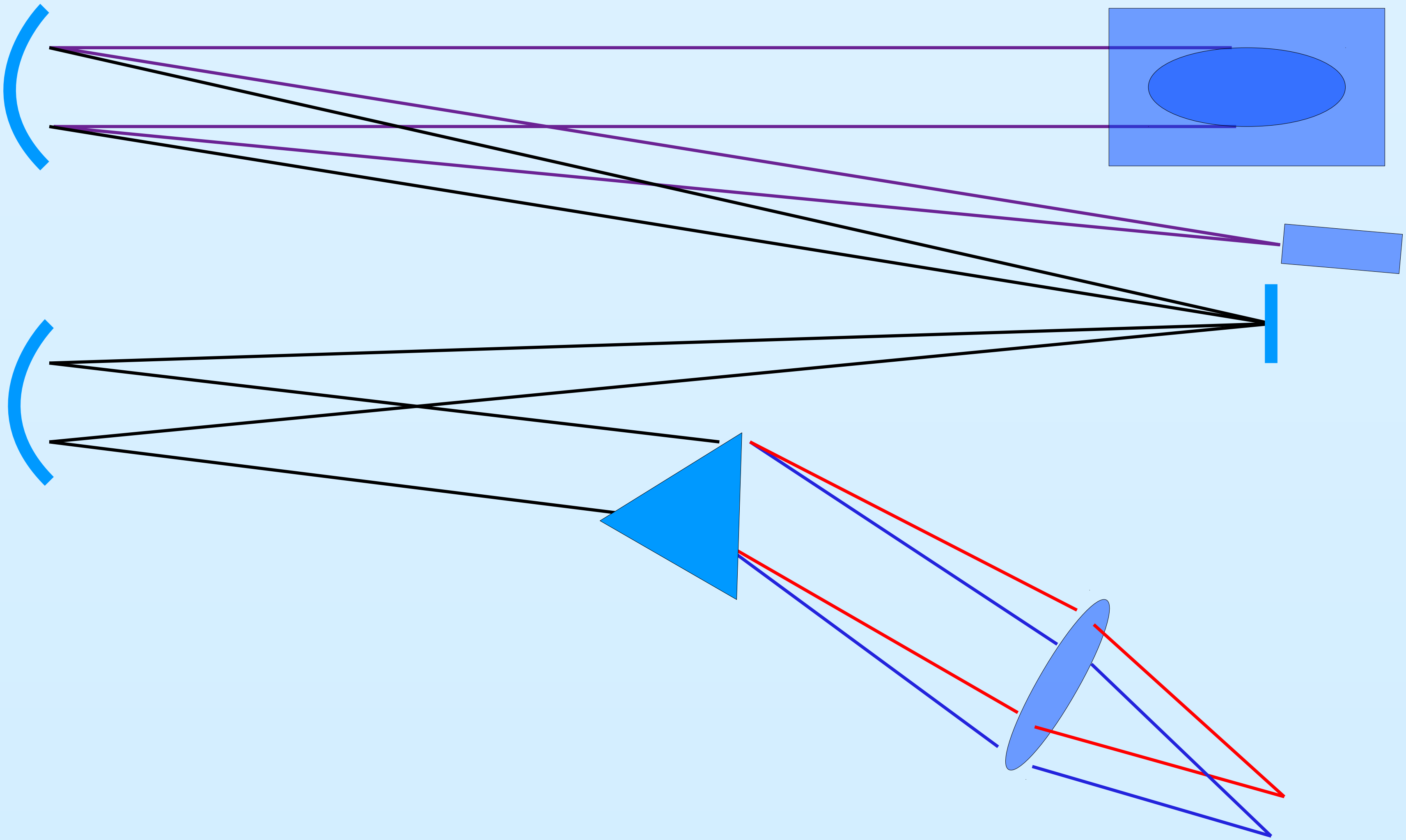
White-pupil design



But, with one more optical element :

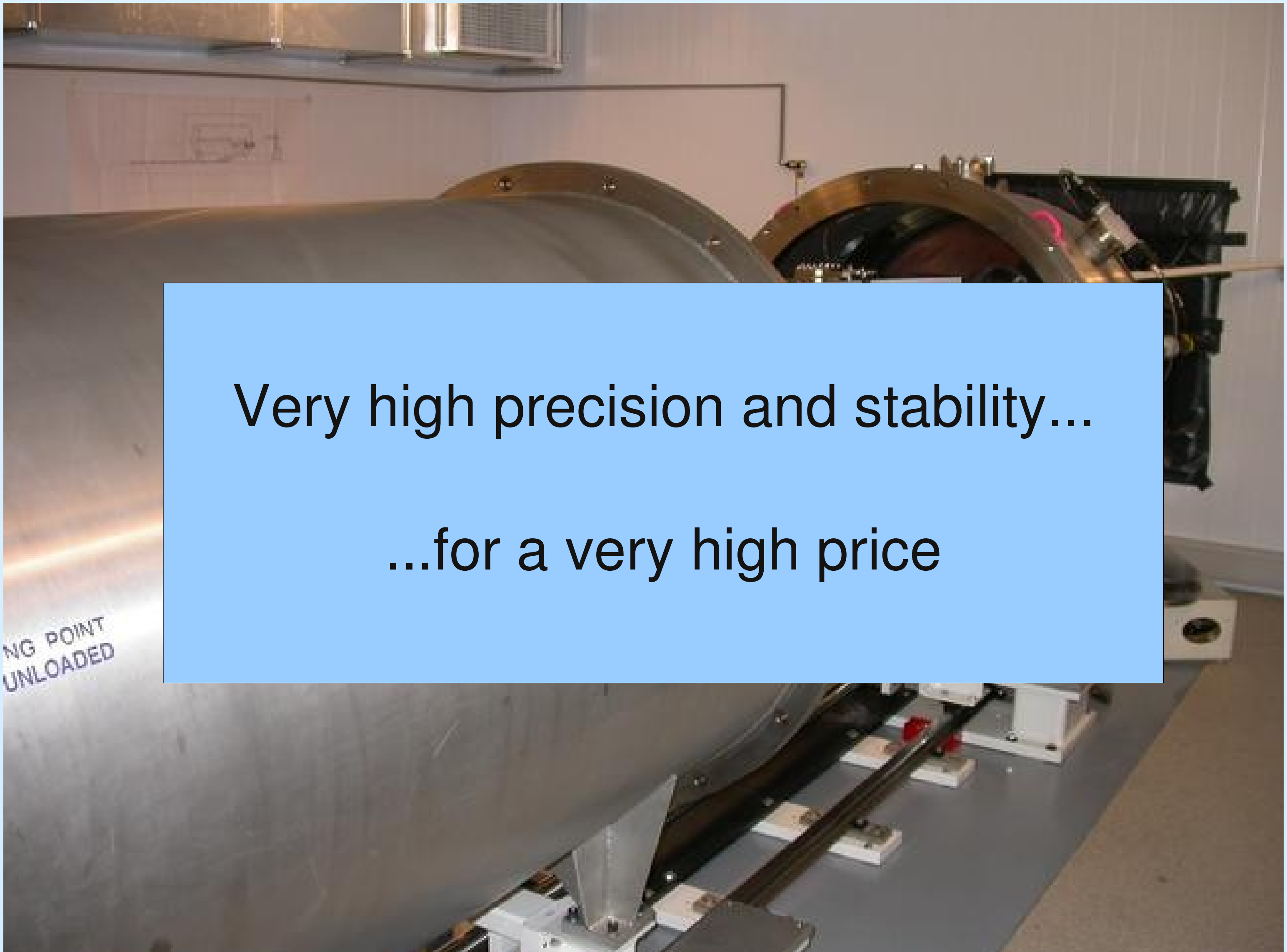


White-pupil design



Temperature Stabilization

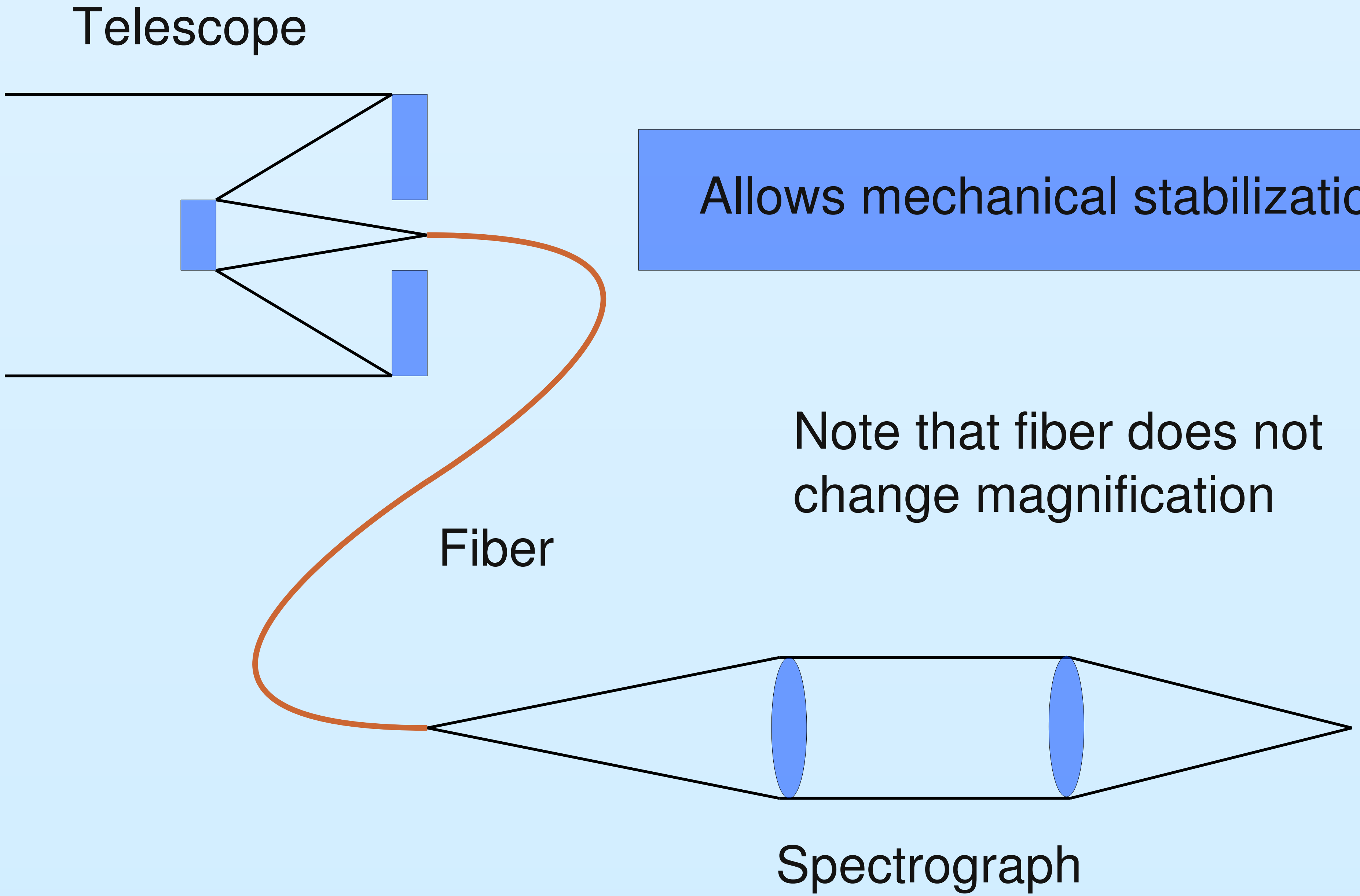
Temperature Stabilization



Very high precision and stability...

...for a very high price

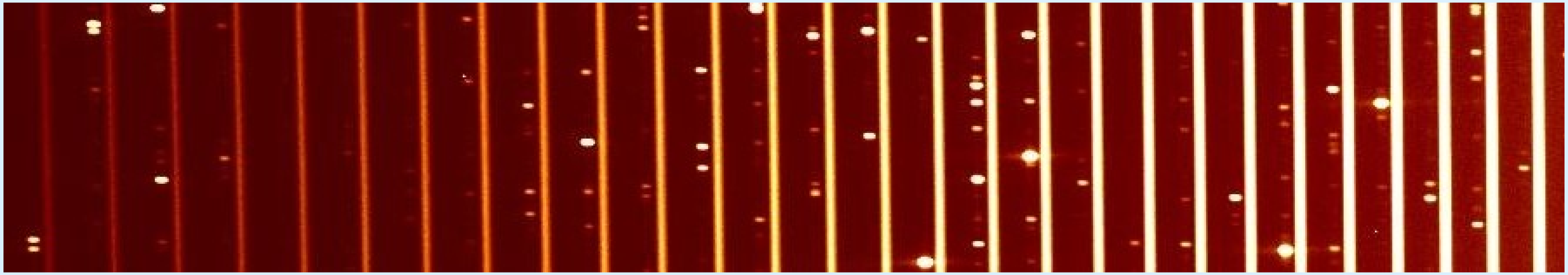
Use optical fibers



Allows mechanical stabilization

Note that fiber does not change magnification

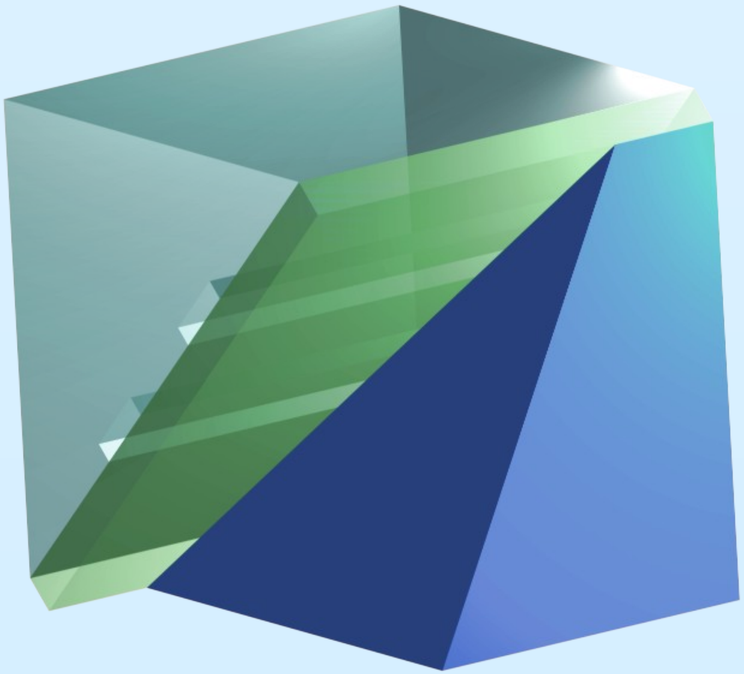
Improve 'stability' with simultaneous ThAr



If the inter-order space is large, one can add a second slit/fiber. For example :

- Simultaneous calibration lamp light
- Sky background
- Multi-object fiber-fed spectroscopy

Bowen-Walraven image slicer



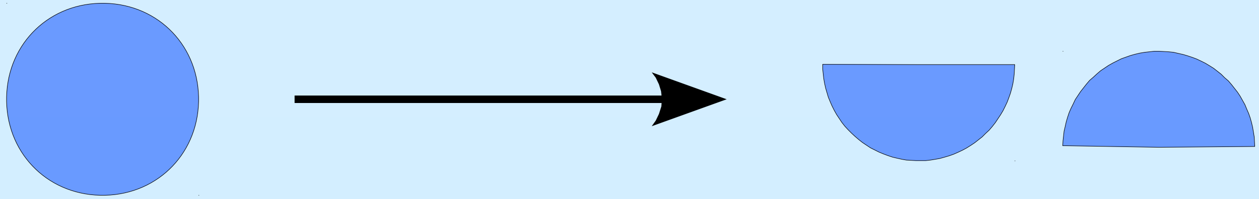
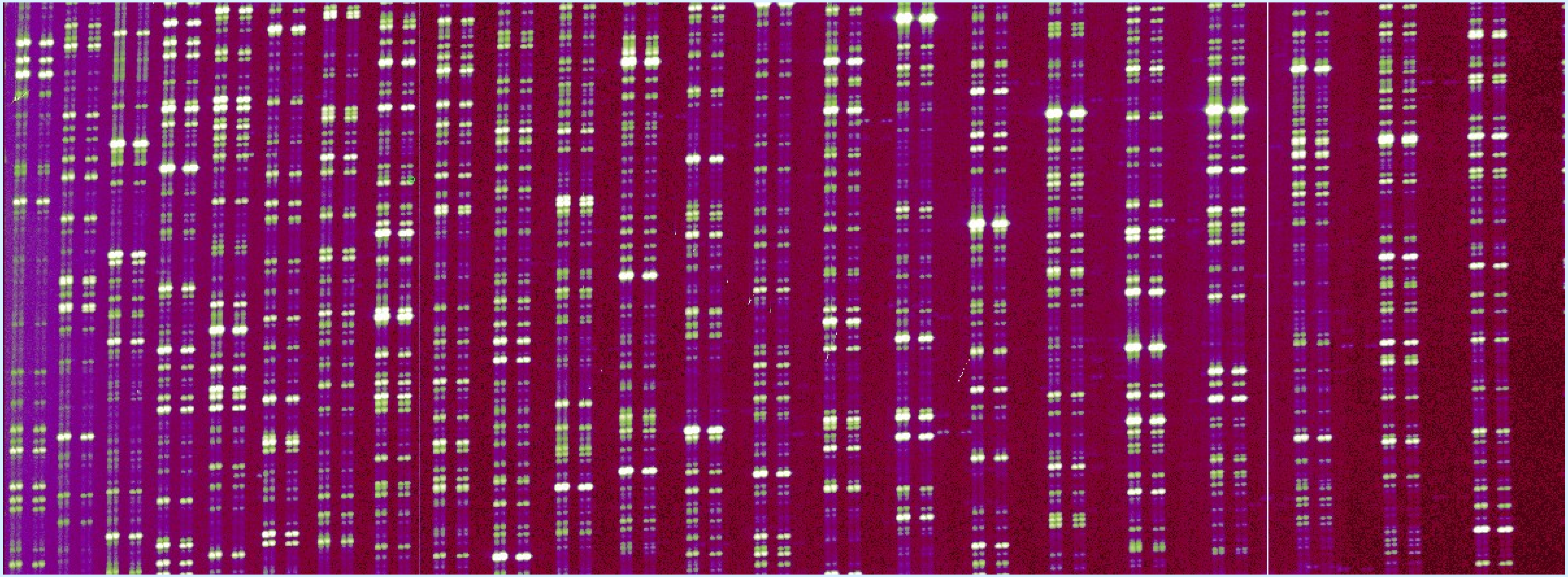


Image slicer



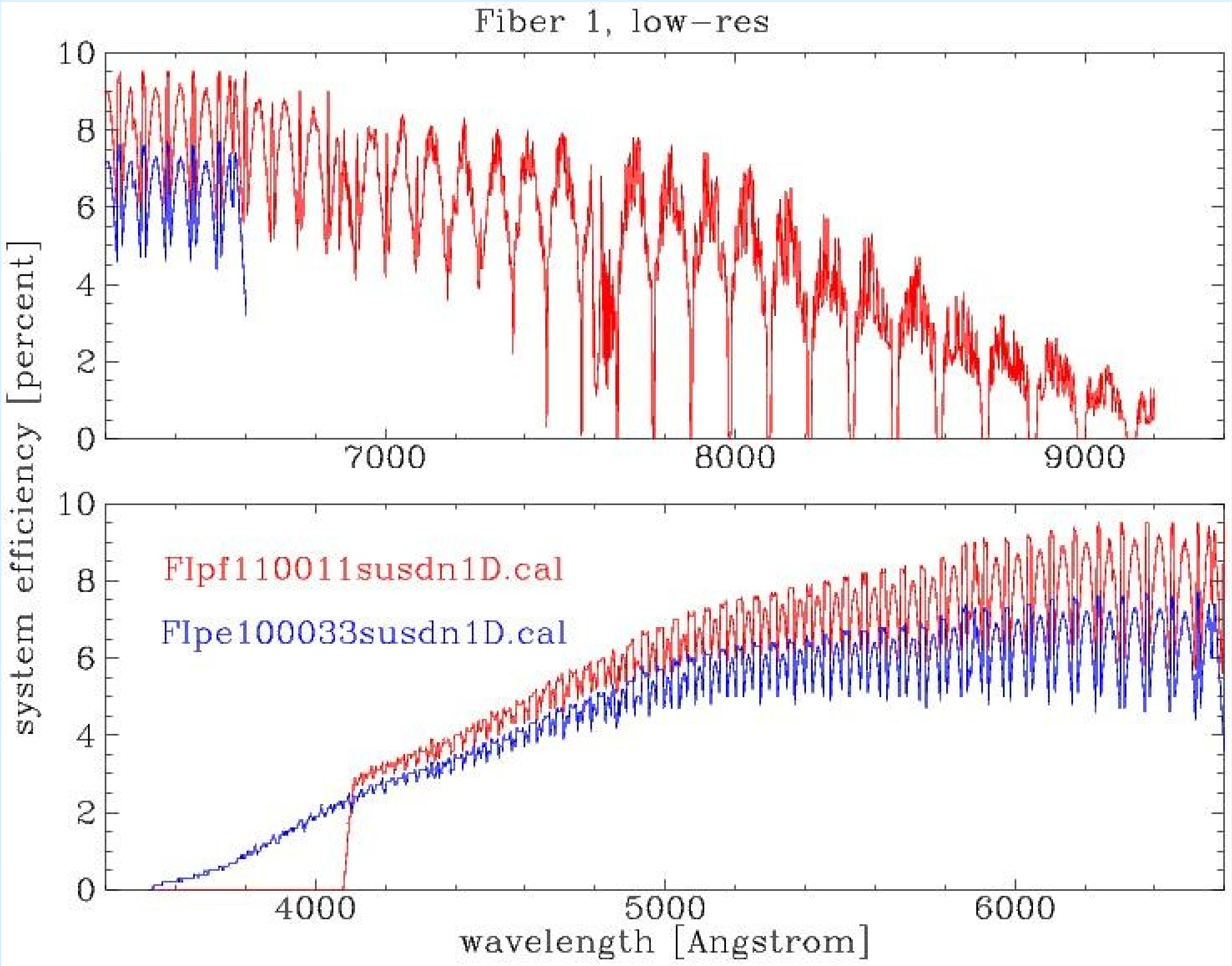
Resolution is not everything

Spectral resolution is not the only parameter that determines how good a spectrograph is

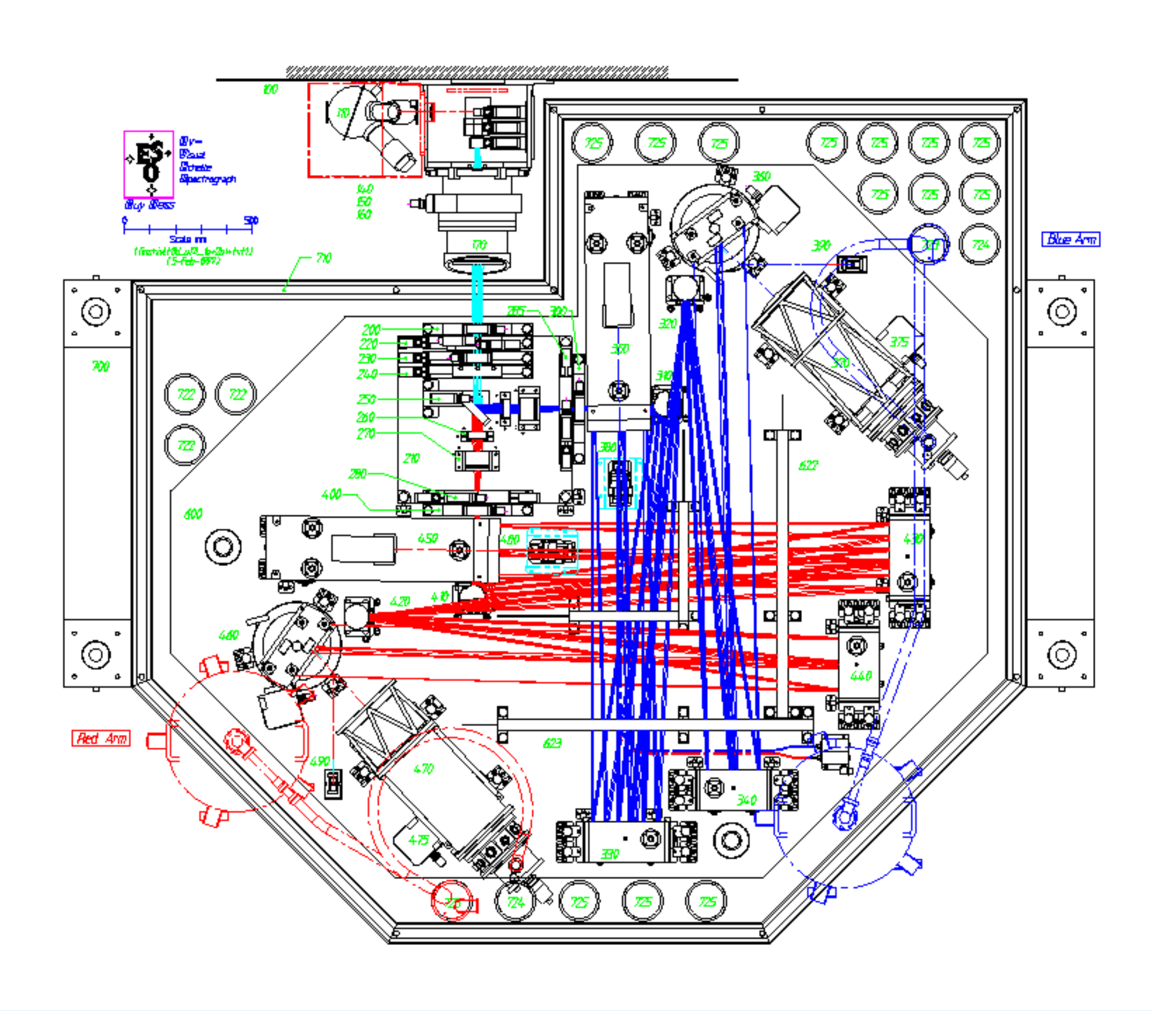
Other important factors are :

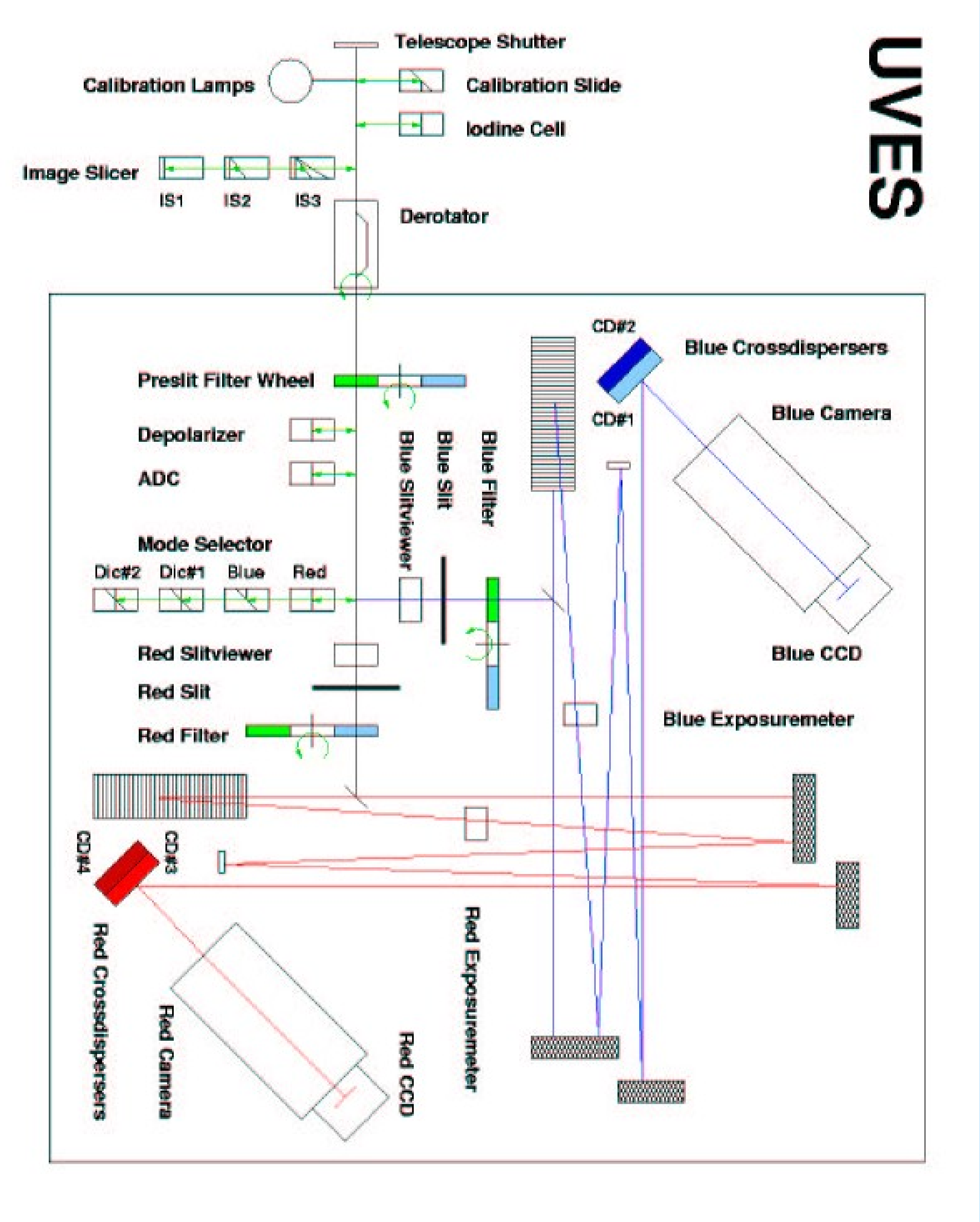
- Telescope
- Size of the 'slit' on the sky
- Short and long-term stability of the instrument
- Efficiency (throughput)

Throughput of FIES



Optical layout of UVES




UVES
Telescope Shutter
Calibration Lamps
Calibration Slide
Iodine Cell
Image Slicer
IS1
IS2
IS3
Derotator
CD#2
Blue Crossdispersers
Preslit Filter Wheel
CD#1
Blue Camera
Depolarizer
ADC
Blue Slitviewer
Blue Slit
Blue Filter
Mode Selector
Dic#2
Dic#1
Blue
Red
Blue CCD
Red Slitviewer
Red Slit
Red Filter
Blue Exposuremeter
CD#4
CD#3
Red Crossdispersers
Red Camera
Red CCD
Red Exposuremeter