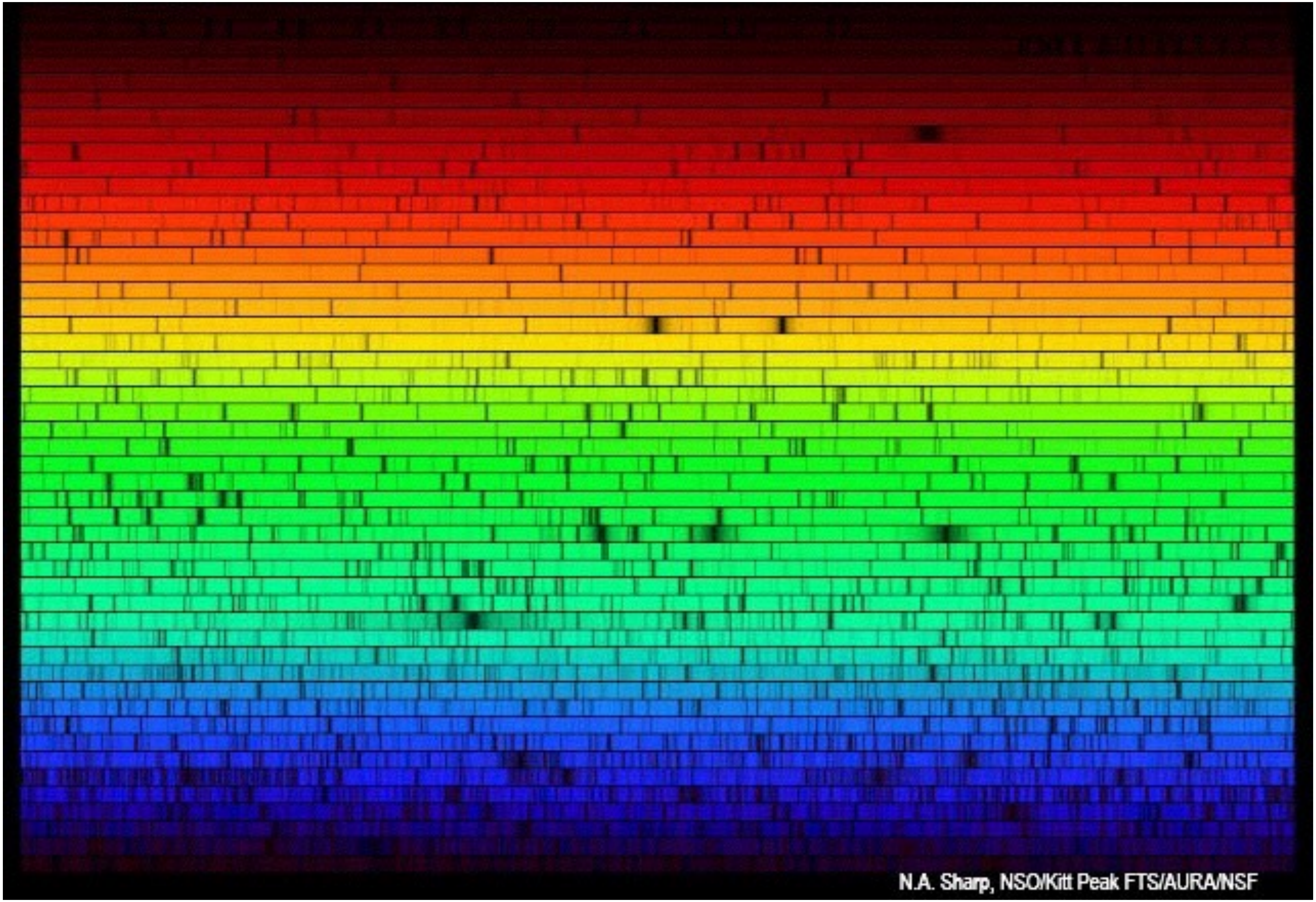
Spectrographs

OAI 2015 - Lecture 10

Matthew Kenworthy // Leiden Observatory

The Solar Spectrum



N.A. Sharp, NSO/Kitt Peak FTS/AURA/NSF

Design drivers for spectrographs

What spectral resolution do you need?

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

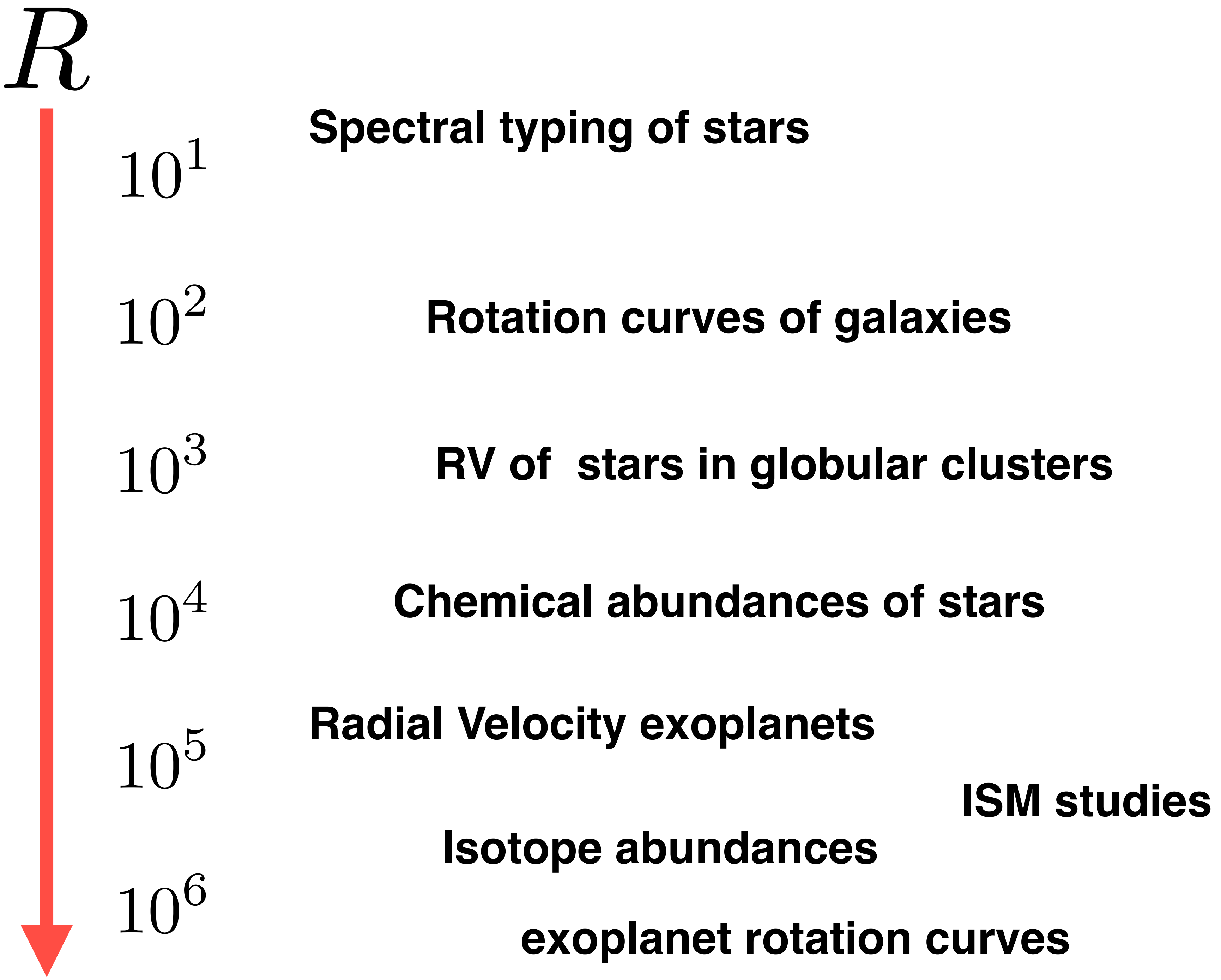
What bandwidth (wavelength range) do you need?

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

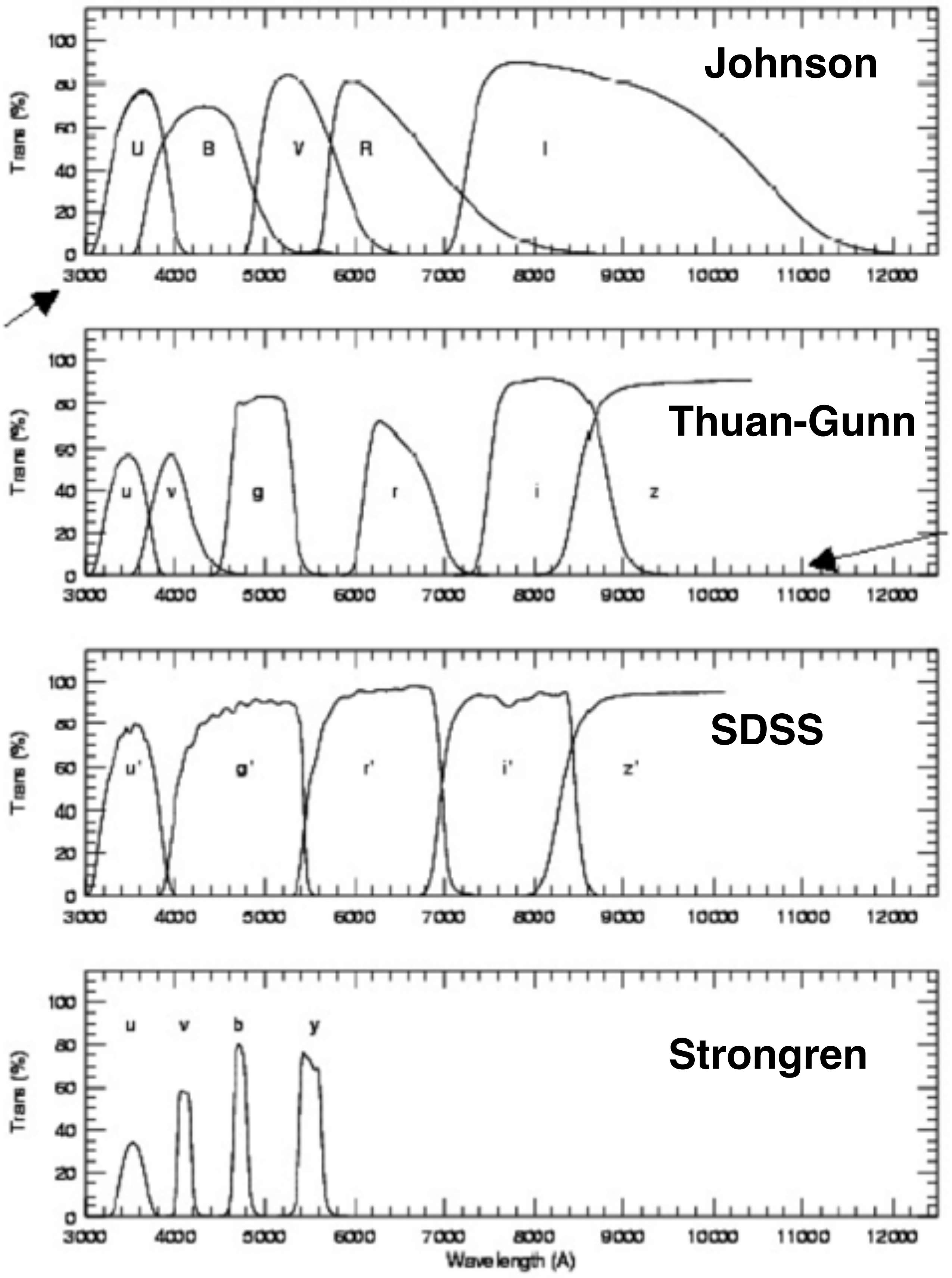
10^5 Radial Velocity exoplanets

ISM studies

Isotope abundances

10^6 exoplanet rotation curves

Basic spectroscopy: colour filters



Take multiple images with different bandpass filters

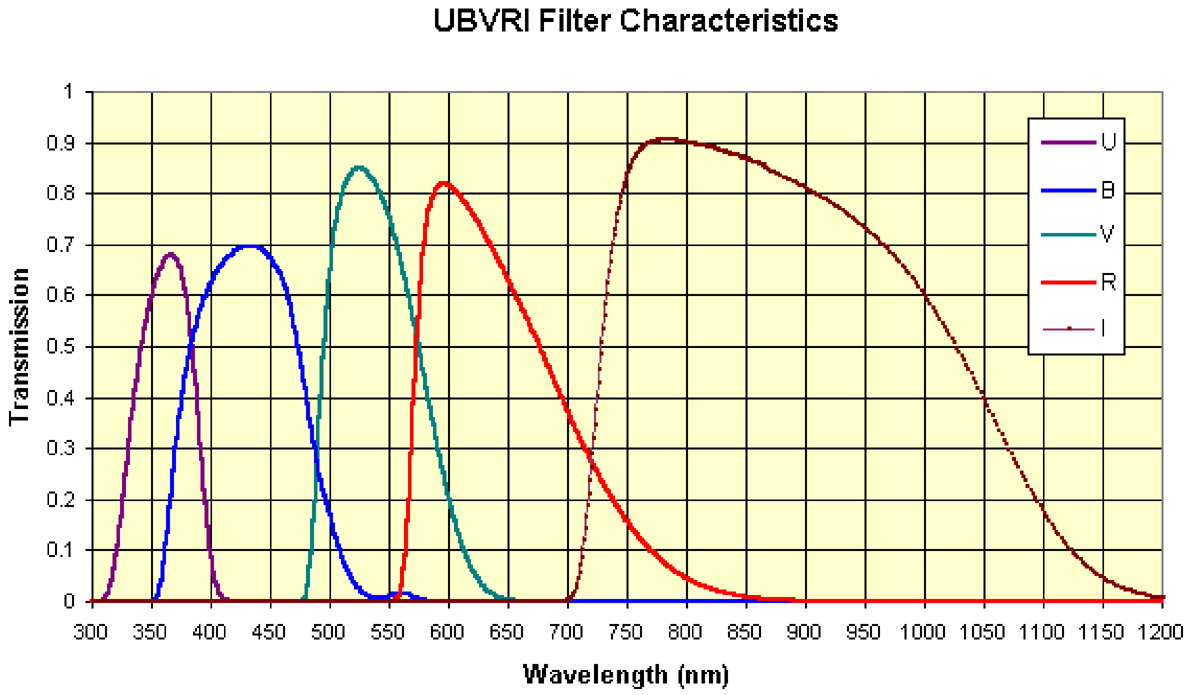
Johnson system designed to measure properties of stars

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

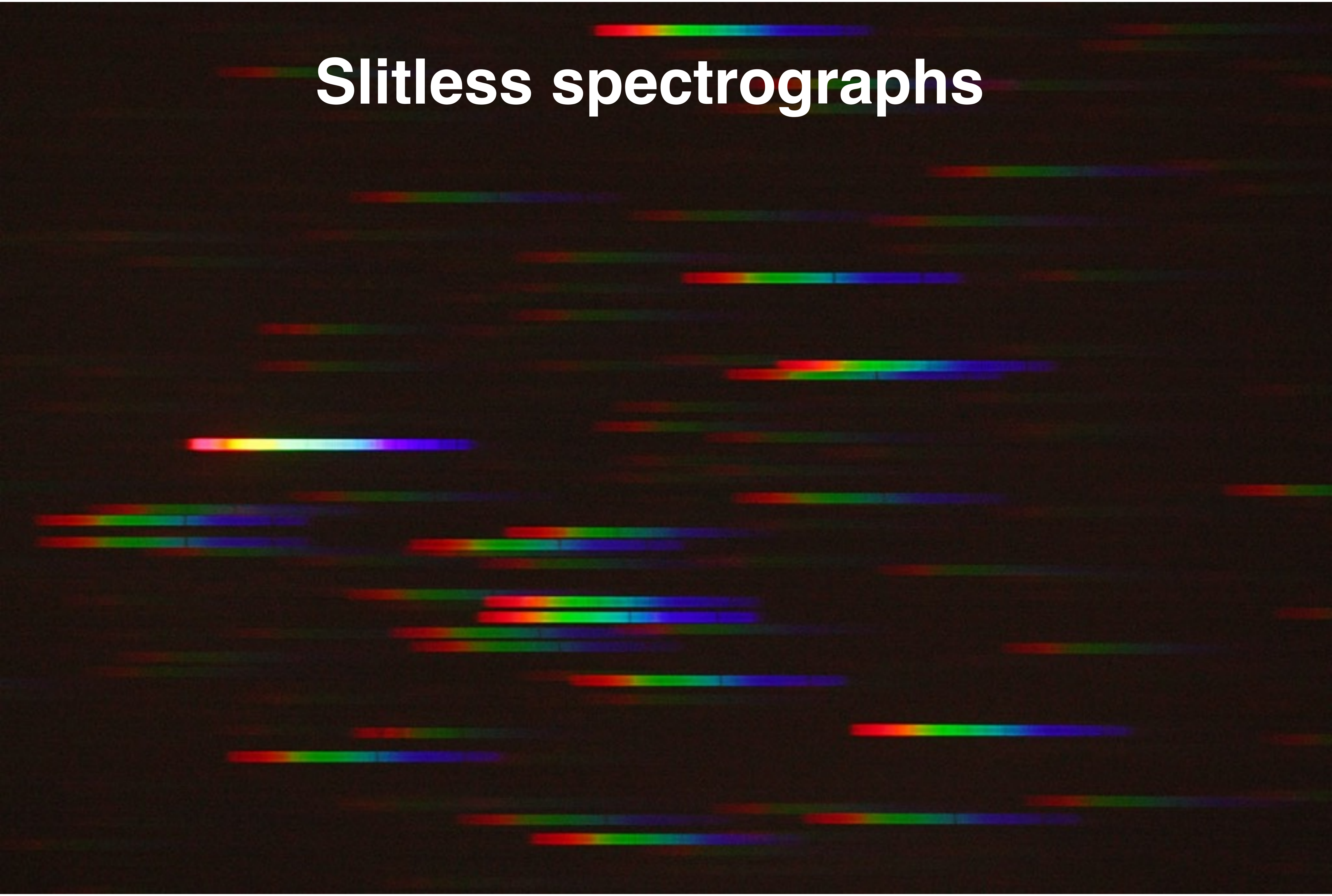
Zero points of (B-V) and (U-B) color indices defined to be zero for A0 V stars

Slitless spectrographs

Put a dispersing element in front of the telescope aperture

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

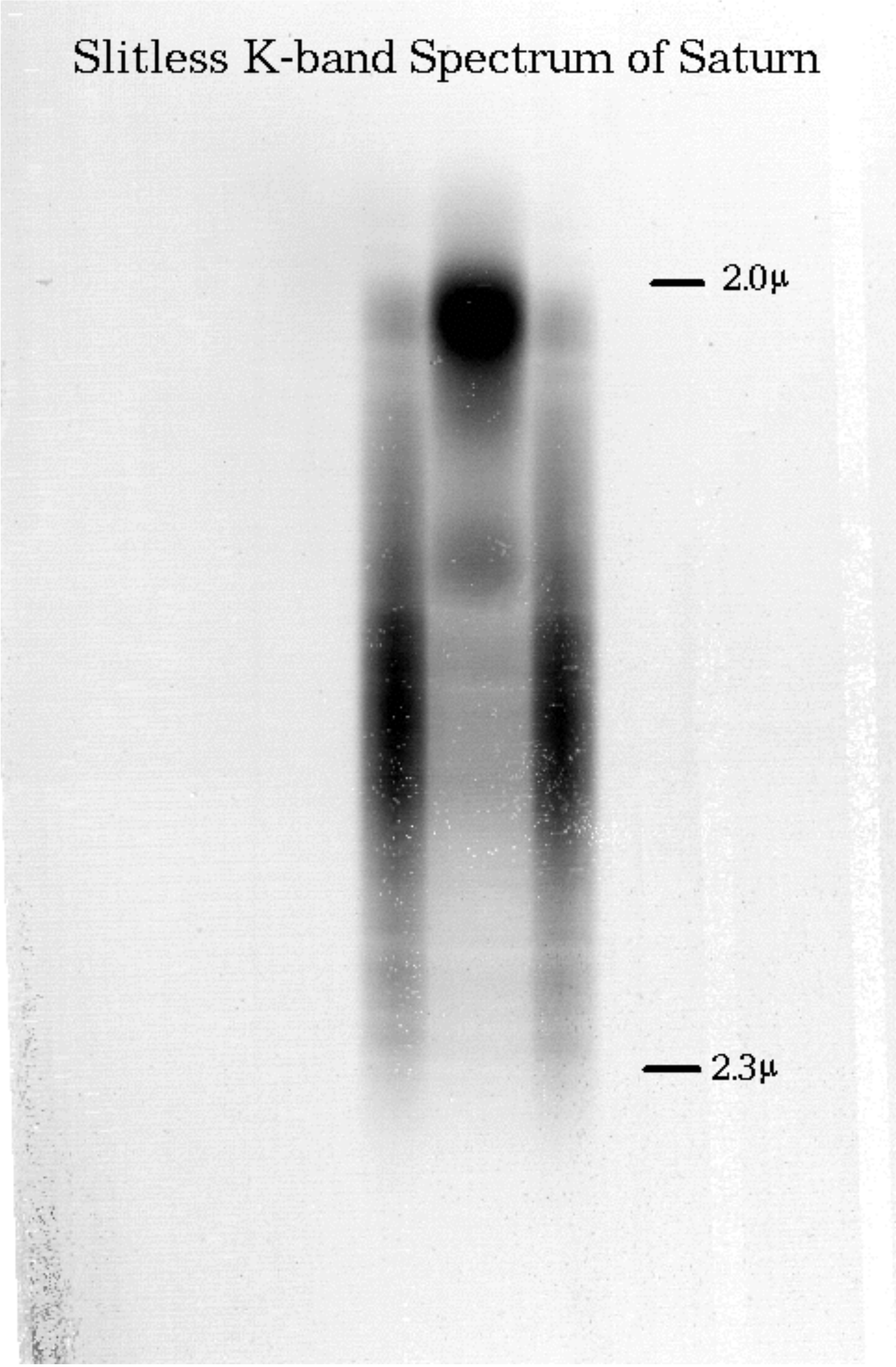
Slitless spectrographs



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

Slitless spectrographs

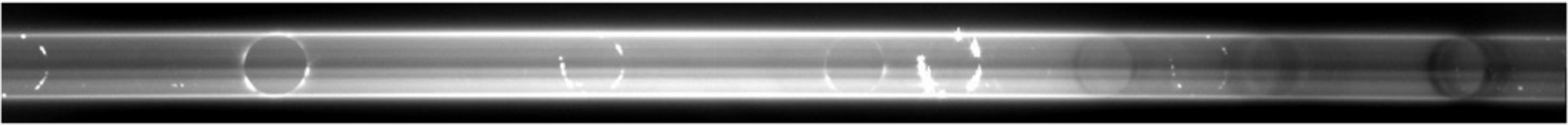
Dispersed



R. Pogge (OSU) with NOAO 2.1m Telescope

Slitless spectrographs

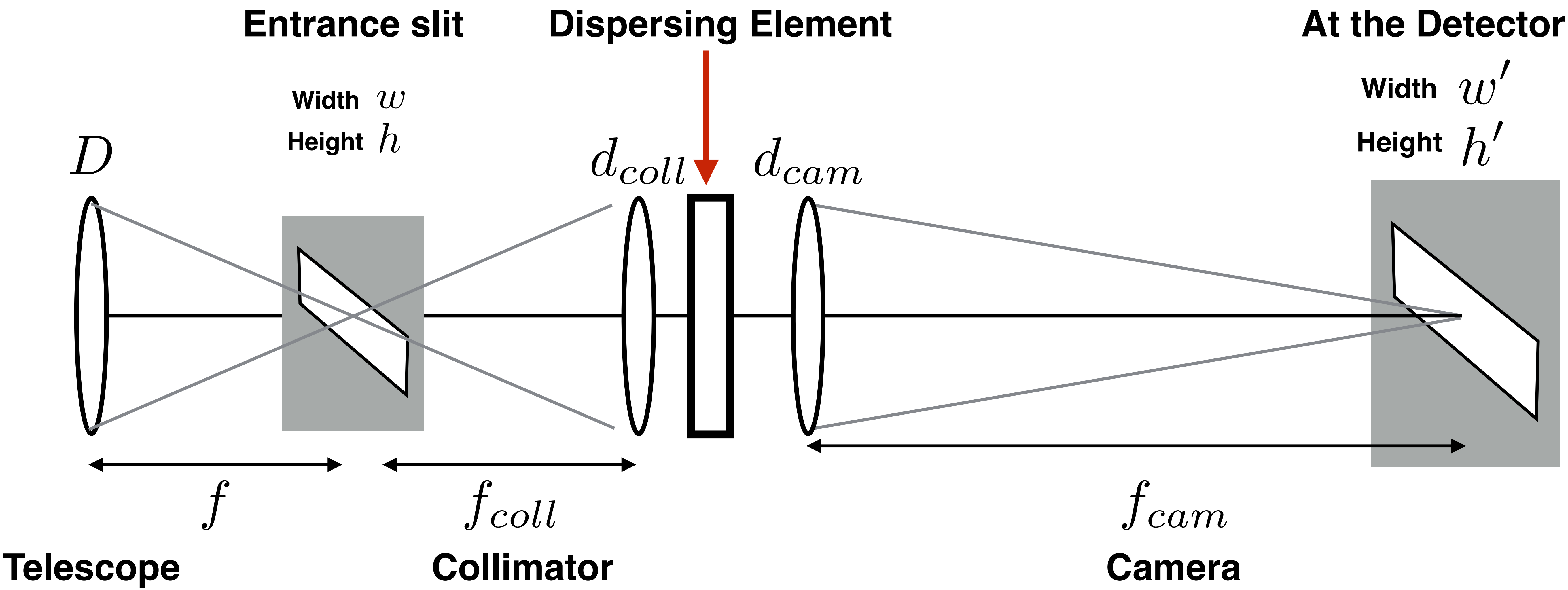
The solar corona
(solar disk is blocked by a coronagraph)



Wavelength

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

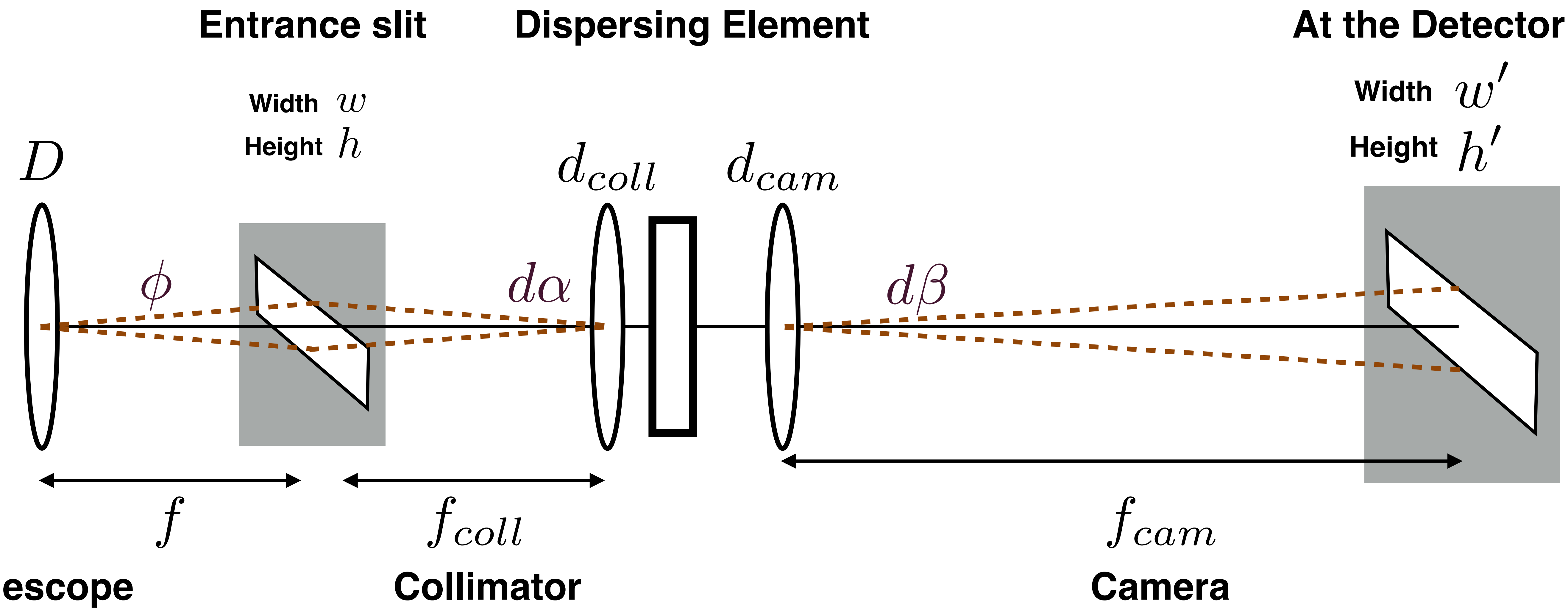
Layout of a spectrograph



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

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

Layout of a spectrograph



Entrance slit

Dispersing Element

At the Detector

Width w

Height h

D

d_{coll}

d_{cam}

Width w'

Height h'

ϕ

$d\alpha$

$d\beta$

f

f_{coll}

f_{cam}

Telescope

Collimator

Camera

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

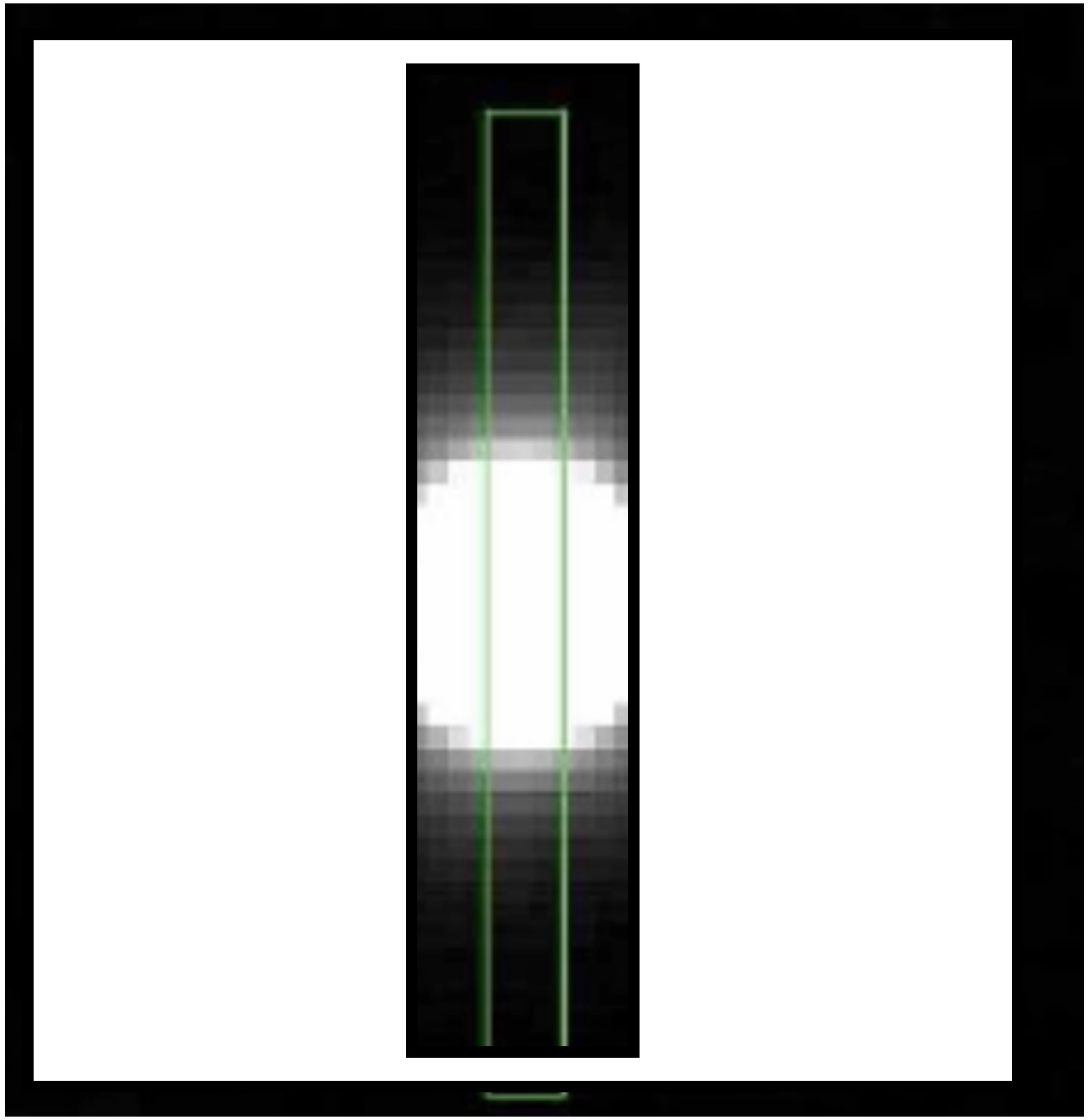
We cannot record three dimensions of data (x,y, wavelength) onto a two dimensional detector, so we need to choose how we fill up our detector area:

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:

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

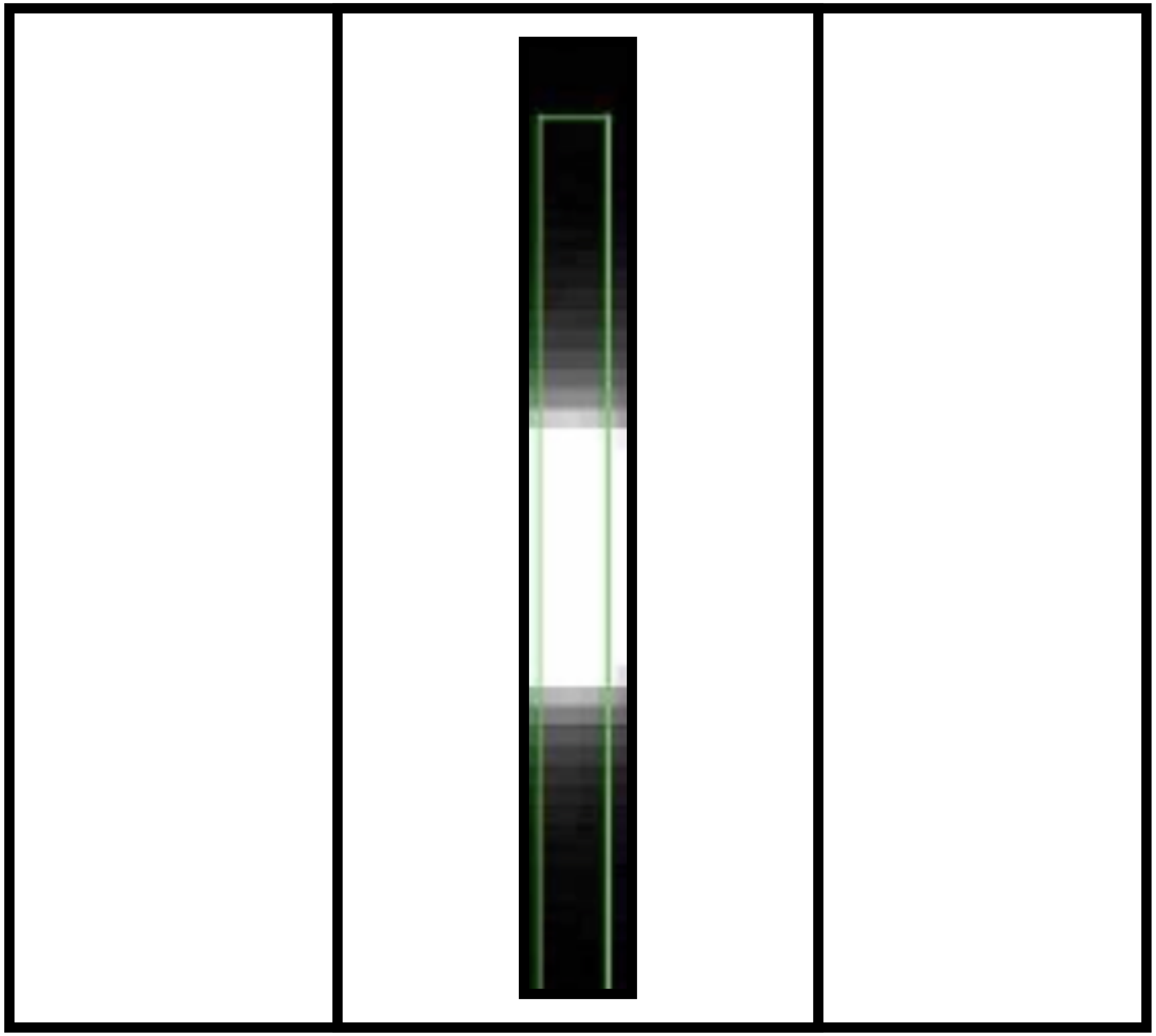


Slit too wide, spectral resolution goes down

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

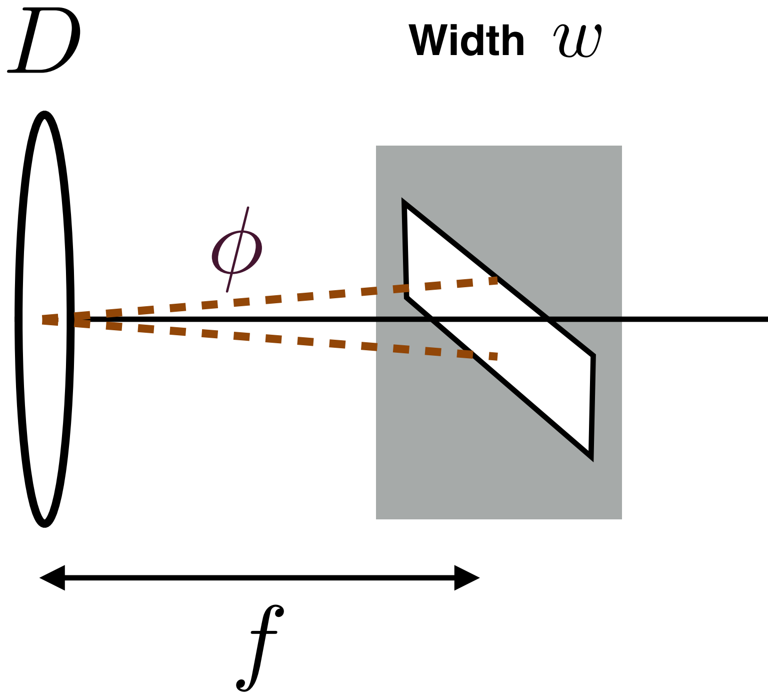
Slit too narrow, flux from seeing limited object is lost

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

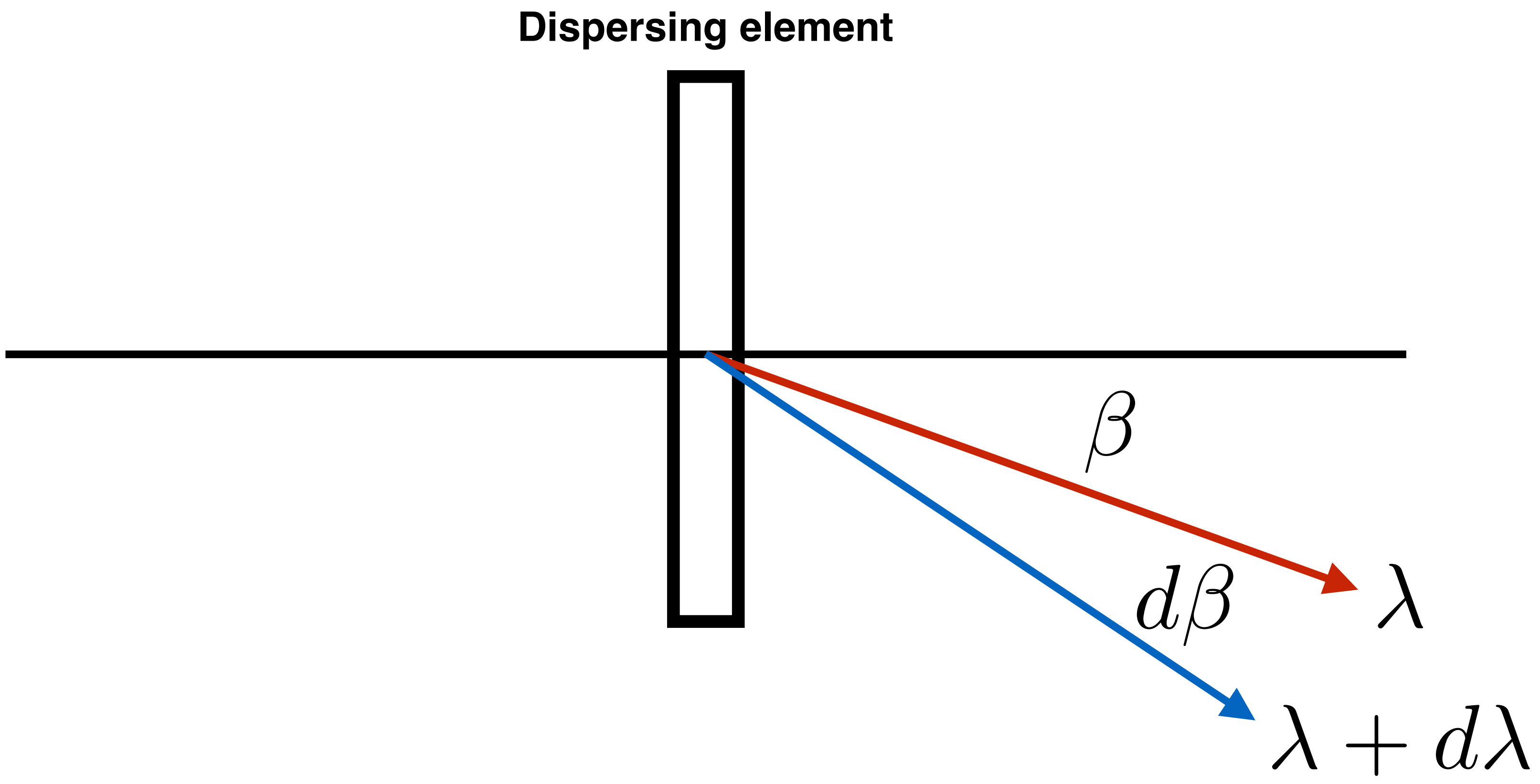
Two types of magnification

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: $$A = \frac{d\beta}{d\lambda}$$

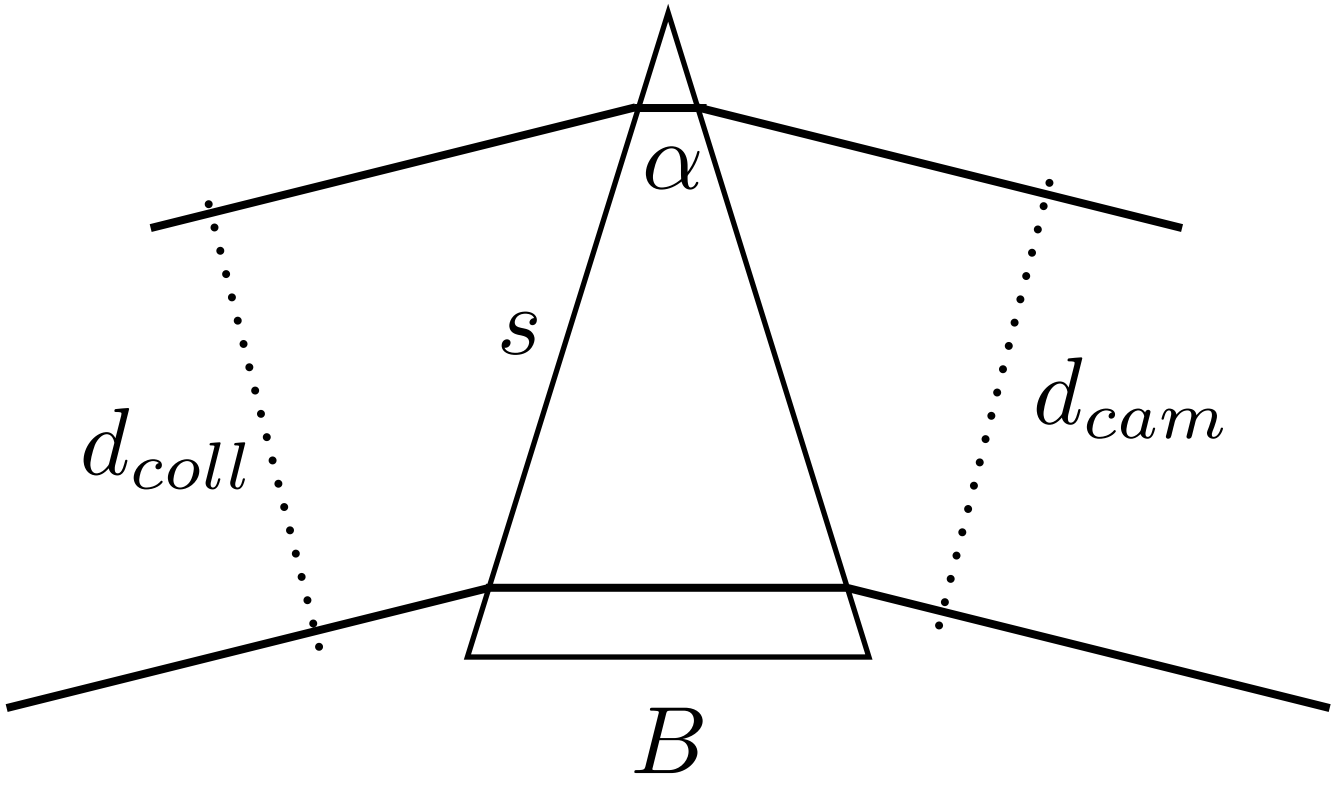


The linear dispersion is then: $$\frac{dl}{d\lambda} = f_{cam} A$$

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.

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



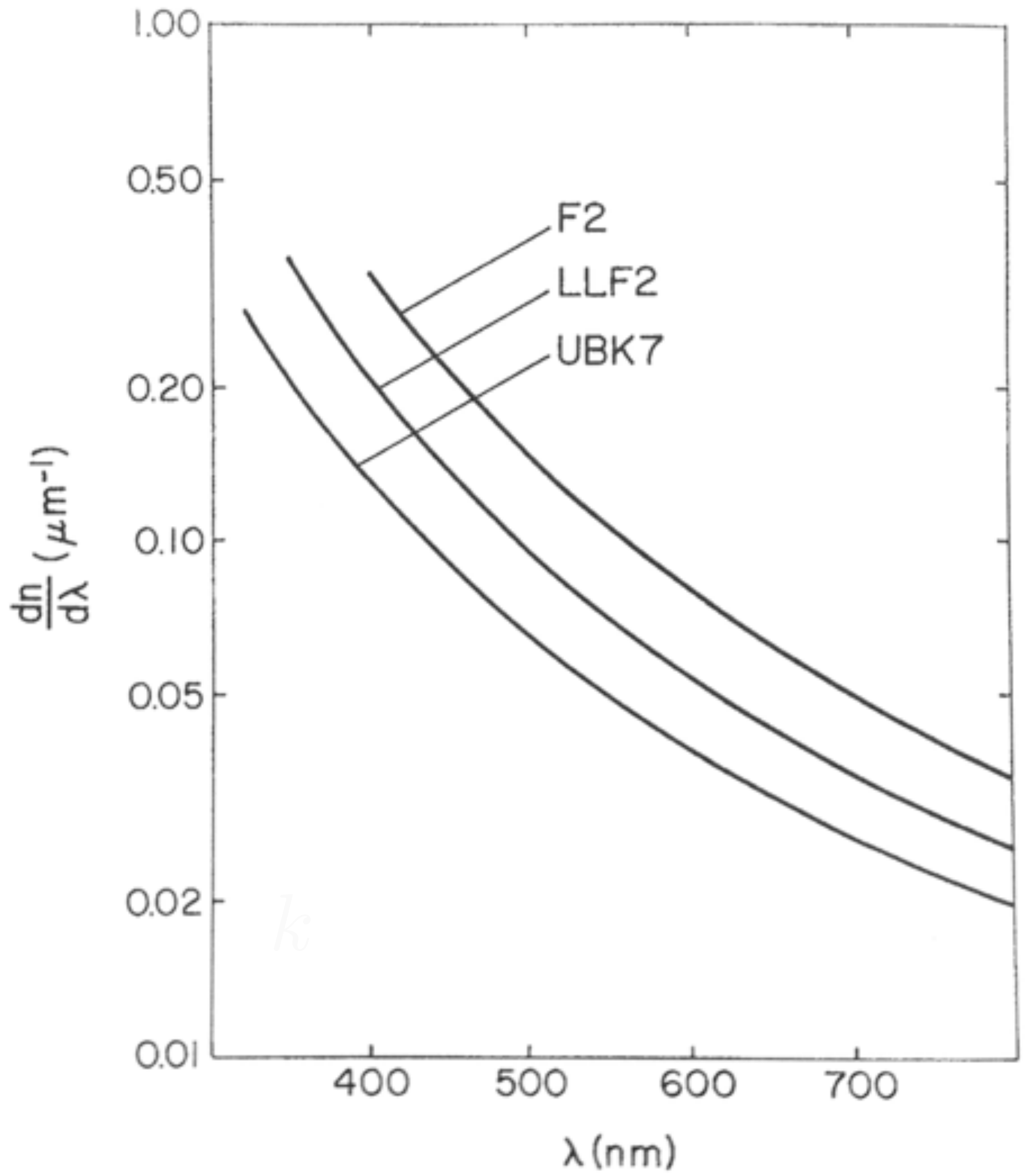
Angular dispersion changes with wavelength

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.

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



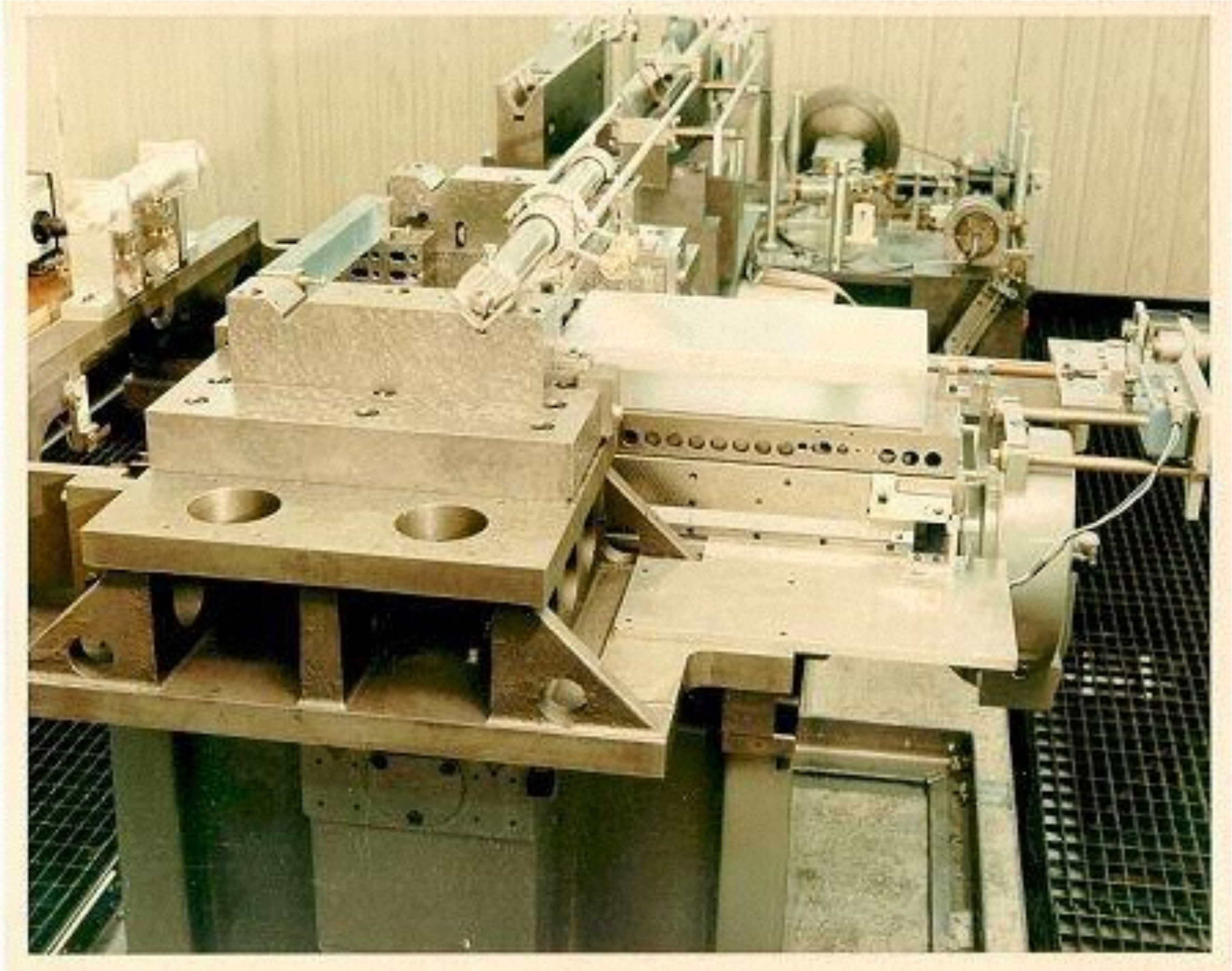
Diffraction grating

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

Made by David Rittenhouse in 1785

Reinvented by Frauenhofer in 1821

Manufactured using ruling engines in temperature controlled rooms



Diffraction grating

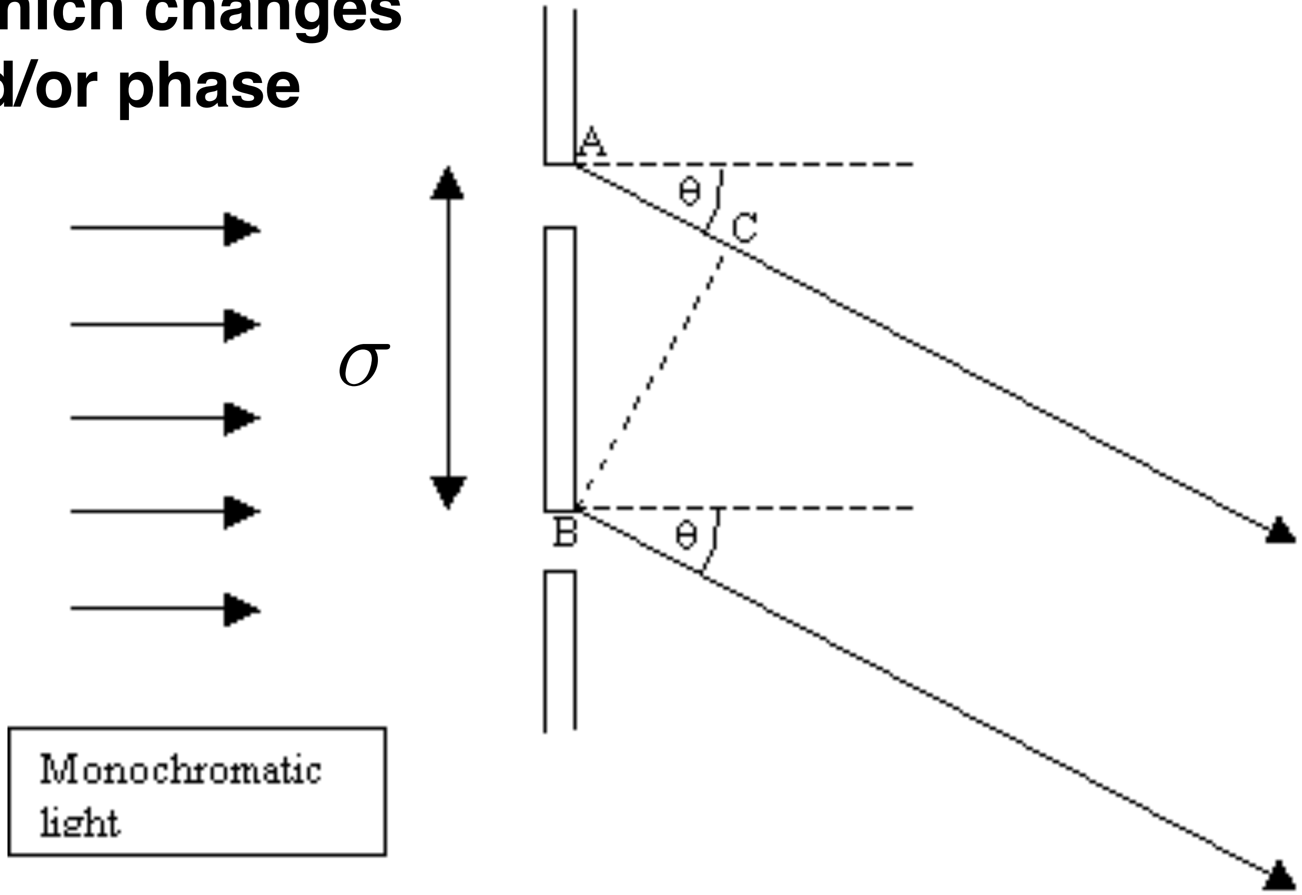
Frauenhofer gratings resolved Solar absorption spectrum, and labelled the absorption lines with letters (A,B,C,D…)

Diffraction grating

HARPS grating

Diffraction grating

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



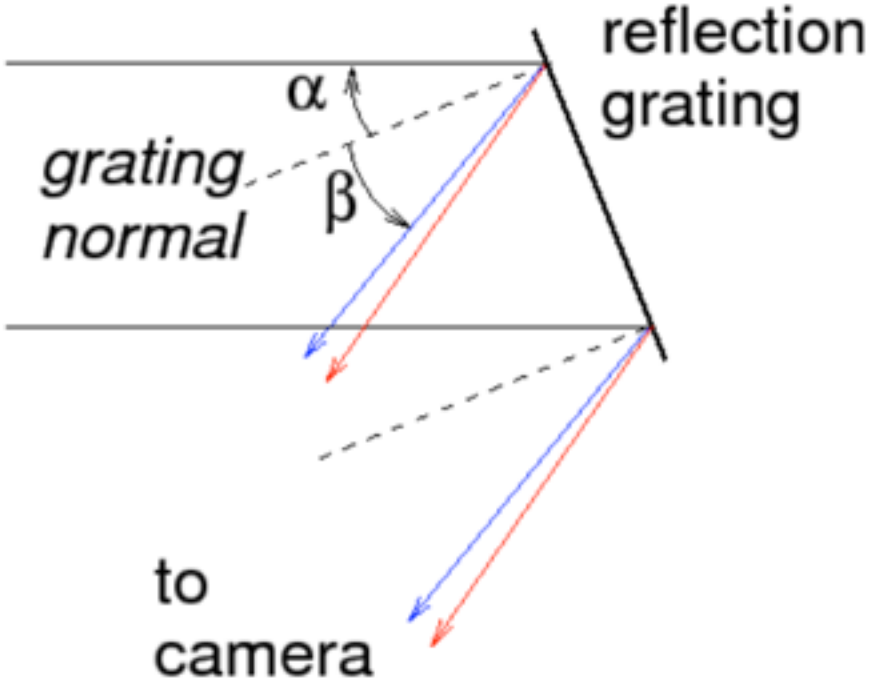
Direction of constructive interference is wavelength dependent

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:

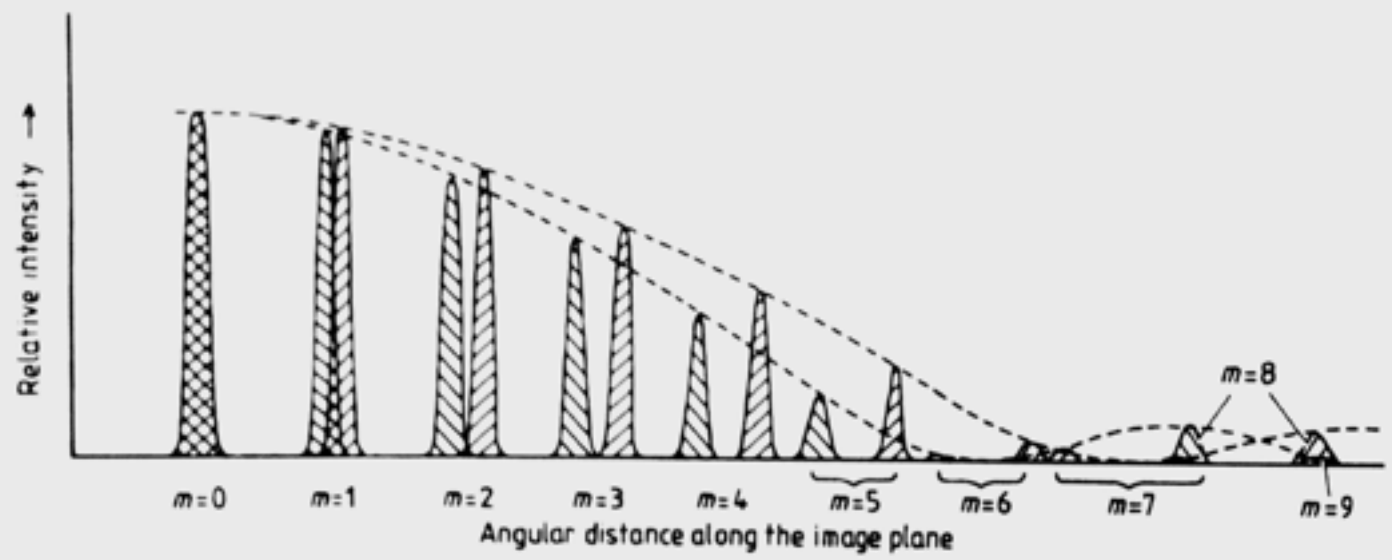


Figure 4.1.10. A portion of the image structure for a single bichromatic point source viewed through several apertures.

The free spectral range of a spectrograph is given by:

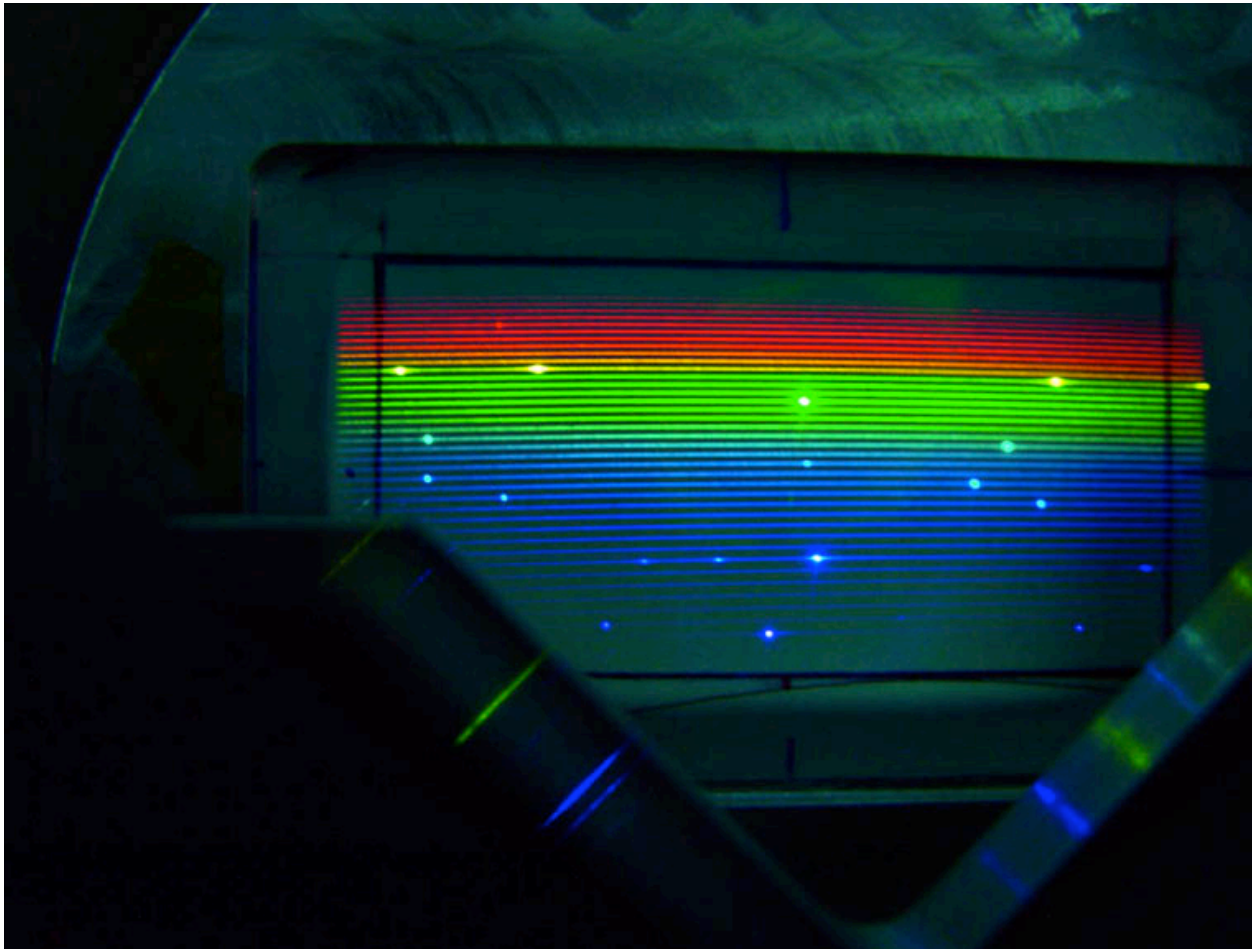
$$\lambda' - \lambda = \lambda/m$$

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

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

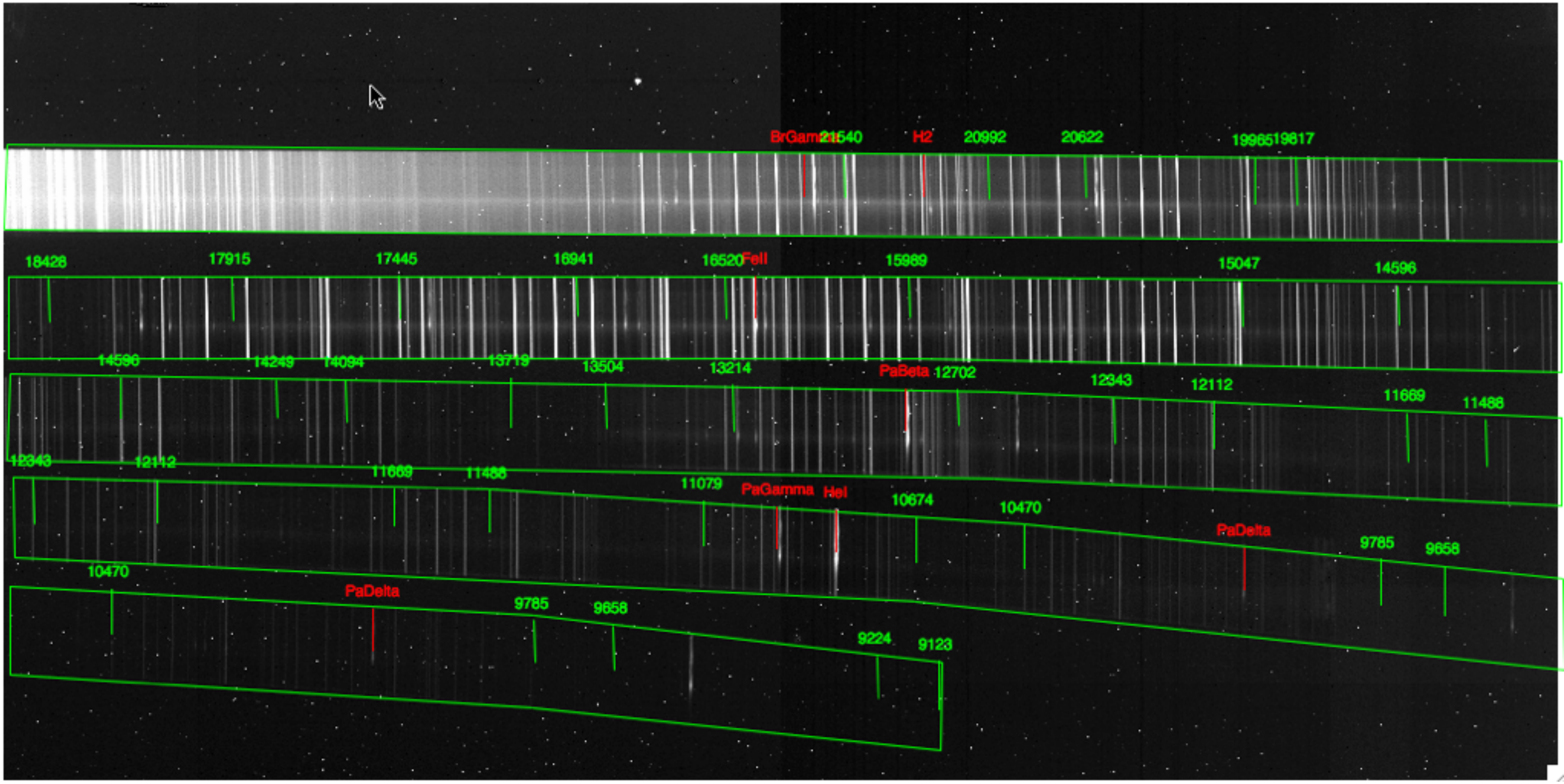
Higher spectral orders

CROSS disperser to split out the different spectral orders



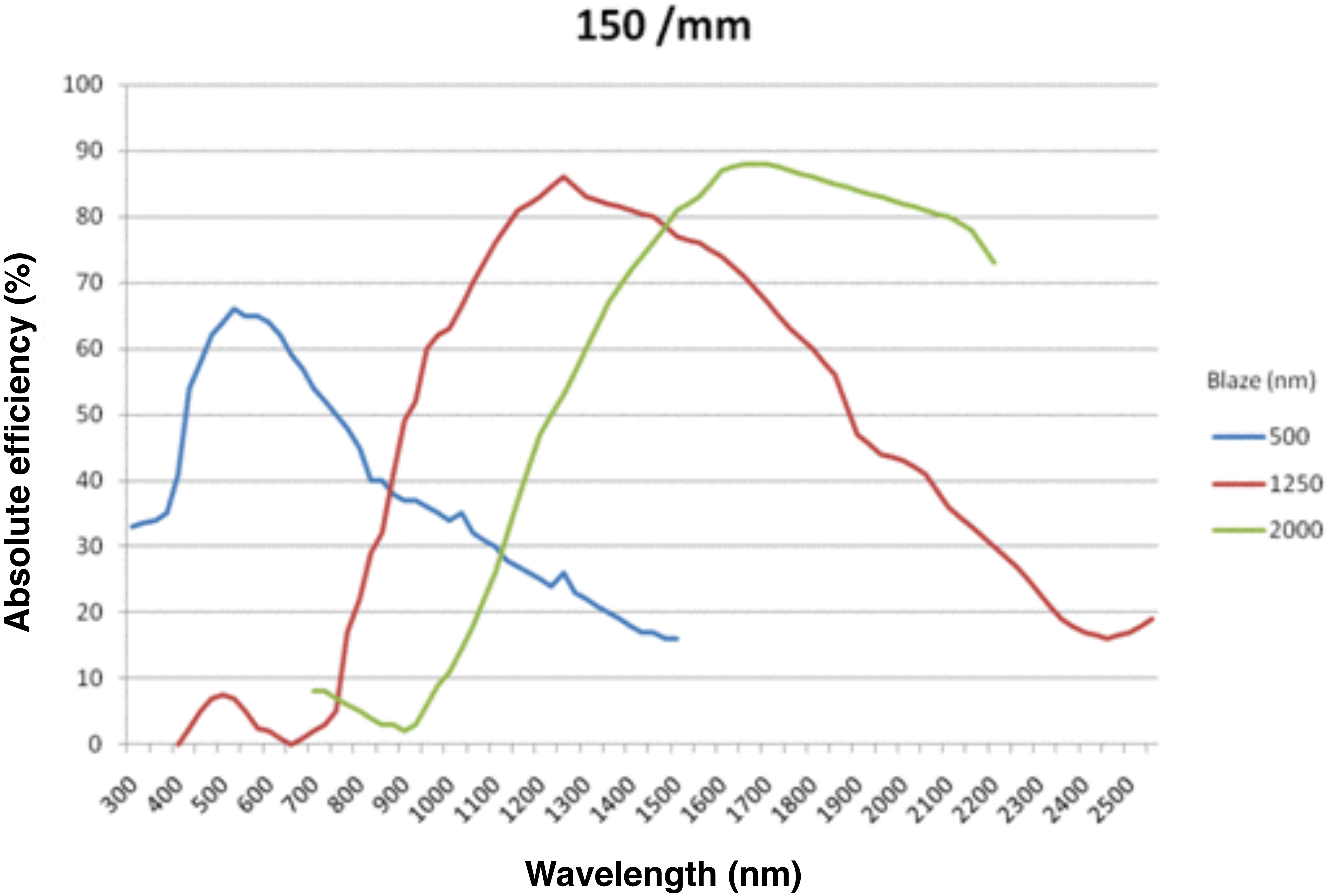
Higher spectral orders

CROSS disperser to split out the different spectral orders

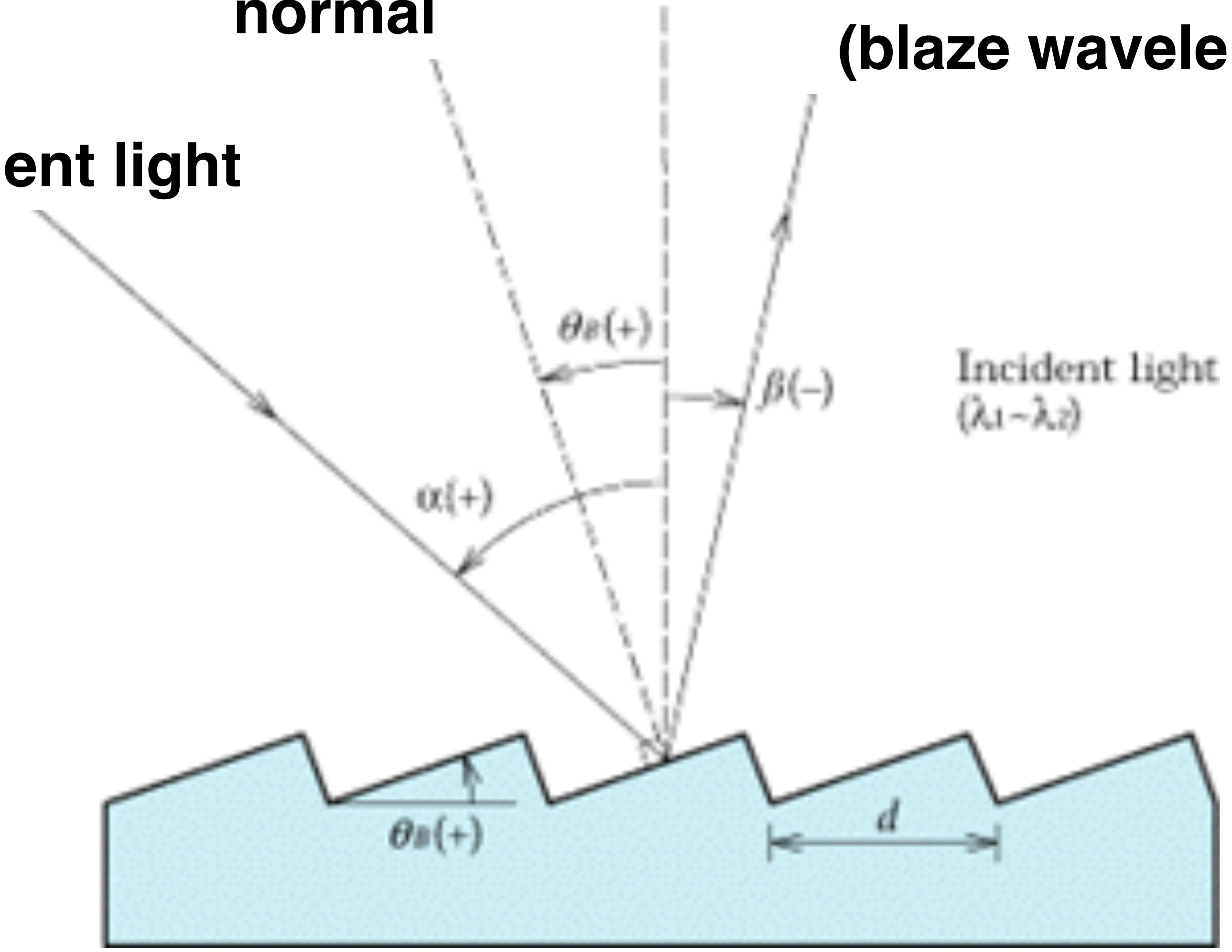


Trispec

Diffraction grating efficiency



Optimising the grating efficiency



Grating normal

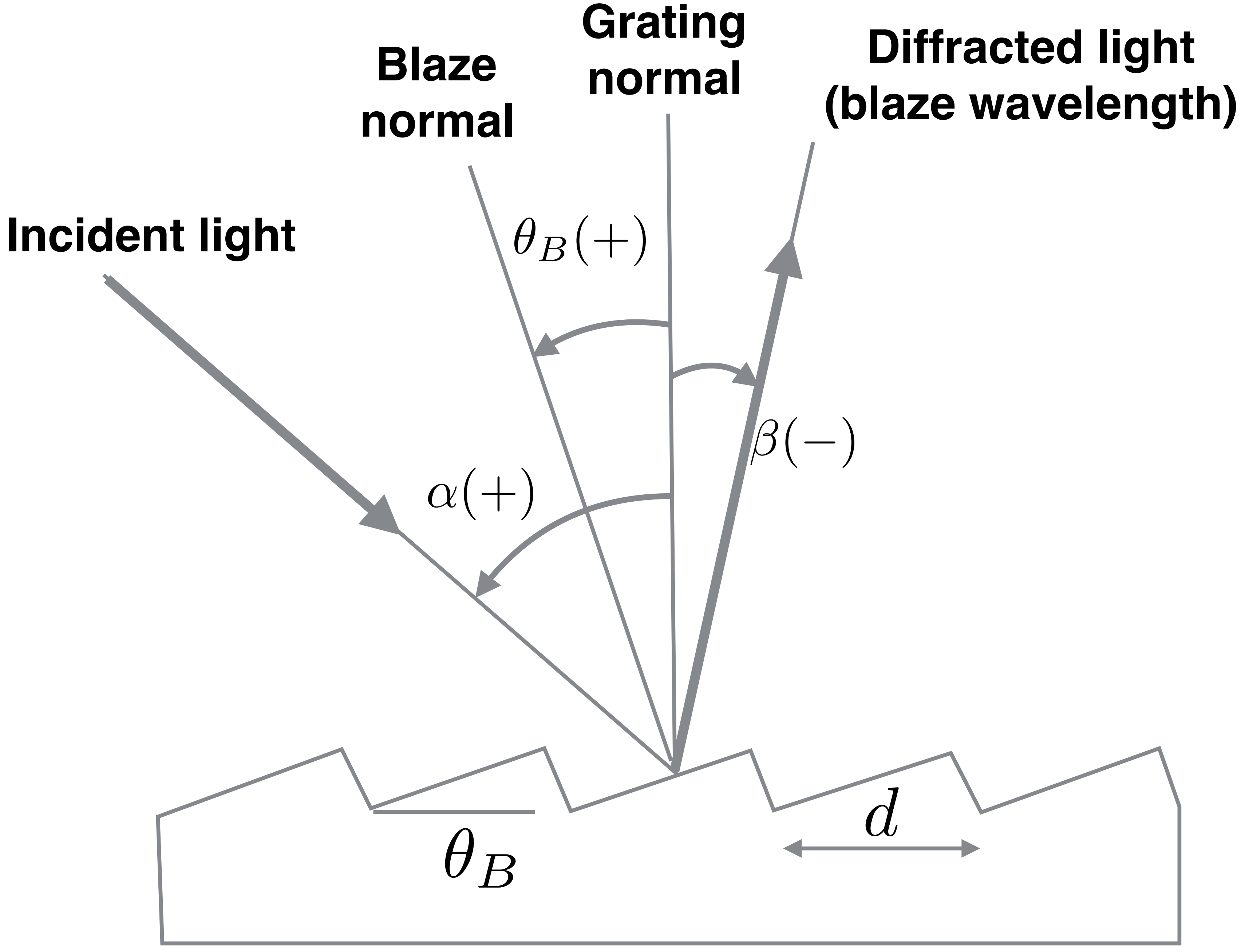
Blaze normal

Diffracted light (blaze wavelength)

Incident light

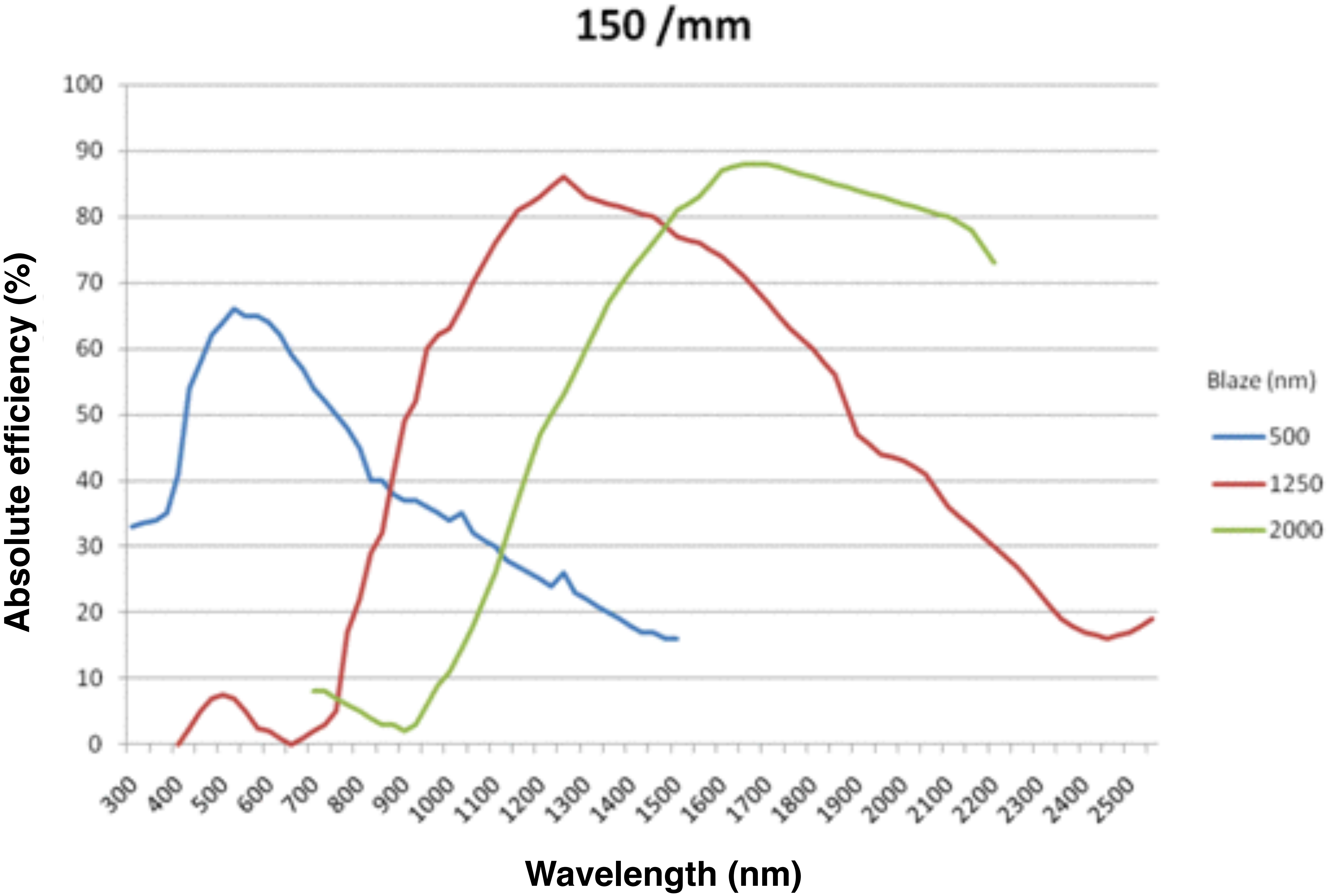
Making the facets of the diffraction grating tilt over so that the diffracted light also goes out along the science wavelength

Optimising the grating efficiency

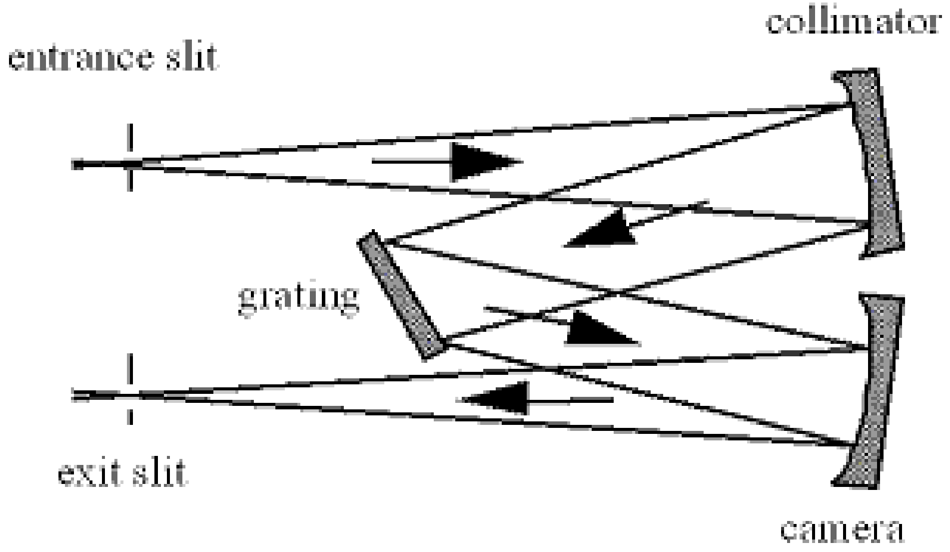


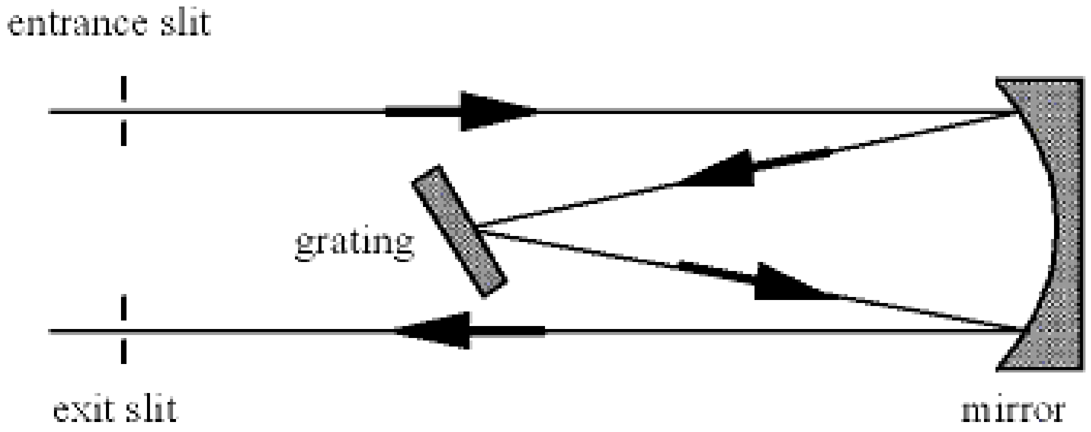
$$\theta_B = \frac{\alpha+\beta}{2} \quad \lambda_B = \frac{2}{nm} \sin\theta_B \cos(\alpha - \theta_B)$$

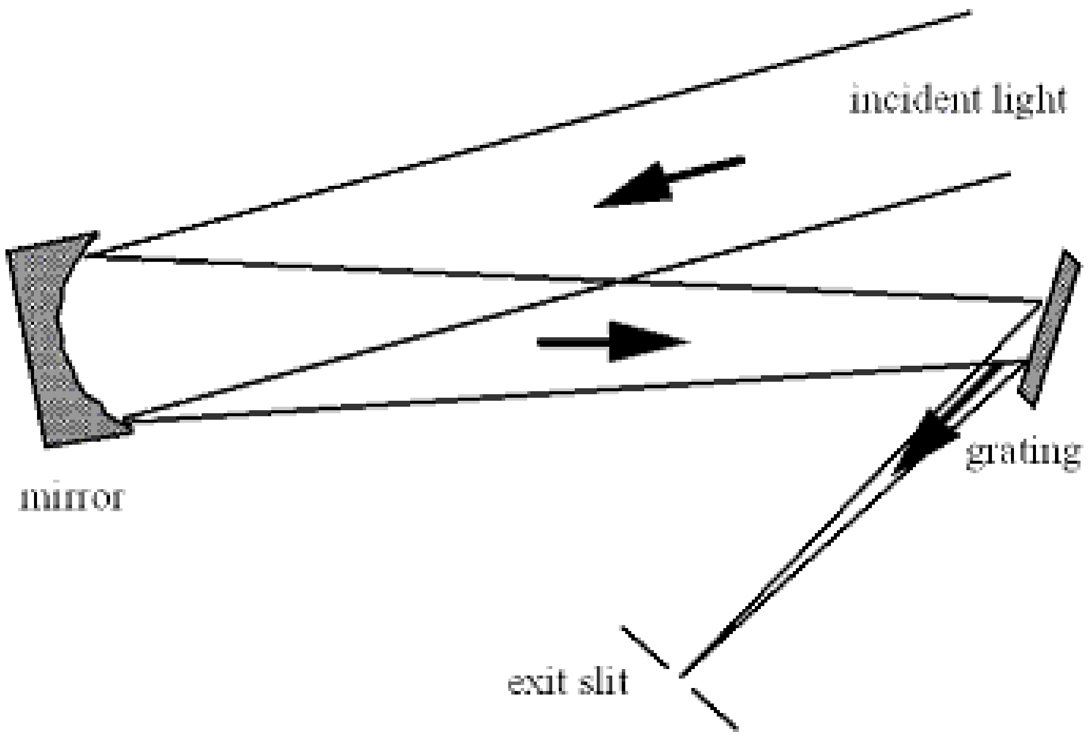
Peak efficiencies at blaze wavelengths

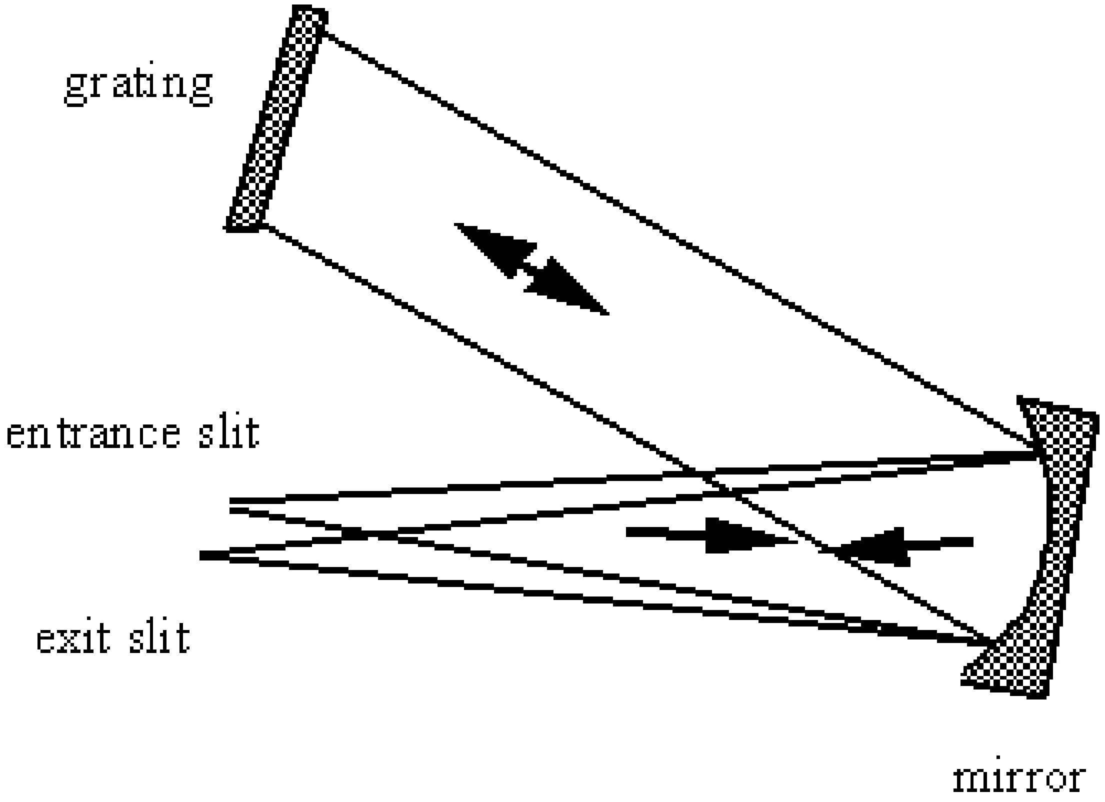


Common spectrograph configurations

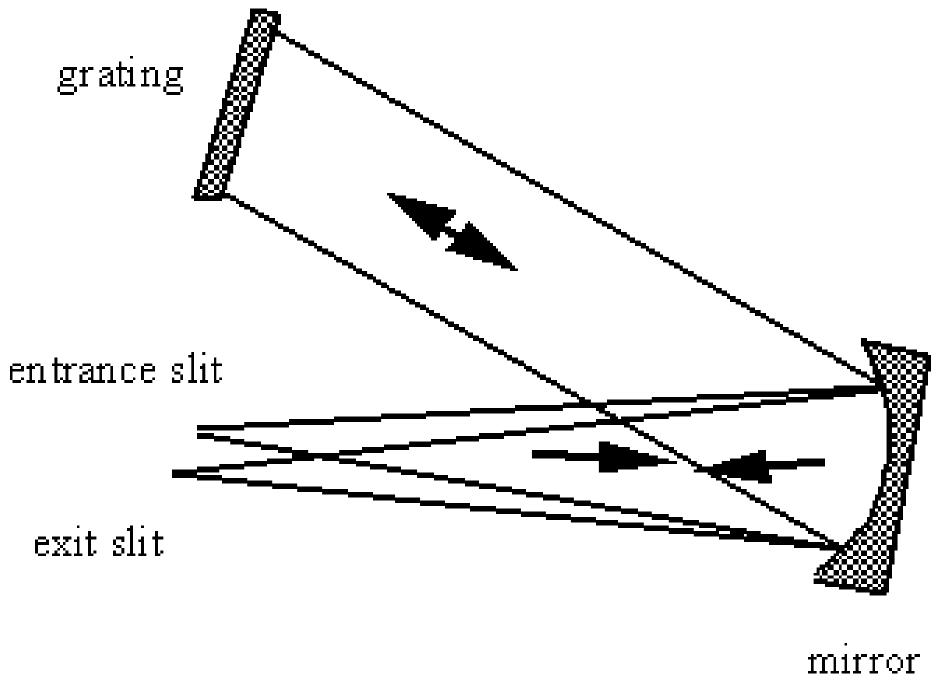








The Littrow spectrograph



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

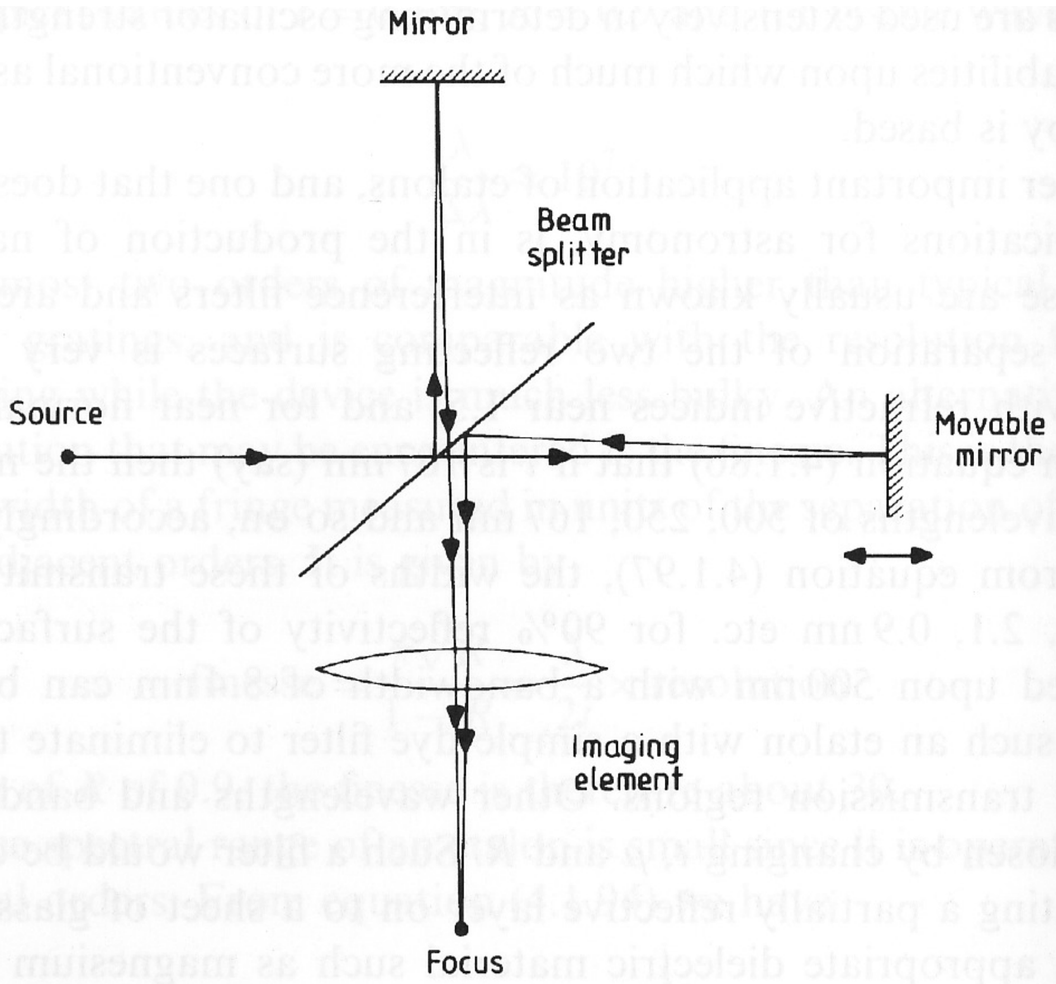
The smallest resolution for the spectrograph should be sampled at the minimum of the Nyquist frequency, which is 2 pixels per resolution element.

Spectral dispersion per pixel is:

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

where μ is the pixel size in mm.

Fourier Transform Spectrographs



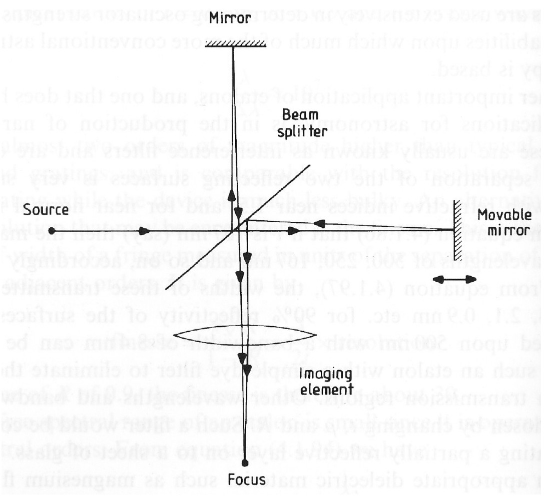
A Michelson interferometer with one moving arm

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:

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

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

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:

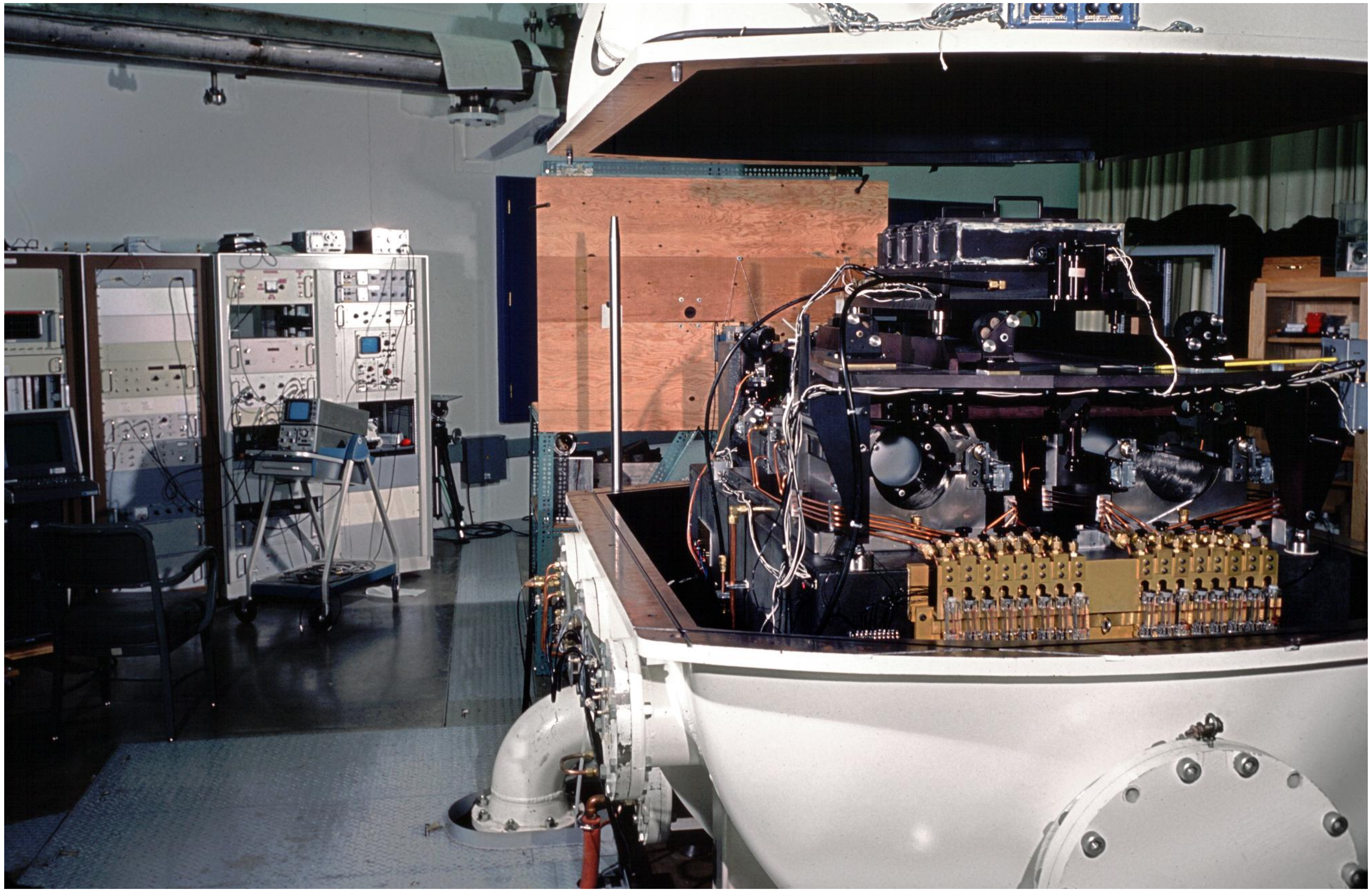
$$\Delta k = 2\pi/L$$

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

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

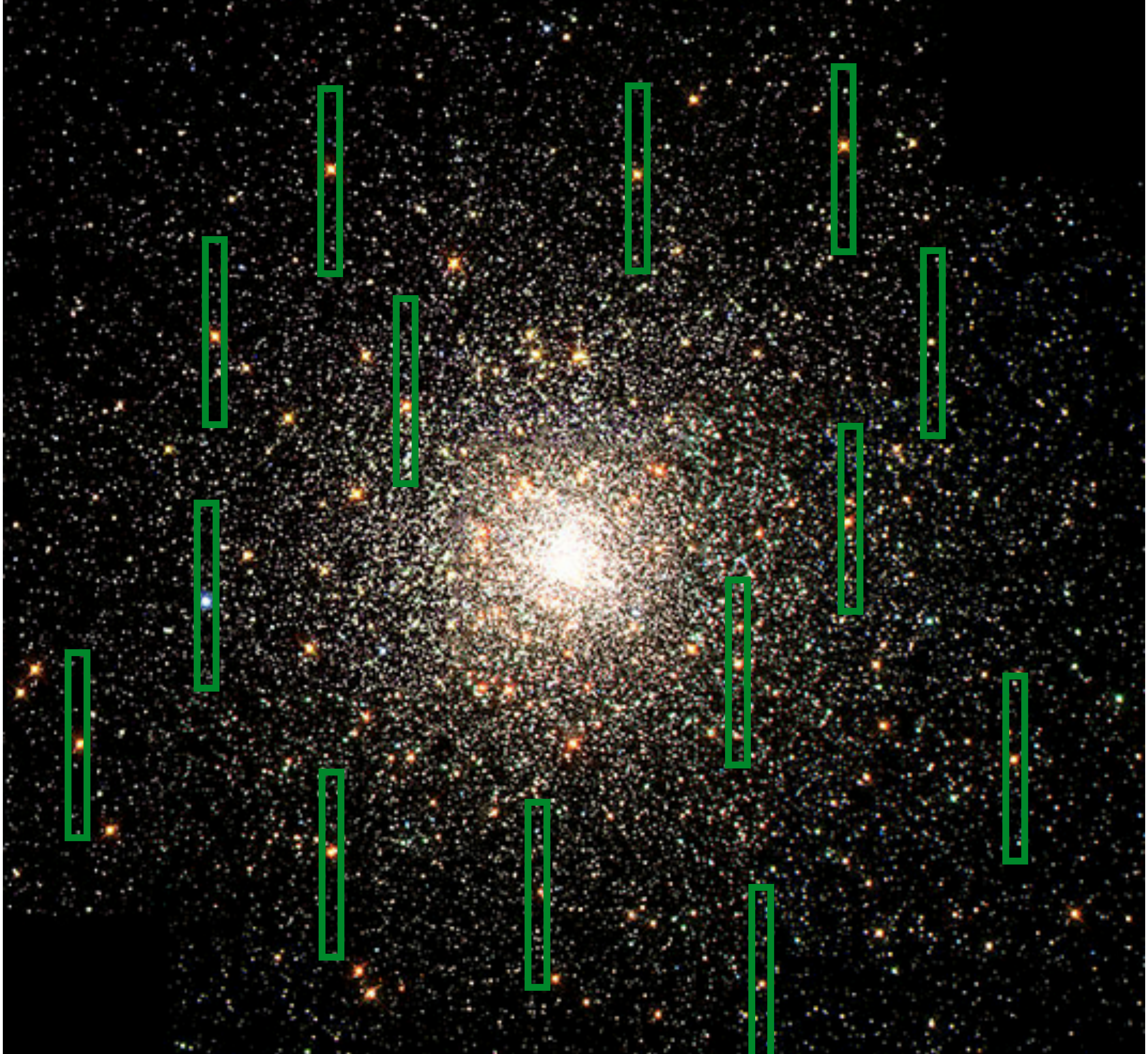
CONS: very susceptible to any change in background flux

Fourier Transform Spectrographs



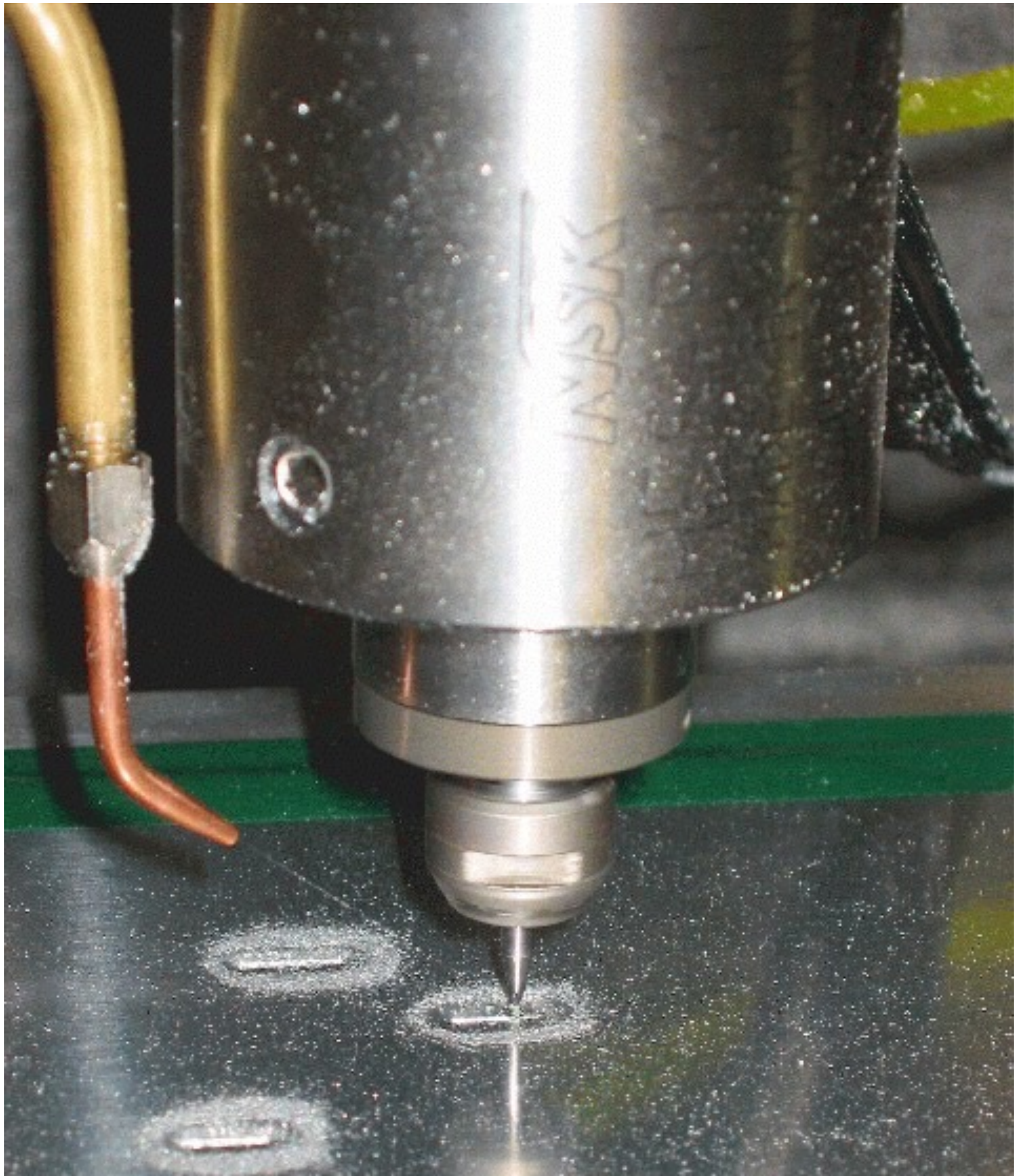
1m Kitt Peak FTS - Eglin, Hanna, NOAO/AURA/NSF

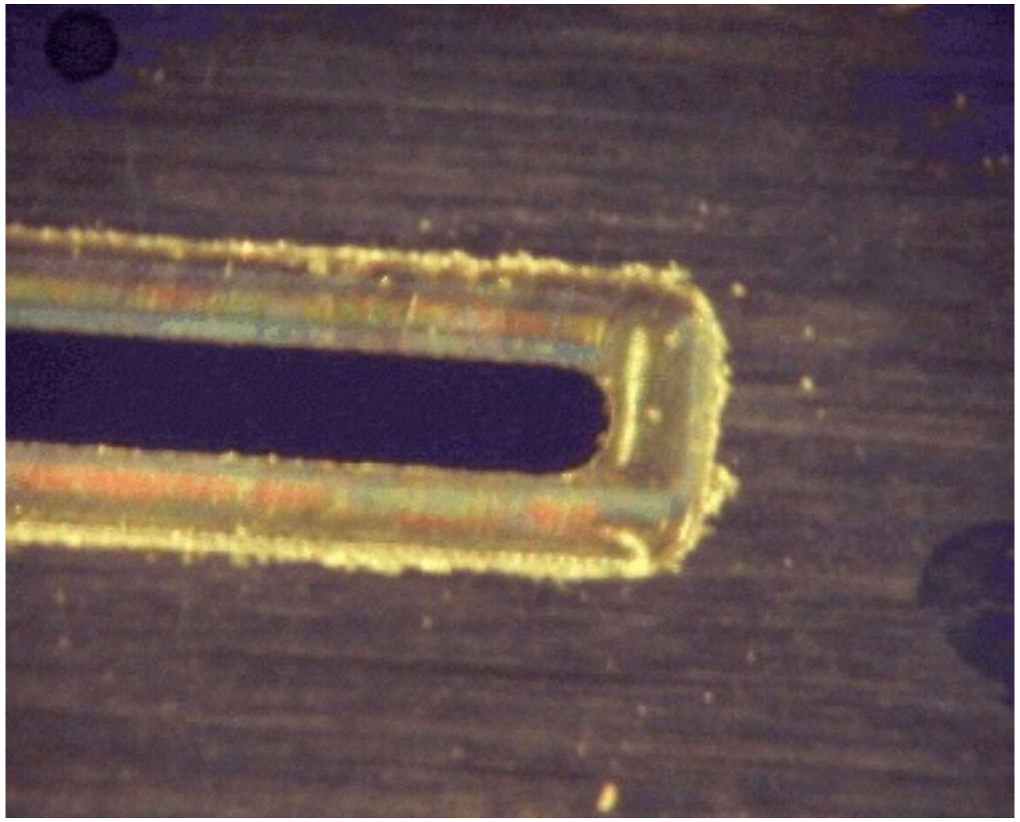
Multi-Object Spectrographs



Multi Object Spectrographs - drilled spectro slits

DEIMOS slit masks milled with 0.015 inch diameter bits





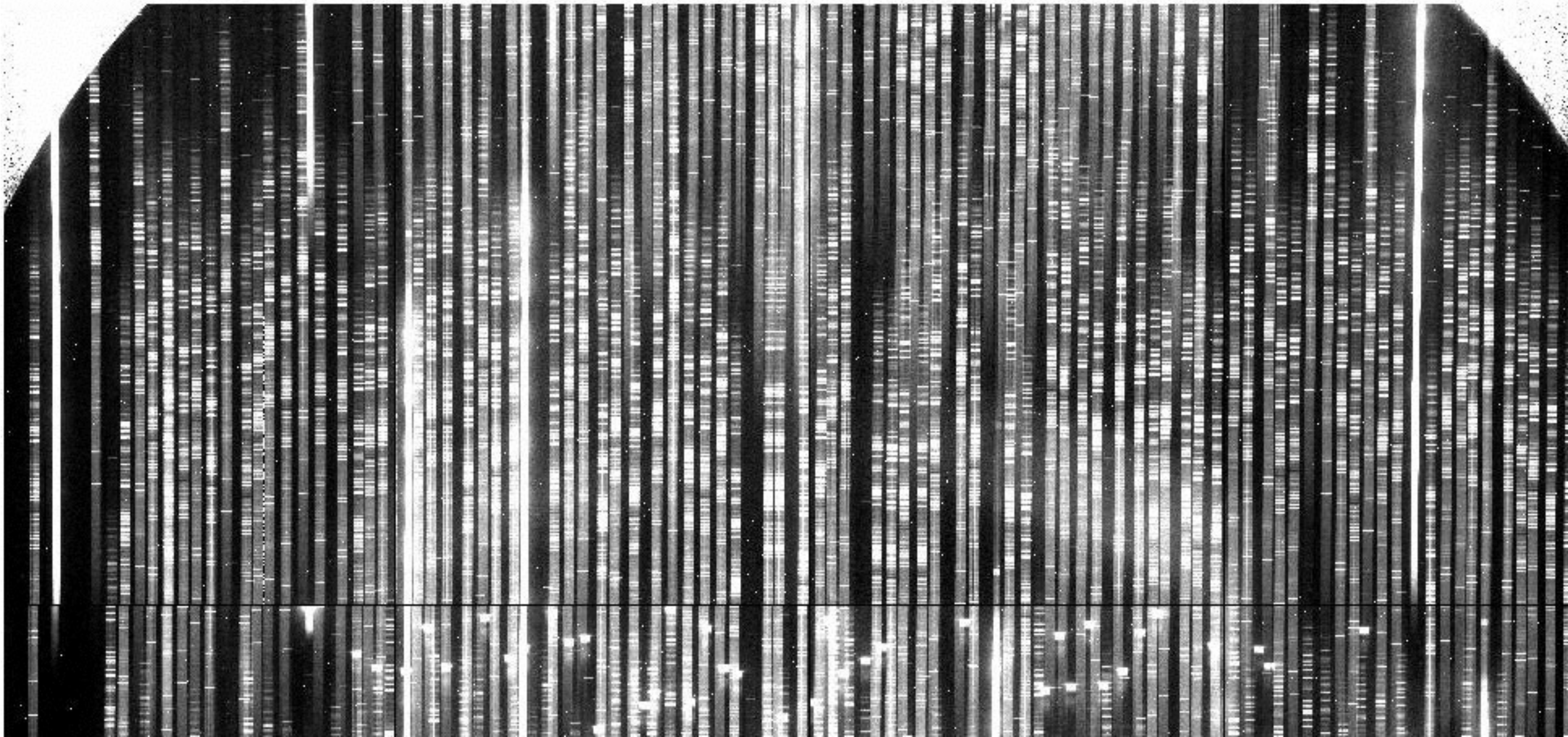
http://www.ucolick.org/~phillips/deimos_ref/masks.html

Multi Object Spectrographs - laser cut slits

IMACS on the Magellan 6.5m telescope

First spectrum with 240 slits

http://www.lco.cl/telescopes-information/magellan/instruments/imacs/

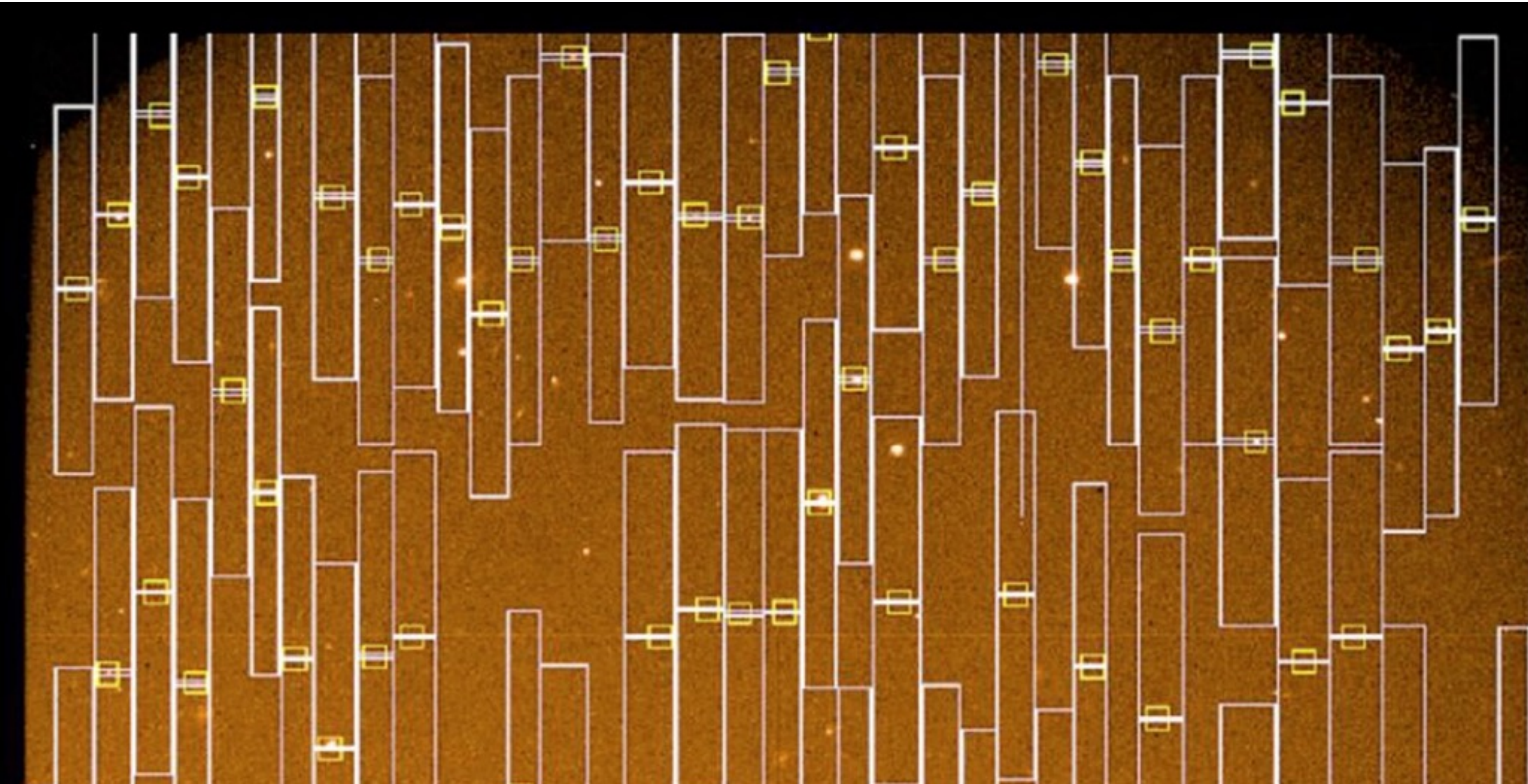


Multi Object Spectrographs - laser cut slits

VIMOS on the VLT telescopes

You decide where to put the slits on the science field

Can take up to two weeks to manufacture

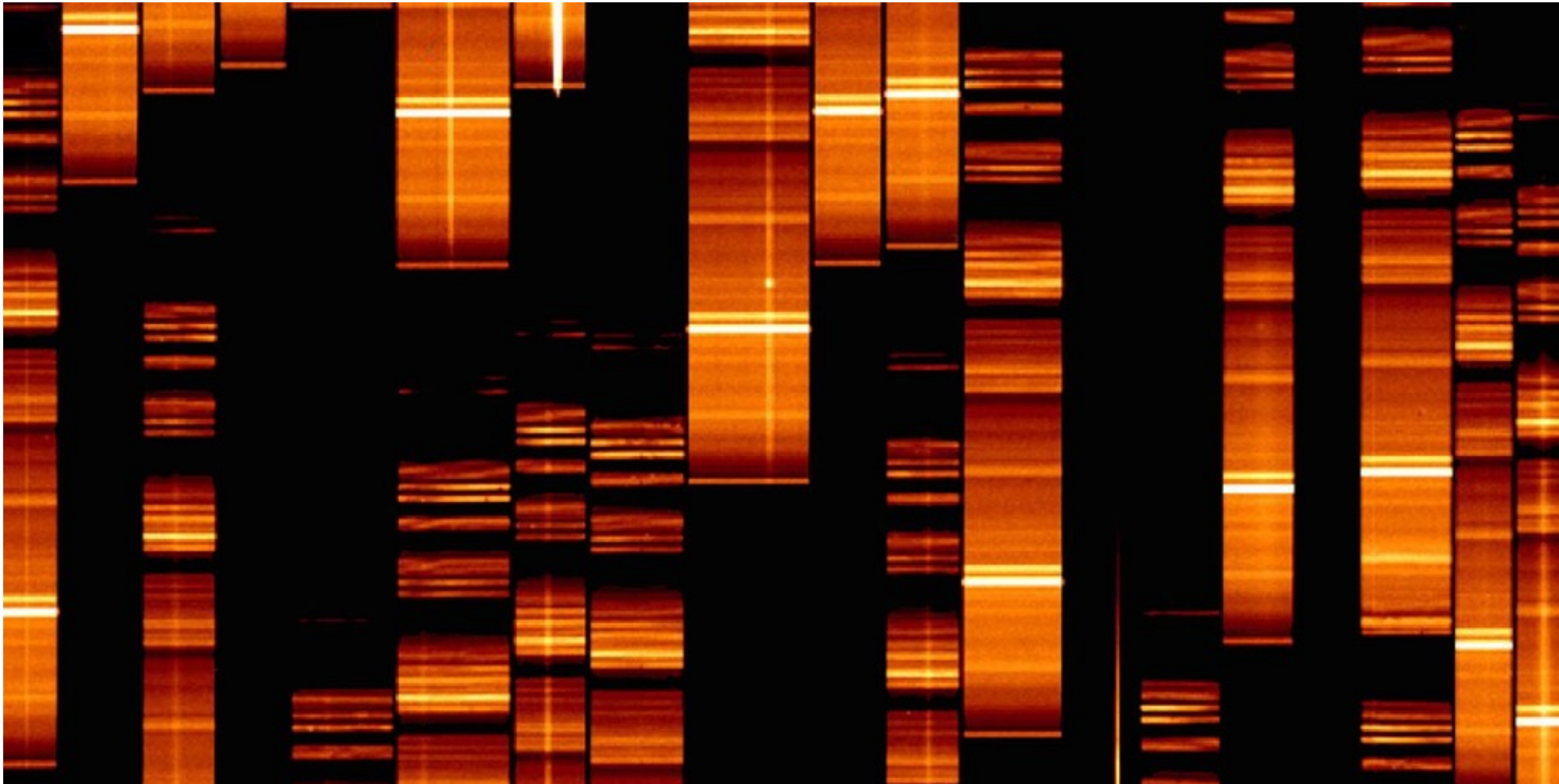


Multi Object Spectrographs - laser cut slits

VIMOS on the VLT telescopes

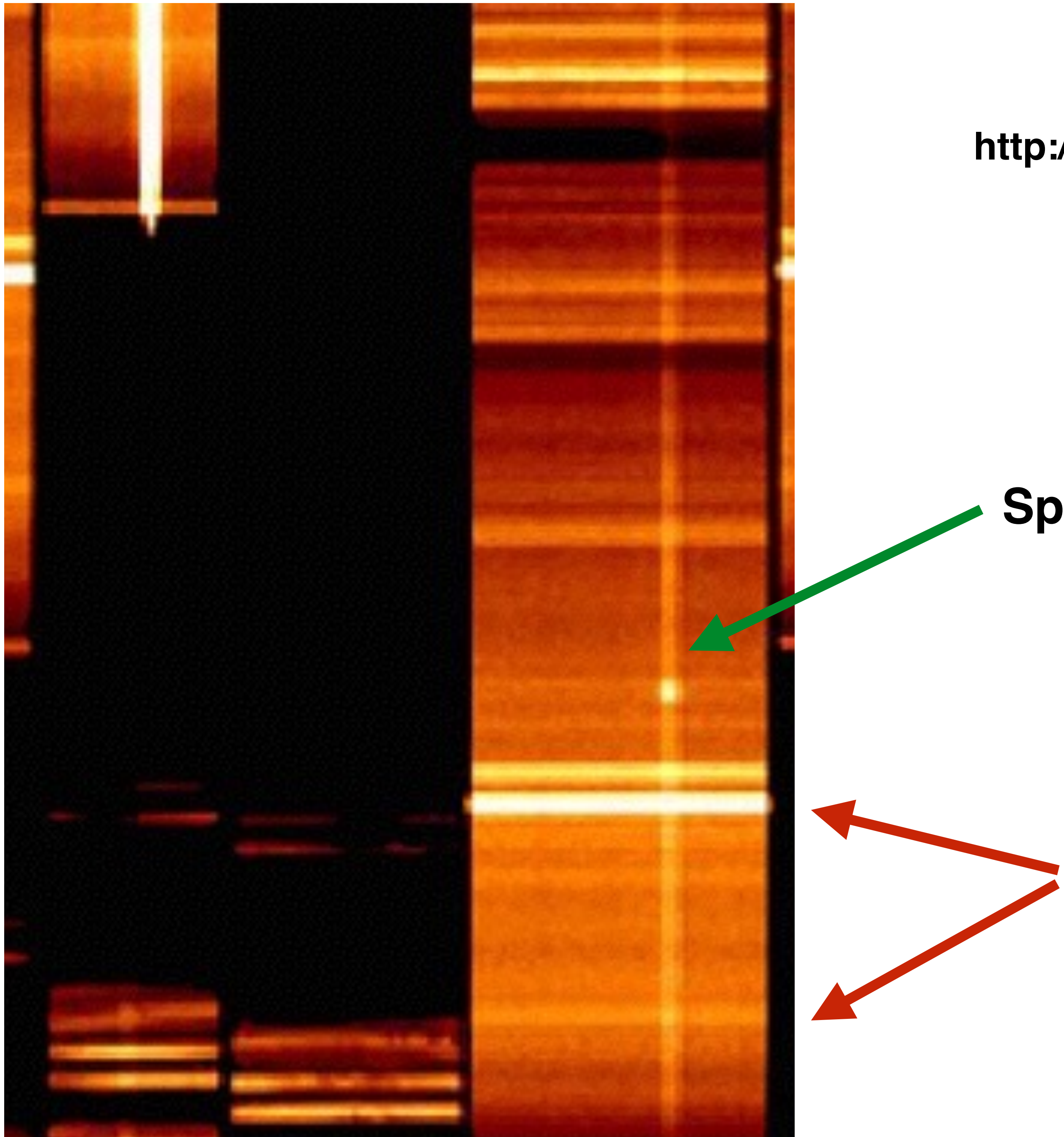
Number of spectra limited by sky coverage

http://www.eso.org/public/news/eso0209/



Night sky emission lines in NIR

VIMOS on the VLT telescopes



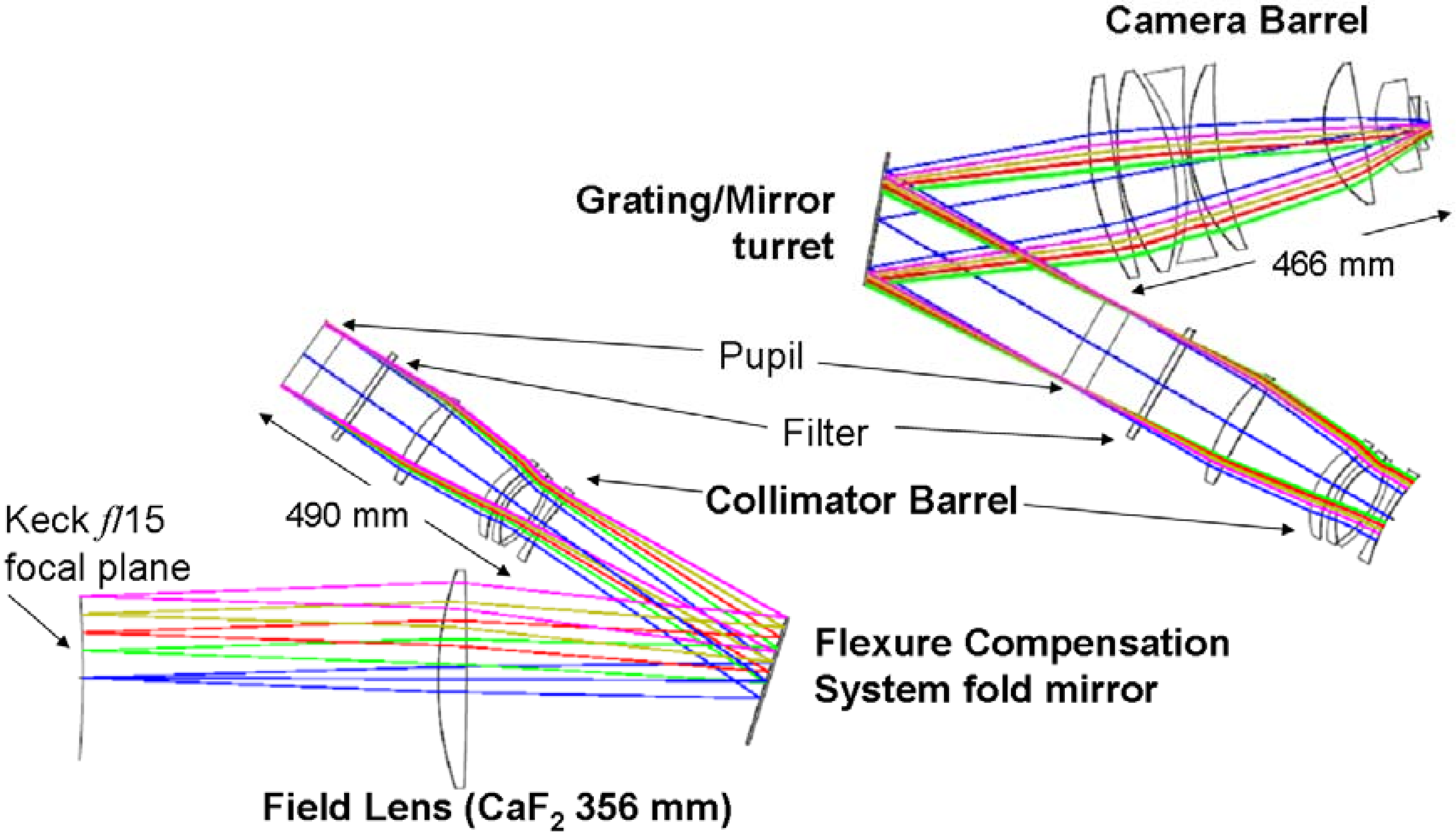
http://www.eso.org/public/news/eso0209/

Spectrum of galaxy

Night sky emission lines

Configurable slits on MOSFIRE (Keck)

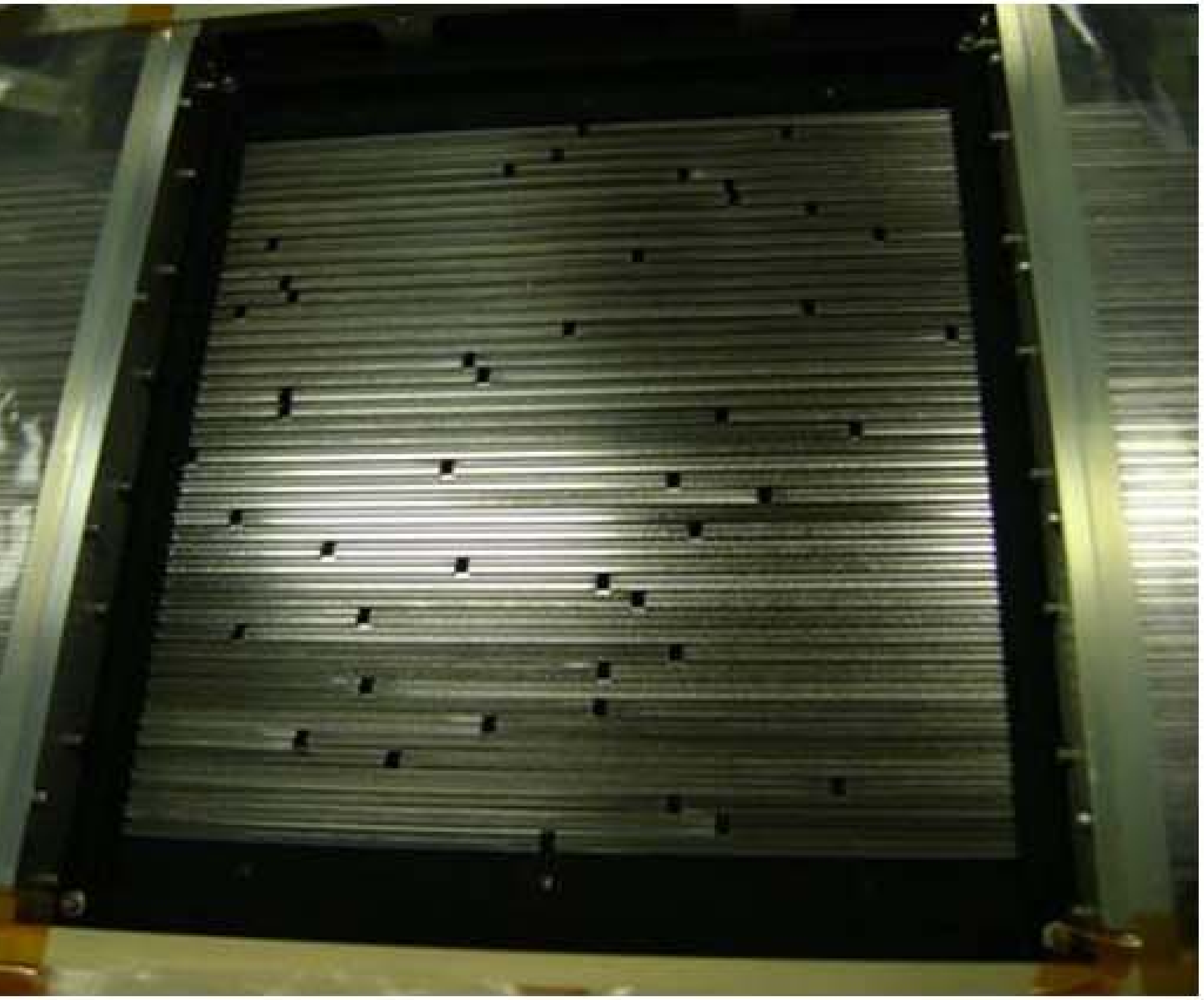
NIR multi-object spectrograph

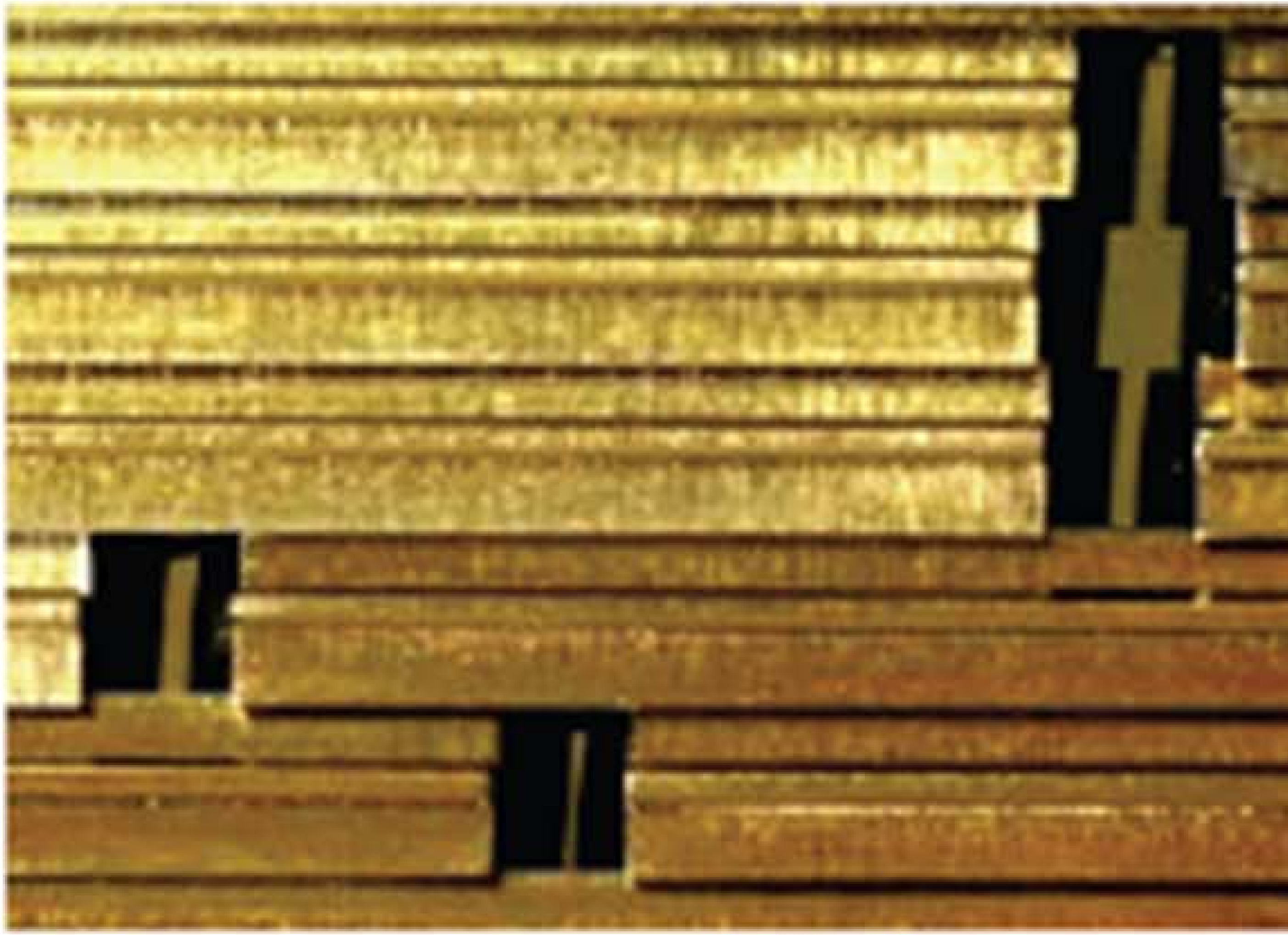


McLean 2012

Configurable Slit Unit (CSU)

Cryogenic slits can be reconfigured in cold and in vacuum dewar!





McLean 2010

Configurable slits on MOSFIRE (Keck)

Adjustable mechanical slits allow for much faster configuration

McLean 2012

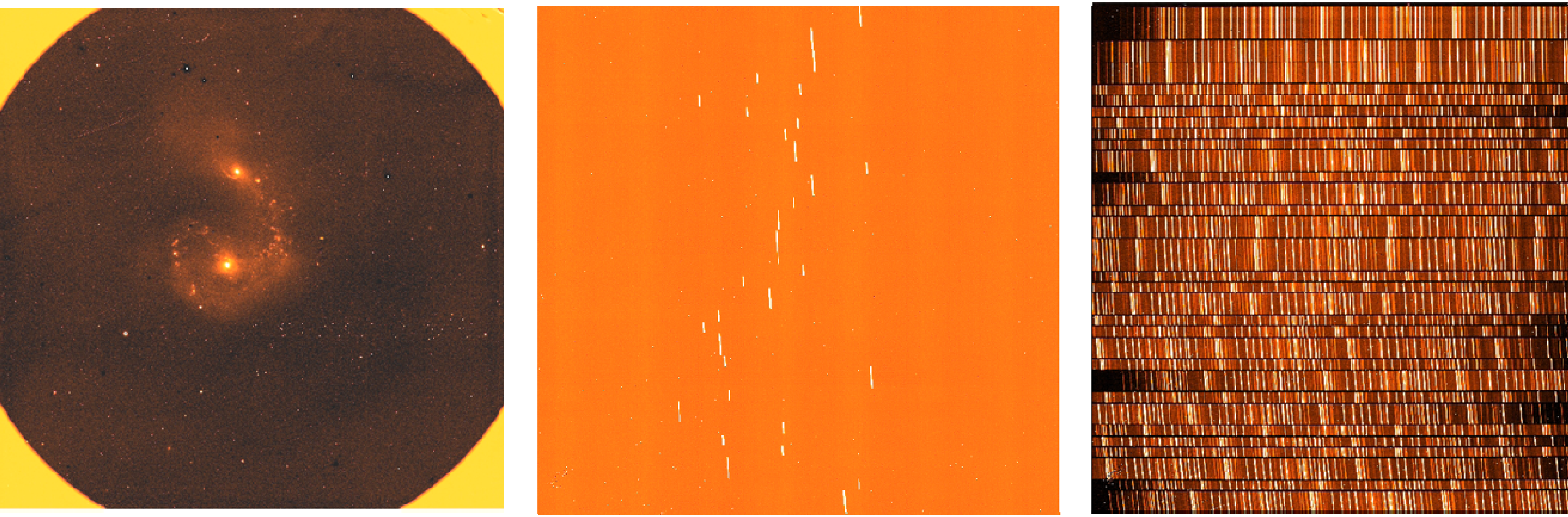
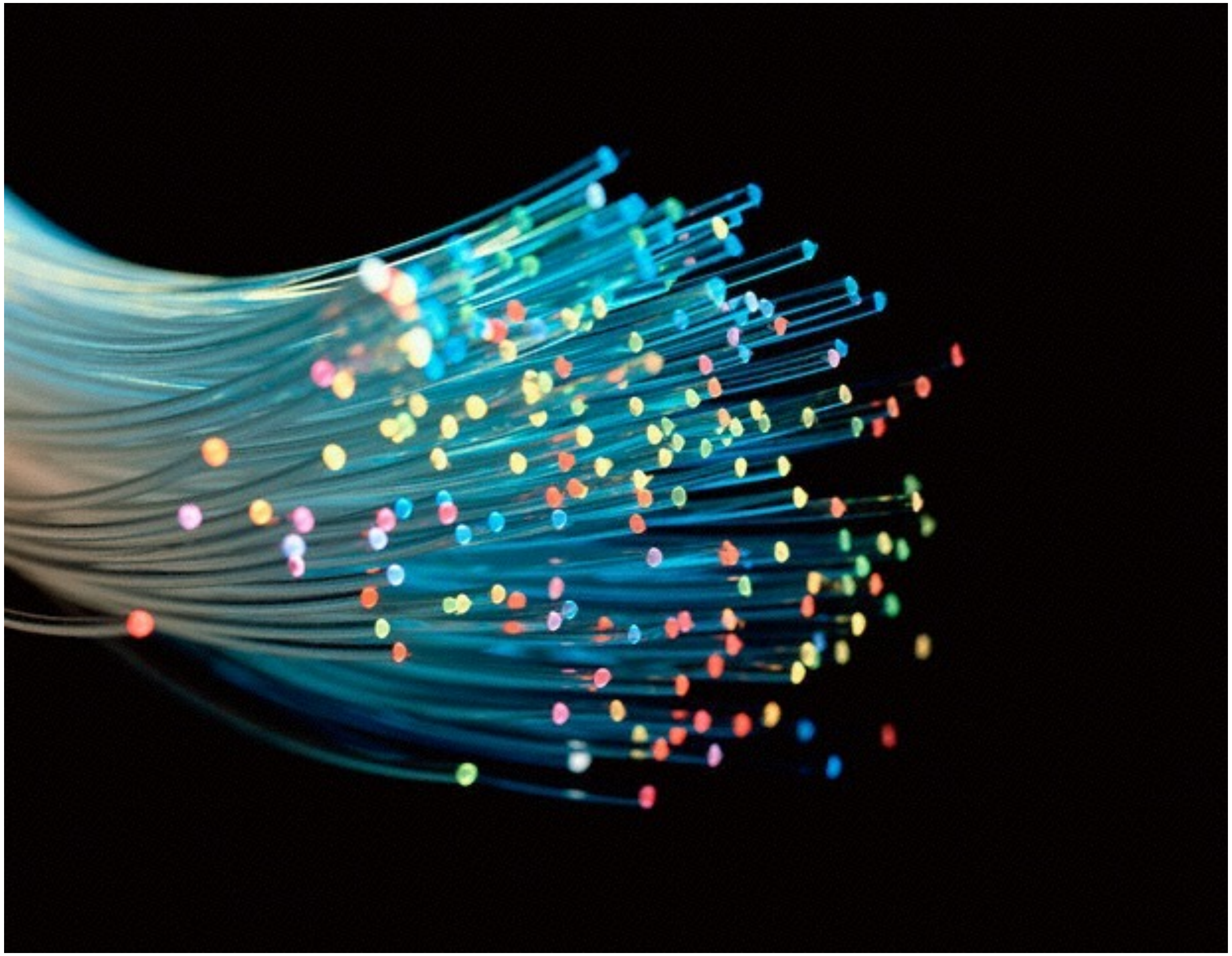
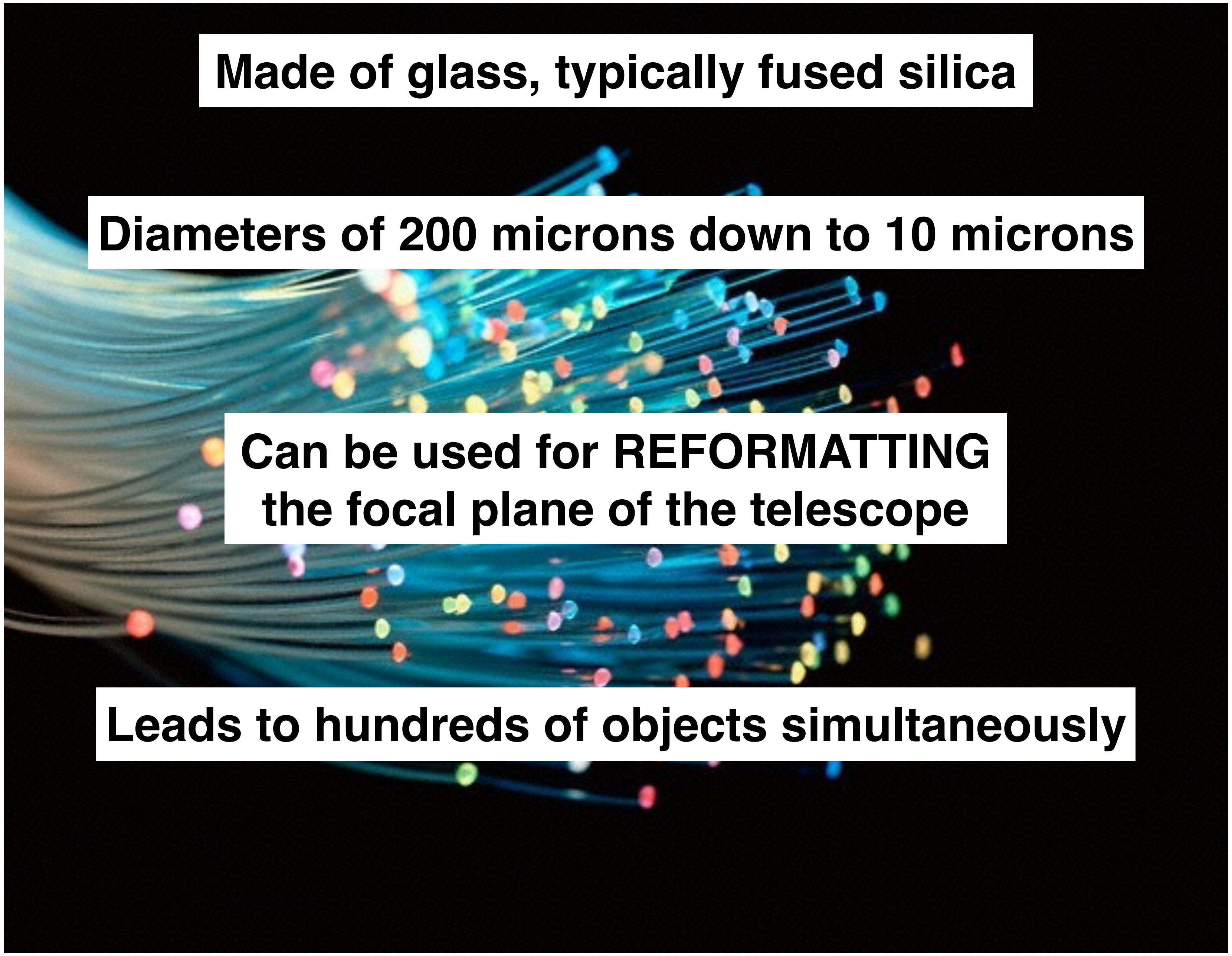


Figure 7. On the left is the layout of the MOSFIRE field on the sky with a 58s J-band image of The Antennae galaxies. The middle image is of a slit mask and the right image is the night sky emission with this mask in H-band.

Fibre Optics



Fibre Optics



Made of glass, typically fused silica

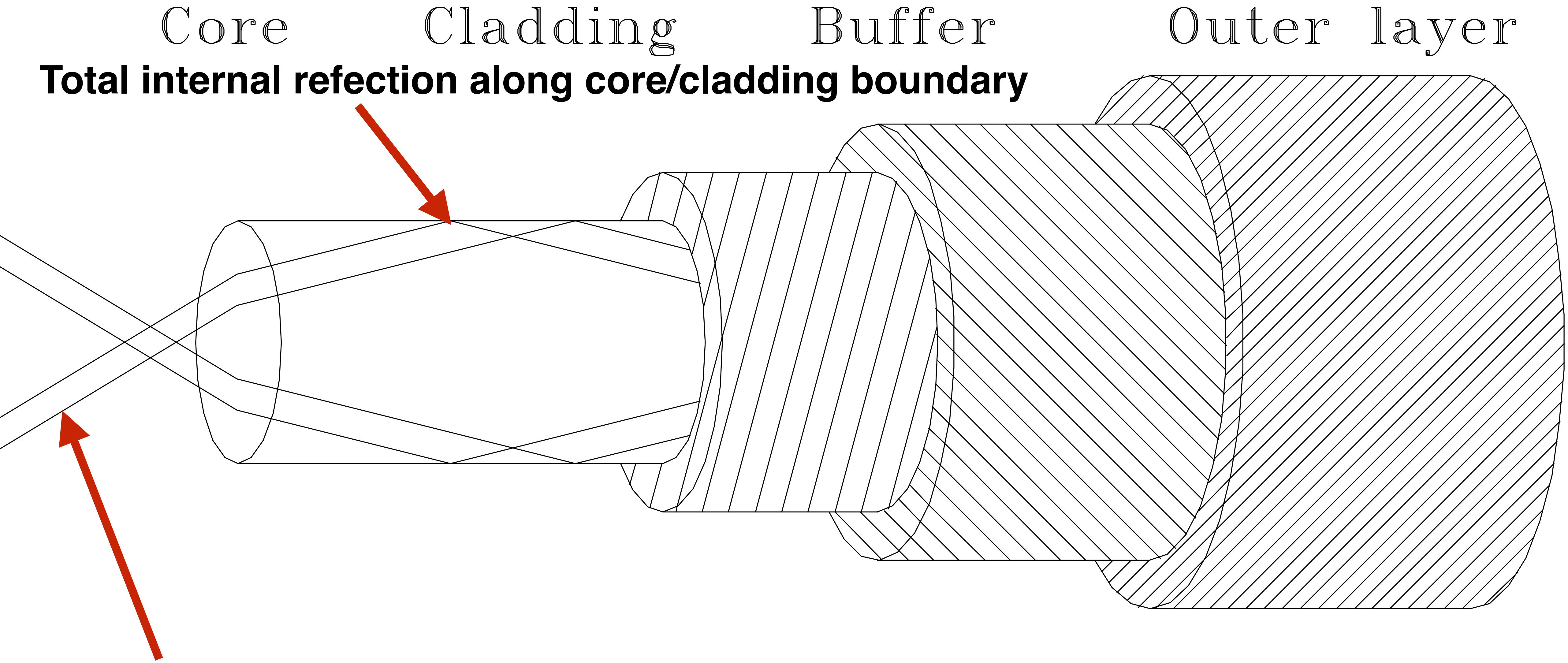
Diameters of 200 microns down to 10 microns

Can be used for REFORMATTING
the focal plane of the telescope

Leads to hundreds of objects simultaneously

Structure of an optical fibre

Cladding has higher refractive index than core material



Total internal refection along core/cladding boundary

Largest acceptance angle dependent on core and cladding refractive indices

Everything is big when you are 100 microns in size

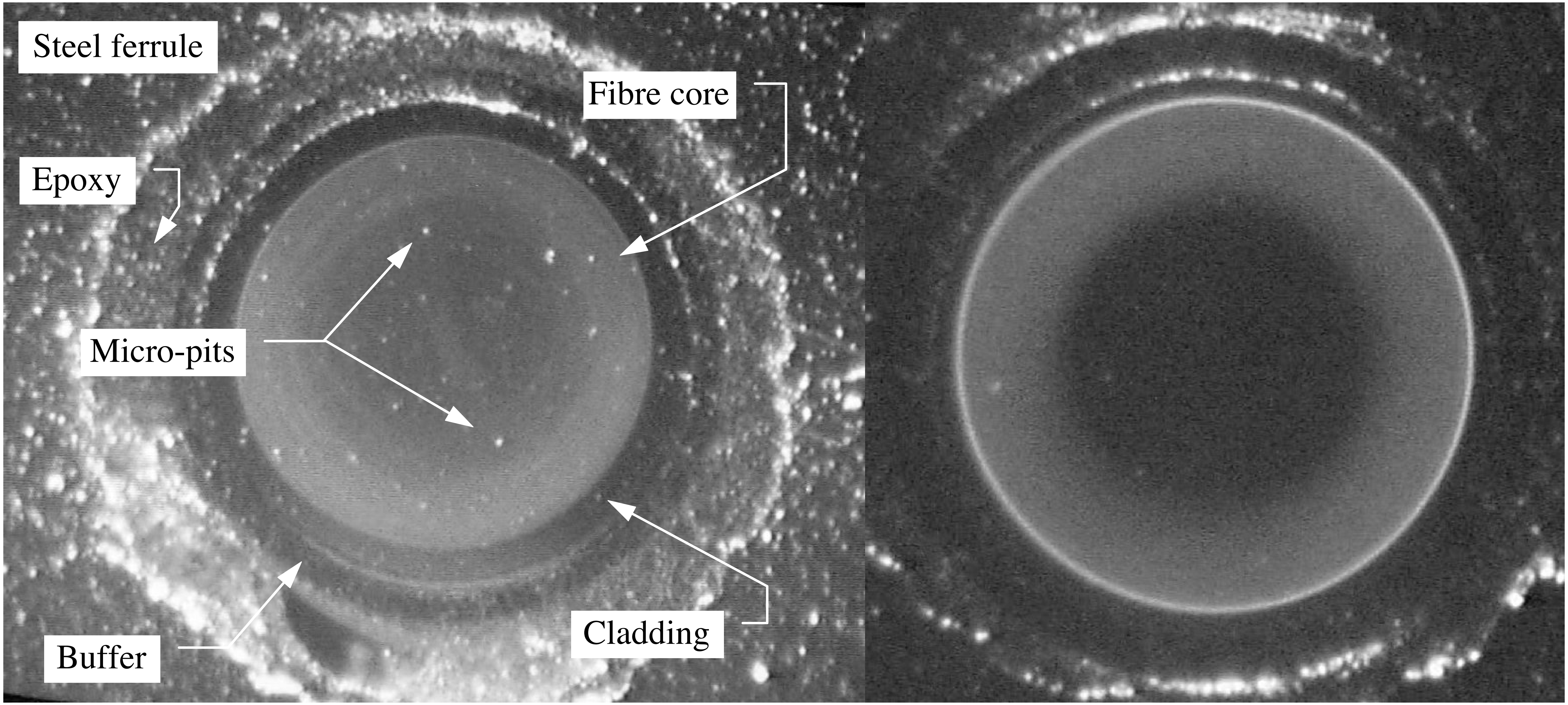
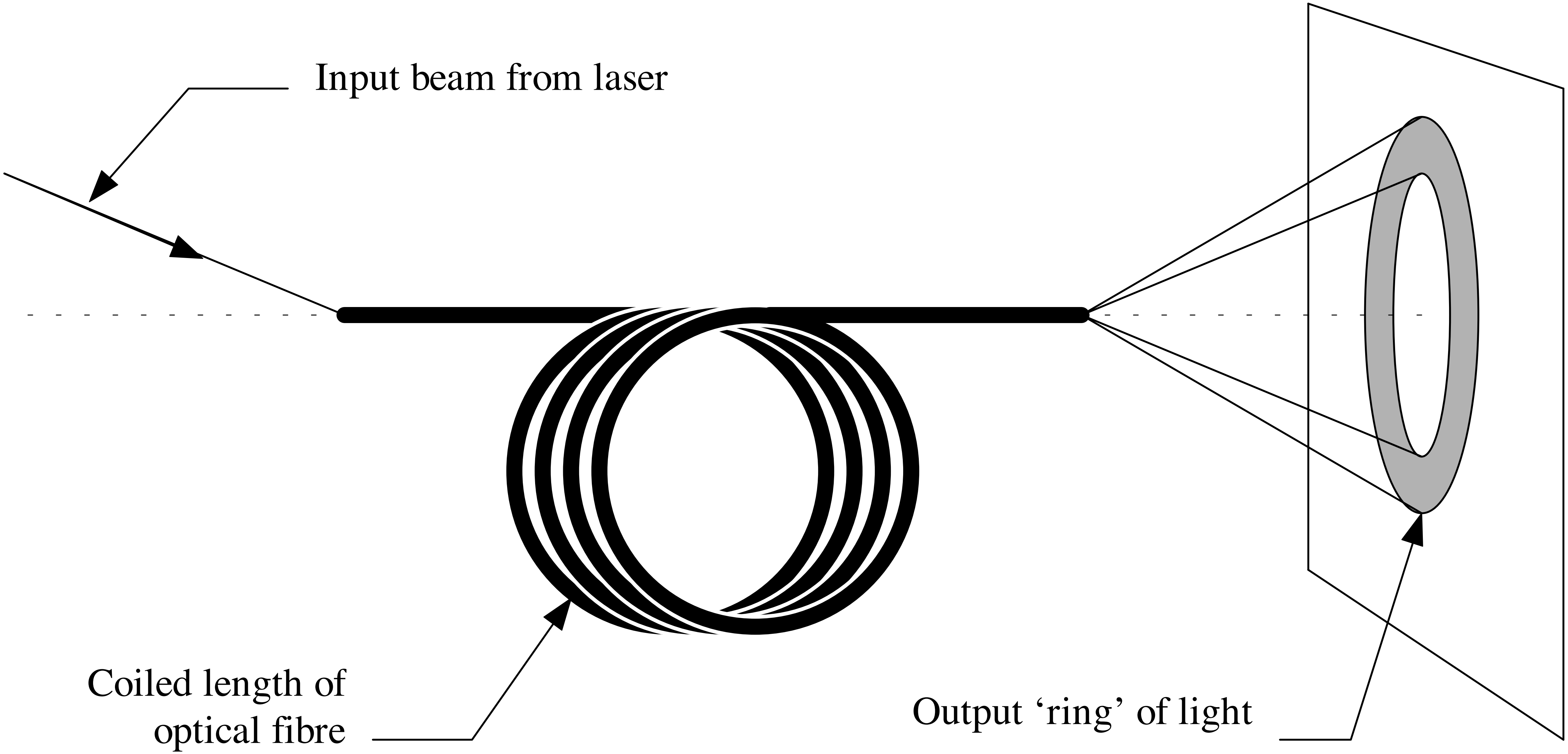


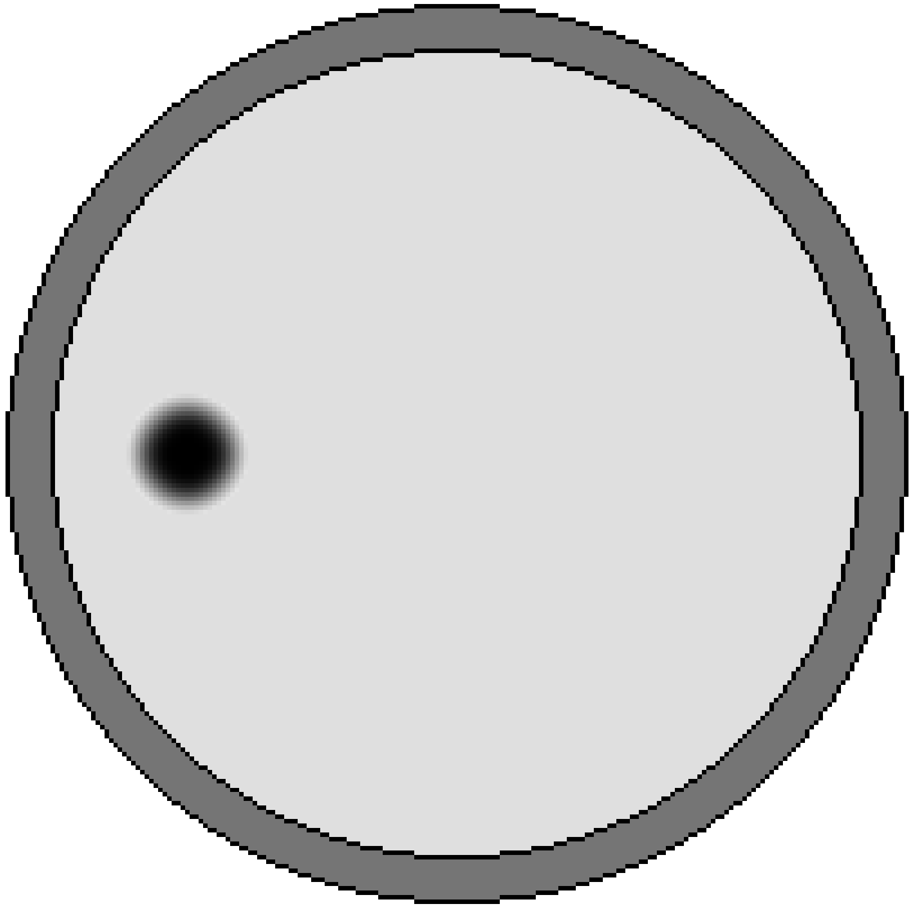
Figure 2-14 *Examining the fibre faces*. On the left the fibre face is checked for micro-pits - several can be clearly seen. On the right the back-illuminated fibre shows a clean ring of light across the face of the fibre.

Optical Fibre - azimuthal scrambling

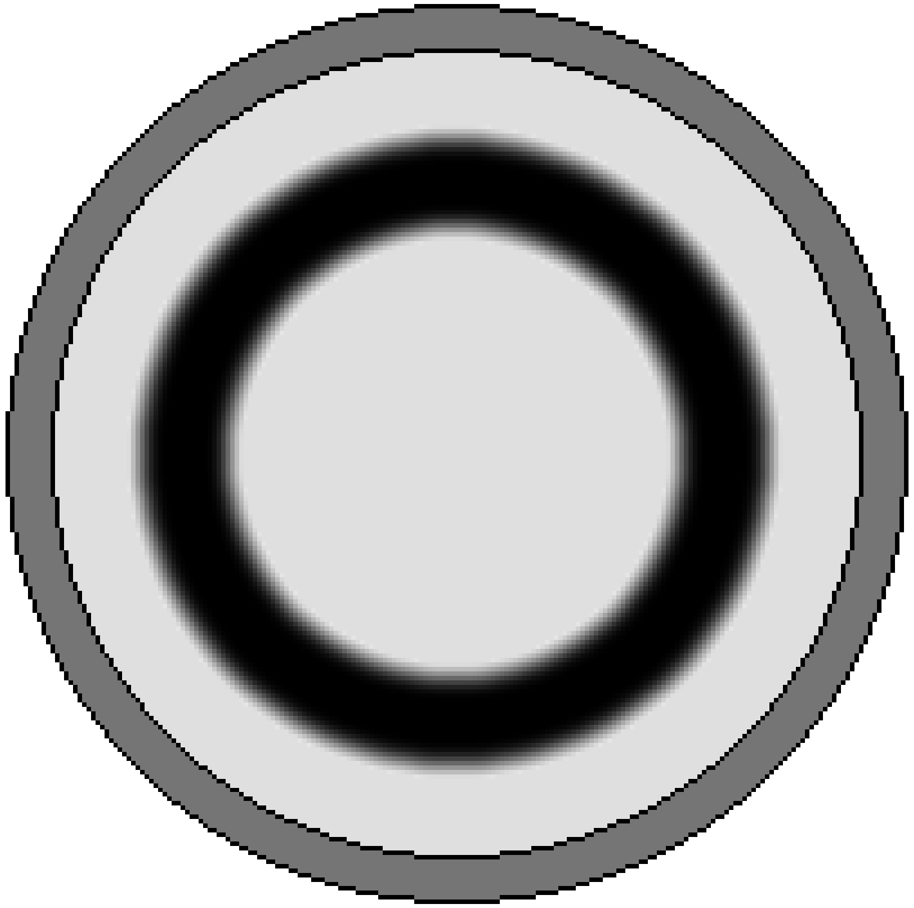


Thousands of internal reflections from curved interface

Optical Fibre - azimuthal scrambling



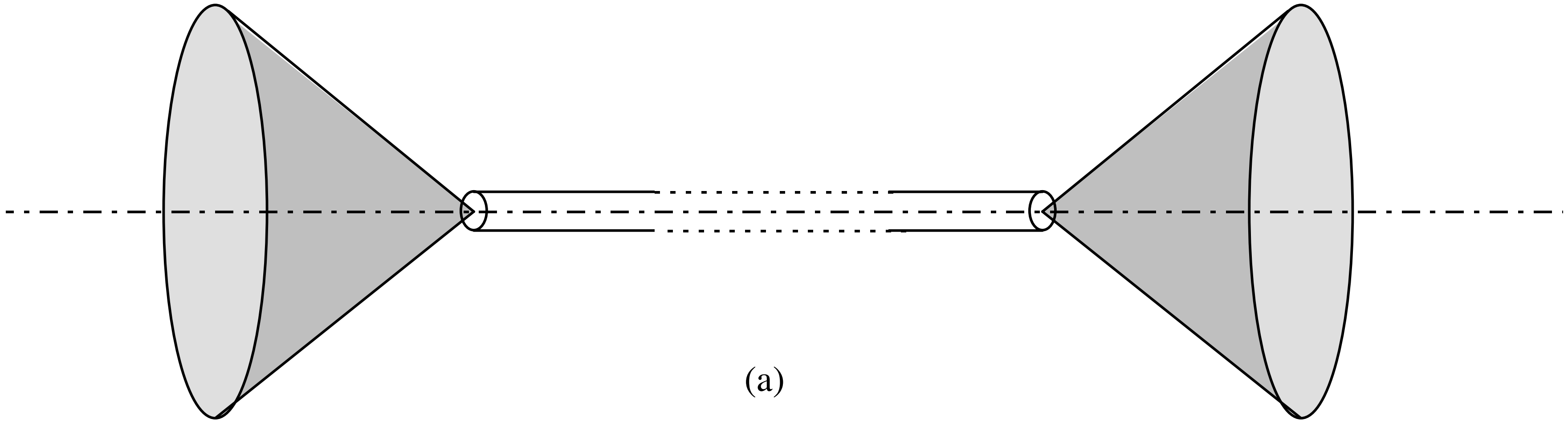
Input fibre face



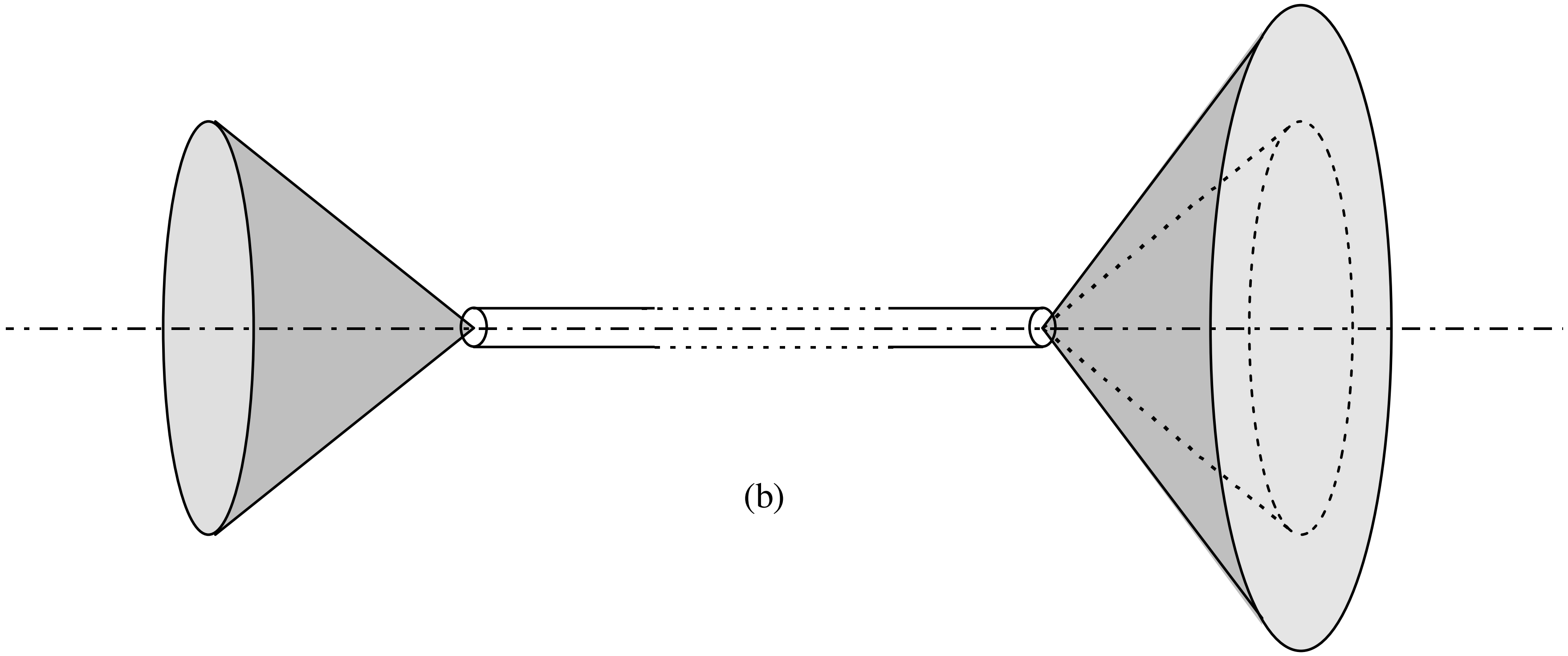
Output fibre face

Looking down on the end of the polished fibre end

Optical Fibre - Focal Ratio Degradation



Ideal preservation of input beam angle and output beam angle



Deformation and stress causes light to ‘spread’ in output angle cone

Loss of flux from FRD if you don't make the output optics bigger in size

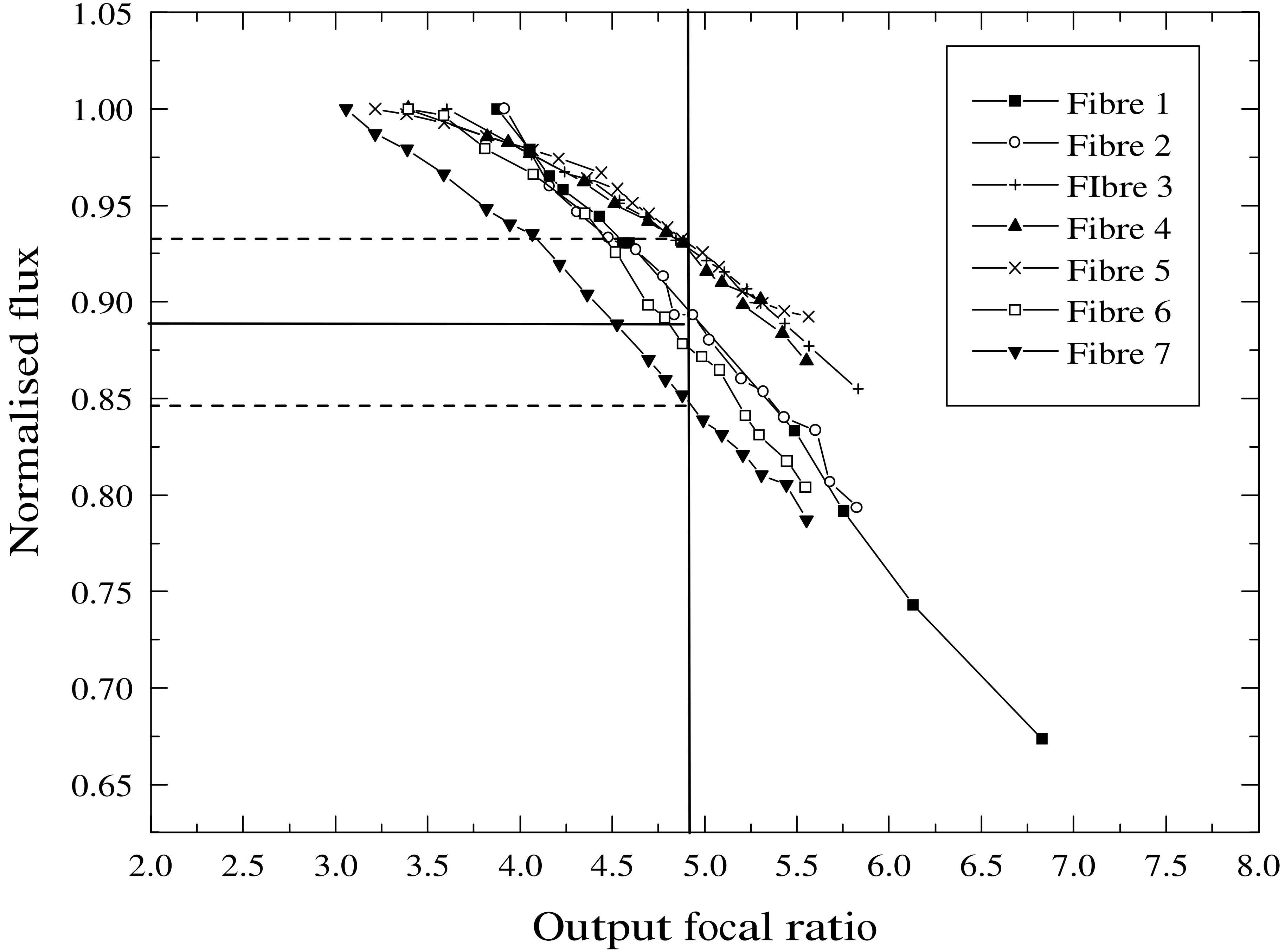


Figure 2-19 *FRD test results for seven SPIRAL fibres*. This is for a 16m length of Polymicro 50/70/90/110μm fibre measured at 600nm.

Plug plates drilled manually to match target fields

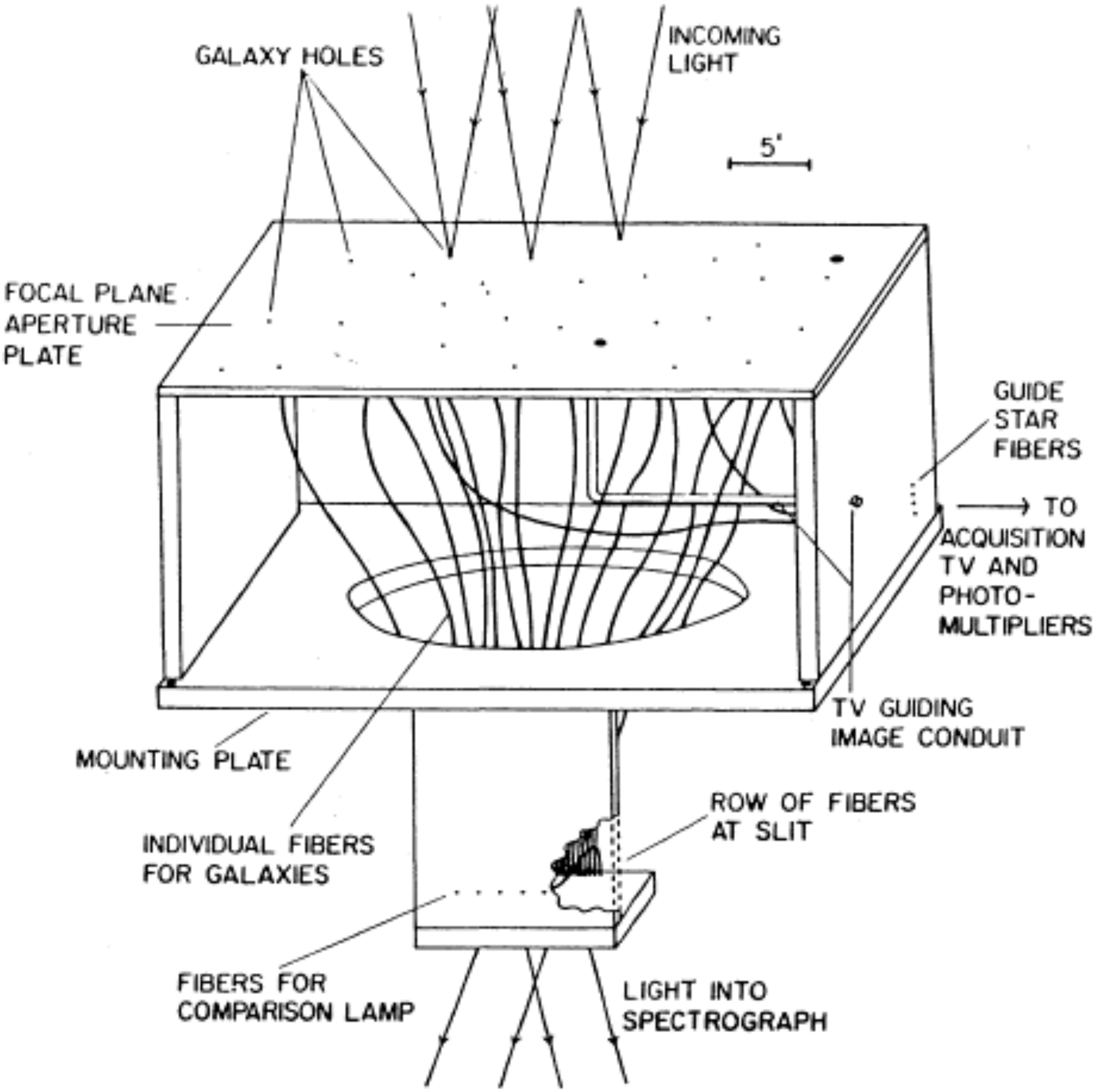
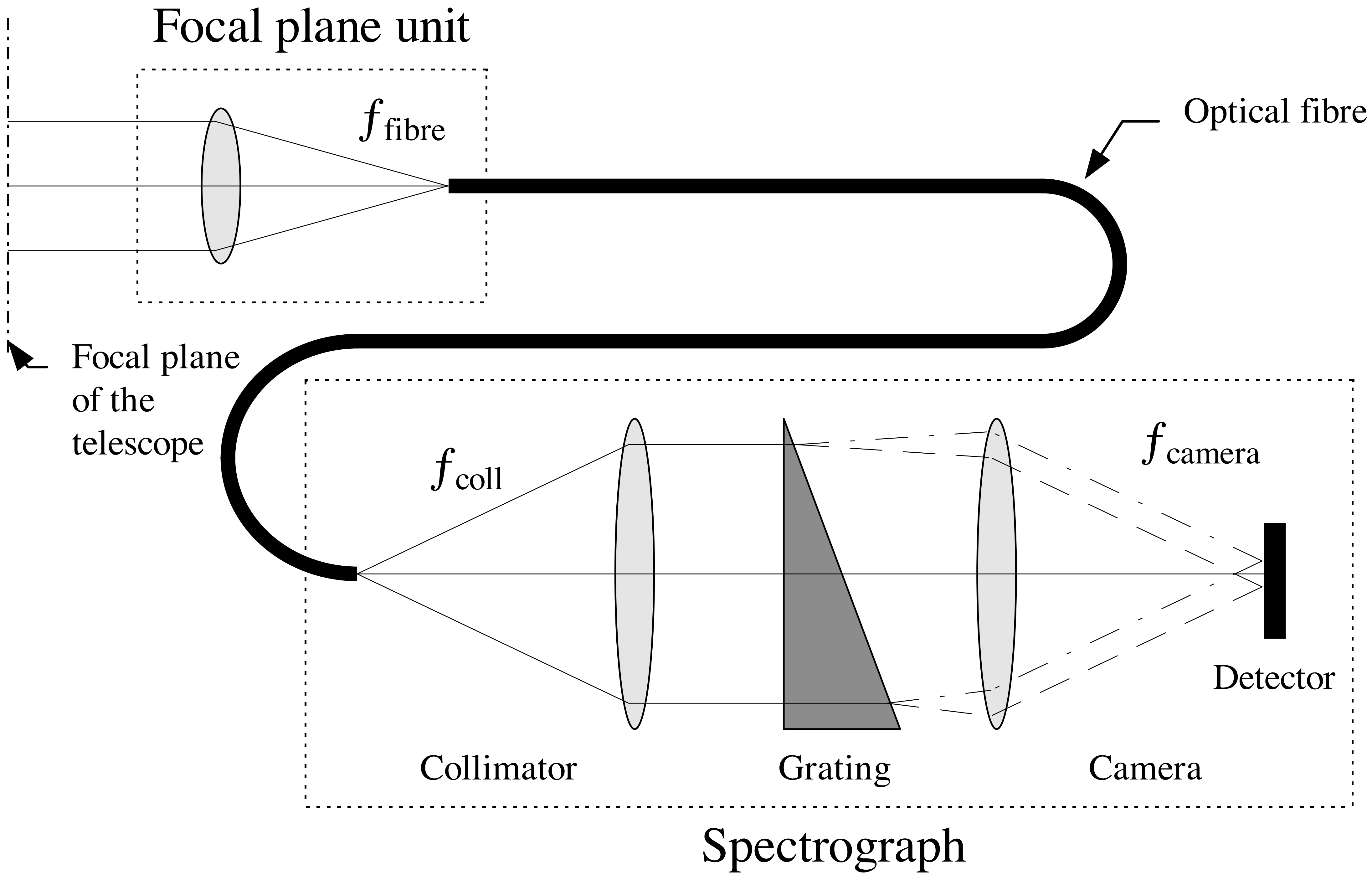


Figure 2. Schematic drawing of the aperture plate nucleus of the MEDUSA spectrograph.

Hill 1988 ASPC

Optical Fibre Spectrograph



Gluing optical fibres onto a glass plate(!)

The fine plate-scale (67 arcsec/mm) meant that drilling holes in brass plates was not an option for fibre positioning, due to thermal and other considerations. The required positioning accuracy for the fibres was 10 µm over the whole field (think of sticking a pin in a cricket pitch with a precision of 1 mm). It was one of the editors of these proceedings who suggested a viable alternative. Tacking the fibres directly onto transparent star and galaxy images on a positive copy of the target field using UV-curing cement seemed like a blindingly obvious solution to David Malin, with his background in photography and polymer chemistry.

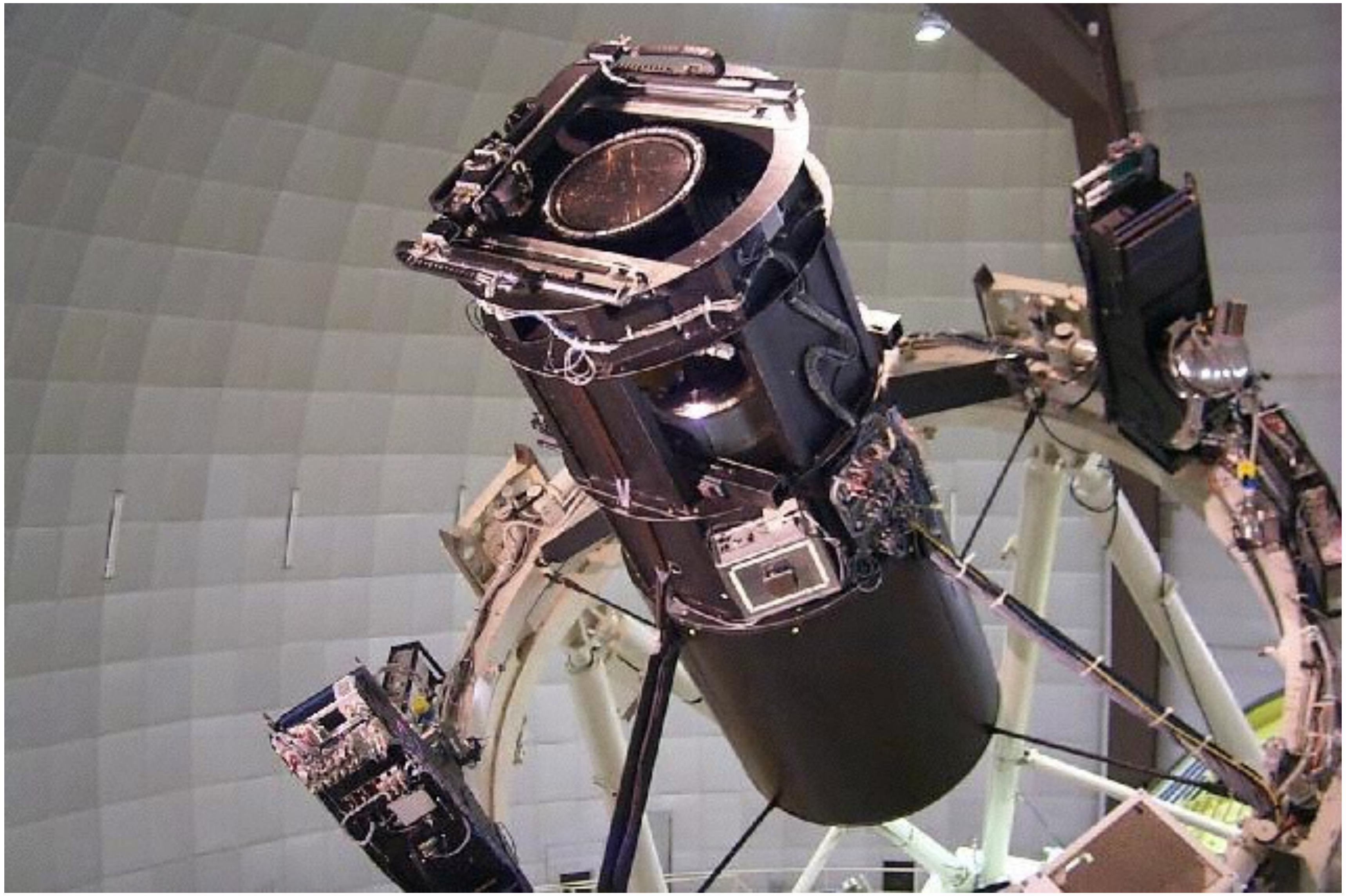
Unlikely as it sounds, this technique worked rather well when it was tried out late in 1983. It required a special plate-holder to support the glass positive plate and bend it to the focal curvature. This had the same dimensions as the photographic plate-holders, so it could be loaded via the existing elevator, and was built for the project by UKST technicians Eric Coyte and Magnus Paterson (Fig. 3). It was another nine months before the necessary components for a fibre acquisition system had been built, but by October 1984, sets of stars spread over the full 6.5 degrees square field of the telescope were being simultaneously acquired. By then, too, the system had a name—FLAIR, for Fibre-Linked Array Image Reformatter. What else?

Fred Watson

Robotic positioners - 2dF

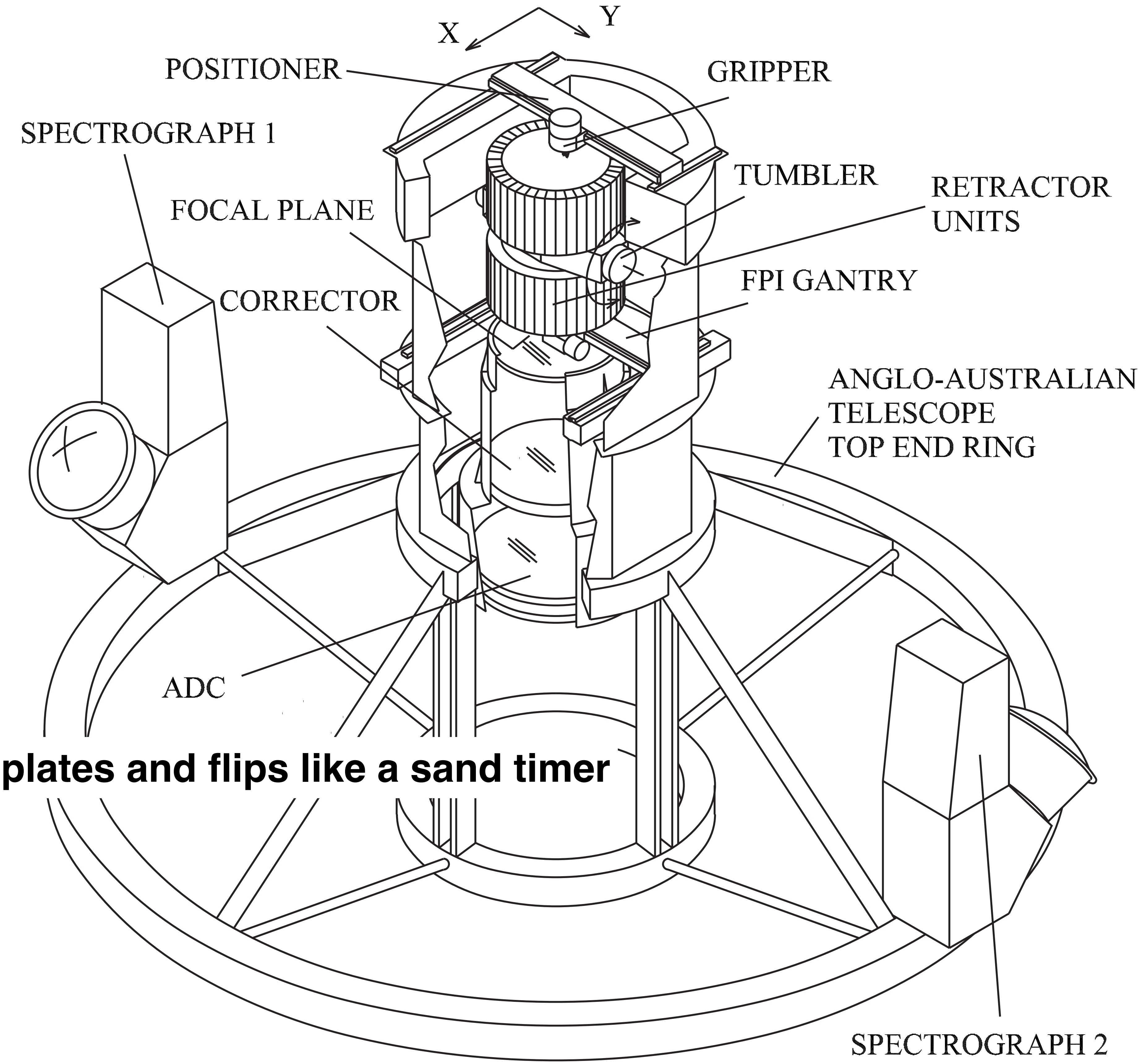
Sits at prime focus of 4m Anglo-Australian Telescope

400 fibres positioned whilst other 400 are observing!



Diameter of 140 microns (2.1 arcsec on the sky)

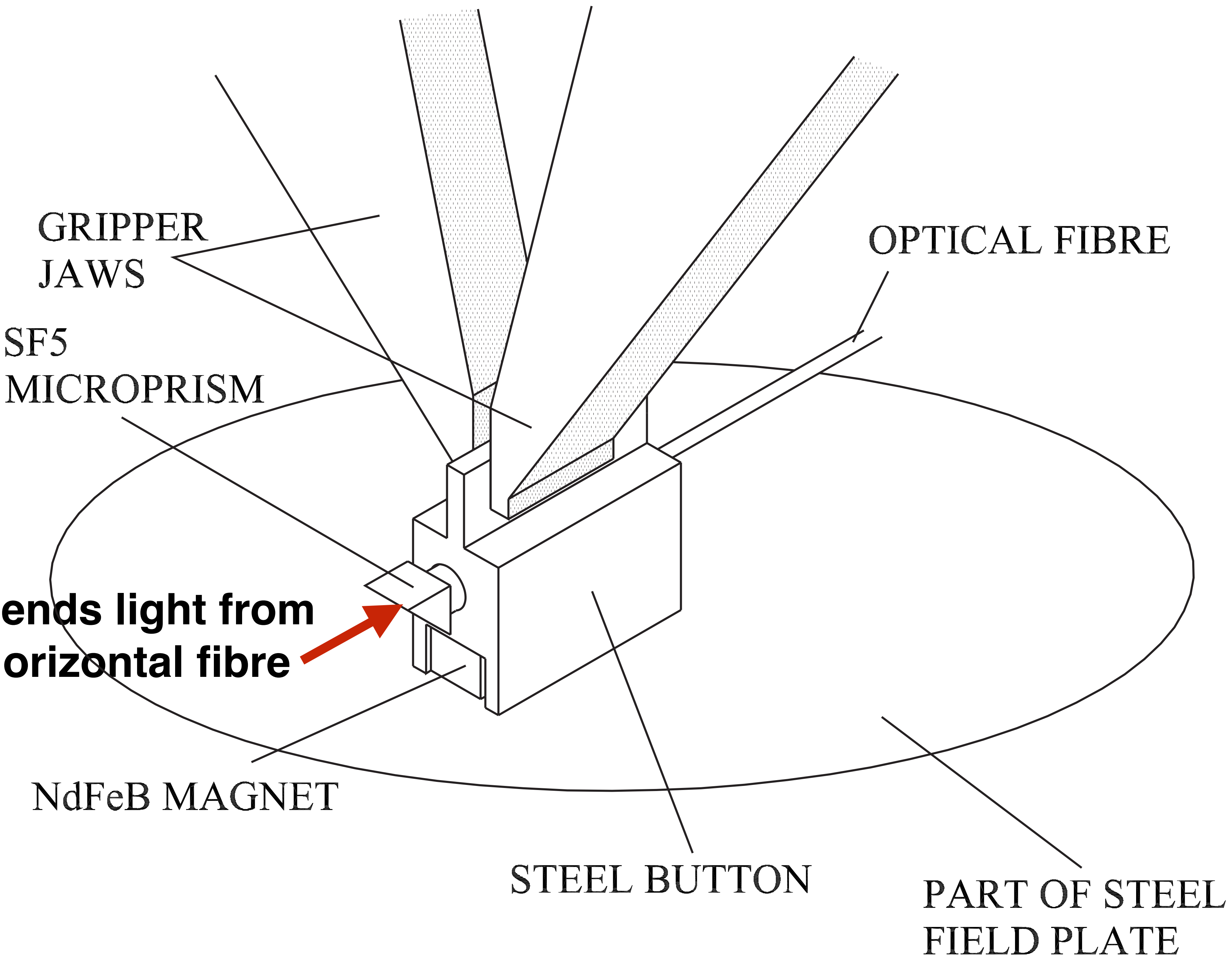
Robotic positioners - 2dF



Tumbler has two plates and flips like a sand timer

Lewis (2002)

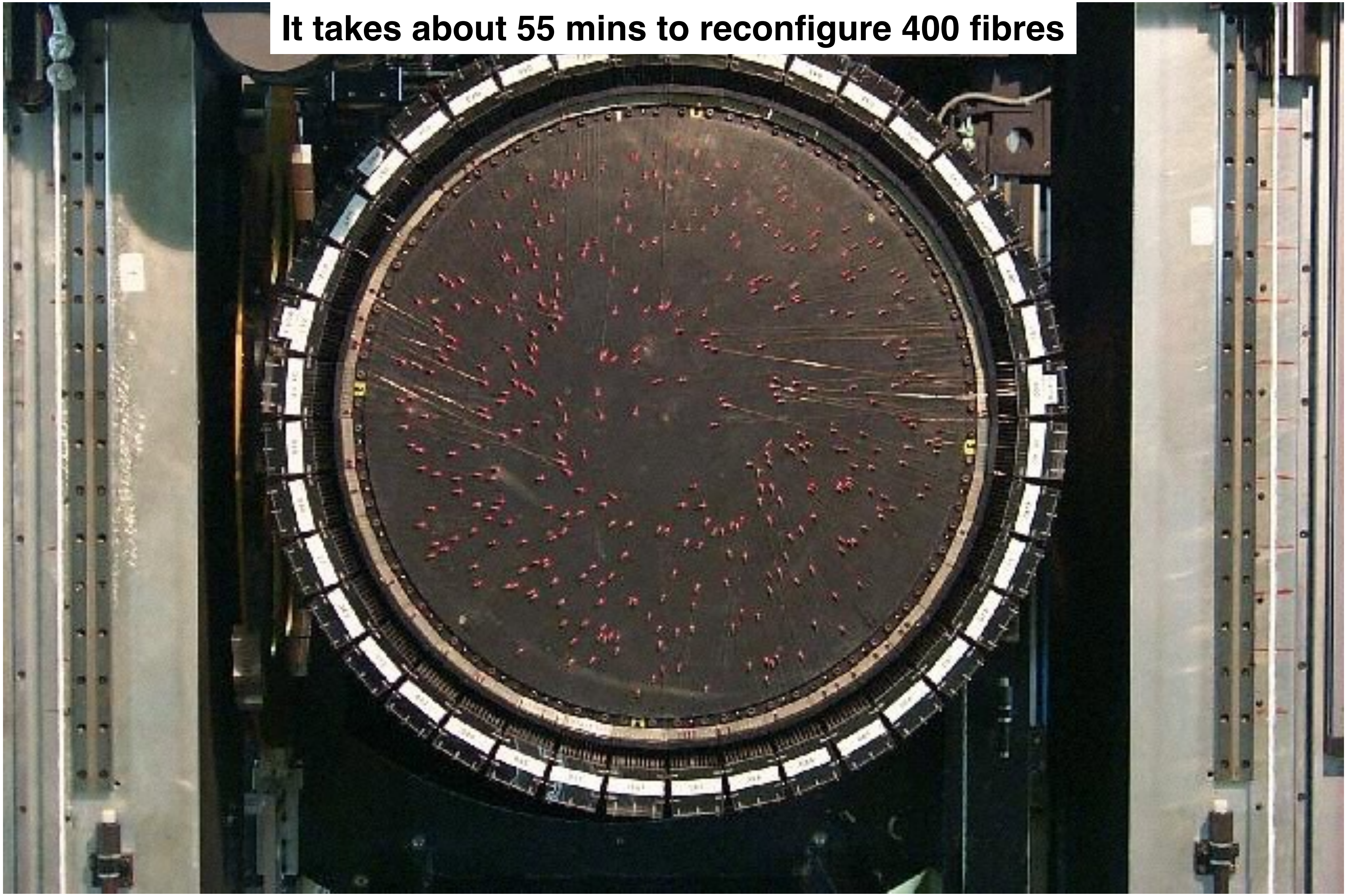
Robotic positioners - 2dF



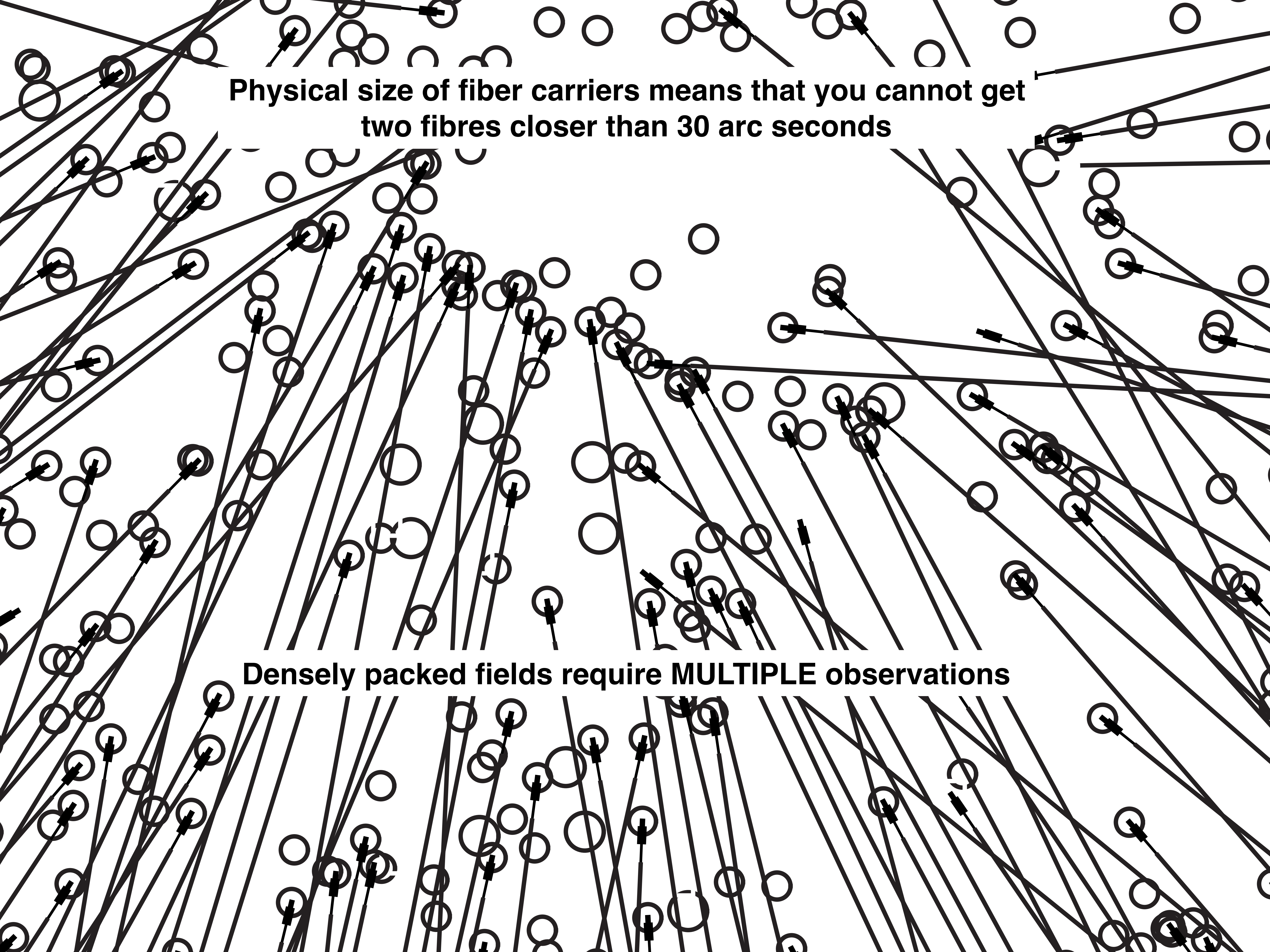
1.2mm prism sends light from vertical into horizontal fibre

Lewis (2002)

Robotic positioners - 2dF



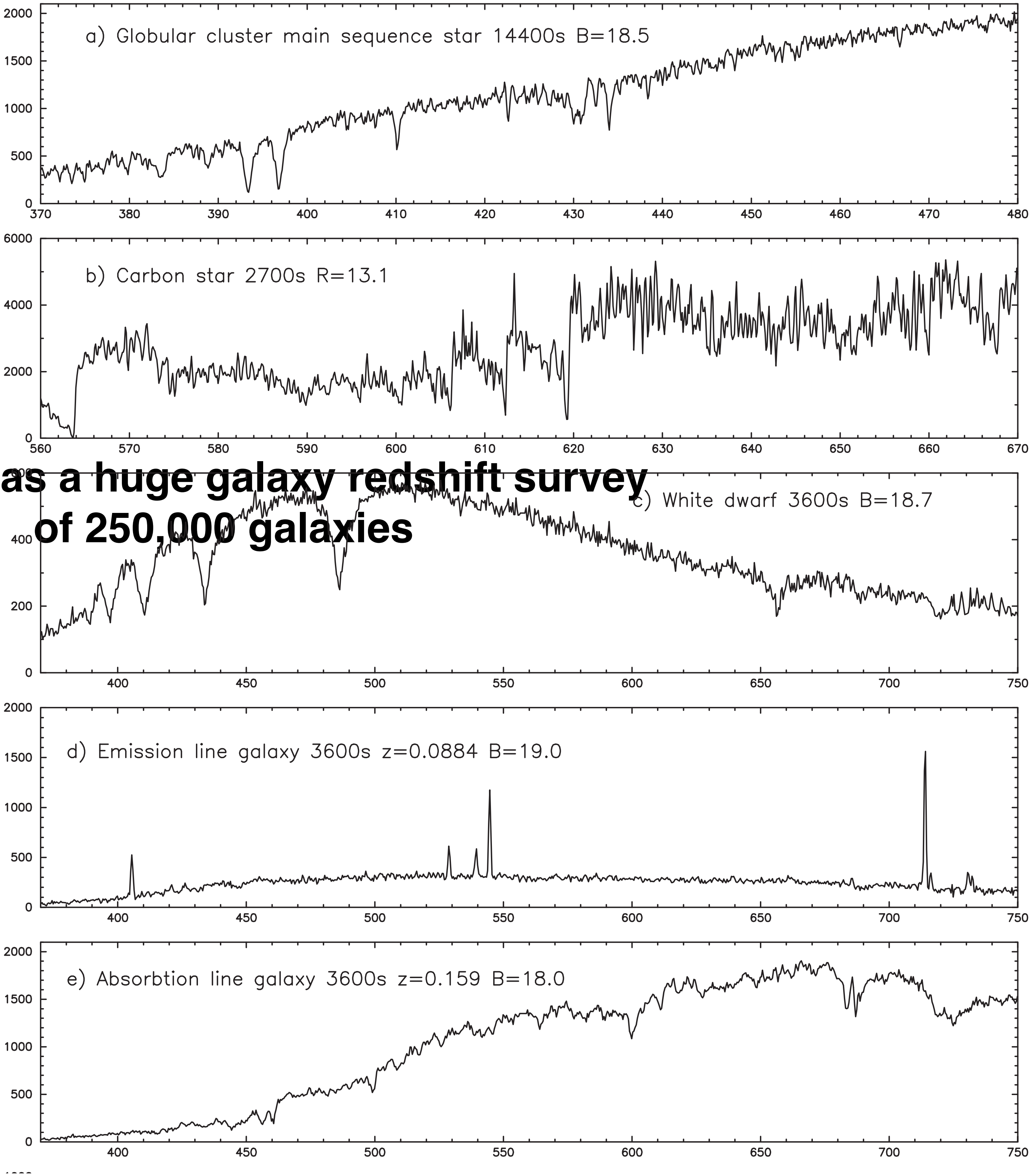
It takes about 55 mins to reconfigure 400 fibres



Physical size of fiber carriers means that you cannot get two fibres closer than 30 arc seconds

Densely packed fields require MULTIPLE observations

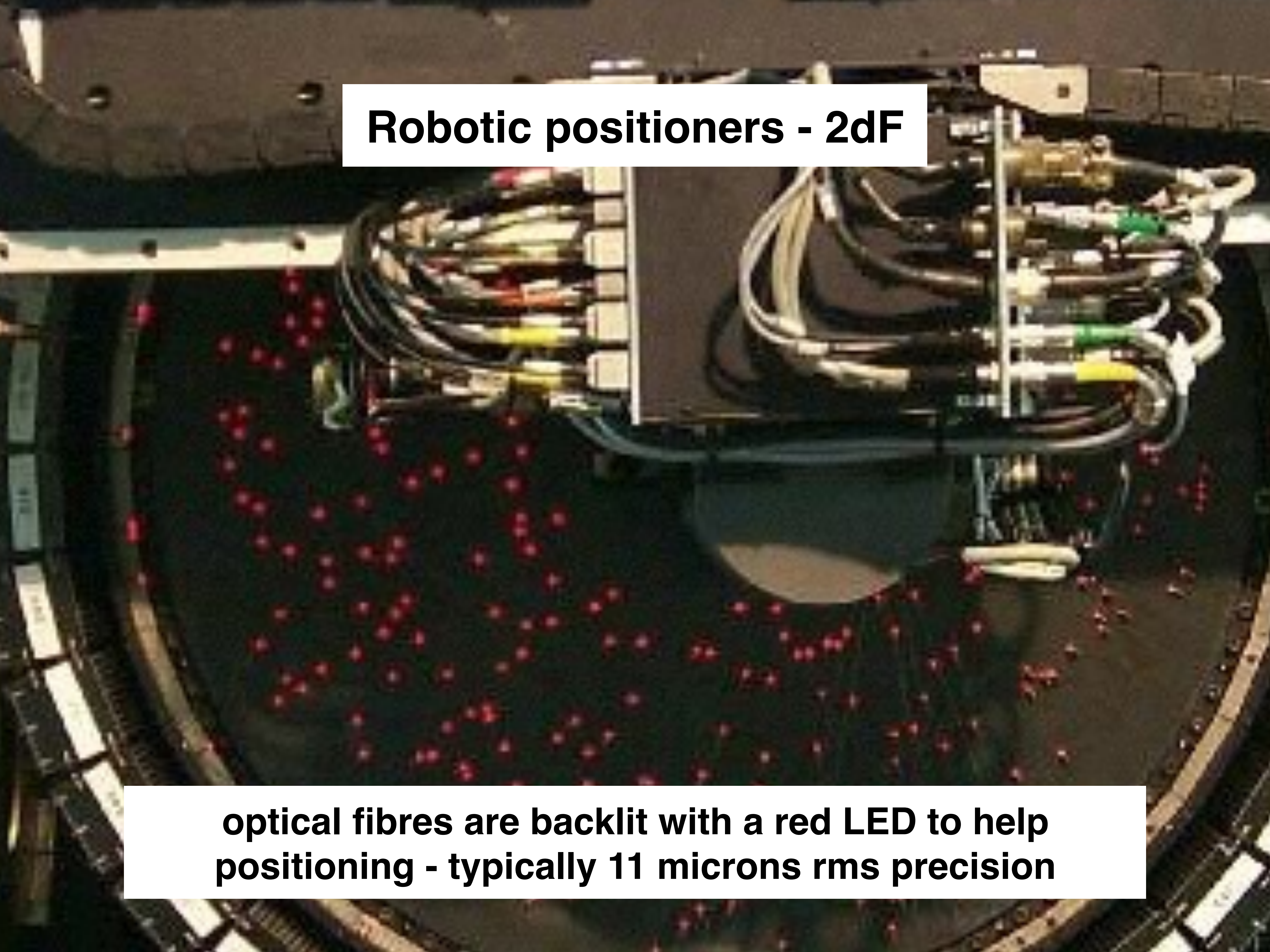
Robotic positioners - 2dF



Science was a huge galaxy redshift survey of 250,000 galaxies

Lewis (2002)

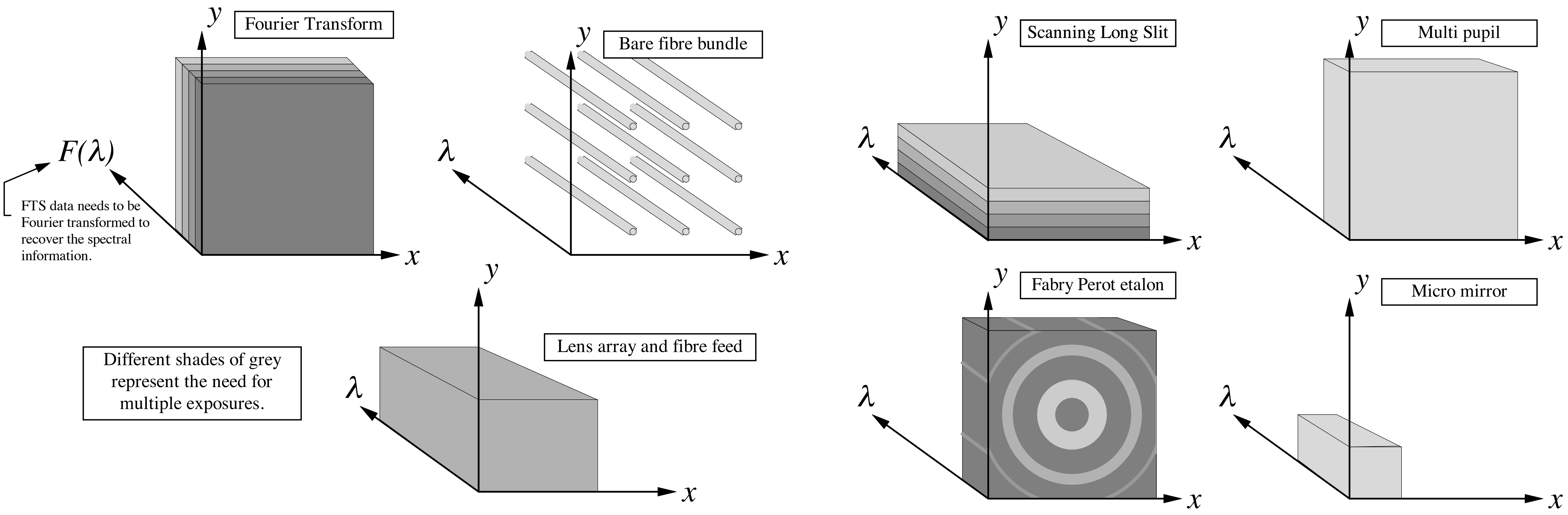
Robotic positioners - 2dF



optical fibres are backlit with a red LED to help positioning - typically 11 microns rms precision

3D Spectroscopy

3D spectroscopy



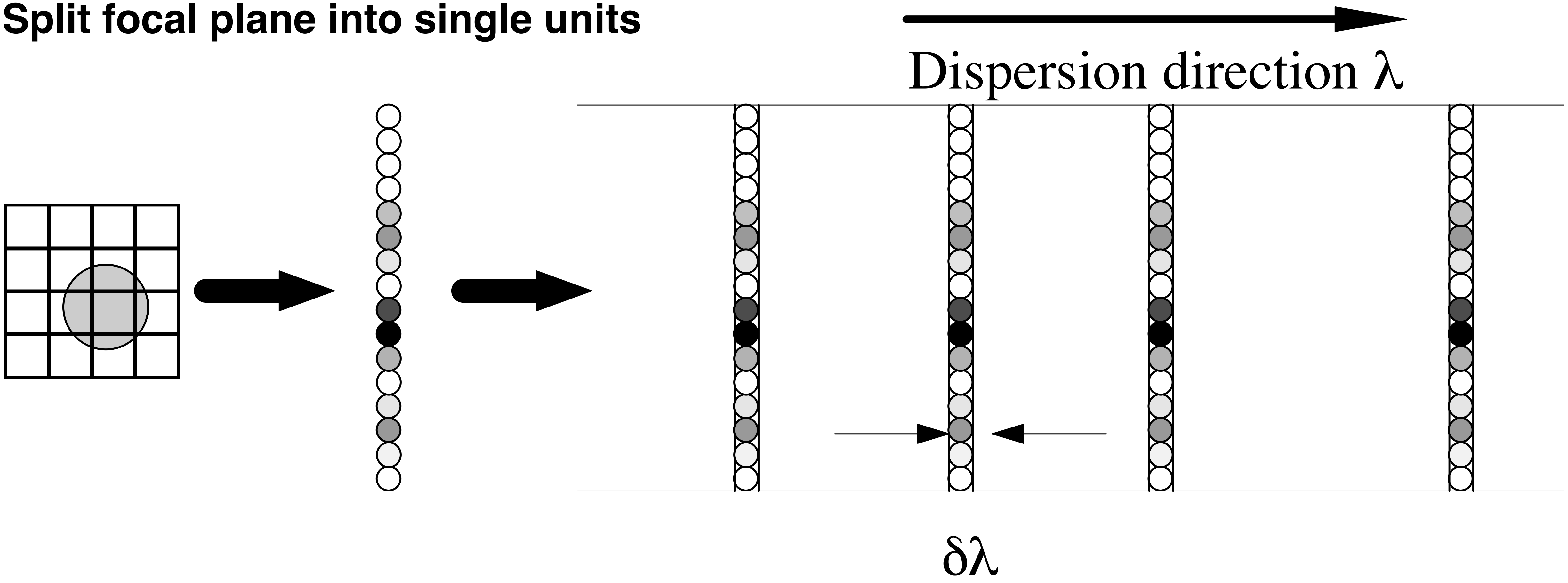
FTS data needs to be Fourier transformed to recover the spectral information.

Different shades of grey represent the need for multiple exposures.

Optical Fibre Image Reformatter

Use the flexibility of fibres to reformat the 2D sky into a 1D entrance slit

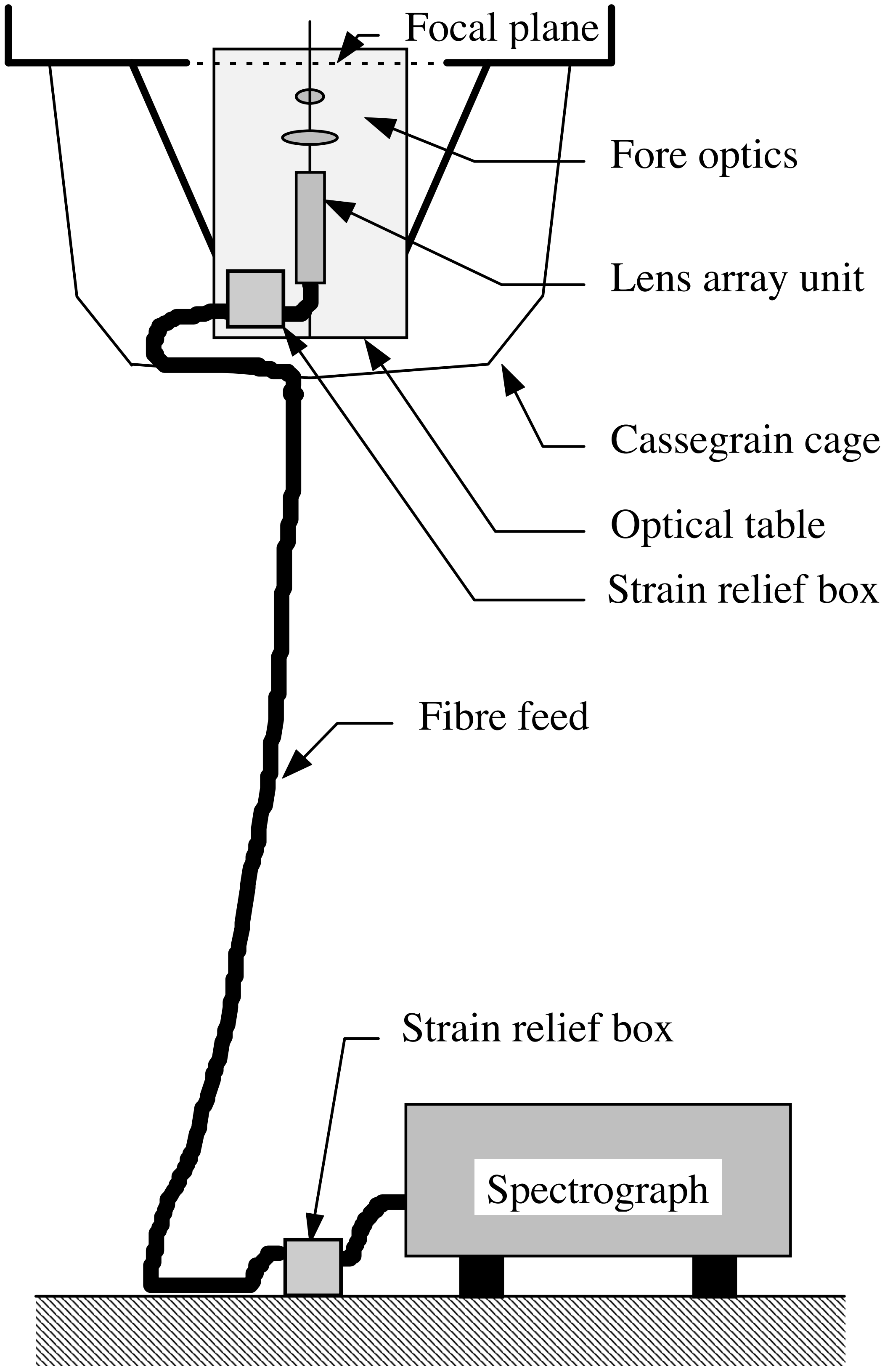
Split focal plane into single units

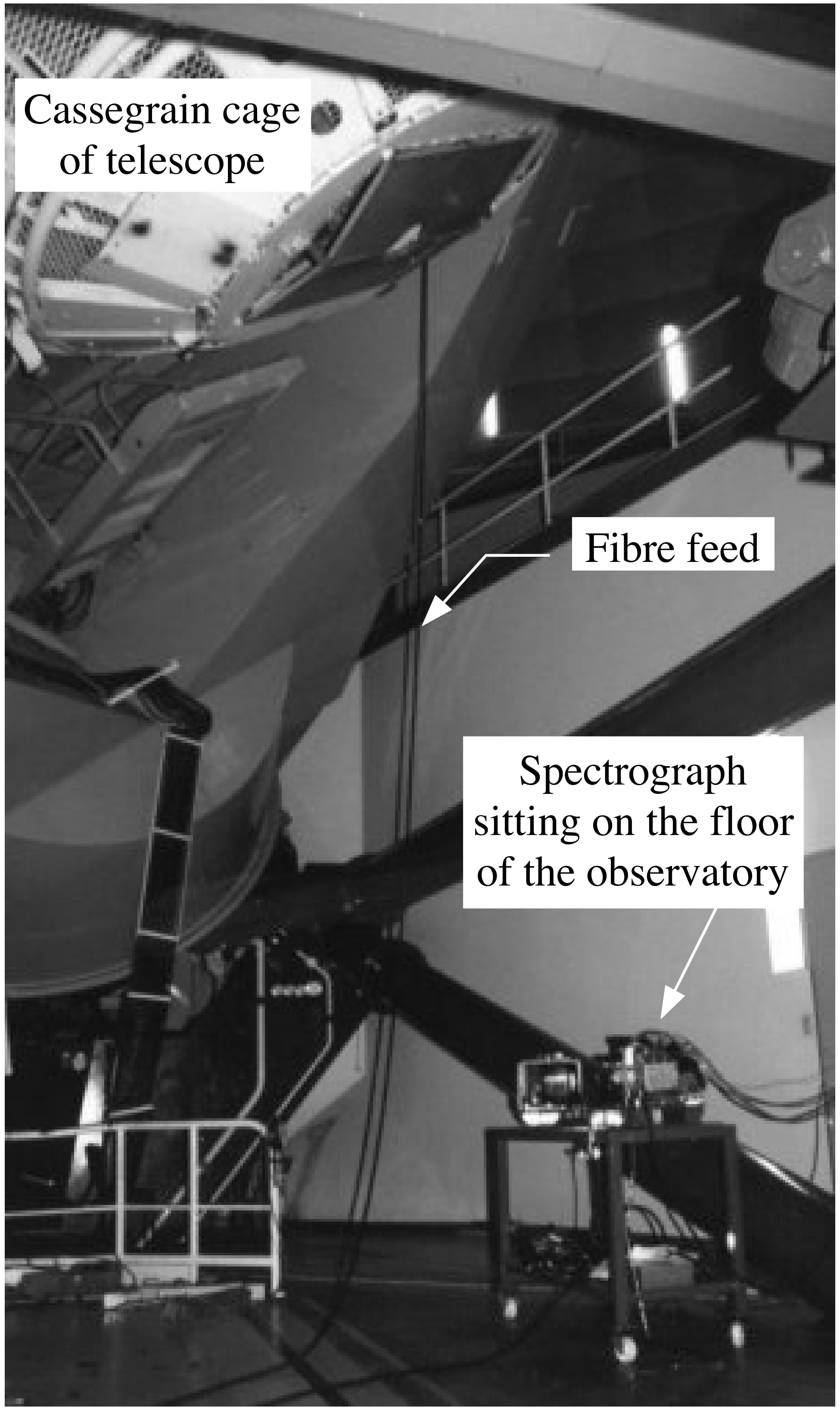


Fibers take light from telescope focus to the spectrograph

Spectrograph disperses the light

Spectrograph can sit on floor of the observatory instead of at the focus





Optical Fibre

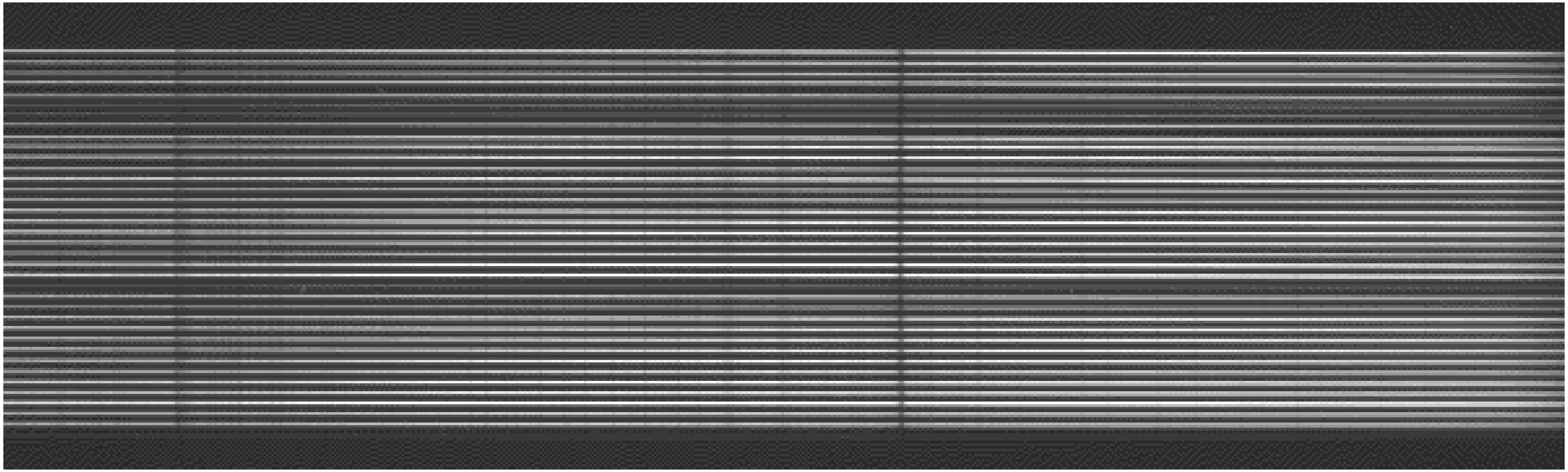


Figure 6-1 *A raw IFS data frame*. In this data frame from SPIRAL the dispersion axis is across the page and the 37 separate fibre tracks can be seen. This is a twilight sky exposure, clearly showing absorption features in the atmosphere and the variation in throughput between fibres.

Hexagonal lenslets on the sky

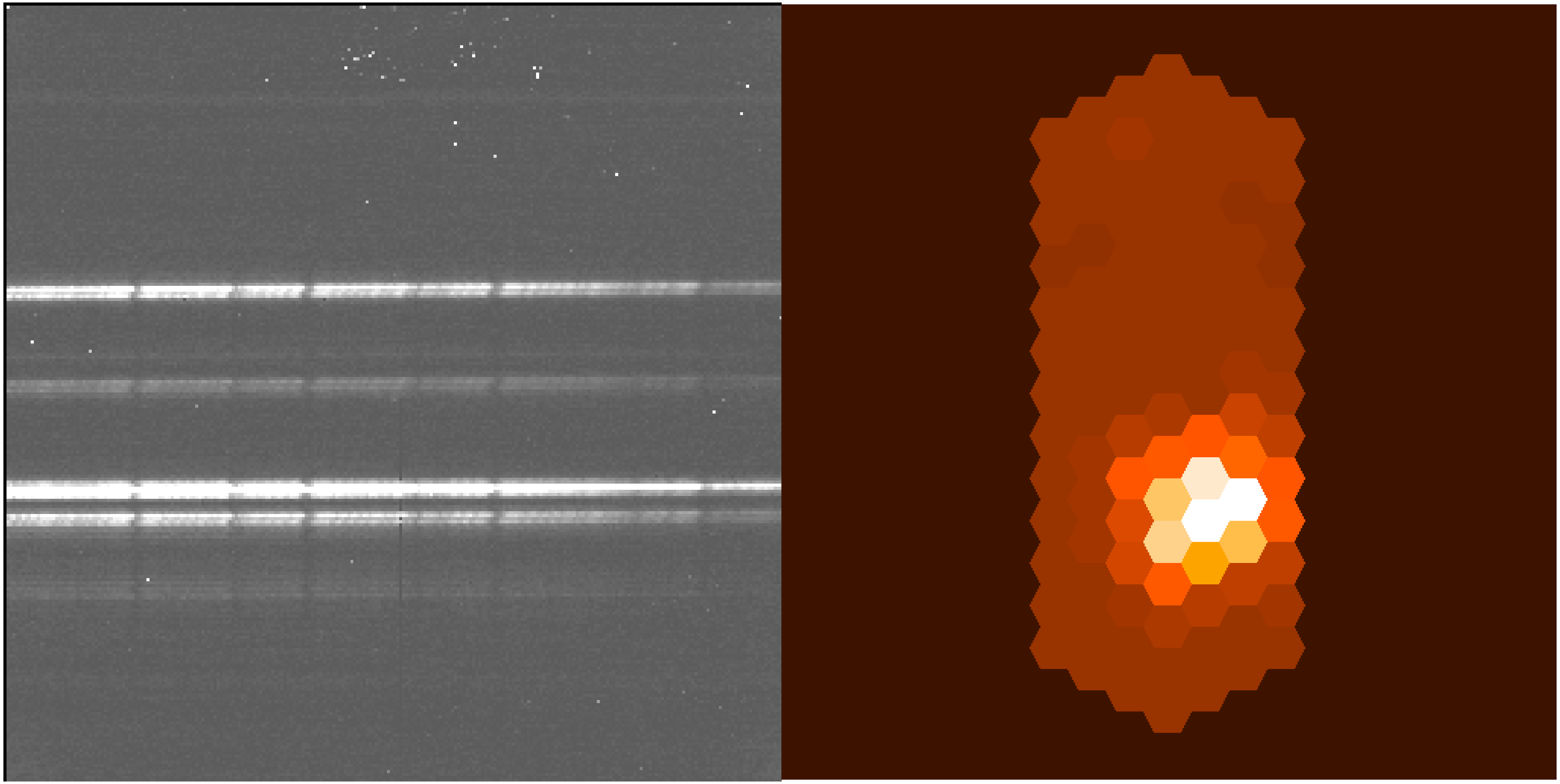
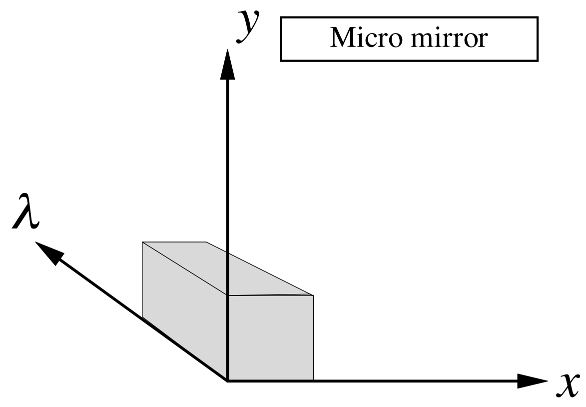


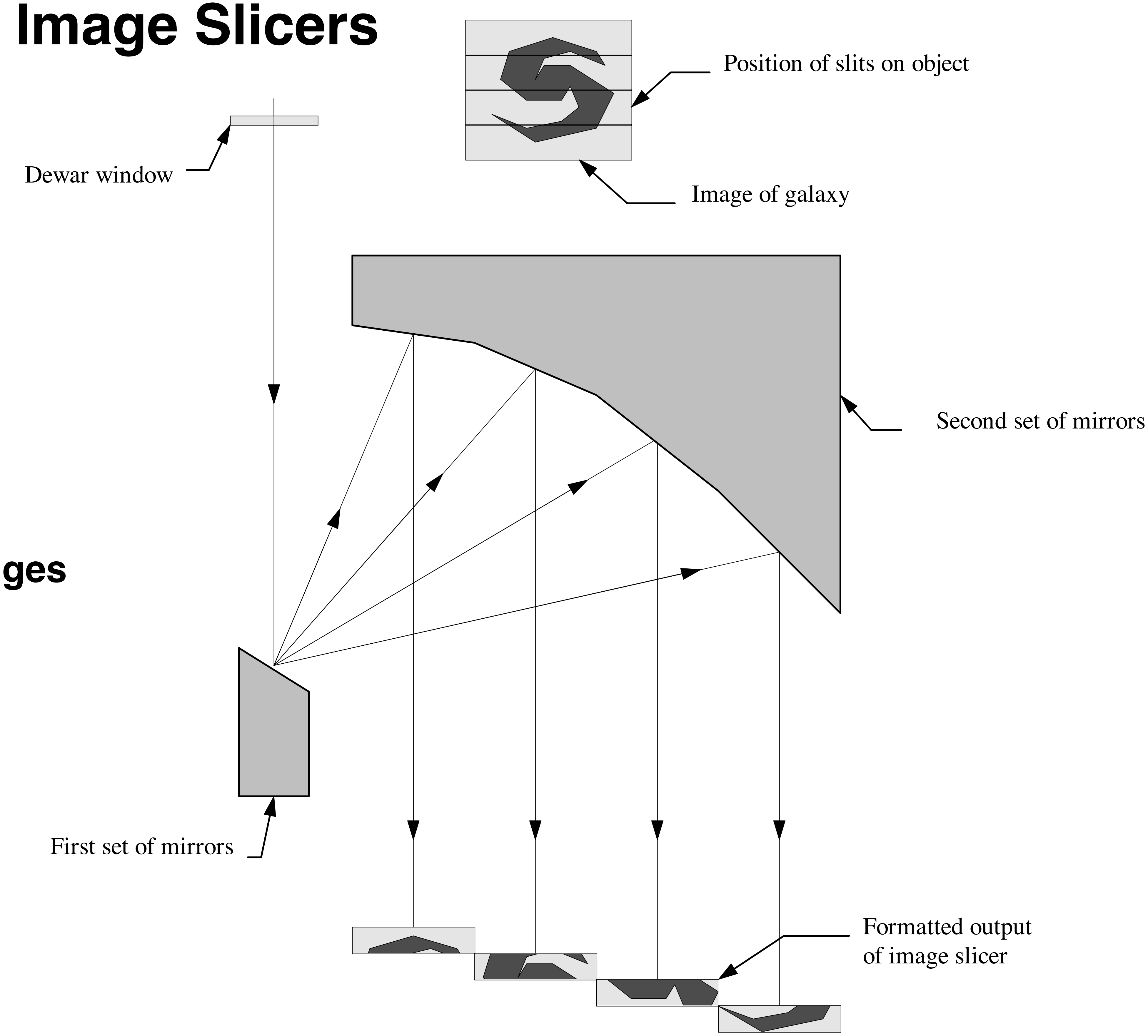
Figure 9-1 *Image reconstruction using the LDISPLAY software*. The image of the left is a raw image from the COHSI spectrograph. By knowing the relation between fibres on the sky and fibres in the slit an image can be reconstructed (right-hand panel).

Image Slicers

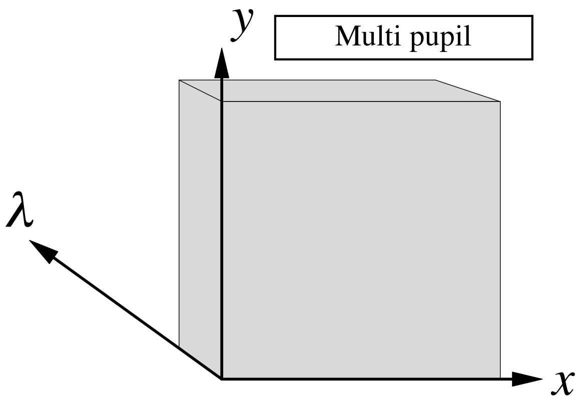


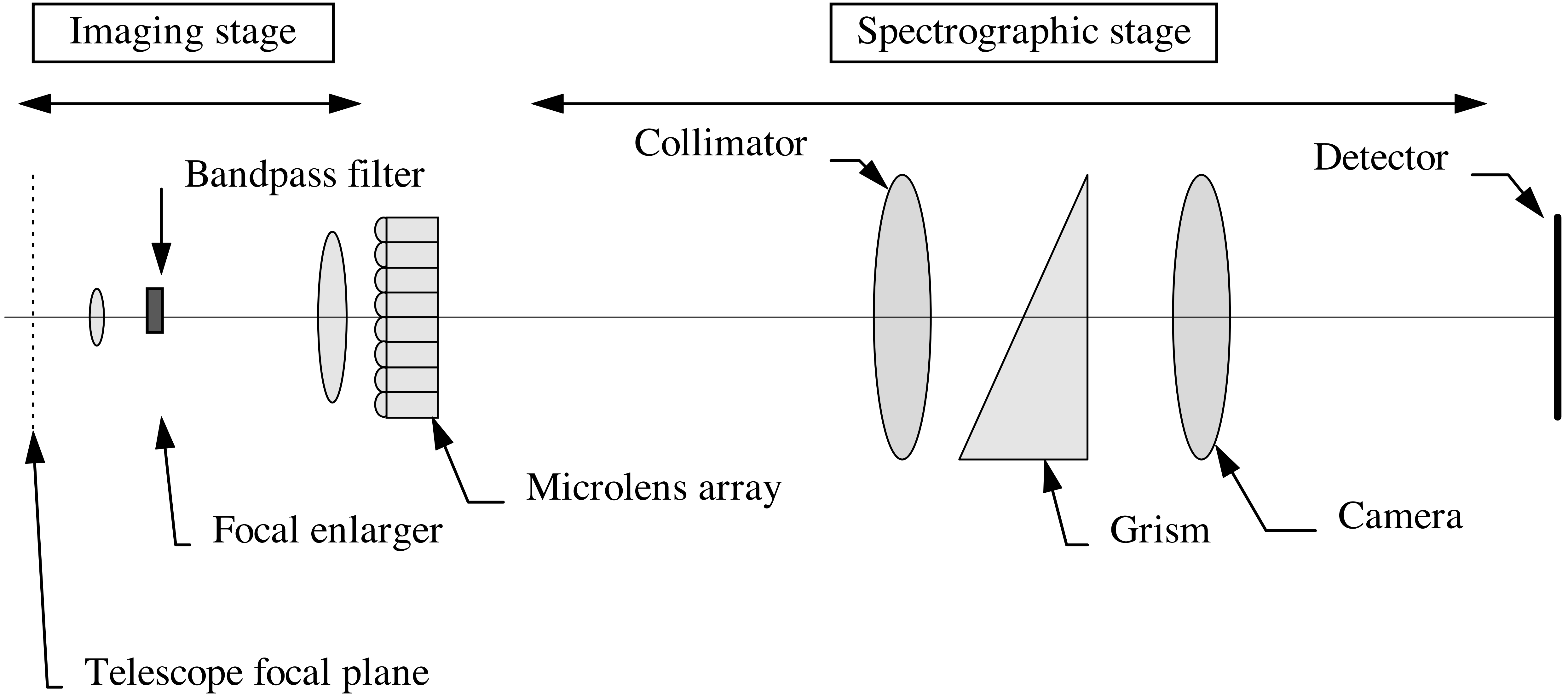
Small field of views

Large wavelength ranges



Multi pupil reimagers

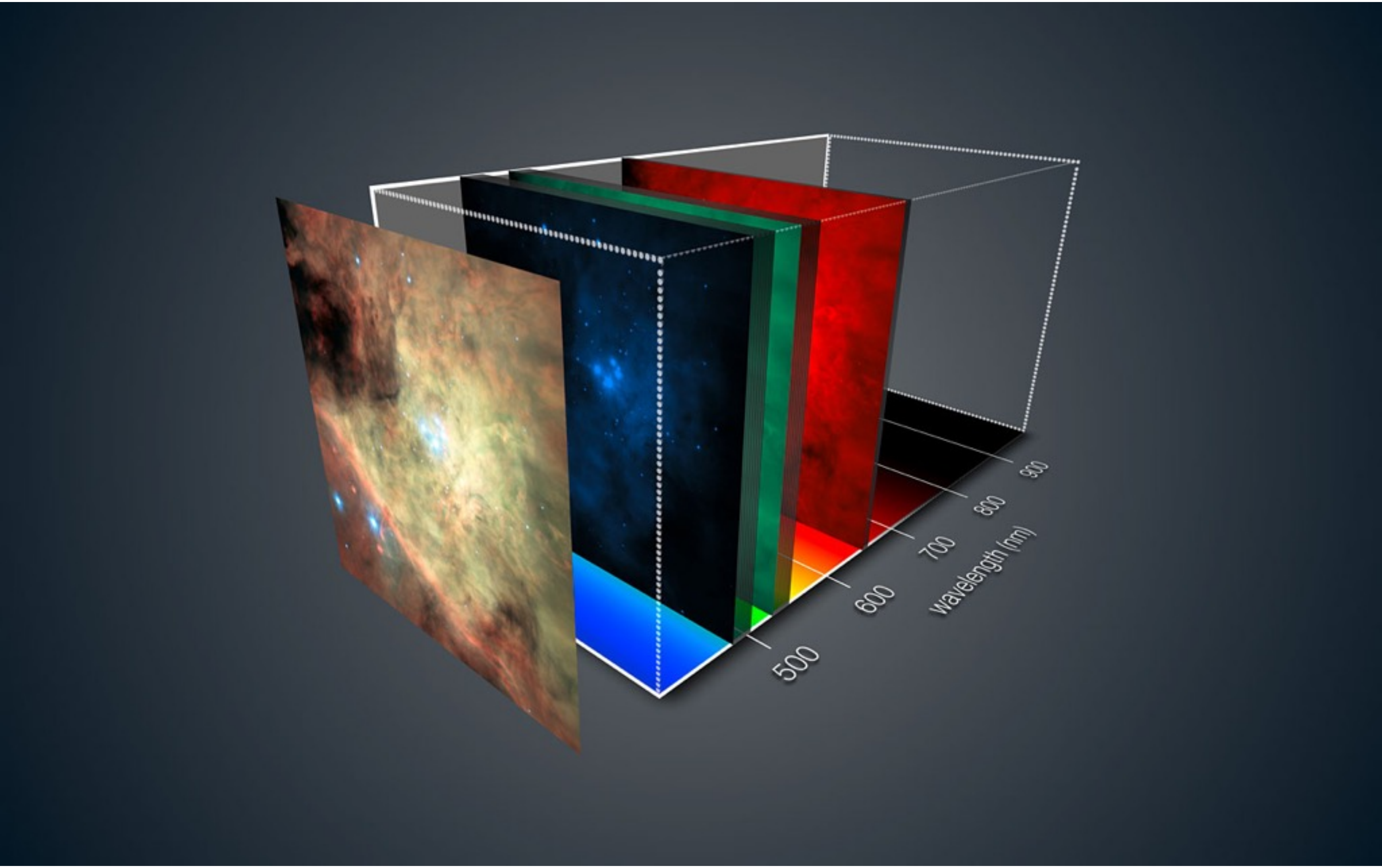




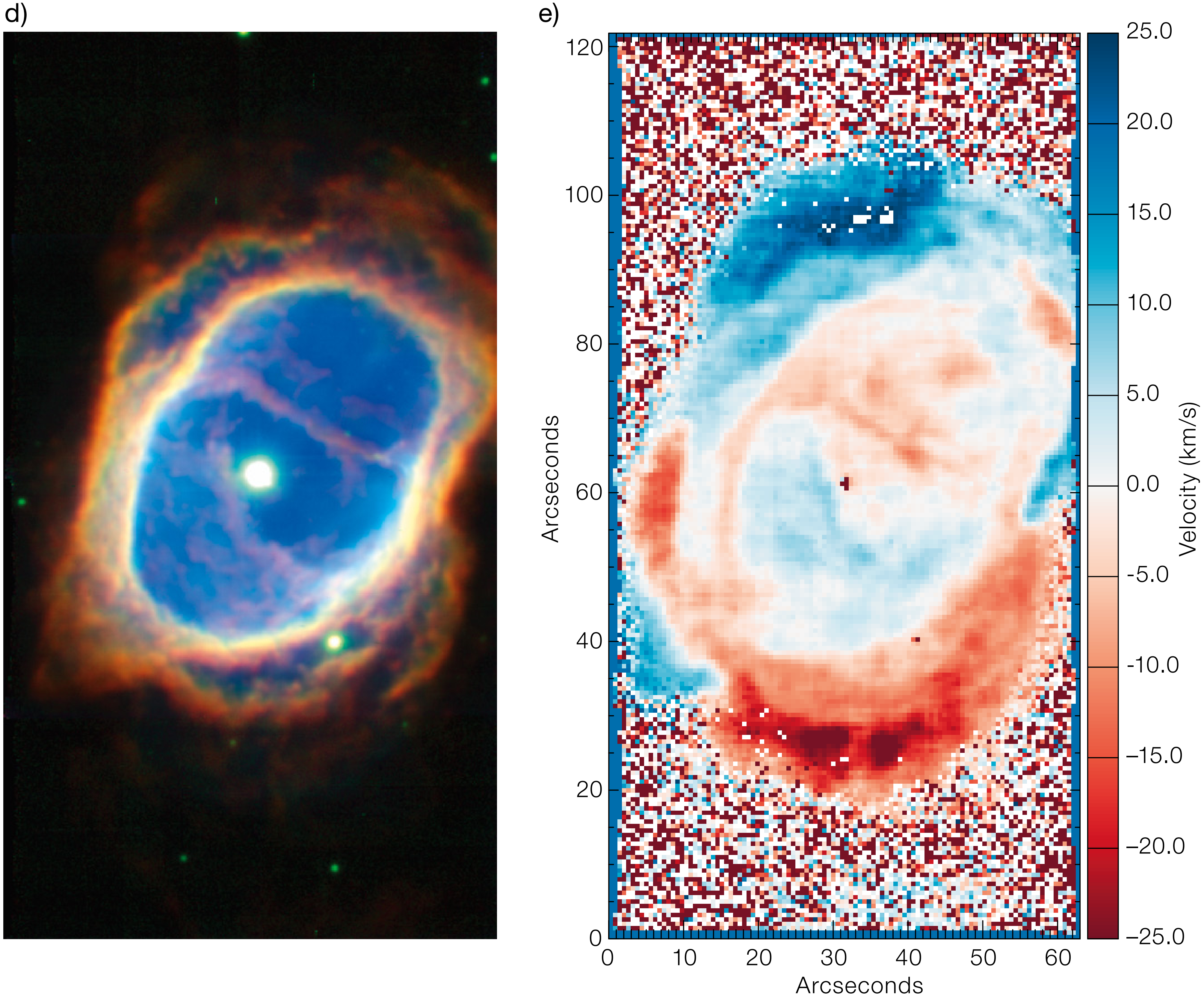
Microlenslet array cuts focal plane into tiny images

Disperse these images into short spectra -> limited wavelength range

MUSE on VLT - 24 Integral Field Spectrographs

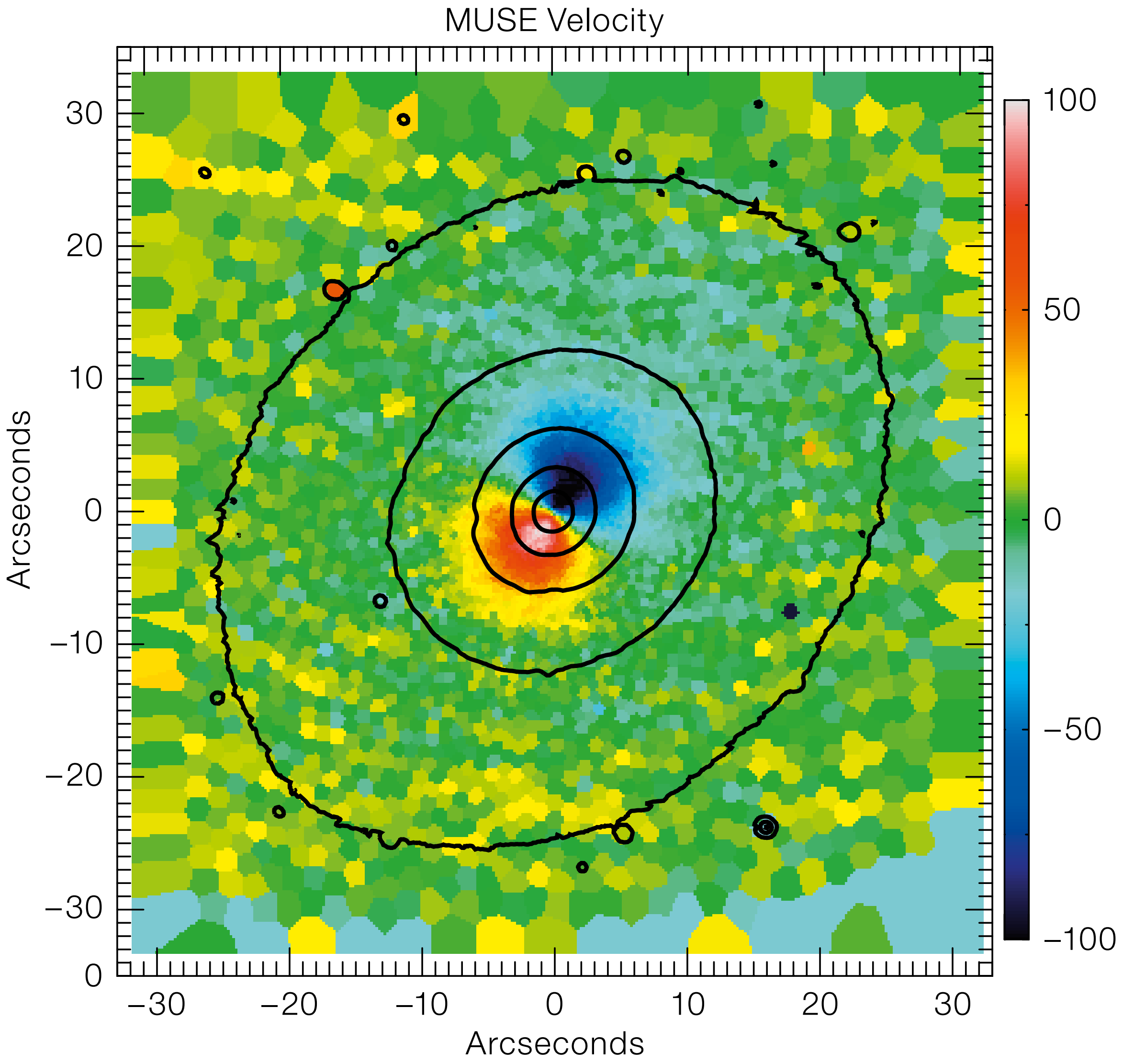


MUSE velocity fields

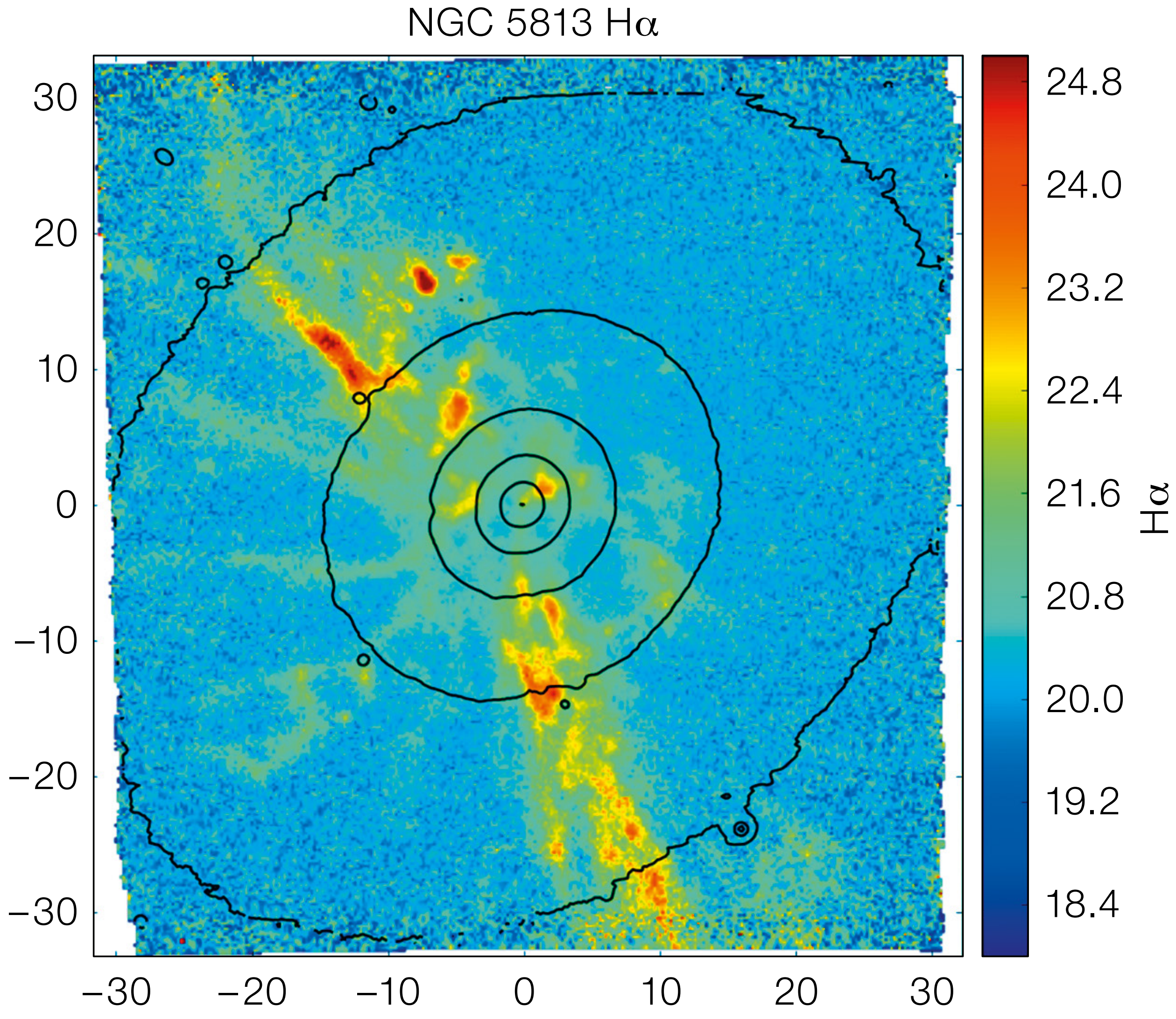


Complete wavelength coverage gives both abundances, velocity fields of different species of atomic transition

f)



g)



MUSE on VLT - 24 Integral Field Spectrographs