Astronomical Telescopes and Instruments 2020

Lecture 10: Spectrographs

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Online Expectations

- Lecture as a whole is not being recorded
- Slides in PDF format and videos will be available after the lecture
- PDFs include quizzes with correct answers shown in green
- Mute your microphone
- Camera on or off: your choice
- When you have questions:
  - Please write them in the room chat
  - Questions will be answered at the end of each lecture block

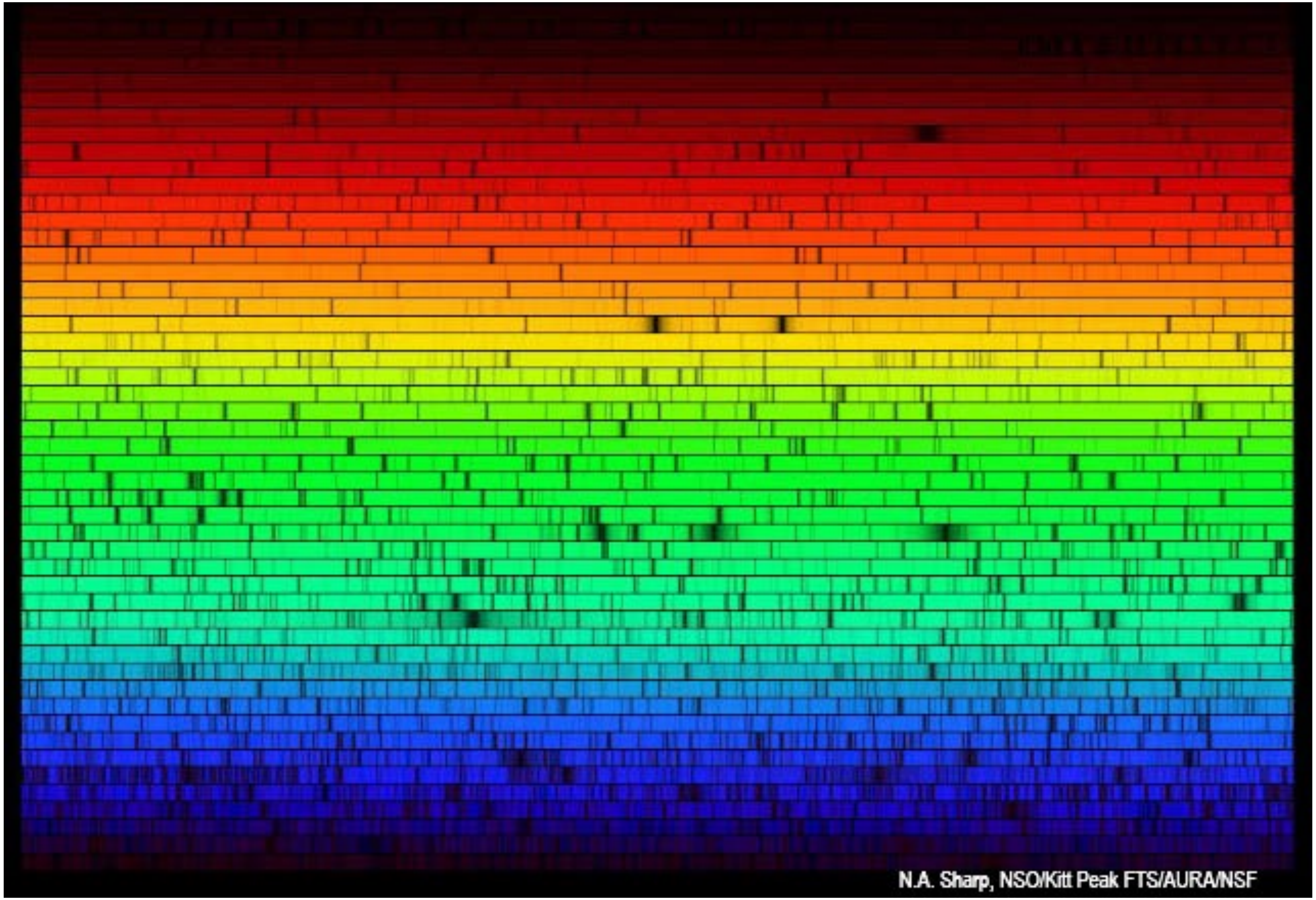
Lecture 10 Videos

- 3.1 Diffraction
- 3.2 Fraunhofer Diffraction
- 3.3 Transfer Functions
- 3.4 Coherence and Interference

Lecture 10: Spectrographs

10.1 Filters and basic spectrographs

The Solar Spectrum



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

Radial Velocity exoplanets

10^5

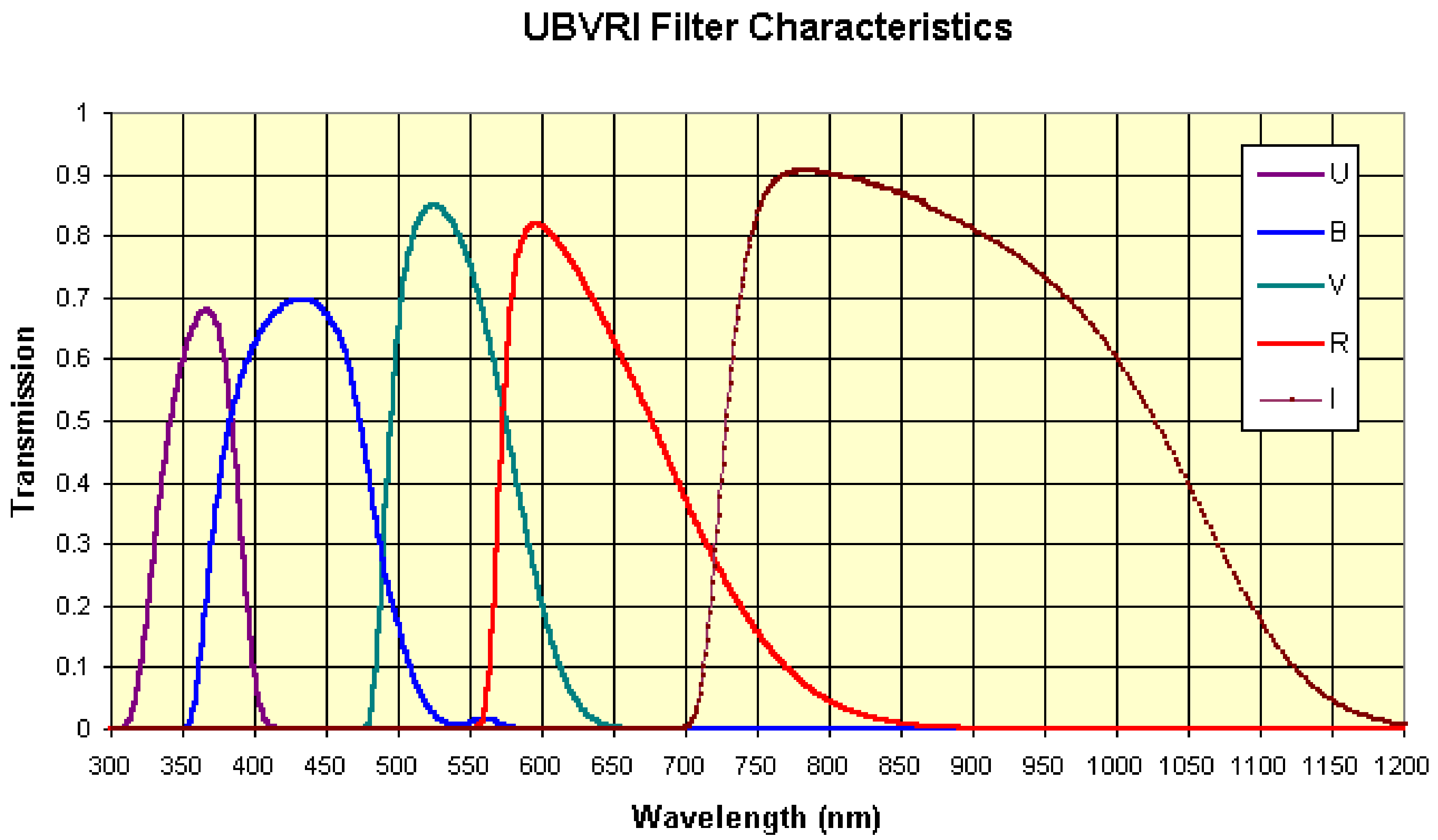
ISM studies

Isotope abundances

10^6

exoplanet rotation curves

Basic spectroscopy: colour filters



www.sbig.com/products/filters.htm

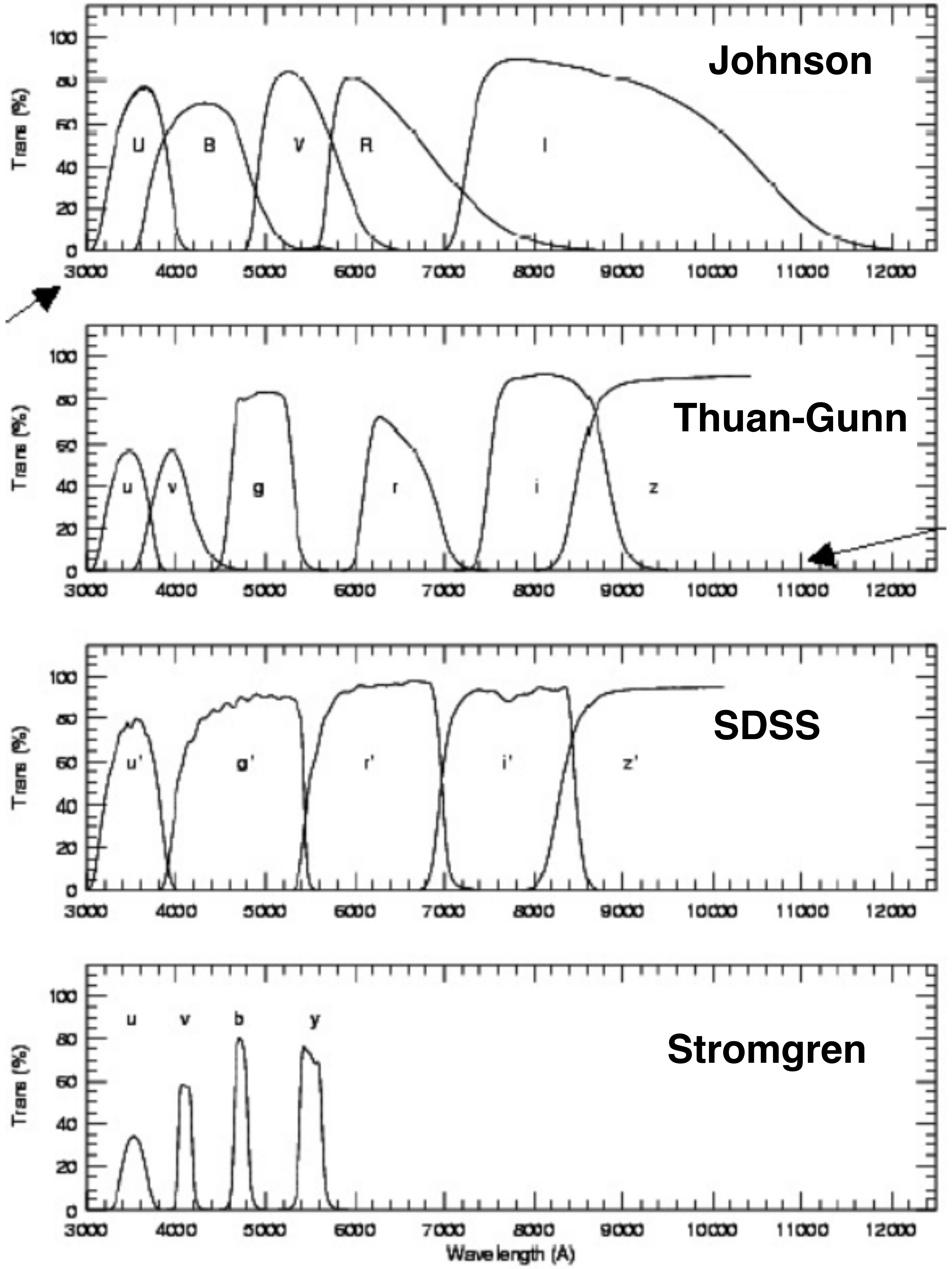
VRIJKLMNQ by Johnson (1960)

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

Basic spectroscopy: colour filters



measures properties of stars

used for galaxy observations

Faint galaxy classification

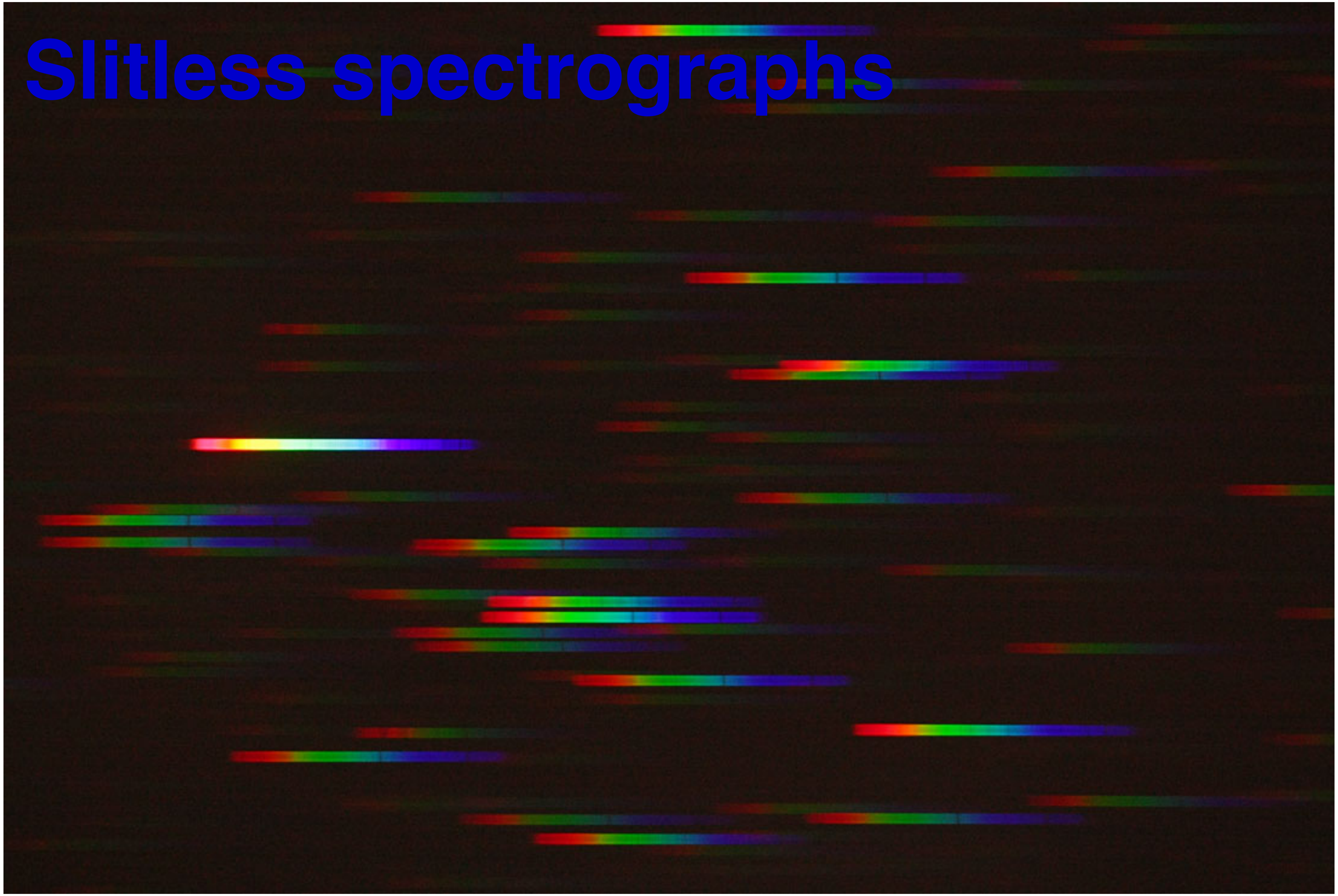
Sensitivity to stellar properties - metallicity, temperature, surface gravity

Slitless spectrographs

Put a dispersing element in front of the telescope aperture

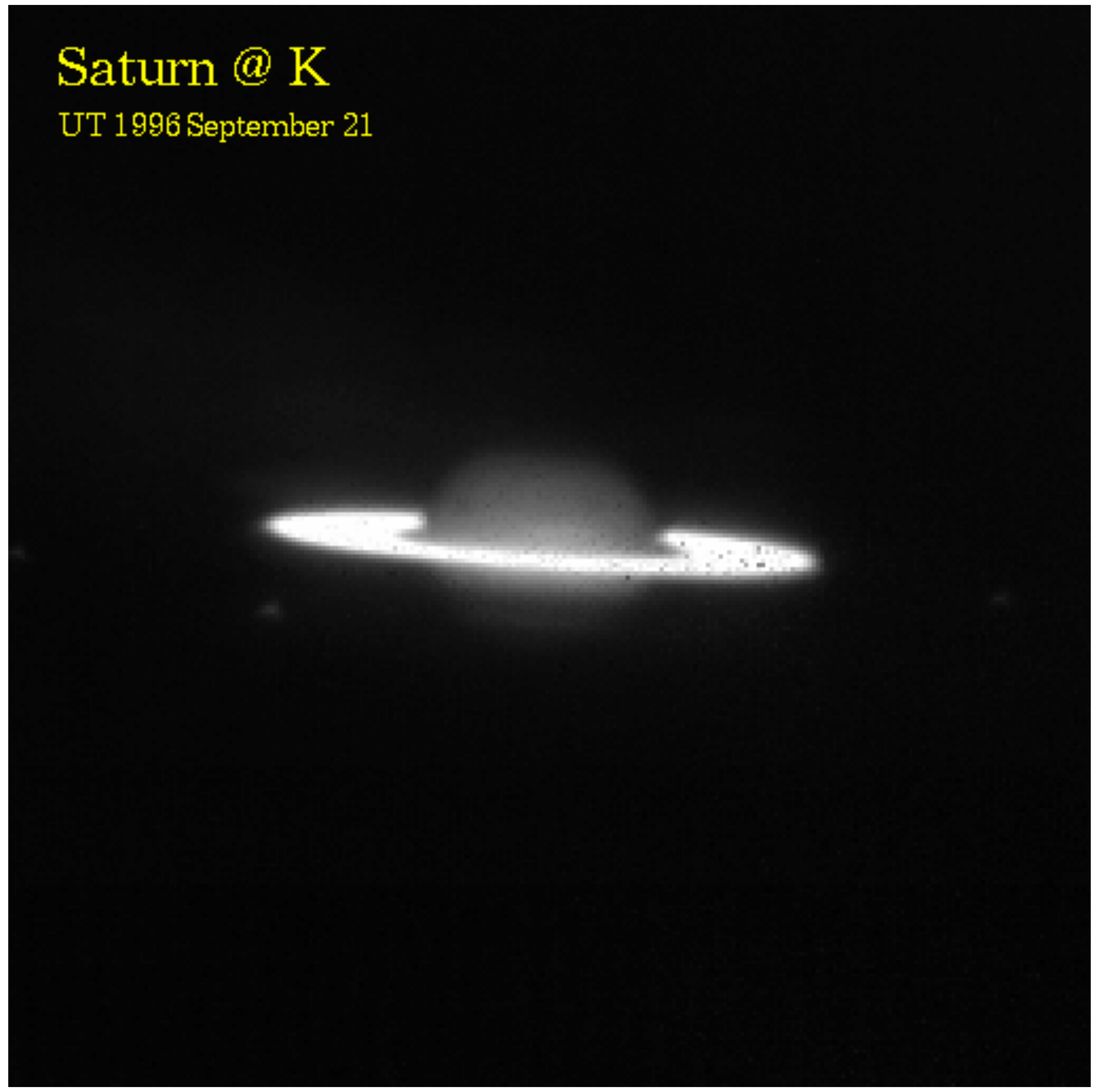
http://www.lpl.arizona.edu/~rhill/

Slitless spectrographs

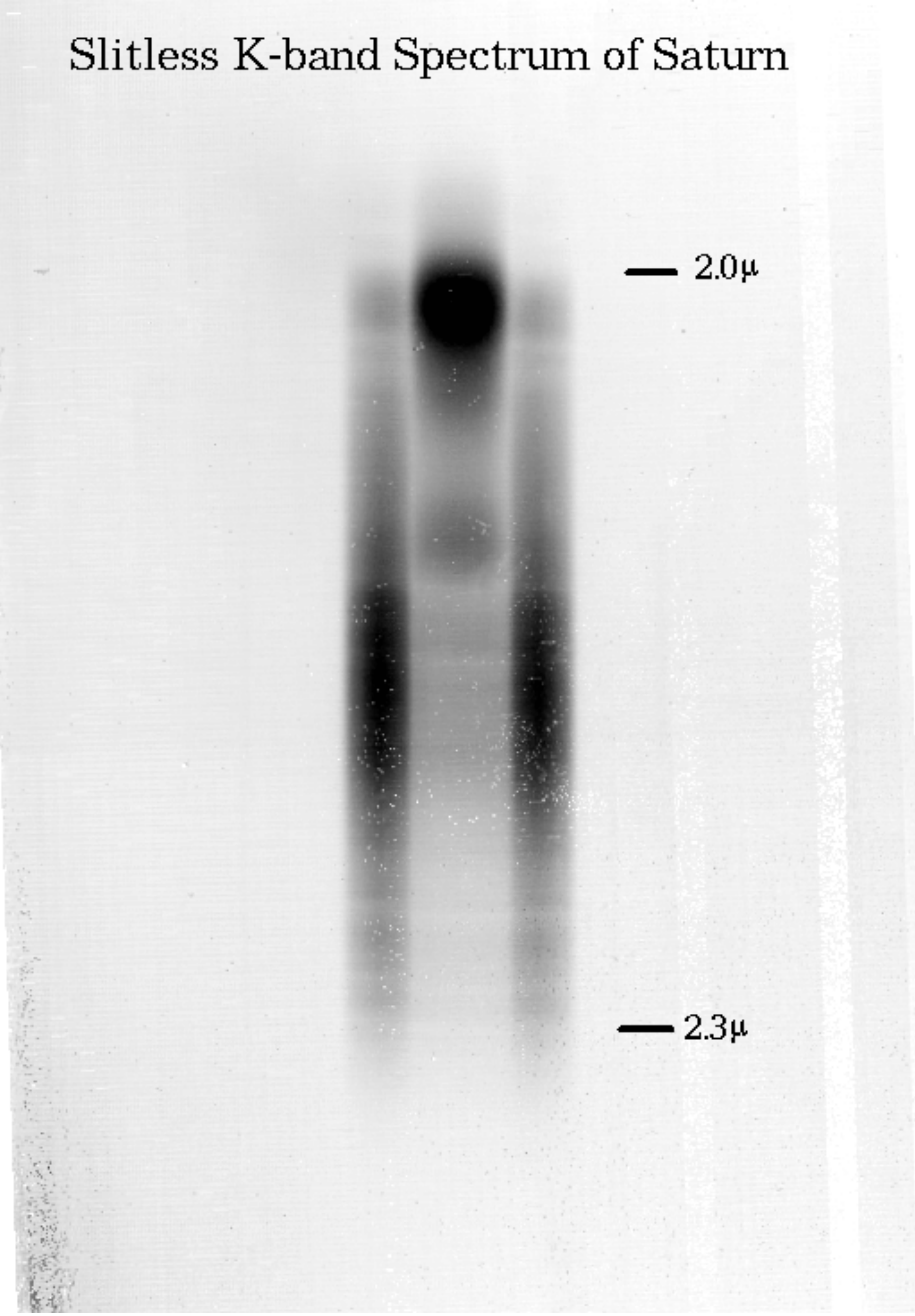


http://theketelsens.blogspot.nl/2011/01/seeing-light.html

Slitless spectrographs



Dispersed

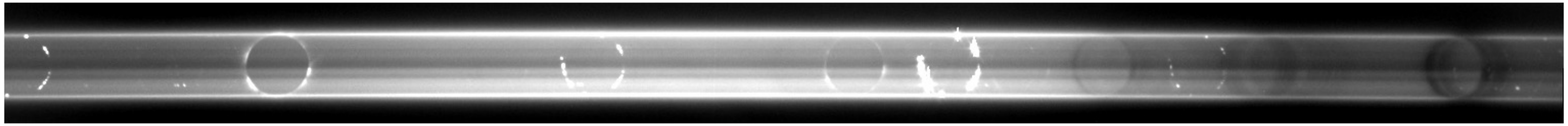


R. Pogge (OSU) with NOAO 2.1m Telescope

Slitless spectrographs

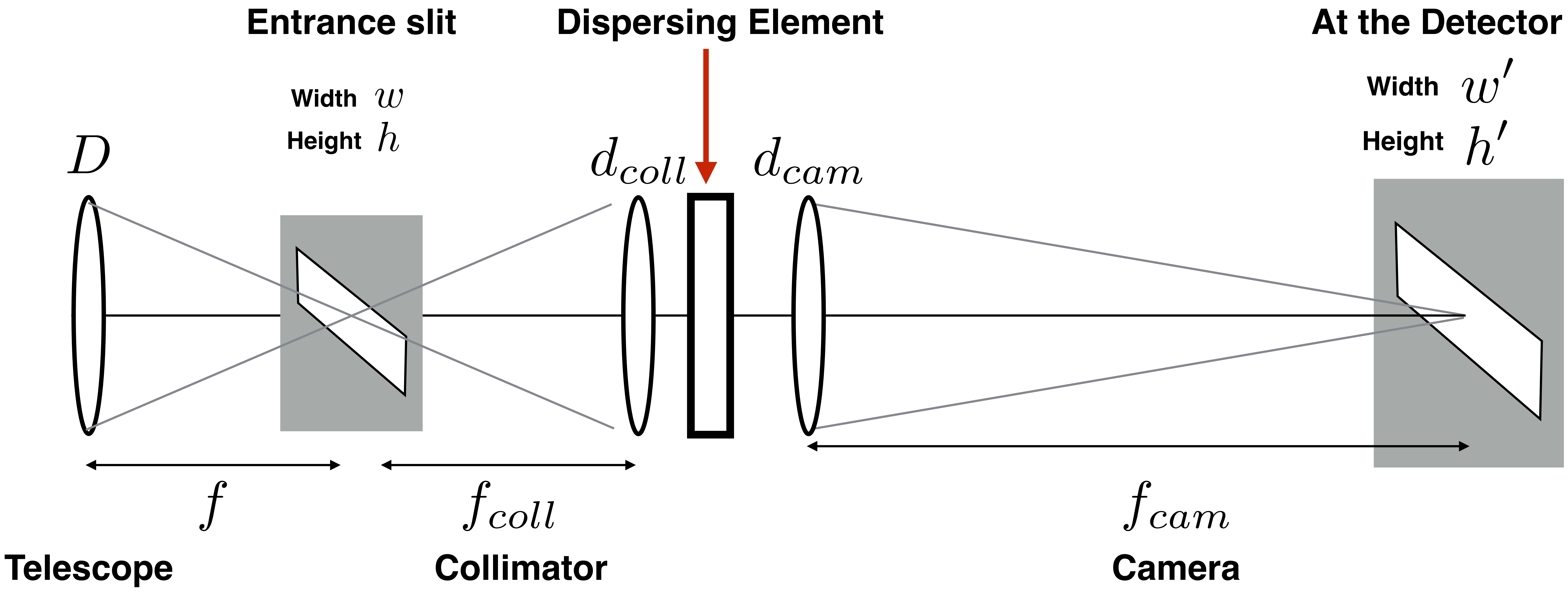
http://www.astro.virginia.edu/class/majewski/astr313/lectures/spectroscopy/spectrographs.html

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



Wavelength

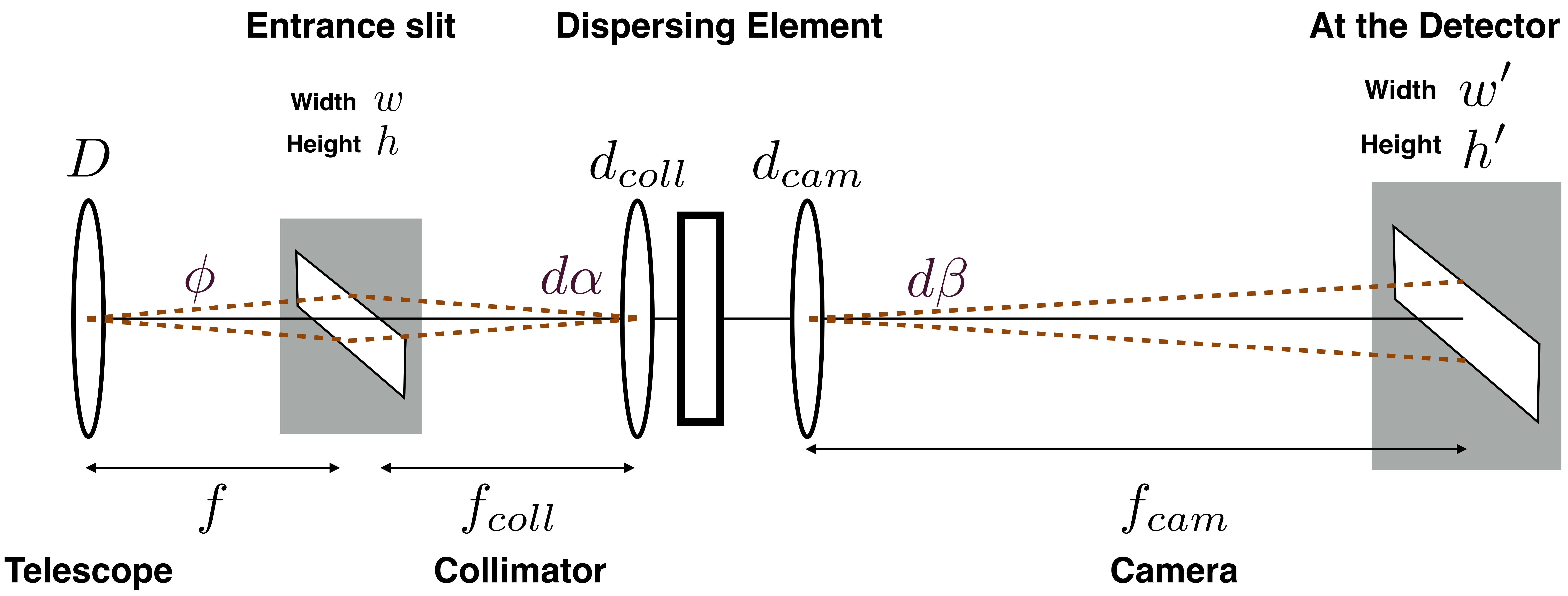
Layout of a spectrograph: linear dimensions



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

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

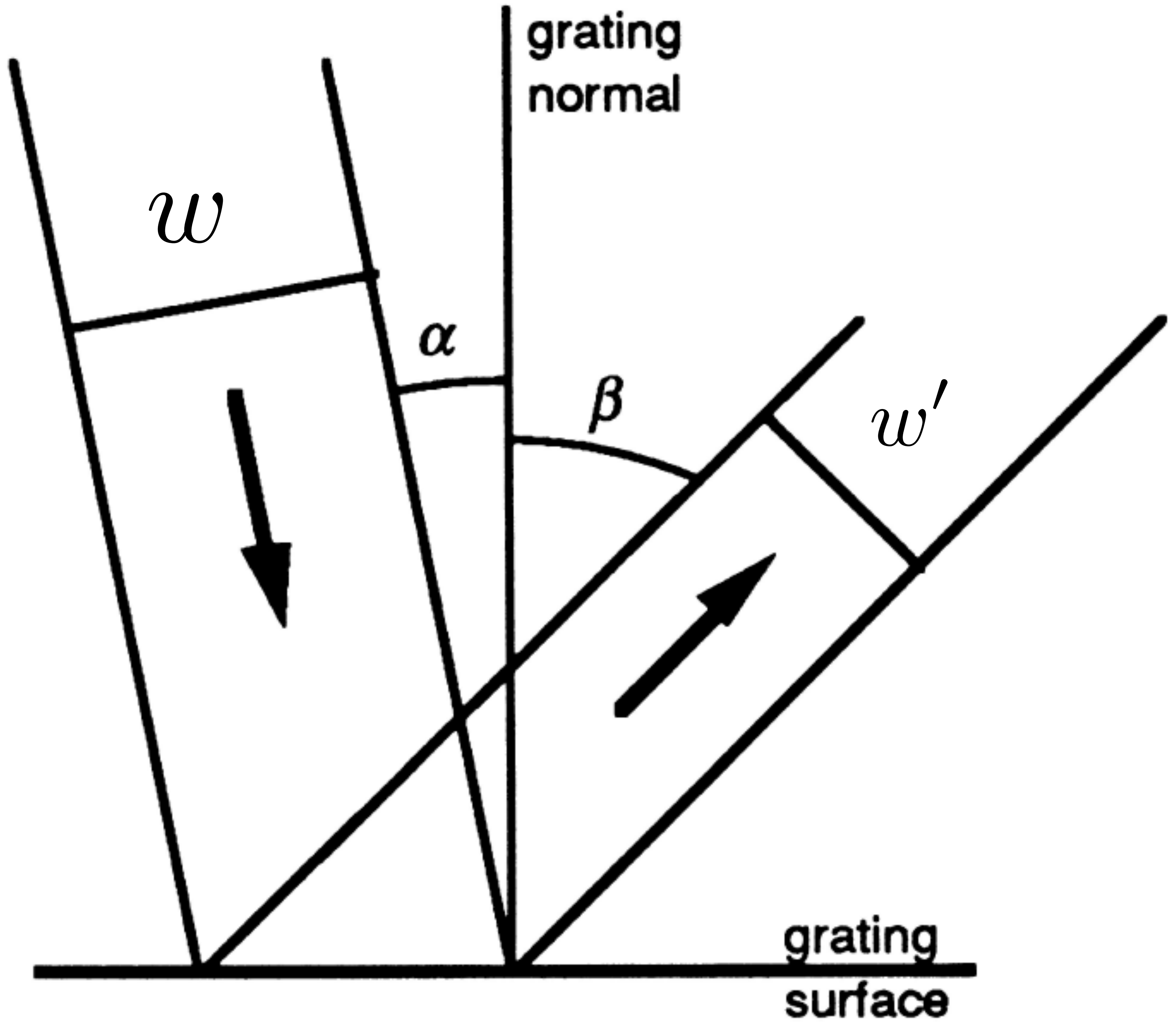
Layout of a spectrograph: angular sizes



Anamorphic magnification means that magnification along mutually perpendicular radii is different

$$\frac{w}{h} \neq \frac{w'}{h'}$$

Anamorphic magnification



- **The incoming beam perpendicular to this image remains the same height, but the width of the beam w is dispersed into a new direction with width w'.**
- **Anamorphic factor** $r = \frac{w'}{w}$
- **Littrow and VPH are r=1**

https://nickkonidaris.com/2014/10/17/anamorphic-factor/

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 $\text{Å}/\text{mm}$.

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:

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

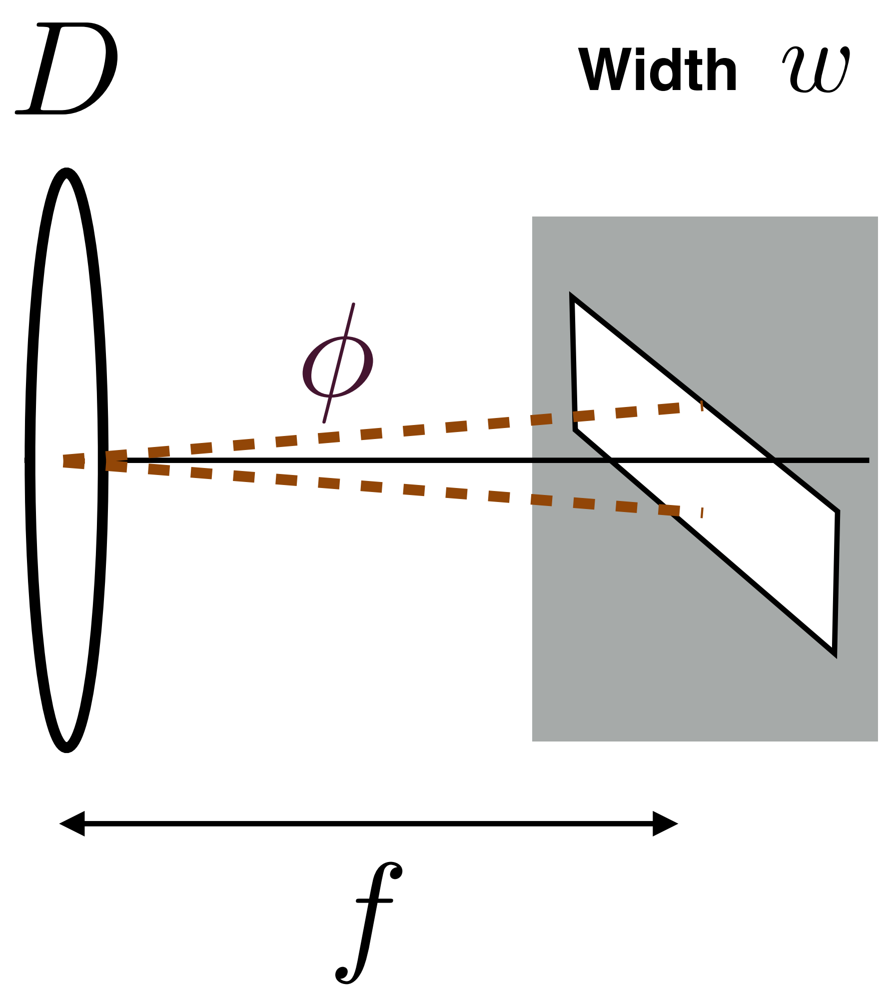
Slit too narrow, flux from seeing limited object is lost

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

Relating slit size and image size on detector

The size of the slit that the detector sees is therefore given by:

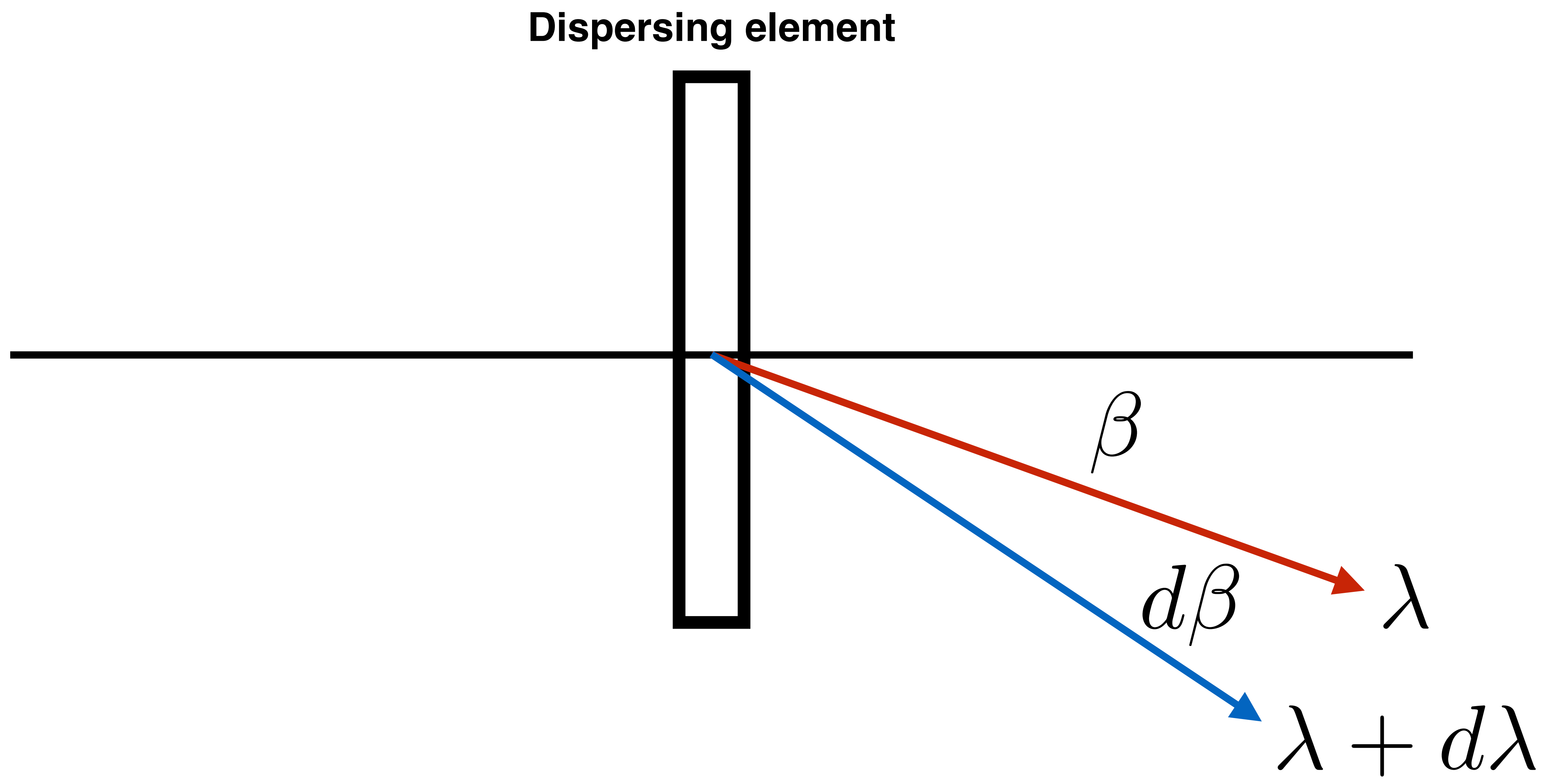
$$w' = rw\frac{f_{cam}}{f_{coll}} = r\phi f\frac{f_{cam}}{f_{coll}}$$

Lecture 10: Spectrographs

10.2 Dispersing Elements

Definition of Dispersion

The angular dispersion is given by: $$A = \frac{d\beta}{d\lambda}$$

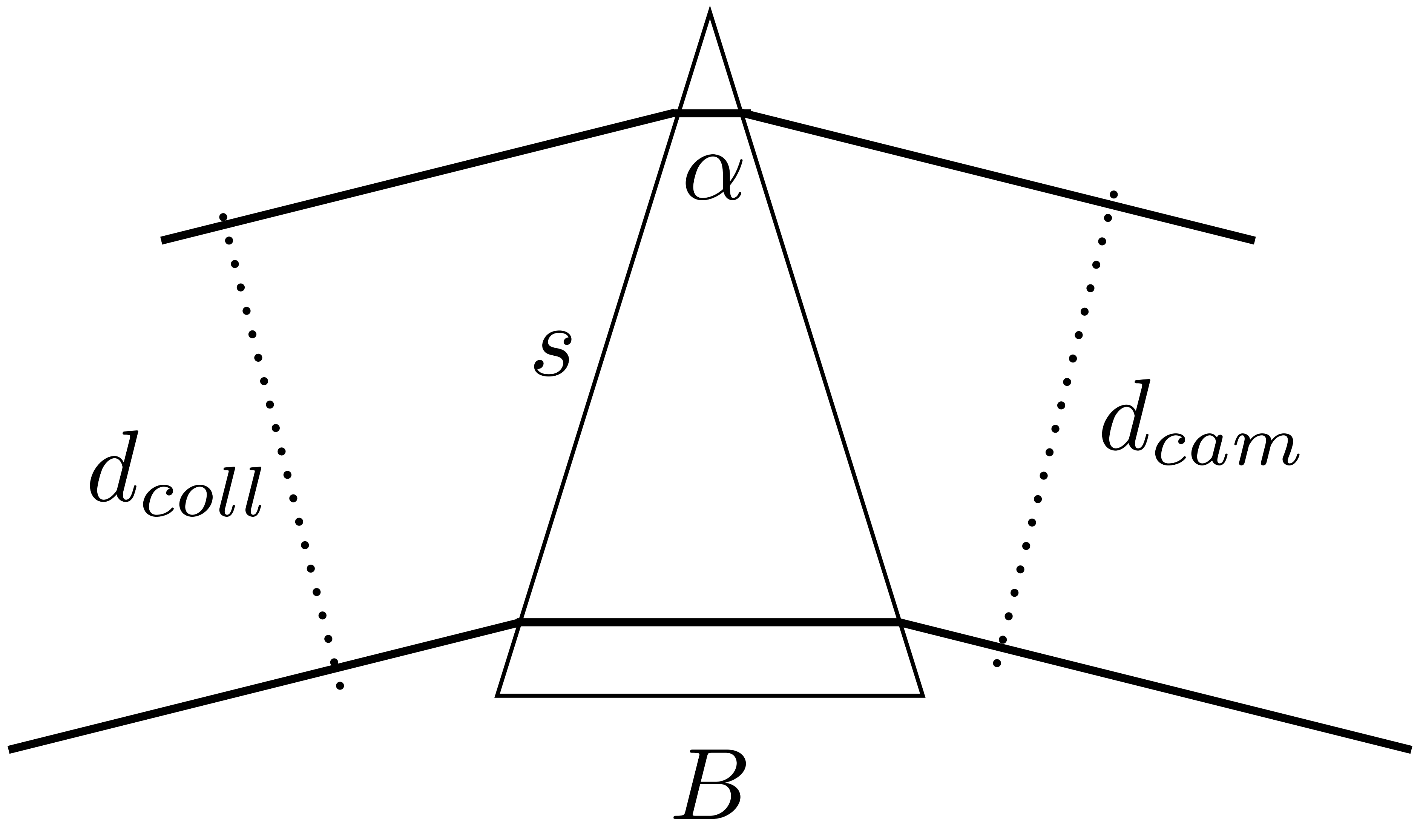


The linear dispersion is then: $$\frac{dl}{d\lambda} = f_{cam} A$$

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.

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



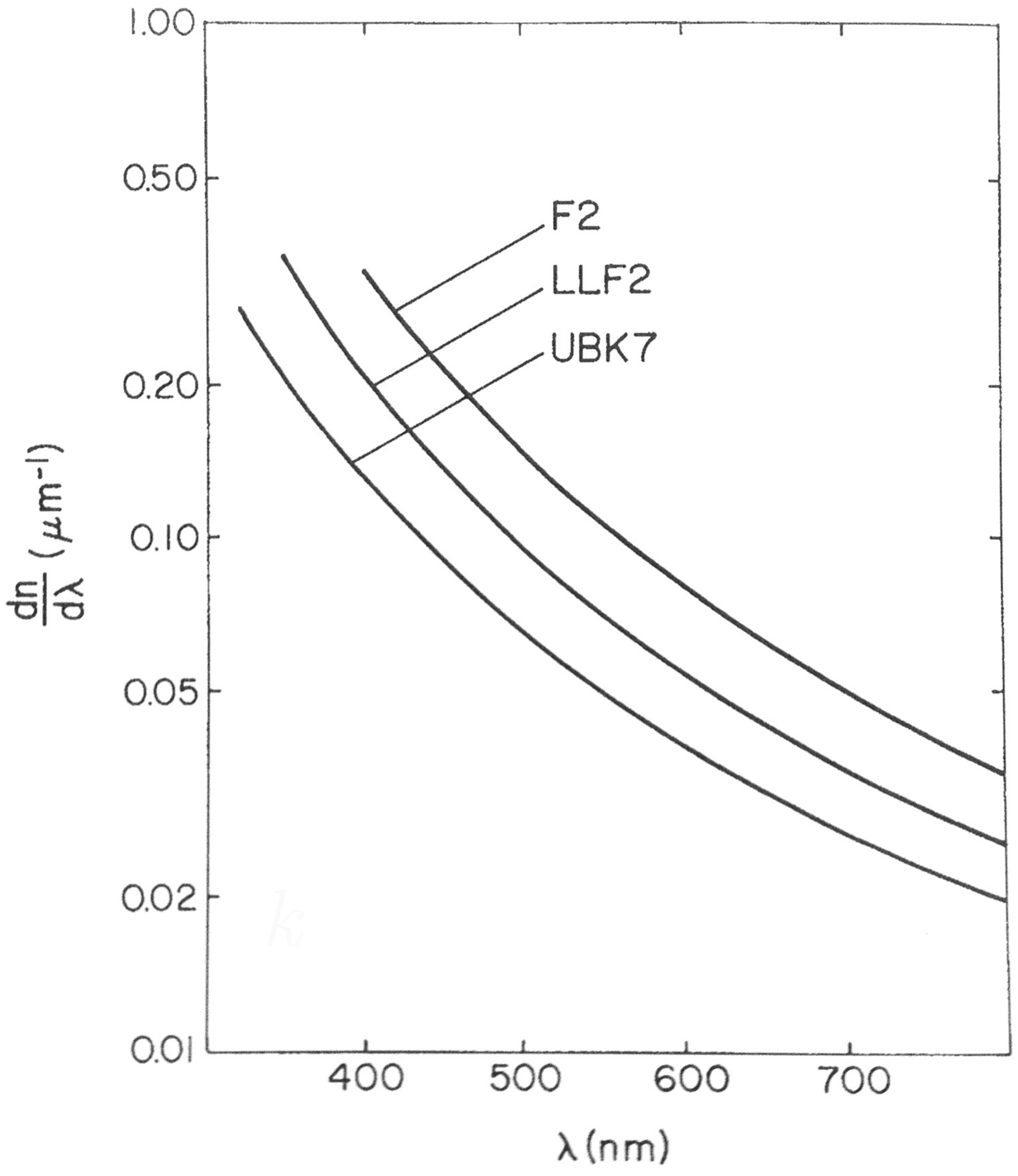
Angular dispersion changes with wavelength

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.

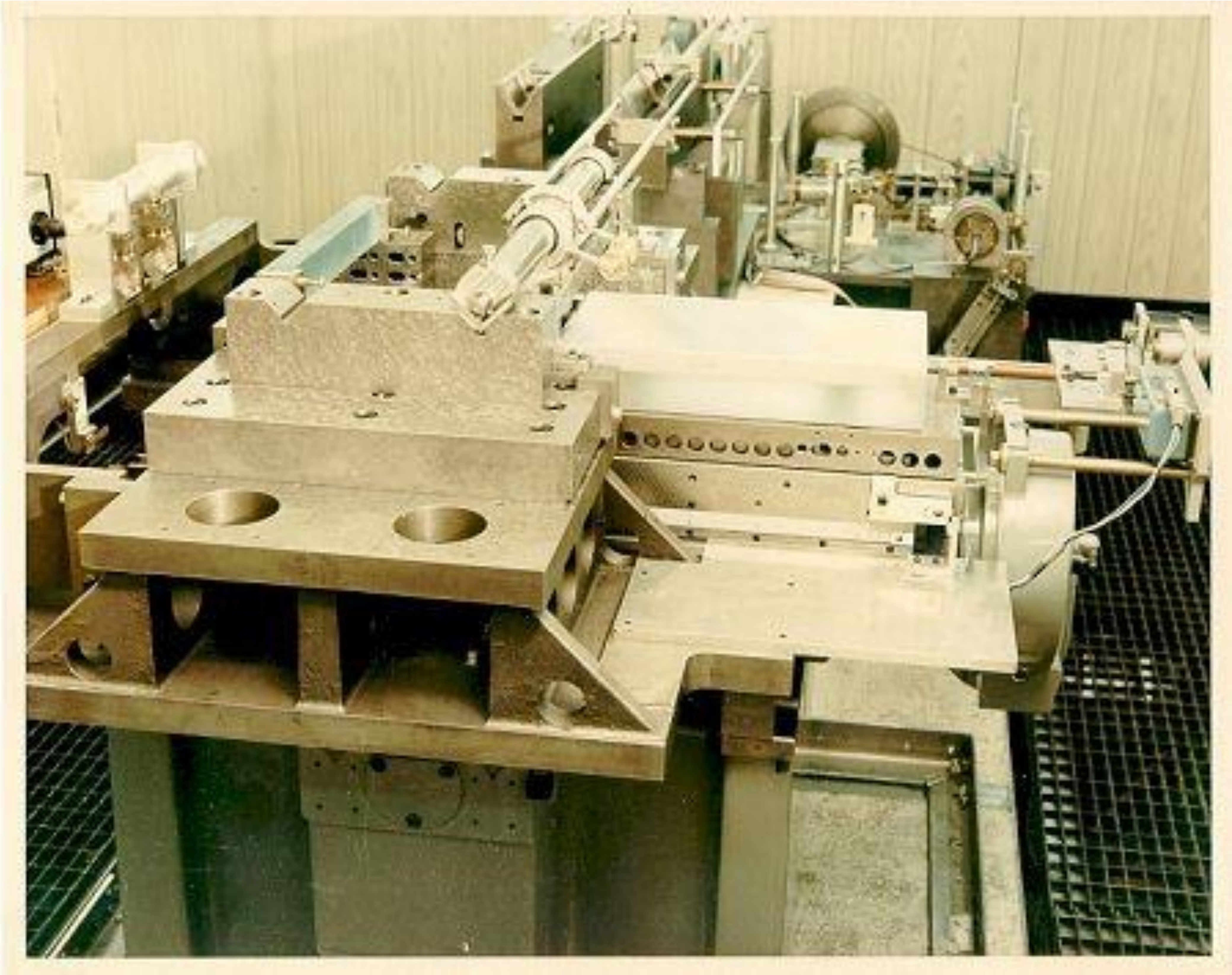
$$A = \frac{d\beta}{d\lambda} = \frac{B}{d_{cam}} \frac{dn}{d\lambda}$$



Diffraction grating

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

Manufactured using ruling engines in temperature controlled rooms



Made by David Rittenhouse in 1785

Reinvented by Frauenhofer in 1821

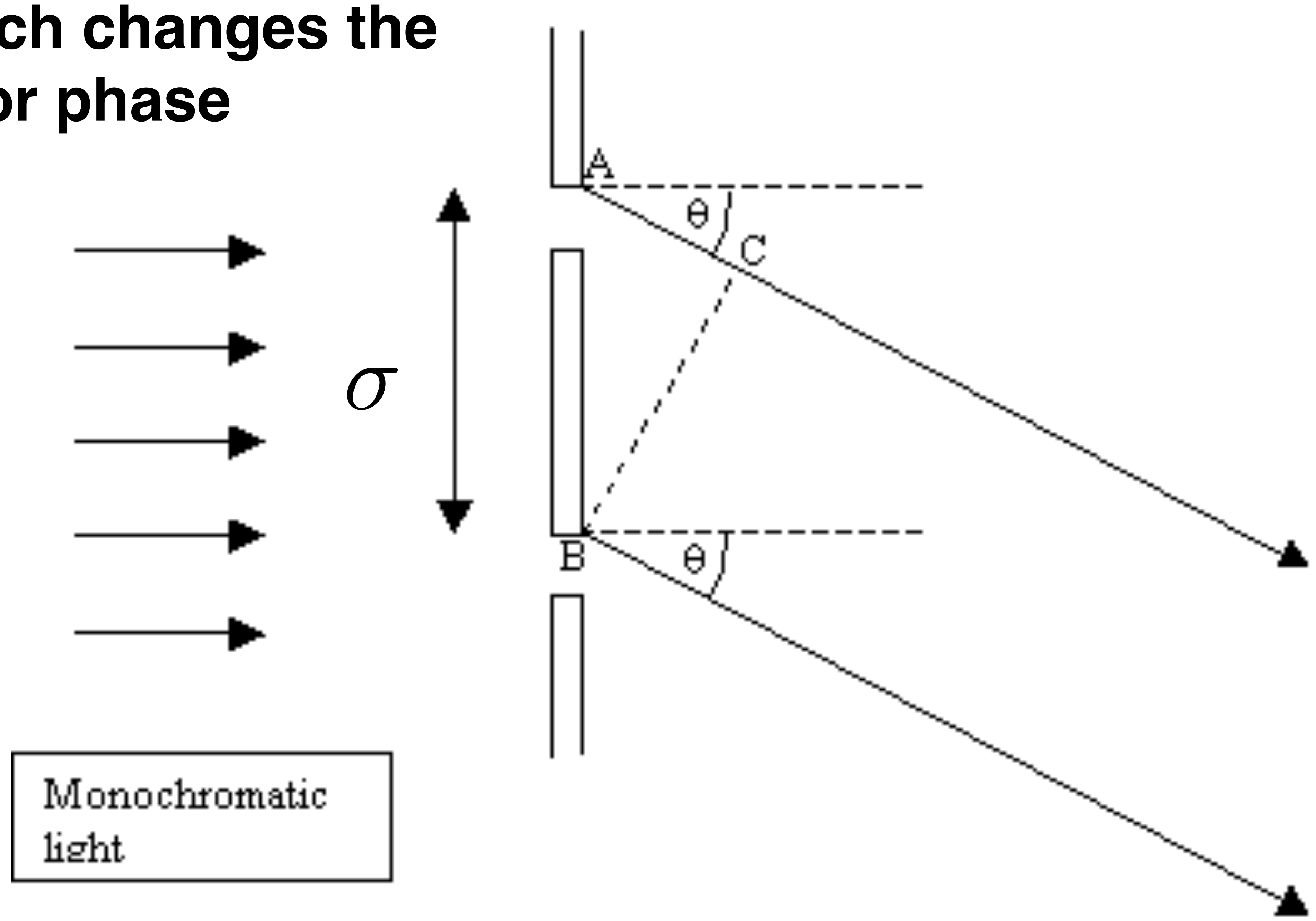
Diffraction grating

HARPS grating

Diffraction grating

$$m\lambda = \sigma \sin\theta$$

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

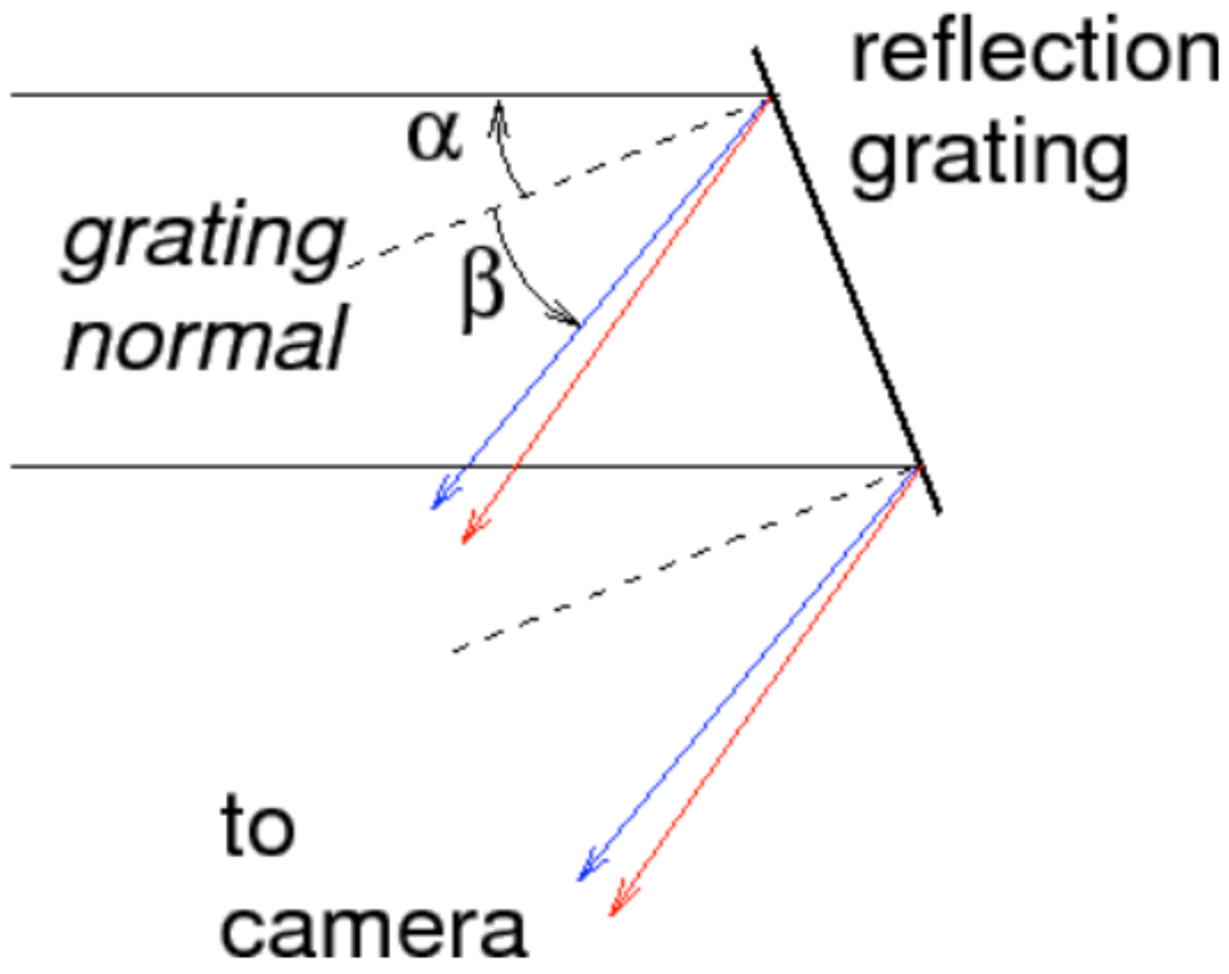


Direction of constructive interference is wavelength dependent

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)

$$m\lambda = \sigma(\sin\alpha \pm \sin\beta)$$



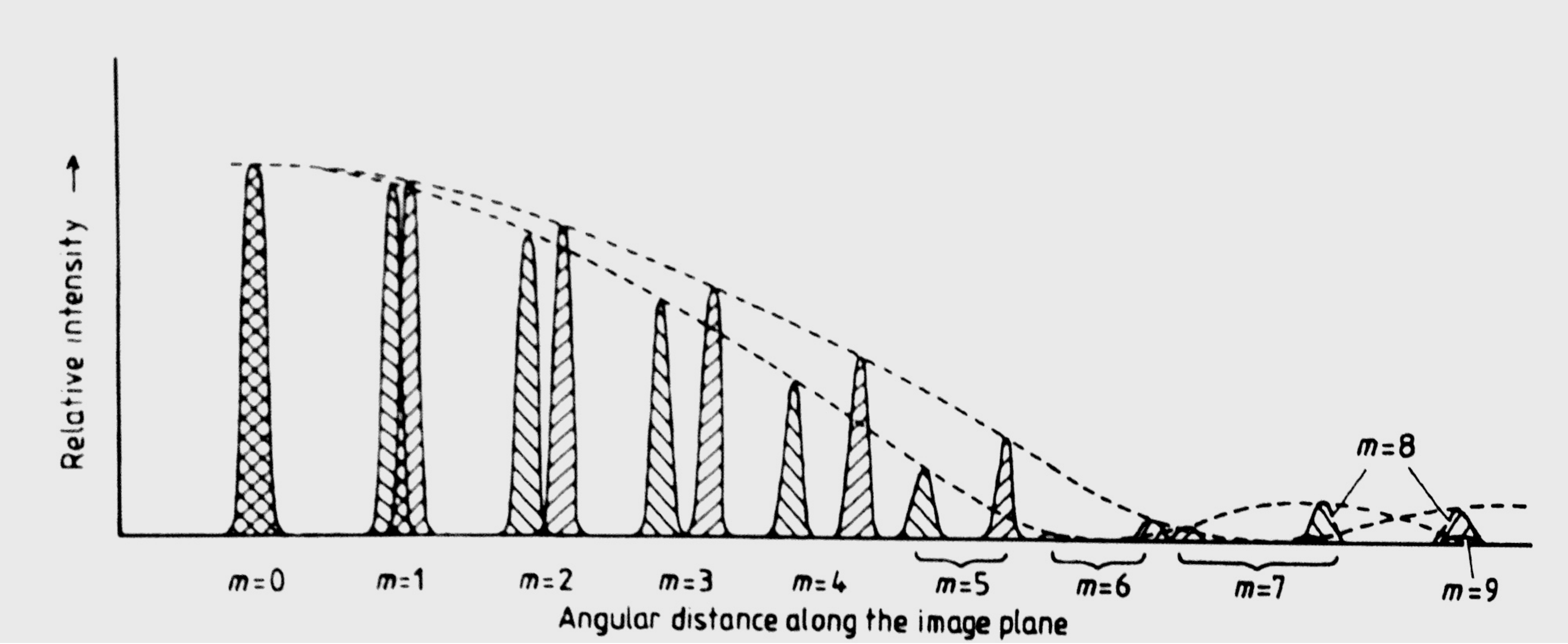
… where the sign is positive for reflection, negative for transmission

Angular dispersion $$A = \frac{d\beta}{d\alpha} = \frac{m}{\sigma\cos\beta}$$

Typically 600 lines per mm and used at 60 degrees incidence

Higher spectral orders

Higher order dispersion from the grating will result in overlapping spectra:



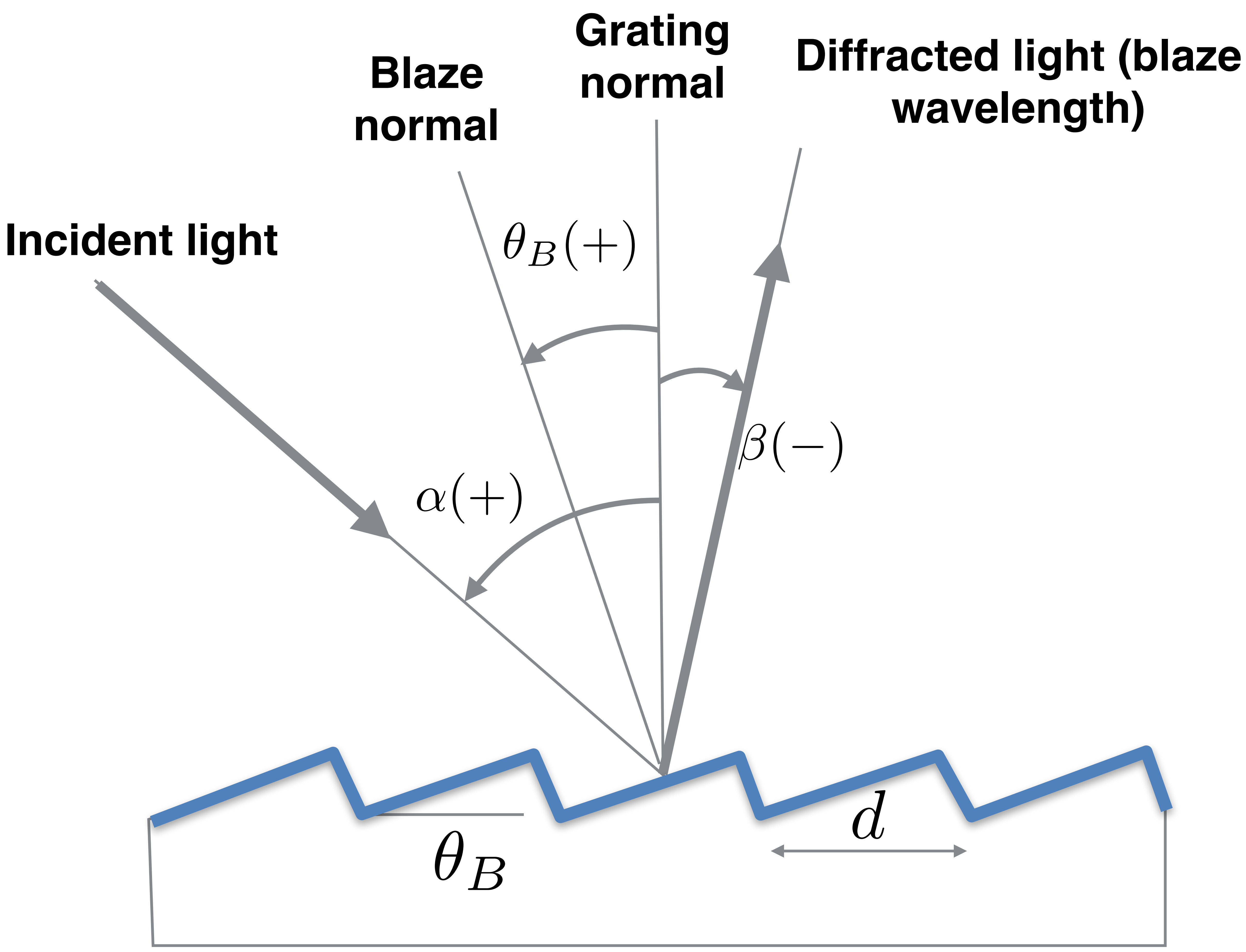
We can either use an ORDER BLOCKING FILTER or a CROSS DISPERSER to split out the different spectral orders

The free spectral range of a spectrograph is given by:

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

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

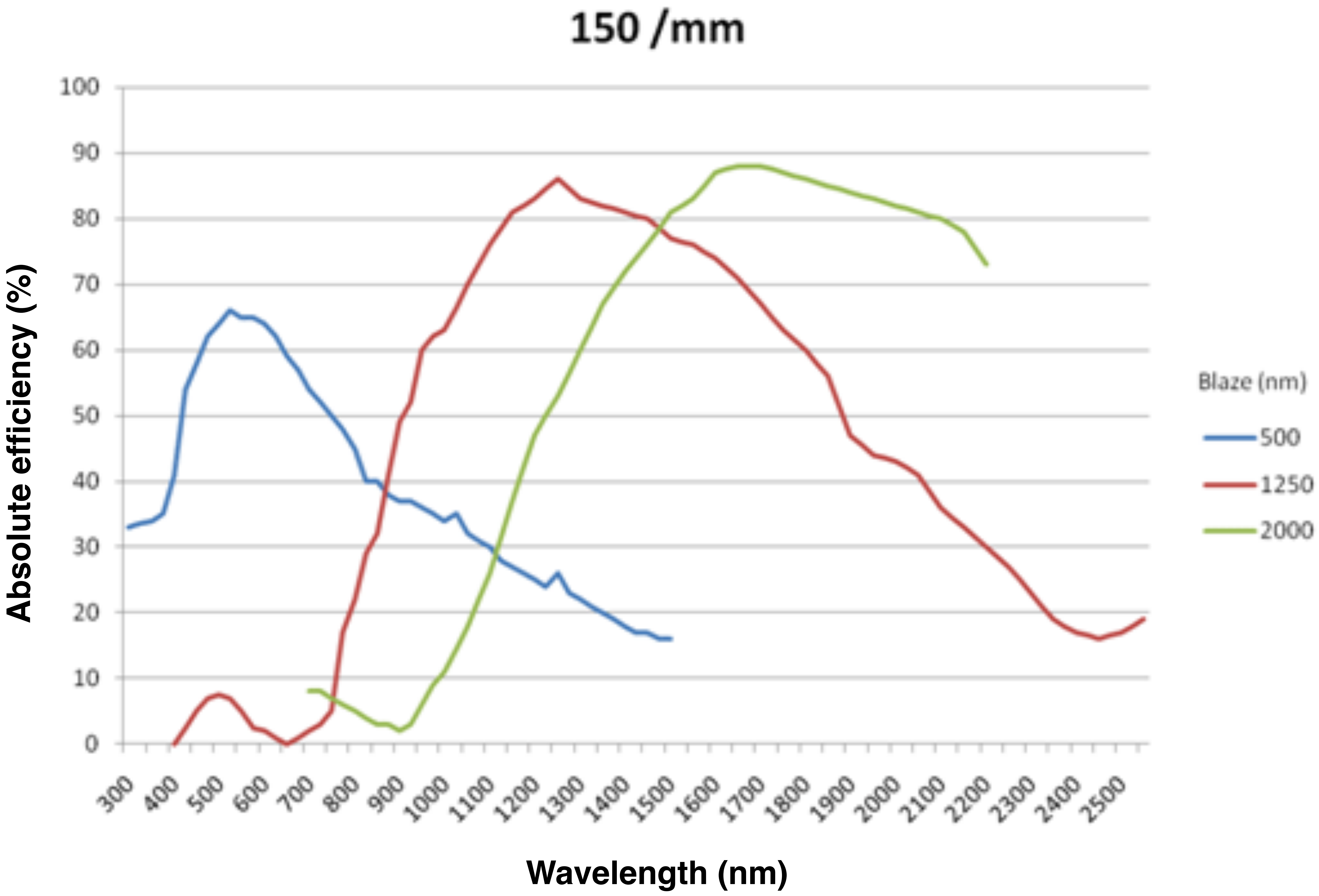
Optimising the grating efficiency



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

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

Peak efficiencies at blaze wavelengths



Increasing spectral resolution with diffraction gratings

Increasing σ is difficult, and $\cos\beta$ cannot be greater than unity

Angular dispersion $$A = \frac{d\beta}{d\alpha} = \frac{m}{\sigma\cos\beta}$$

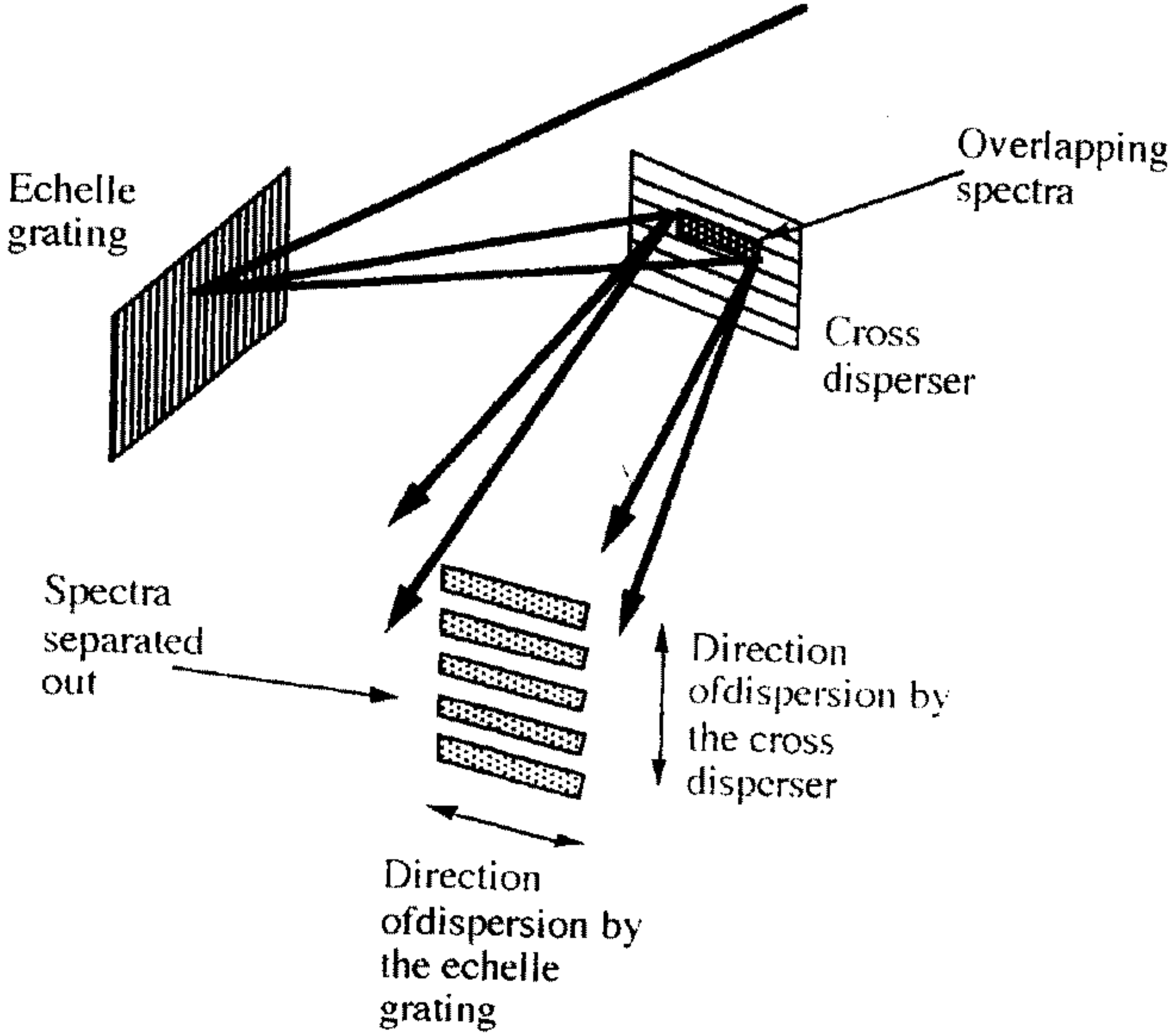
Look at large values of m to get high spectral resolution

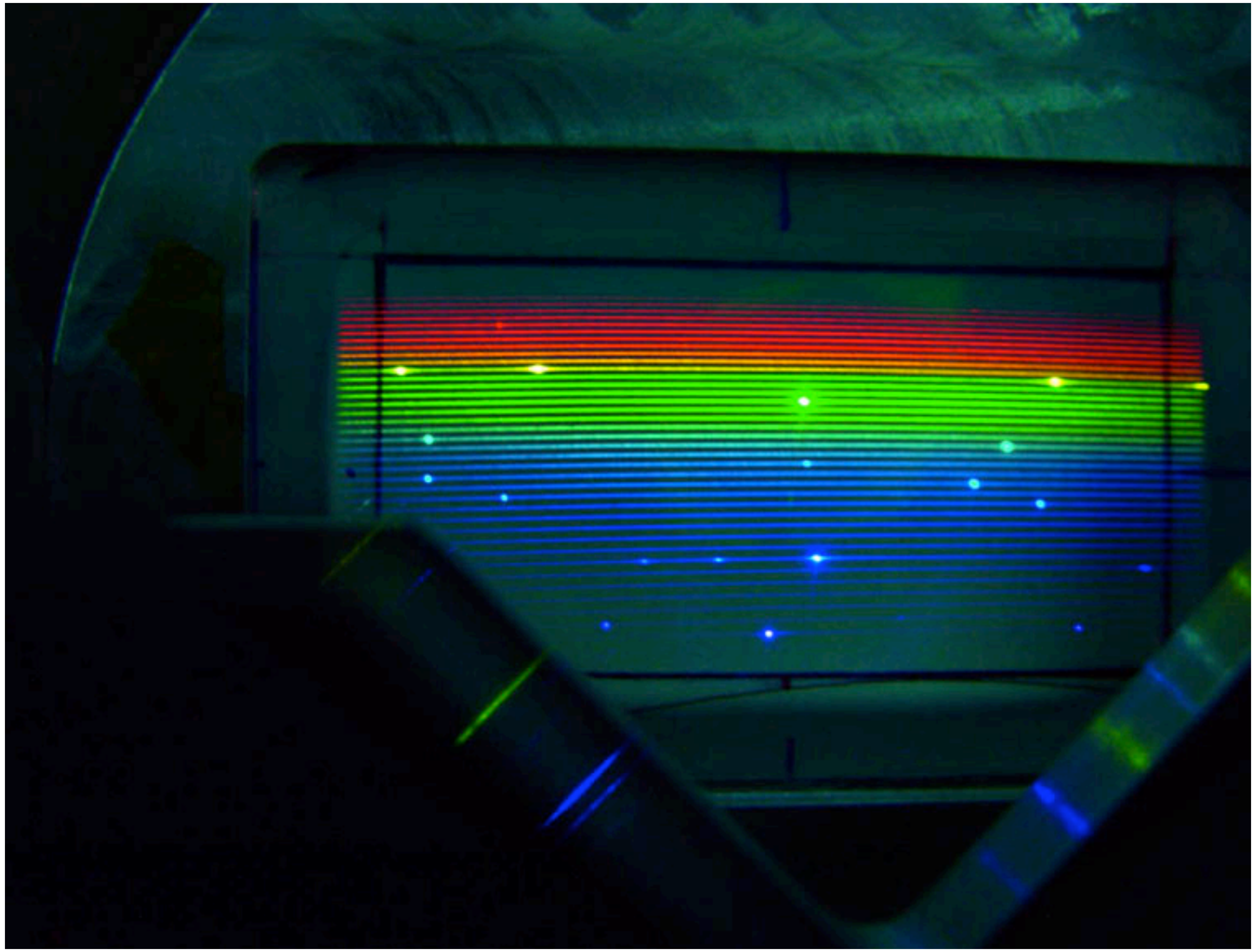
$$R = nm$$

where n is the total number of illuminated grooves

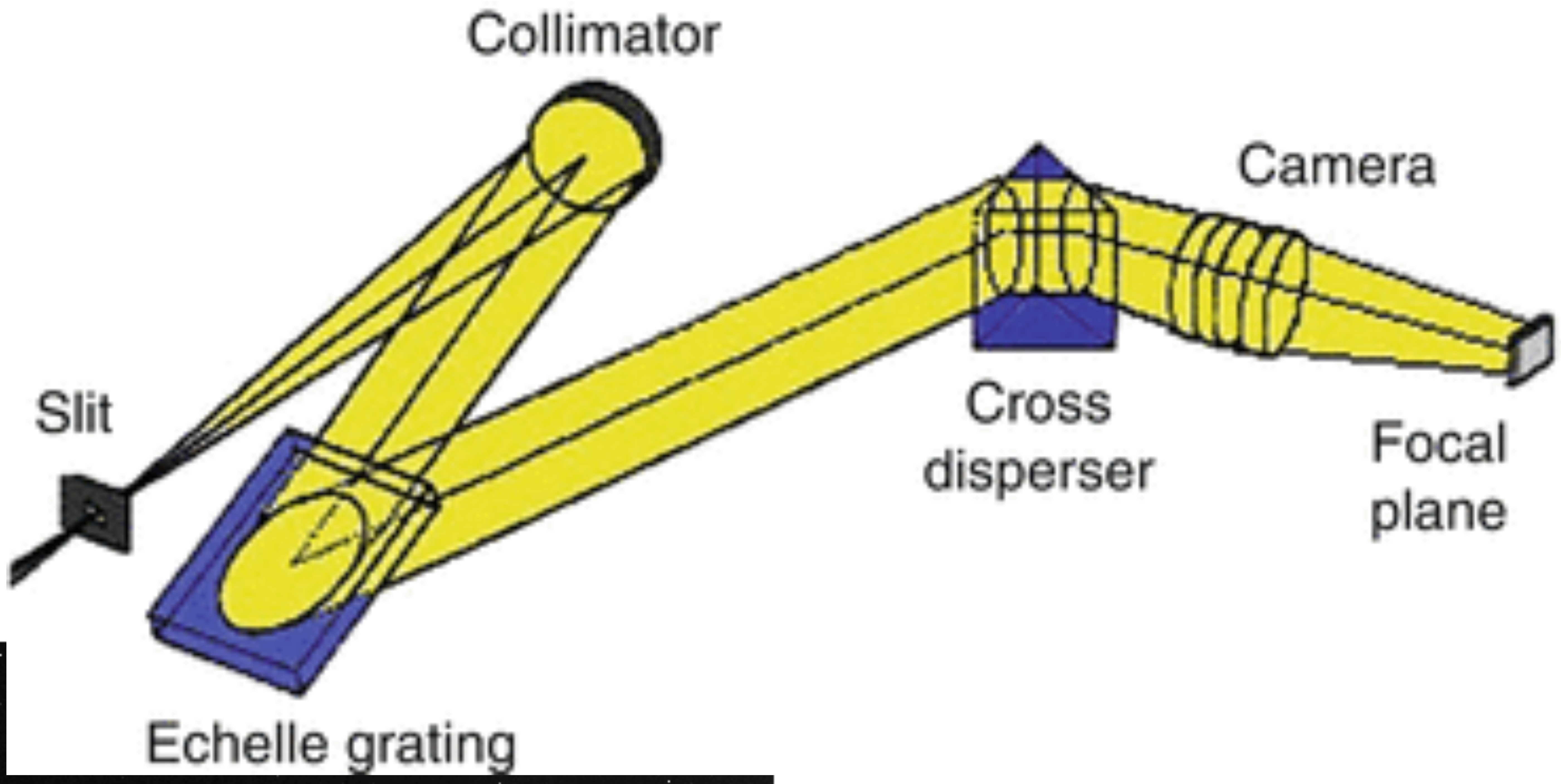
Higher spectral orders

CROSS disperser to split out the different spectral orders



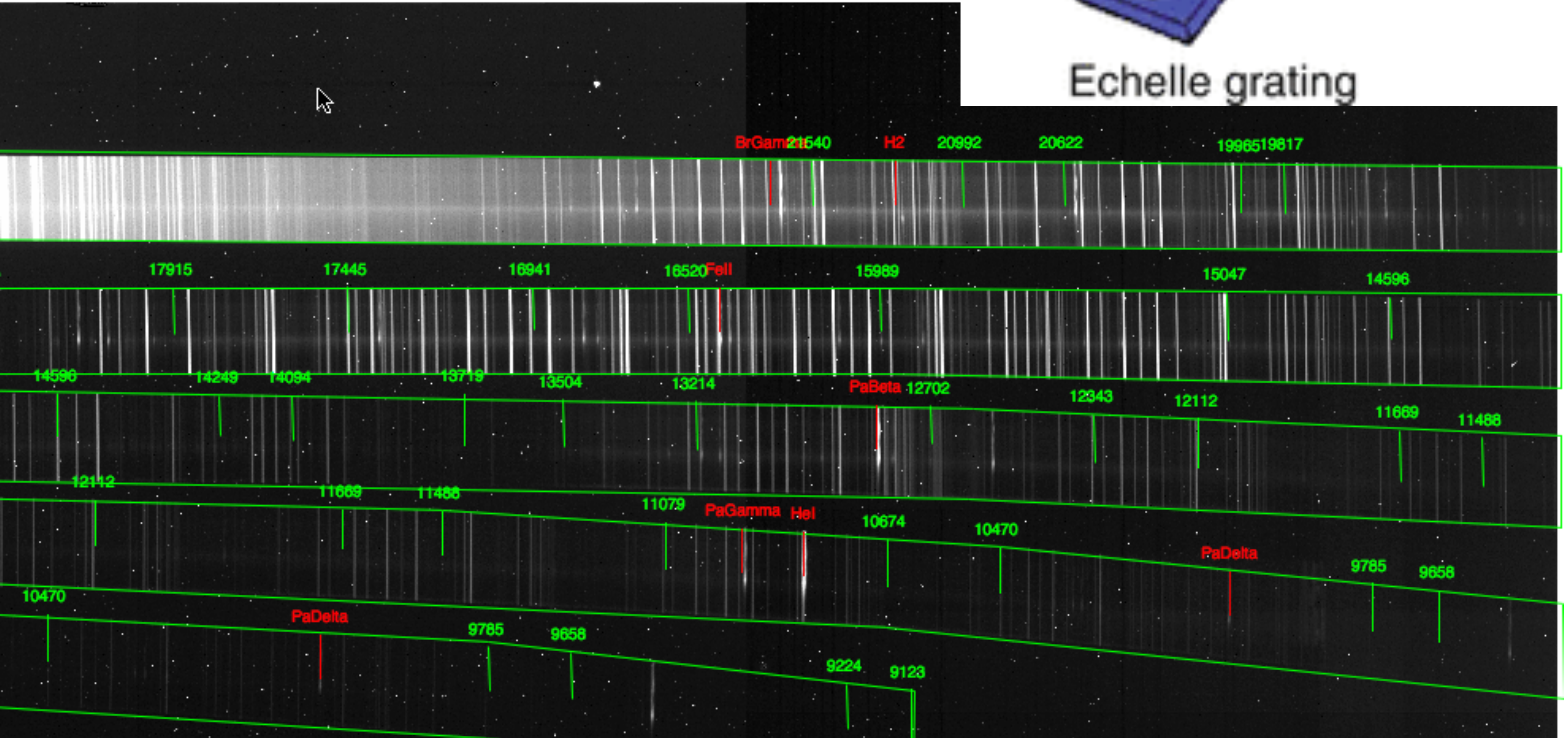


Higher spectral orders



Glass prism as a cross disperser

Trispec

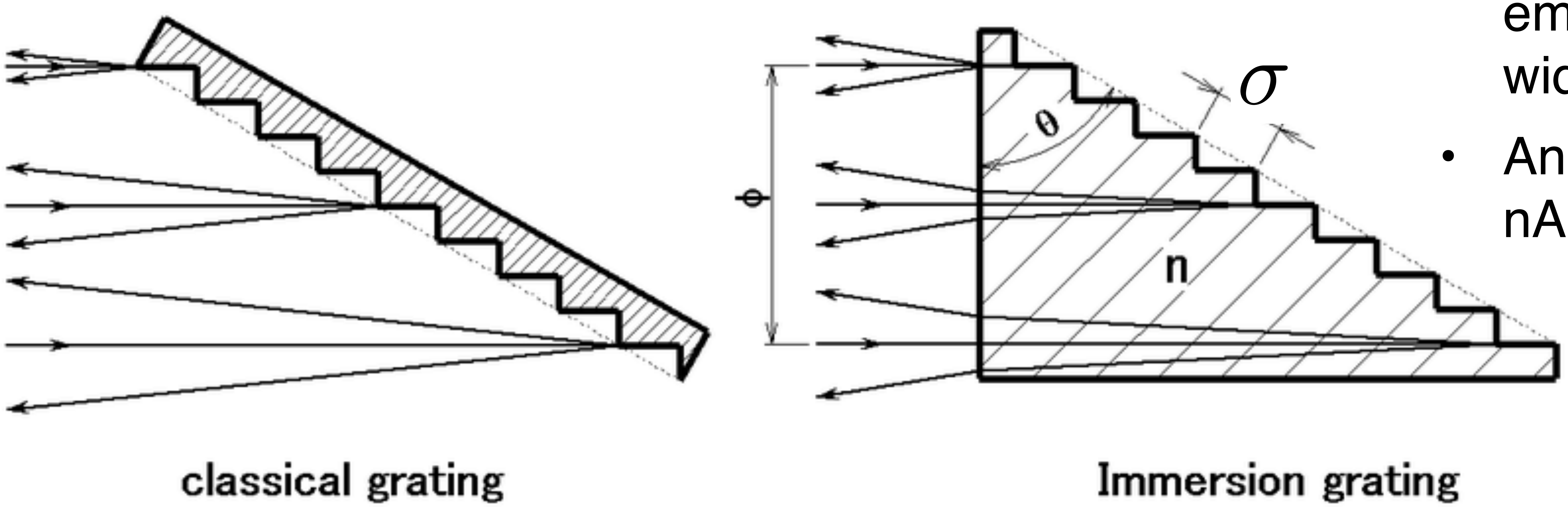


Lecture 10: Spectrographs

10.3 Immersed Gratings and other Spectrographs

Immersion Gratings

$$m\lambda = n\sigma(\sin\beta + \sin\alpha)$$

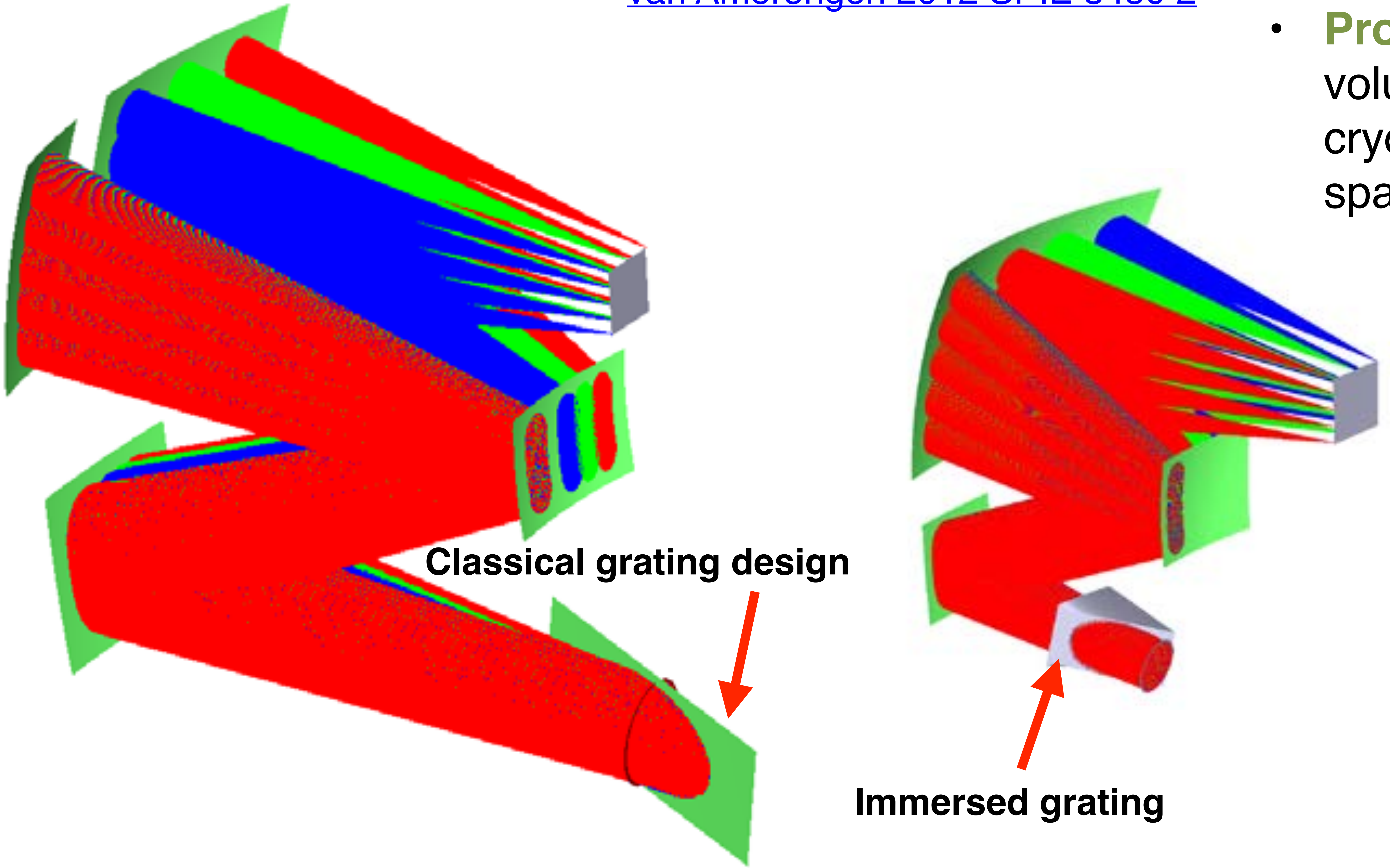


- Grating equation inside medium of refractive index n emerges from the grating at a wider angle.
- Angular dispersion A of prism is nA inside immersion grating

Angular dispersion within material $$A = \frac{m}{n\sigma\cos\beta}$$

IG spectrograph takes much smaller volume

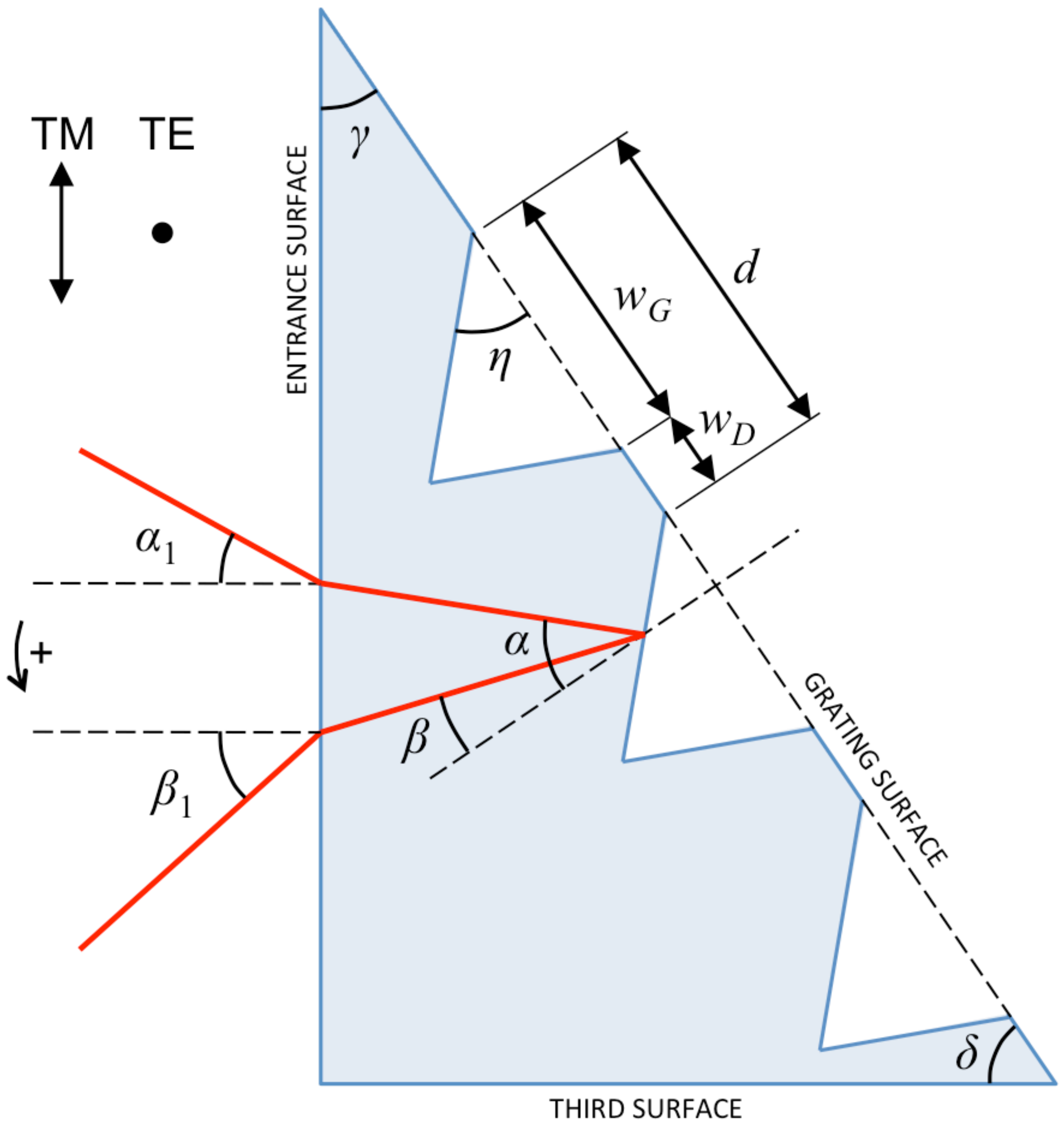
van Amerongen 2012 SPIE 8450 2

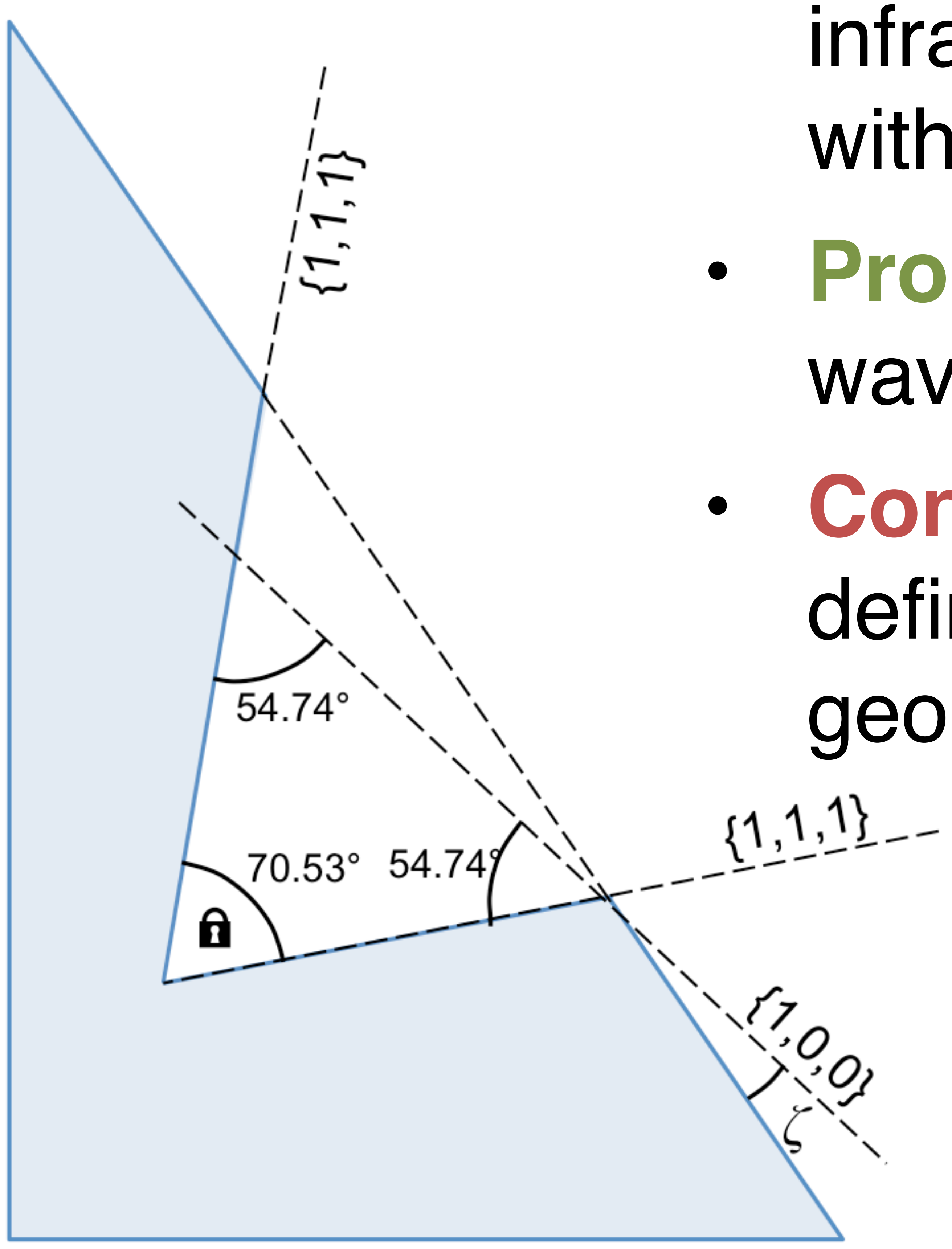


- **Pros:** Much smaller volume ideal for cryogenic cooling and space based applications

Silicon gratings

[Rodenhuis 2015 SPIE 9626]

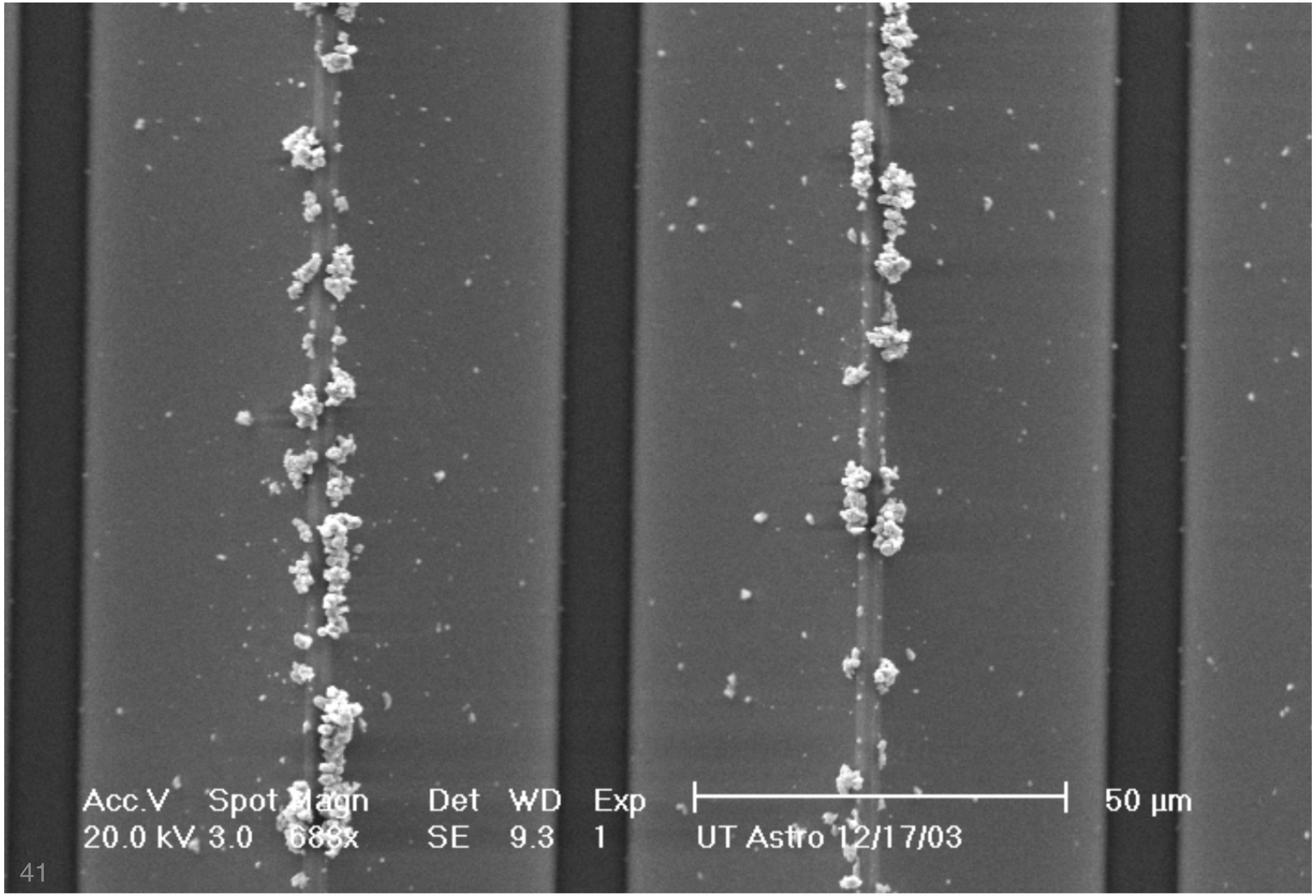


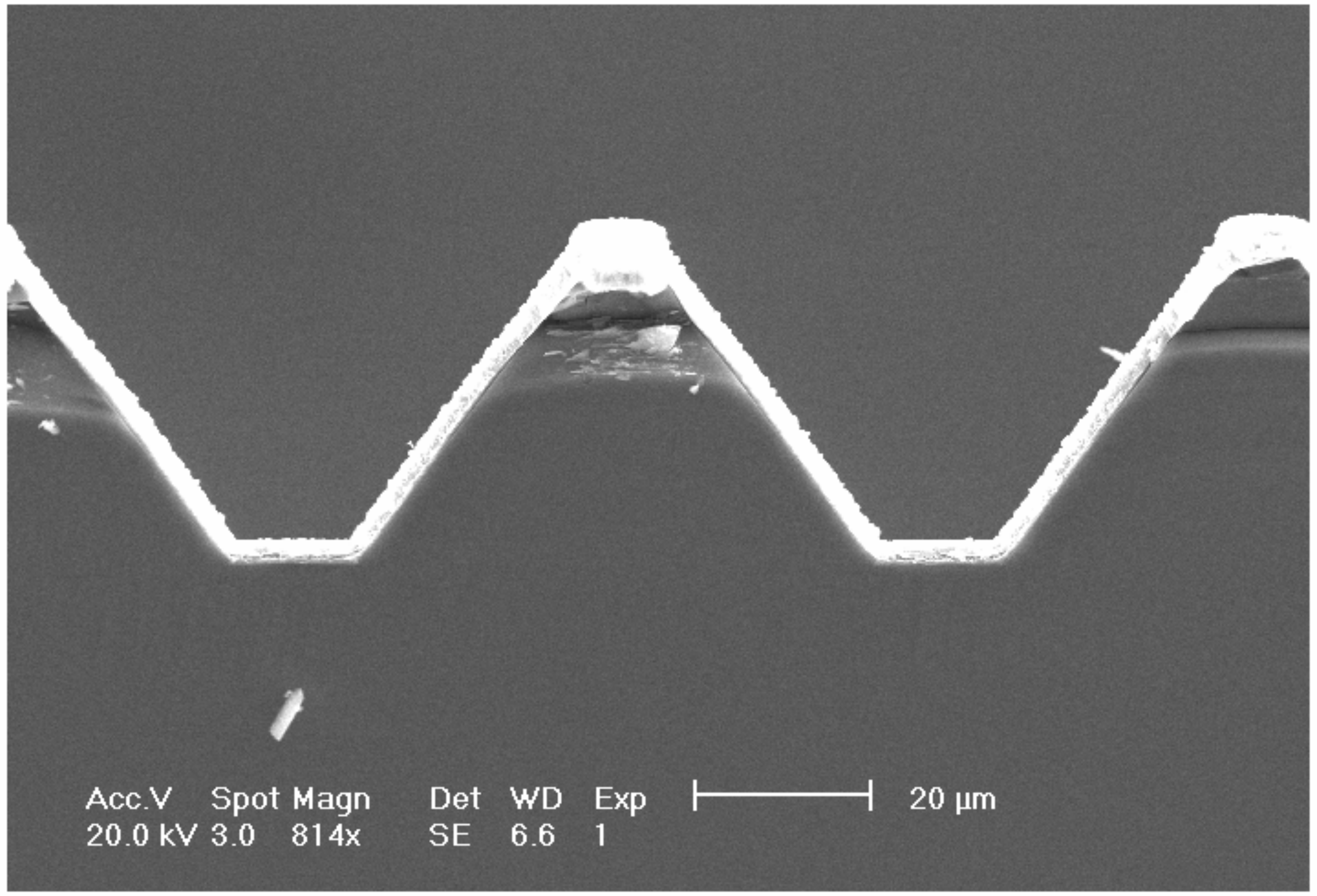


- **Pro:** Si is ideal for mid infrared spectroscopy with n= 3.4
- **Pro:** Si for 1 to 7 microns wavelength
- **Con:** Crystal lattice defines the grating geometry

Etched silicon under SEM

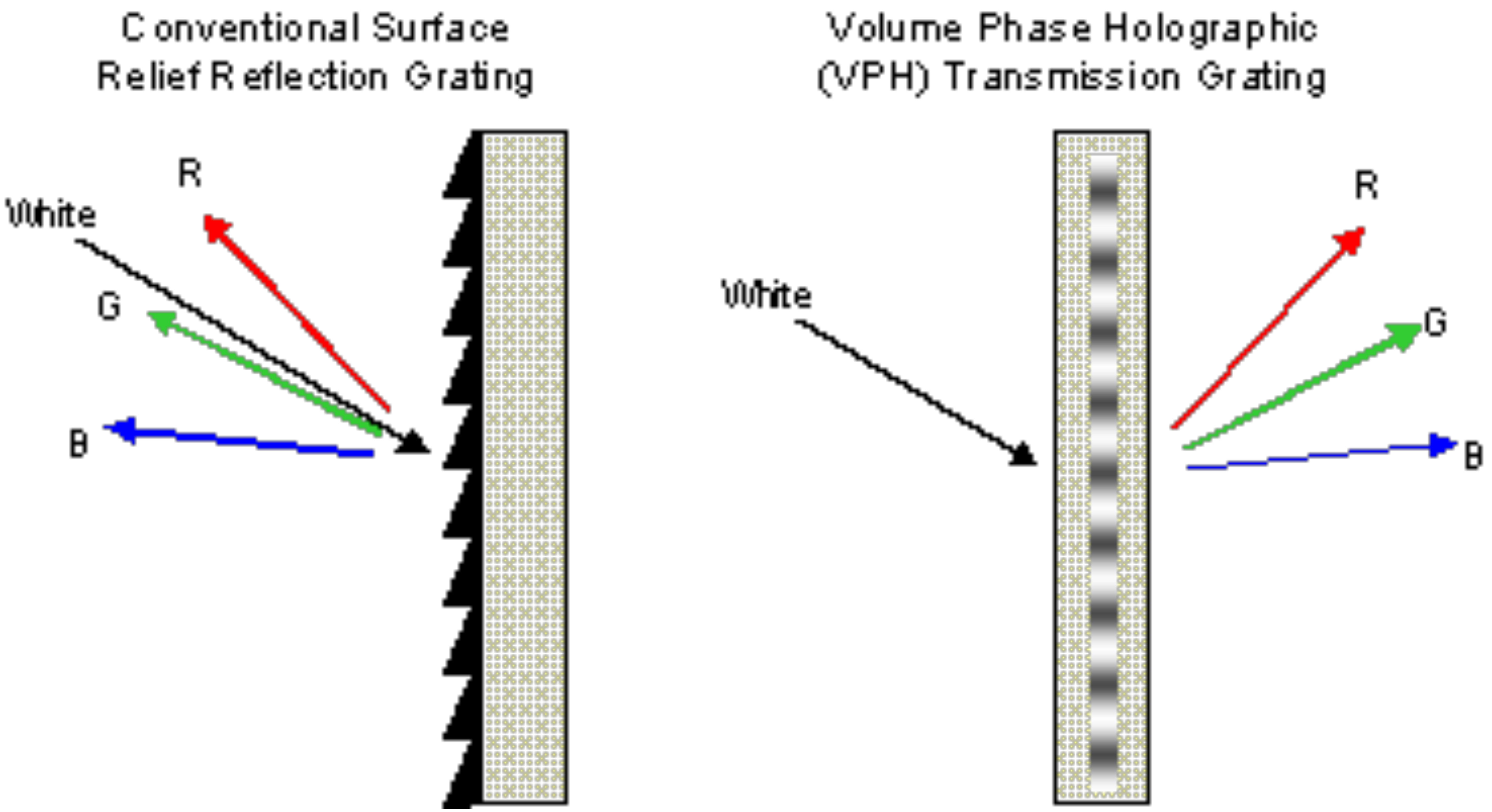
[Marsh "Production and evaluation of silicon immersed gratings"]





- **Pro:** Extremely clean grooves mean little scattered light

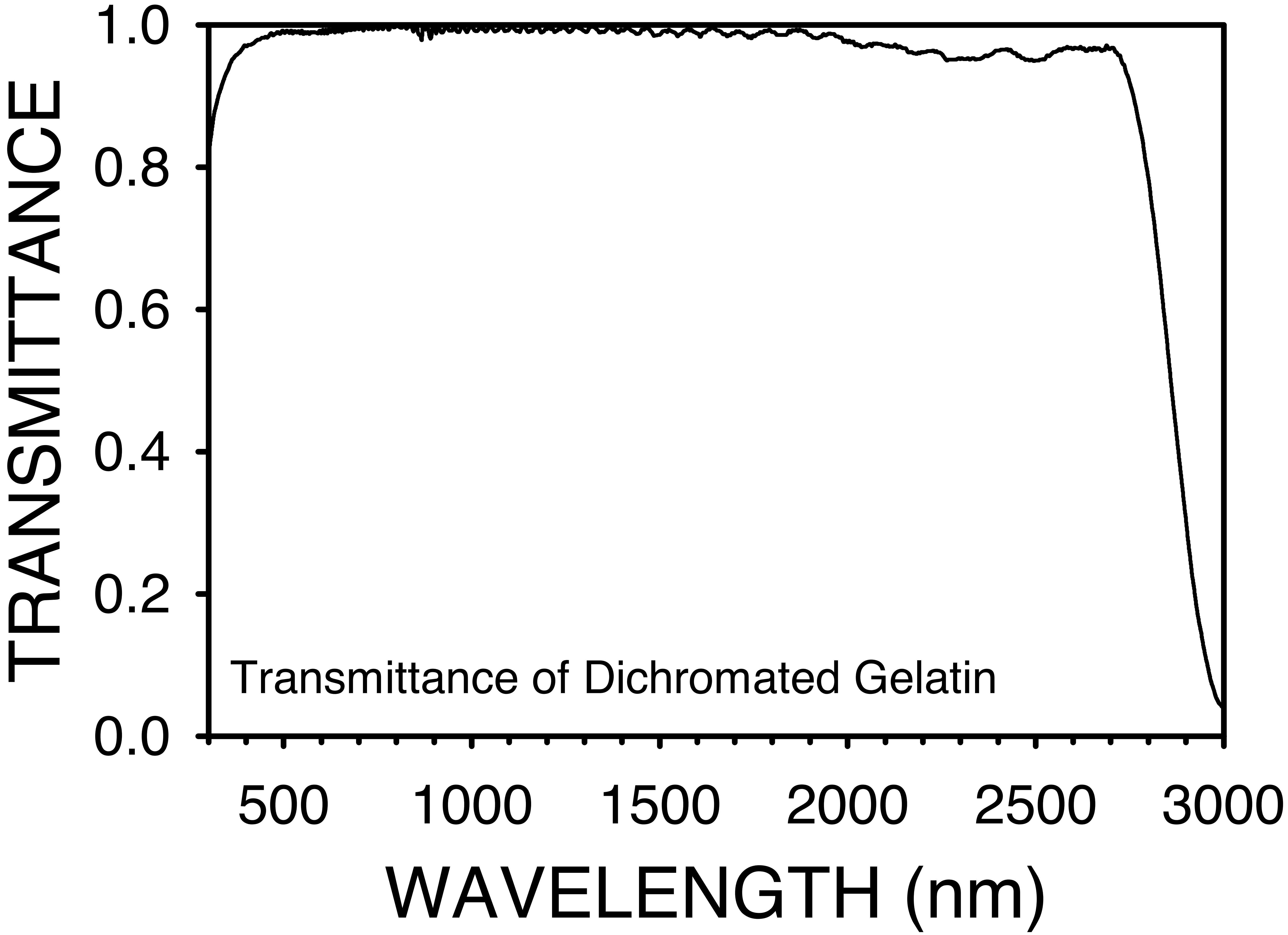
Volume Phase Holographic Gratings



- Any periodic structure acts as a diffraction grating
- VPH is a transmissive optic
- Two lasers set up a periodic pattern within a volume of light sensitive material, then fixed with UV light

Volume Phase Holographic Gratings

Typical thickness of DHG of 15 microns



Barden PASP 1998

- Dichromated Gelatin (DHG) with periodic index n held inside glass prisms

Volume Phase Holographic Gratings

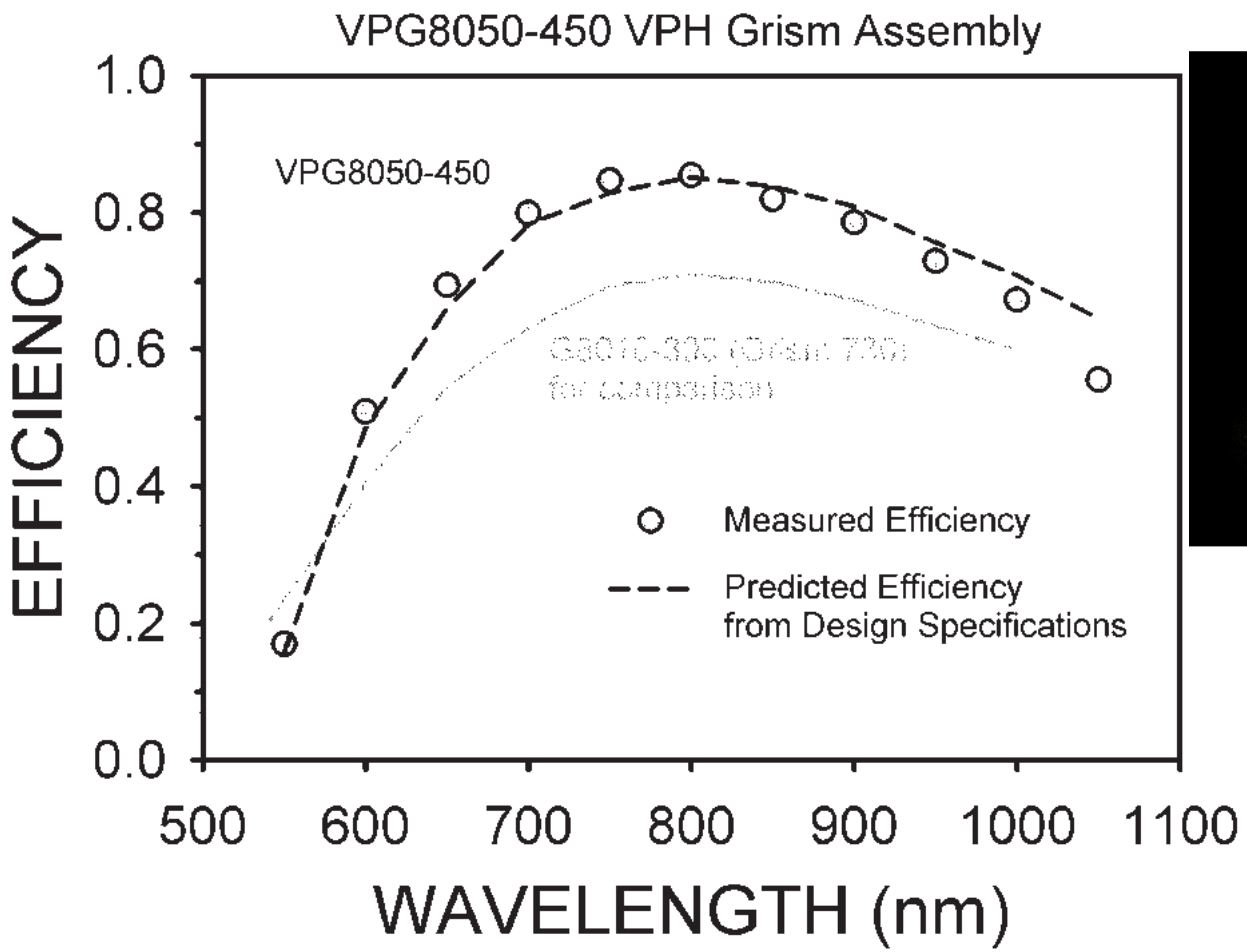
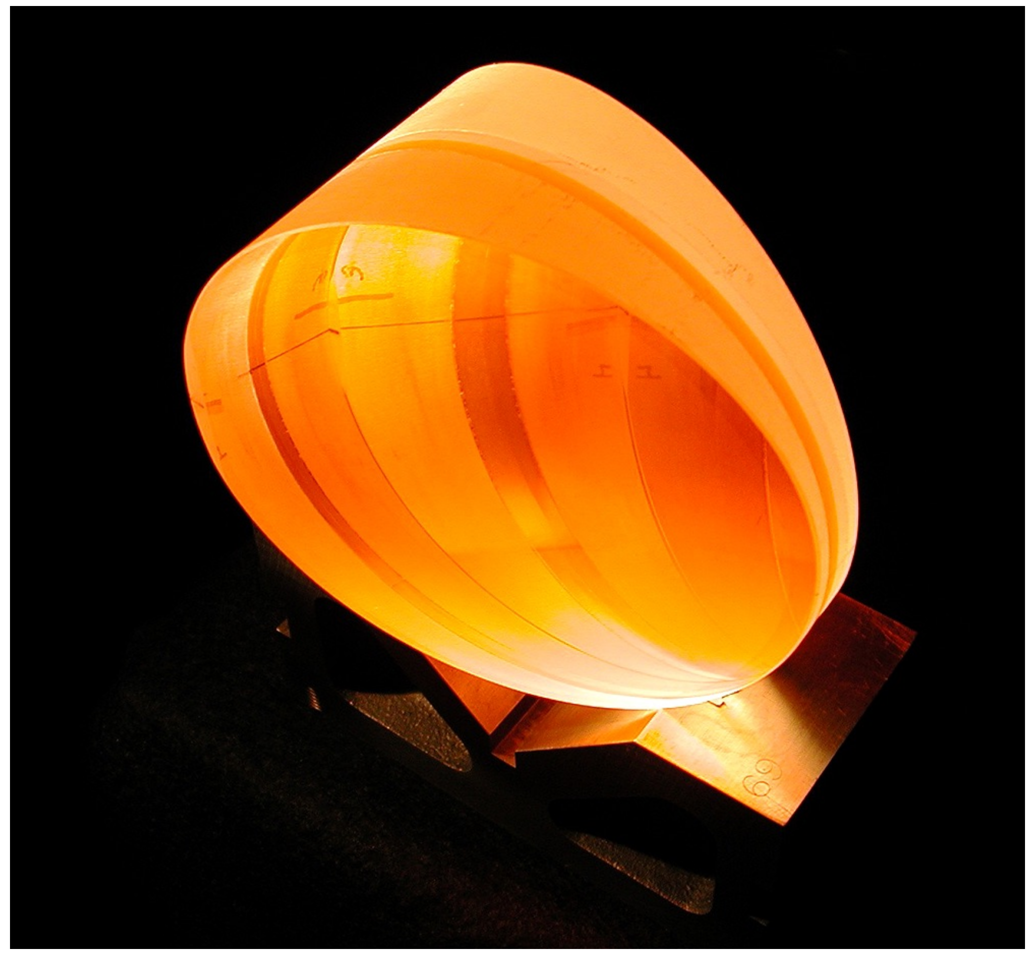


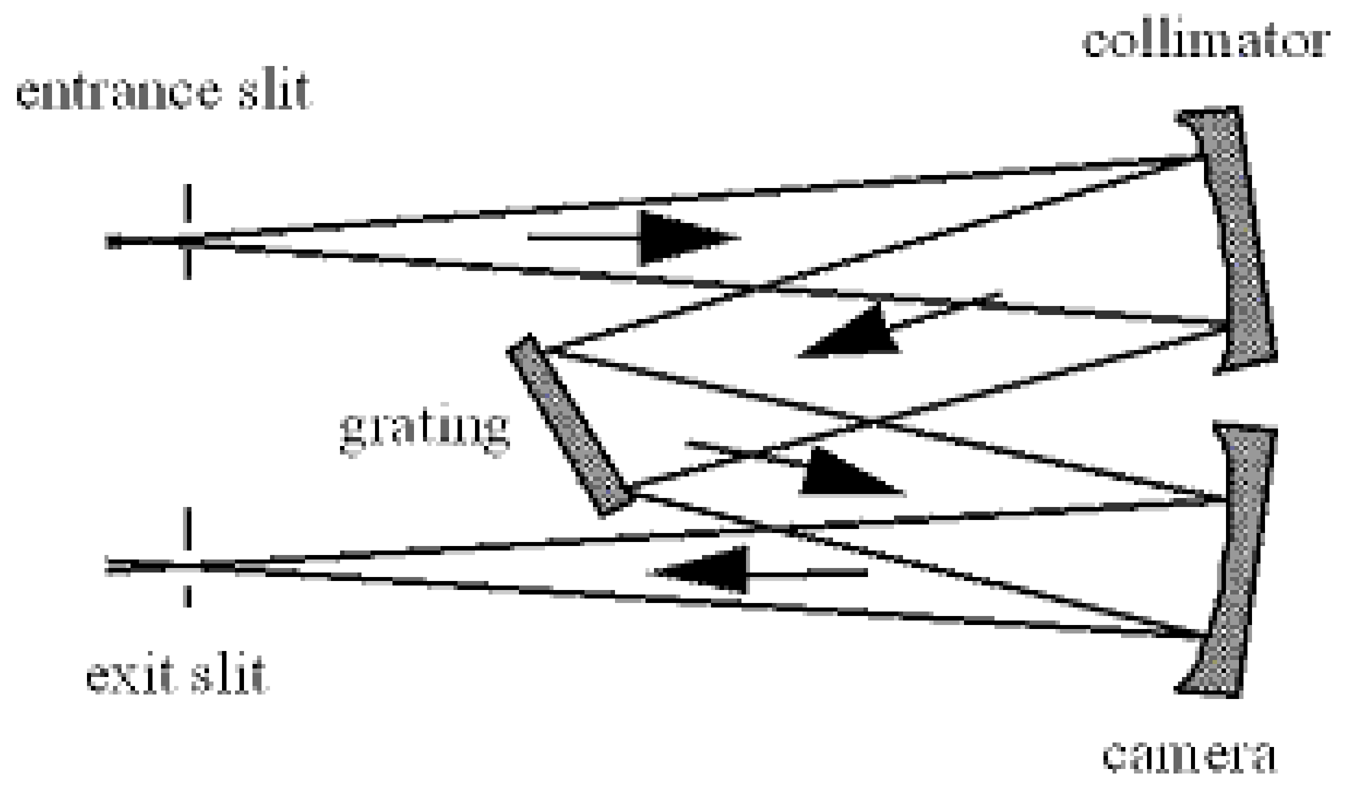
Figure 3: Efficiency curve for grism

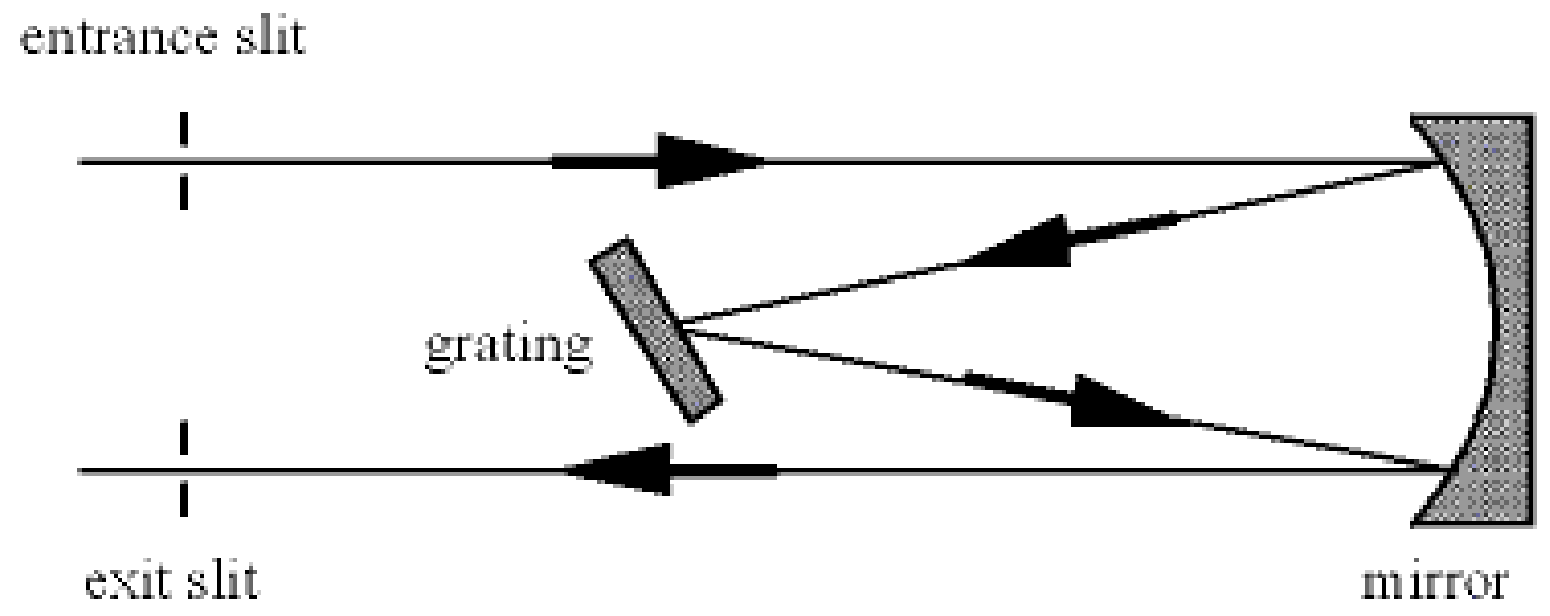


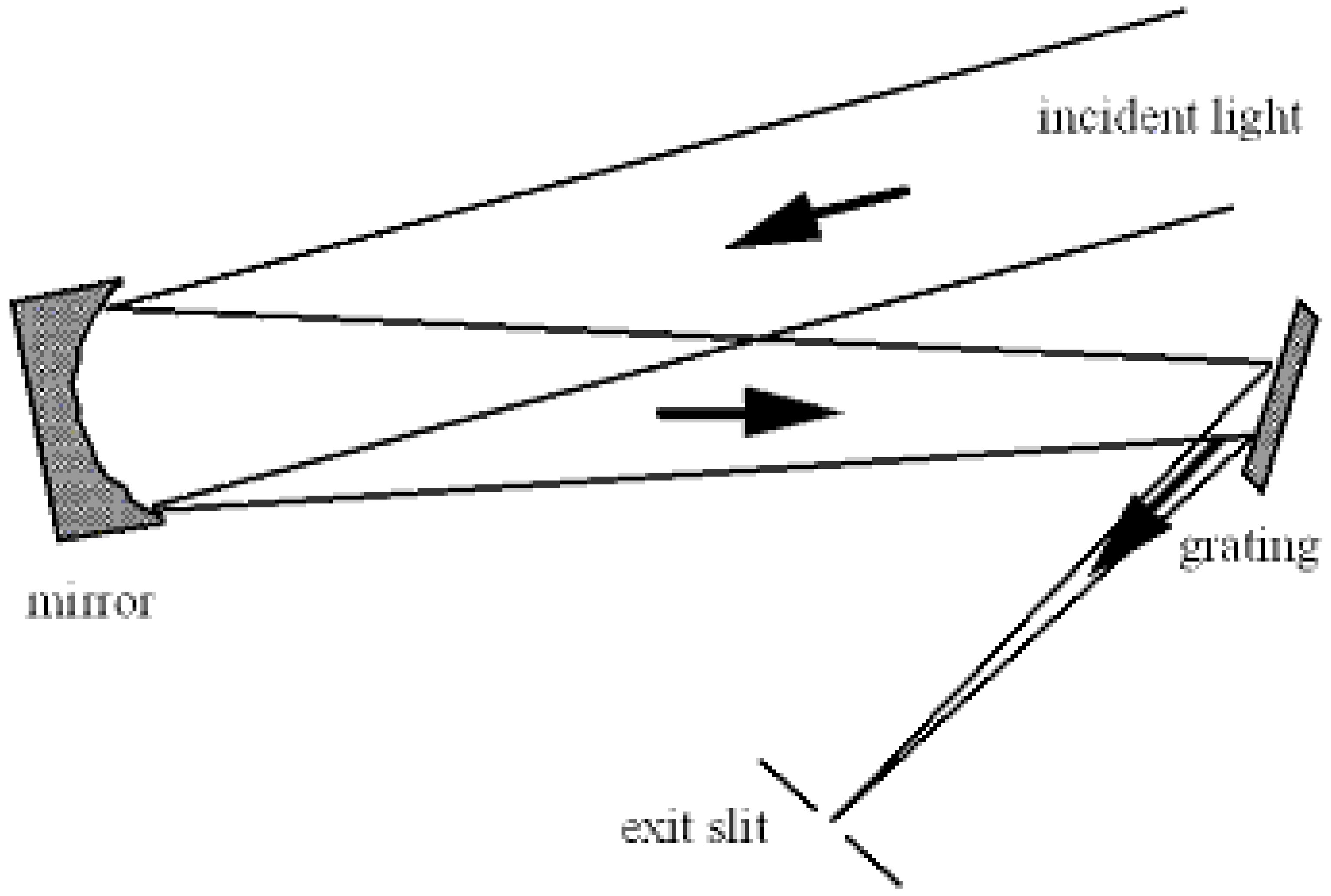
NOAO Newsletter 2001 67

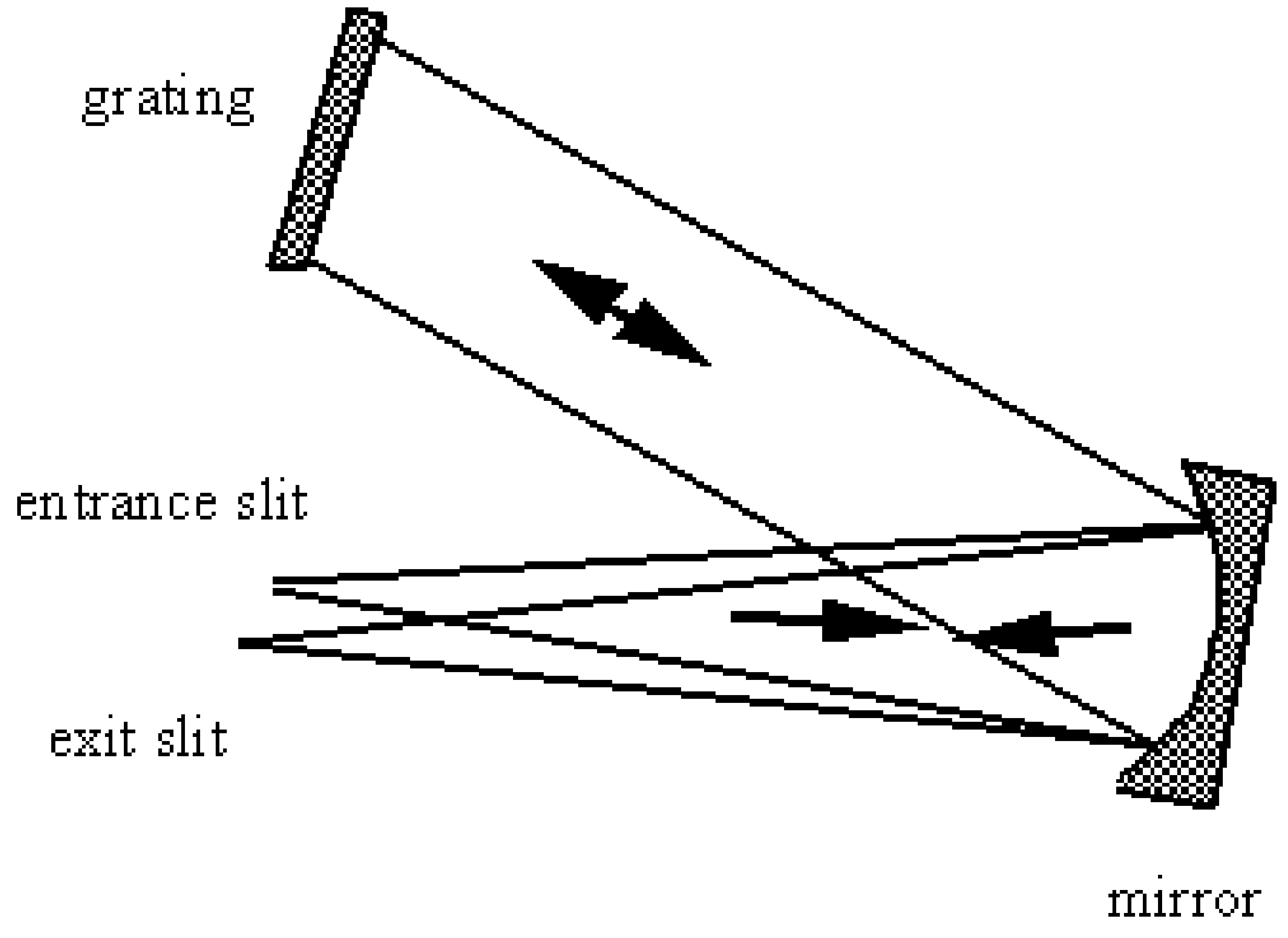
- **Pros:** high throughput and transmission efficiencies
-

Common spectrograph configurations

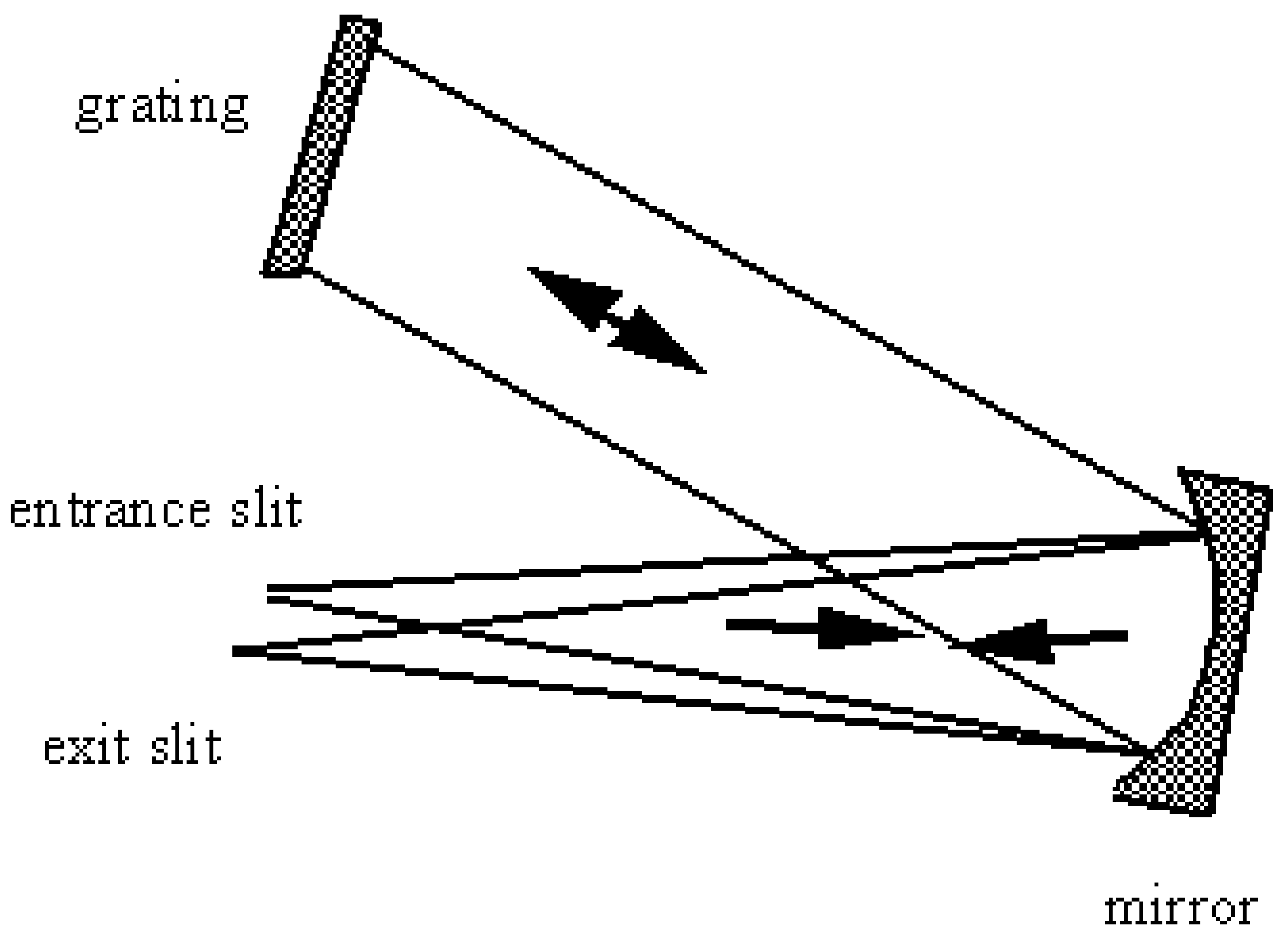








The Littrow spectrograph



Incident angle equals diffracted angle:

$$\alpha = \beta$$

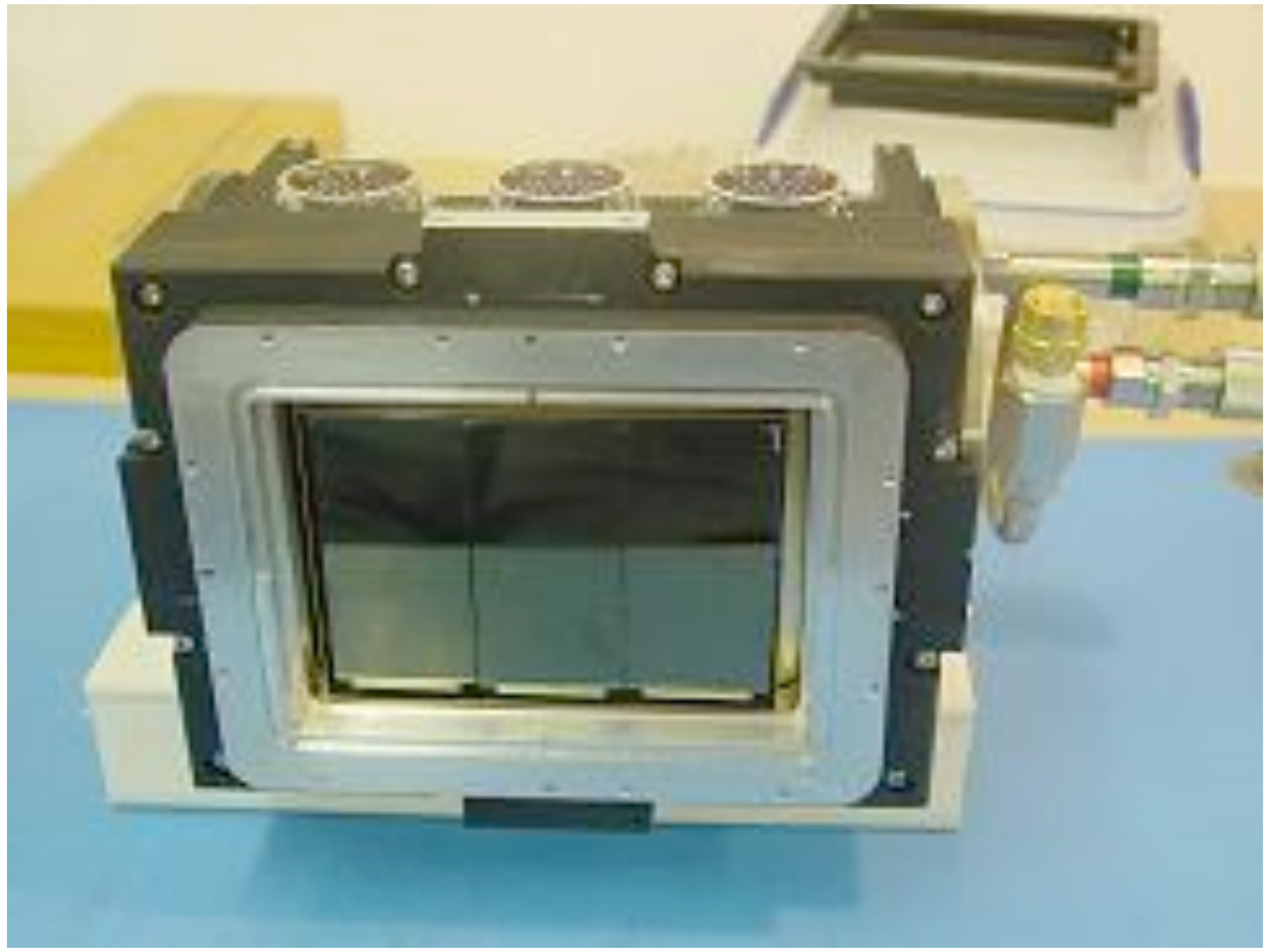
So for Littrow:

$$\lambda = \frac{2\sigma \sin \alpha}{m}$$

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.

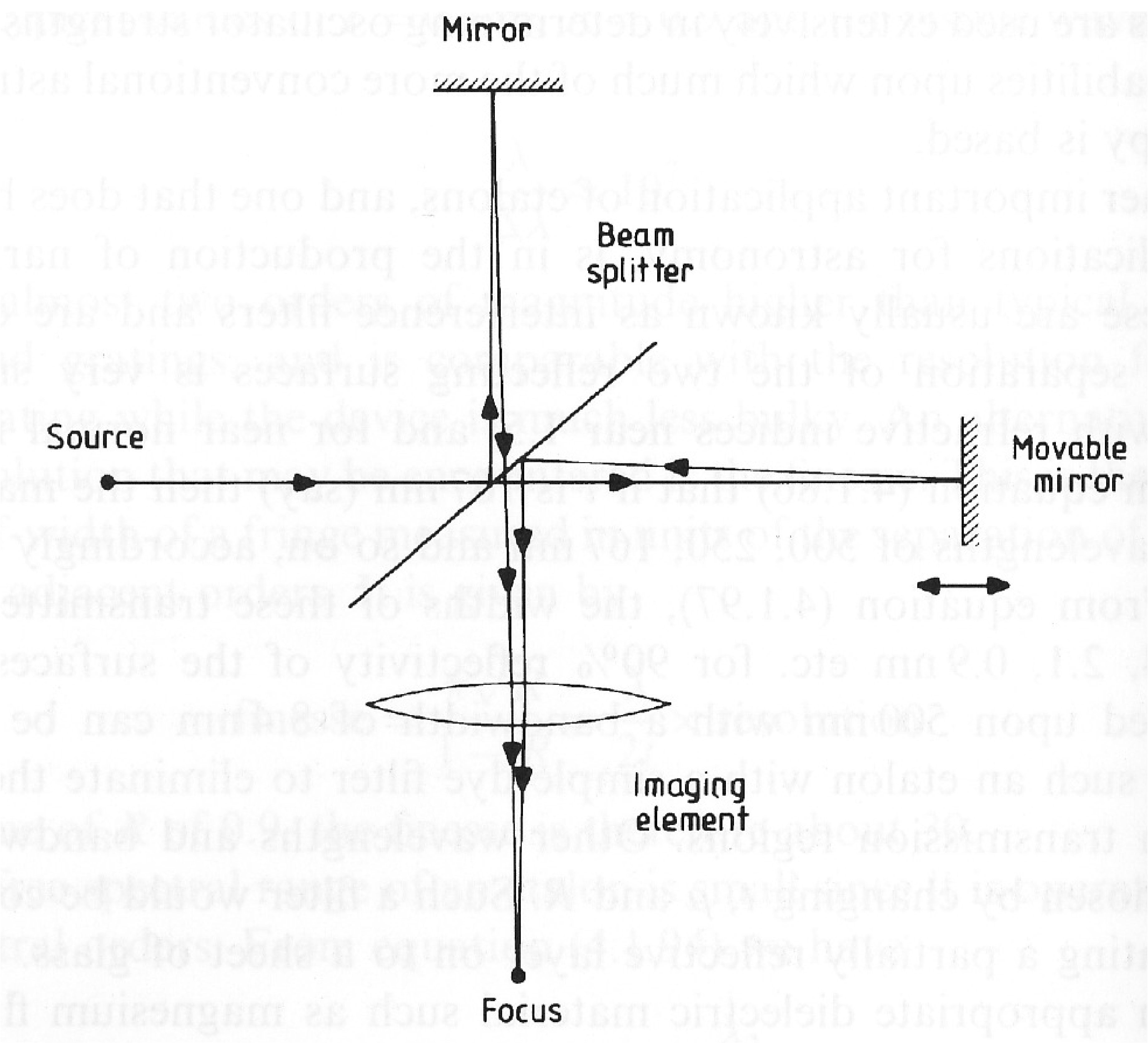


Spectral dispersion per pixel is:

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

where μ is the pixel size in mm.

Fourier Transform Spectrographs



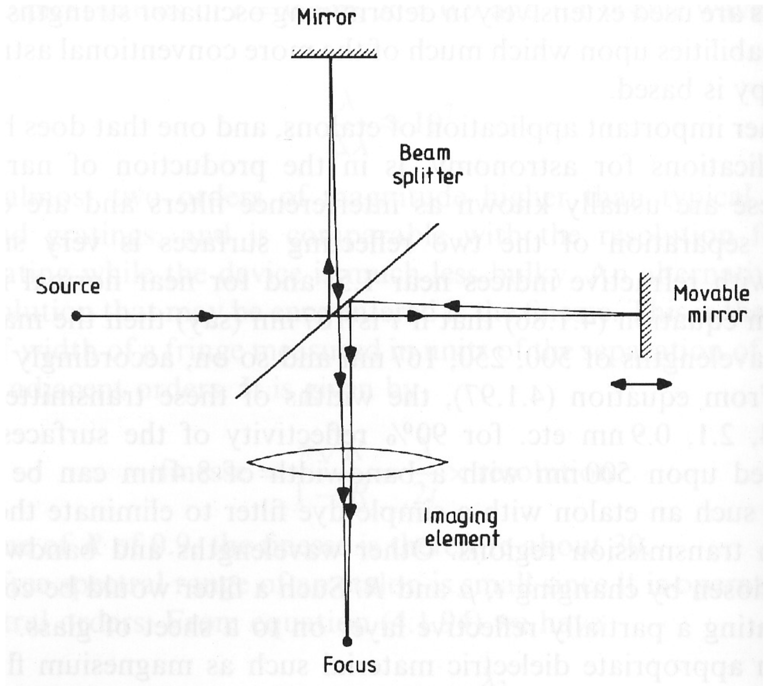
A Michelson interferometer with one moving arm

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:

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

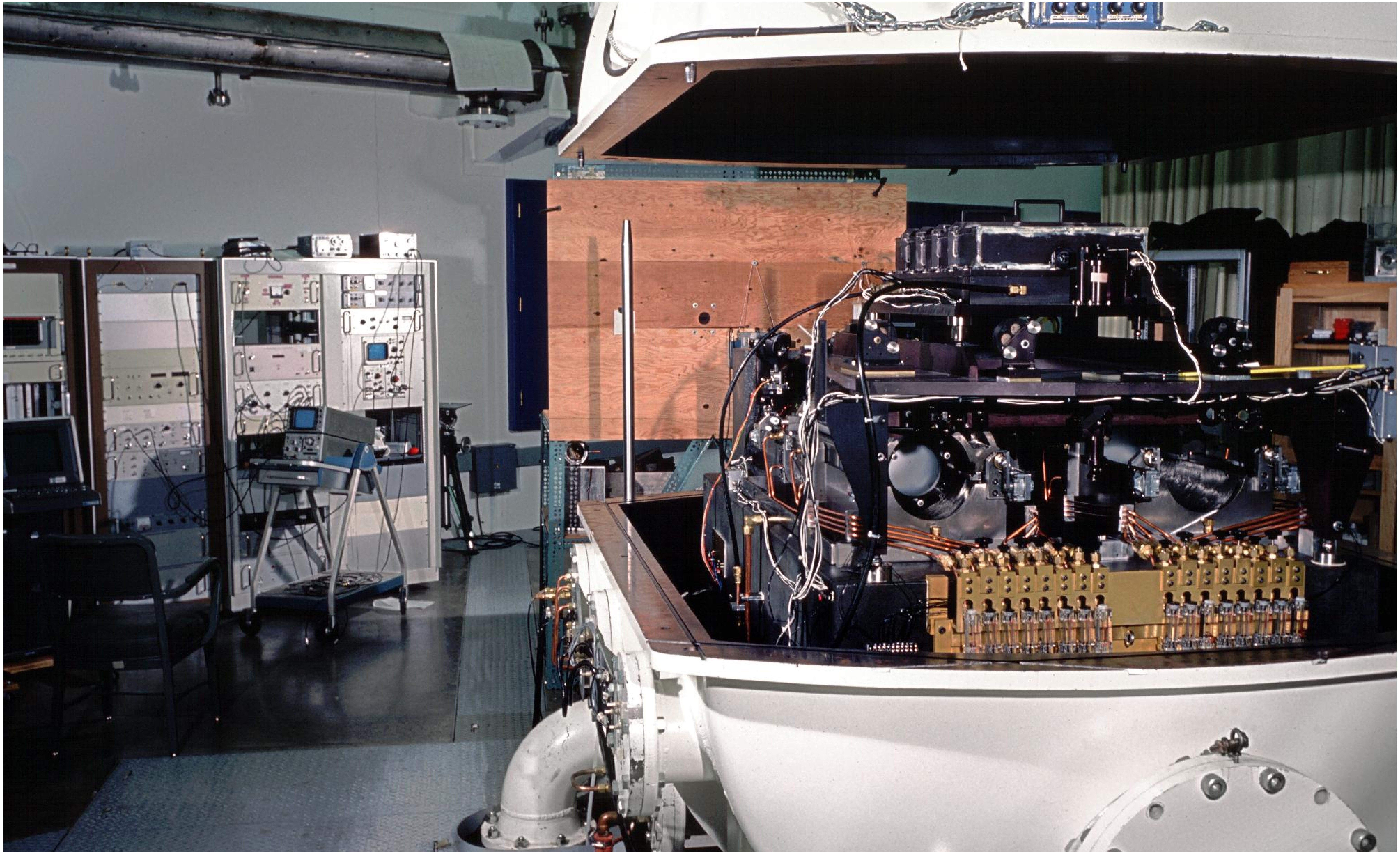
$$\lambda/\delta\lambda = 2 \times 10^6$$

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

CONS: very susceptible to any change in background flux

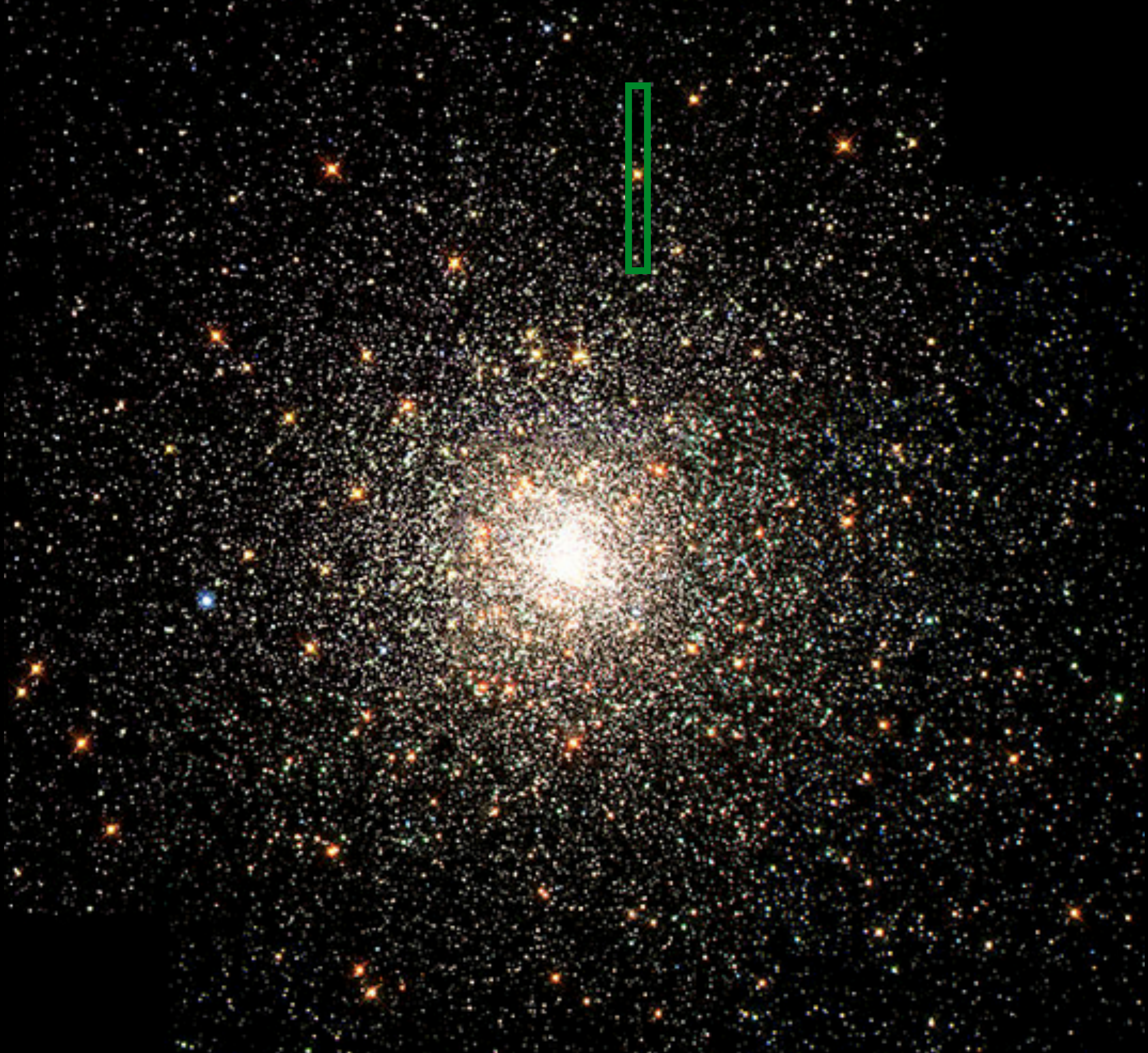
1m Kitt Peak FTS - Eglin, Hanna, NOAO/AURA/NSF

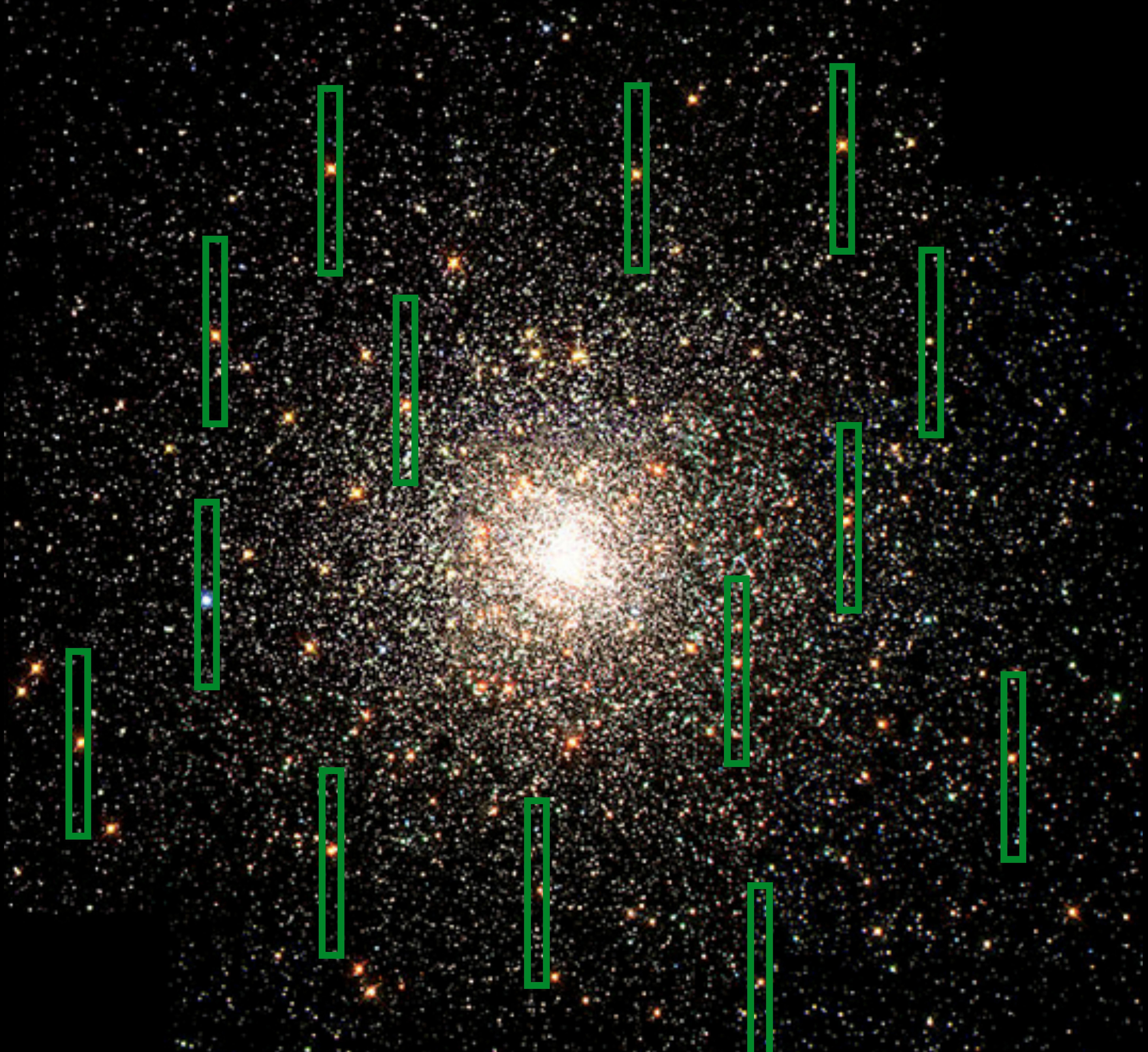
Fourier Transform Spectrographs



Lecture 10: Spectrographs

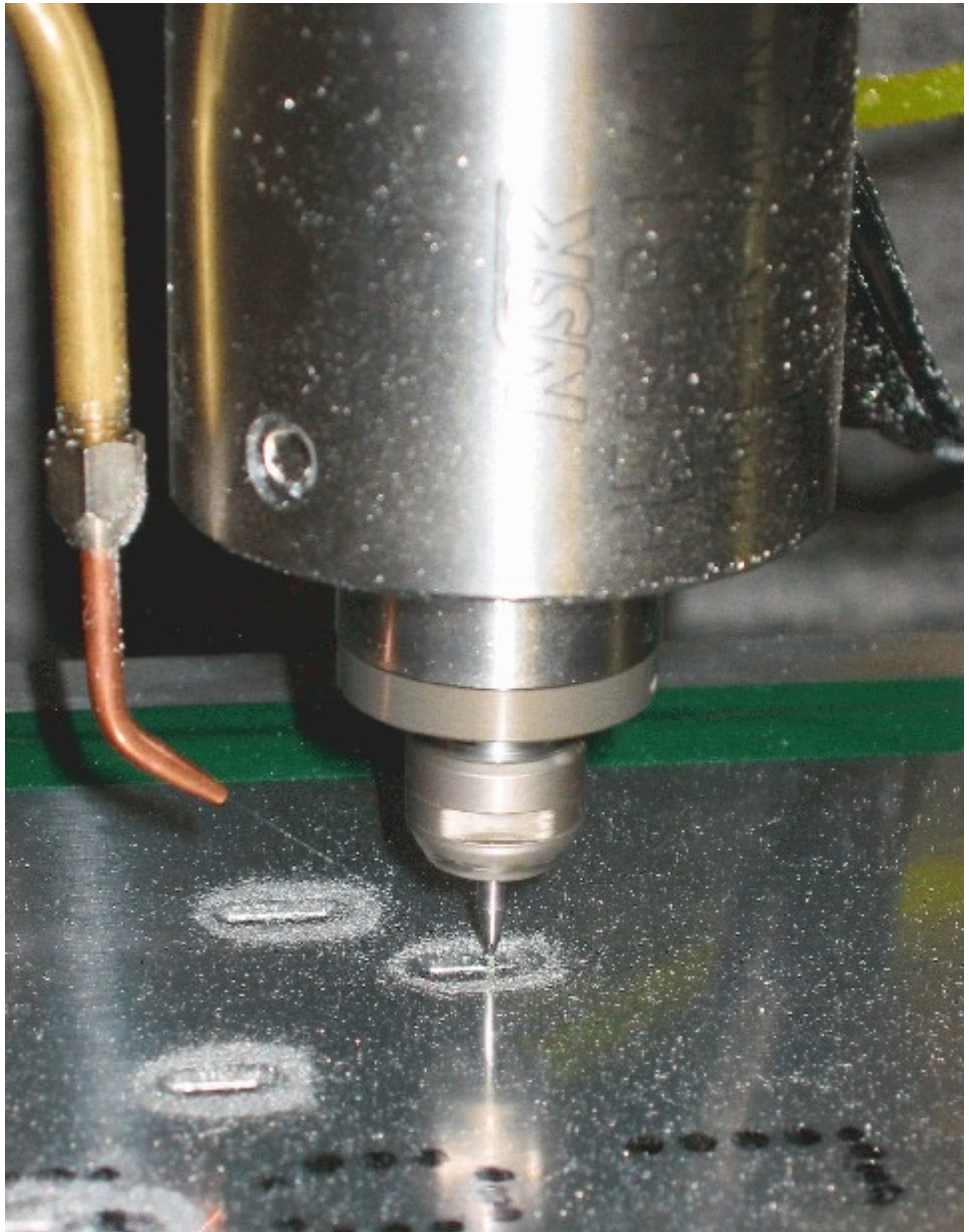
10.4 Multi Object Spectrographs



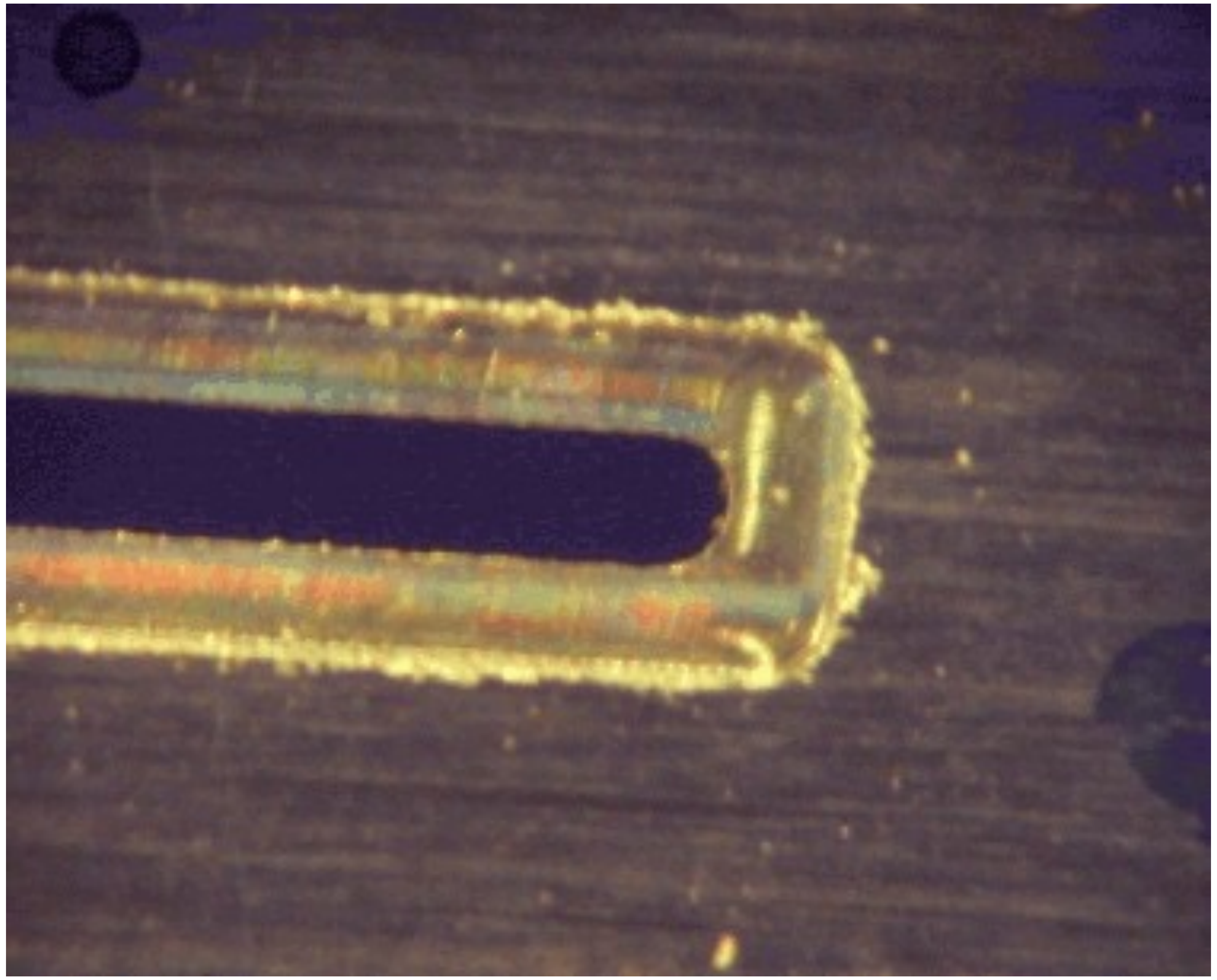


Multi Object Spectrographs - drilled spectro slits

DEIMOS slit masks milled with 0.015 inch diameter bits



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

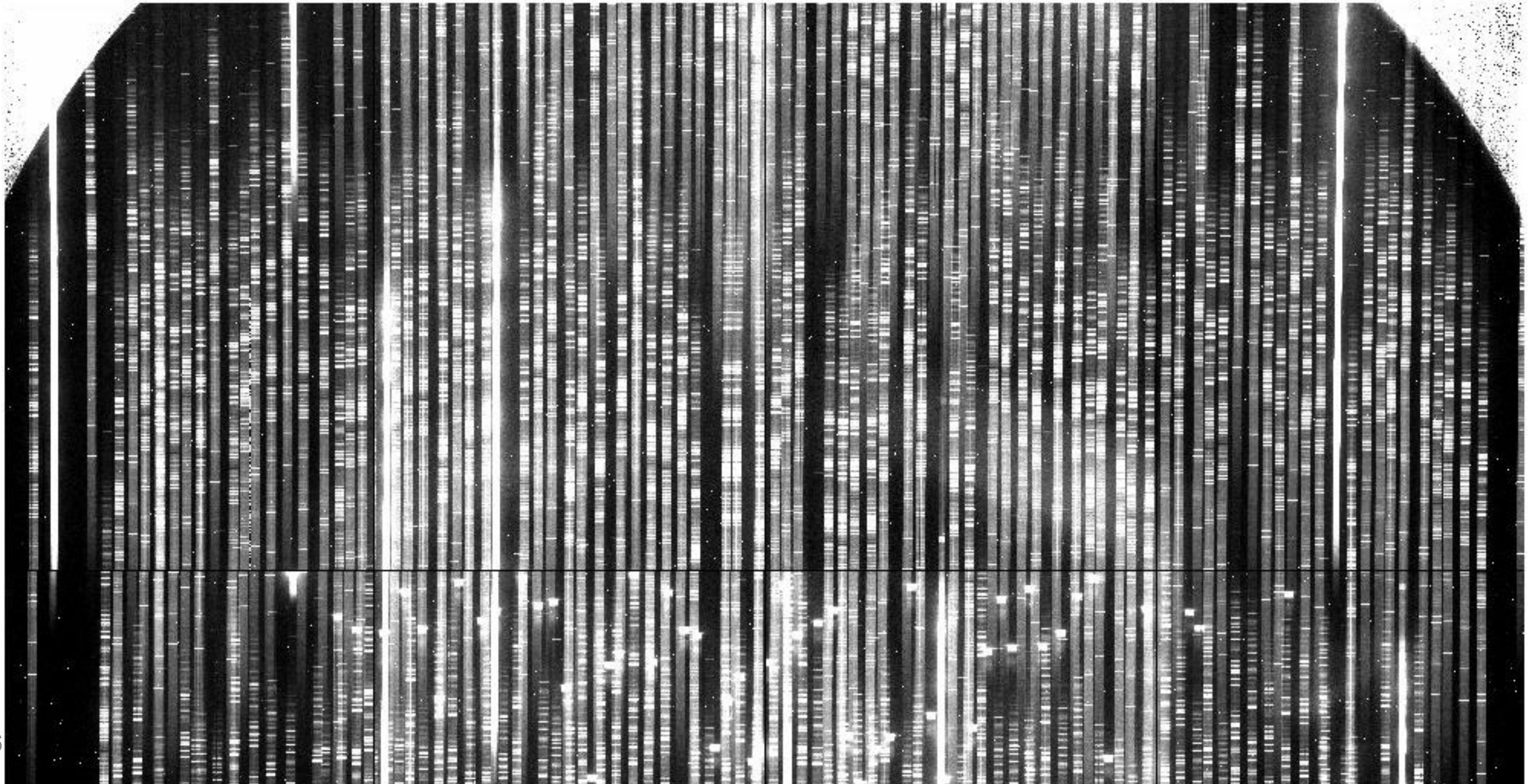


Multi Object Spectrographs - laser cut slits

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

IMACS on the Magellan 6.5m telescope

First spectrum with 240 slits

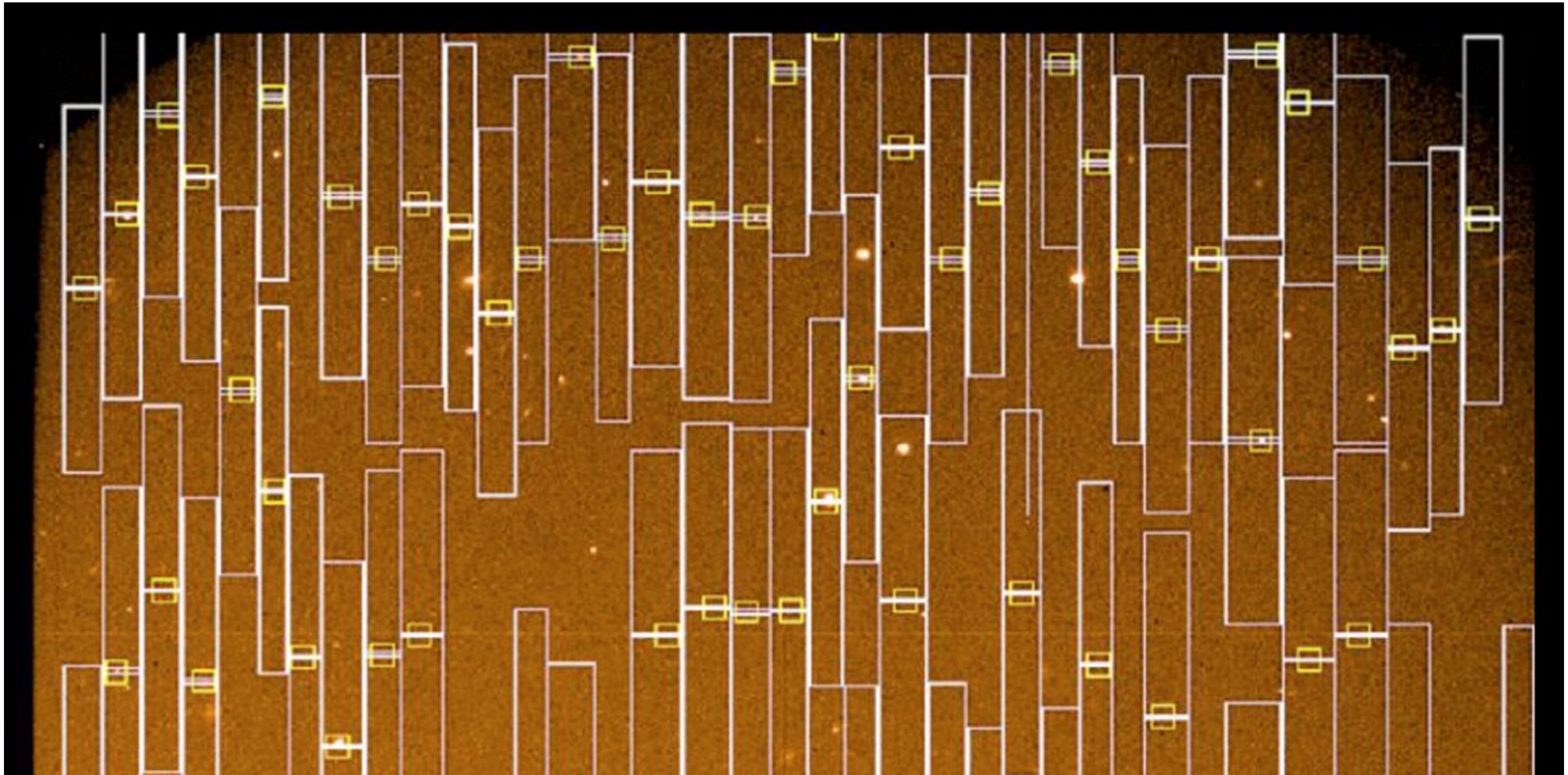


Multi Object Spectrographs - laser cut slits

VIMOS on the VLT telescopes

You decide where to put the slits on the science field

Can take up to two weeks to manufacture

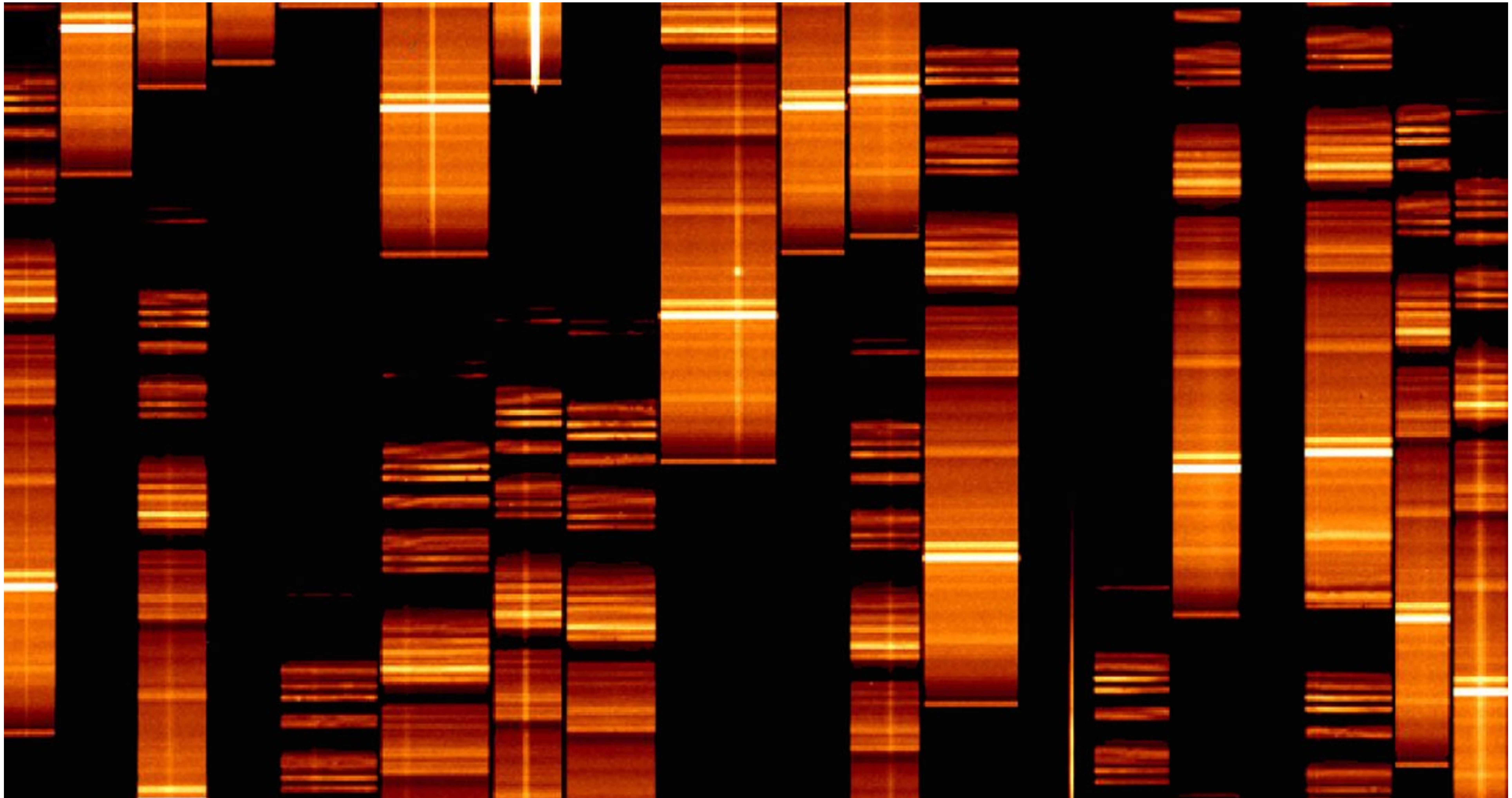


Multi Object Spectrographs - laser cut slits

VIMOS on the VLT telescopes

Number of spectra limited by sky coverage

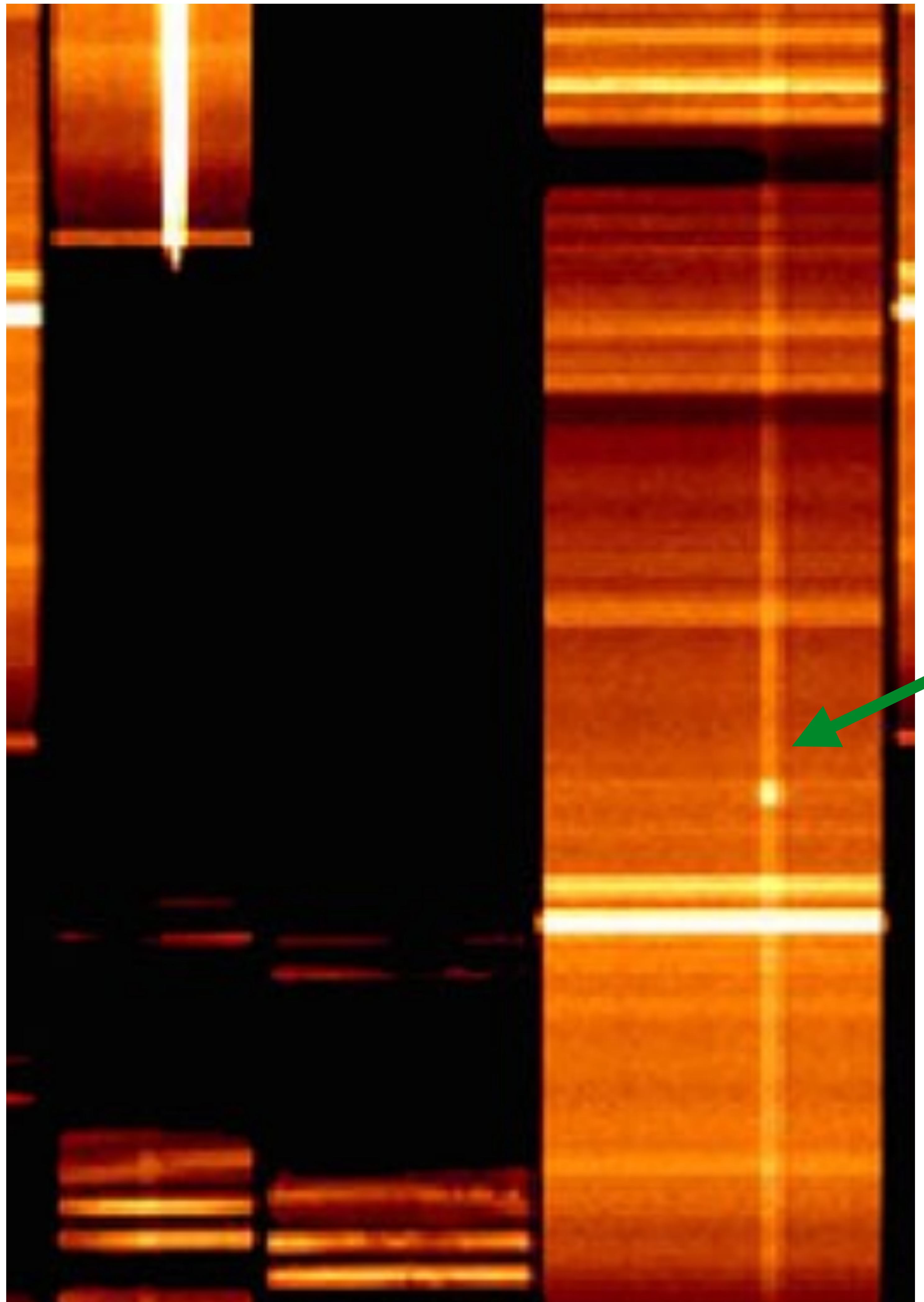
http://www.eso.org/public/news/eso0209/



Night sky emission lines in NIR

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

VIMOS on the VLT telescopes

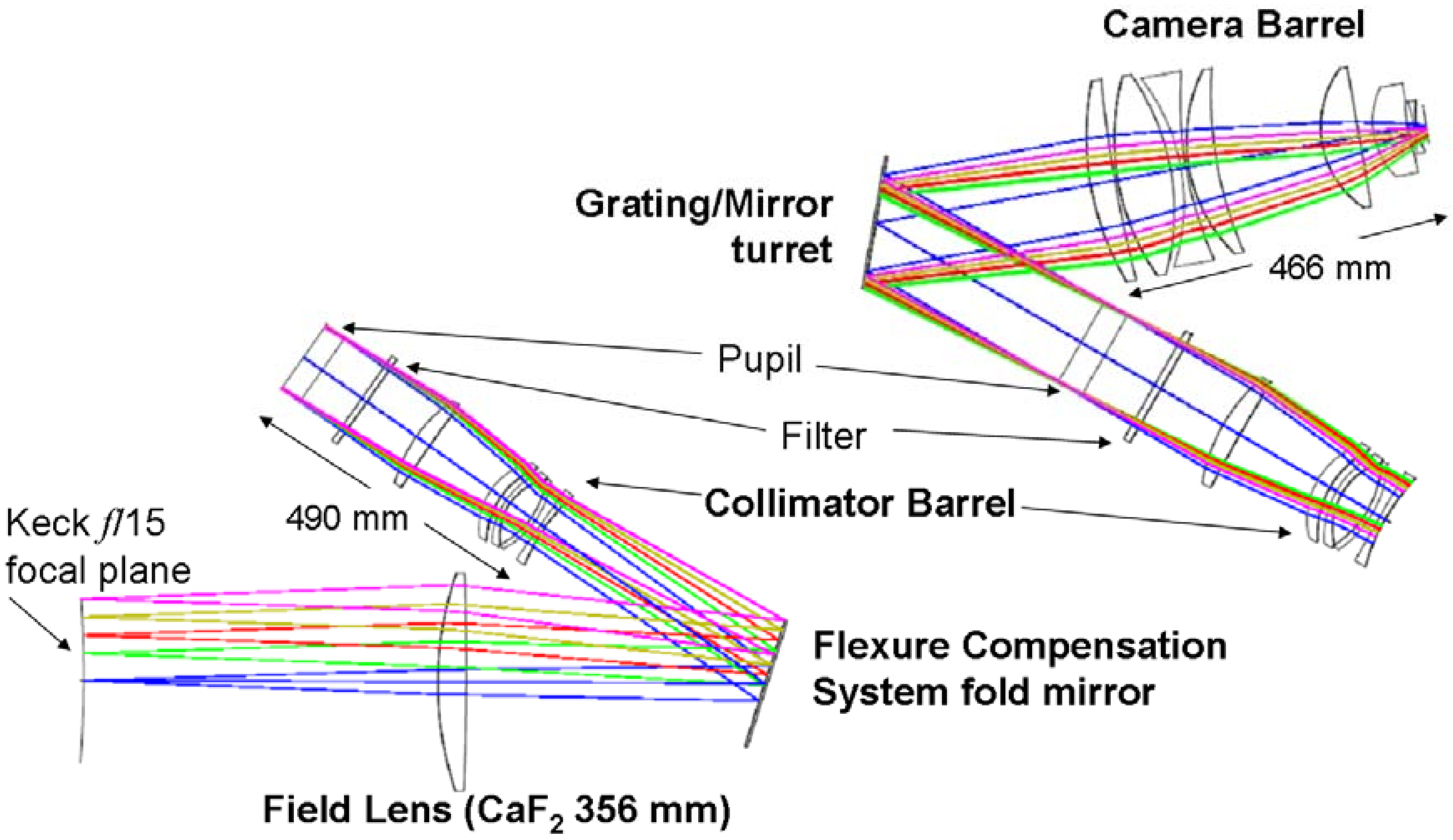


Spectrum of galaxy

Night sky emission lines

Configurable slits on MOSFIRE (Keck)

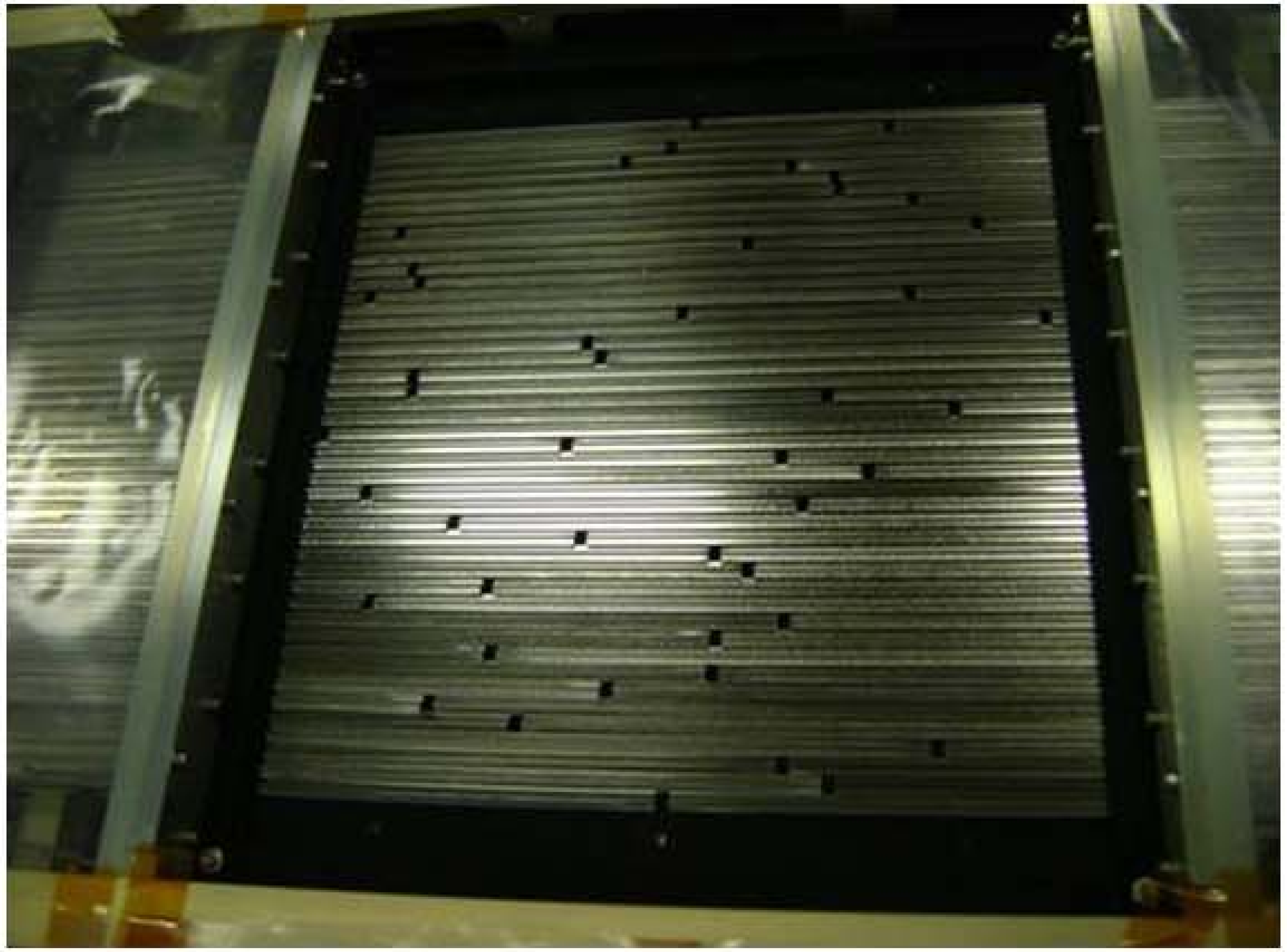
NIR multi-object spectrograph

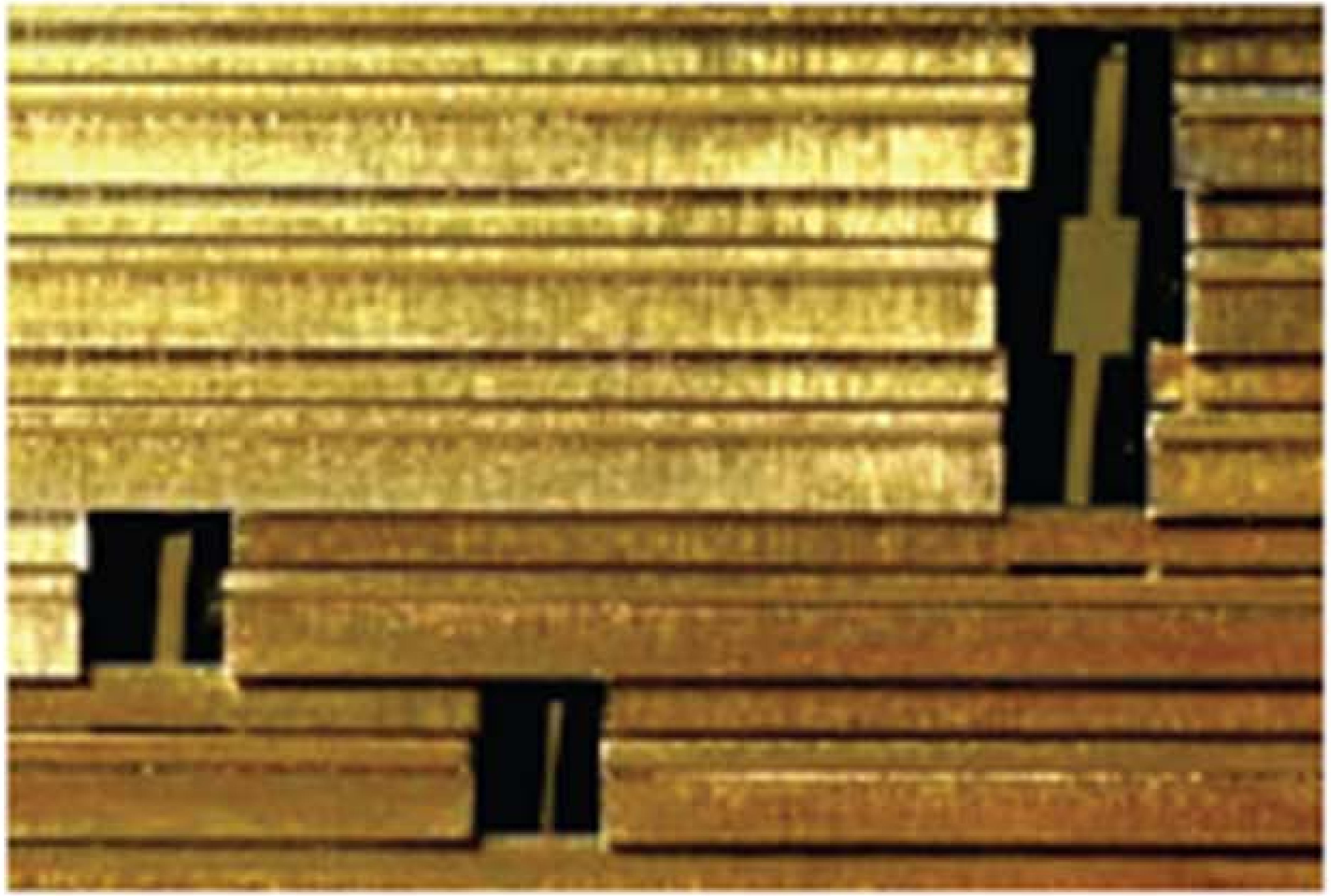


McLean 2012

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

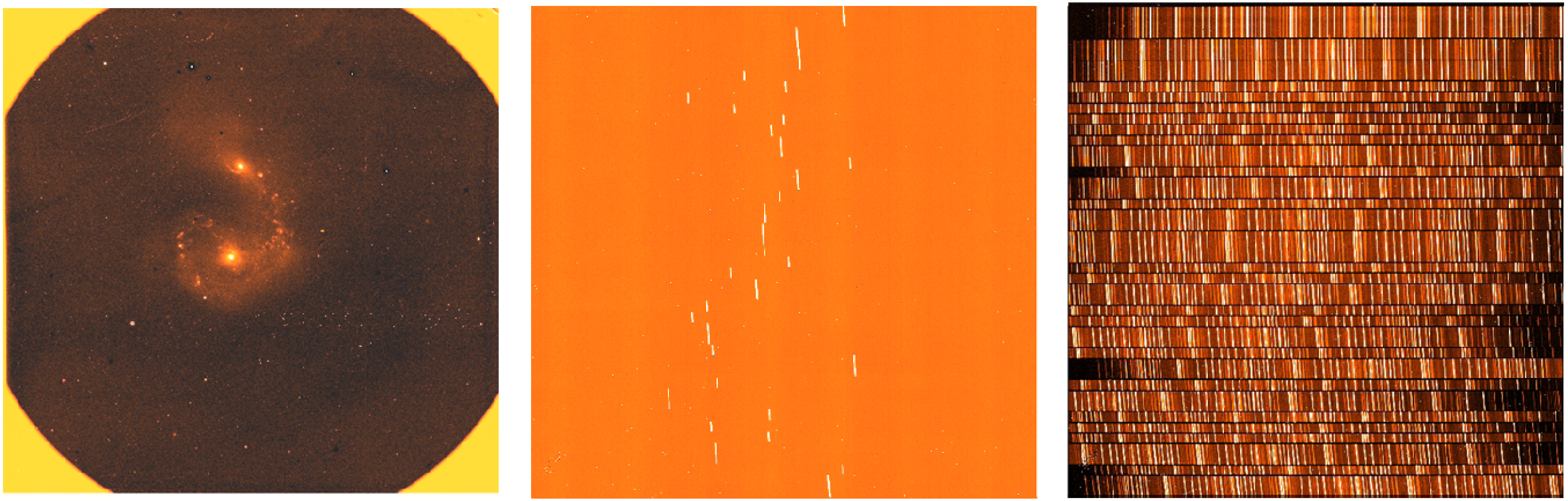
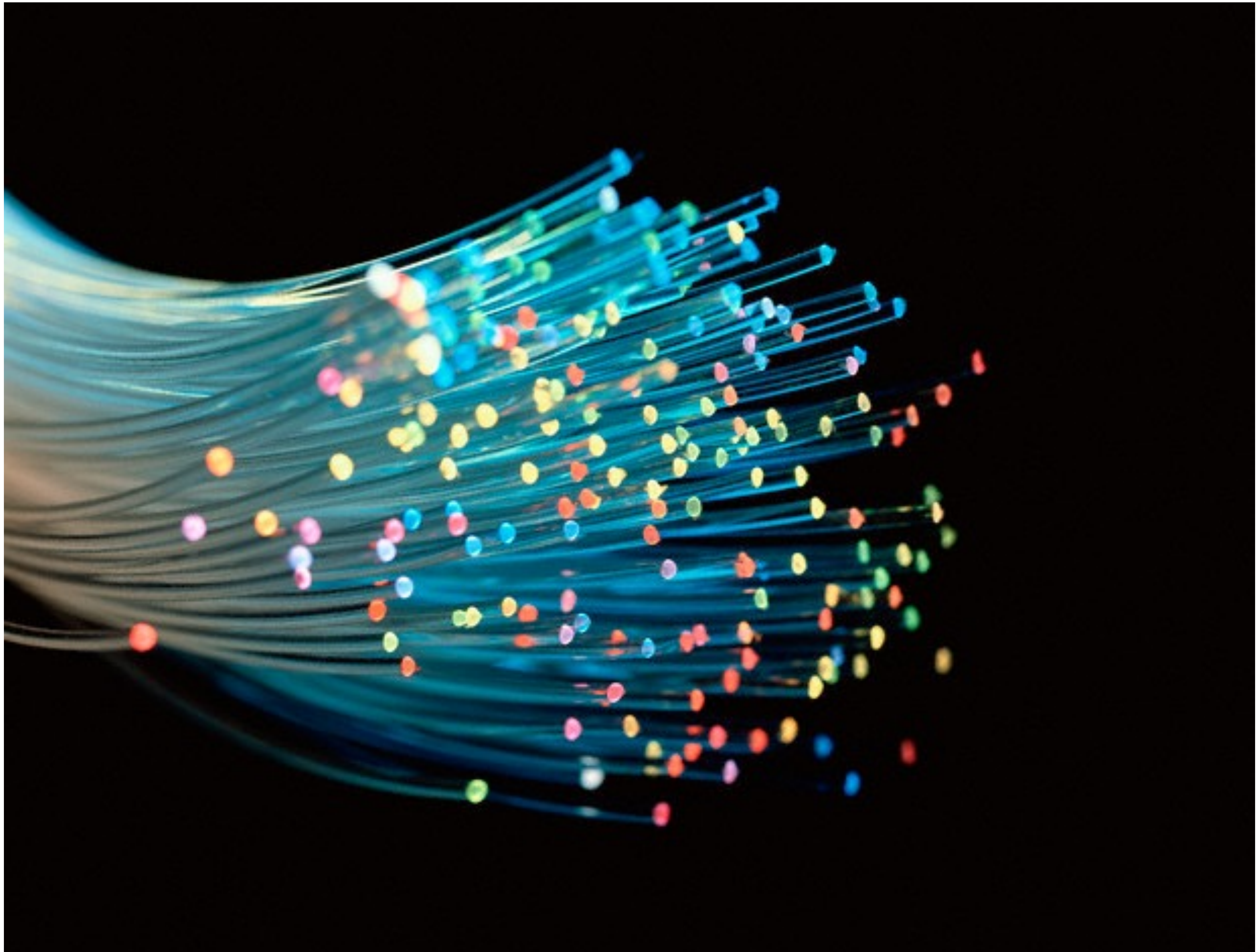


Figure 7. On the left is the layout of the MOSFIRE field on the sky with a 58s J-band image of The Antennae galaxies. The middle image is of a slit mask and the right image is the night sky emission with this mask in H-band.

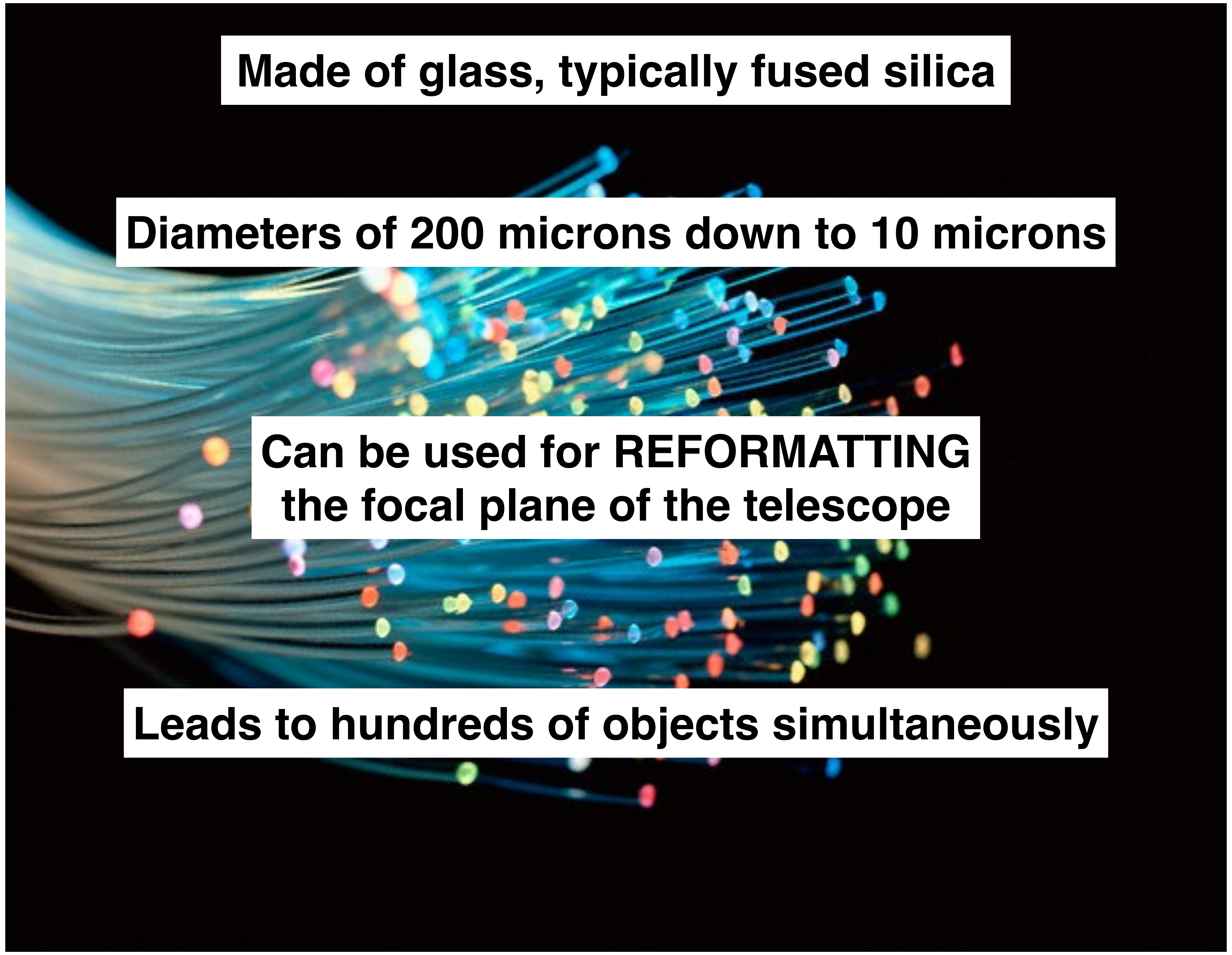
Lecture 10: Spectrographs

10.5 Fibre fed Spectrographs

Fibre Optics

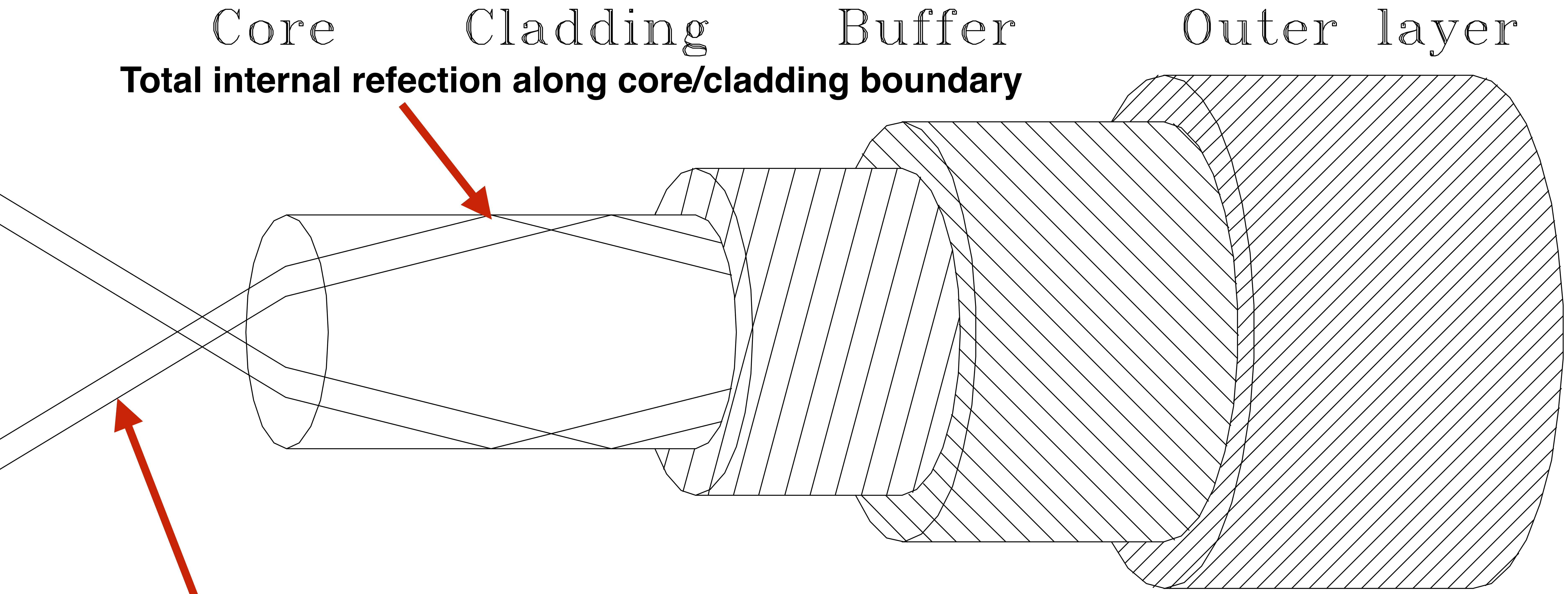


Fibre Optics



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

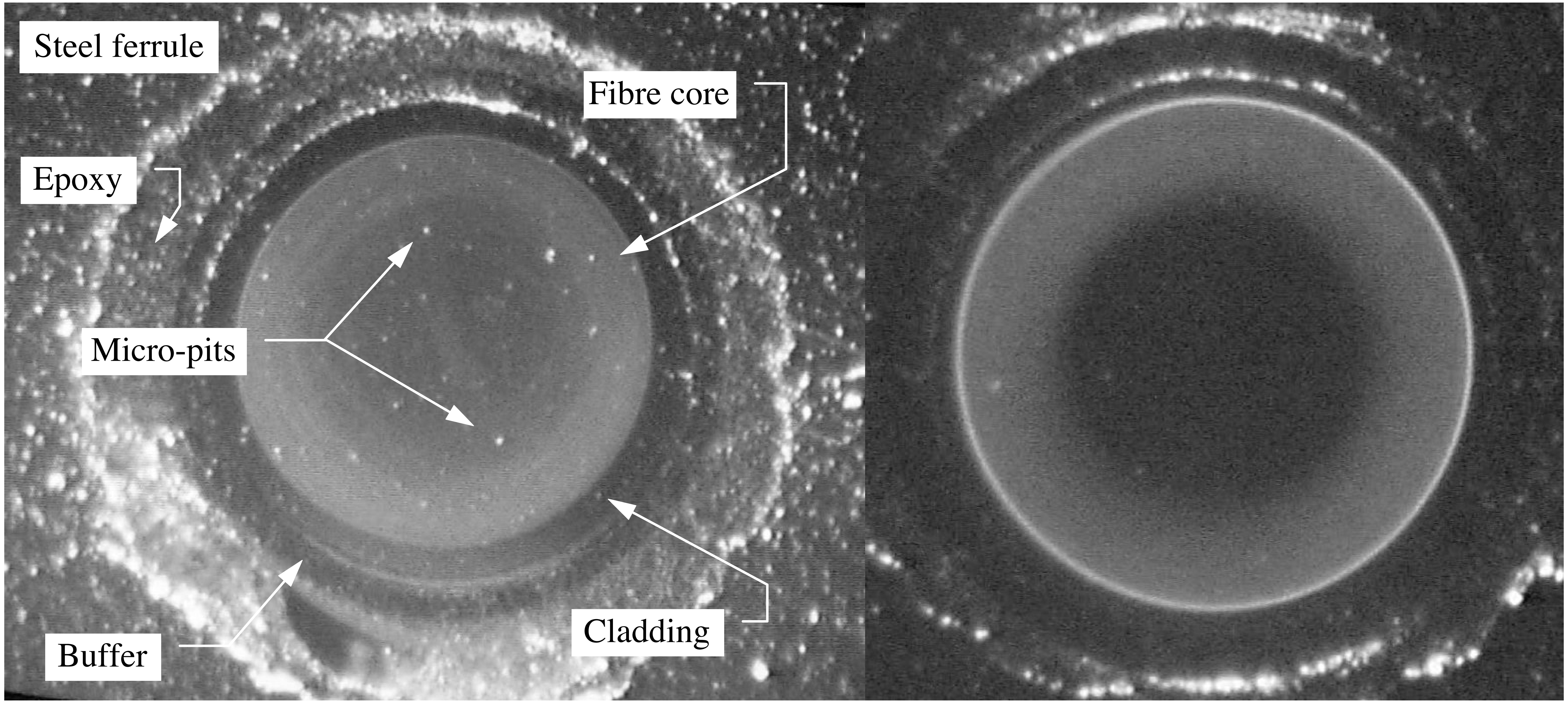
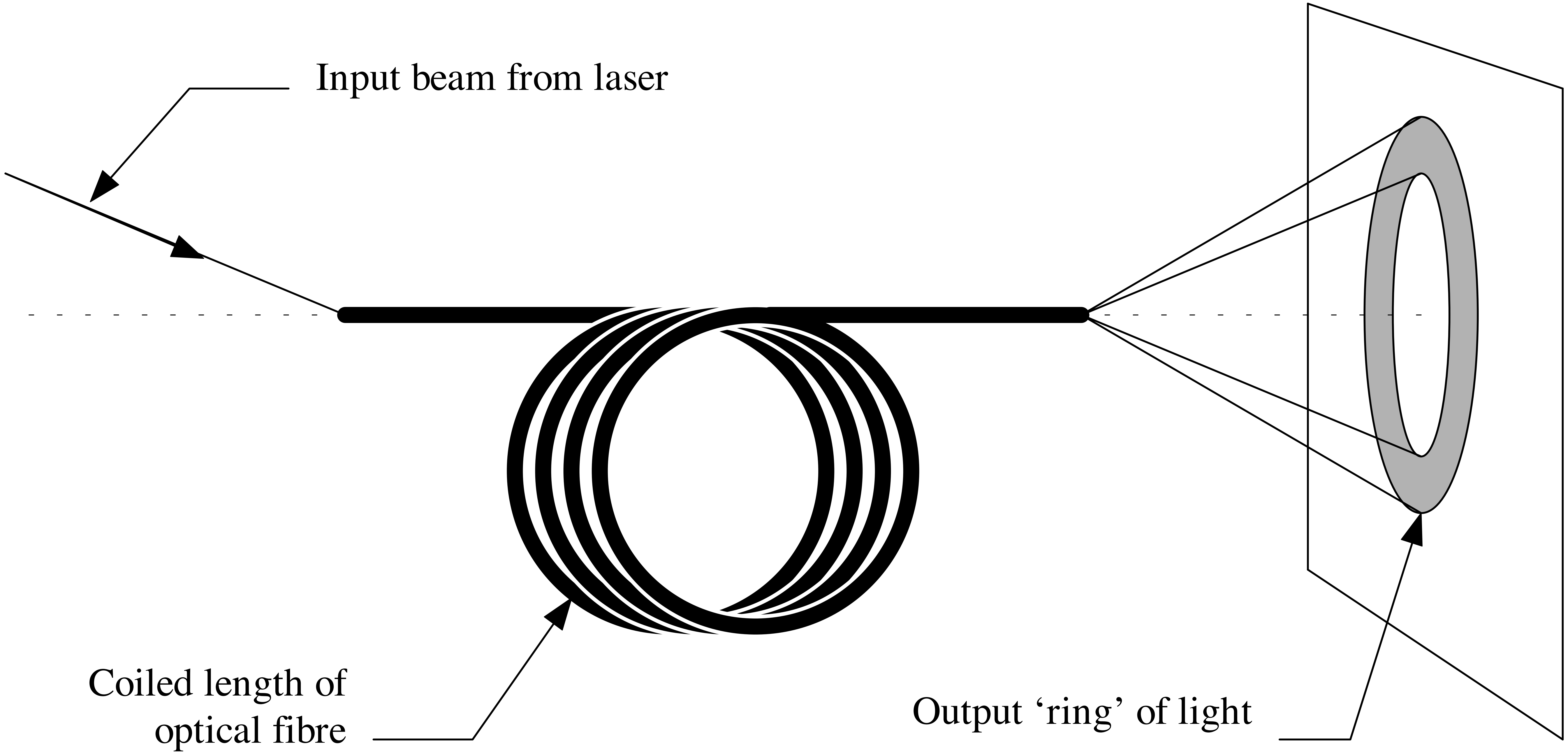


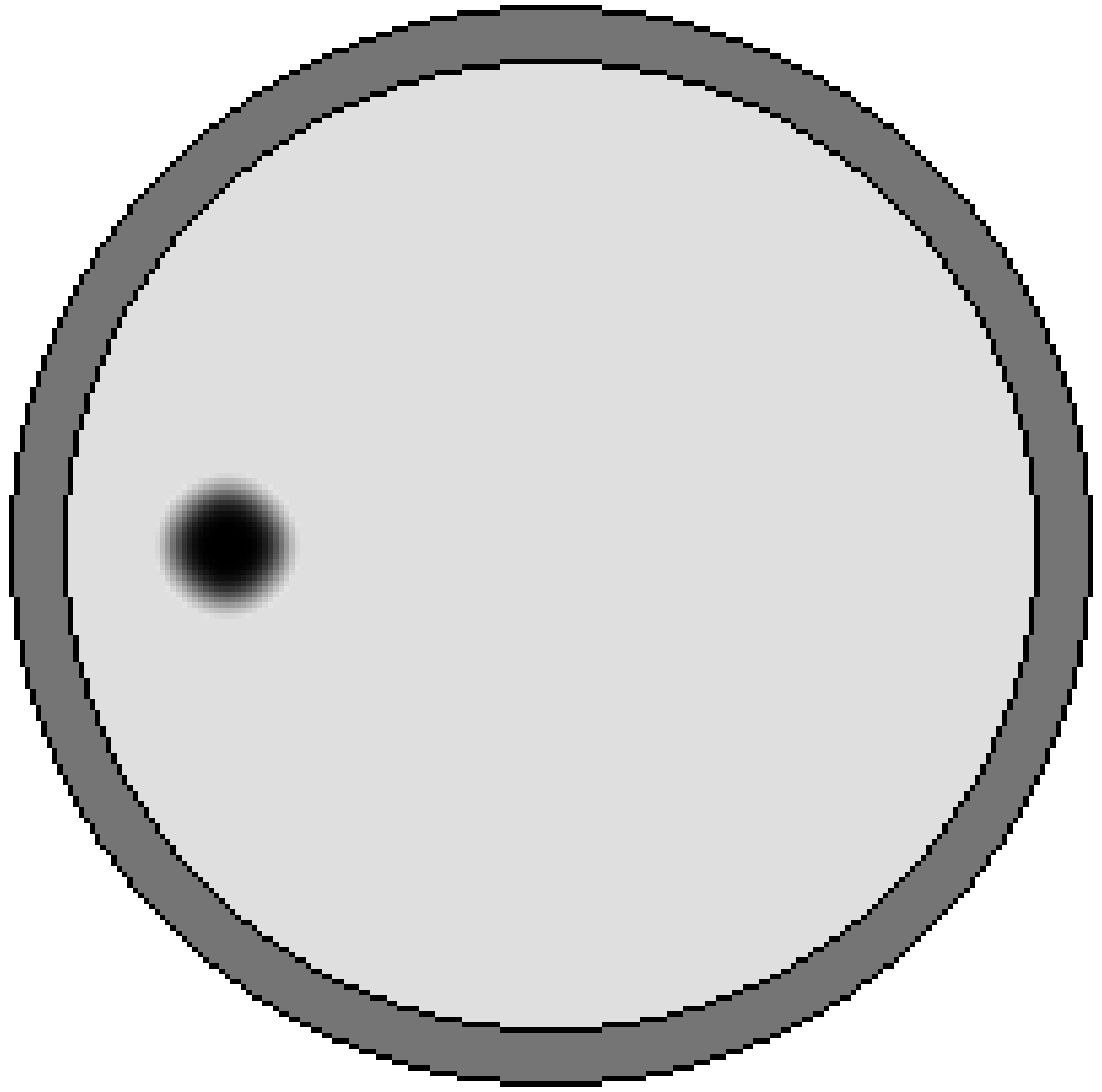
Figure 2-14 *Examining the fibre faces*. On the left the fibre face is checked for micro-pits - several can be clearly seen. On the right the back-illuminated fibre shows a clean ring of light across the face of the fibre.

Optical Fibre - azimuthal scrambling

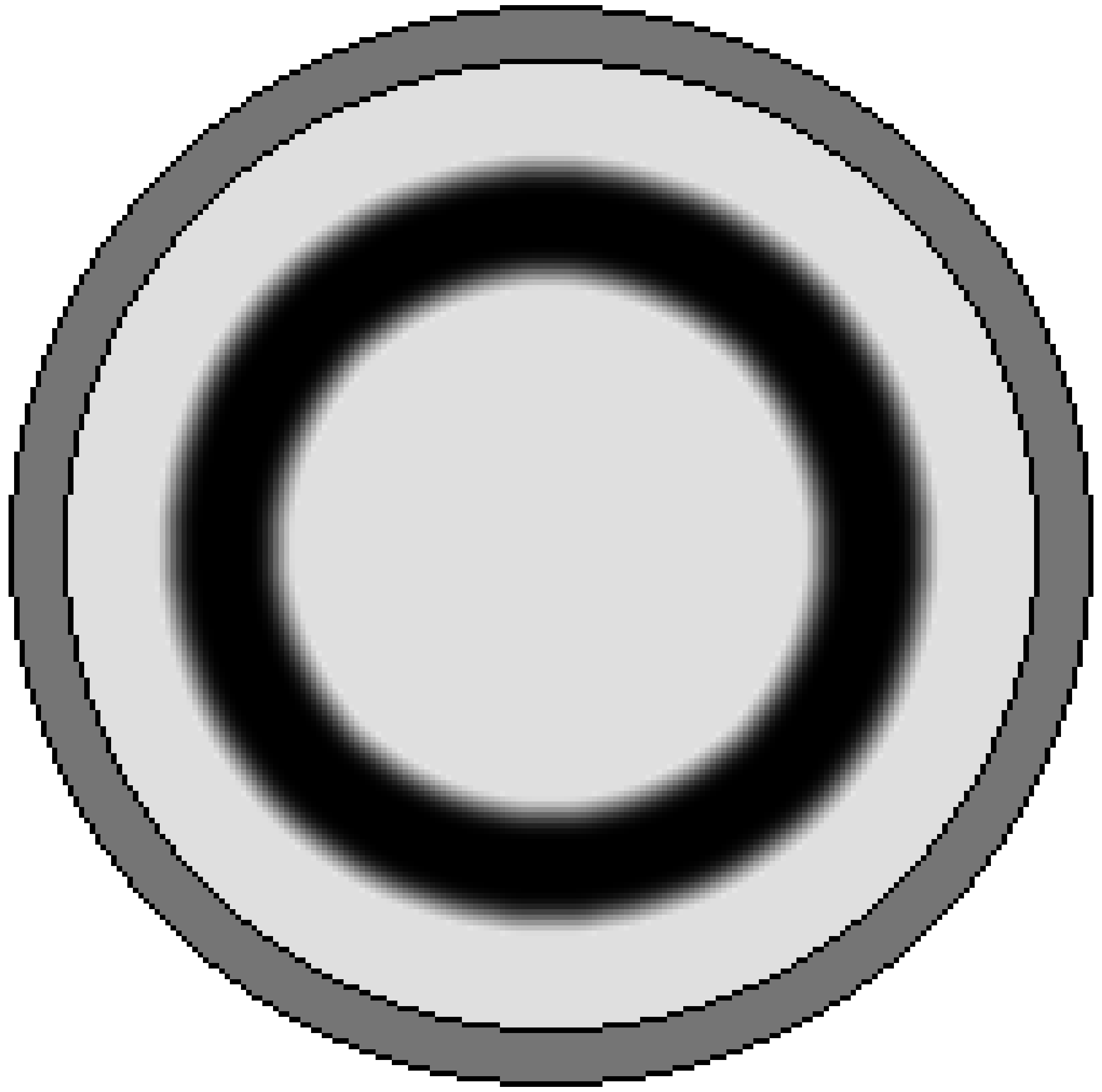


Thousands of internal reflections from curved interface

Optical Fibre - azimuthal scrambling



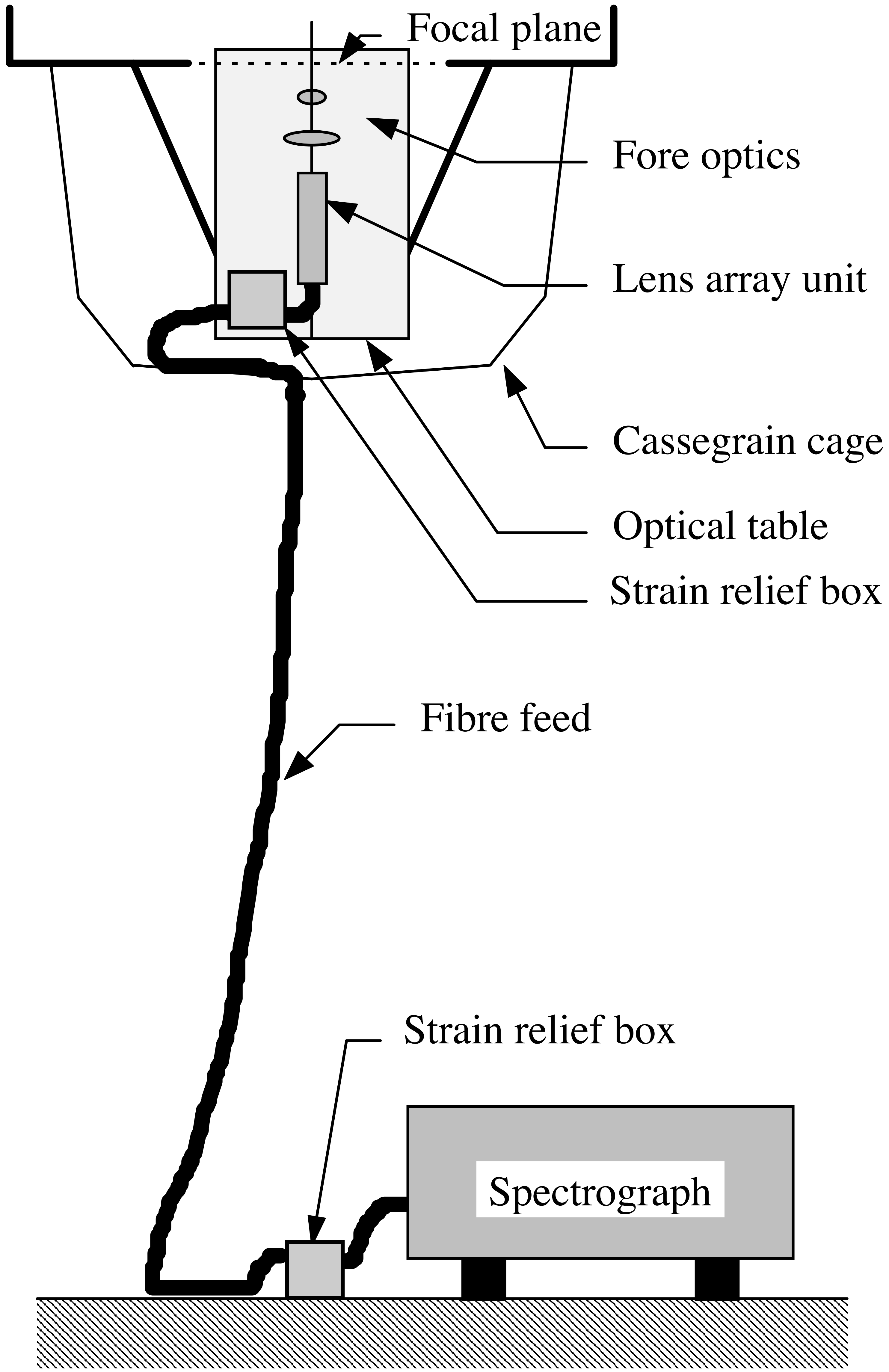
Input fibre face

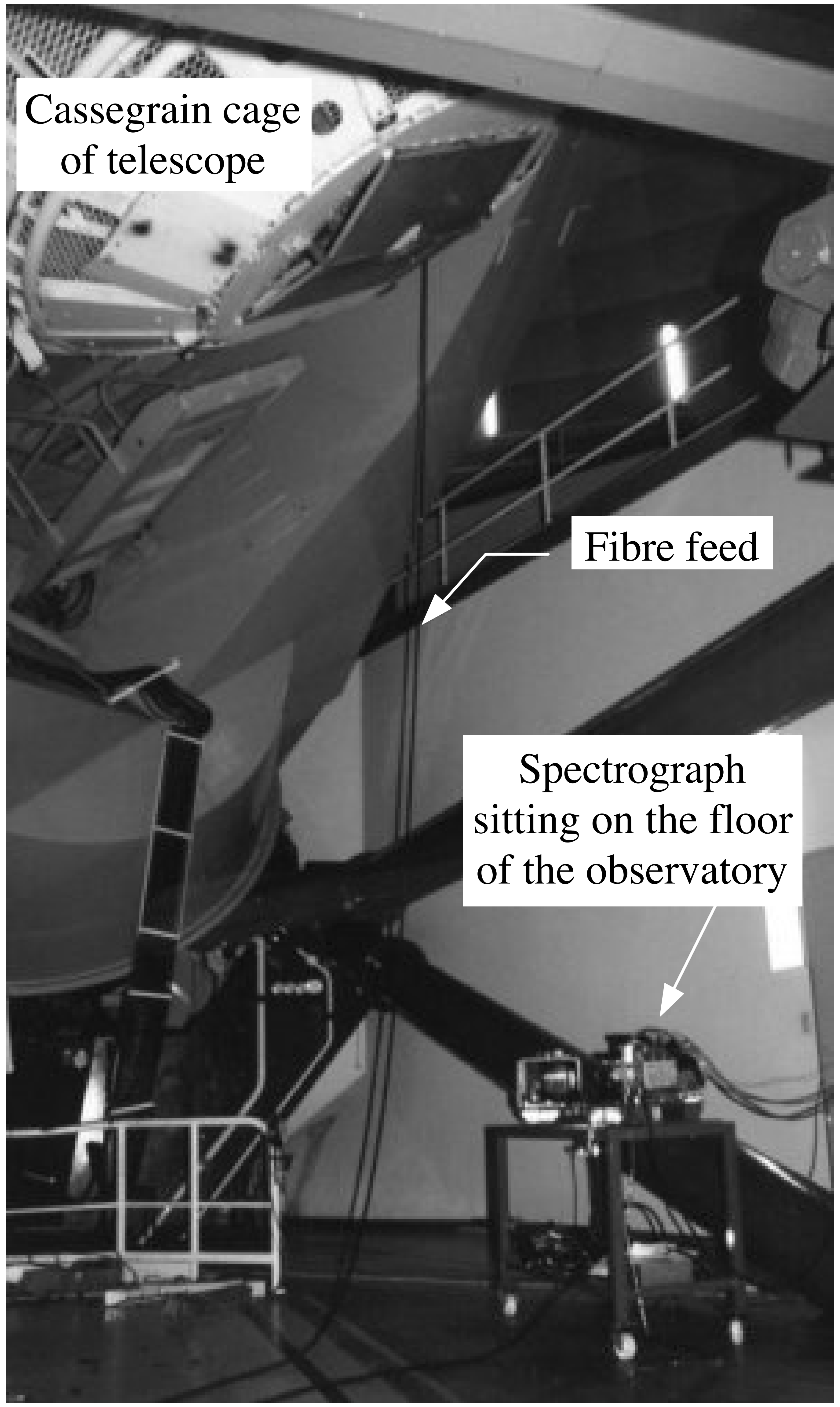


Output fibre face

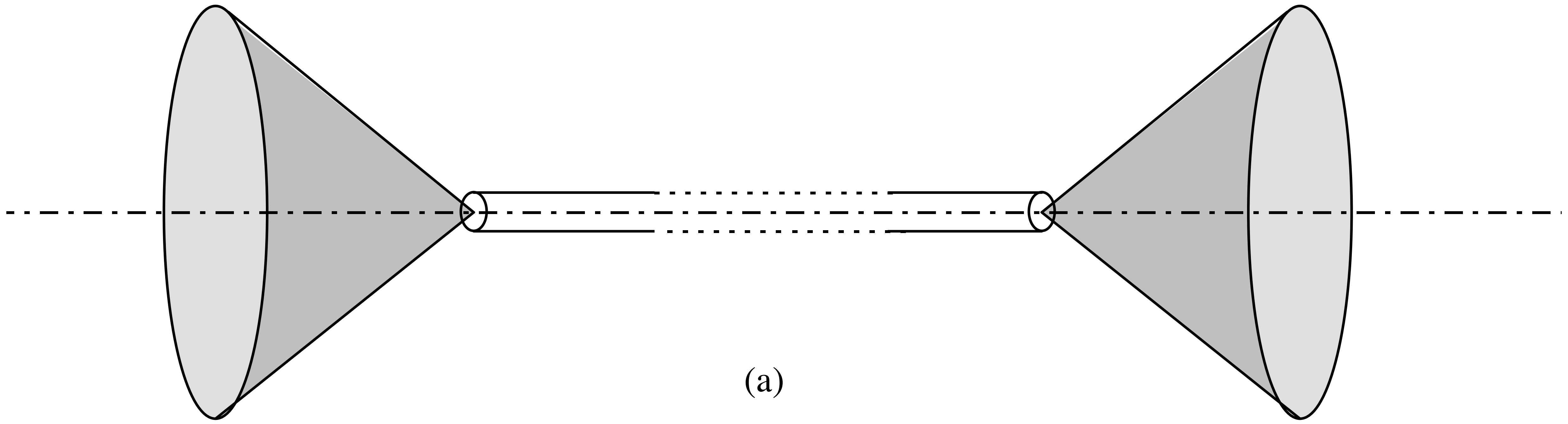
Looking down on the end of the polished fibre end

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

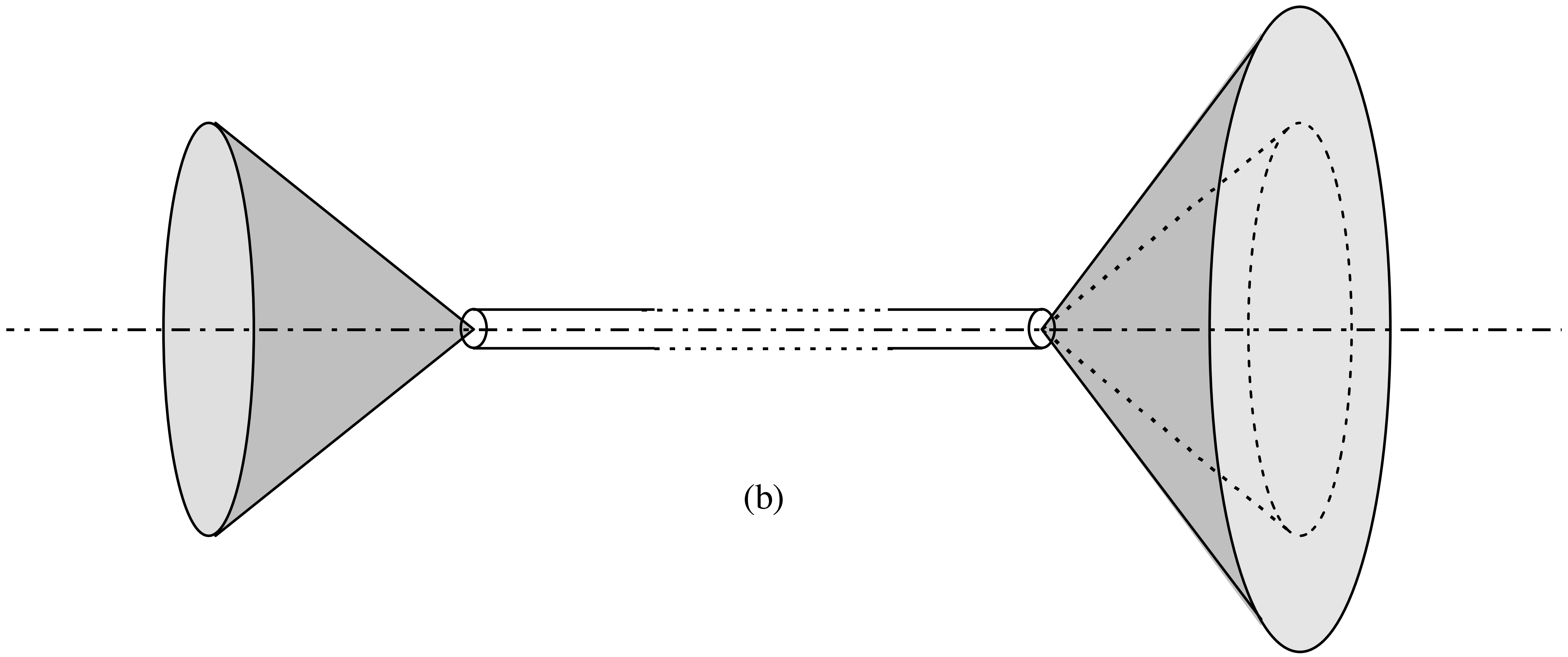




Optical Fibre - Focal Ratio Degradation

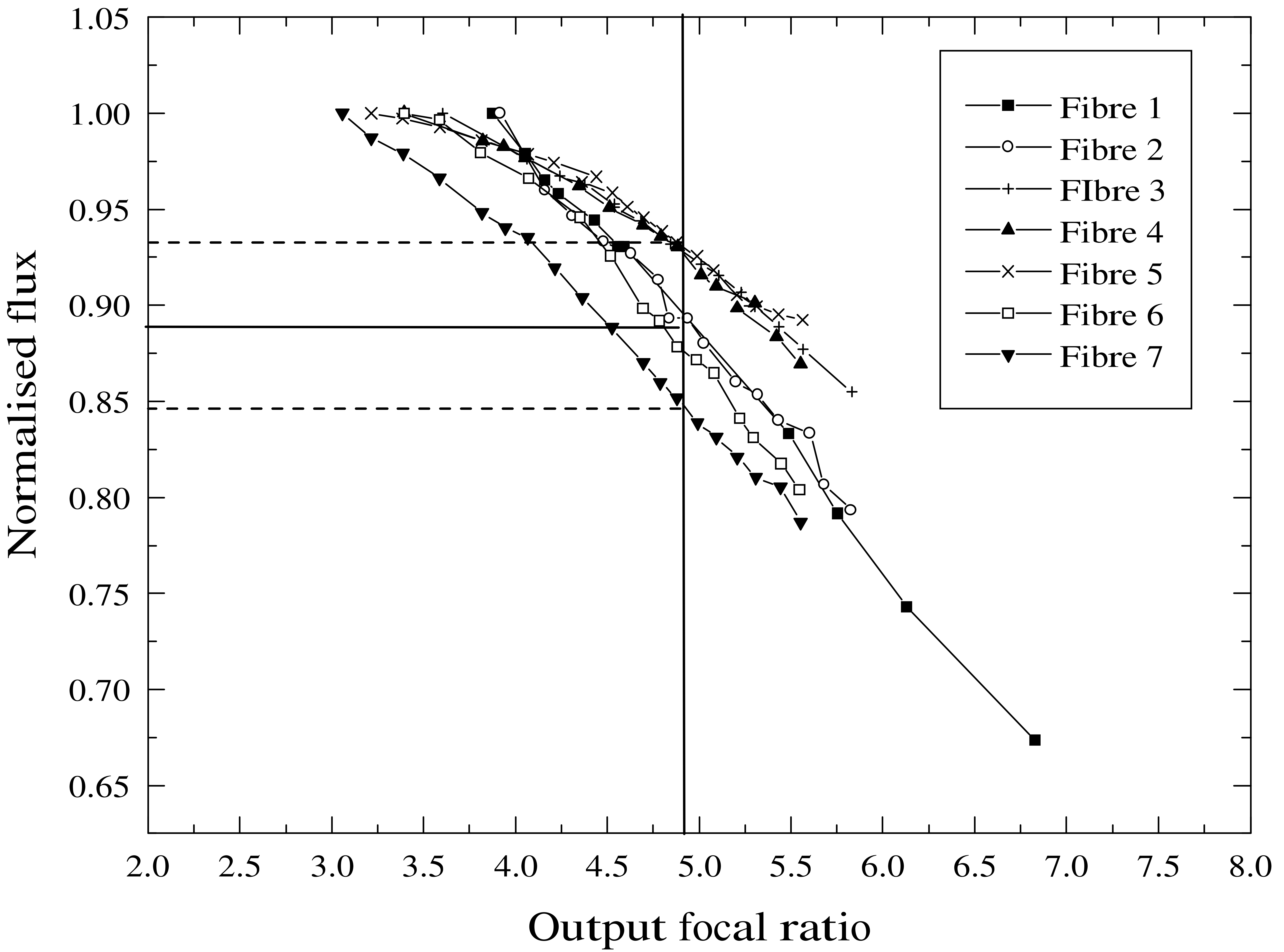


Ideal preservation of input beam angle and output beam angle



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



Plug plates drilled manually to match target fields

Hill 1988 ASPC

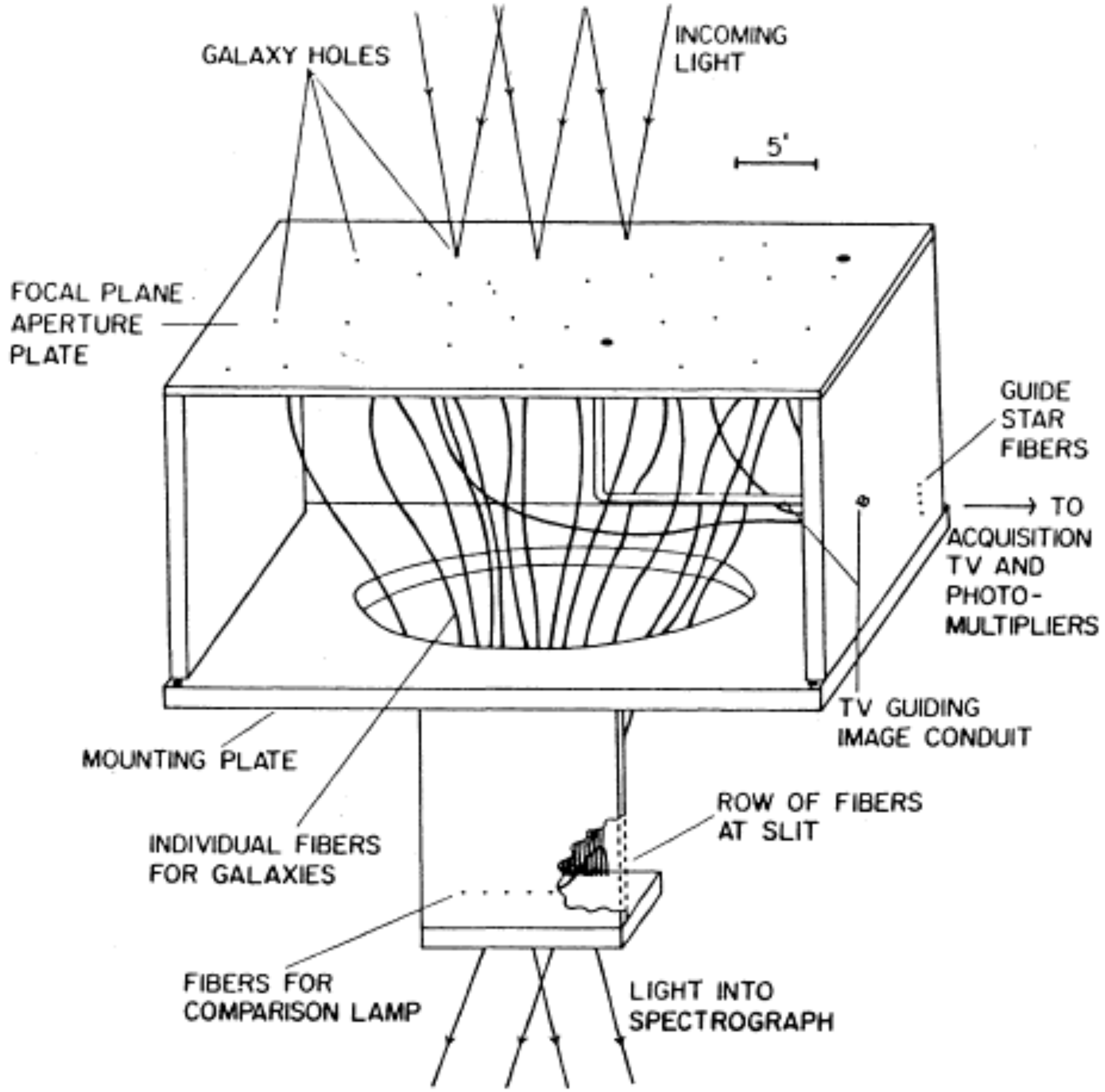
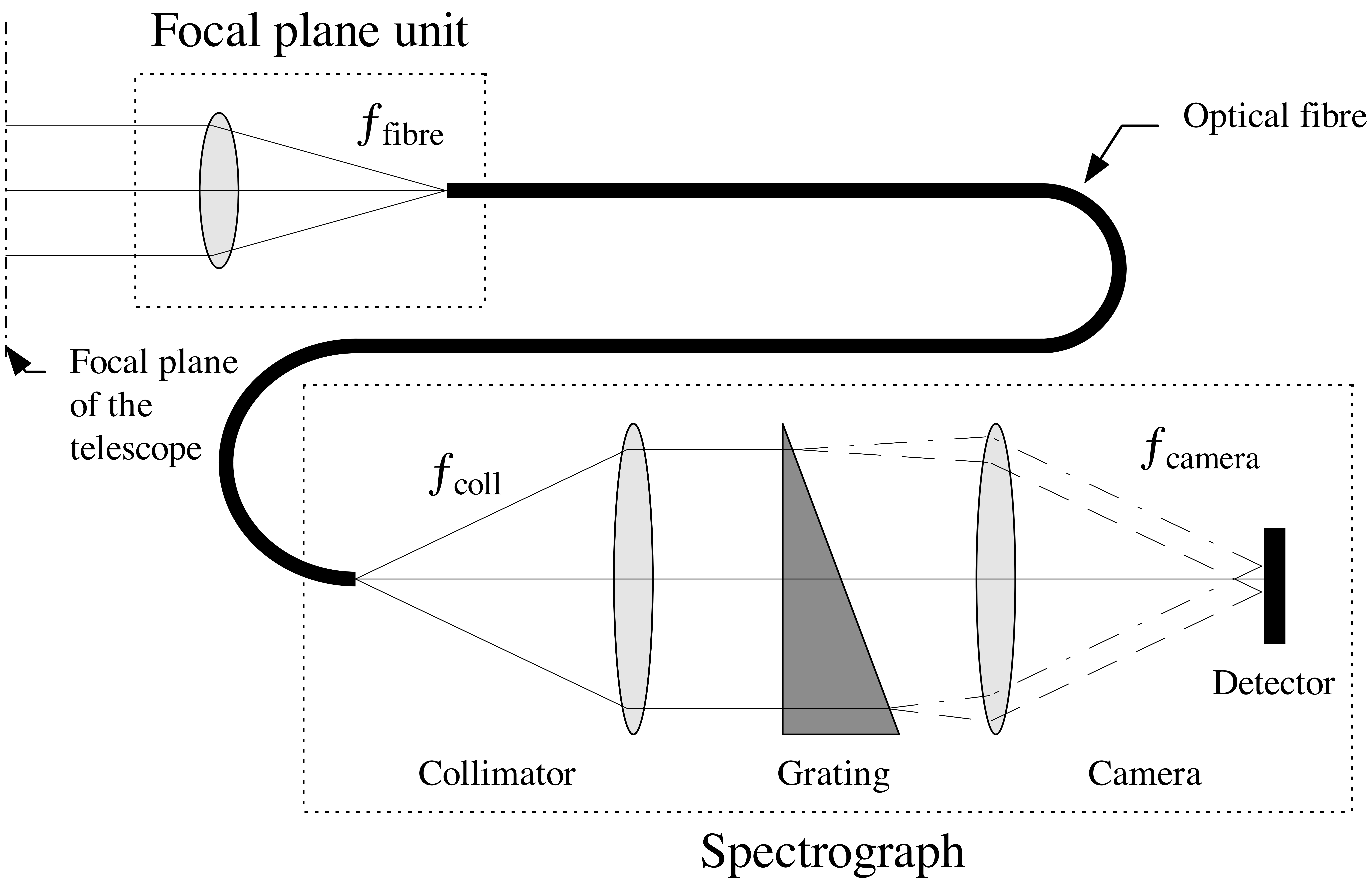


Figure 2. Schematic drawing of the aperture plate nucleus of the MEDUSA spectrograph.

Optical Fibre Spectrograph



Gluing optical fibres onto a glass plate(!)

Fred Watson

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?

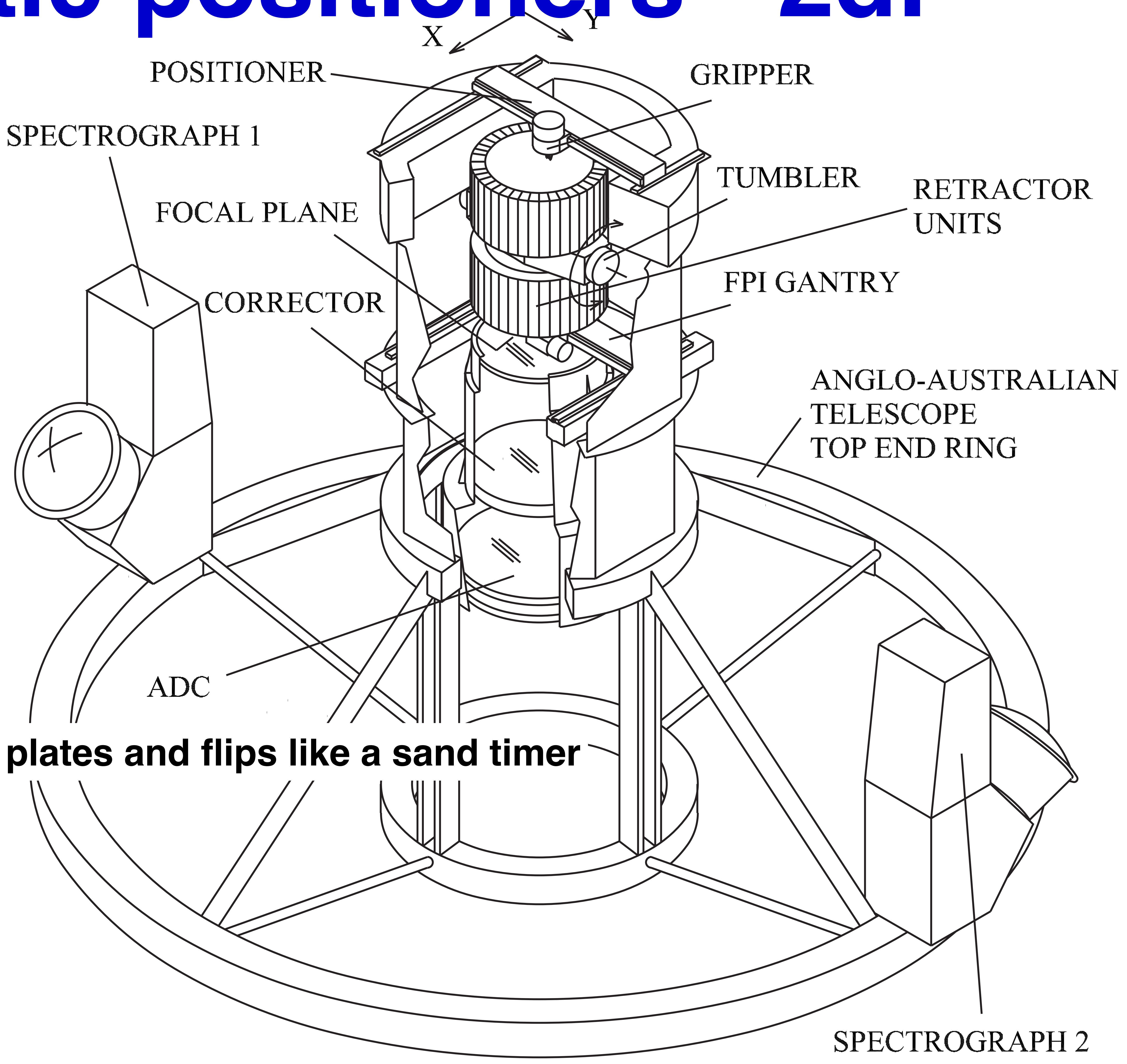
Robotic positioners - 2dF

Sits at prime focus of 4m Anglo-Australian Telescope

Diameter of 140 microns
(2.1 arcsec on the sky)

400 fibres positioned whilst
other 400 are observing

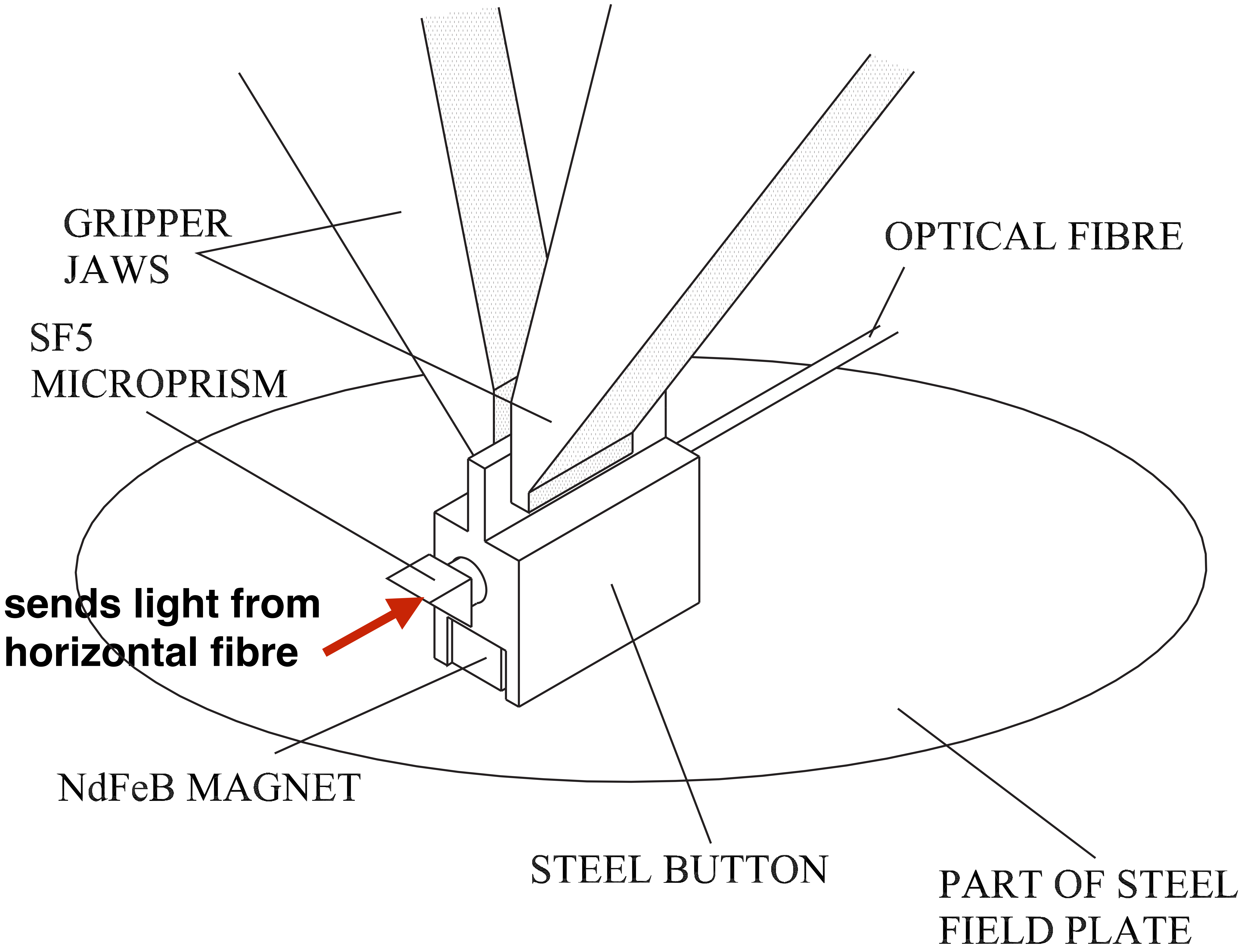
Robotic positioners - 2dF



Tumbler has two plates and flips like a sand timer

Lewis (2002)

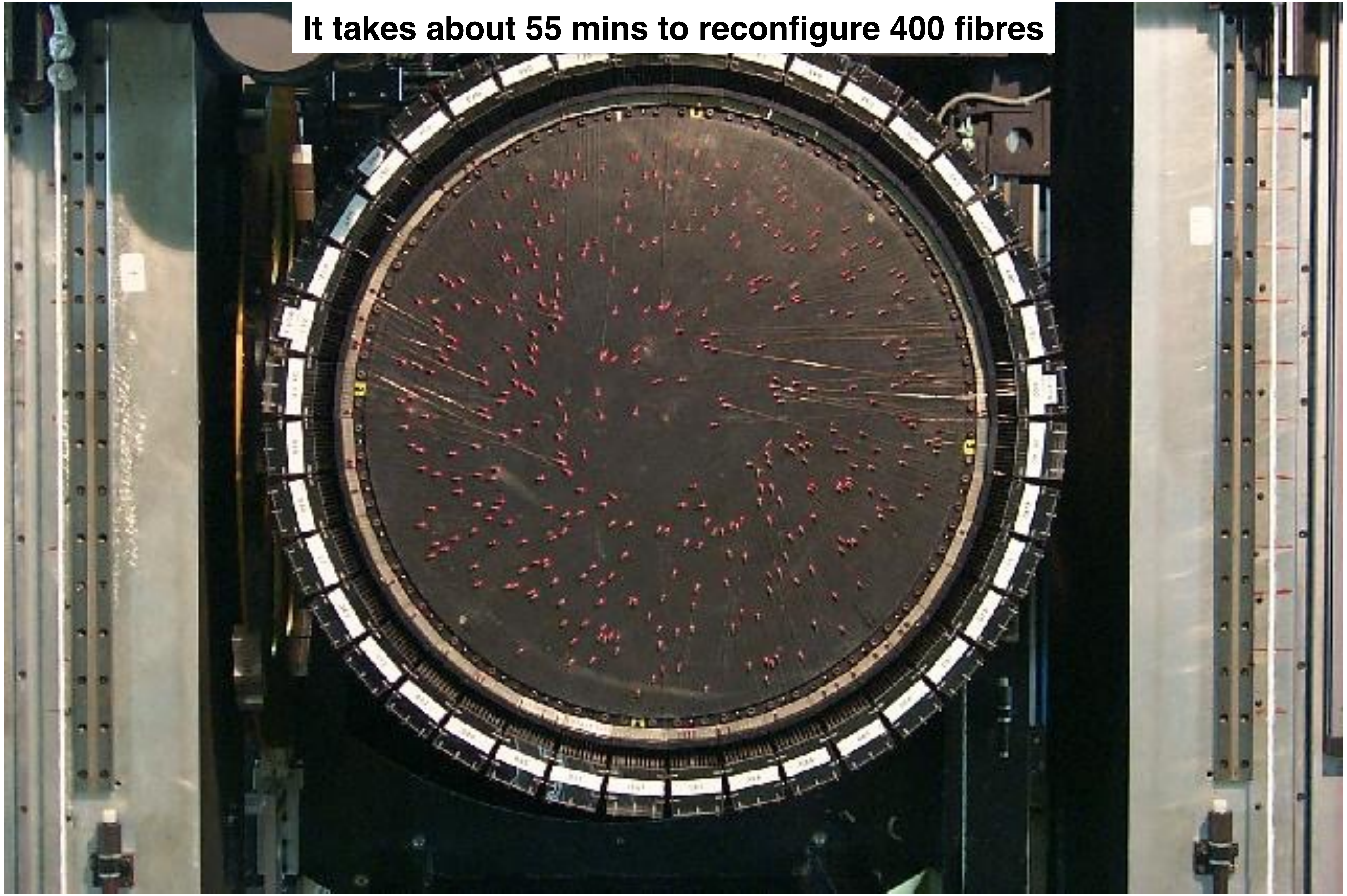
Robotic positioners - 2dF



1.2mm prism sends light from vertical into horizontal fibre

Lewis (2002)

Robotic positioners - 2dF

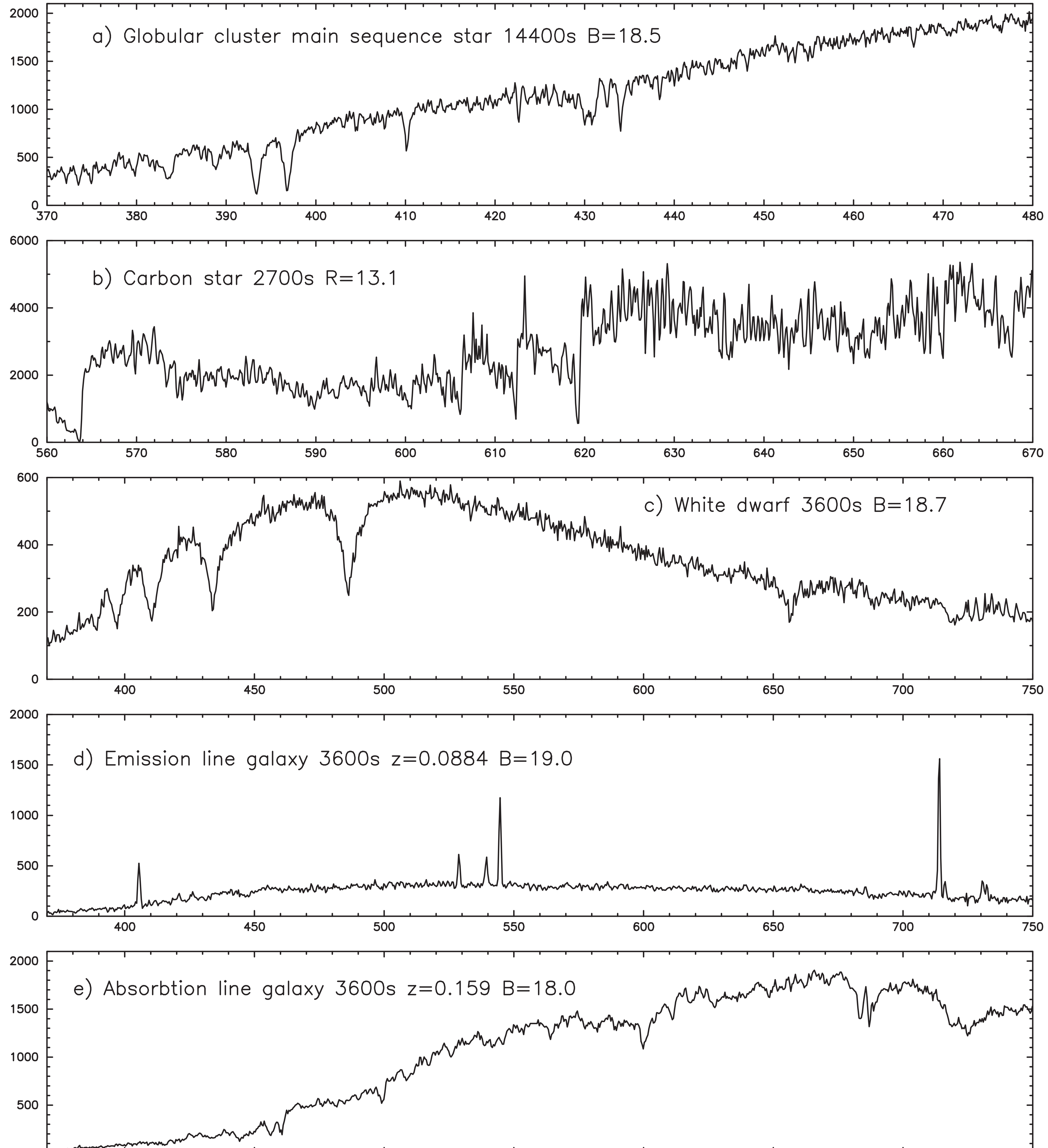


Physical size of fiber carriers - cannot get two fibres closer than 30 arc seconds

Densely packed fields require MULTIPLE observations

Robotic positioners - 2dF

Lewis (2002)



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

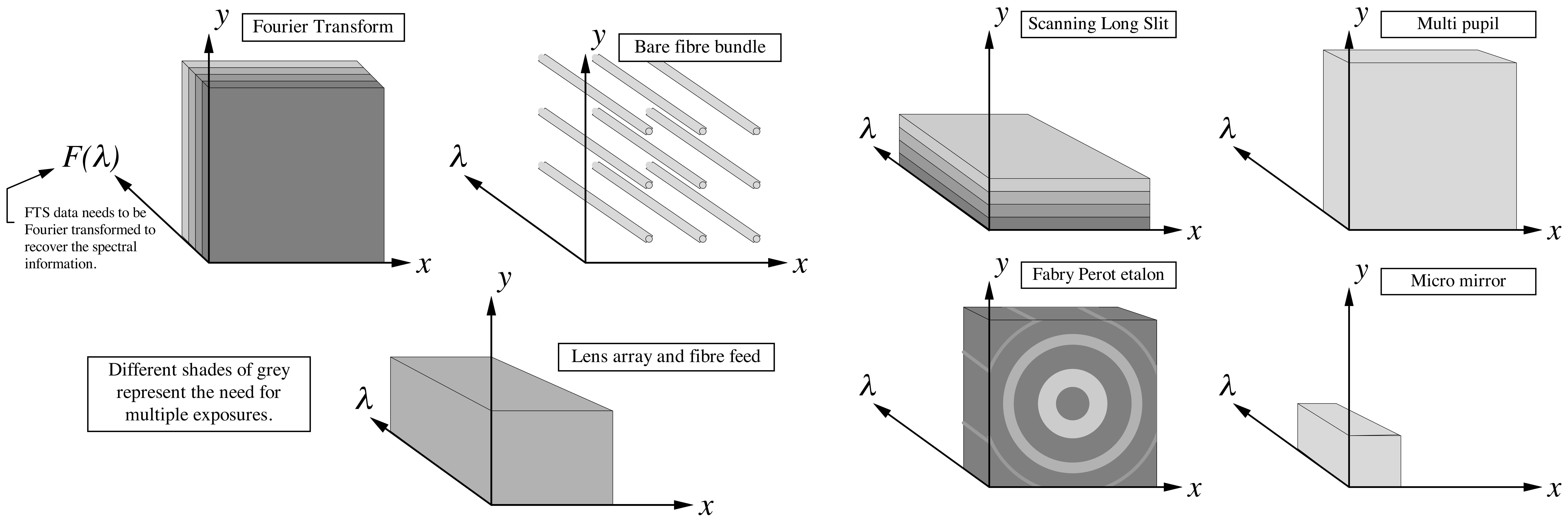
Robotic positioners - 2dF

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

Lecture 10: Spectrographs

10.6 Three Dimensional Spectroscopy

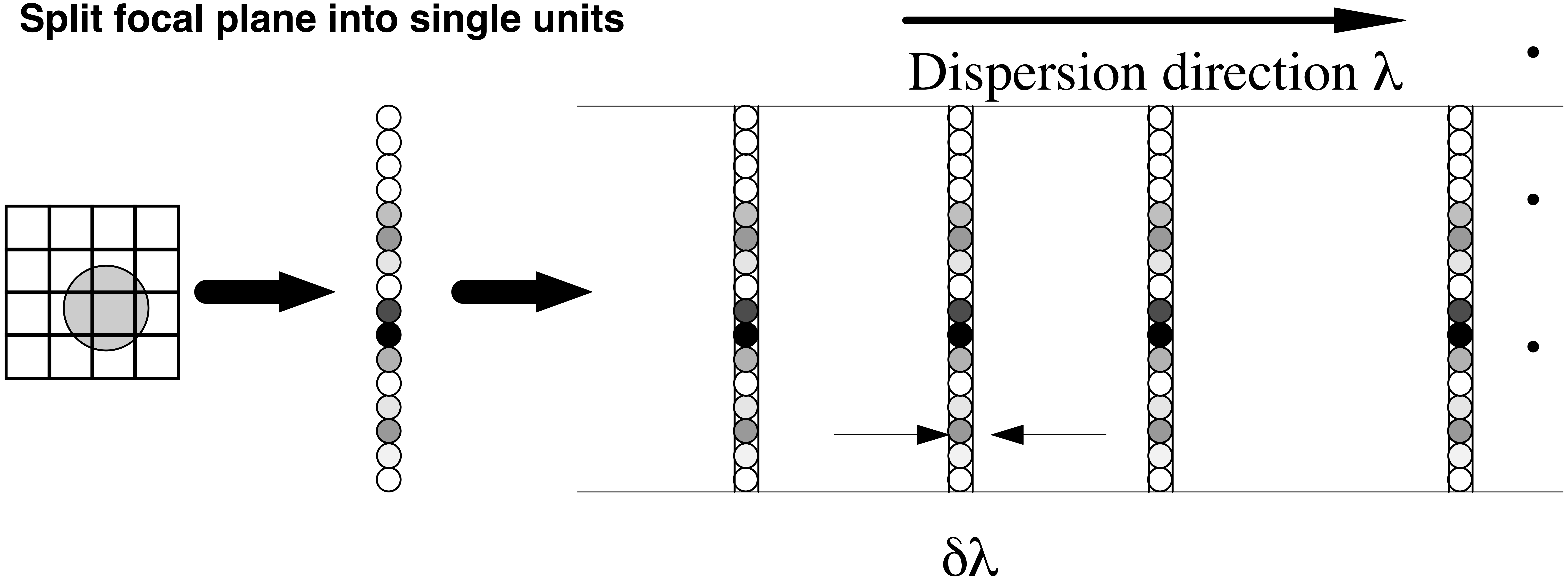
3D spectroscopy



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

- **Pros:** complete reformatting of the sky possible
- Decouples IFU from spectrograph
- **Cons:** typically small (10 arcsec) fields of view
- **Cons:** variable fibre transmission

Optical Fibre

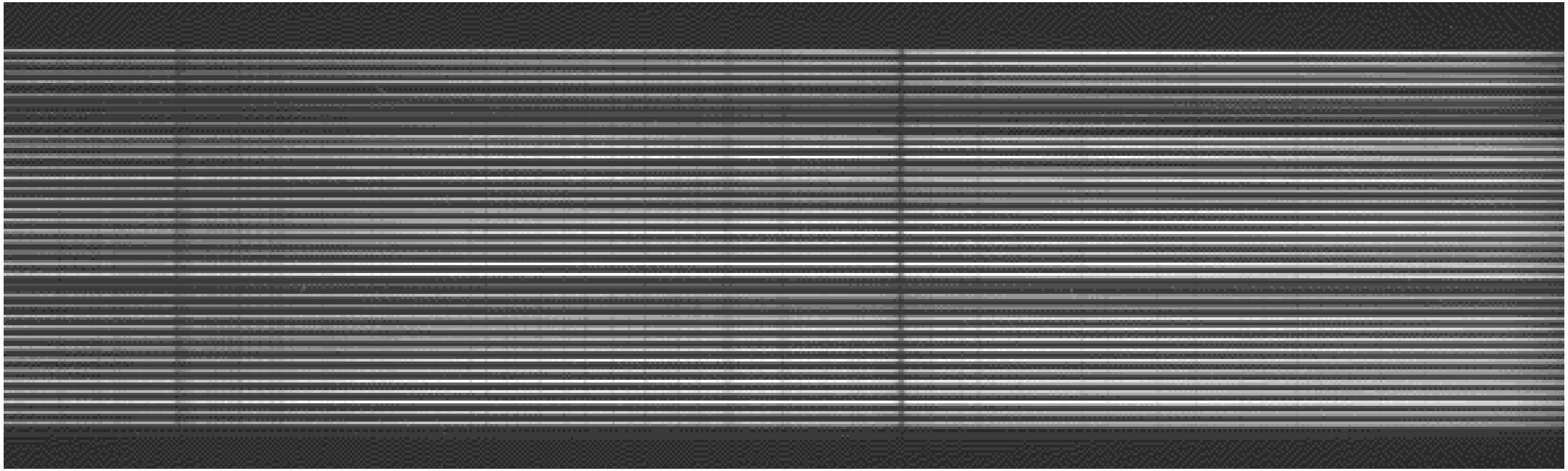


Figure 6-1 *A raw IFS data frame*. In this data frame from SPIRAL the dispersion axis is across the page and the 37 separate fibre tracks can be seen. This is a twilight sky exposure, clearly showing absorption features in the atmosphere and the variation in throughput between fibres.

Hexagonal lenslets on the sky

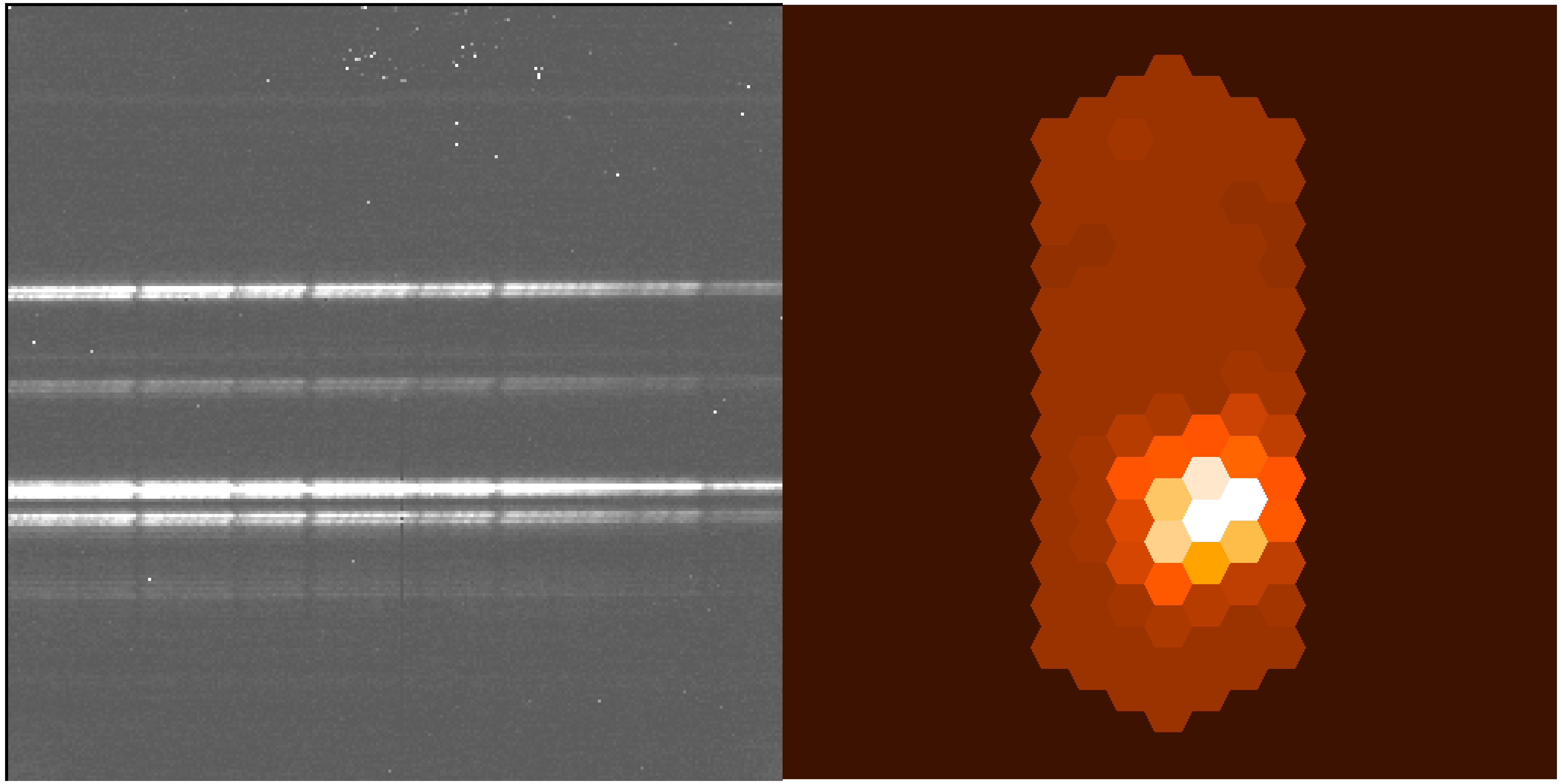
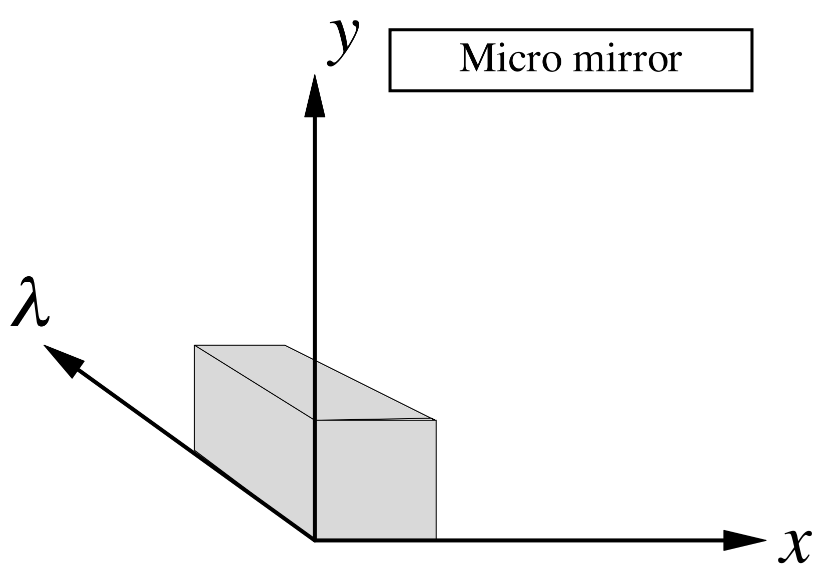


Figure 9-1 *Image reconstruction using the LDISPLAY software*. The image of the left is a raw image from the COHSI spectrograph. By knowing the relation between fibres on the sky and fibres in the slit an image can be reconstructed (right-hand panel).

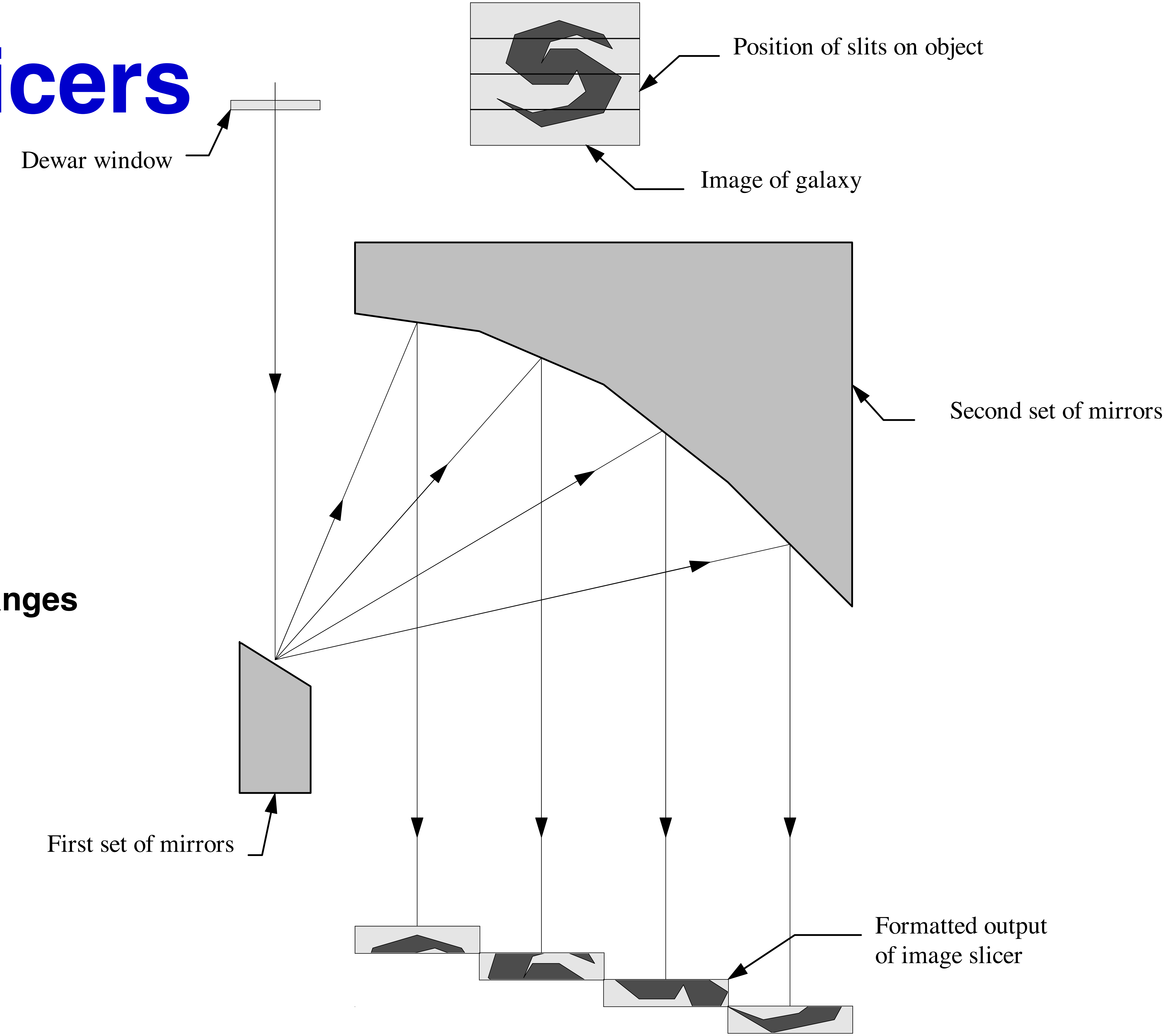
- **Pros:** (x,y) versus wavelength can be designed for the science case
- **Cons:** typically small (10 arcsec) fields of view

Image Slicers



Small field of views

Large wavelength ranges



SPIFFI image slicer

[Eisenhauer 2003 ESO Messenger 113 17 25]

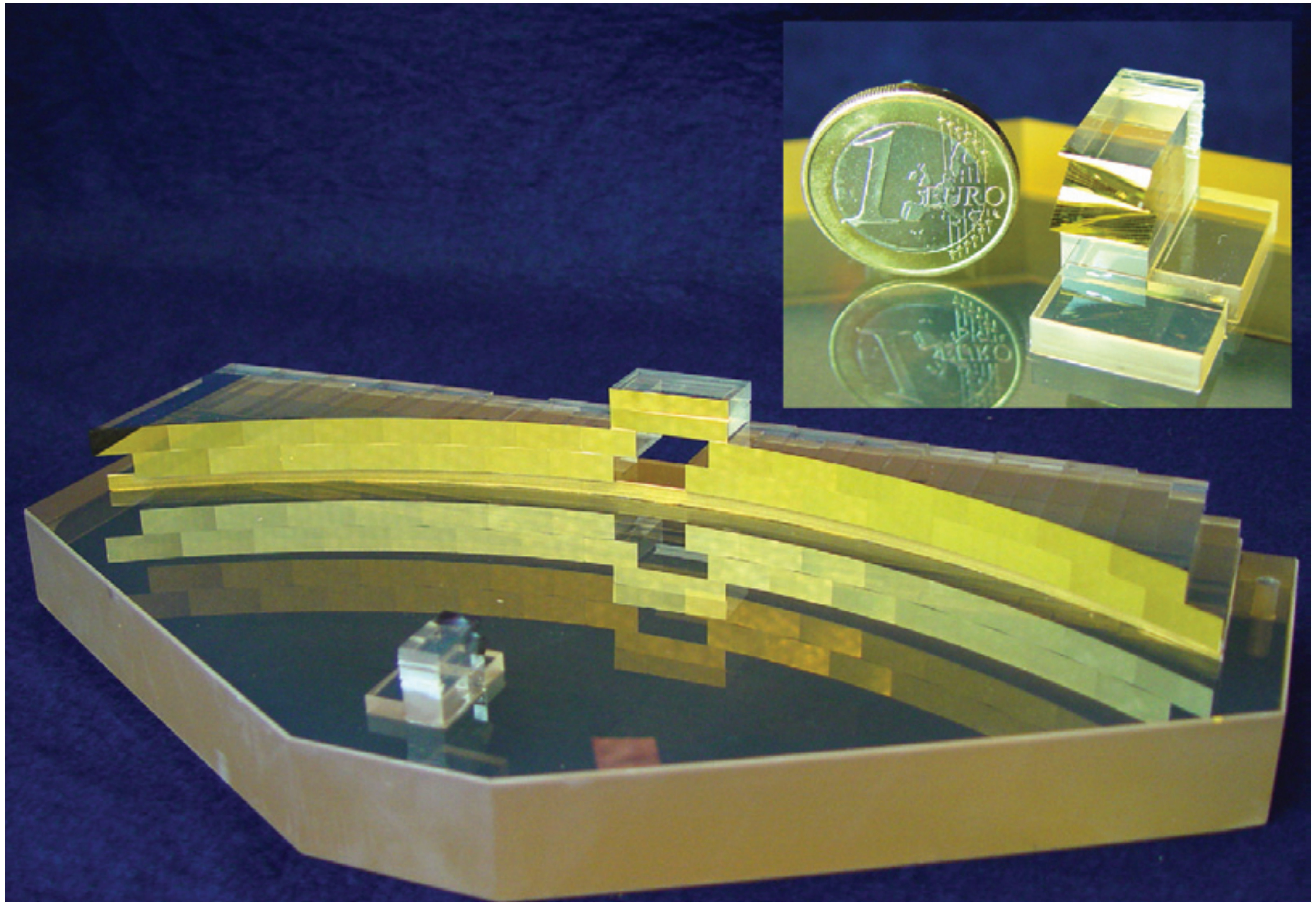


Figure 2: SPIFFI image slicer: The light enters through the hole in the big slicer. A stack of 32 small mirrors 'the' small' slicer – slices the image and redirects the light towards the 32 mirrors of the 'big' slicer, which rearranges the slitlets to a 31 cm long pseudo-long-slit. The small inset shows an enlargement of the small slicer.

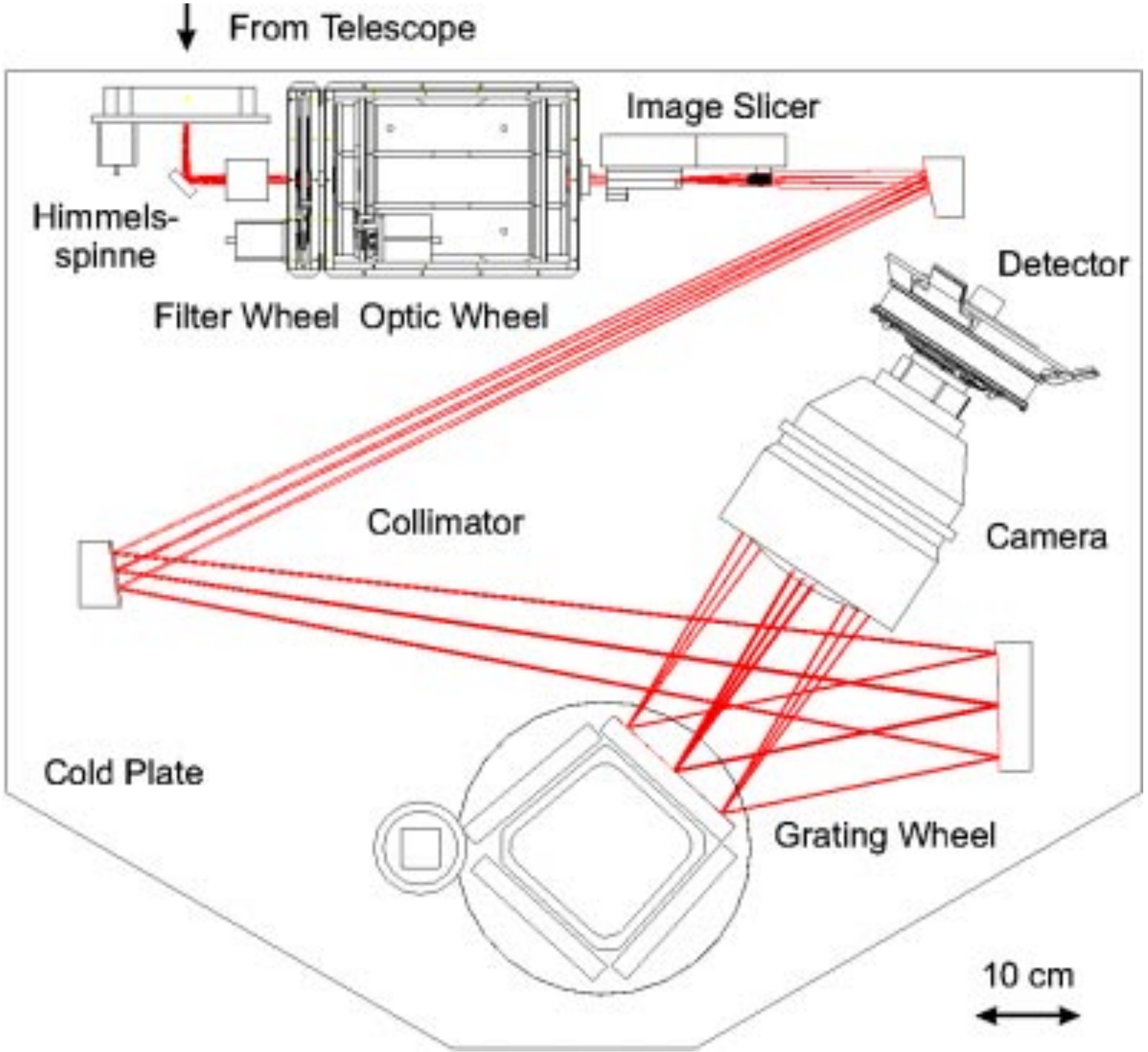
The small slicer cuts a square field of view into 32 slitlets, each of which is 32 pixels longs. The large slicer rearranges the 32 slitlets into a 1024 pixel long slit.

Mirror widths are **300 microns** with less than 10% loss

Cryogenic requirements mean all reflective surfaces, aligned at warm temperatures.

Schematic drawing of SPIFFI

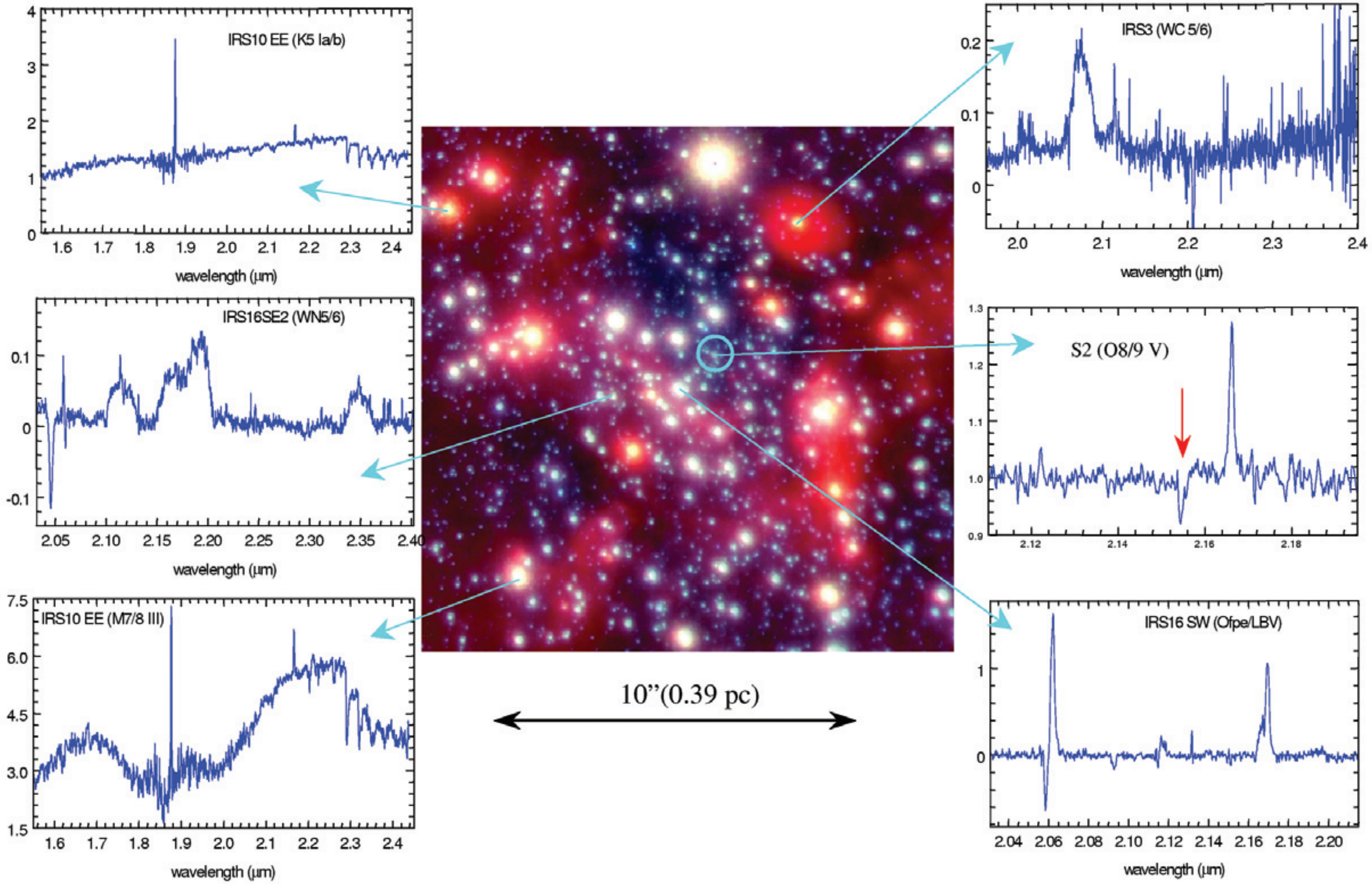
Eisenhauer 2000 SPIE



SPIFFI works in the wavelength ranger from 1.1 to 2.5 micrometers with a spectral resolving power ranging from R equals 2000 to 4500. Pixel scale ranges from 0.25 to 0.025 seconds of arc. The SPIFFI field-of-view consists of 32 by 32 pixels which are rearranged with an image slicer to a form a long slit.

Science from SPIFFI

[Eisenhauer 2003 ESO Messenger 113 17 25]

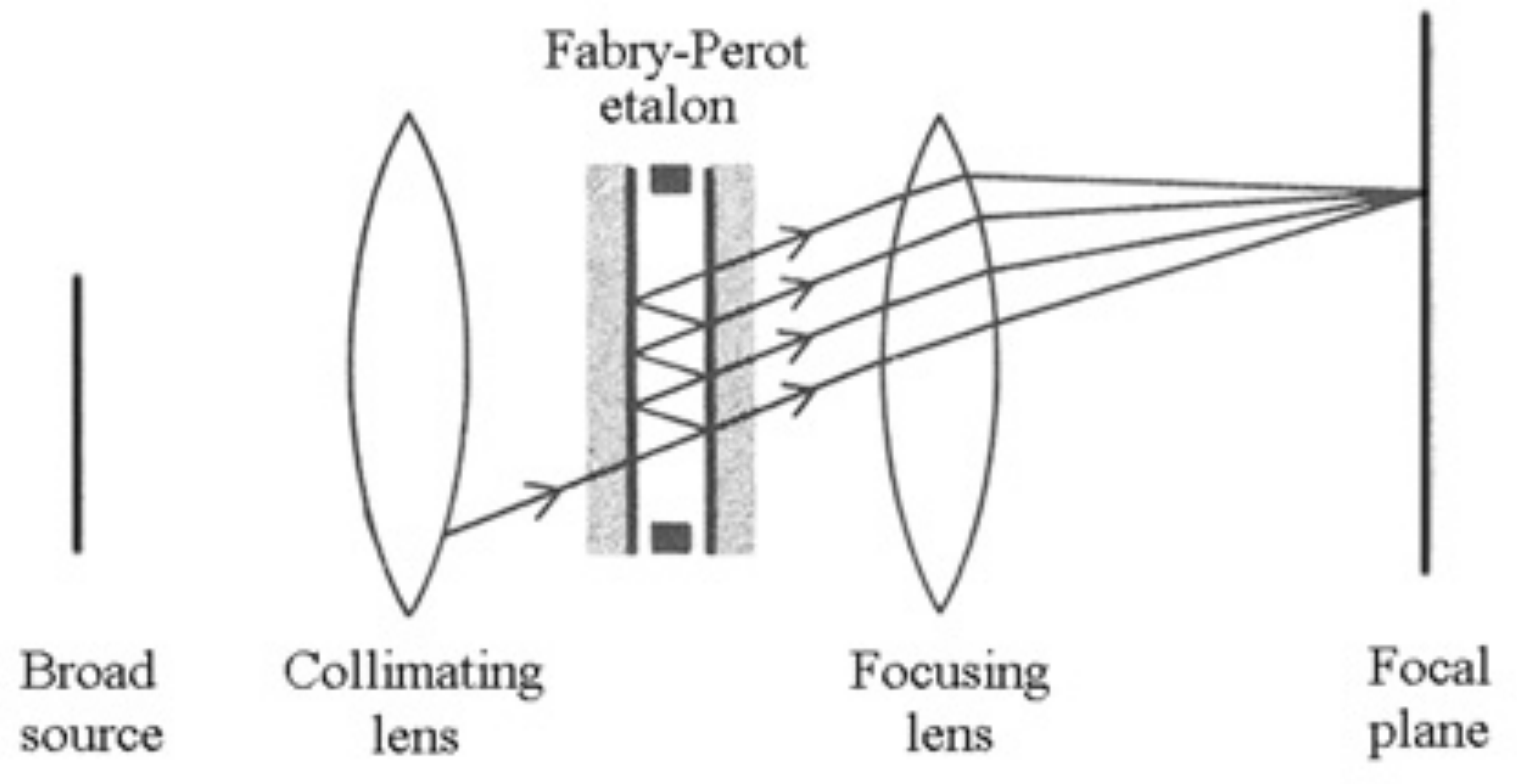


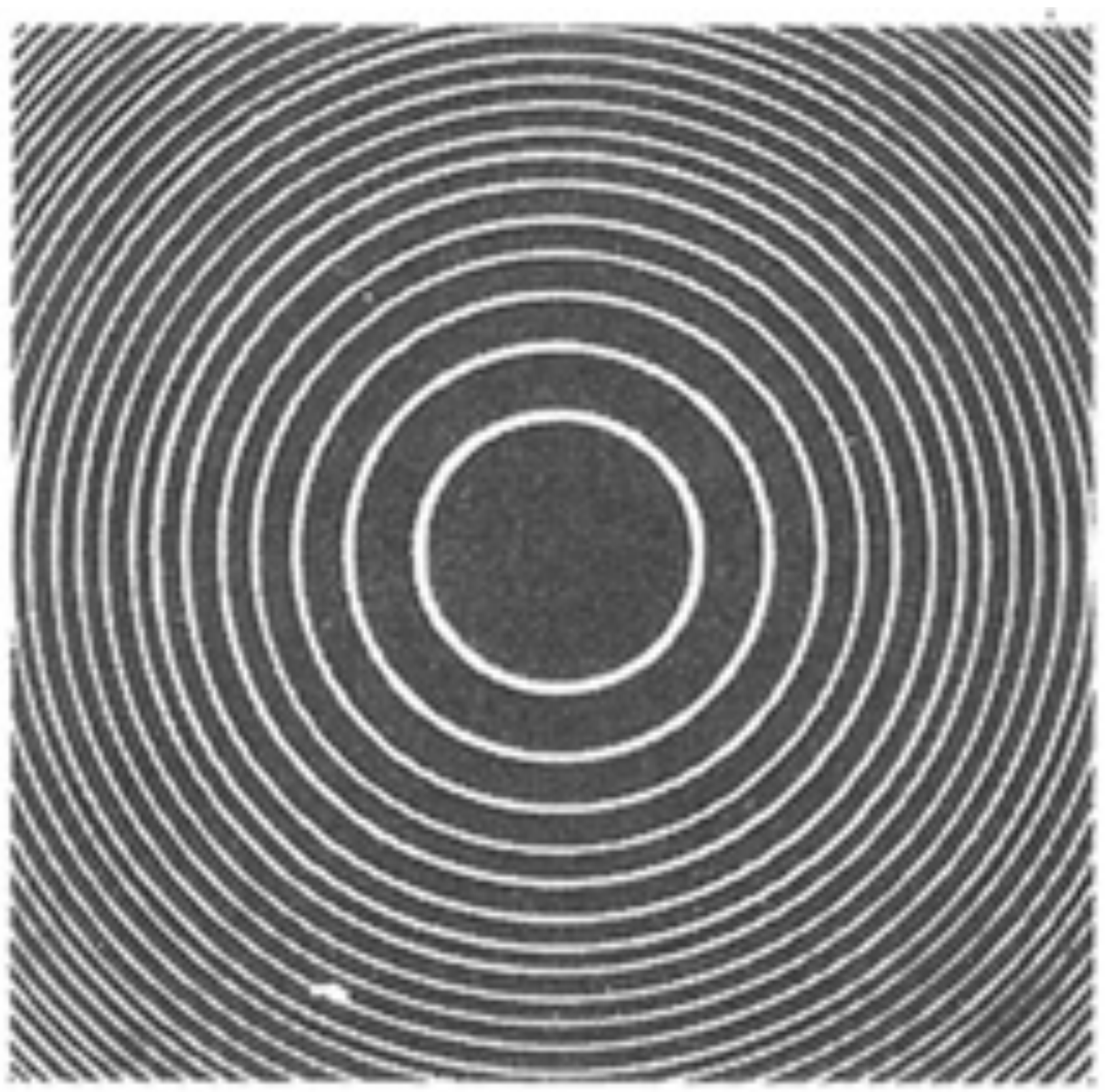
- A spectrum obtained for every pixel (called a "spaxel") on the sky

Fabry Perot Imager

[Rangwala 2008 ApJ 135 5]

- **Pros:** large field of view possible





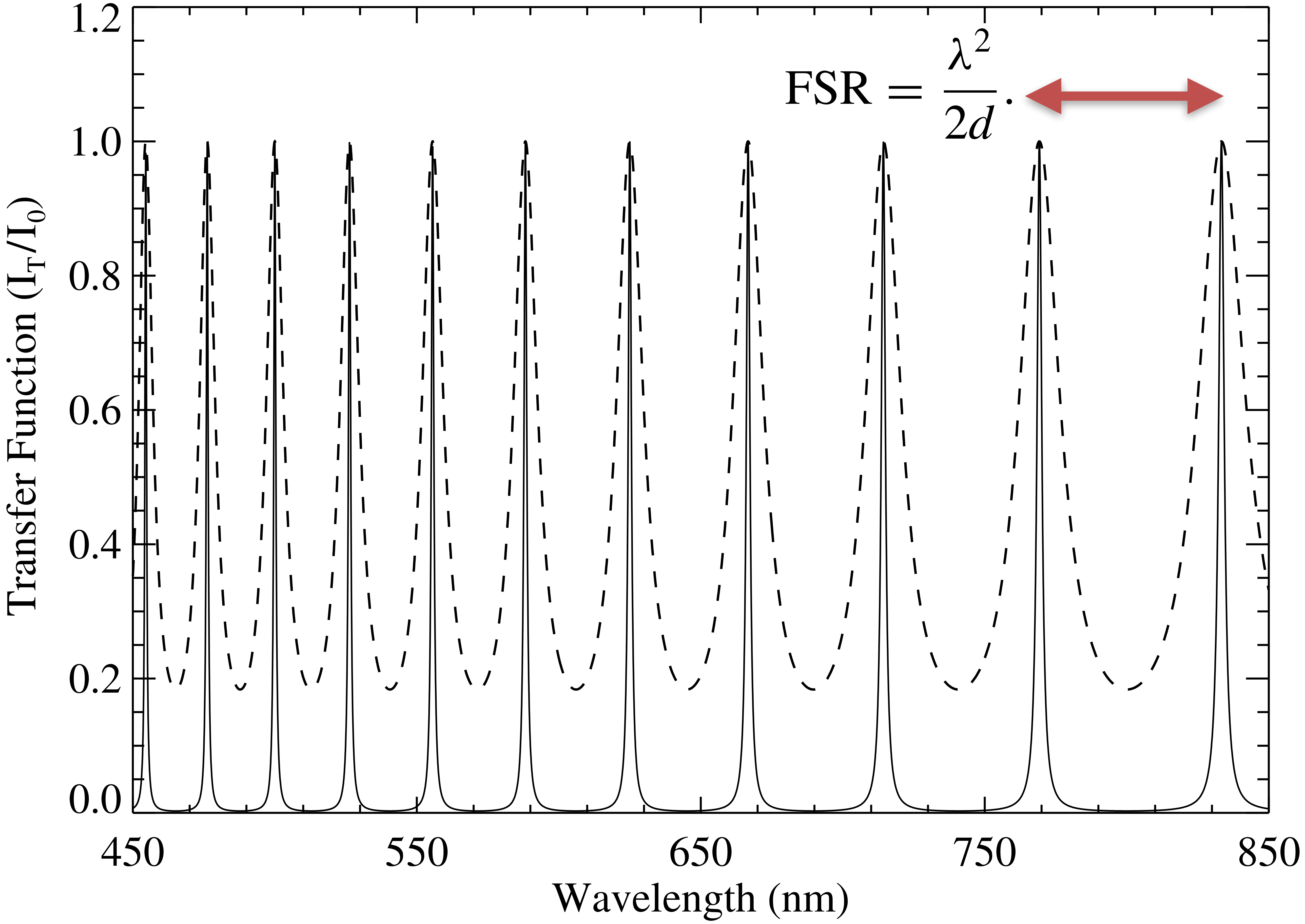
Ring System

FP as a function of angle - a monochromatic source will produce concentric rings across the field of view

$$2d \cos\theta = N\lambda$$

Fabry Perot Imager

[Rangwala 2008 ApJ 135 5](#)



$$I_T = I_0 \frac{T^2}{(1-R)^2} \frac{1}{1 + F \sin^2(\Delta/2)} \qquad (3)$$

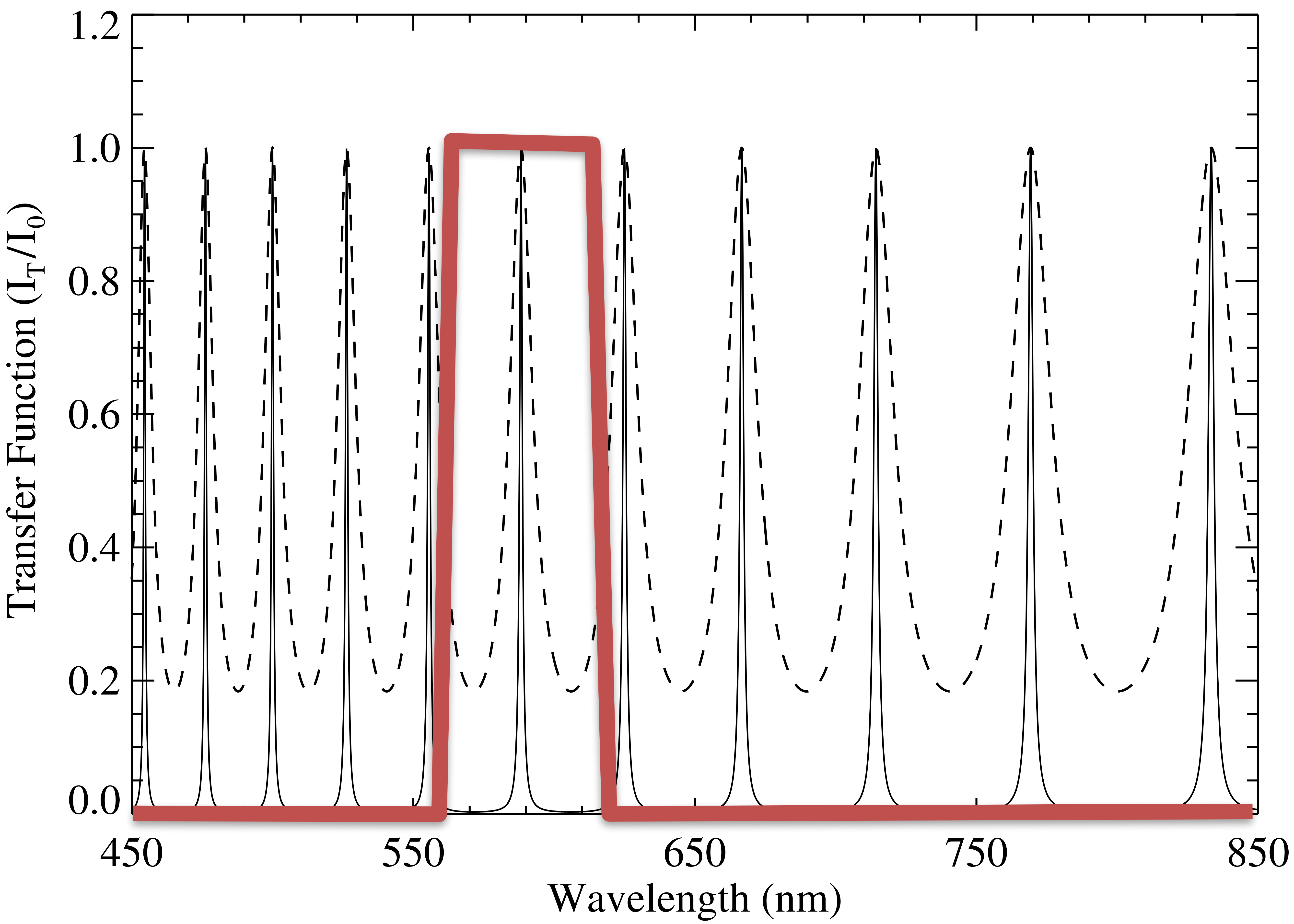
where I_0 is the intensity of the incident beam, R and T are the reflectance and transmittance of the high-reflectance coatings, $\Delta = 4\pi d \cos\theta/\lambda$ is the phase difference between two successive reflections, and $F = 4R/(1-R)^2$. (Note that ideal coatings will have no absorption or scattering, so $T = 1 - R$ and the peak transmission of the etalon is 100%.)

- **Cons:** limited bandwidth (science case is kinematics of galaxies in OI, H Alpha, OIII,….)

An ideal FP etalon with d=5 microns and R=0.8 (solid) R=0.5 (dashed)

Use order sorting filters

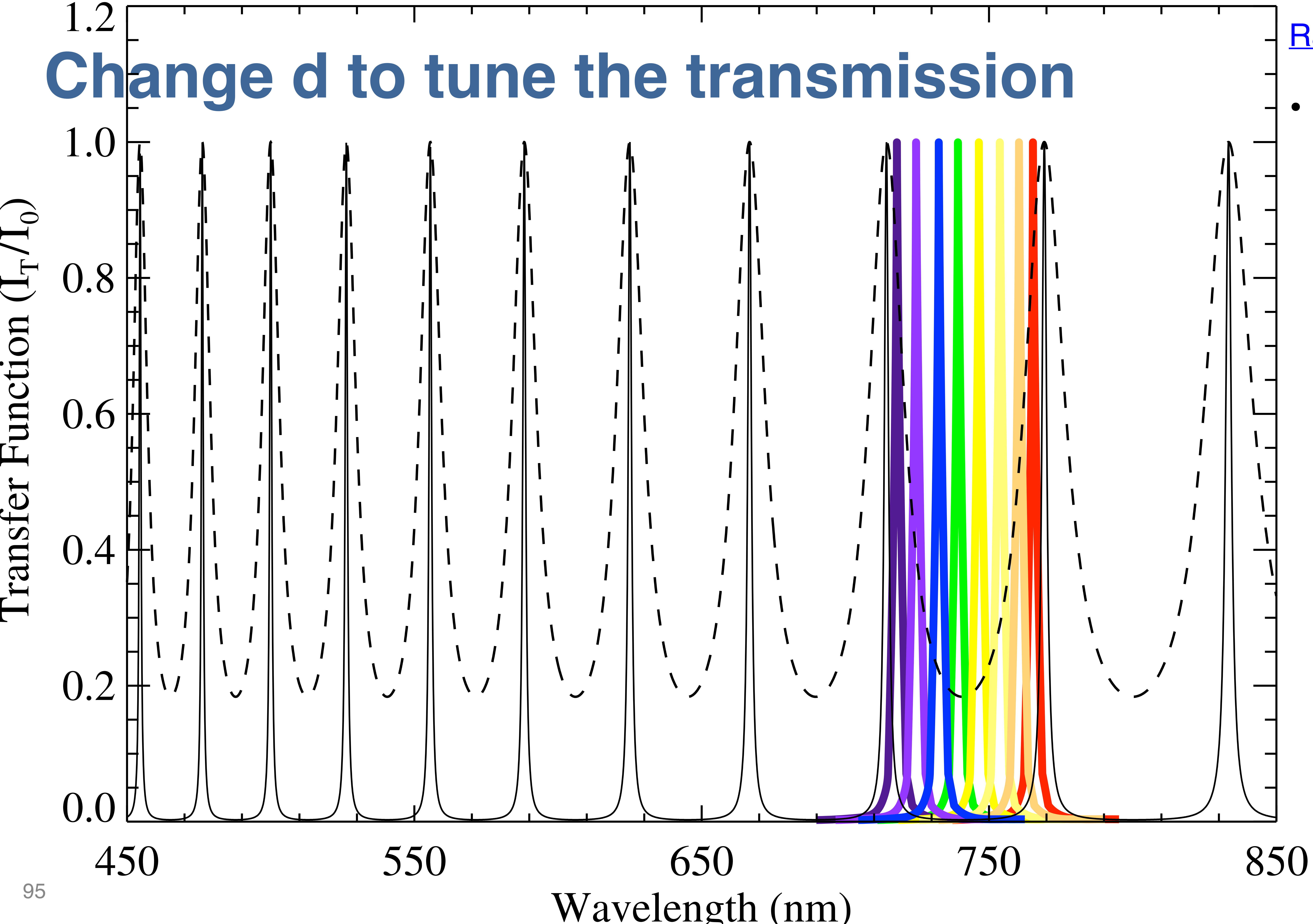
Rangwala 2008 ApJ 135 5



- Different order sorting filters can select the velocity range you are sensitive to and the emission line that you want to study.

An ideal FP etalon with d=5 microns and R=0.8 (solid) R=0.5 (dashed)

Change d to tune the transmission



Rangwala 2008 ApJ 135 5

- Number of distinct wavelengths resolved is the reflection finesse

$$\mathcal{F}_R = \frac{\pi}{2}\sqrt{F} = \pi\frac{\sqrt{R}}{(1-R)}.$$

Airglow produces rings in FP images

[Moiseev 2015 AstBu 70 494]

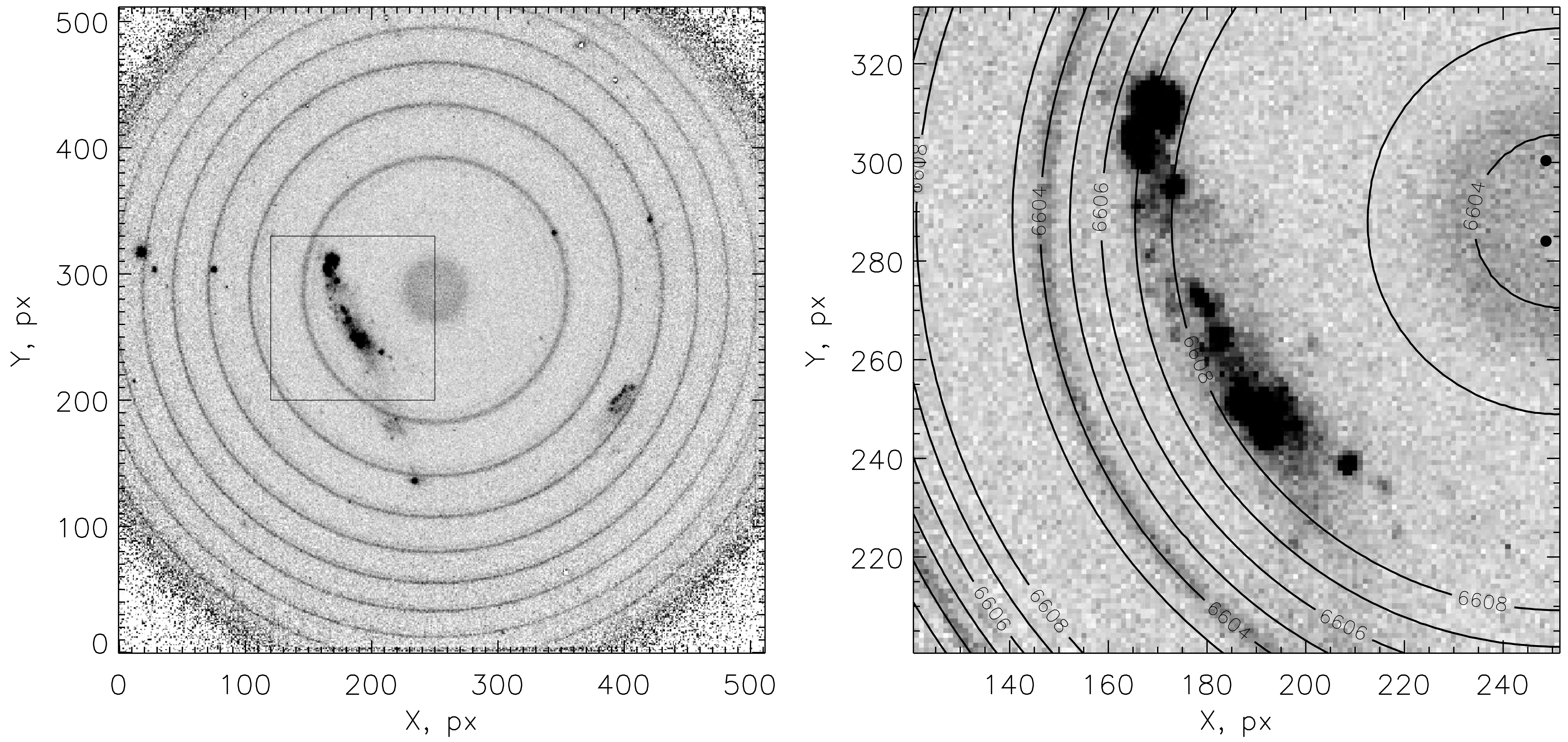


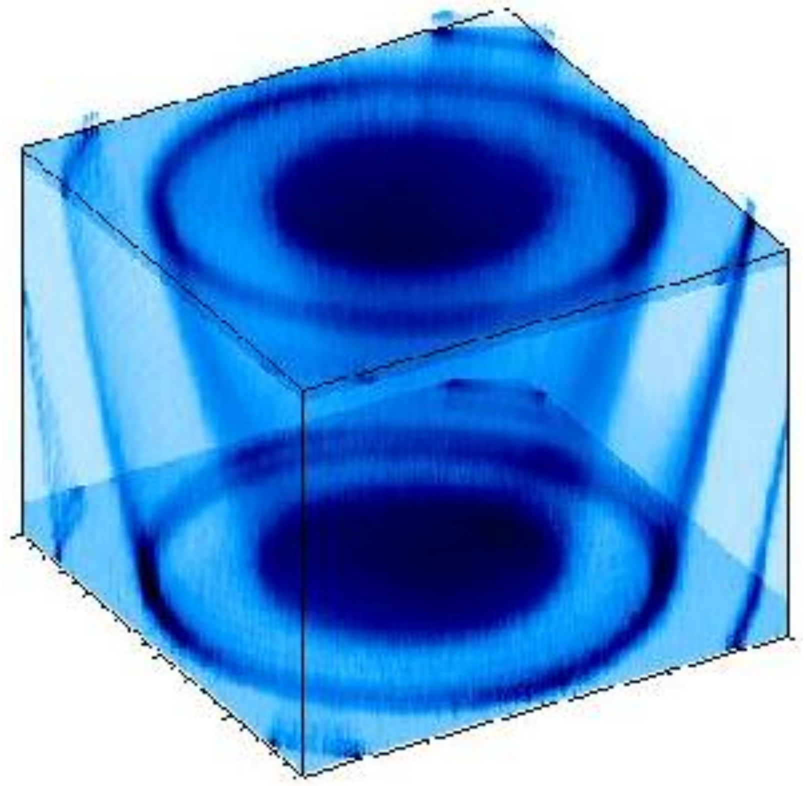
Fig. 4. Hα observations of the galaxy UGC 260 with IFP751 mounted on SCORPIO-2. Left: an example of a frame with both the emission from the galaxy and the rings from the λ 6604 airglow line are immediately apparent. The square area is shown in the right panel, the contours indicate the wavelength scale with a contour step of 1 Å.

Pros: wide FOV

Cons: airglow lines can be variable and difficult to remove

Reassembling a 3D cube from FP data

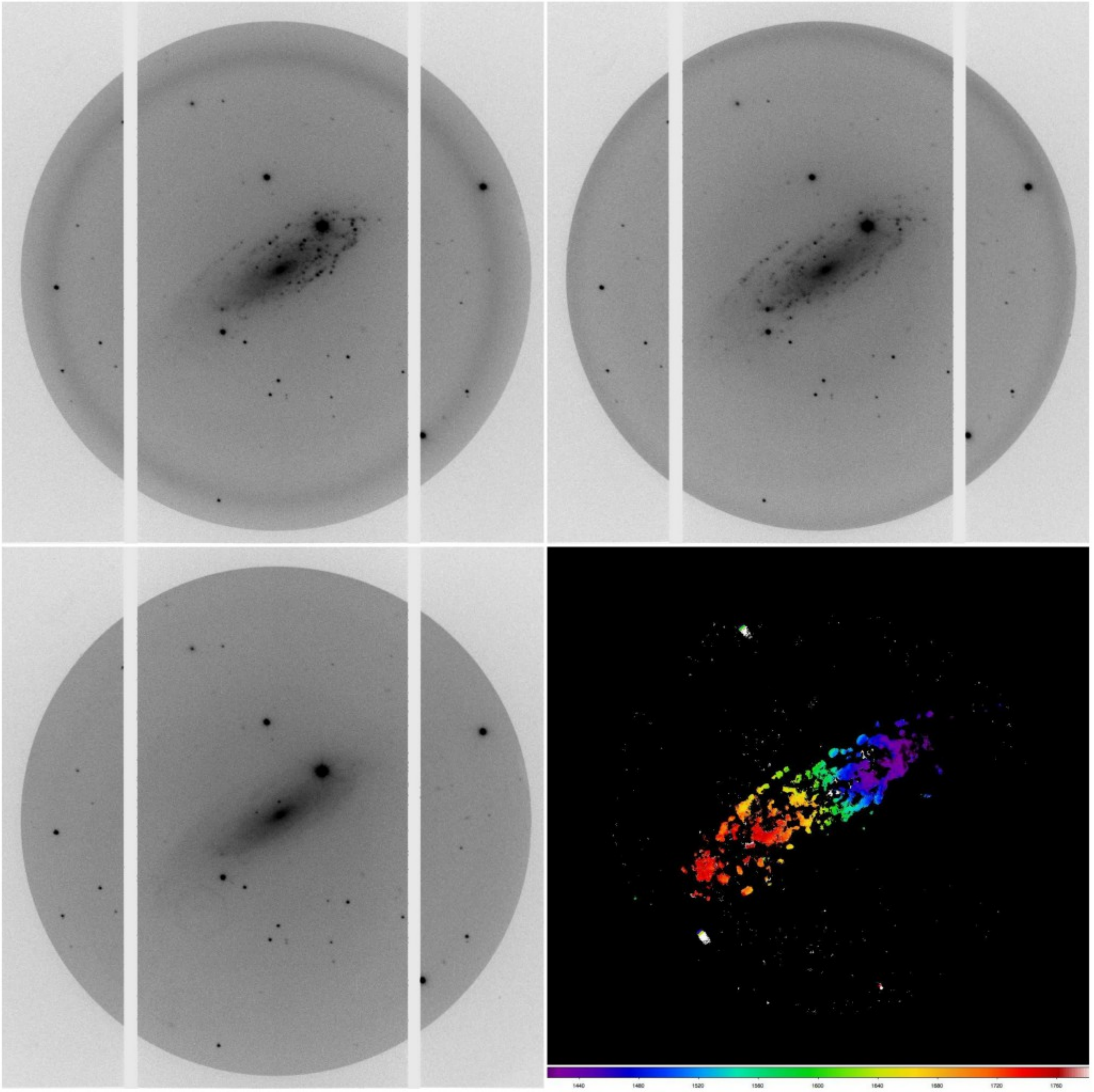
- Surfaces of constant wavelength are **CONIC** sections through the data cube
- **Cons:** reconstruction of complex spectral profiles is non trivial and very complex if seeing conditions change during the exposures

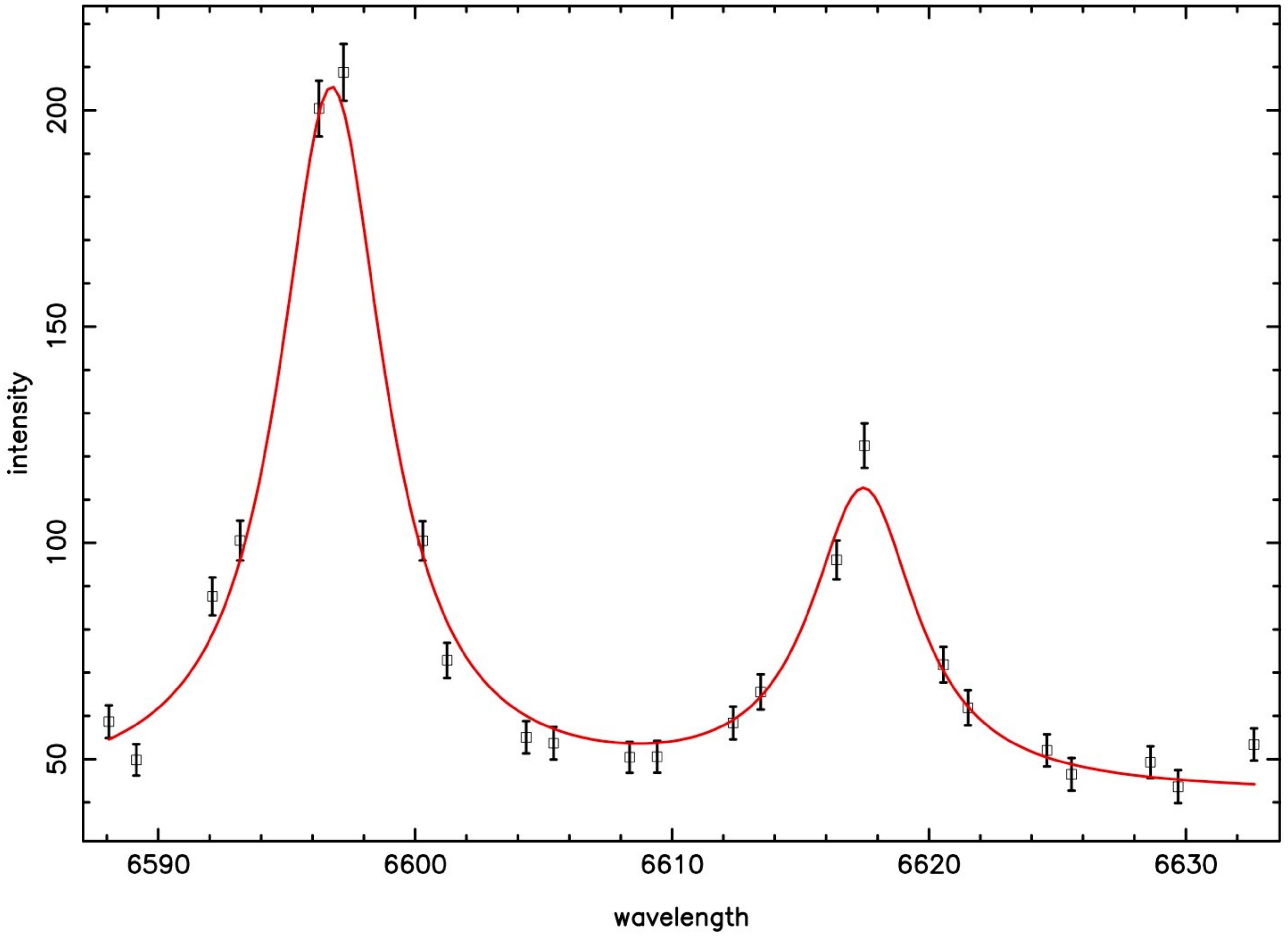


live learn love eat https://www.sao.ru/hq/lsfvo/devices/scorpio/ifp/cubes.html

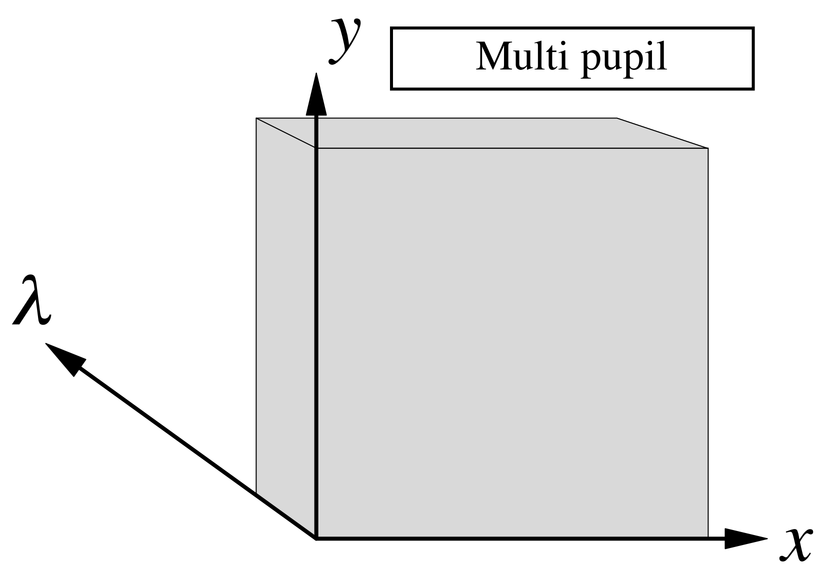
SALT FP imaging of NGC 1325

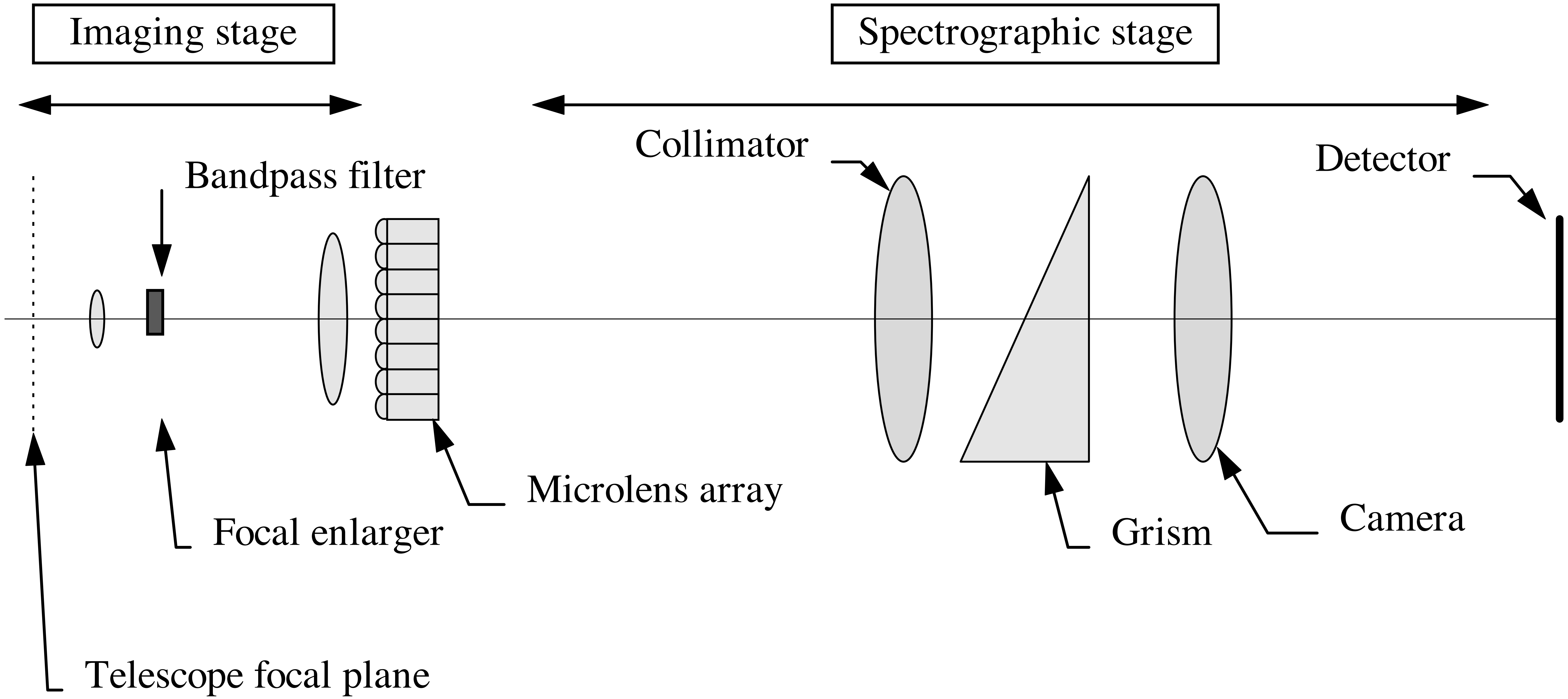
https://www.salt.ac.za/news/fabry-perot/





Multi pupil reimagers



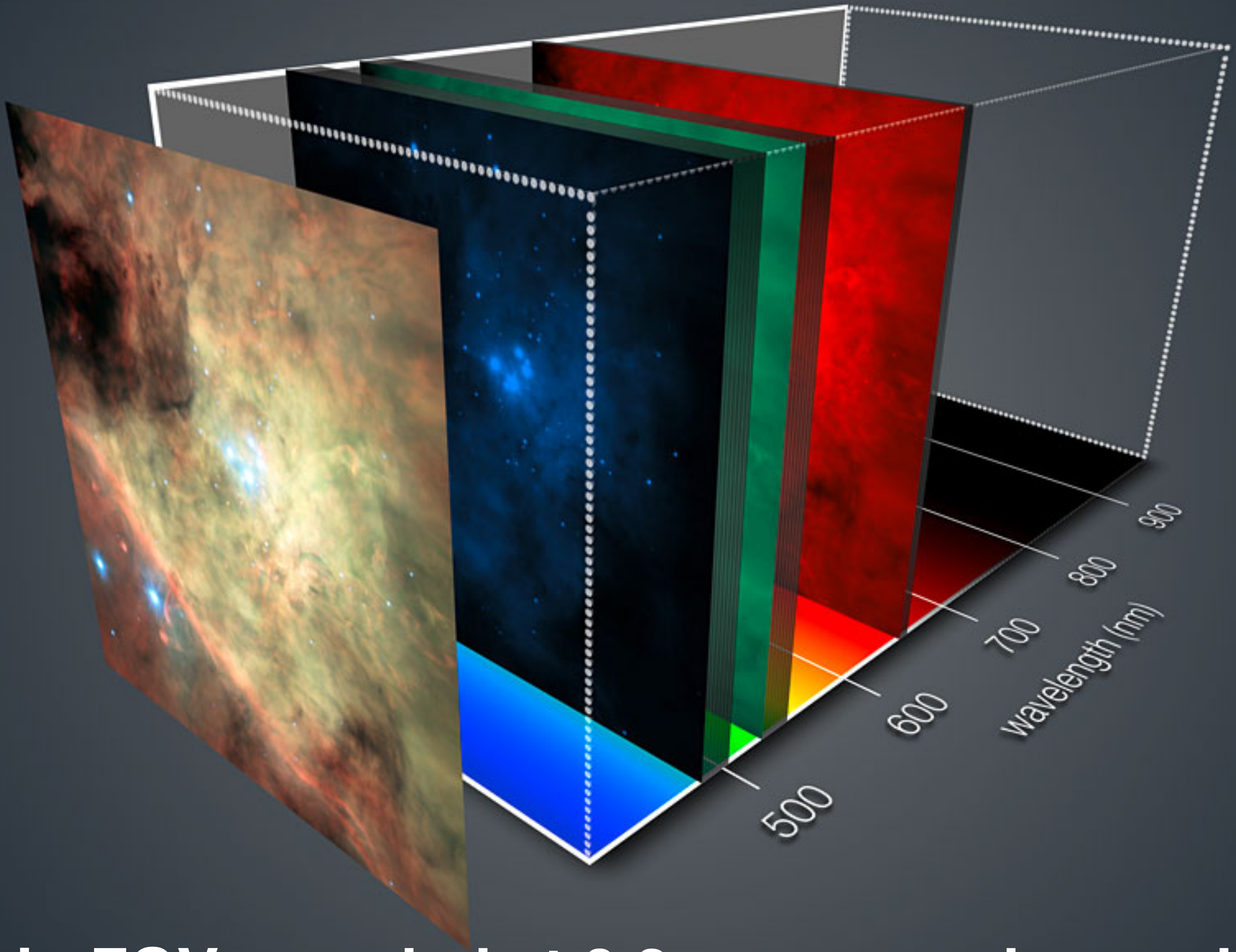


- **Pros:** very compact design
- **Pros:** large field of view
- **Cons:** limited spectral range

Microlenslet array cuts focal plane into tiny images

Disperse these images into short spectra -> limited wavelength range

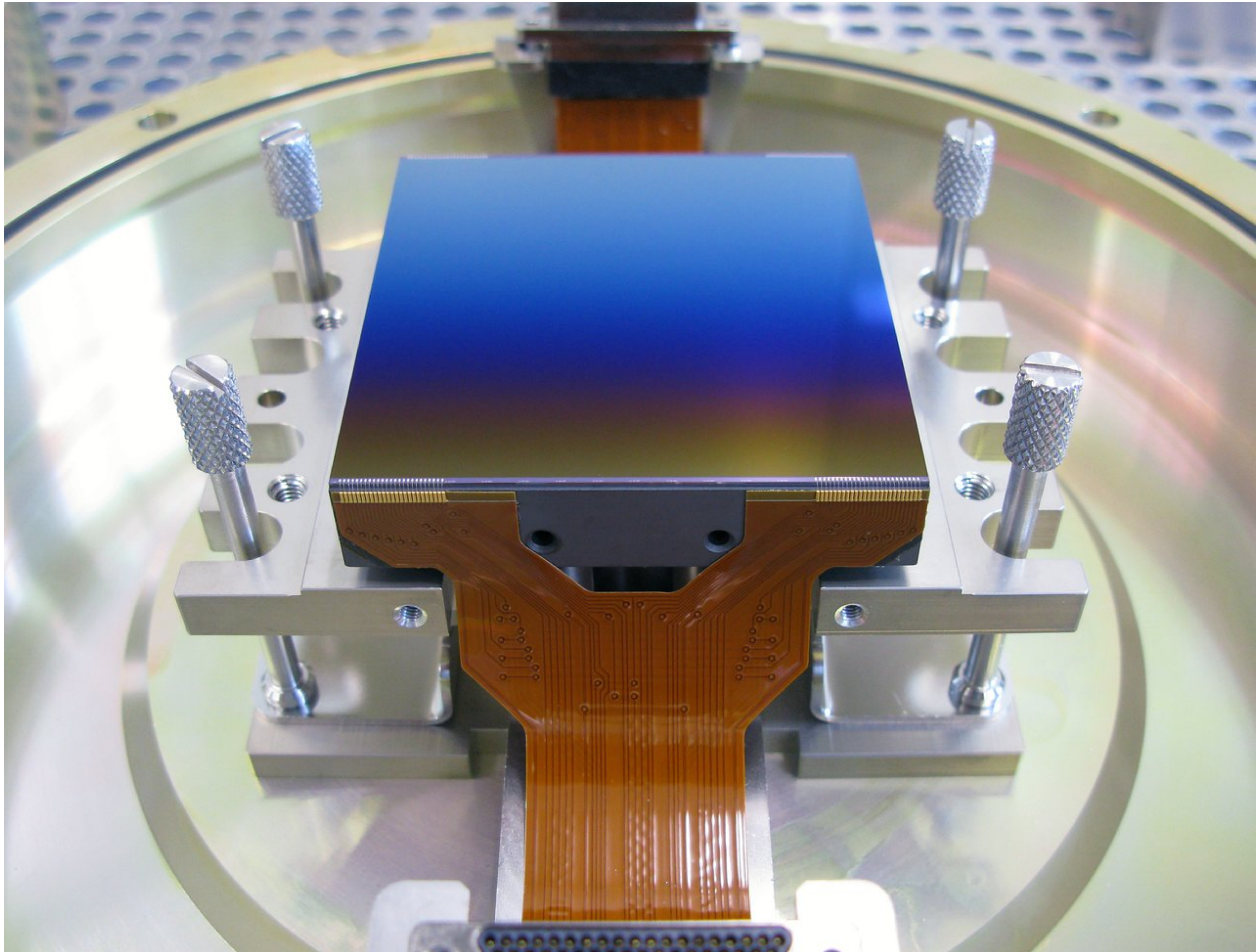
MUSE on VLT - 24 Integral Field Spectrographs



1 by 1 arcmin FOV sampled at 0.2 arc second spaxels on the VLT

MUSE detector 4096x4096

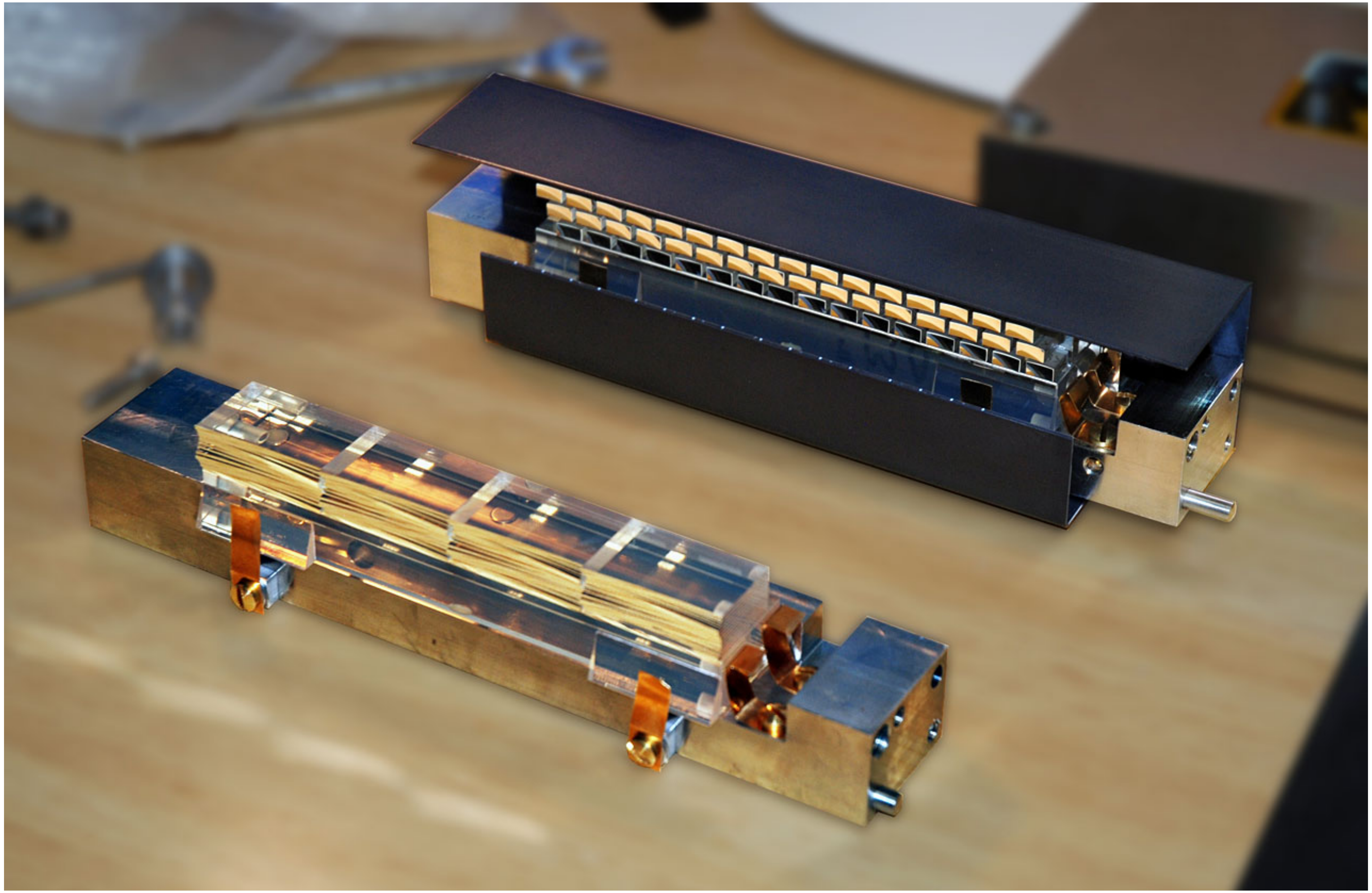
https://www.eso.org/public/images/ann1012d/



- 24 CCDs in MUSE, each with 4096 by 4096 pixels
- 1’ by 1’ field of view split up and sent into 24 spectrographs

MUSE image slicer

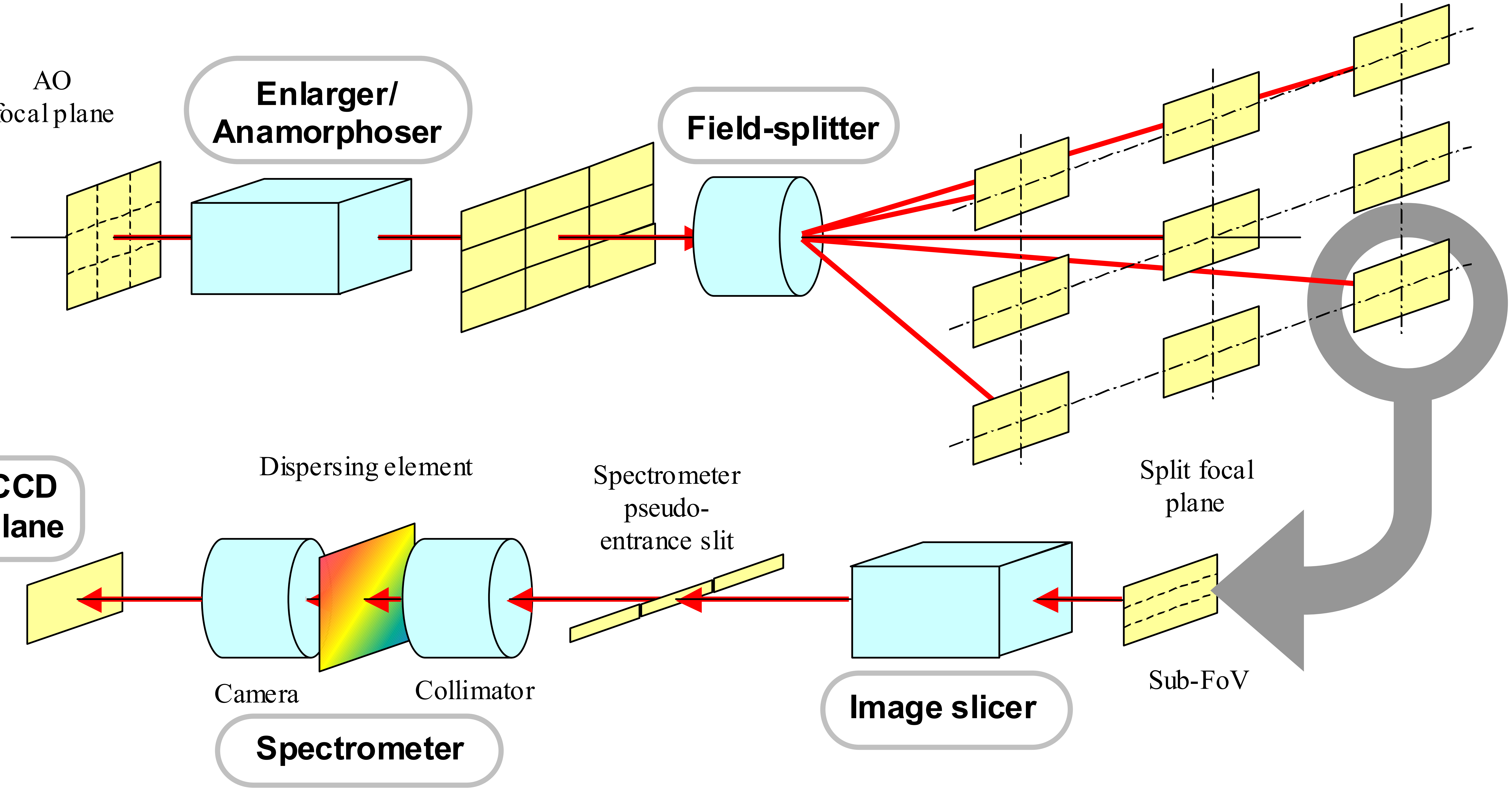
https://cdn.eso.org/images/screen/ann1012b.jpg



Two optical elements: the image dissector array (in front) made of 48 thin (0.9 mm) off-axis spherical mirrors and the focusing mirror array made of 48 round off-axis spherical mirrors.

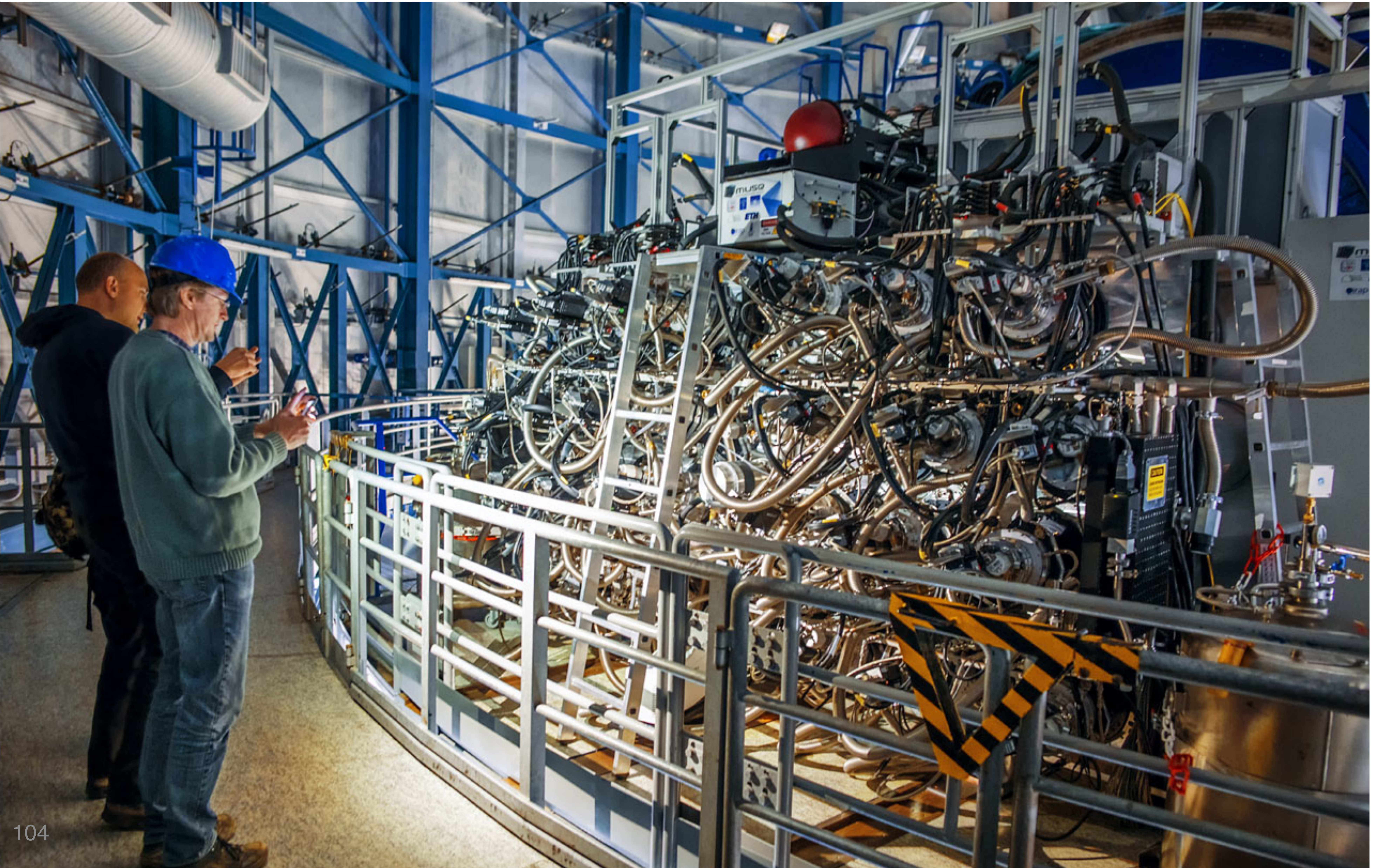
MUSE on the VLT

Henault SPIE 2018



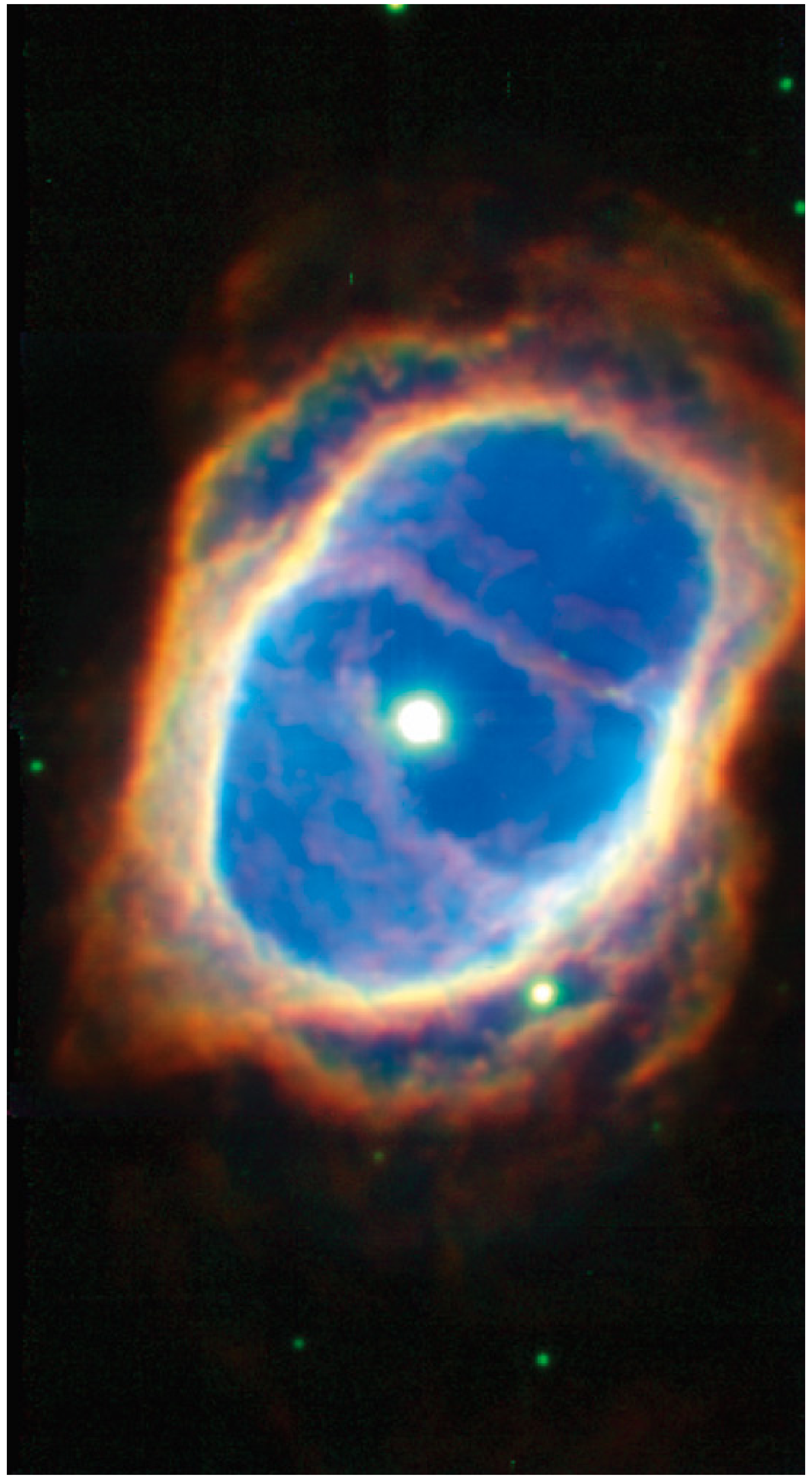
MUSE on the VLT

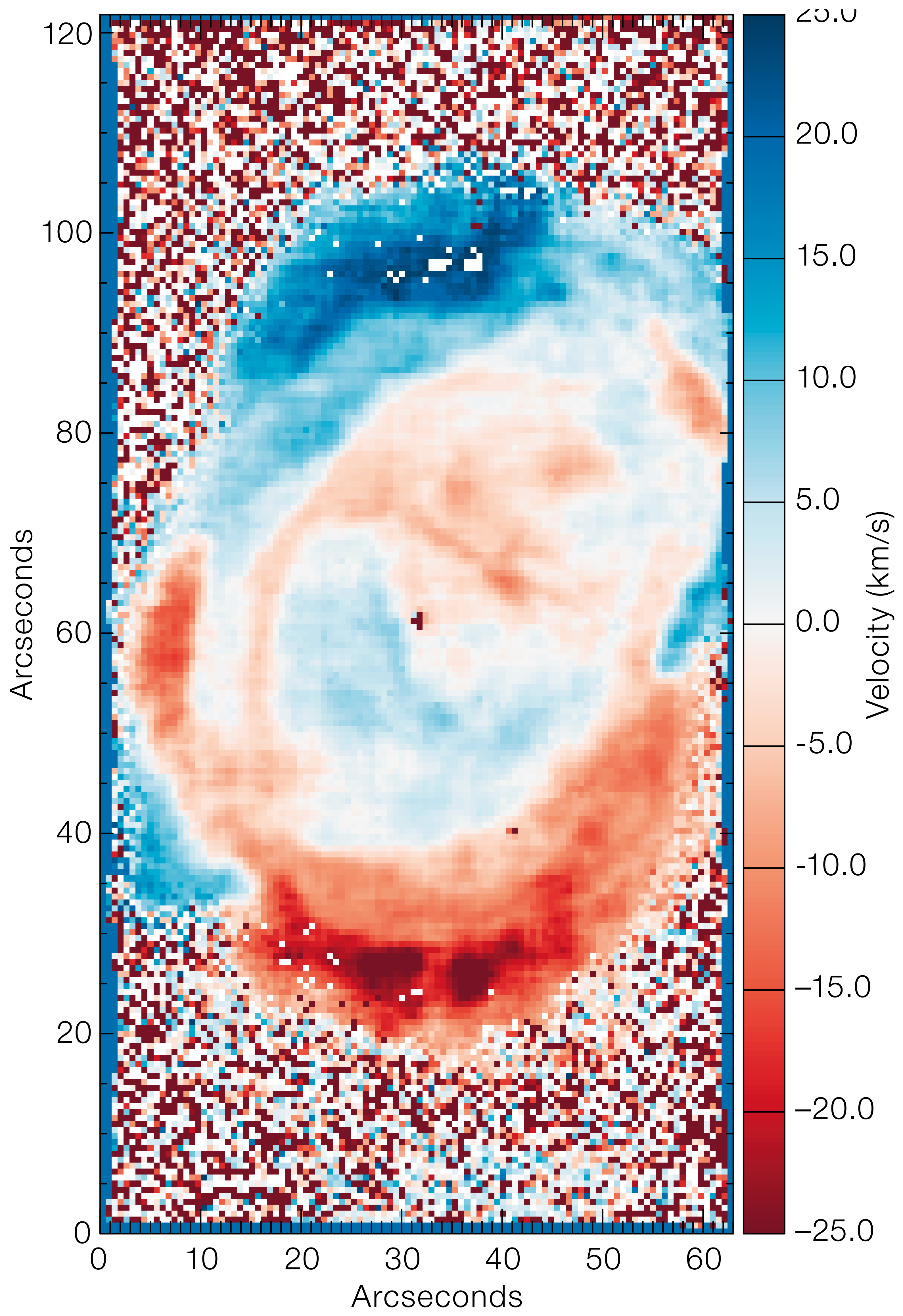
ESO



MUSE velocity fields

[Bacon 2007 MUSE]





- 24 CCDs in MUSE, each with 4096 by 4096 pixels

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