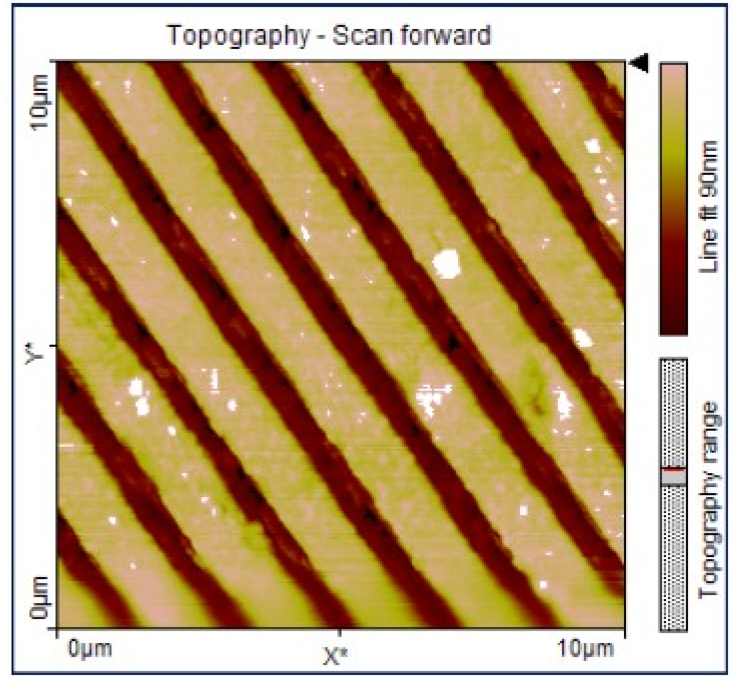
AGA5802
Spectroscopy: grating, filters, arcs

- *Gratings*
- *Filters (blocking order filters)*
- **Dichroics (double spectrophaps)**
- *Linear dispersion of the spectrum*
- Basic design of spectrographs
- *Wavelength calibration lamps (arcs)*
- *Grisms*

Bibliography: To Measure the Sky, Kitchin, Lena and others

Prof. Jorge Meléndez

Dispersion by a diffraction grating (rede de difração)



CD-Blank

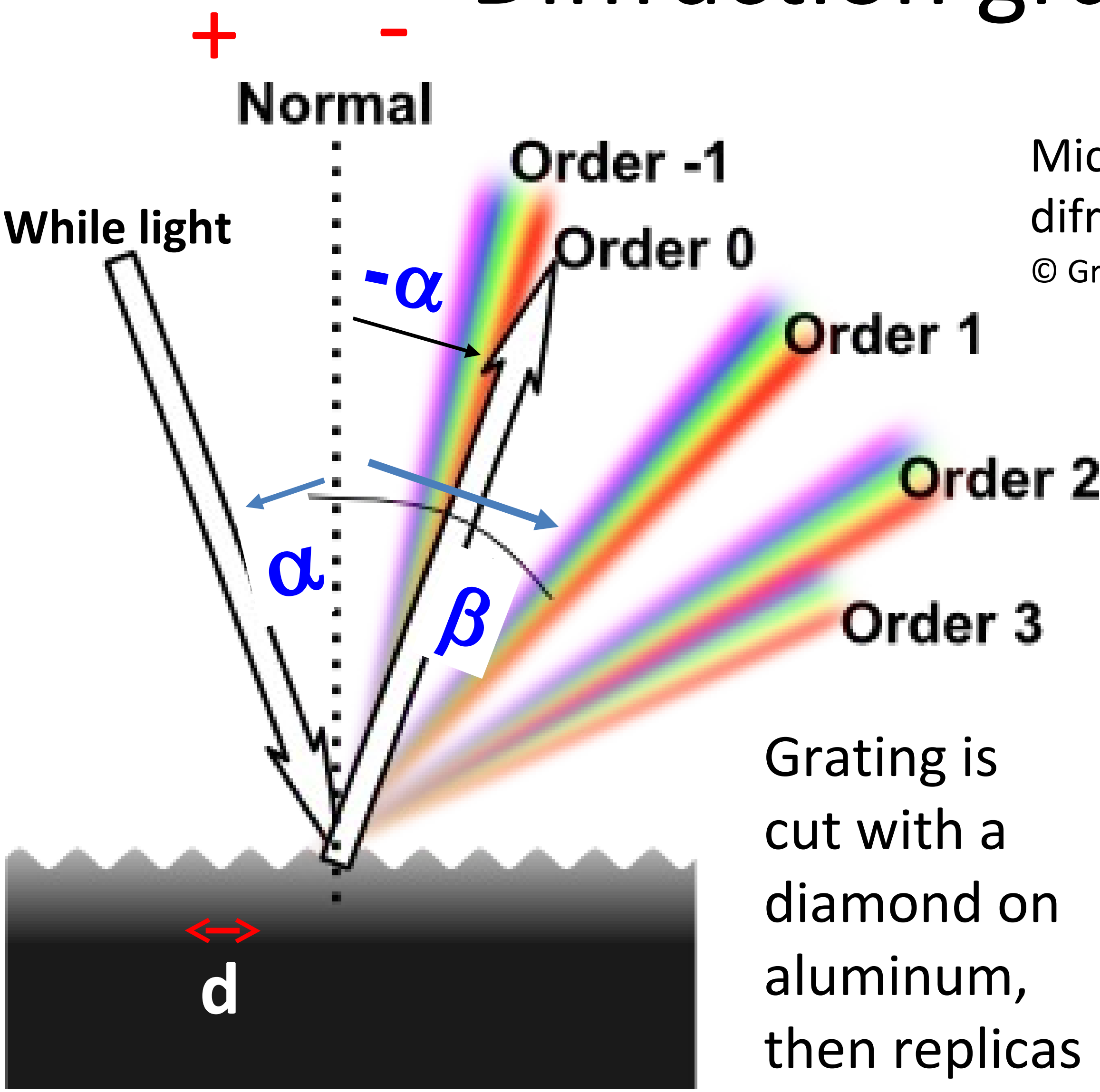
(10 µm scan)

Track pitch = 1.57 µm

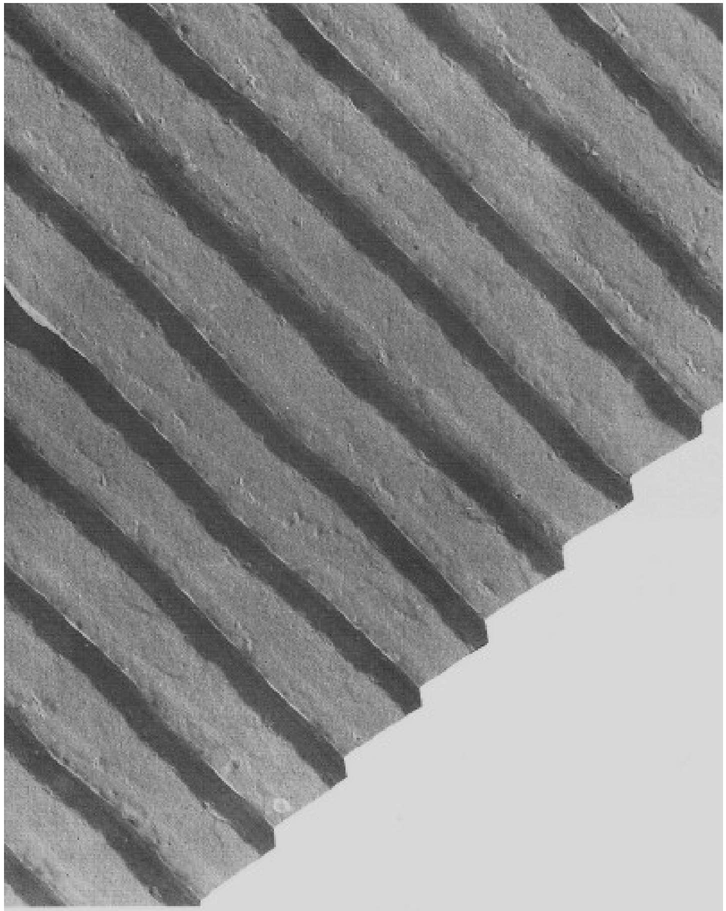
Type -------- Capacity --- Track pitch   how many per mm (1 mm = 10^3 µm)**?**

CD ------------- 0.7 Gb --- 1.6 µm → 10^3um/1,6um = 625 lines/mm
DVD ----------- 4.7 GB --- 0.74 µm → 10^3um/0,74um = 1351 lines/mm
Blu-ray Disc --- 25 GB ---- 0.32 µm → 10^3um/0,74um = 3125 lines/mm

Diffraction grating



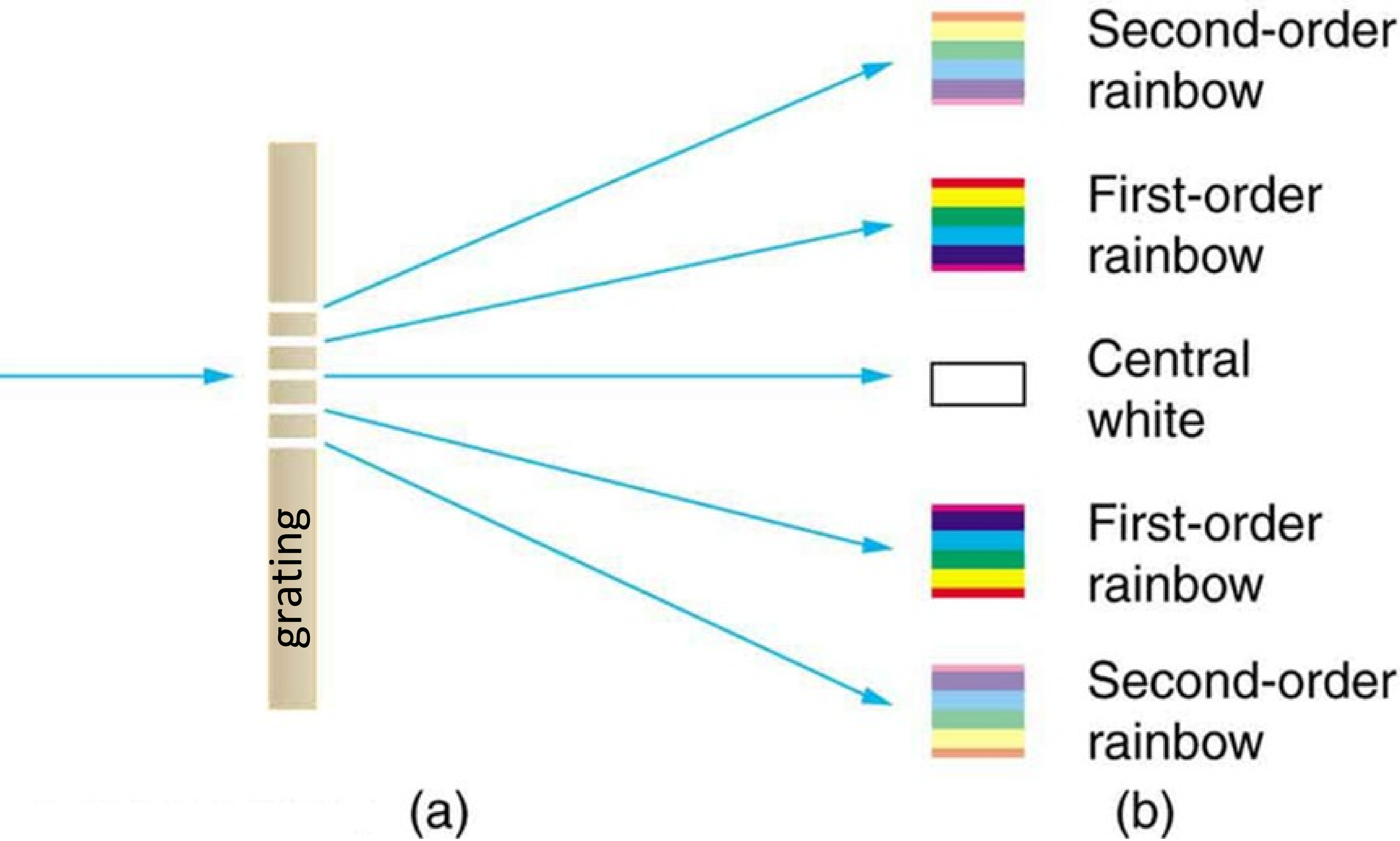
Microscopic picture of part of a difraction gratting of 1180 lines/mm



This microscopic picture shows the rulings on a plane reflection grating having 1180 lines/mm. (Courtesy of Jarrell-Ash.)

Grating is cut with a diamond on aluminum, then replicas are made

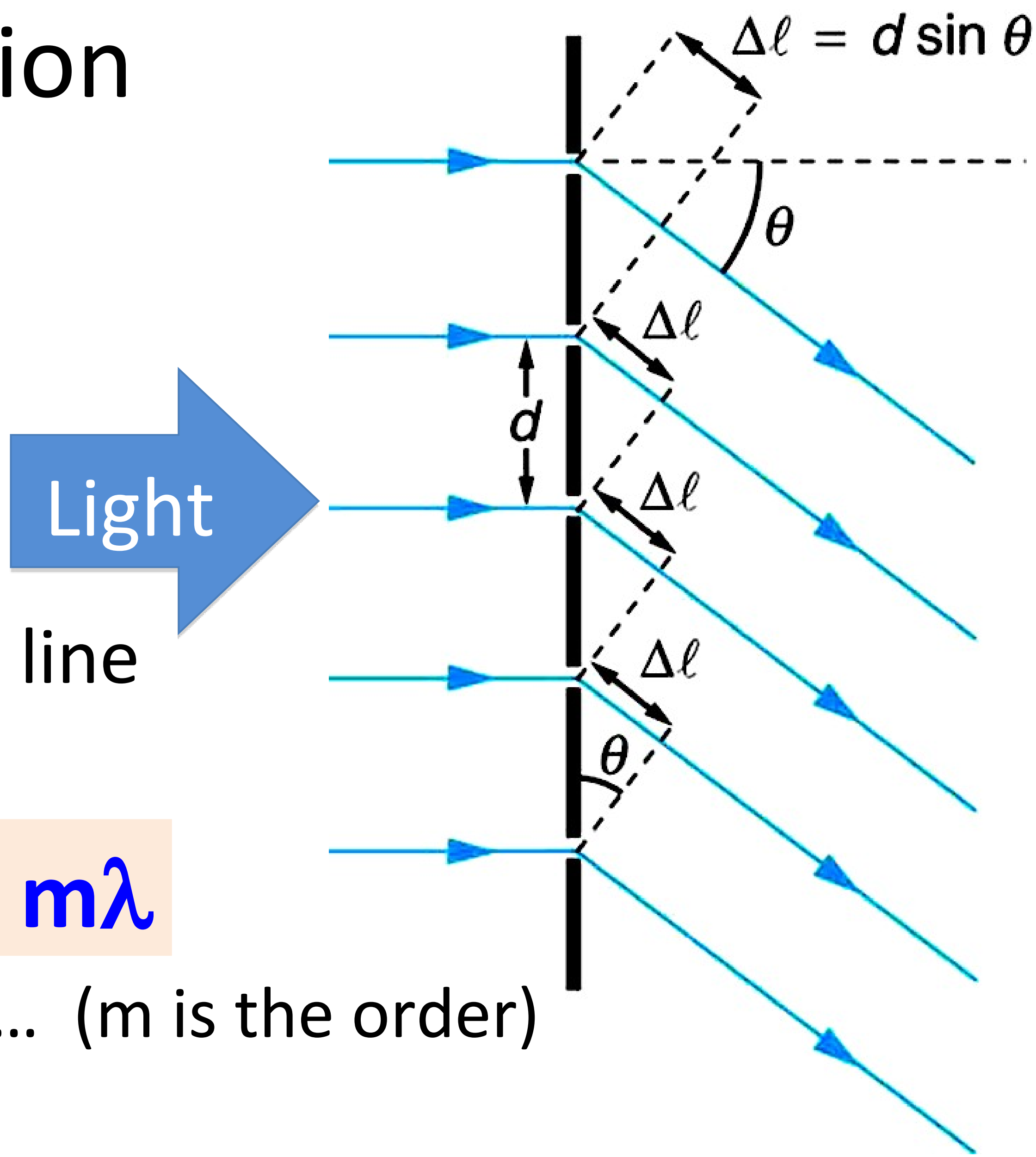
Spectrum formed by diffraction grating



https://opentextbc.ca/physicstestbook2/chapter/multiple-slit-diffraction/

Grating equation

Difference in optical path length:



For **constructive interference** at the line of wavelength λ:

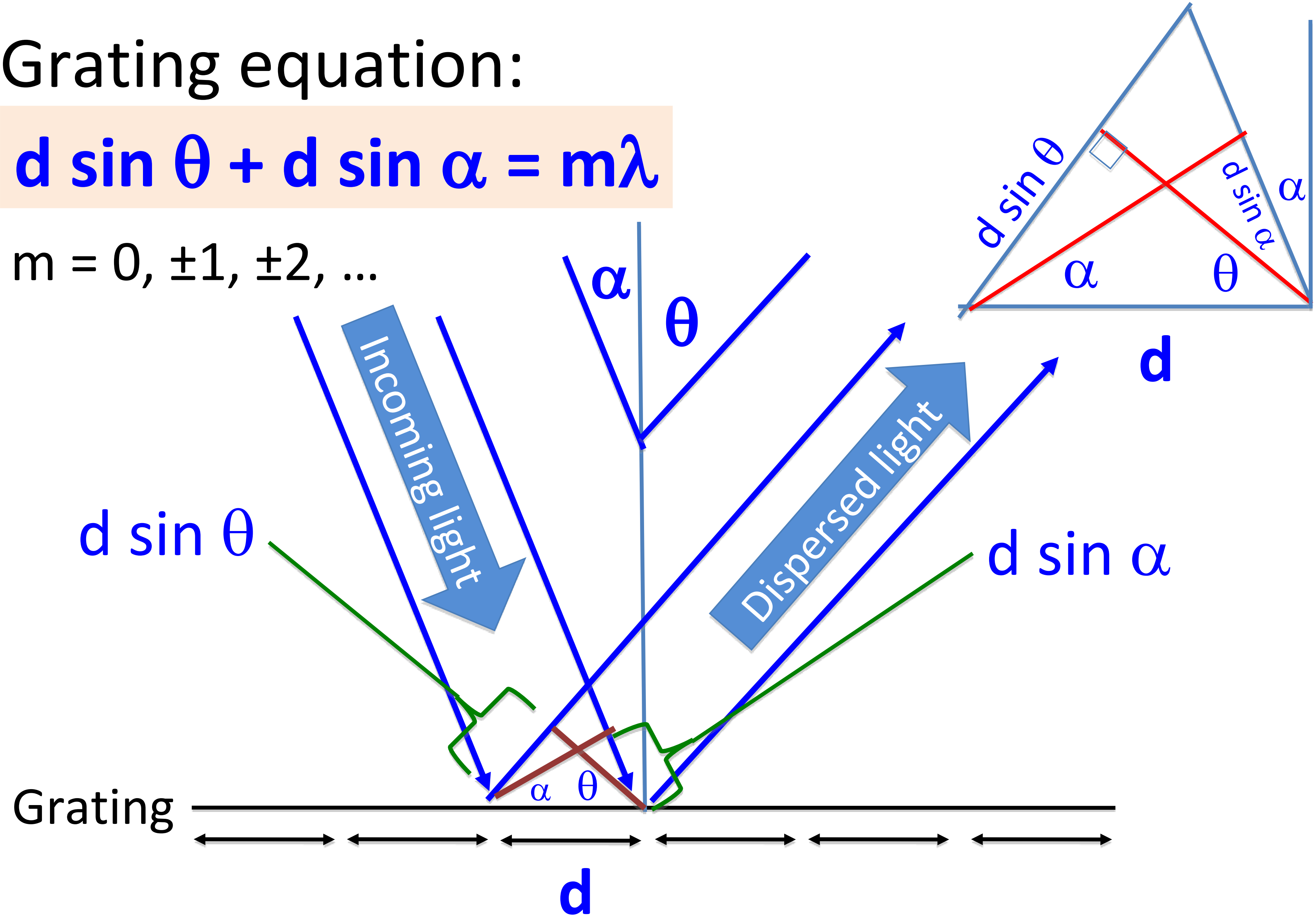
$$\mathbf{d \sin \theta = m\lambda}$$

m = 0, ±1, ±2, … (m is the order)

Grating equation:

$$d \sin\theta + d \sin\alpha = m\lambda$$

$m = 0, \pm 1, \pm 2, \ldots$



Angular dispersion of a grating

$$d(\sin \alpha + \sin \theta) = m\lambda$$

$$\sin \theta = m\lambda/d - \sin \alpha$$

Differentiating the grating equation :

$$\frac{d\theta}{d\lambda} = \frac{m}{d \cos \theta}$$

- $\cos \theta$ changes only slowly with λ → dispersion of the grating does not change much with wavelength
- Dispersion can be increased at higher orders

Resolving power R of the grating

$$R = N\,m$$

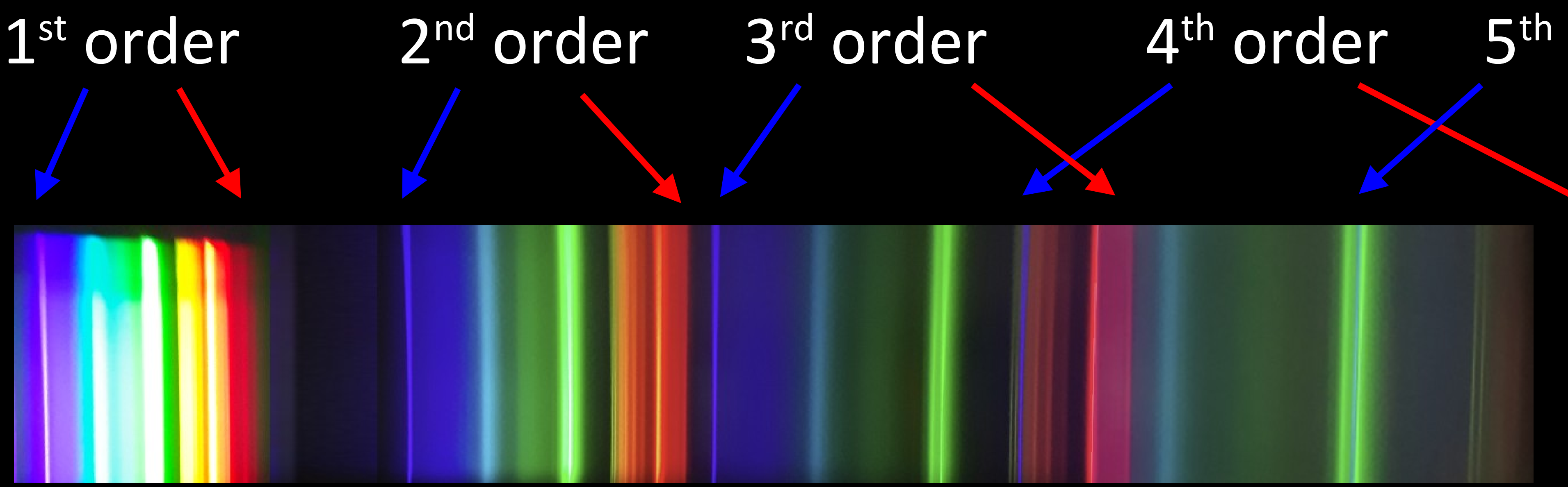
N: number of lines across the grating; m: order

Example: grating 500 lines mm^{-1} in a grating of length = 10mm, at second order:

N = (500 lines/mm) x 10 mm = 5000 lines

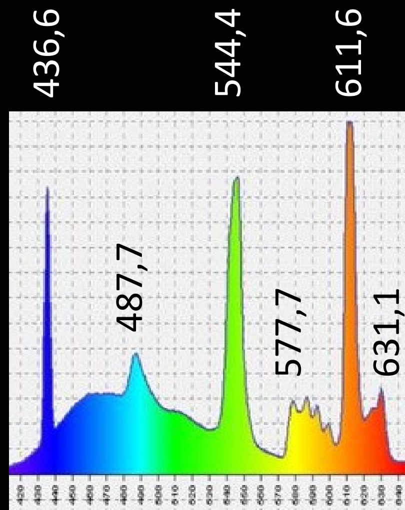
R = 5000 x 2 = 10 000

This high resolving power is actually limited by the slit width of the spectrograph, therefore it is rarely achieved in practice.



Spectrograph: Claikson Benedito

Pictures (composite): Jorge Meléndez

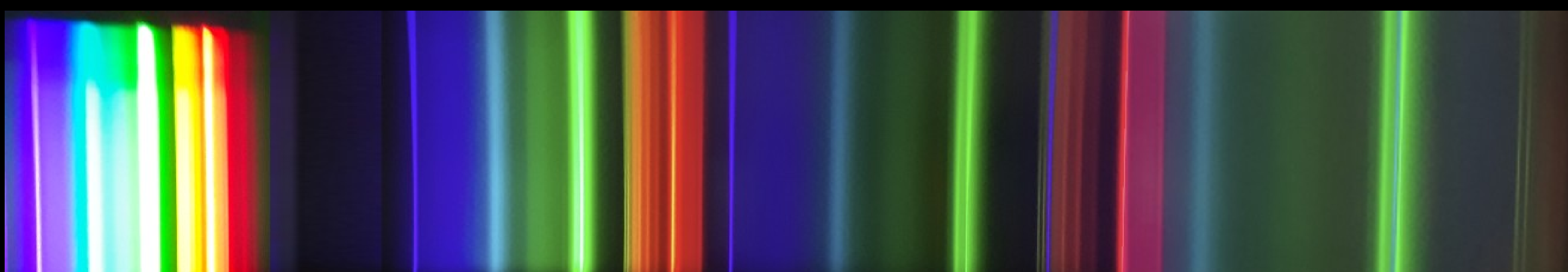


Espectro registrado pelo celular

~436 – 631 nm

https://www.popularmechanics.com/technology/gadgets/reviews/g164/incandescent-vs-compact-fluorescent-vs-led-ultimate-light-bulb-test/

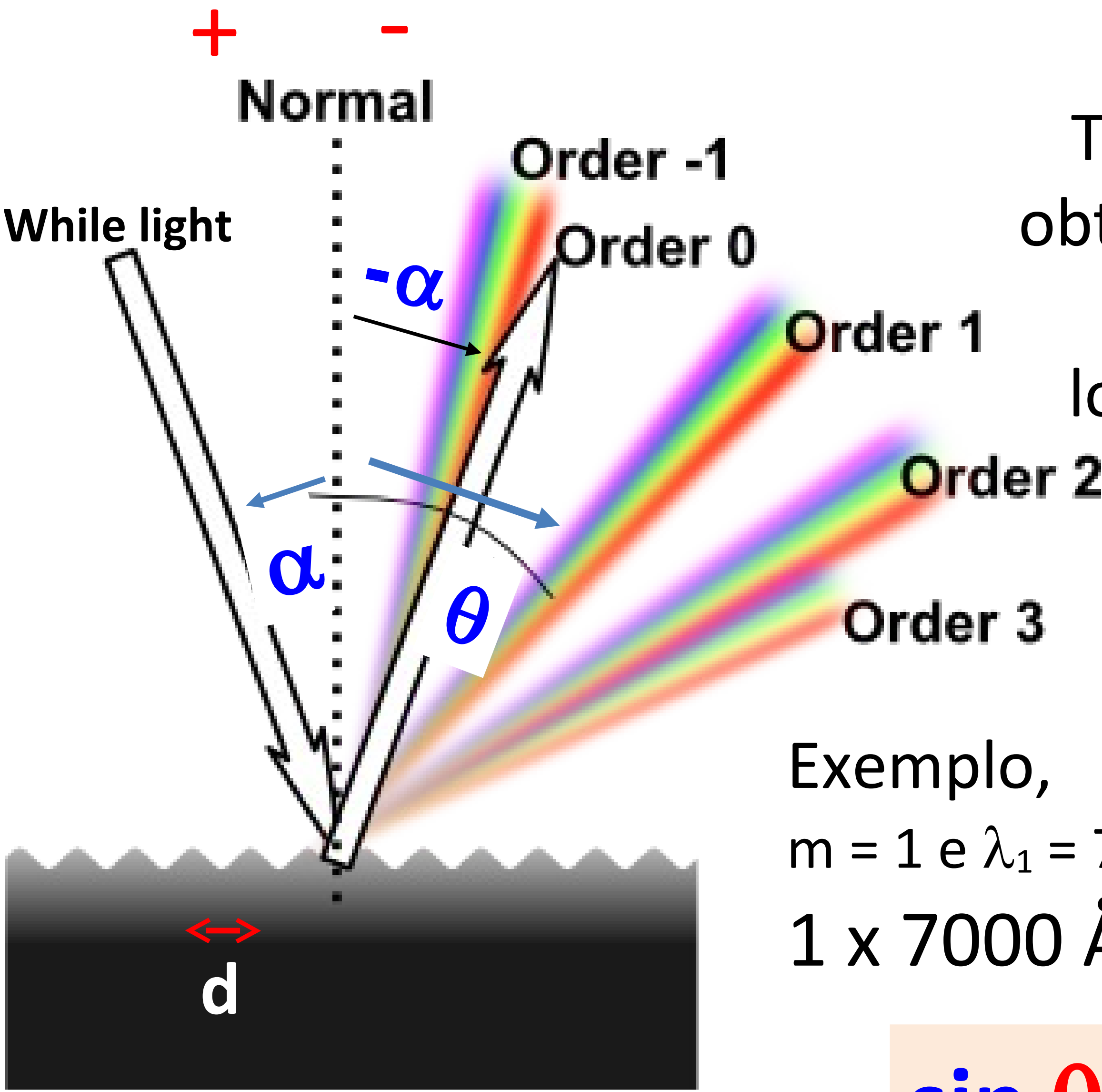
1st order 2nd order 3rd order 4th order 5th



Spectrograph: Claikson Benedito

Pictures (composite): Jorge Meléndez

Angular overlap of grating orders



The same angle θ can be obtained for higher orders *m* and correspondingly lower *1/m* wavelengths

$$\sin\theta = m\lambda / d$$

$m = 0, \pm1, \pm2, \ldots$

Exemplo,

$m = 1$ e $\lambda_1 = 7000Å$ e $m = 2$ e $\lambda_2 = 3500Å$

$1 \times 7000\ Å = 2 \times 3500\ Å$

$$\sin\theta = m\lambda/d - \sin\alpha$$

Angular overlap of grating orders

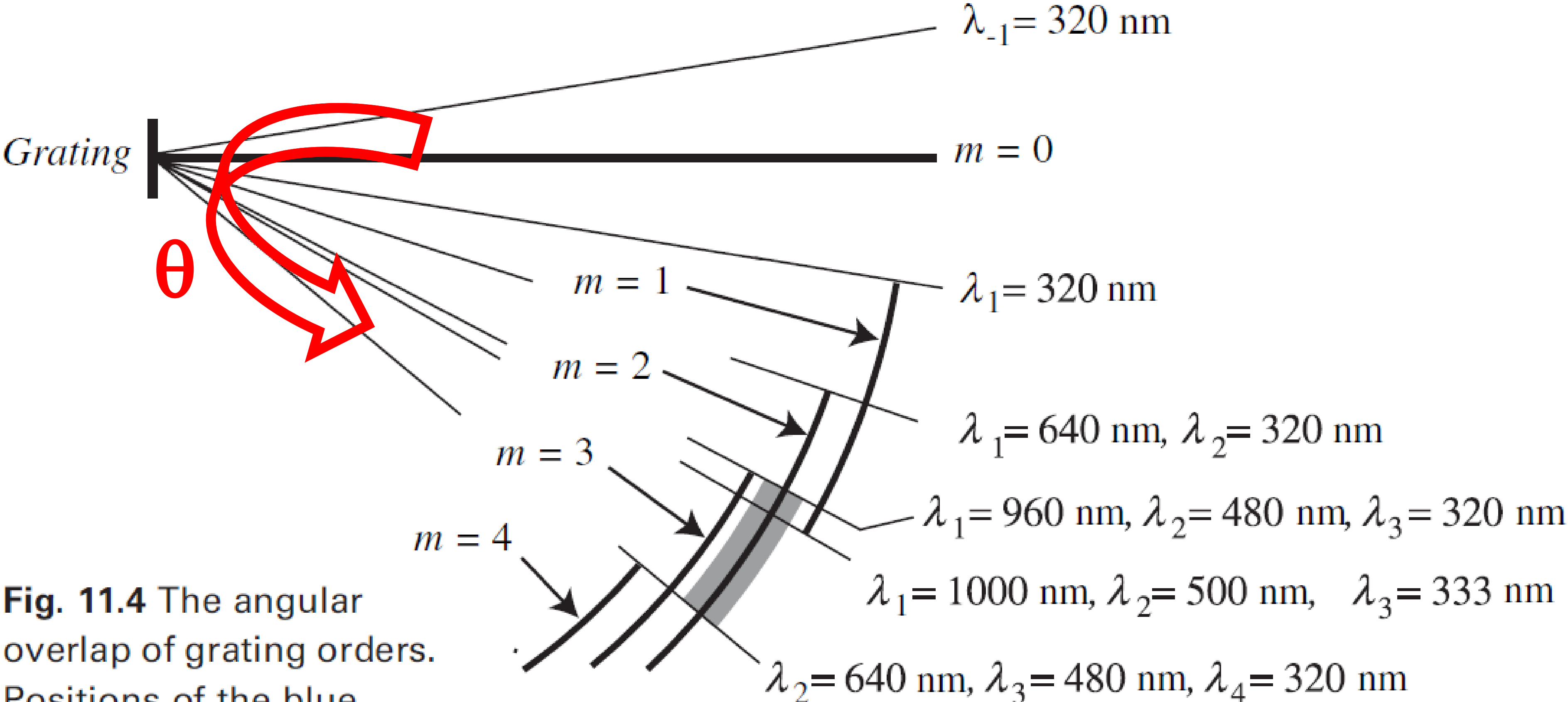


Fig. 11.4 The angular overlap of grating orders. Positions of the blue edges (taken to be at 320 nm) of orders –1 through +4 are shown. The thick gray arc shows the free spectral range of the second order, assuming λ_{max} = 640 nm.

$$\sin \theta = m\lambda/d - \sin \alpha$$

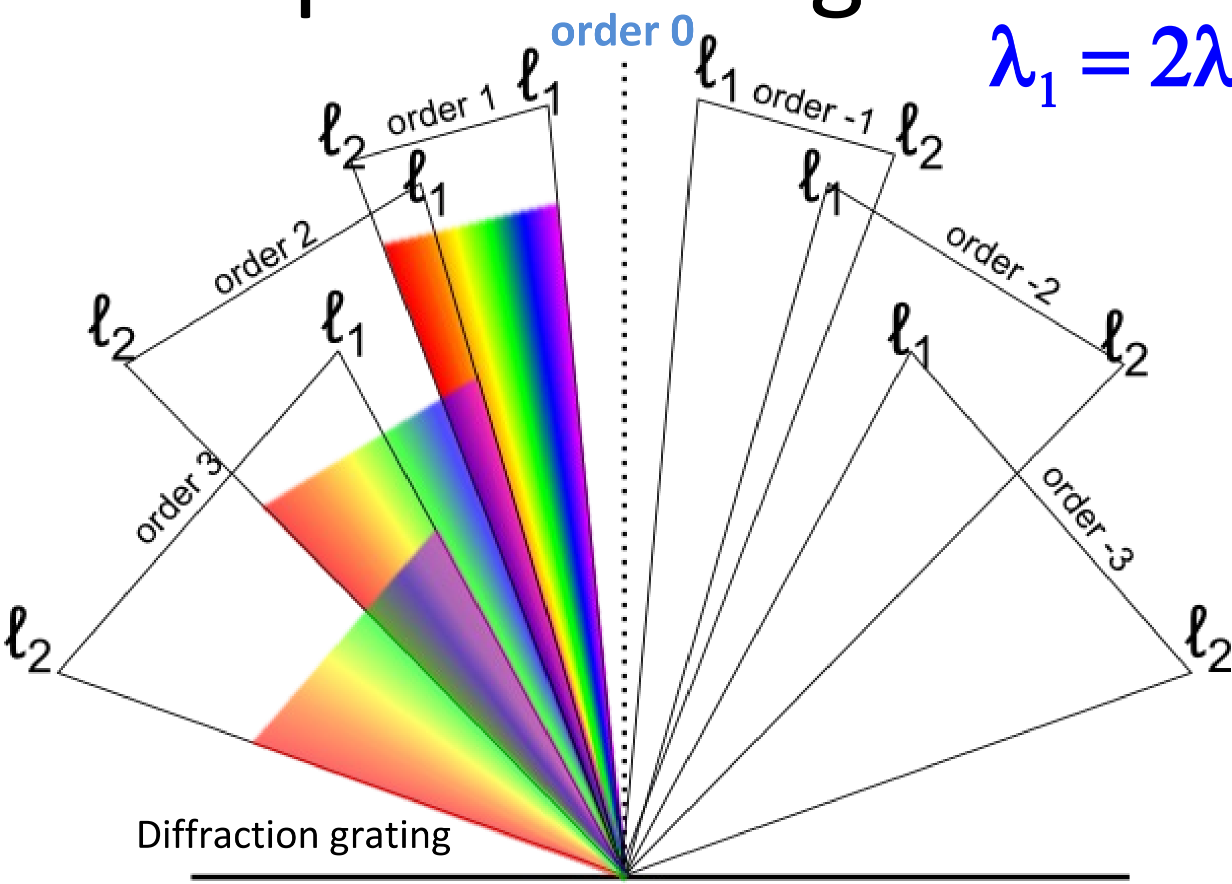
$$\lambda_1 = 2\lambda_2 = 3\lambda_3 = \ldots = m\lambda_m$$

$$\lambda_m = \lambda_1 / m$$

Free spectral range

$$\sin\theta = m\lambda/d - \sin\alpha$$

$$\lambda_1 = 2\lambda_2 = 3\lambda_3 = \ldots = m\lambda_m$$



For ex., we would have the same angle θ for:

λ_1 = 8000 Å

λ_2 = 4000 Å

λ_3 = 2666 Å

…

$\lambda_m = \lambda_1/m$

$\lambda_{m+1} = \lambda_1/(m+1)$

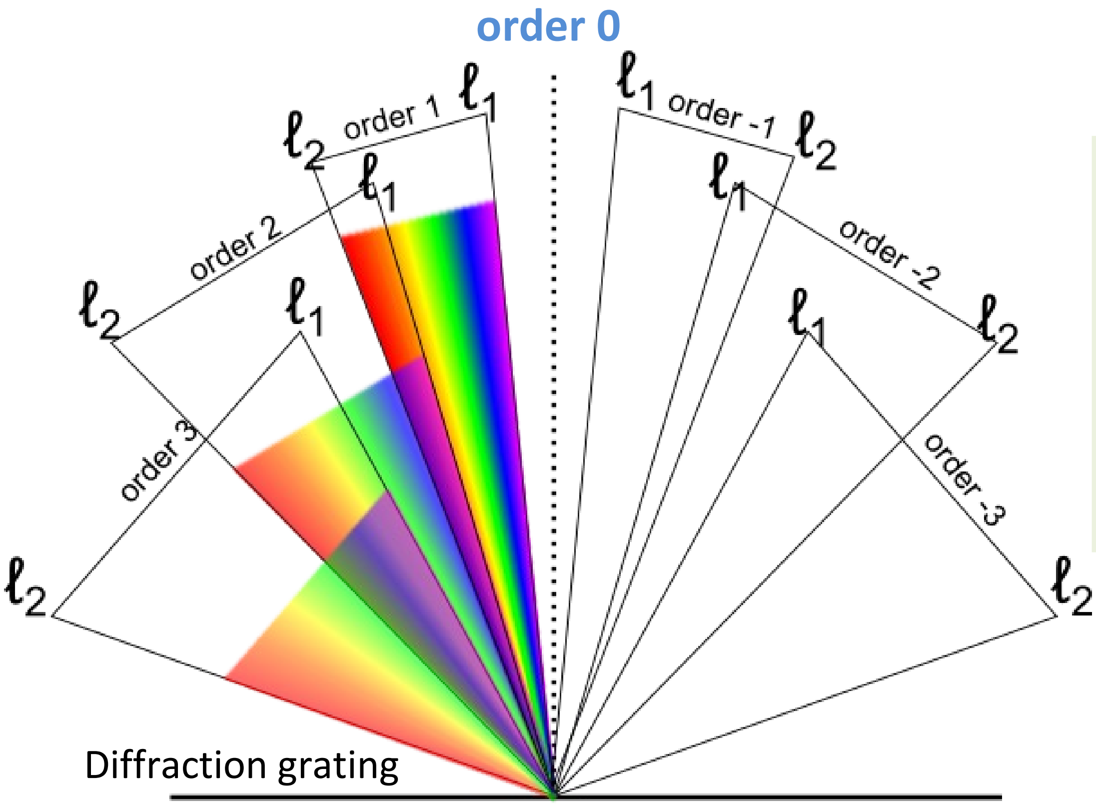
$(m+1)\,\lambda_{m+1} = m\,\lambda_m$

$$\lambda_{m+1} = \frac{m}{(m+1)}\lambda_m$$

Minimum λ to avoid contamination of the order m, by order m+1

Practical coverage of an order

$\sin\theta = m\lambda/d - \sin\alpha$



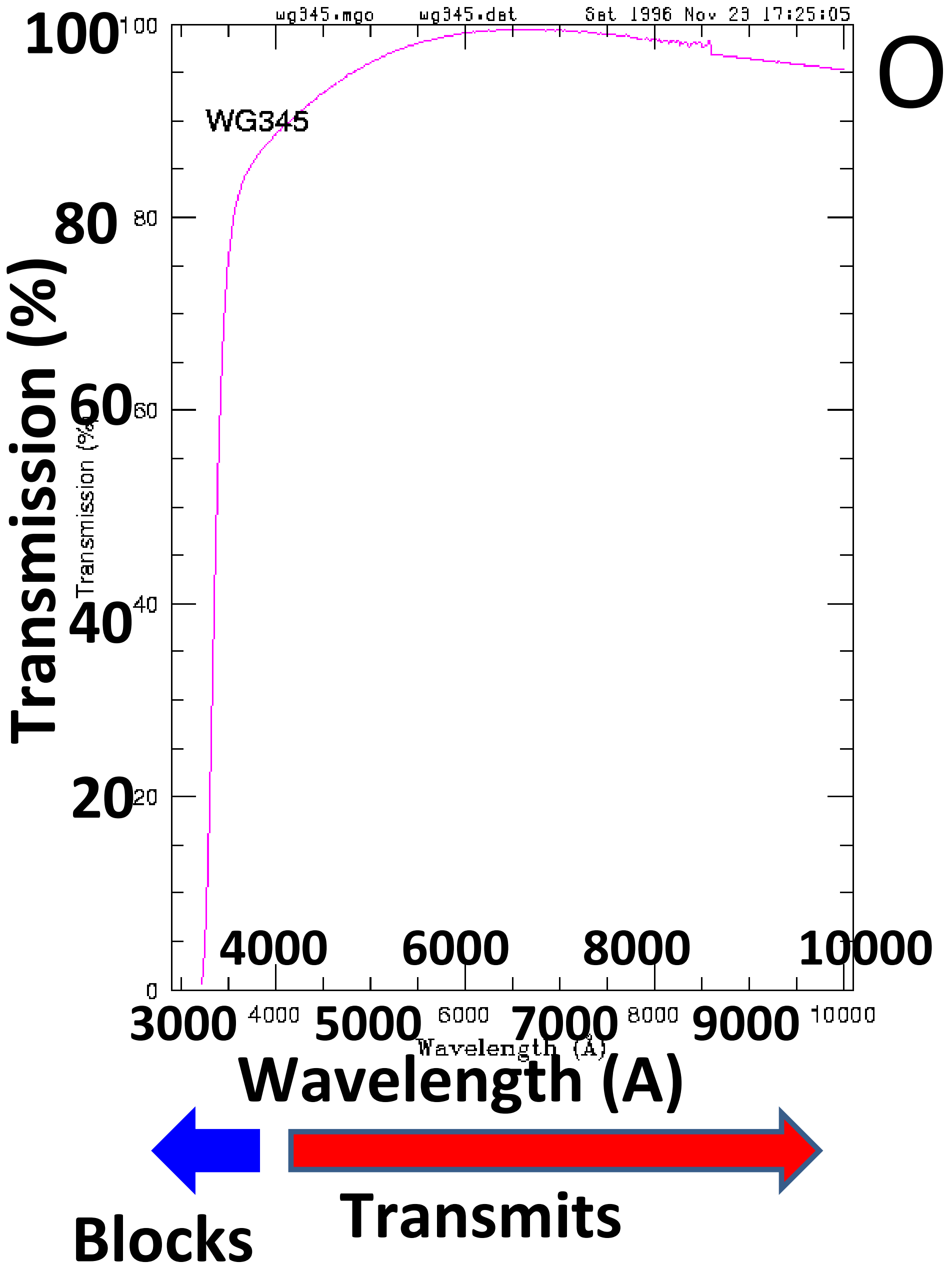
$$\lambda_{m+1} = \frac{m}{(m+1)}\lambda_m$$

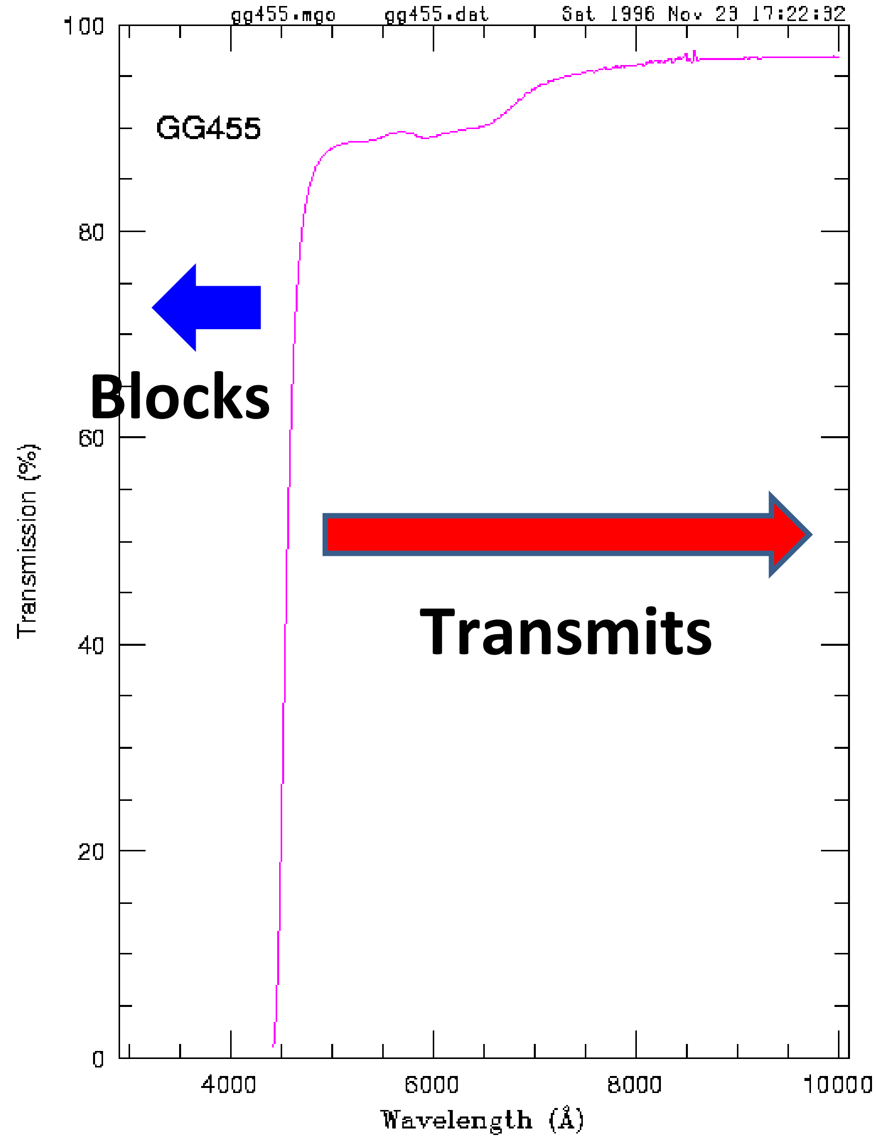
For maximum $\lambda = \lambda_{max}$ at order m, the minimum λ is set by the next order λ_{m+1}:

$$\lambda_{m+1} = \frac{m}{(m+1)}\lambda_{max}$$

For ex., for λ_{max} = 9000 Å at 1st order, we have contamination from $\lambda_2 = 4500$ Å of the 2nd order. We need a filter to block $\lambda < 4500$ Å, to observe in 4500-9000 Å

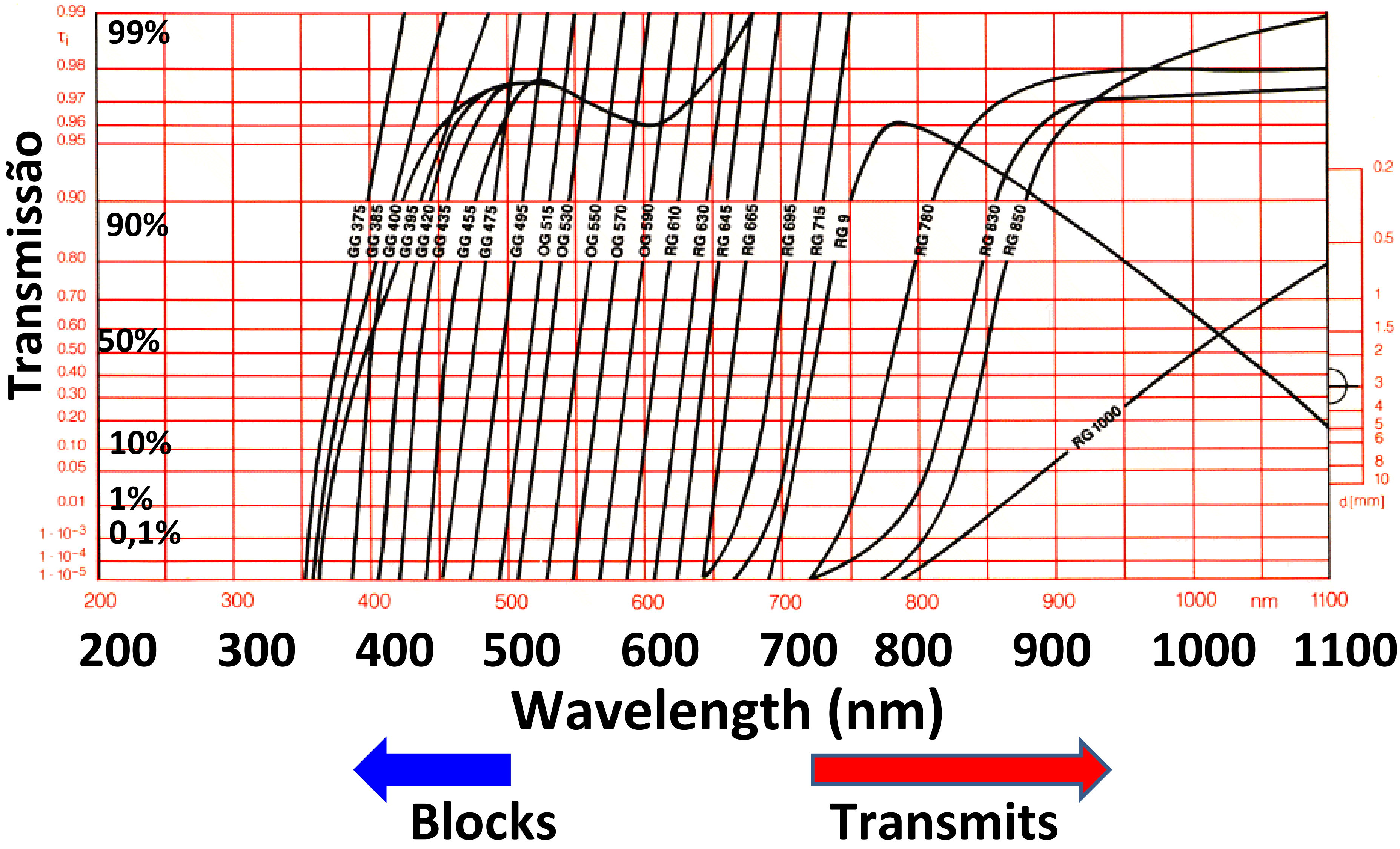
Order blocking filters





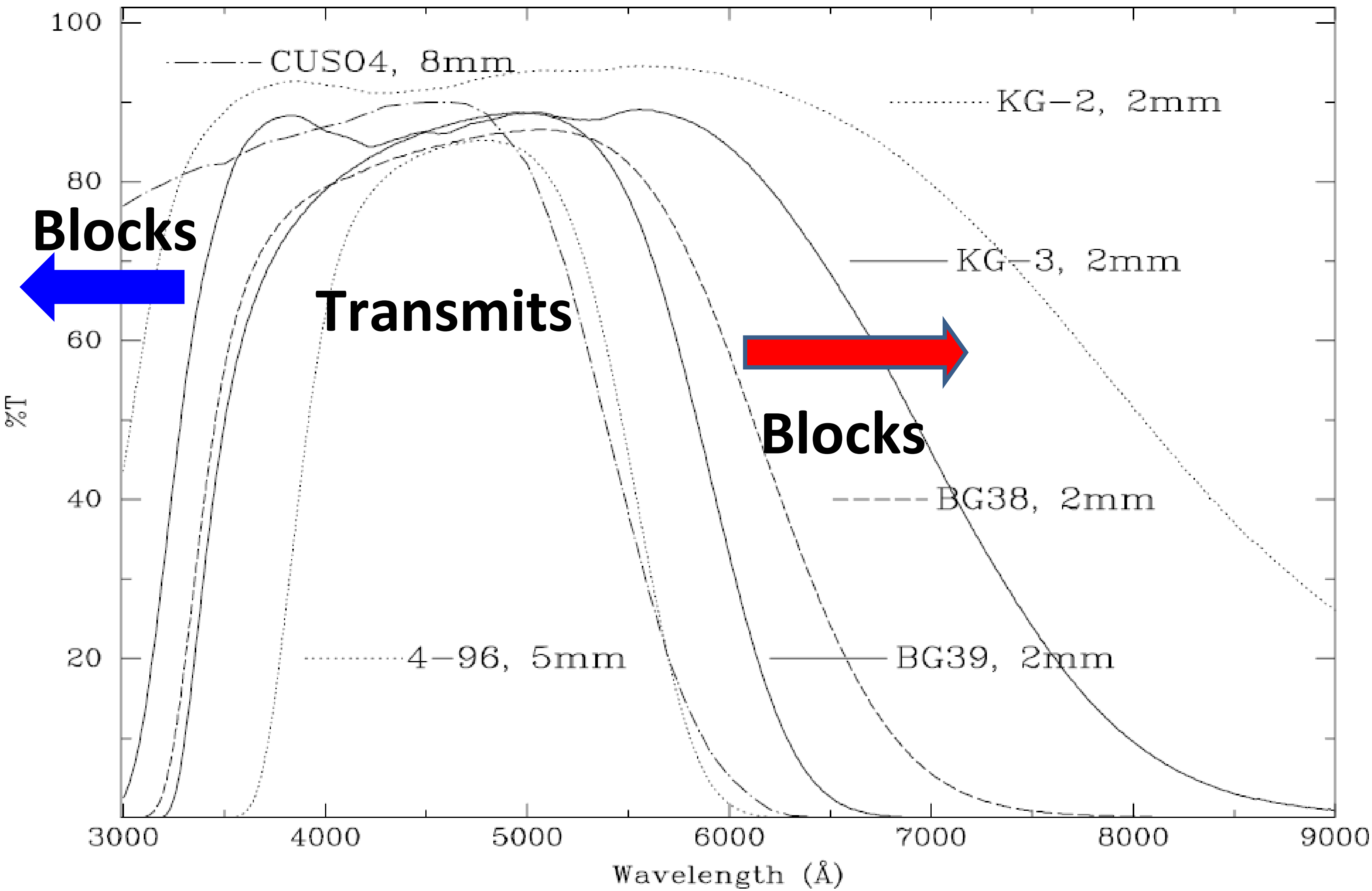
Examples from **1.5-m R-C Spectrograph**:
http://www.ctio.noao.edu/spectrographs/60spec/filters.html

Order blocking filters



http://www.as.utexas.edu/mcdonald/facilities/2.7m/lcs.html

Red blocking filters

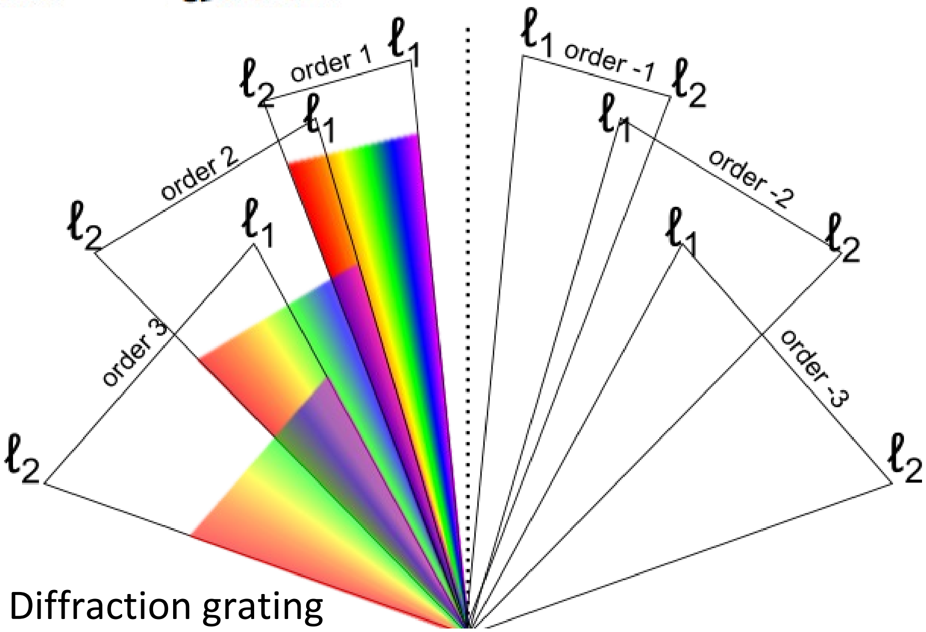


http://www.noao.edu/kpno/manuals/l2mspect/

$$\frac{d\theta}{d\lambda} = \frac{m}{d\cos\theta}$$

Free spectral range ($\Delta\lambda_{FSR}$)

order 0



The free spectral range (FSR) is the coverage in λ that is not blocked

Lambda minimum:

$$\lambda_{m+1} = \frac{m}{(m+1)}\lambda_{max}$$

$$\Delta\lambda_{FSR} = \lambda_{max} - \frac{m}{(m+1)}\lambda_{max} = \frac{\lambda_{max}}{(m+1)}$$

For example, for λ_{max} = 900nm at 1st order we would have $\Delta\lambda_{FSR} = 450$nm → we can observe in the range 450 - 900 nm

Blazed gratings (redes com blazing)

Disadvantage of flat gratings: much light is lost at order 0 and other orders.

In gratings with blazing the facet of each ruling has an angle, concentrating most of the light around a given wavelength

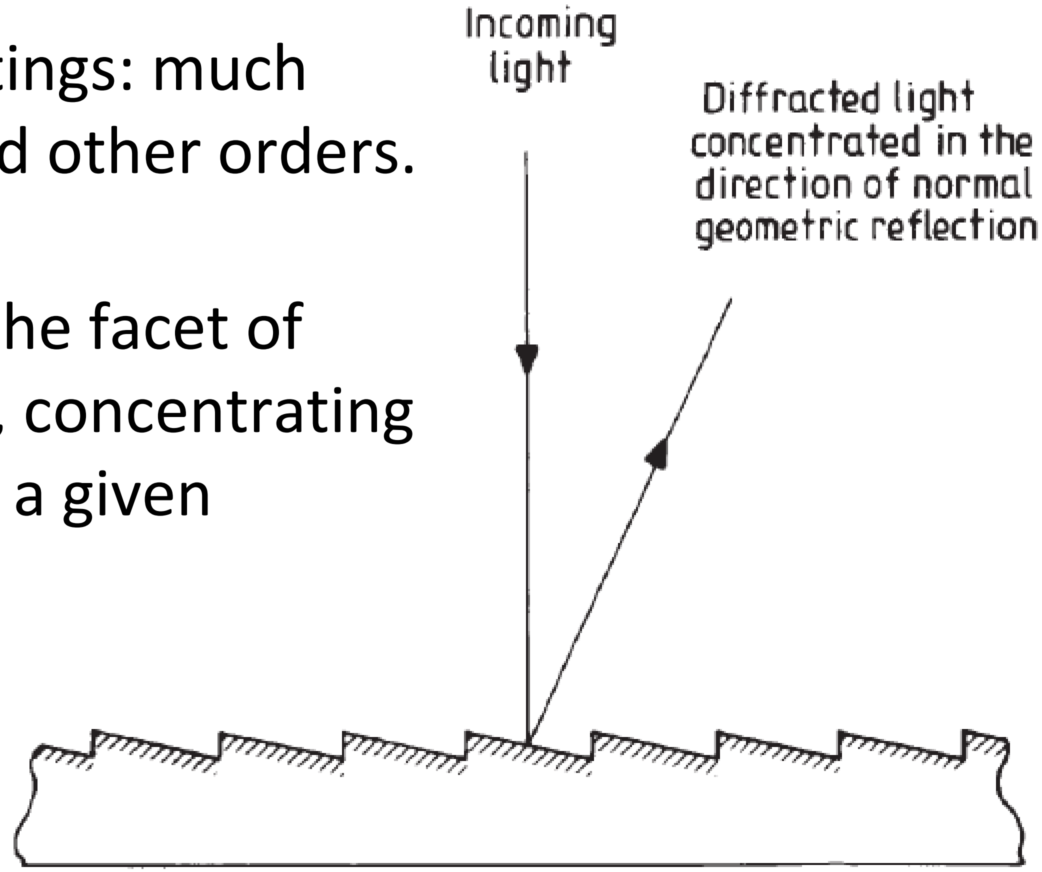
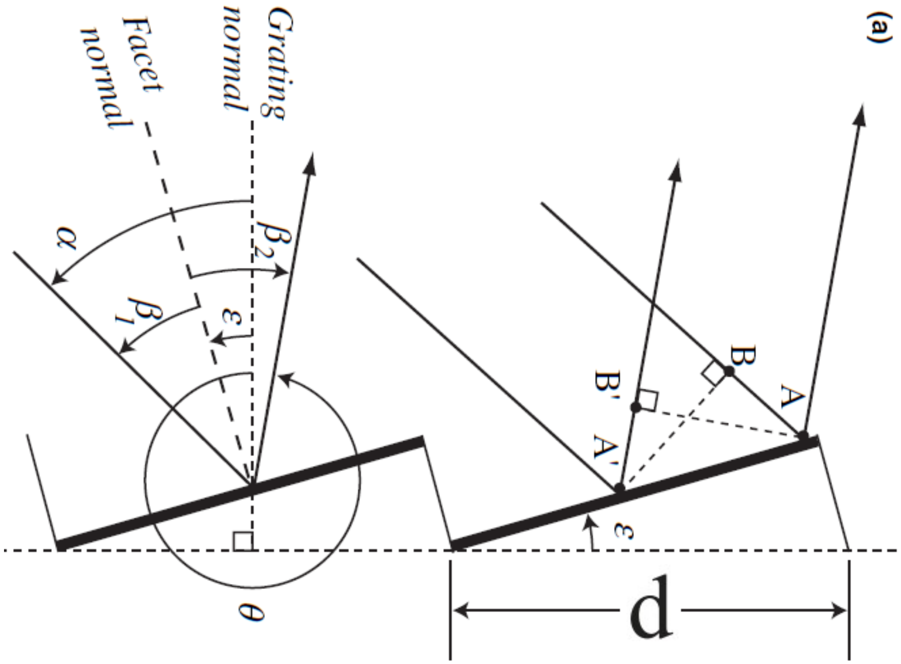


Figure 4.1.5. Enlarged section through a blazed reflection grating.



© To Measure the Sky

Blazed gratings

Best tilt to concentrate light in a given λ:

$$\alpha = \beta + \varepsilon$$
$$\theta = 2\pi + \varepsilon - \beta$$
$$\alpha + \theta = 2\varepsilon$$

$$\beta + \varepsilon = \alpha \text{ and } (\varepsilon - \beta) = \theta$$

Grating equation: $\sin\theta + \sin\alpha = m\lambda/d$

In the book "To Measure the Sky" is α, but is wrong

$$\sin(\varepsilon - \beta) + \sin(\beta + \varepsilon) = m\lambda/d$$

which reduces to: $\sin(\varepsilon) = m\lambda/2d\cos(\beta)$

Blaze wavelength λ_b:

$$\lambda_b = \frac{2d}{m}\sin(\varepsilon)\cos(\alpha - \varepsilon)$$

Blazing's efficiency

The efficiency is maximum at blaze wavelength λ_b, with the efficiency decreasing to 50% at:

• $\lambda_{min} = 2/3\ \lambda_b$

• $\lambda_{max} = 3/2\ \lambda_b$

Example, λ_b = 6000 Å → we can cover with efficiency > 50% (max efficiency): 4000 – 9000 Å.

Example

http://www.as.utexas.edu/mcdonald/facilities/2.7m/lcs.html

Diffraction Gratings available for LCS

Gratings are blazed for use in first order.

grating number	lines/mm	blaze (Å)	effective blaze (Å)	dispersion λ/ one-pixel $\Delta\lambda$ (TI1 CCD)
40	300	4200	3900	550
41	300	7500	6000	550
42	300	10000	9200	550
43	600	4000	3700	1100
44	600	7500	6900	1100
45	600	10000	9200	1100
46	1200	4000	3700	2200
47	1200	6000	5500	2200
48	1200	7500	6900	2200

Important points

1. Due to blazing, the grating is optimized for a particular region of the spectrum (although you can use several gratings, of course).
2. Due to order overlapping, the spectral coverage is limited
3. Different elements (e.g. CCD) could be optimized for a given spectral region

Is complicated to cover all the optical spectrum (300 - 1000nm) with only 1 spectrograph

"Double spectrograph" ☺

Double spectrograph (2 arms)

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC
94:586–594, June 1982

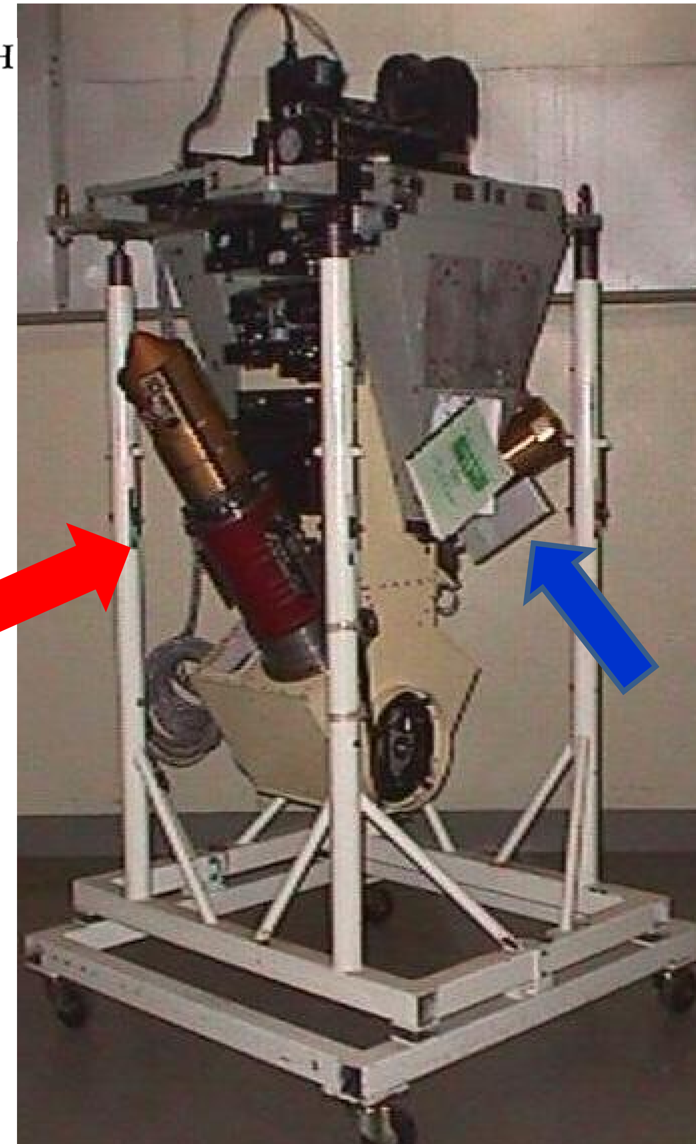
AN EFFICIENT LOW- AND MODERATE-RESOLUTION SPECTROGRAPH FOR THE HALE TELESCOPE

J. B. OKE AND J. E. GUNN*
Palomar Observatory, California Institute of Technology, Pasadena, California 91125

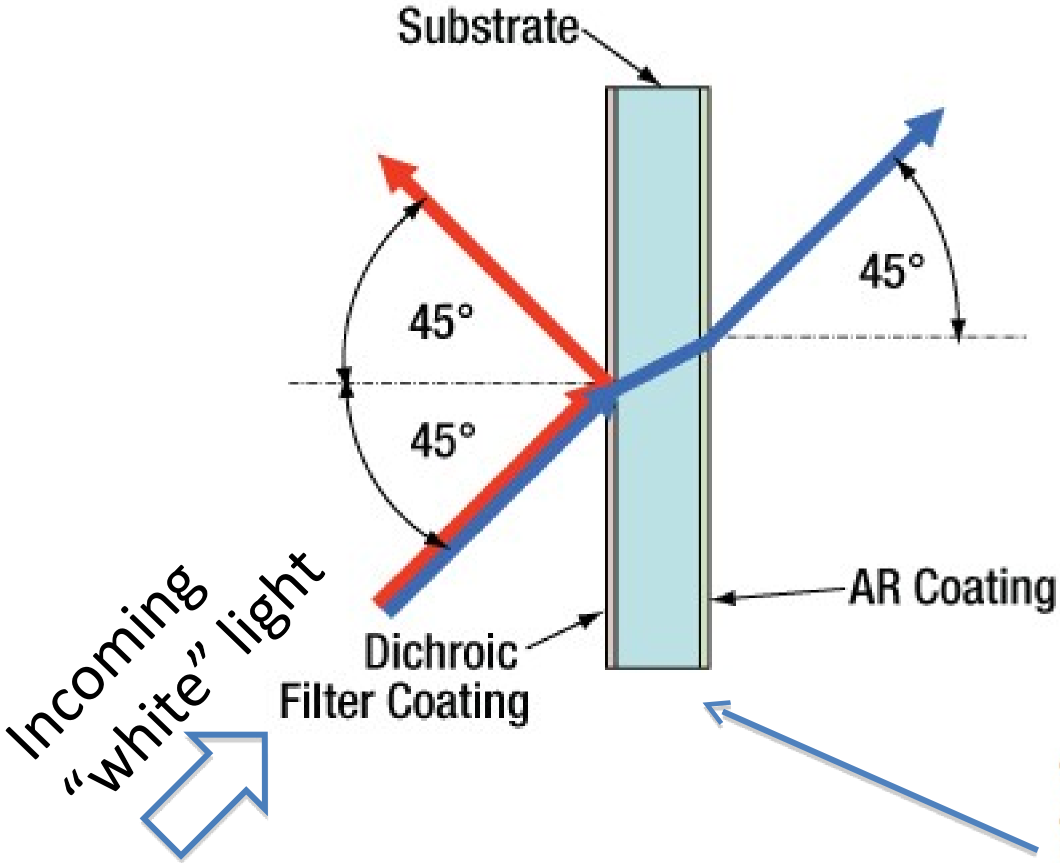
Double spectrograph for the Palomar telescope (5 meters).

RED side covers 550-1000 nm

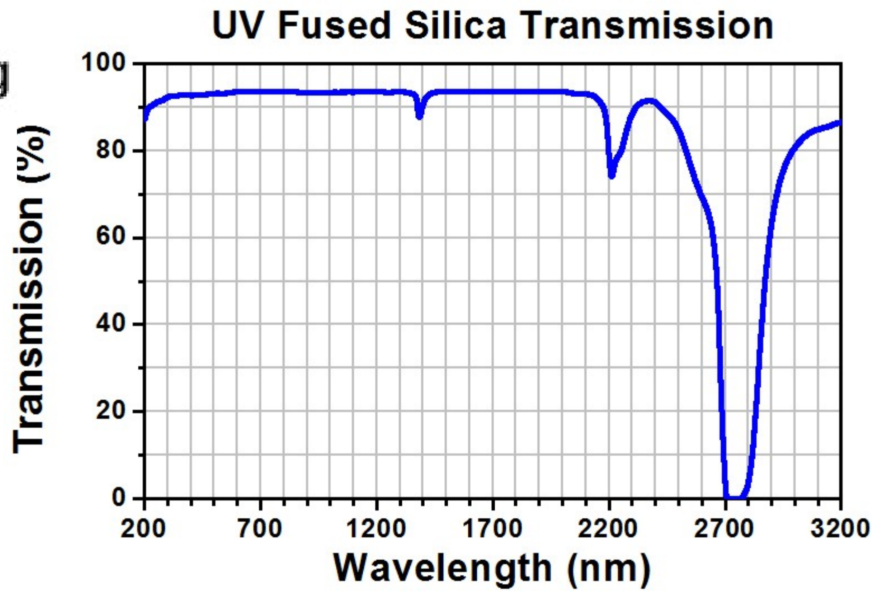
BLUE side is optimized for 300-550 nm



Dichroic: dichroic reflecting coating on one surface & antireflection coating on the opposing surface

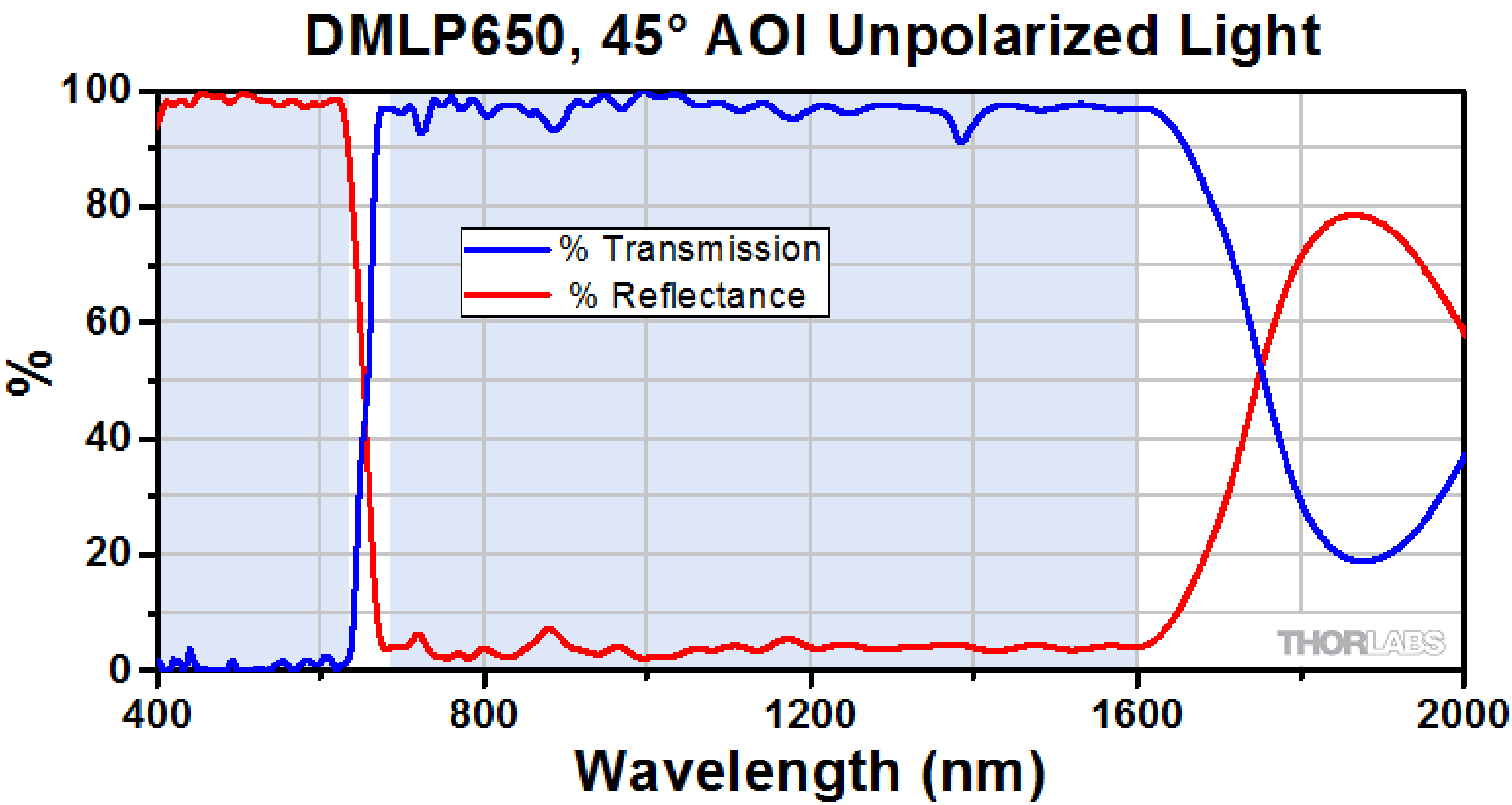


Substrate: UV fused silica



https://www.thorlabs.com/newgrouppage9.cfm?objectgroup_id=3313

ThorLabs: Longpass Dichroic Mirrors/Beamsplitters: 650 nm Cutoff Wavelength

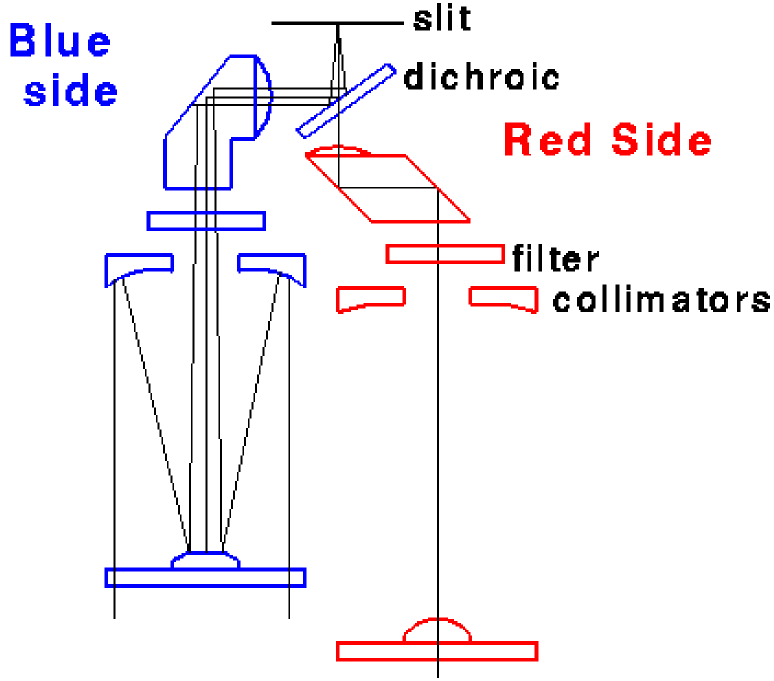


https://www.thorlabs.com/
newgrouppage9.cfm?objectgroup_id=3313

Dichroic: light into different λ
→ double spectrograph

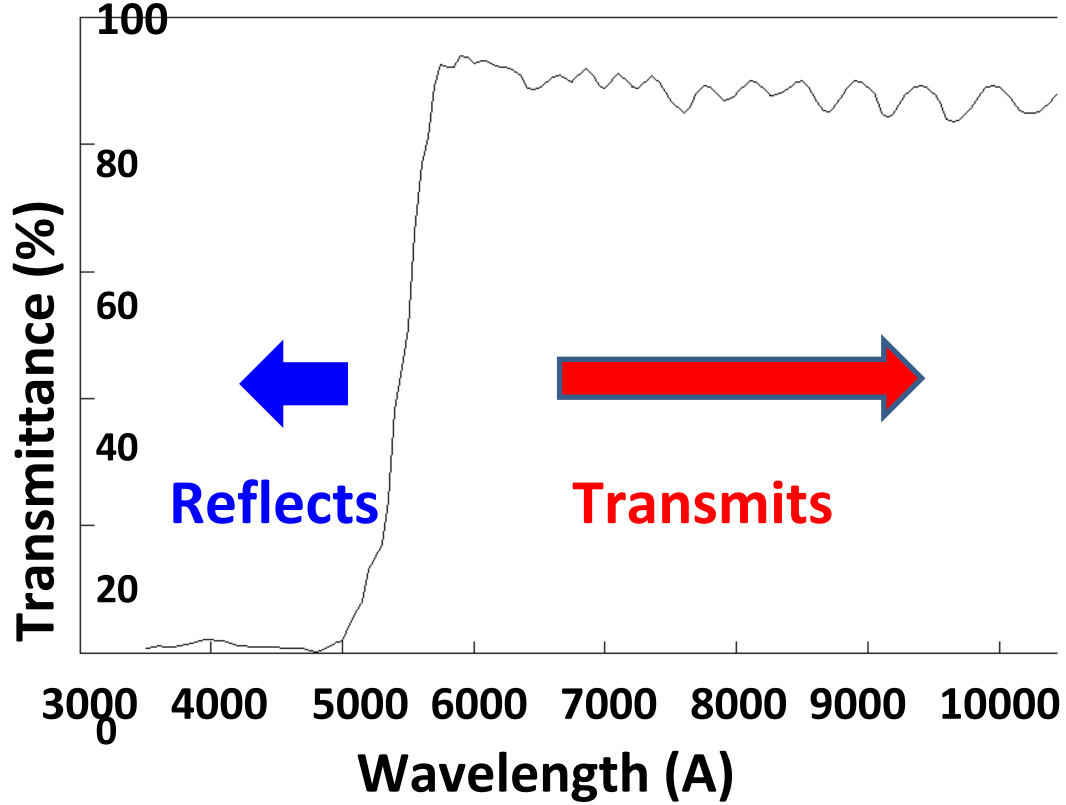
reflect & transmit light

Example : Palomar Double Spectrograph



Upper portion of Double Spectrograph
(after Oke and Gunn, 1982)

Dichroic D55



Gratings for the Palomar double spectrograph

(F) GRATING SPECS (lines/mm, blaze, dispersion)

R ~ 1.000 to 10.000

Overview of Gratings

lines/mm	1st order blaze (Å)	Useful range (Å) (to blaze 1/2-intensity)	Red camera dispersion (Å/mm)	Blue camera dispersion (Å/mm)
158 [a]	7560	5000 – 11300	201 1st [c]	135 2nd [d]
300 [b]	3990	2700-6000	–	140 1st
316 [a]	7150	4800 – 10700	102 1st	–
600 [b]	3780	2500 – 5700	–	71 1st
600 [a]	9500	6300 – 14300	54 1st	–
1200 [b]	4700	3100 – 7100	–	36 1st
1200	7100	4700 – 10700	27 1st	36 1st
1200	9400	6300 – 14100	26 1st	35 1st

[a] silver coating, can be used only longward of 3500Å; [b] can be used only in blue spectrograph; [c] first order; [d] second order.

Setting Grating Angles

Order: 1 **Side:** Red **Slit Width:** 1"

Grating: 158 lines/mm, blazed at 7560 Å

Wavelength: 7000 Å

Clear Form | Calculate

Theta = 20° 49.4' (20.824°)

Order: 1 **Grating:** 158 lines/mm, 7560 Å blaze
Side: Red **Center wavelength:** 7000 Å
Best wavelength*: 3907.6 Å

Resolution: 10.31 Å/slitwidth 441.4 km/s/slitwidth
Resolving Power: 679
Dispersion: 201.3249 Å/mm 3.020 Å/pixel 129.3 km/s/pixel
Coverage: 12369.4 Å 529749 km/s

https://sites.astro.caltech.edu/palomar/observer/200inchResources/dbspoverview.html

Goodman High Throughput Spectrograph (GTHS)

Goodman, o espectrógrafo do Telescópio SOAR, é eficiente mas tem cobertura espectral restrita (only 1 arm, although 2 cameras, blue and red, are available)

https://noirlab.edu/science/programs/ctio/instruments/goodman-high-throughput-spectrograph/instrument-characteristics

- **Wavelength range:** 320 – 900 nm
- **Two Cameras (detectors) are available** (with various binning and region-of-interest options)
  - **Blue Camera:** optimized for the **UV, down to 320nm**
  - **Red Camera:** best response **redward of ~400nm with negligible fringing**
    - **Which Camera: Blue or Red?**
    - The Blue Camera is recommended for programs requiring the highest possible throughput blueward of ~4500 A, down to the atmospheric UV cutoff. Also, programs attempting fast time-series photometry should use the Blue Camera, since at present it has more flexible choice of Regions of Interest (ROI).
    - For all other programs, the Red Camera provides roughly equal response as the Blue Camera around ~4500 A and is better at redder wavelengths, with almost no fringing out to 9500 A.

Consulta de Interesse Científico: Novo Espectrógrafo do Telescópio SOAR

O escritório nacional do Telescópio SOAR está buscando analisar o interesse científico da comunidade em relação a um novo espectrógrafo de baixa resolução e ampla cobertura espectral. Esse novo instrumento não tem a intenção de substituir o espectrógrafo Goodman, mas sim oferecer uma alternativa com maior cobertura espectral simultânea e uma configuração única, com o objetivo de reduzir o tempo morto e facilitar a redução automática de dados.

Gostaríamos de convidá-lo a entrar em contato até o dia 5/junho/2023. Envie um e-mail para lfraga@lna.br com as seguintes informações:

1) Título do projeto de pesquisa. 2) Breve resumo do projeto, destacando como as características do novo espectrógrafo seriam vantajosas. 3) Quais parâmetros específicos você considera importantes em relação à cobertura espectral, resolução e tamanho da fenda?

Linear dispersion of the spectrum on the CCD (valid for both prisms & gratings)

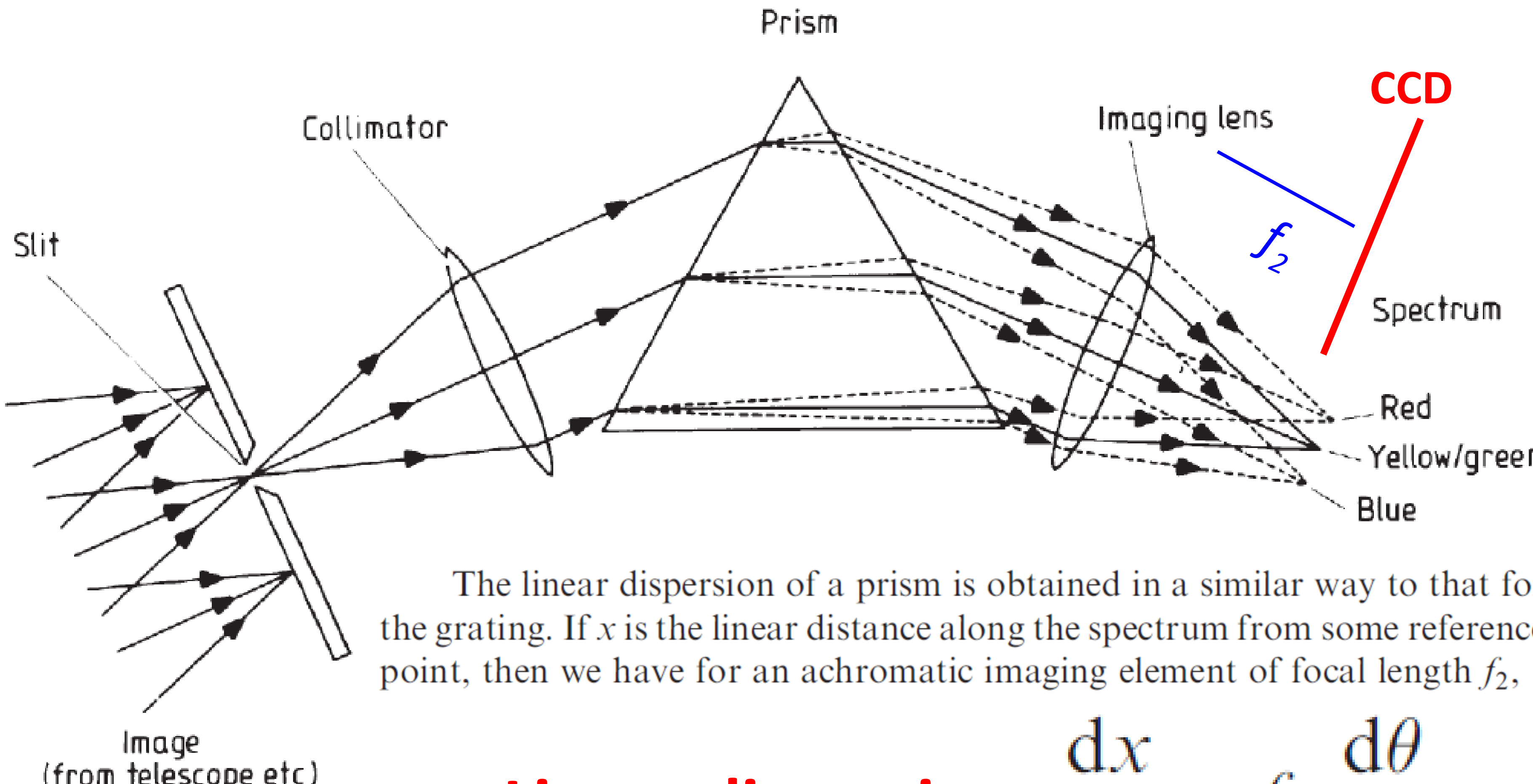
Angular dispersion of prism

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \approx \frac{-180AB}{\pi(\lambda - C)^2} \quad {}^\circ\mathrm{m}^{-1}$$

Angular dispersion of grating

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} = \frac{m}{\mathbf{d}\cos\theta}$$

Linear dispersion dx/dλ on the CCD



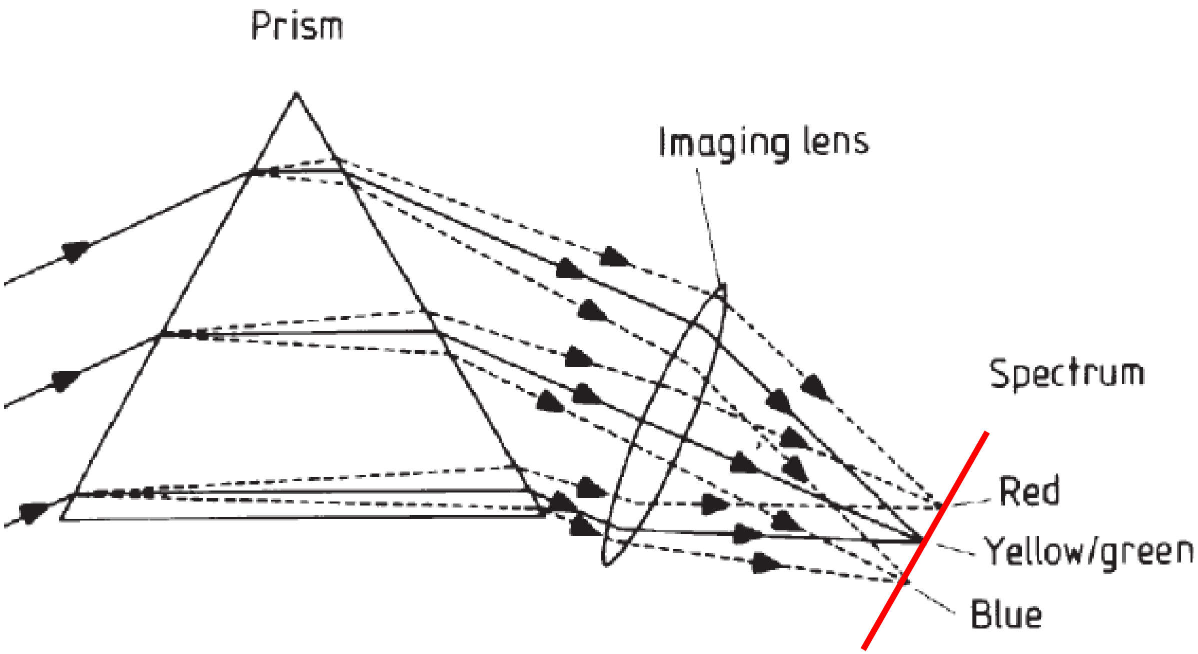
The linear dispersion of a prism is obtained in a similar way to that for the grating. If x is the linear distance along the spectrum from some reference point, then we have for an achromatic imaging element of focal length f_2,

Linear dispersion

$$\frac{dx}{d\lambda} = f_2 \frac{d\theta}{d\lambda}$$

Figure 4.1.12. Basic optical

Example for a prism ($\alpha = 60^{o}$)



apex angle of 60°

$1.39 \times 10^{7}\ ^\circ\mathrm{m}^{-1}$

$$\frac{\mathrm{d}\theta}{\mathrm{d}\lambda} \approx \frac{-180AB}{\pi(\lambda - C)^2}\quad {}^\circ\mathrm{m}^{-1}$$

In a prism, typical value:
$d\theta/d\lambda = 1{,}39 \times 10^{7}\ ^{o}m^{-1}$

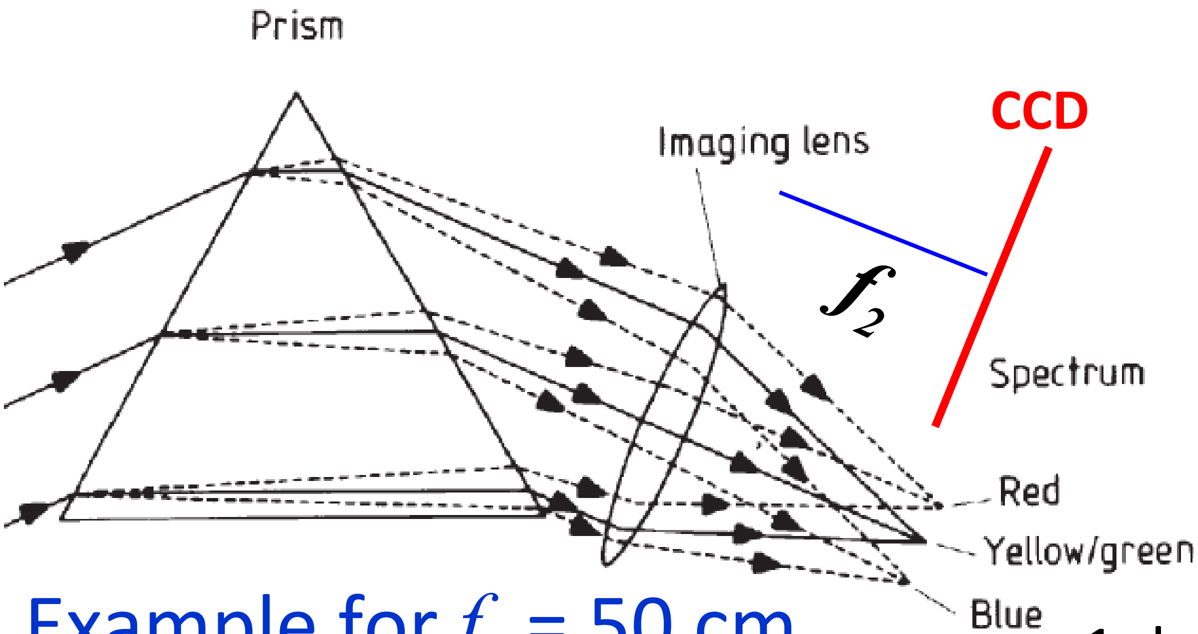
Compute $d\theta$ for $d\lambda$ = 1 Å

$d\theta = (d\theta/d\lambda)d\lambda = (1{,}39 \times 10^{7}\ ^{o}m^{-1}) \times 10^{-10}$ m

$d\theta = 1{,}39 \times 10^{-3}\ ^{o} = 5$ arcsec

Linear dispersion $dx/d\lambda$ on CCD: multiply by focal distance f_2

Linear dispersion dx/dλ



Linear dispersion:

$$\frac{\mathrm{d}x}{\mathrm{d}\lambda} = f_2 \frac{\mathrm{d}\theta}{\mathrm{d}\lambda}$$

In a prism, typical

$\mathrm{d}\theta/\mathrm{d}\lambda = 1{,}39 \times 10^{7}\ {}^{\mathrm{o}}\mathrm{m}^{-1}$

1 degree = 0,0174 radians

$\mathrm{d}\theta/\mathrm{d}\lambda = 2{,}426 \times 10^{5}$ radians m^{-1}

Example for f_2 = 50 cm

Estimate dx in dλ=2Å

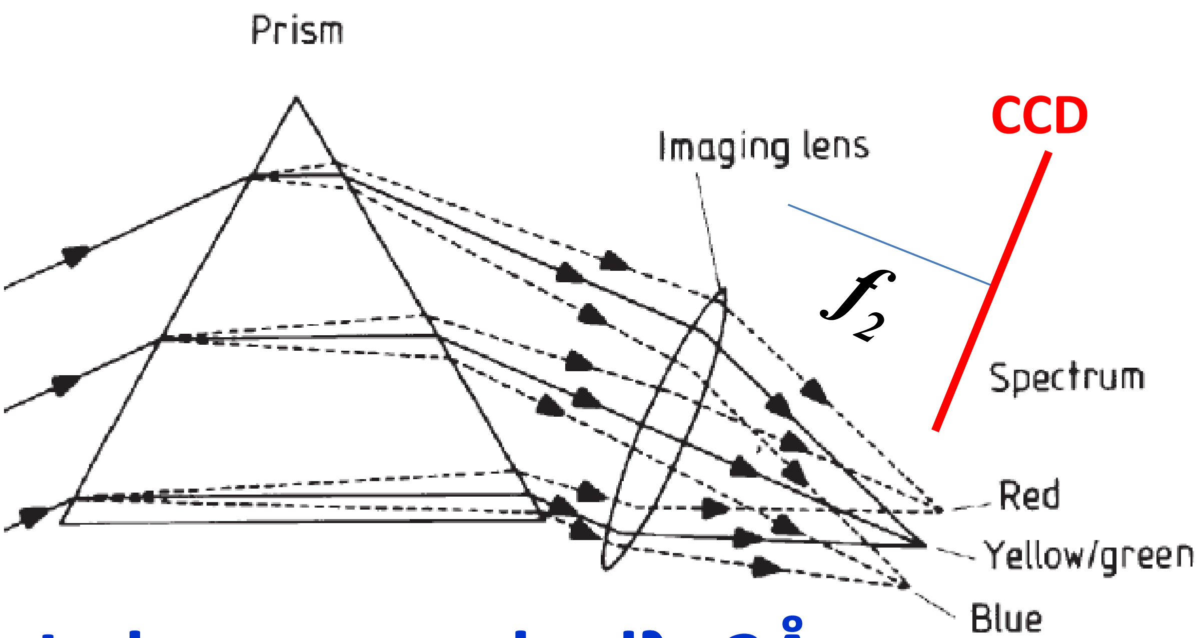
How many 12-μm pixels?

$\mathrm{d}x/\mathrm{d}\lambda = f_2\, \mathrm{d}\theta/\ \mathrm{d}\lambda$ = 0,5m x 2,426 x 10^5 radians m^{-1} = 1,21 x 10^5

dx = dλ x 1,21 x 10^5 = 2Å x 1,21 x 10^5 = 2,42 x 10^5 x 10^{-4}μm

dx = 24 μm. If pixel is 12 μm → 2 pixels fall within 2Å

Reciprocal linear dispersion *p* (plate factor)



Linear dispersion:

$$\frac{\mathrm{d}x}{\mathrm{d}\lambda} = f_2 \frac{\mathrm{d}\theta}{\mathrm{d}\lambda}$$

Reciprocal linear dispersion:

$$p = \frac{\mathrm{d}\lambda}{\mathrm{d}x} = \frac{1}{f_2}\frac{\mathrm{d}\lambda}{\mathrm{d}\theta}$$

In last example dλ=2Å

dx = 24 μm = 24 x 10^{-6}m = 24 x 10^{-3}mm

p = dλ/dx = 2 Å / 24 x 10^{-3}mm

p = 83 Å / mm

High dispersion (high resolution) and low dispersion (low resolution) spectroscopy

high dispersion (spectroscopy) means:

Large linear dispersion $\frac{dx}{d\lambda}$

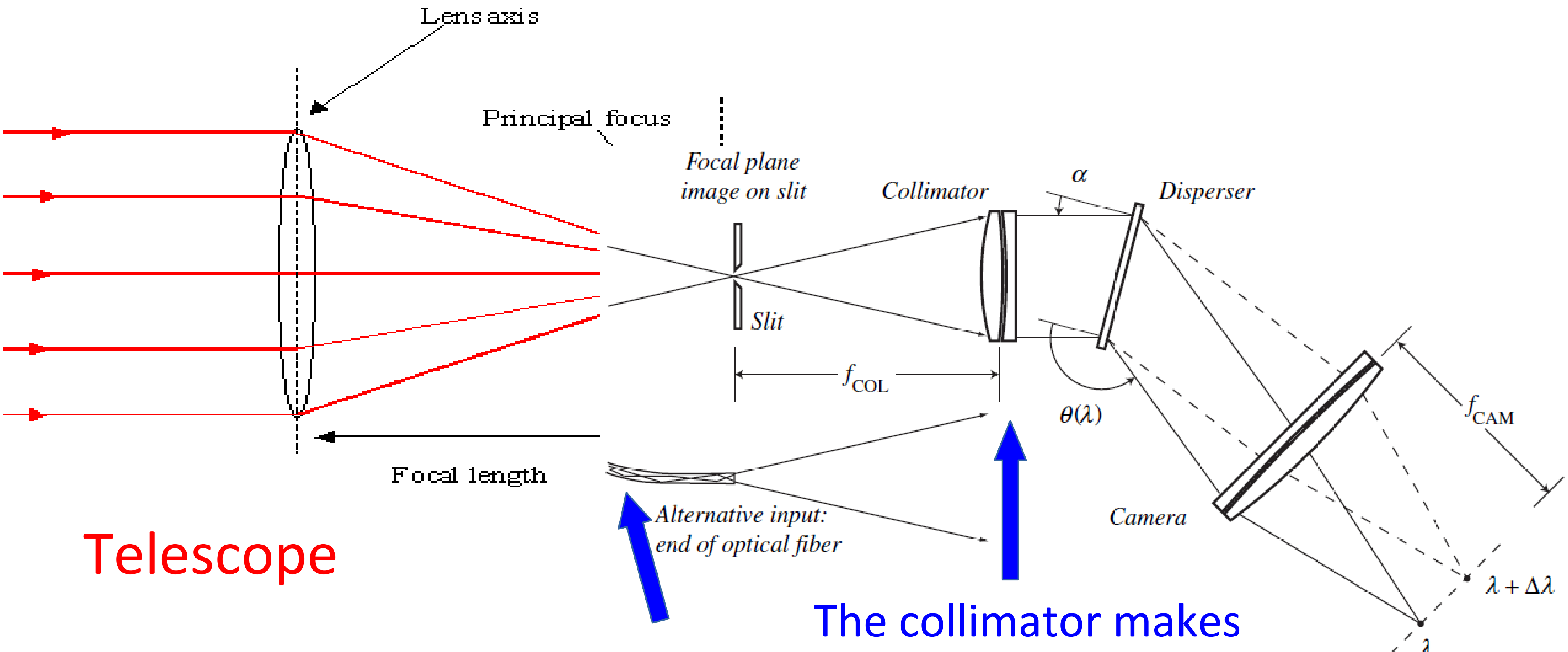
or small plate factor $\frac{d\lambda}{dx}$ for ex.: p ~ 5Å/mm

low dispersion (spectroscopy) means:

Low linear dispersion, i.e. large plate factor,
por ex.: p ~ 100 Å/mm

Large or small plate factor is not used anymore.
Only mentioned here for completeness.

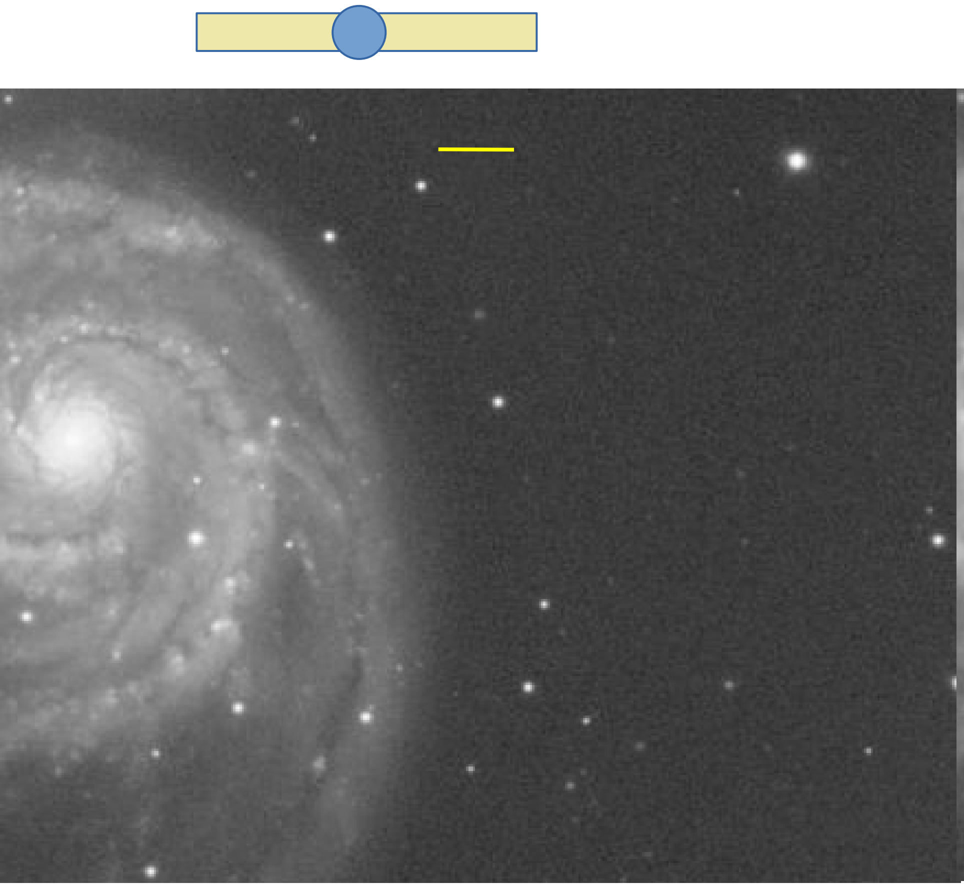
Basic design of spectrographs



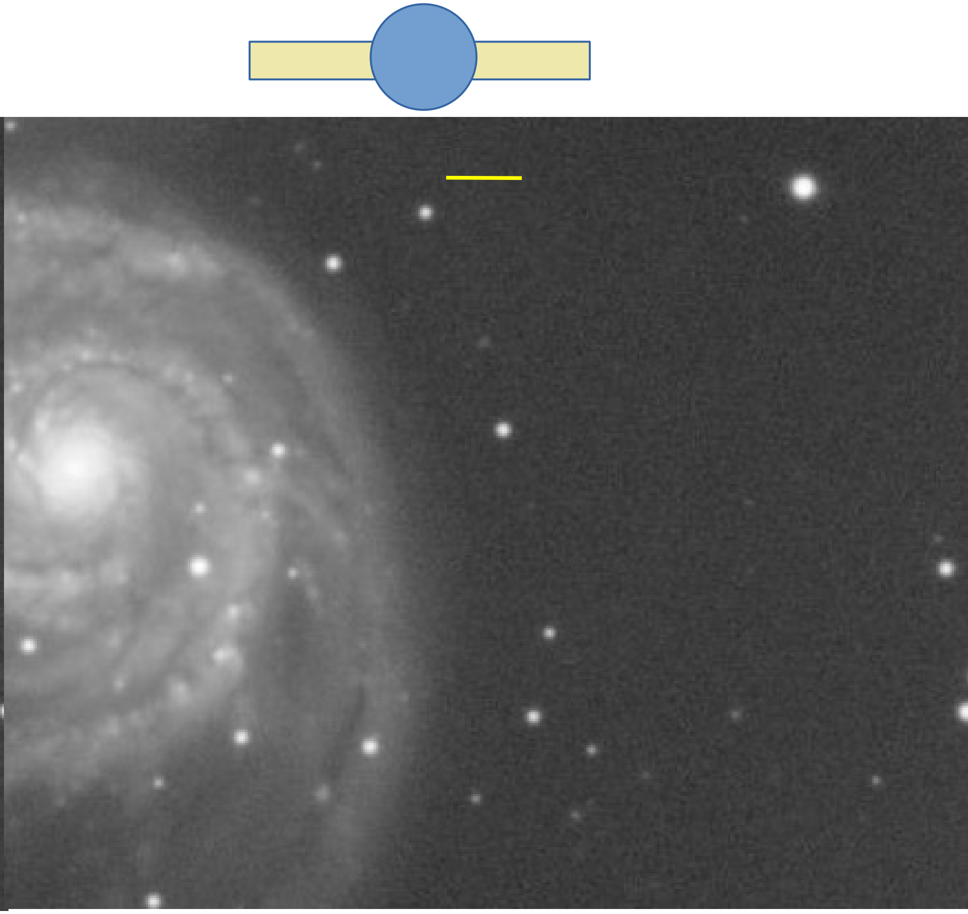
Optical fiber is important for stability on the incoming light on the slit (key for precise radial velocities -exoplanets)

The collimator makes parallel the diverging light from the slit, directing the collimated beam towards the grating https://www.cloudynights.com/topic/654671-effects-of-goodbad-seeing-and-meteoblue-failure/

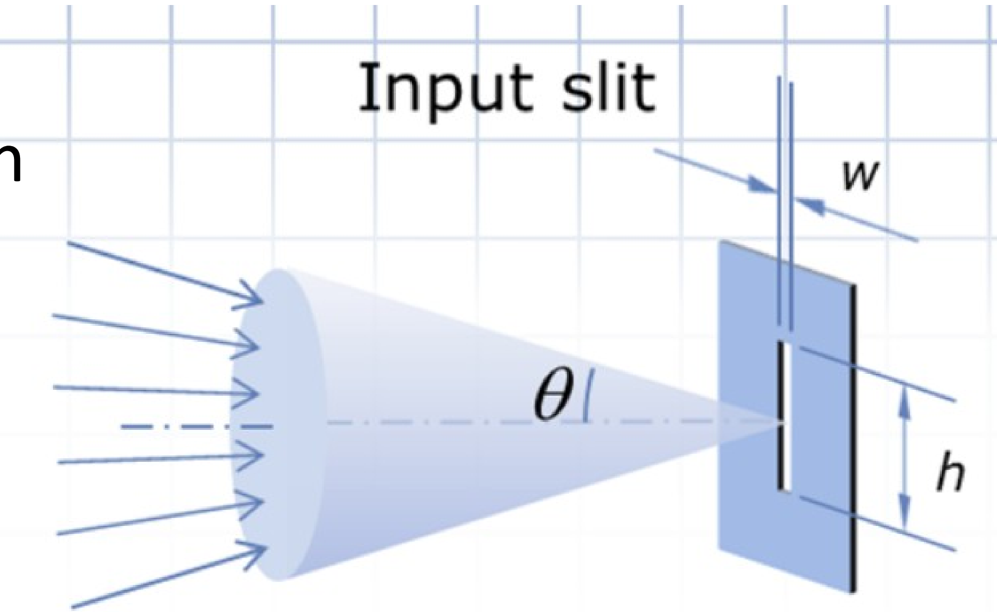
Good seeing:
little or almost no slit loss



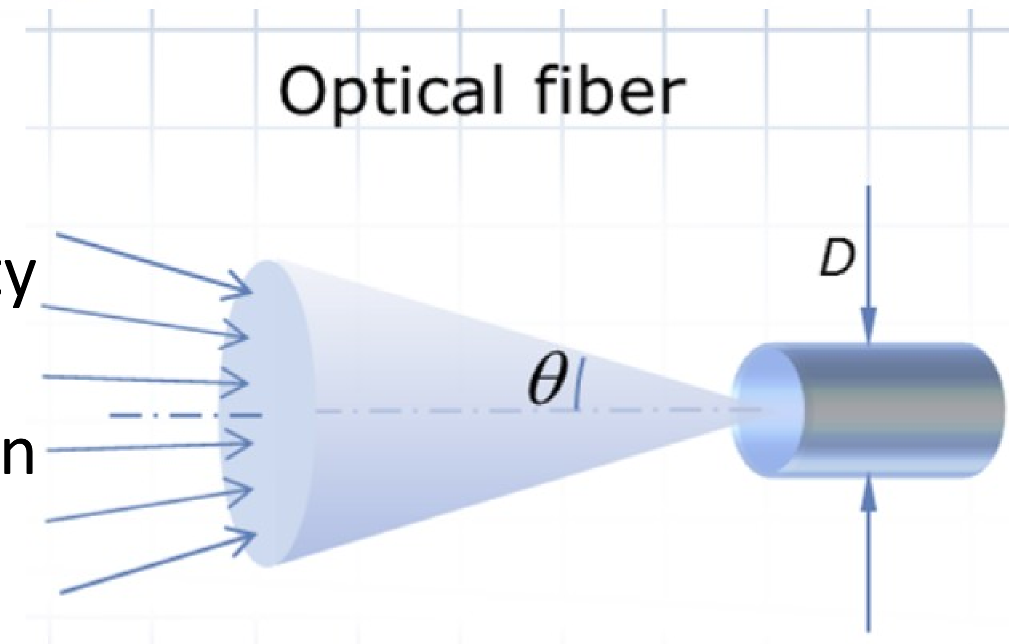
Bad seeing:
large slit loss



Classical spectrographs receive starlight directly on the slit. However, the illumination on the slit can change with variations of the stellar seeing disk



Modern spectrographs receive starlight through a long optical fiber → stability of the slit illumination. Important for high precision (≤ 1 m/s) radial velocities



https://ibsen.com/resources/spectrometer-resources/coupling-into-your-spectrometer/

Properties of the basic spectrograph

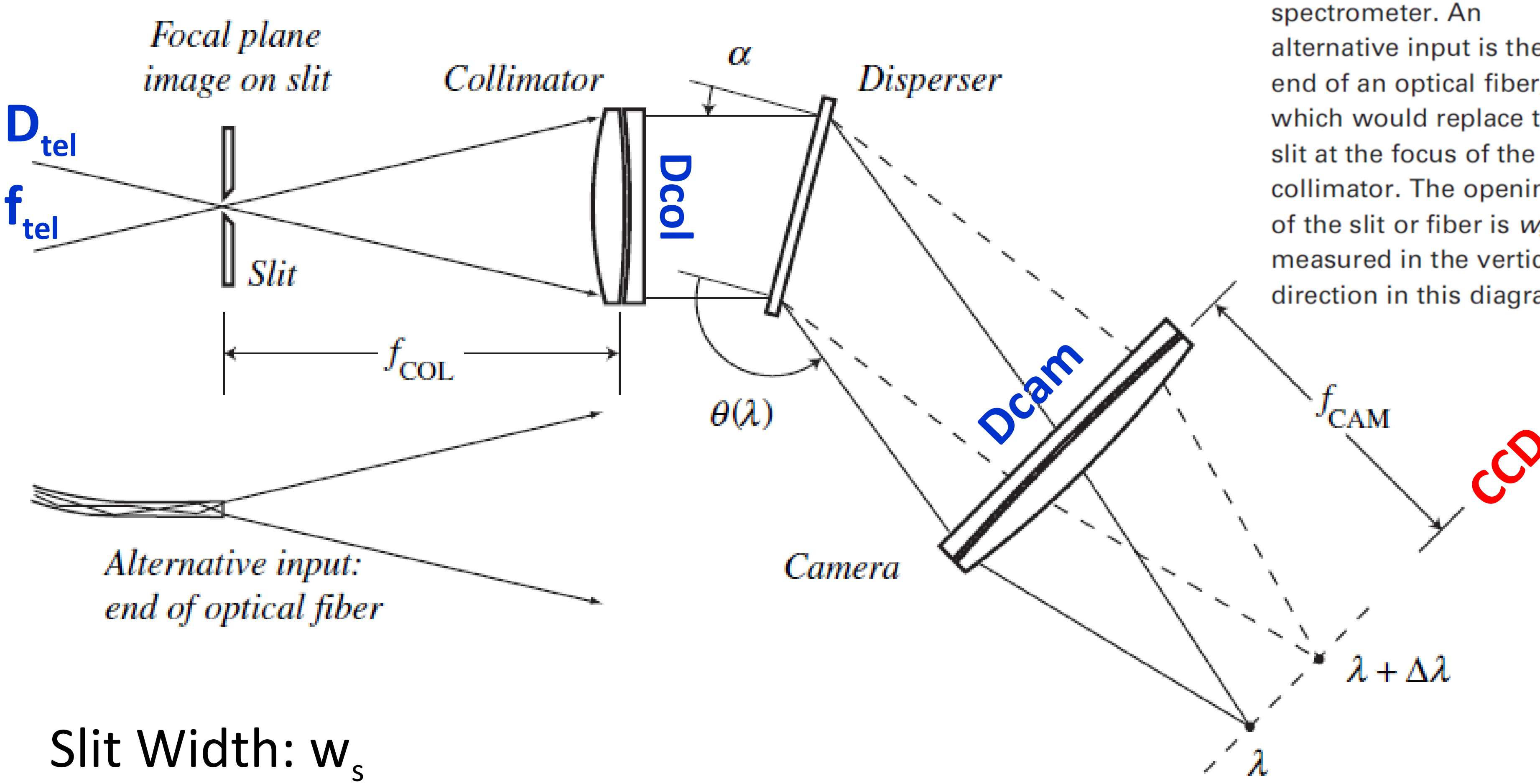


Fig. 11.12 A simple, all-transmission slit spectrometer. An alternative input is the end of an optical fiber, which would replace the slit at the focus of the collimator. The opening of the slit or fiber is w_s, measured in the vertical direction in this diagram.

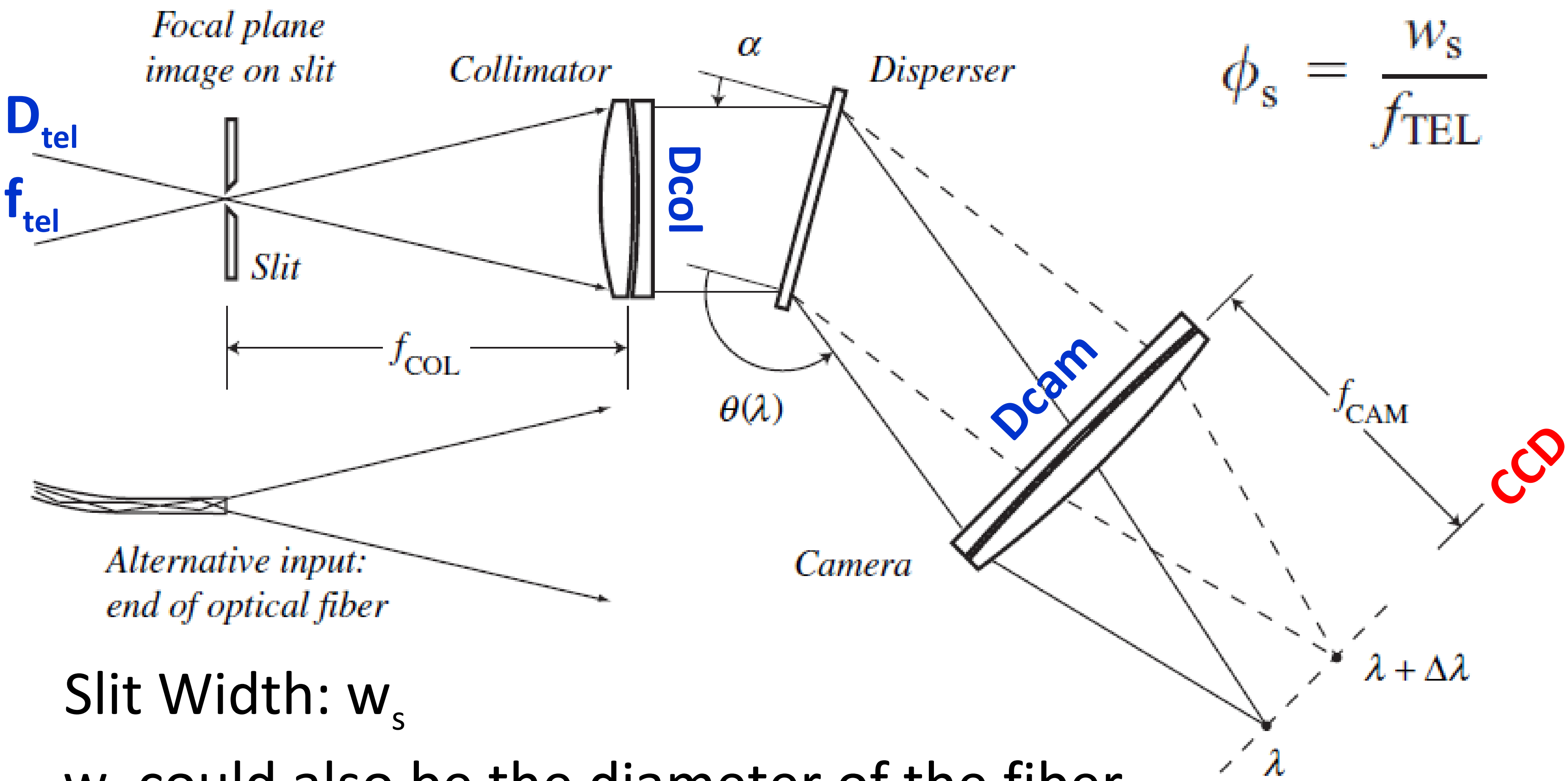
Slit Width: w_s

D_{tel}, f_{tel}: aperture & effective focal distance of the telescope

Angular size of the slit on the sky

The angular size of the slit on the sky is :

$$\phi_s = \frac{w_s}{f_{TEL}}$$

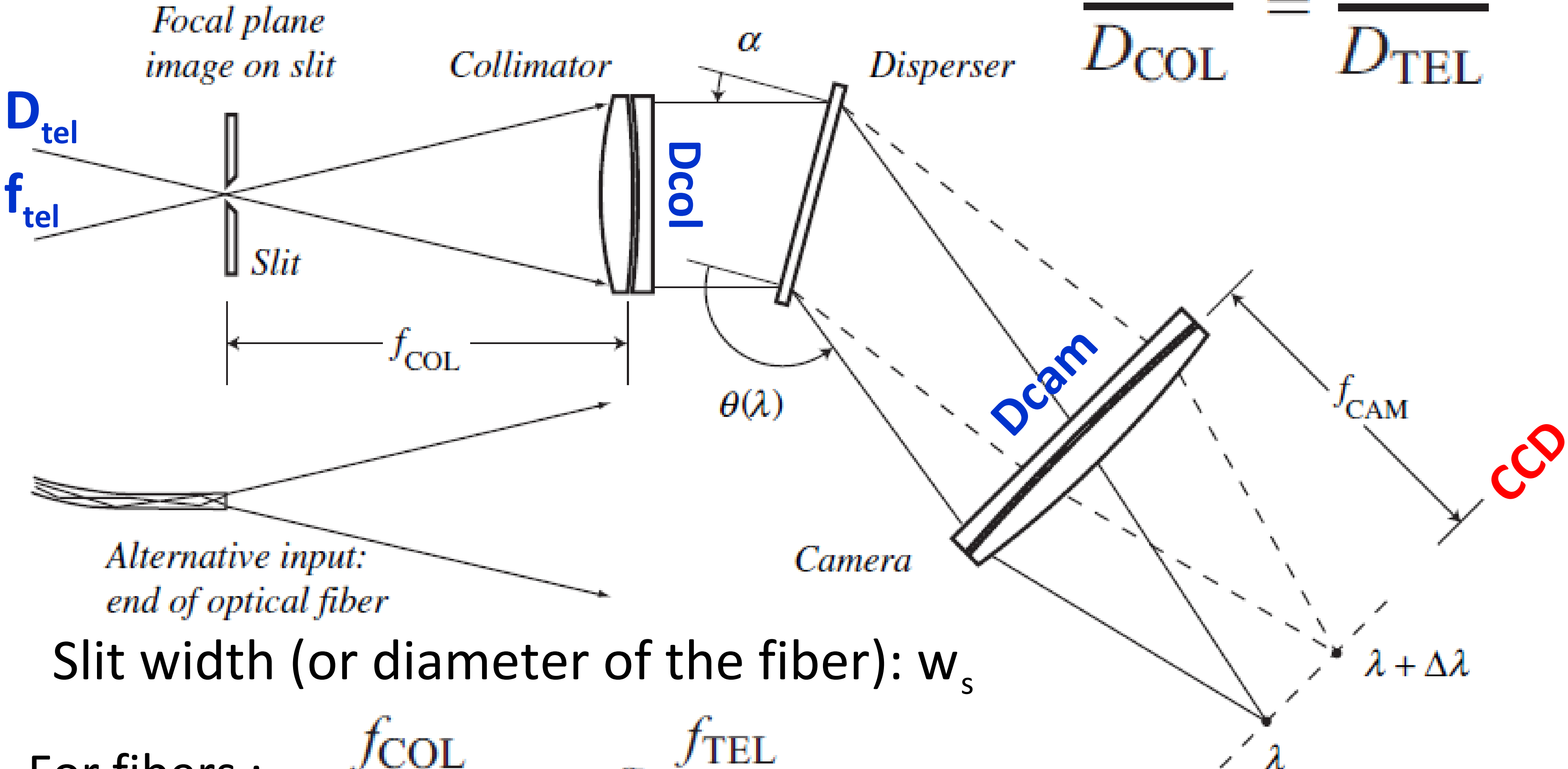


Slit Width: w_s

w_s could also be the diameter of the fiber

How to define the collimator's focal ratio f/#?

The optimal design must satisfy : $$\frac{f_{COL}}{D_{COL}} = \frac{f_{TEL}}{D_{TEL}}$$



Slit width (or diameter of the fiber): w_s

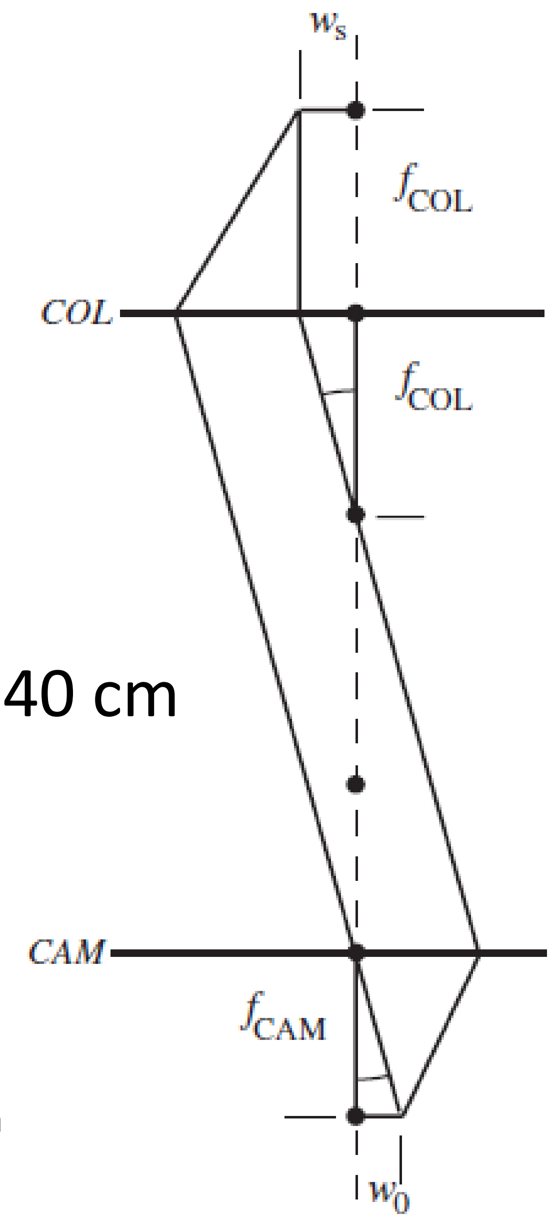
For fibers : $$\frac{f_{COL}}{D_{COL}} = g_f \frac{f_{TEL}}{D_{TEL}}$$

The fiber may degrade the focal distance of the transmitted bean, therefore the relation includes a factor g_f , which could be < 1, depending on the extension & quality of the fiber

What is the size of the slit (or fiber) on the detector, w_0 ?

- Without the disperser:

$$w_0 = w_s \, f_{CAM}/f_{COL}$$



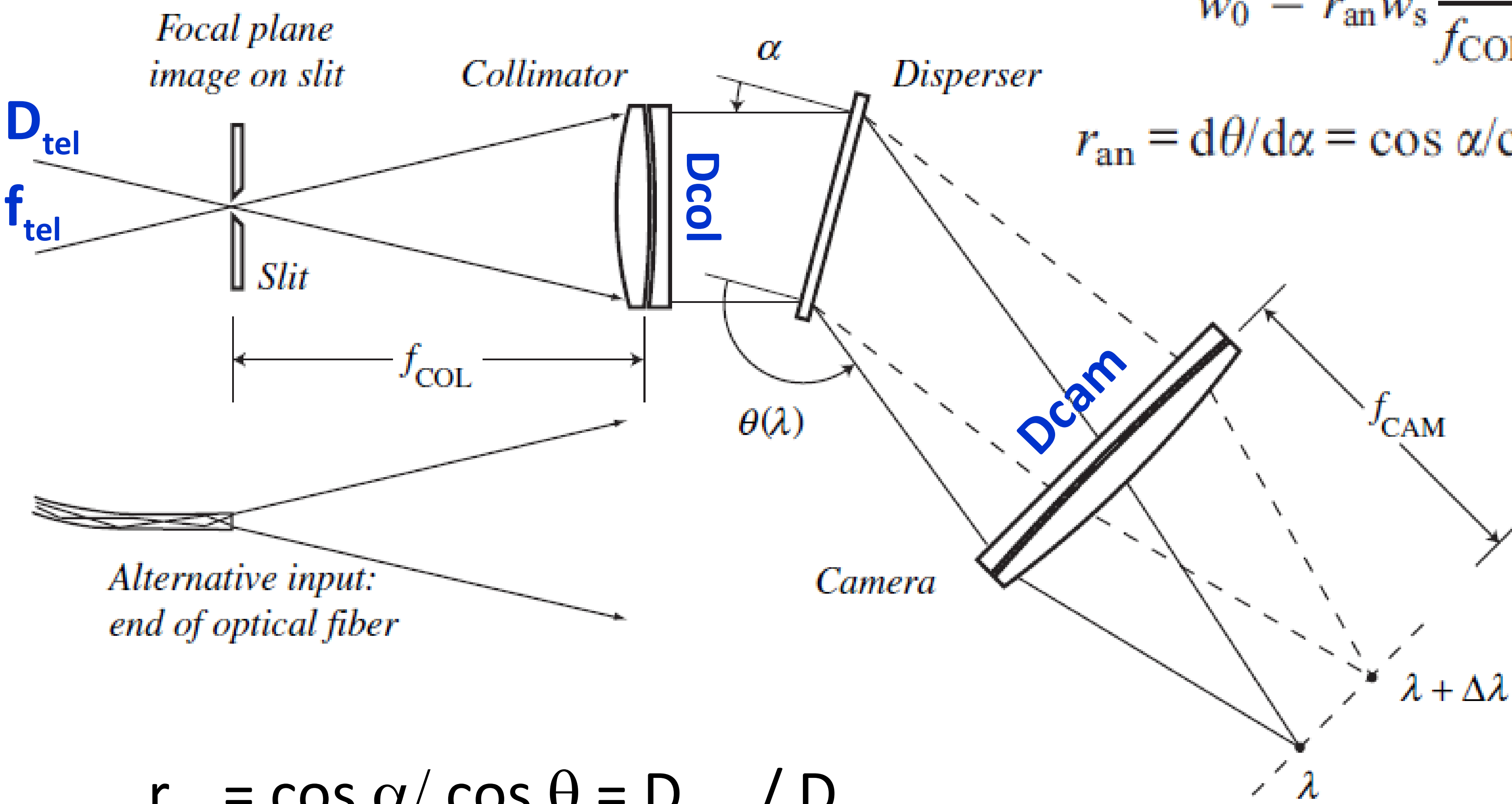
For example:

If w_s = 0,04 mm, fcam = 10 cm, fcol = 40 cm

→ w_0 = ¼ w_s = 0,01 mm

However, the disperser introduces a (anamorphic) magnification factor $\mathbf{r_{an}}$

What is the size of the slit or fiber on the detector (w_0)?

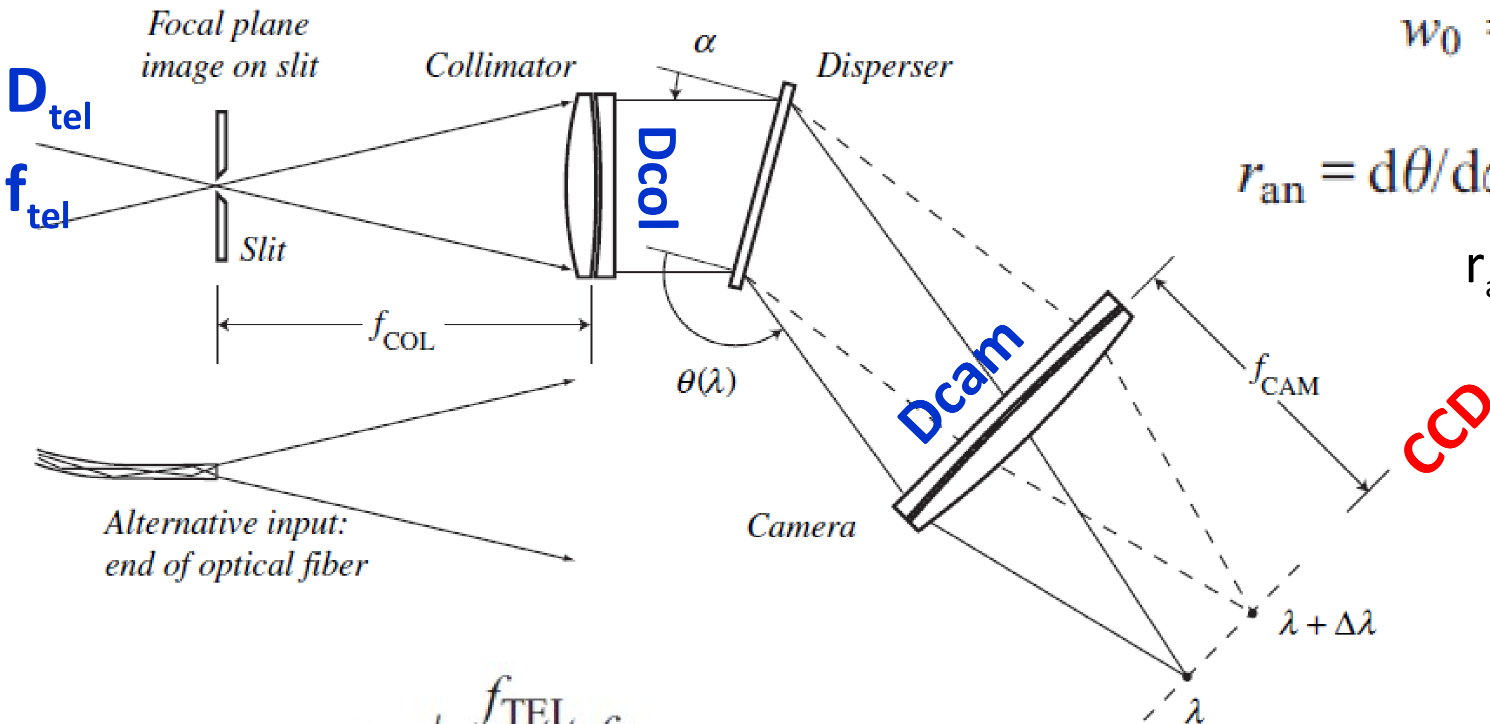


$$w_0 = r_{an} w_s \frac{f_{CAM}}{f_{COL}}$$

$$r_{an} = d\theta/d\alpha = \cos\alpha/\cos\theta.$$

$$r_{an} = \cos\alpha / \cos\theta = D_{COL} / D_{CAM}$$

What is the size of the slit on the detector (w_0) using the angle subtended by the slit on the sky?



$$w_0 = r_{an} w_s \frac{f_{CAM}}{f_{COL}}$$

$$r_{an} = d\theta/d\alpha = \cos\alpha/\cos\theta.$$

$r_{an} = D_{COL} / D_{CAM}$

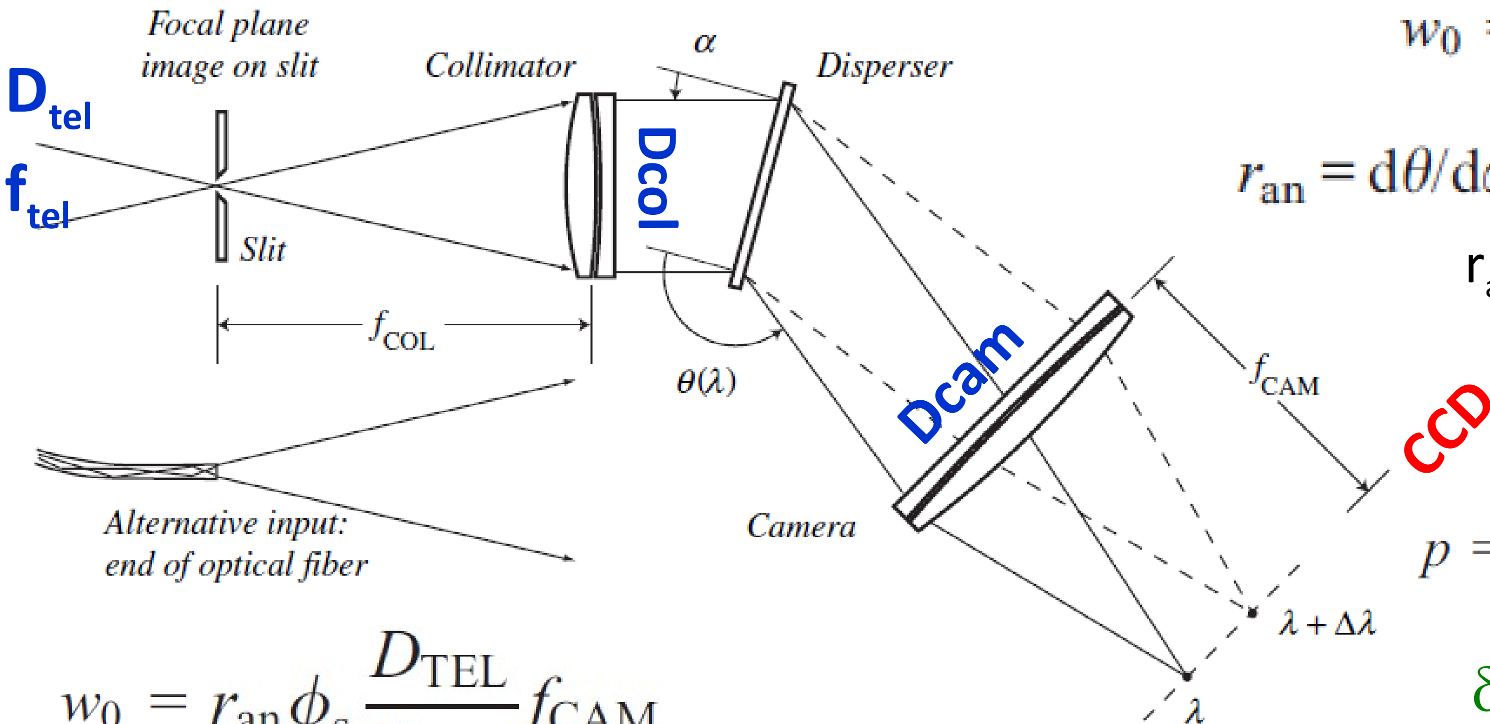
Angle of the slit on the sky:

$$\phi_s = \frac{w_s}{f_{TEL}}$$

$$w_0 = r_{an}\phi_s \frac{f_{TEL}}{f_{COL}} f_{CAM}$$

We know $\frac{f_{COL}}{D_{COL}} = \frac{f_{TEL}}{D_{TEL}}$ $\Rightarrow$ $w_0 = r_{an}\phi_s \frac{D_{TEL}}{D_{COL}} f_{CAM}$

Resolution $\delta\lambda_0$ of the spectrograph



$$w_0 = r_{\mathrm{an}} w_{\mathrm{s}} \frac{f_{\mathrm{CAM}}}{f_{\mathrm{COL}}}$$

$$r_{\mathrm{an}} = \mathrm{d}\theta/\mathrm{d}\alpha = \cos\alpha/\cos\theta.$$

$$r_{an} = D_{COL} / D_{CAM}$$

Using:

$$p = \frac{\mathrm{d}\lambda}{\mathrm{d}x} = \frac{1}{f_{\mathrm{CAM}}}\frac{\mathrm{d}\lambda}{\mathrm{d}\theta}$$

$$\delta\lambda_0 = w_0\, p$$

$$w_0 = r_{\mathrm{an}} \phi_{\mathrm{s}} \frac{D_{\mathrm{TEL}}}{D_{\mathrm{COL}}} f_{\mathrm{CAM}}$$

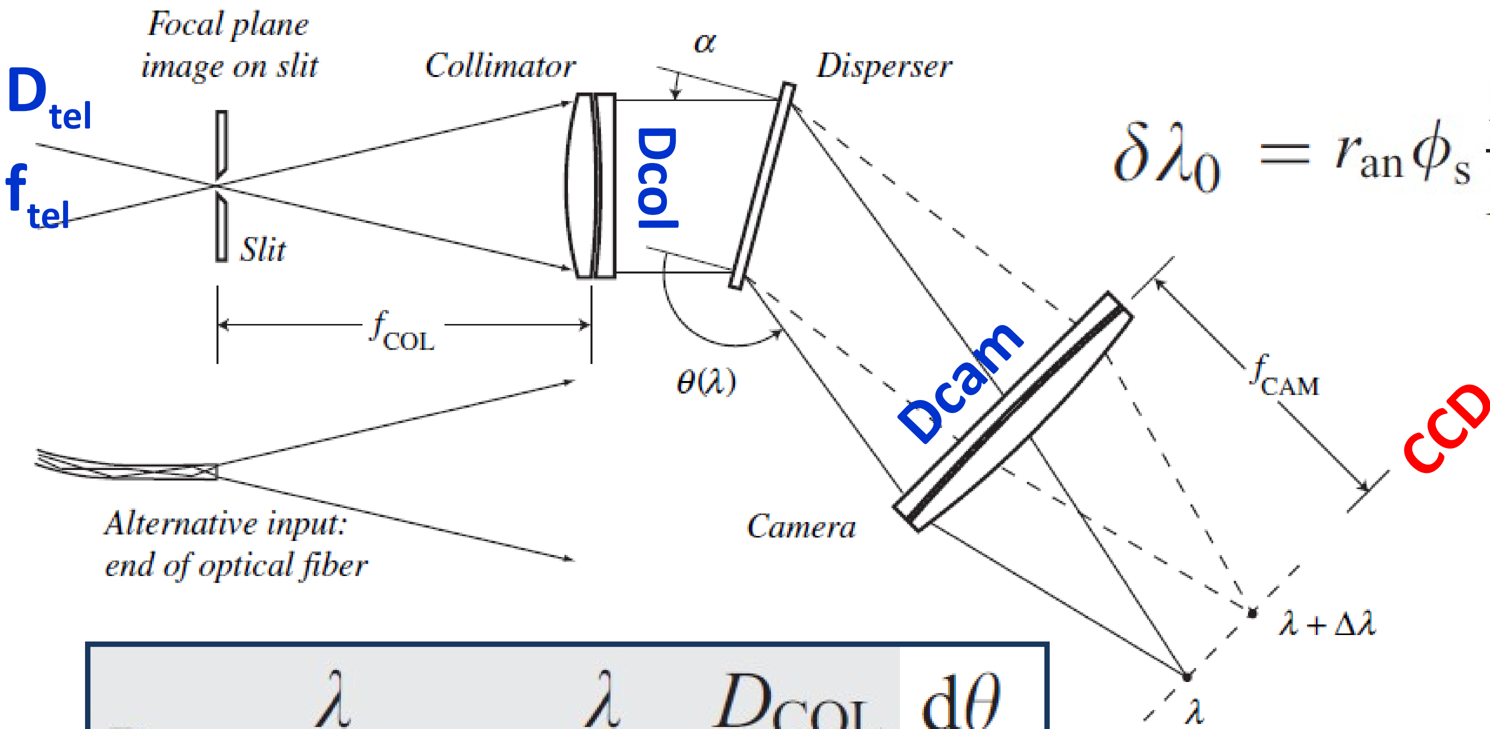
$$\delta\lambda_0 = r_{\mathrm{an}} \phi_{\mathrm{s}} \frac{D_{\mathrm{TEL}}}{D_{\mathrm{COL}}} f_{\mathrm{CAM}}\, p$$

Other forms :

$$\boxed{\delta\lambda_0 = \phi_{\mathrm{s}} \frac{D_{\mathrm{TEL}}}{D_{\mathrm{CAM}}} \frac{\mathrm{d}\lambda}{\mathrm{d}\theta}}$$

$$\boxed{\delta\lambda_0 = r_{\mathrm{an}} \phi_{\mathrm{s}} \frac{D_{\mathrm{TEL}}}{D_{\mathrm{COL}}} \frac{\mathrm{d}\lambda}{\mathrm{d}\theta}}$$

Resolving power R (= $\lambda/\delta\lambda_0$) of the spectrograph



$$\delta\lambda_0 = r_{an}\phi_s \frac{D_{TEL}}{D_{COL}} \frac{d\lambda}{d\theta}$$

$$\boxed{R = \frac{\lambda}{\delta\lambda_0} = \frac{\lambda}{r_{an}\phi_s} \frac{D_{COL}}{D_{TEL}} \frac{d\theta}{d\lambda}}$$

Ideally the angle of the slit on the sky should be < seeing: $\phi_s < \phi_{seeing}$

However, if seeing is lower than ϕ_s → use ϕ_{seeing} for R

Actually, we can have different slit sizes

The resolution does not change if we use the spectrograph at other telescope, because it depends only on properties of the spectrograph

$$\boxed{R = \frac{\lambda}{\delta\lambda_0} = \frac{\lambda}{r_{an}\phi_s}\frac{D_{COL}}{D_{TEL}}\frac{d\theta}{d\lambda}}$$

$$\phi_s = \frac{w_s}{f_{TEL}} \Rightarrow R = \frac{\lambda}{\delta\lambda_0} = \frac{\lambda}{r_{an} w_s}\frac{D_{COL}}{D_{TEL}} f_{TEL}\frac{d\theta}{d\lambda}$$

$$R = \frac{\lambda}{d\lambda} = \frac{\lambda f_{COL}}{r_{an} w_s}\frac{d\theta}{d\lambda}$$

Resolving power depends on the focal distance of the spectrograph's collimator f_{COL} , the slit width w_s, and dispersion of the grating $d\theta/d\lambda$

Can we use a spectrograph designed for a different telescope?

Yes, IF the focal ratio is similar between the spectrograph and telescopes

PHOENIX INFRARED HIGH-RESOLUTION SPECTROGRAPH

At the 2.1 m the 4 pixel slit is 1.4 arcsec wide. At the 4 m it is 0.7 arcsec wide

http://www.noao.edu/kpno/phoenix/

The Phoenix infrared spectrograph has f/15, and has been used at the 2.1m & 4m Kitt Peak telescopes (both f/15) and at the 8m Gemini (f/16). However, the angular size of the slit changes with the focal distance of the telescope:

$$\phi_s = \frac{w_s}{f_{TEL}}$$

Resolution vs. slit width w_s

Phoenix spectrograph at Kitt Peak (2m & 4m)

$$R = \frac{\lambda}{d\lambda} = \frac{\lambda f_{COL}}{r_{an} w_s} \frac{d\theta}{d\lambda}$$

$$\boxed{\phi_s = \frac{w_s}{f_{TEL}}}$$

- EXAMPLE with PHOENIX spectrograph, slits available: 2 pixel (54 μm), 3 pixel (81 μm), and 4 pixel (107 μm)
- w_s = 4 pixels on detector → R = 50 000
- w_s = 2 pixels on detector → should be R = 100 000, but due to problems in the optics it is actually R = 75 000
- w_s = 3 pixels on detector → should be R = 75 000, but it is actually R = 63 000

PHOENIX INFRARED HIGH-RESOLUTION SPECTROGRAPH

At the 2.1 m the 4 pixel slit is 1.4 arcsec wide. At the 4 m it is 0.7 arcsec wide

The 3 telescopes have about the same focal ratio, f/15

Diameter		2m KittPeak	4m KittPeak	8m Gemini
Focal distance		...	...	...
$w_s = 54\ \mu m$,	$\phi_s =$	...	...	...
$w_s = 81\ \mu m$,	$\phi_s =$	...	...	...
$w_s = 107\ \mu m$,	$\phi_s =$	1.4”	...	...

Adjustable slit

The slit width can be adjusted by hand using a micrometer screw

Slits cut on a polished steel plate

https://mthamilton.ucolick.org/techdocs/instruments/hamspec/slits/

https://www.3bscientific.com/dk/adjustable-slit-k-1008519-u8476675-3b-scientific,p_171_18684.html

Resolution vs. slit width w_s

HIRES spectrograph on 10m Keck telescope has fixed slits of different size cut on a plate

$$R = \frac{\lambda}{d\lambda} = \frac{\lambda f_{COL}}{r_{an} w_s} \frac{d\theta}{d\lambda}$$

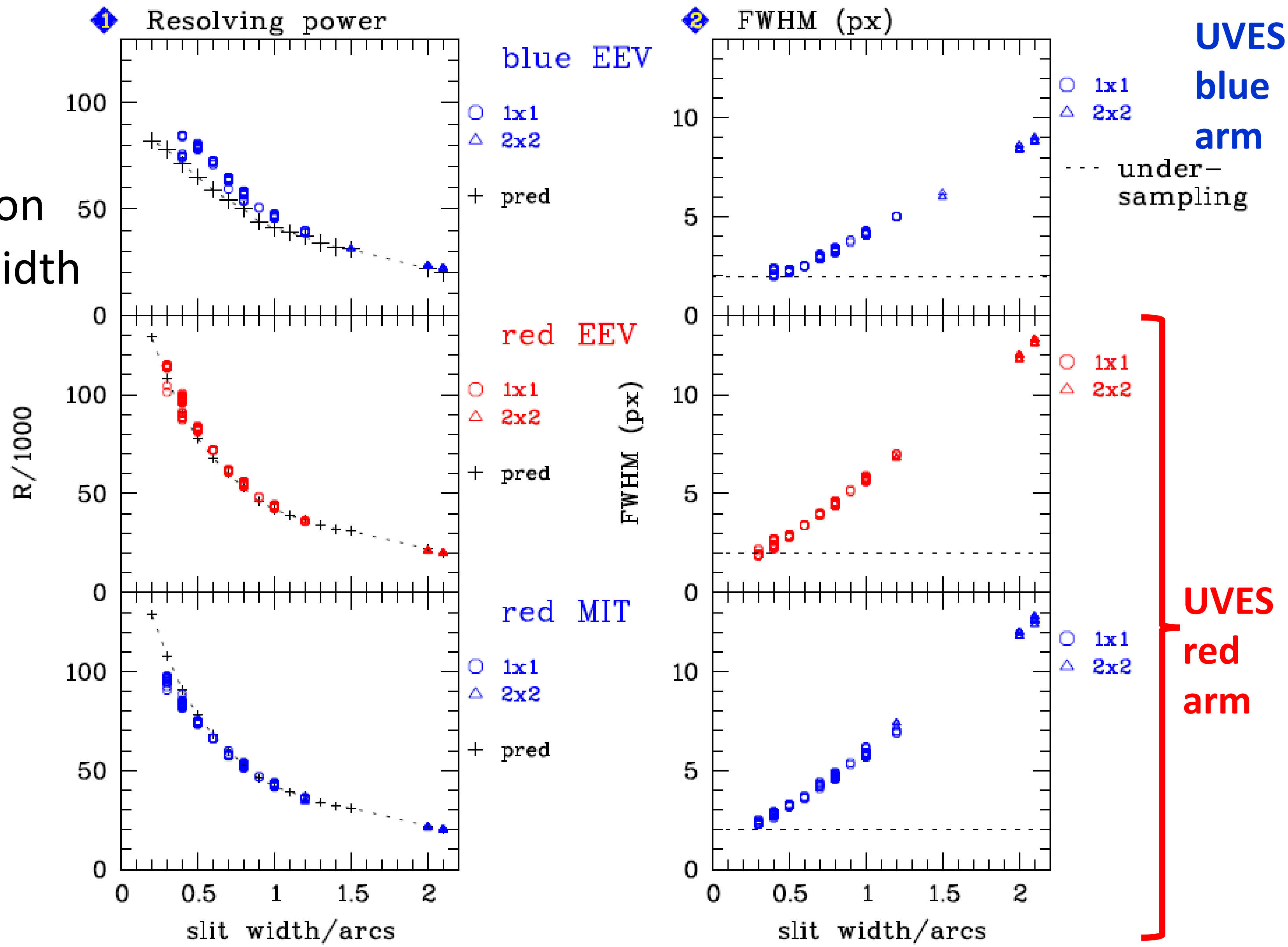
Deckname	Length (")	Width (")	Resolution (calculated)	Resolution (measured*)	Resolution (measured+)
B1	3.5	0.574	72,000	67,000	66,400
B2	7.0	0.574	72,000	67,000	66,400
B3	14.0	0.574	72,000	67,000	66,400
B4	28.0	0.574	72,000	67,000	66,400
B5	3.5	0.861	48,000	49,000	50,000
C1	7.0	0.861	48,000	49,000	50,000
C2	14.0	0.861	48,000	49,000	50,000
C3	28.0	0.861	48,000	49,000	50,000
C4	3.5	1.148	36,000	37,000	37,500
C5	7.0	1.148	36,000	37,000	37,500
D1	14.0	1.148	36,000	37,000	37,500
D2	28.0	1.148	36,000	37,000	37,500
D3	7.0	1.722	24,000	24,000	24,700
D4	14.0	1.722	24,000	24,000	24,700
D5	0.119	0.179	pinhole		
E1	1.0	0.400	103,000	84,000	86,600
E2	3.0	0.400	103,000	84,000	86,600
E3	5.0	0.400	103,000	84,000	86,600
E4	7.0	0.400	103,000	84,000	86,600
E5	1.0	0.800	51,000	52,000	52,000

* Using UV cross-disperser. Average of 5 Th/Ar lines near 4100 A.
+ Using Red cross-disperser. Average of 4 Th/Ar lines near 5240 A.

$$R = \frac{\lambda}{\delta\lambda_0} = \frac{\lambda}{r_{an}\phi_s}\frac{D_{COL}}{D_{TEL}}\frac{d\theta}{d\lambda}$$

UVES spectrograph on 8m VLT telescope

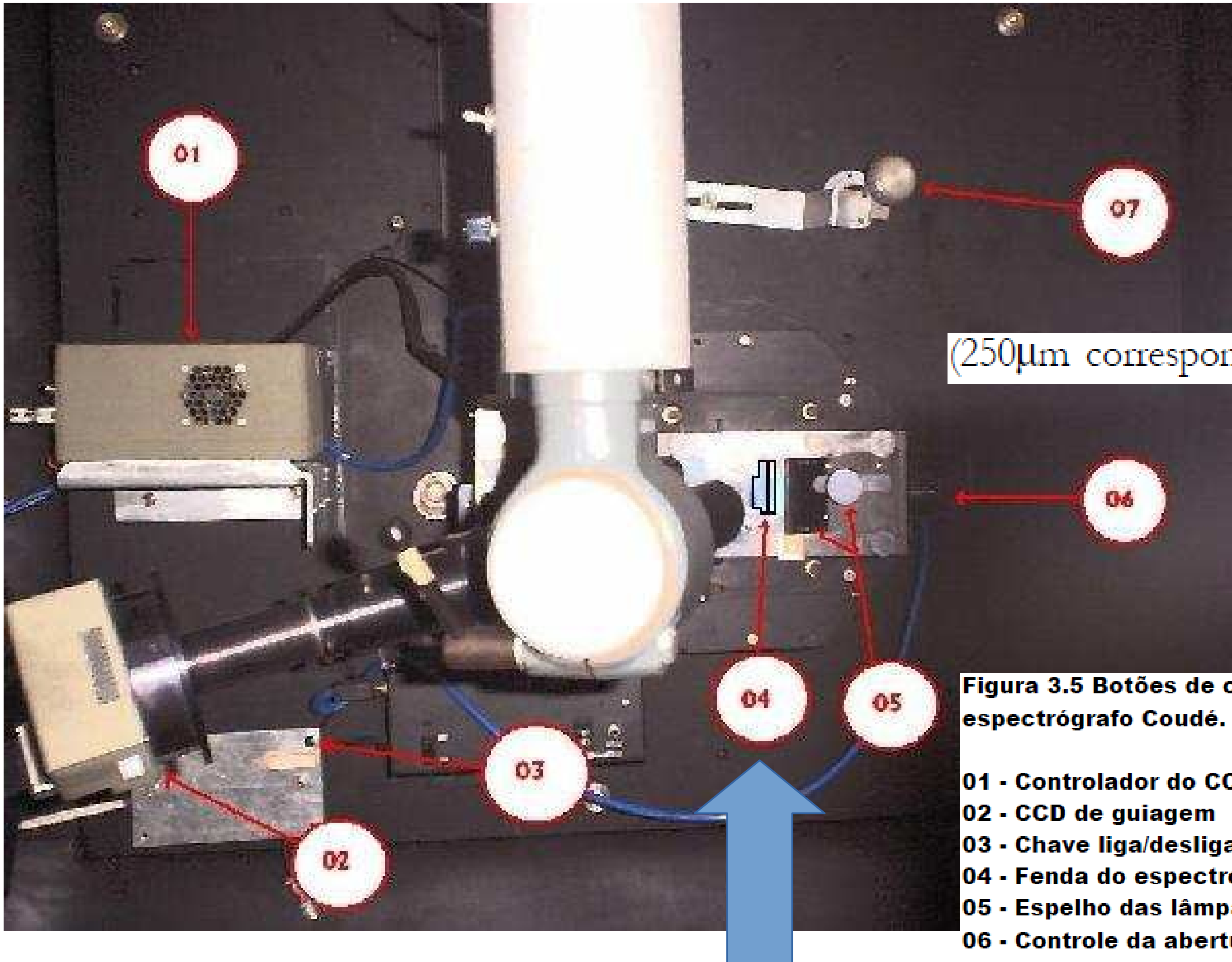
Resolution vs. slit width



http://www.eso.org/sci/facilities/paranal/instruments/uves/doc/

Resolution vs. slit width w_s - Coudé OPD

$$R = \frac{\lambda}{\delta\lambda_0} = \frac{\lambda}{r_{an} w_s} \frac{D_{COL}}{D_{TEL}} \frac{d\theta}{d\lambda}$$



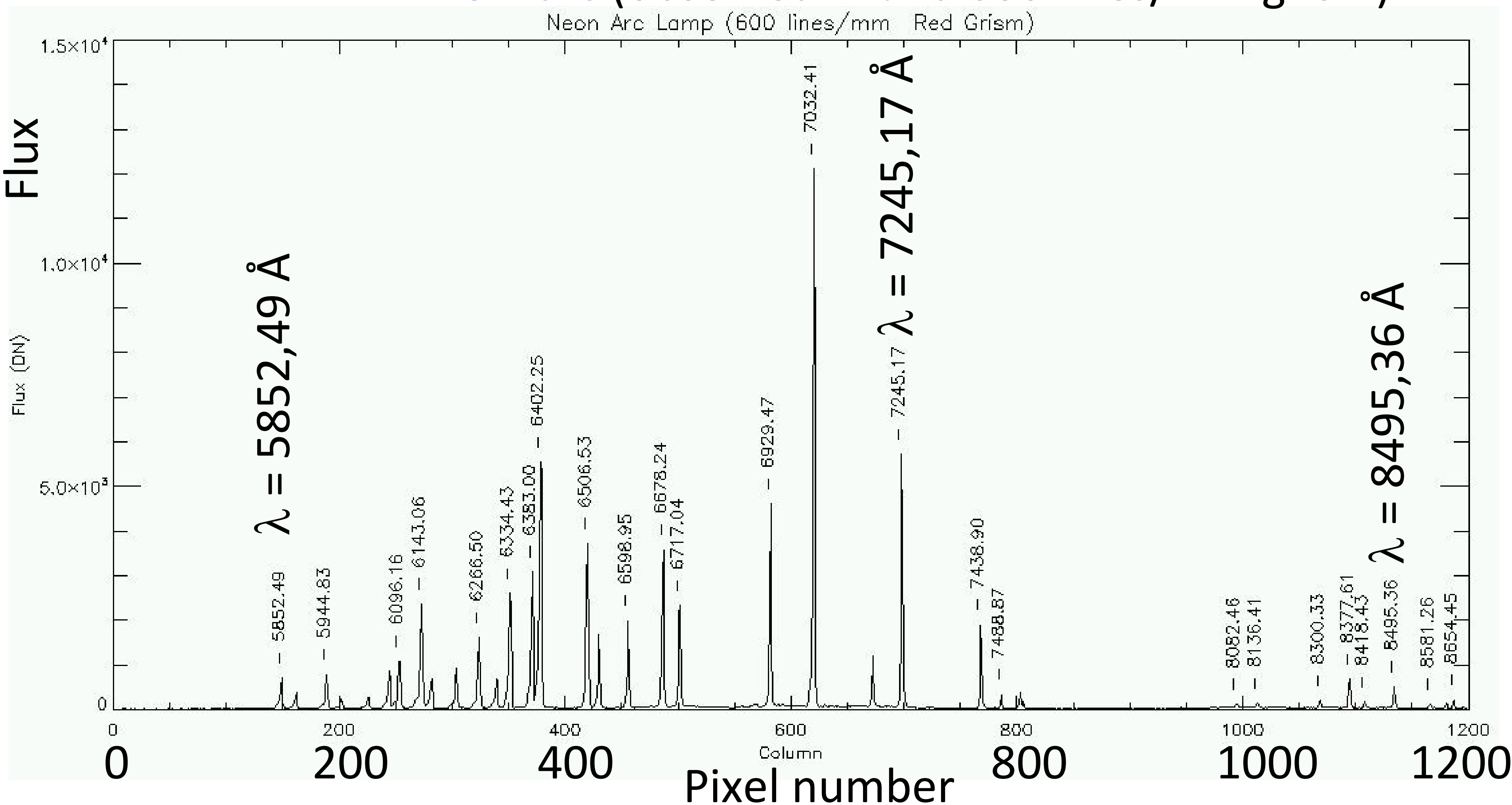
Regule a largura da fenda (250µm correspondem a aproximadamente 1")

Figura 3.5 Botões de controle do espectrógrafo na ante-sala do espectrógrafo Coudé.

01 - Controlador do CCD de guiagem
02 - CCD de guiagem
03 - Chave liga/desliga lâmpada halógena do *flat field* interno
04 - Fenda do espectrógrafo
05 - Espelho das lâmpadas de comparação
06 - Controle da abertura da fenda
07 - Seletor do ângulo da rede de difração (ajuste fino)

Calibration lamps (*a.k.a.* arcs) (to calibrate wavelength)

NEON arc (observed with a 600 lines/mm grism)



http://mthamilton.ucolick.org/techdocs/instruments/nickel_spect/arcSpectra/

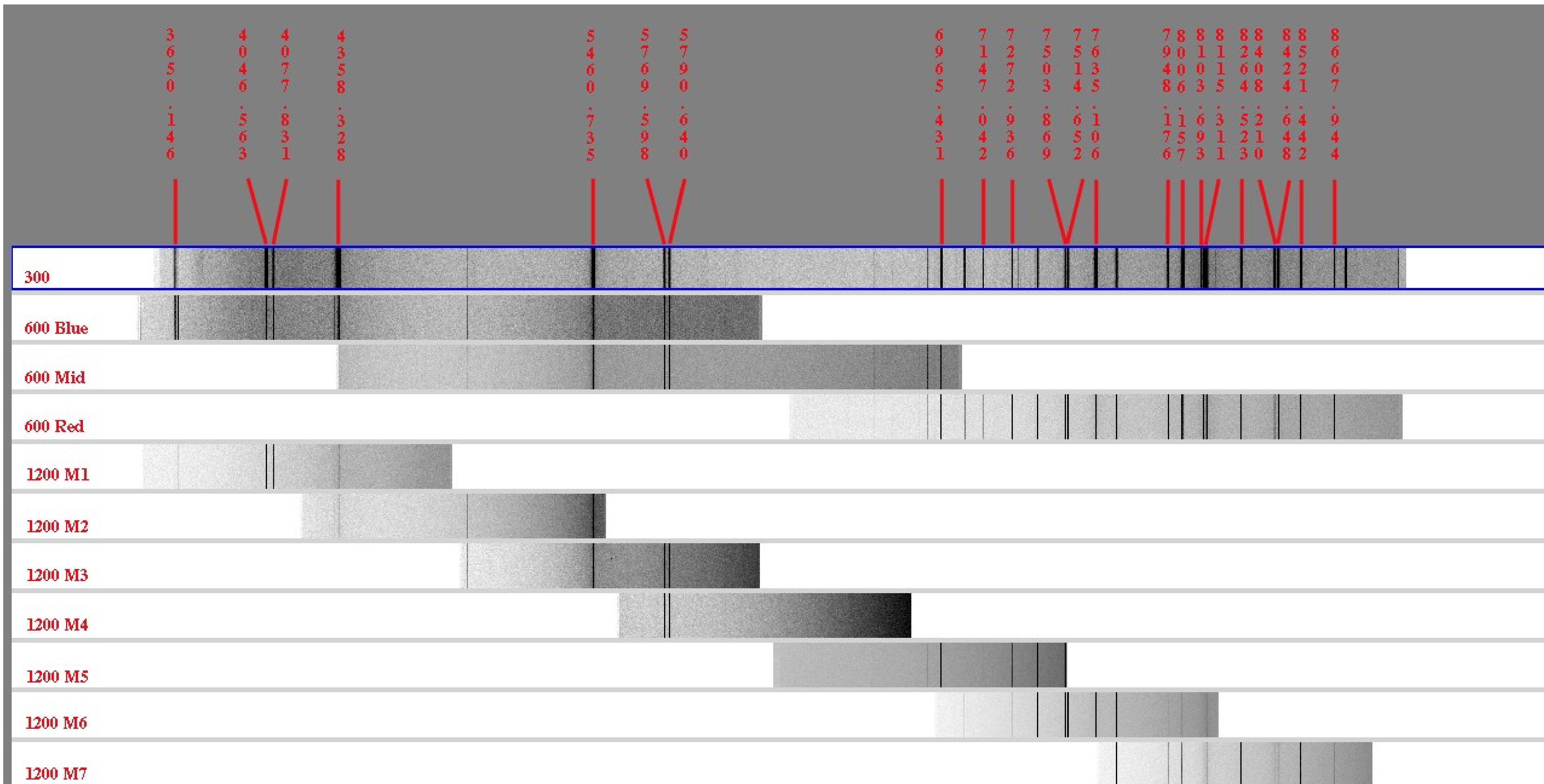
SOAR Goodman HgAr

λ = 3650,146 Å

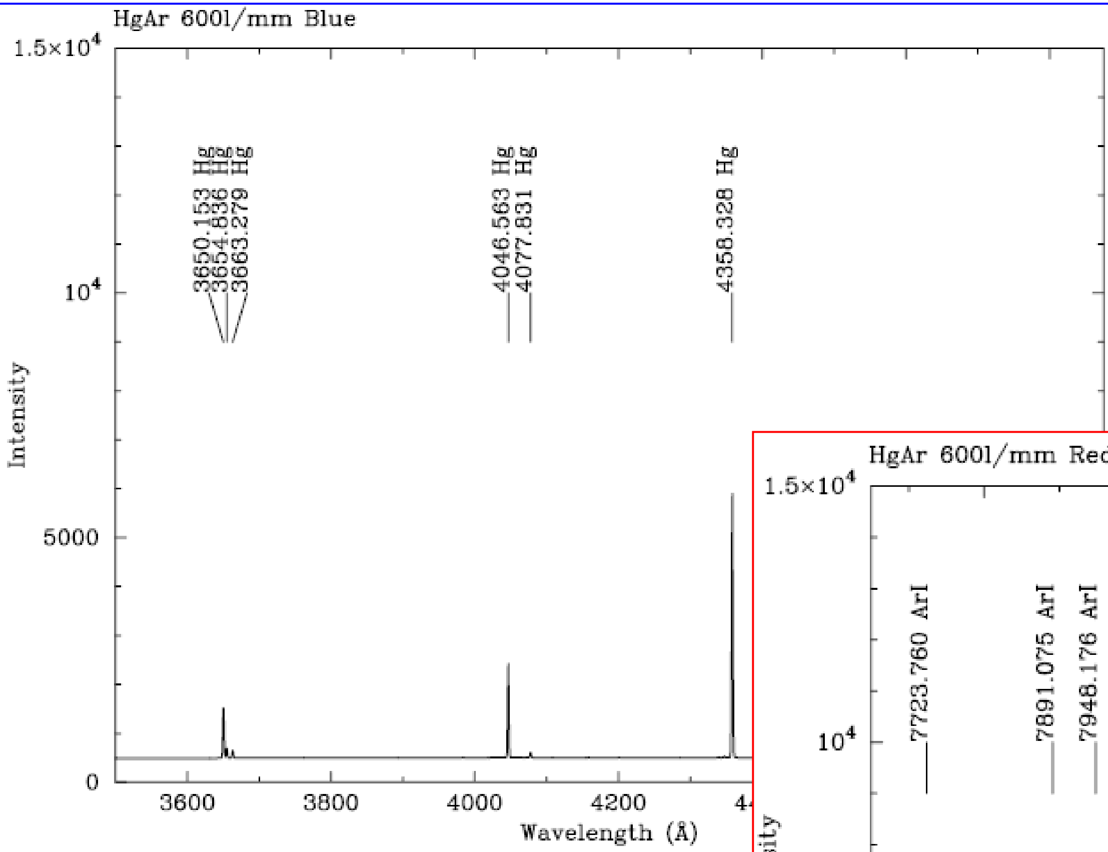
λ = 5460,735 Å

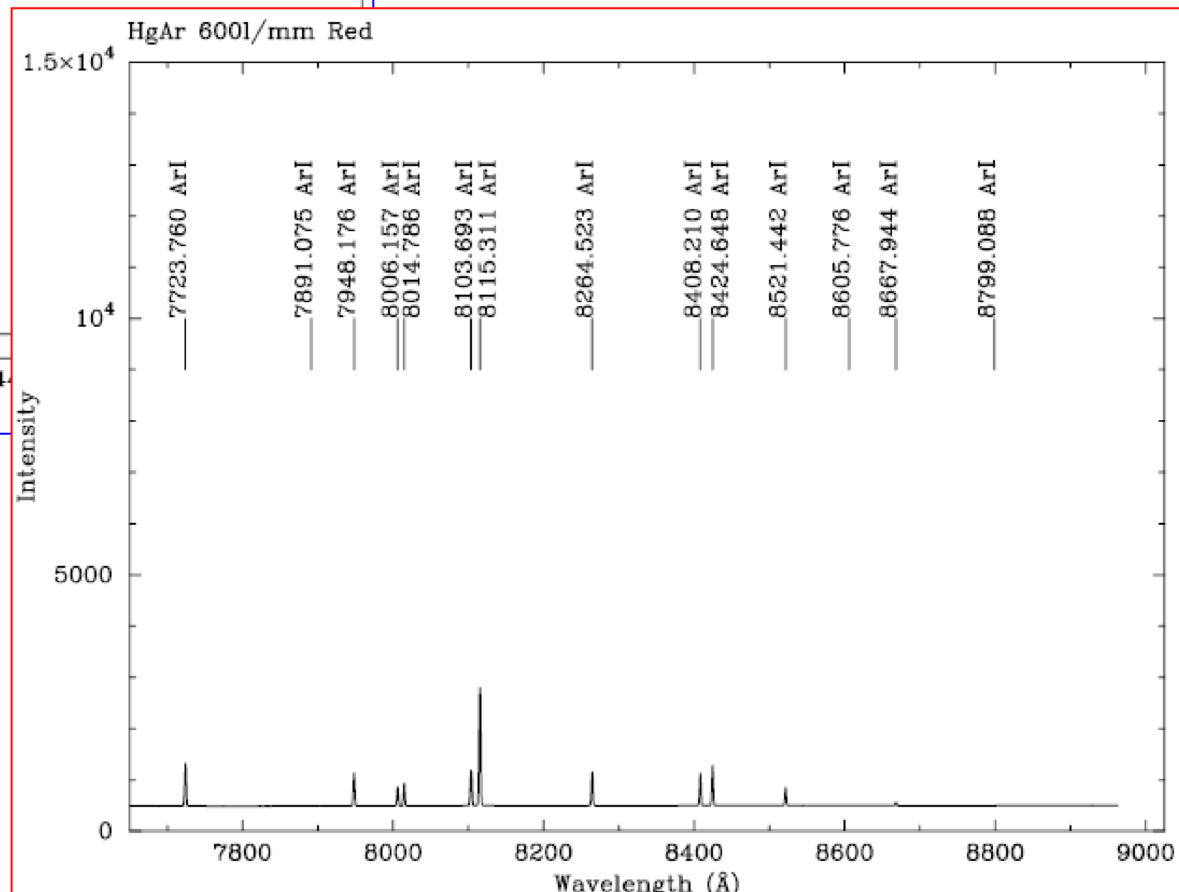
λ = 6965,431 Å

λ = 8667,944 Å



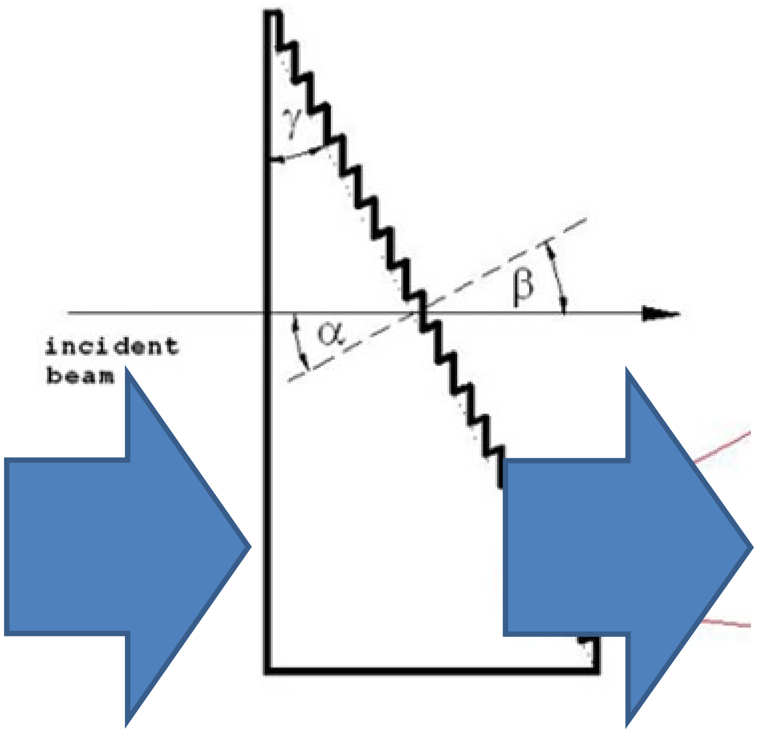
HgAr arc 600 l/mm Goodman /SOAR

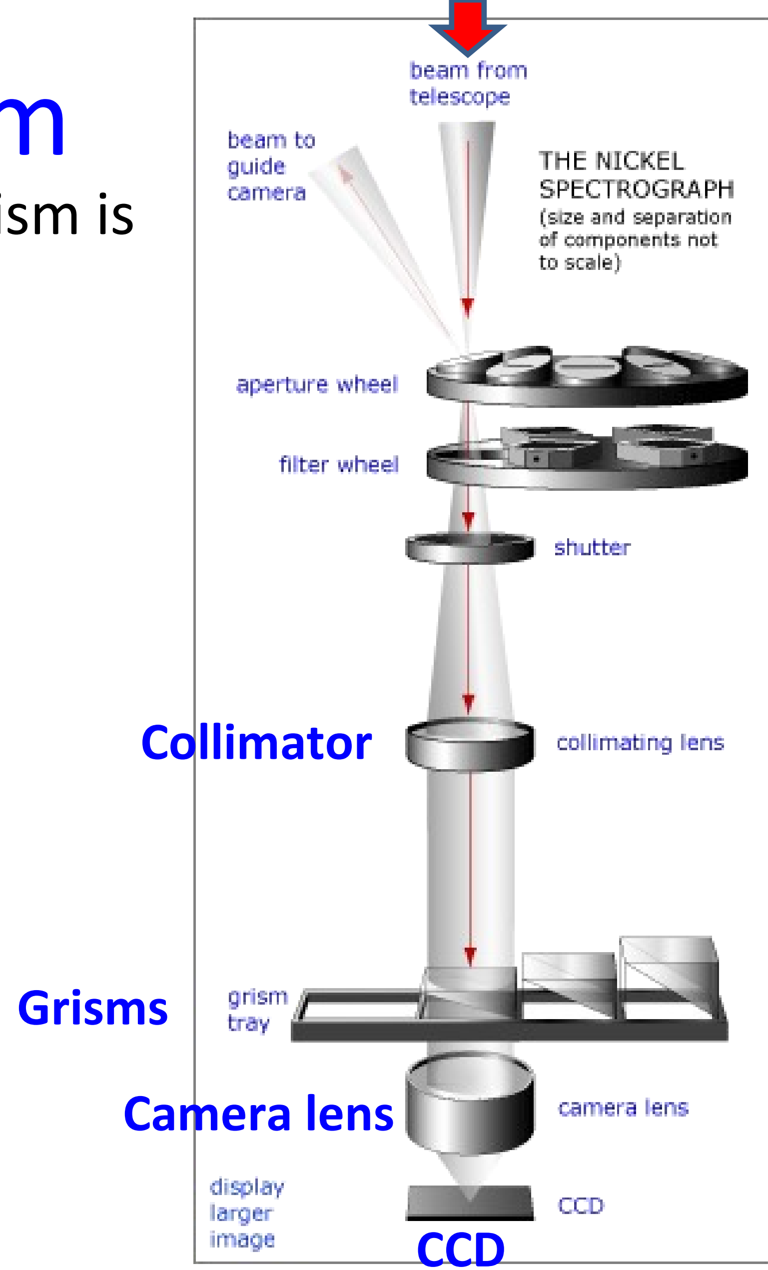




Grism = Grating + Prism

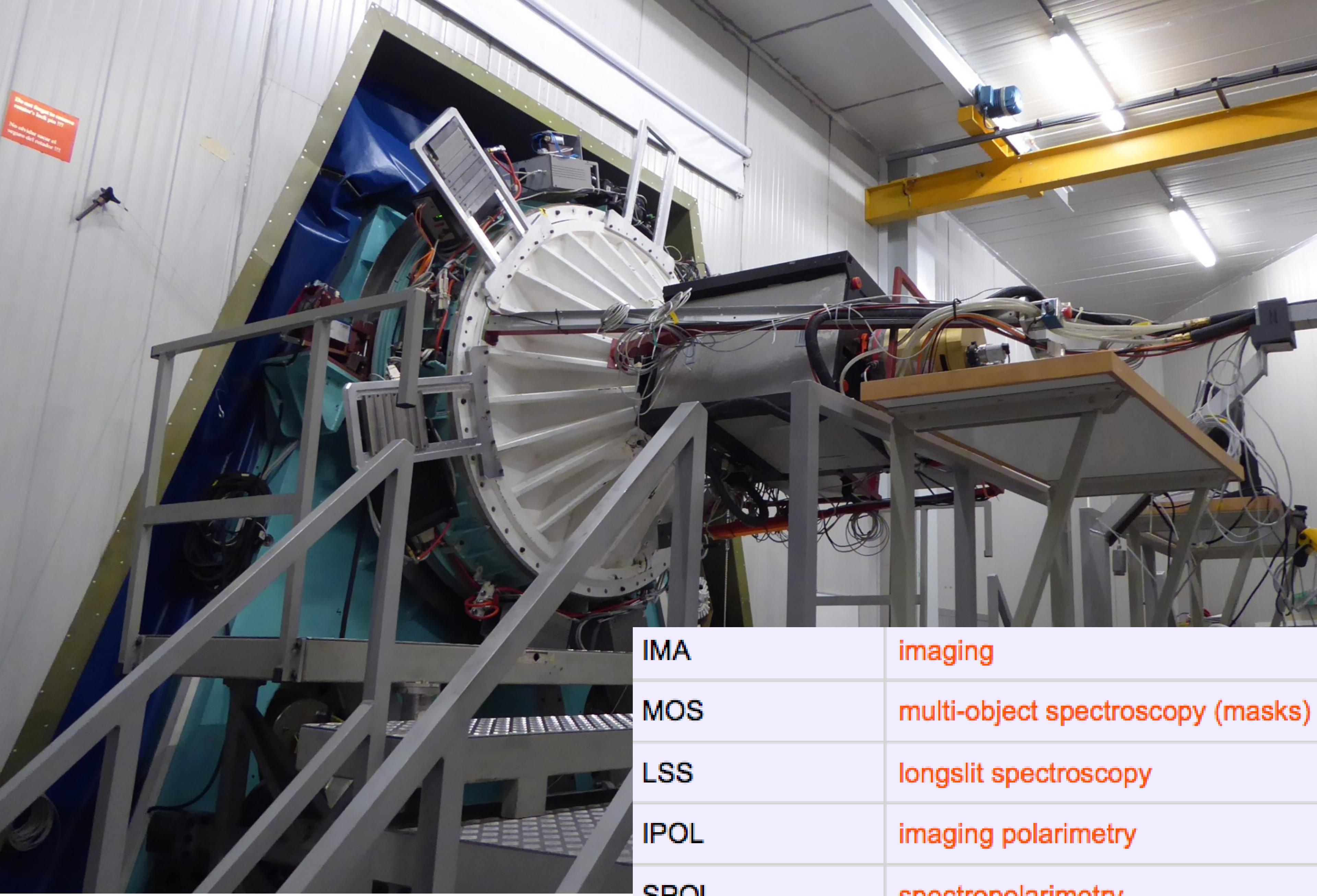
The deviation of the light beam by the prism is compensated by the deviation due to the grating → light passes straight through





The instrument could serve as an imager, removing the grism from the optical path

http://mthamilton.ucolick.org/techdocs/instruments/nickel_spect/hw_overview/

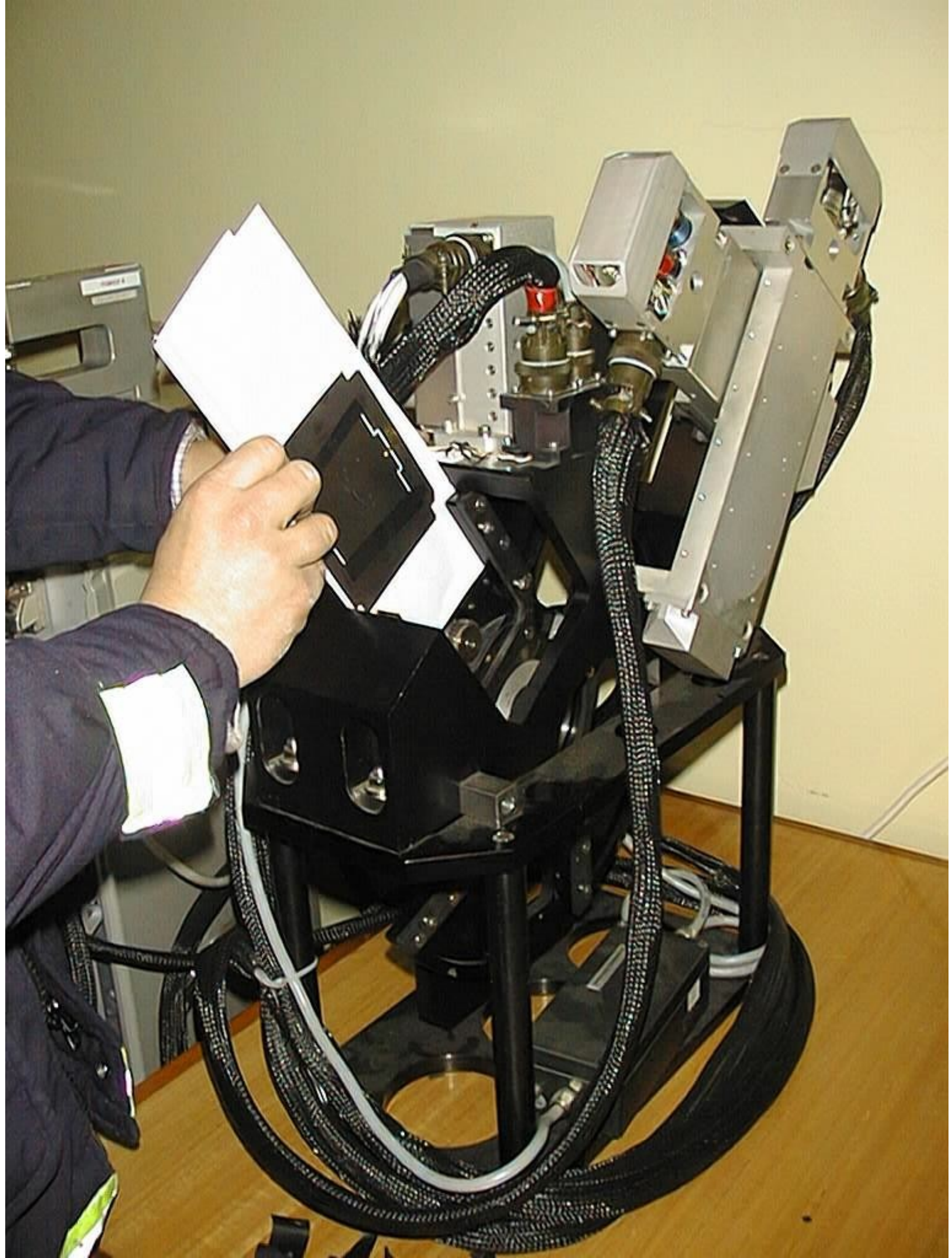


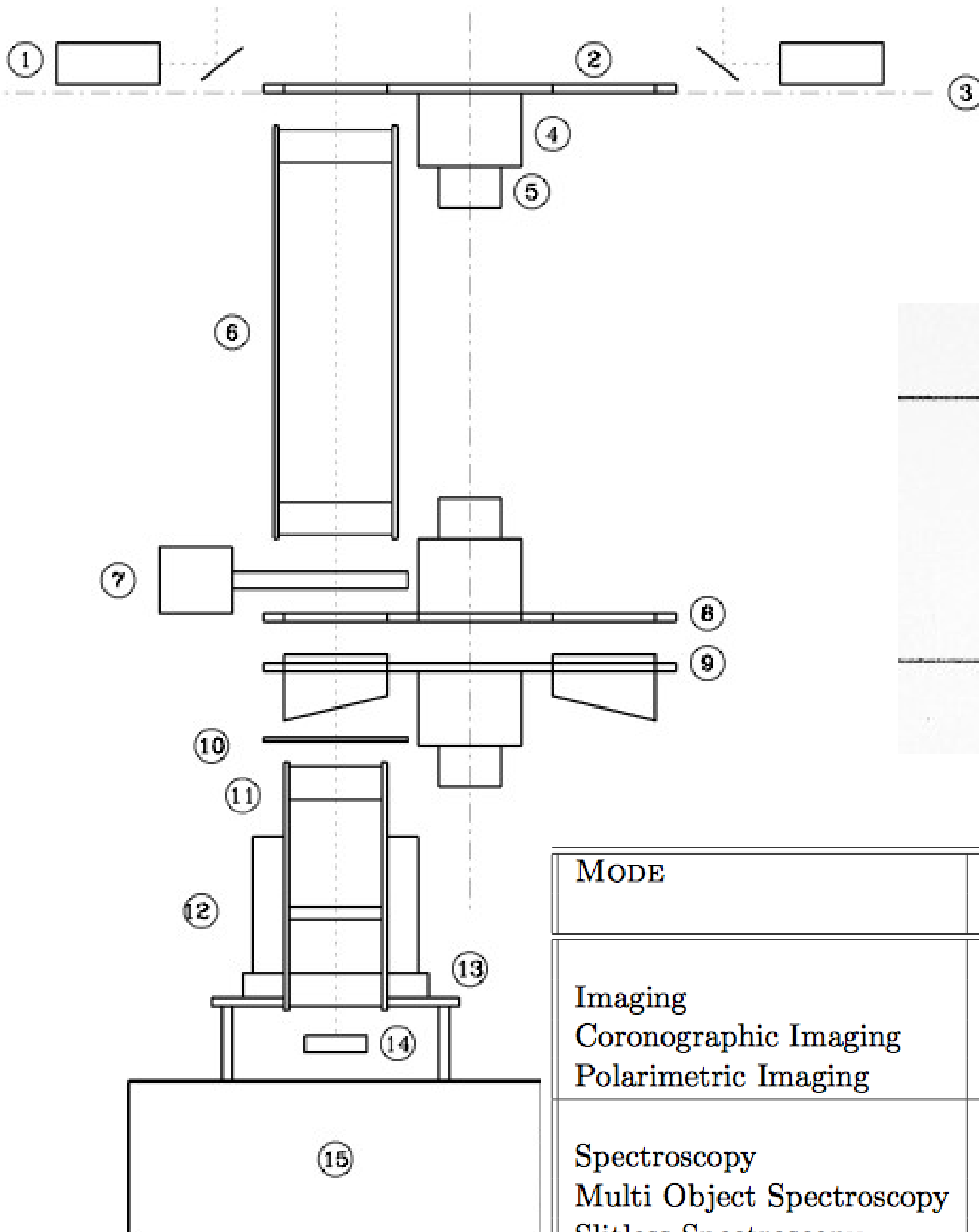
IMA	imaging
MOS	multi-object spectroscopy (masks)
LSS	longslit spectroscopy
IPOL	imaging polarimetry
SPOL	spectropolarimetry
COR	coronography

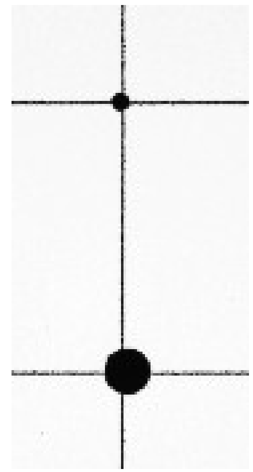
EFOSC2 @ESO NTT


.@ISaviane

Punching EFOSC2 MOS Plates







EFOSC2

1. Calibr. Lamps
2. Aperture Wheel
3. Tel. F. Plane
4. Motor
5. Encoder
6. Collimator
7. Half Wave Plate
8. Filter Wheel
9. Grism Wheel
10. Shutter
11. Camera
12. Thermal Comp.
13. Focus Ring
14. CCD
15. Cryostat

Mode	Aperture Wheel	Filter Wheel	Grism Wheel	HWP/QWP
Imaging	Free	Filter	Free	Out
Coronographic Imaging	Cor. Mask	Filter	Lyot Stop	Out
Polarimetric Imaging	Woll. Mask	Filter	Woll. Prism	In
Spectroscopy	Slit	Free	Grism	Out
Multi Object Spectroscopy	MOS Plate	Free	Grism	Out
Slitless Spectroscopy	Free	Free/Filt.	Grism/Prism	Out
Spectropolarimetry	Slit/Mask	Woll. Prism	Grism	In

Table 1: EFOSC2 Observing Modes.

X-Shooter @ESO VLT

A&A 536, A105 (2011)
DOI: 10.1051/0004-6361/201117752

Astronomy & Astrophysics

X-shooter, the new wide band intermediate resolution spectrograph at the ESO Very Large Telescope

J. Vernet[1], H. Dekker[1], S. D'Odorico[1], L. Kaper[2], P. Kjaergaard[3], F. Hammer[4], S. Randich[5], F. Zerbi[6], P. J. Groot[7], J. Hjorth[3], I. Guinouard[4], R. Navarro[8], T. Adolfse[7], P. W. Albers[7], J.-P. Amans[4], J. J. Andersen[3], M. I. Andersen[3], P. Binetruy[9], P. Bristow[1], R. Castillo[10], F. Chemla[4], L. Christensen[11], P. Conconi[6], R. Conzelmann[1], J. Dam[7], V. De Caprio[12], A. De Ugarte Postigo[3], B. Delabre[1], P. Di Marcantonio[13], M. Downing[1], E. Elswijk[8], G. Finger[1], G. Fischer[1], H. Flores[4], P. François[4], P. Goldoni[9], L. Guglielmi[9], R. Haigron[4], H. Hanenburg[8], I. Hendriks[7], M. Horrobin[14], D. Horville[4], N. C. Jessen[15], F. Kerber[1], L. Kern[1], M. Kiekebusch[1], P. Kleszcz[8], J. Klougart[3], J. Kragt[8], H. H. Larsen[3], J.-L. Lizon[1], C. Lucuix[1], V. Mainieri[1], R. Manuputy[16], C. Martayan[10], E. Mason[17], R. Mazzoleni[6], N. Michaelsen[3], A. Modigliani[1], S. Moehler[1], P. Møller[1], A. Norup Sørensen[3], P. Nørregaard[3], C. Péroux[18], F. Patat[1], E. Pena[10], J. Pragt[8], C. Reinero[10], F. Rigal[8], M. Riva[6], R. Roelfsema[8], F. Royer[4], G. Sacco[19], P. Santin[13], T. Schoenmaker[8], P. Spano[6], E. Sweers[7], R. Ter Horst[8], M. Tintori[20], N. Tromp[8], P. van Dael[7], H. van der Vliet[7], L. Venema[8], M. Vidali[21], J. Vinther[1], P. Vola[18], R. Winters[7], D. Wistisen[3], G. Wulterkens[7], and A. Zacchei[13]

(Affiliations can be found after the references)

Received 21 July 2011 / Accepted 27 September 2011

Table 1. An overview of the hardware and software contributions to X-shooter from the different consortium partners.

ESO	PI S. D'Odorico, PM H. Dekker
	Detector systems Flexure compensation system Cryogenic control electronics Data reduction software Final integration and commissioning
Denmark	PI and PM P. Kjaergaard Rasmussen
Niels Bohr Institute, Copenhagen University, DTU Space, Copenhagen	UVB & VIS spectrograph (mechanics) Instrument backbone Pre-slit optics and calibration system Instrument control electronics
France	PI F. Hammer, PM I. Guinouard
Paris Observatory Meudon Astroparticle and Cosmology Paris	Integral field unit Data reduction software
Italy	PI R. Pallavicini/S. Randich, PM F. Zerbi
INAF Observatory Palermo, INAF Observatory Brera, INAF Observatory Trieste, INAF Observatory Catania	UVB & VIS spectrographs (optics) Instrument Control Software
The Netherlands	PI L. Kaper, PM R. Navarro
Netherlands Research School for Astronomy (NOVA) Astronomical Institute, University of Amsterdam Astronomical Institute, Radboud University Nijmegen ASTRON Dwingeloo	NIR spectrograph NIR cryostat Data reduction software

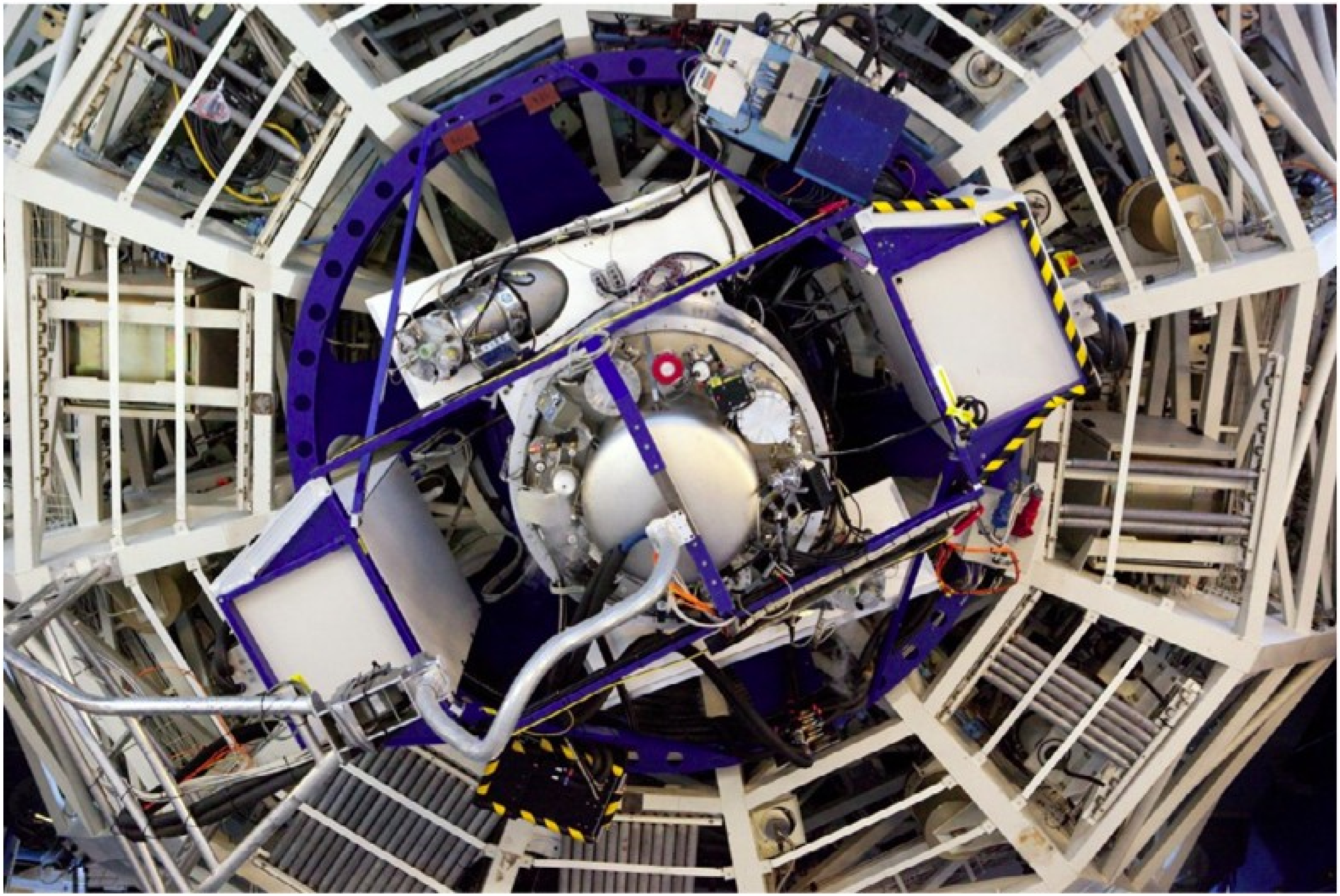
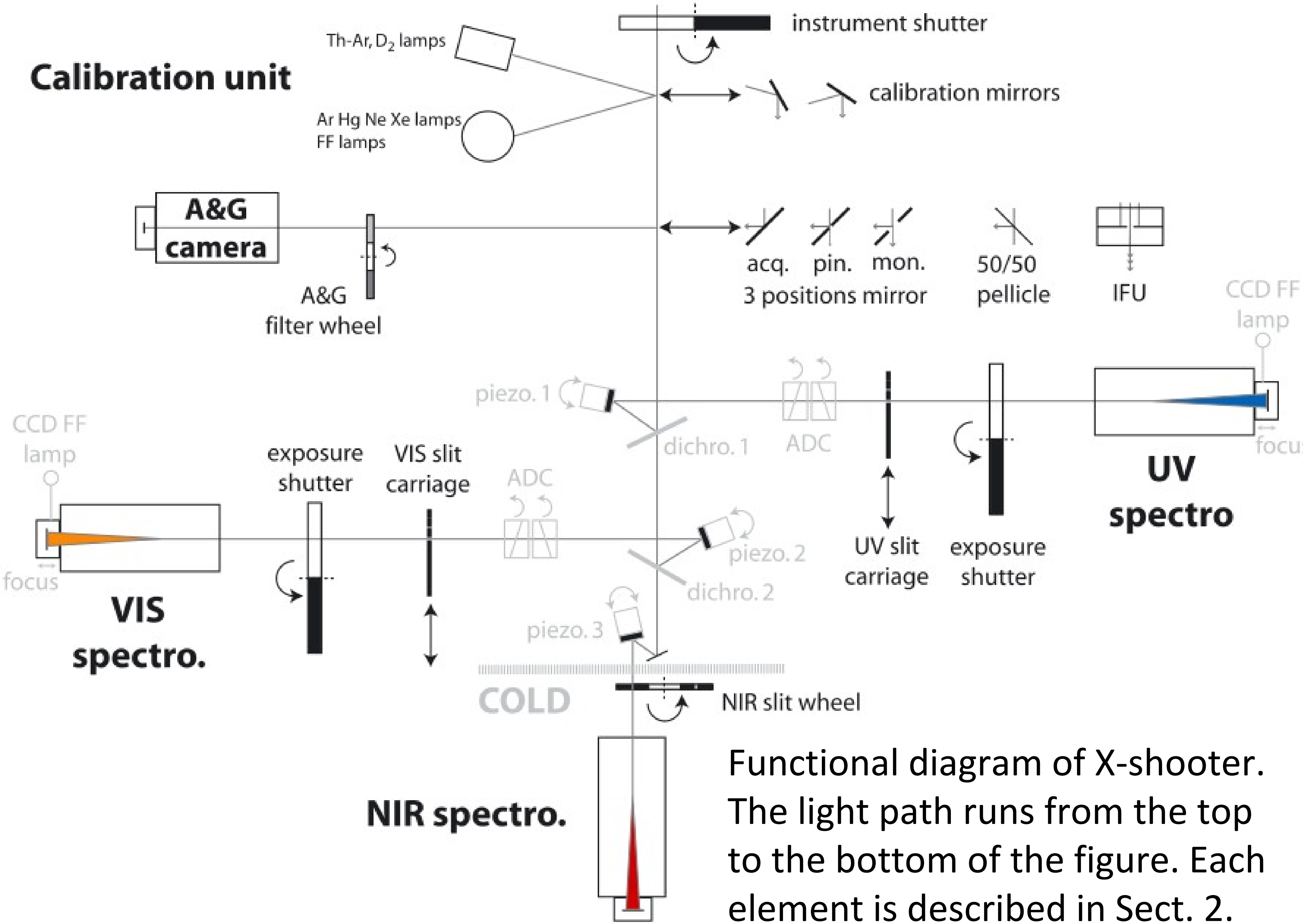


Fig. 1. A view of X-shooter at the Cassegrain focus below the primary mirror cell of the VLT UT2. In this view from below the instrument one sees the UVB and VIS spectrographs at the top and bottom, respectively. The NIR cryostat is visible in the center. The two boxes on the left and on the right are electronic cabinets.



Functional diagram of X-shooter. The light path runs from the top to the bottom of the figure. Each element is described in Sect. 2.

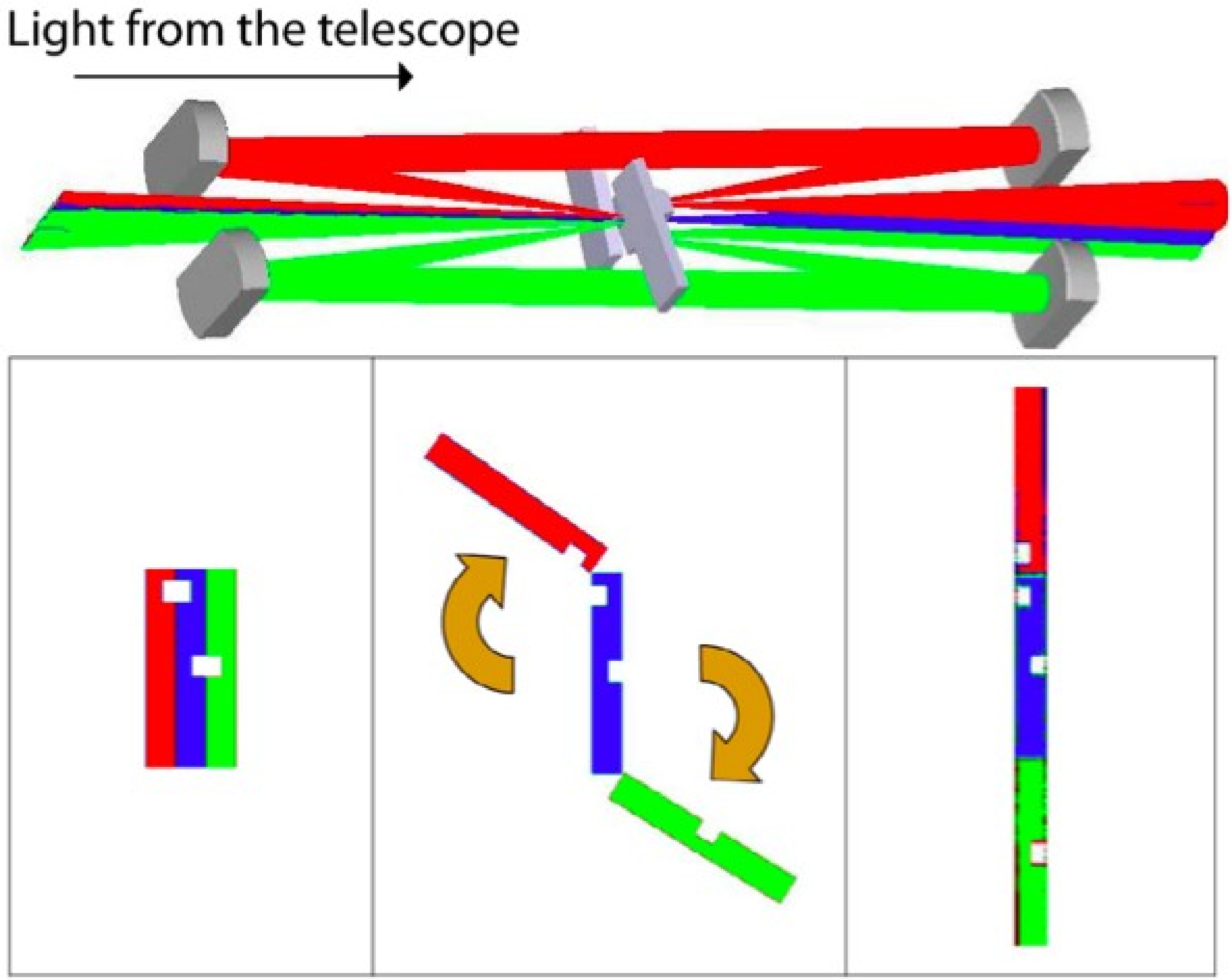


Fig. 3. *Top*: view of the effect of the IFU. The central field is directly transmitted to form the central slitlet (blue) while each lateral field (in red and green) is reflected toward a pair of spherical mirrors, and re-aligned at the end of the central slice to form the exit slit. *Bottom*: the field before (*left*) and after the IFU (*right*). The IFU acts such that the lateral fields are rotated. The two white slots are not real gaps but just guides to help visualize the top and the bottom of each slice in the drawing.

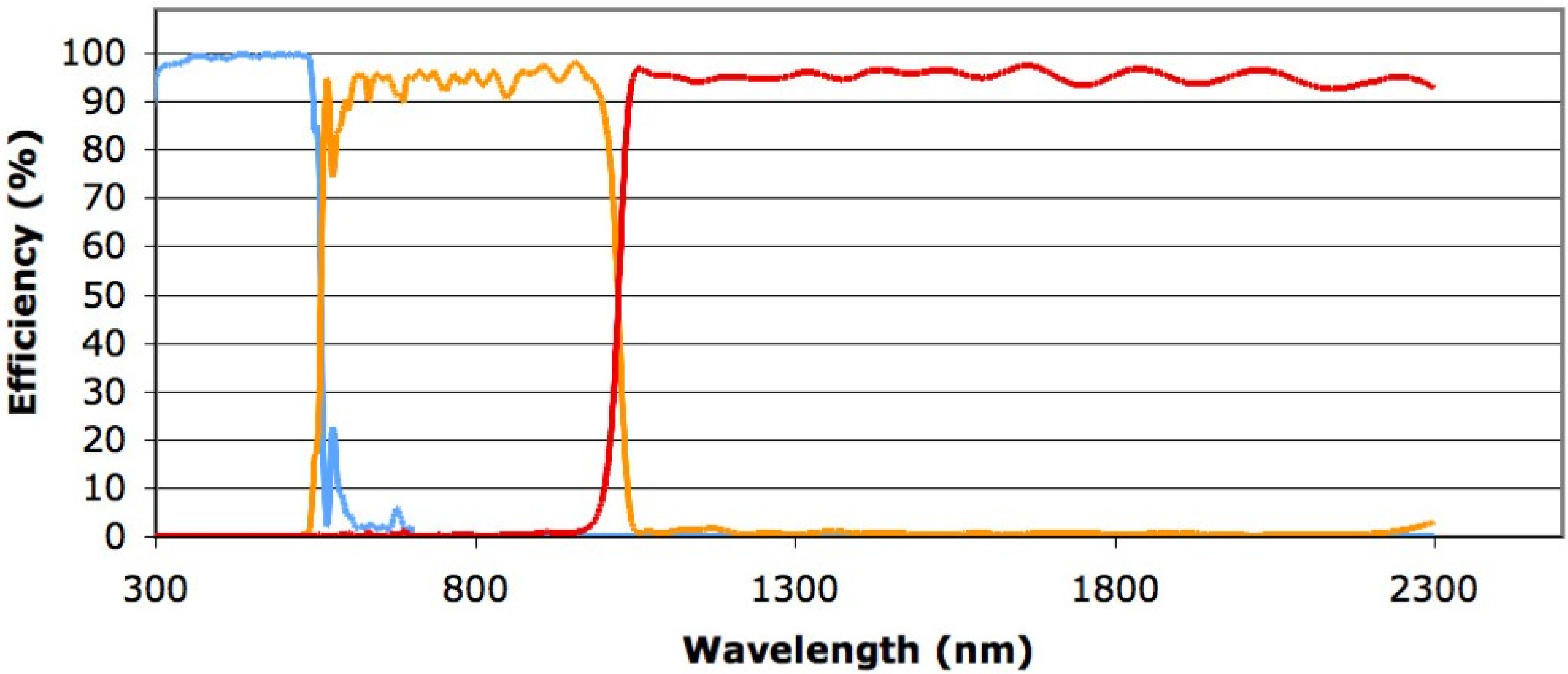
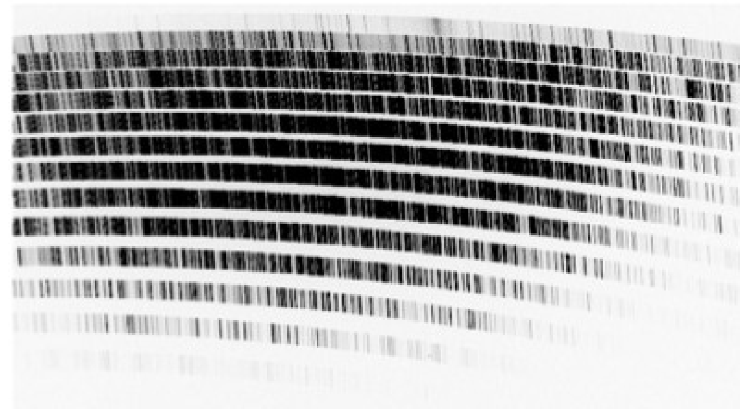
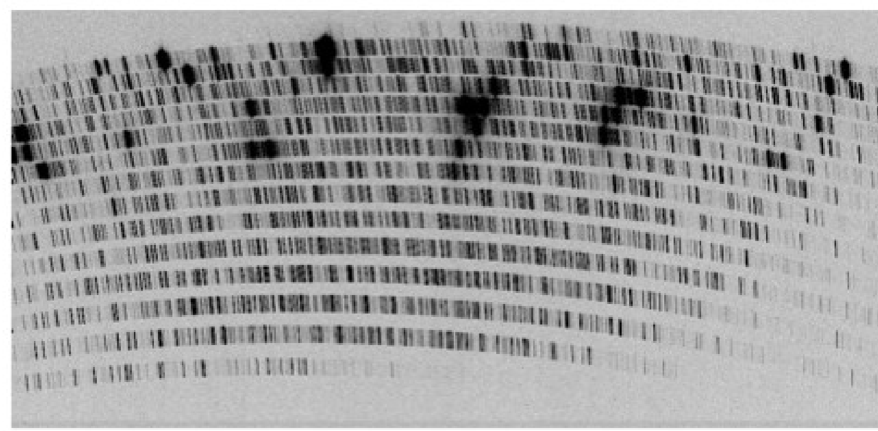
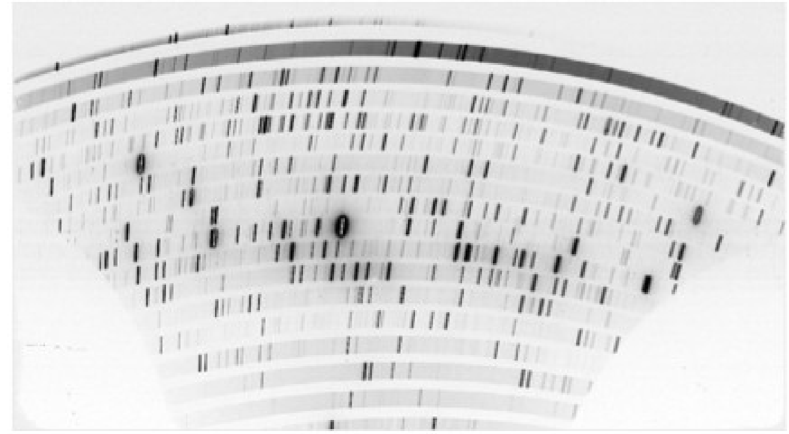


Fig. 4. The combined efficiency of the two dichroic beam splitters. In blue: reflection on the first dichroic; in orange: transmission through the first dichroic and reflection on the second dichroic; in red: transmission through both dichroics.

Table 3. The X-shooter spectral format for the UVB (top), VIS (middle) and NIR (bottom) arm as measured at the telescope.

Order	Min. wavelength (nm)	Blaze wavelength (nm)	Max. wavelength (nm)	Example of a ThAr calibration frame
			UVB	
24	293.6	312.2	322.3	
23	306.2	325.0	336.2	
22	320.0	339.8	351.4	
21	335.1	356.1	368.0	
20	351.8	373.5	386.2	
19	370.1	393.2	406.4	
18	390.6	414.5	428.9	
17	413.4	438.8	454.0	
16	439.1	466.4	482.2	
15	468.3	496.8	514.2	
14	501.6	531.0	550.8	
13	540.1	556.0	593.0	
			VIS	
30	525.3	550.5	561.0	
29	535.8	568.0	580.2	
28	554.6	585.9	600.8	
27	575.2	607.7	622.9	
26	597.4	629.5	646.8	
25	621.3	653.8	672.5	
24	647.2	682.1	700.4	
23	675.4	711.2	730.7	
22	706.1	742.6	763.8	
21	739.7	777.6	800.0	
20	777.0	815.8	839.8	
19	817.6	860.2	883.8	
18	862.9	904.3	932.7	
17	913.7	957.3	987.4	
16	970.7	1001.6	1048.9	

				NIR
26	982.7	1005.8	1034.2	
25	1020.5	1046.0	1076.7	
24	1062.0	1089.6	1122.9	
23	1106.6	1137.0	1173.1	
22	1155.2	1188.6	1228.0	
21	1208.2	1245.2	1288.5	
20	1266.5	1307.5	1355.2	
19	1330.3	1376.3	1429.4	
18	1400.8	1452.8	1511.5	
17	1479.5	1538.2	1604.0	
16	1567.1	1634.4	1708.7	
15	1667.8	1743.3	1823.3	
14	1785.7	1867.9	1952.8	
13	1922.6	2011.5	2102.0	
12	2082.9	2179.3	2275.6	
11	2272.3	2377.28	2480.7	

Notes. The minimum and maximum wavelength recorded on the detector together with the blaze wavelength are given for each order; on the right column, an example of wavelength calibration frame taken with a ThAr lamp for each arm.

Table 4. Measured resolution and sampling as a function of slit width.

	UVB			VIS			NIR	
Slit width (″)	Resolution ($\lambda/\delta\lambda$)	Sampling (pix/FWHM)	Slit width (″)	Resolution ($\lambda/\delta\lambda$)	Sampling (pix/FWHM)	Slit width (″)	Resolution ($\lambda/\delta\lambda$)	Sampling (pix/FWHM)
0.5	9100	3.5	0.4	17 400	3.0	0.4	11 300	2.0
0.8	6300	5.2	0.7	11 000	4.8	0.6	8100	2.8
1.0	5100	6.3	0.9	8800	6.0	0.9	5600	4.0
1.3	4000	8.1	1.2	6700	7.9	1.2	4300	5.3
1.6	3300	9.9	1.5	5400	9.7	1.5	3500	6.6
IFU	7900	4.1	IFU	12 600	4.2	IFU	8100	2.8

Slides from previous years

- Grating equation following the book “To Measure the Sky”