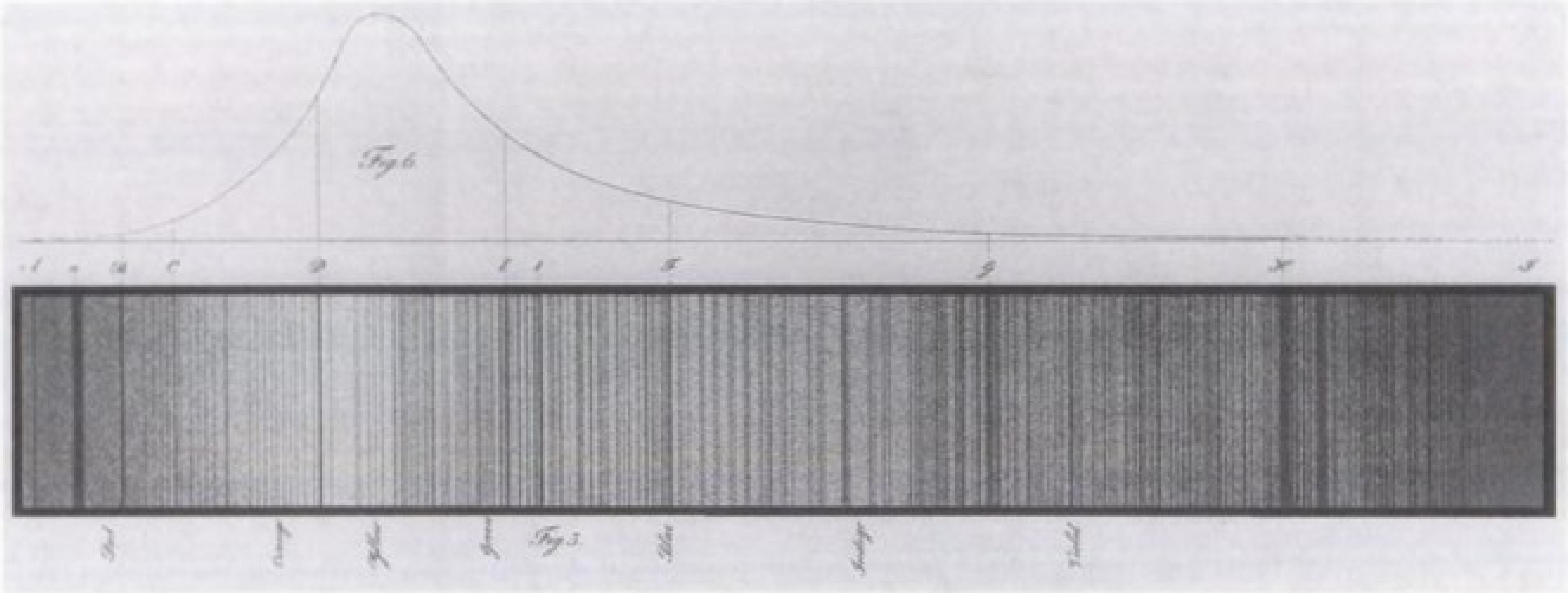
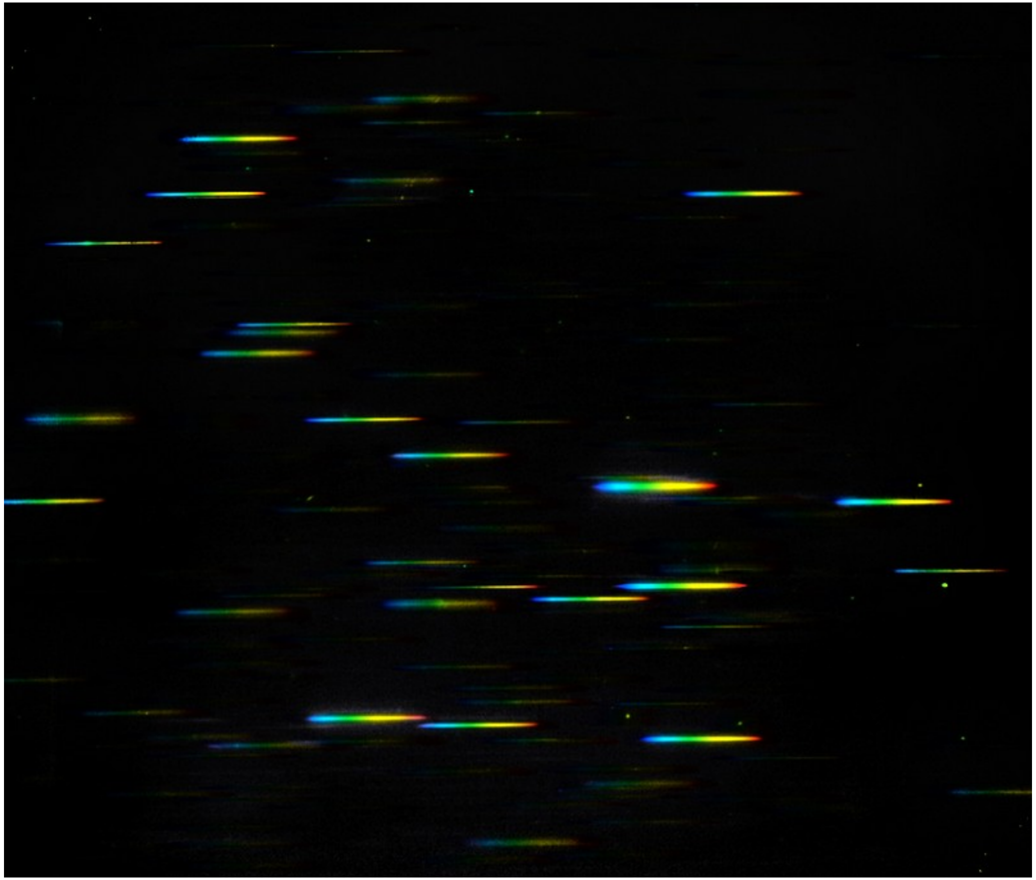
(Day 05)

Spectroscopy



(Solar spectrum by Fraunhofer, 1817; Fig. 3.1 Brand 1995)

Today

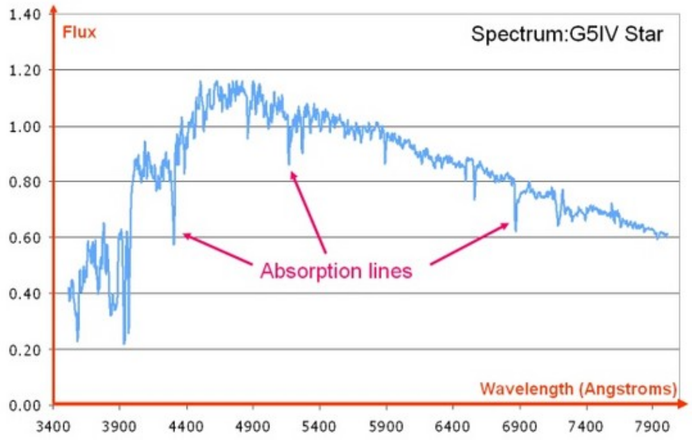


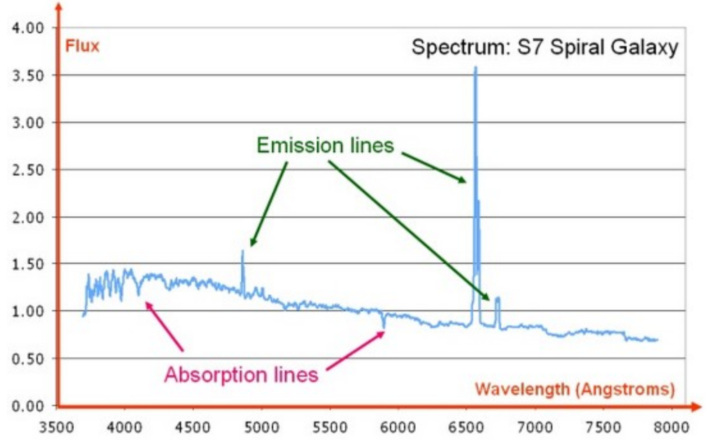
(HST Grism spectra. Copyright: NASA & ESA)

1. Planning spectroscopic observations
2. Spectroscopy: concepts
3. FORS2
4. X-Shooter
5. FLAMES
6. UVES
7. ESPRESSO
8. MUSE

What is spectroscopy?

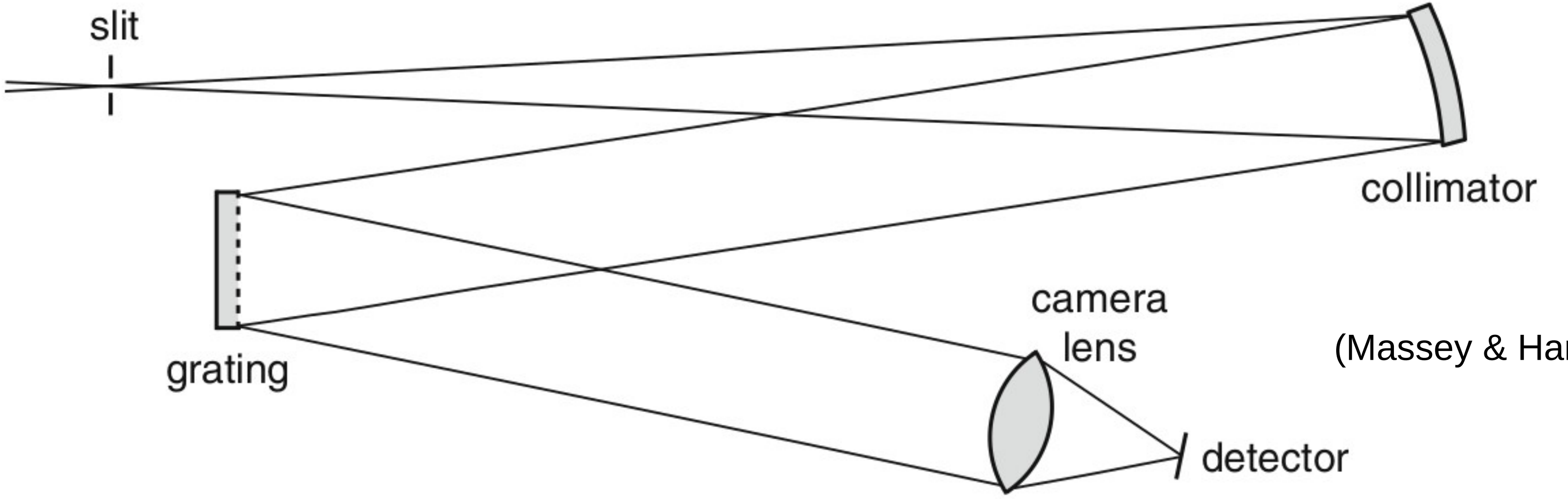
- Dispersing the light to measure flux (or intensity) as a function of wavelength
- The spectrum of an object contains information on temperature, density, chemical composition
- Doppler shift – radial velocity / redshift
- The spectrum: continuum, absorption and emission lines
- Thermal and non-thermal continuum sources of radiation
- Lines tell about the interaction of matter with radiation





(Credit: COSMOS - The SAO Encyclopedia of Astronomy)

Basic layout of a spectrograph

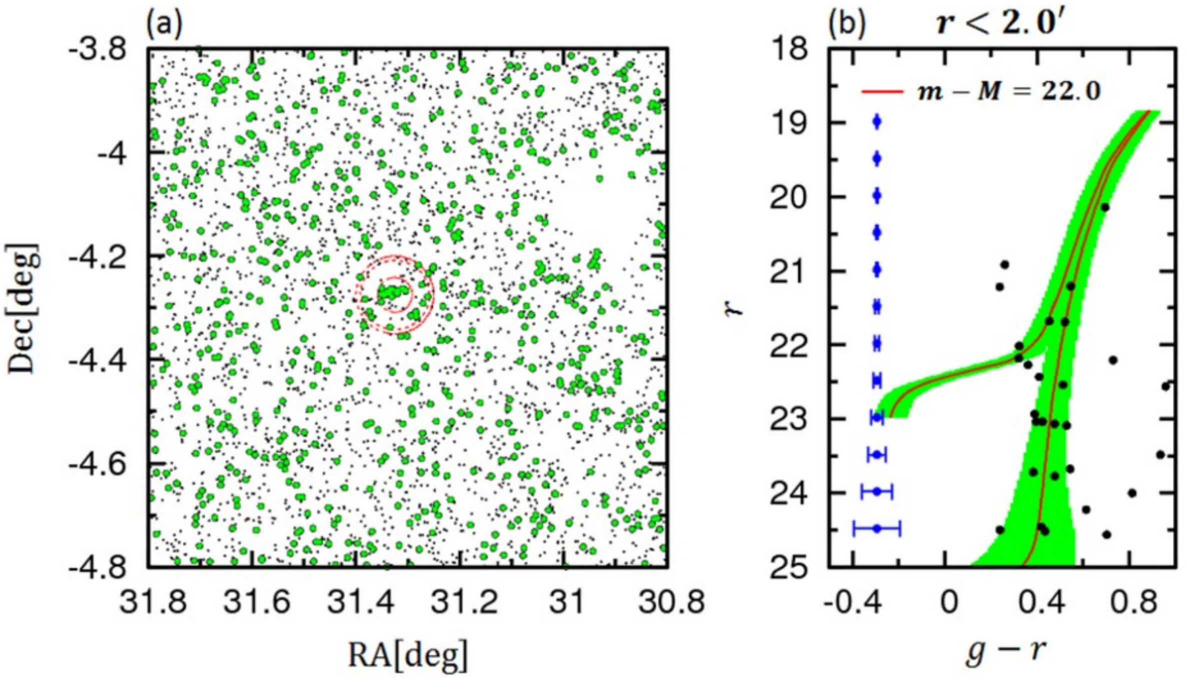


(Massey & Hanson 2013)

- Light is collected and focussed by the **telescope**
- **Entrance slit** (on the telescope focal plane): isolates the light of the source of interest
- **Collimator**: sends a parallel beam to the dispersing element
- **Prism, Grism, or Grating**: disperses the light
- **Camera:** images the spectrum onto the detector

Let’s go back to our science case

- An overdensity of stars has been identified with Gaia
- Previous photometric observations confirmed it as a physical object
- The CMD gave a list of likely members
- We want to confirm the association of the stars (with radial velocities)
- And have an idea of their chemical composition
- **Spectroscopy** of as many candidates as possible
- Field of ~9’ of diameter



(Homma et al. 2018)

If you want to observe with the VLT, read the call for proposals

- Updated list of offered instruments
- Informs on recent policy changes
- and on future plans for the instruments
- Describes important definitions (proposal types, observing modes, OBs, ...)
- Several links for additional information
- Binding document if the proposal is approved
- **Reading is a must for 1st time users!**

ESO Call for Proposals – P109

Proposal Deadline: 23 September 2021, 12:00 noon CEST

Optical spectrographs @VLT

Paranal Instruments Summary Table

Instrument	Spectral Coverage	Observing Mode	Spectral Resolution	Multiplex	Note	Telescope
FORS2	optical 330 - 1100 nm	imaging (incl. configurable occulting bars), long slit and multi-object spectroscopy, spectropolarimetry, imaging polarimetry	260 - 2600	yes	Spectroscopy with ~7' long slit, ~20" multi-slit, and laser-cut slit masks; multiple object spectroscopy; RRM	VLT UT1
KMOS	near-IR 0.8 - 2.5 µm	multi-object integral field spectroscopy (24 arms)	1800 - 4000	yes	24-arms Integral Field Spectroscopy; 2.8x2.8", 0.2" sampling IFU over a 7.2' field;	VLT UT1
FLAMES	optical 370 - 950 nm	multi-fibre echelle,integral field spectroscopy	6000 - 47000	yes	132 Medusa fibres; 15 deployable IFUs, one large IFU; GIRAFFE: single echelle order; 8 fibres to UVES	VLT UT2
VISIR	mid-IR: 4.5 - 21 µm	M, N and Q band normal and burst-mode imaging; coronagraphy (Angular Groove Phase Mask, 4-Quadrant Phase Mask); N band low resolution long slit spectroscopy; high-resolution long slit and cross-dispersed spectroscopy	~400, 20000	no	pixel size of 0.045 and 0.076 arcsec in imaging, and 0.076 arcsec in spectroscopy	VLT UT2
UVES	optical 300 - 1100 nm	echelle, image slicer, slit spectroscopy	up to 80,000 (blue arm) / 110,000 (red arm)	no	long slit capability in single order; iodine cell; RRM	VLT UT2
SPHERE	optical: 500 - 900 nm near-IR: 0.95 - 2.32 µm	high-contrast imaging, dual-band imaging, integral field spectroscopy, differential-polarimetric imaging with or without classical, apodized pupil Lyot coronagraphs, sparse aperture mask	~30, 50, 400	no	extreme AO with optical wave-front sensor; fast star hopping; RRM	VLT UT3

https://www.eso.org/sci/facilities/lpo/cfp/cfp109/instrument_summary.html

Optical spectrographs @VLT

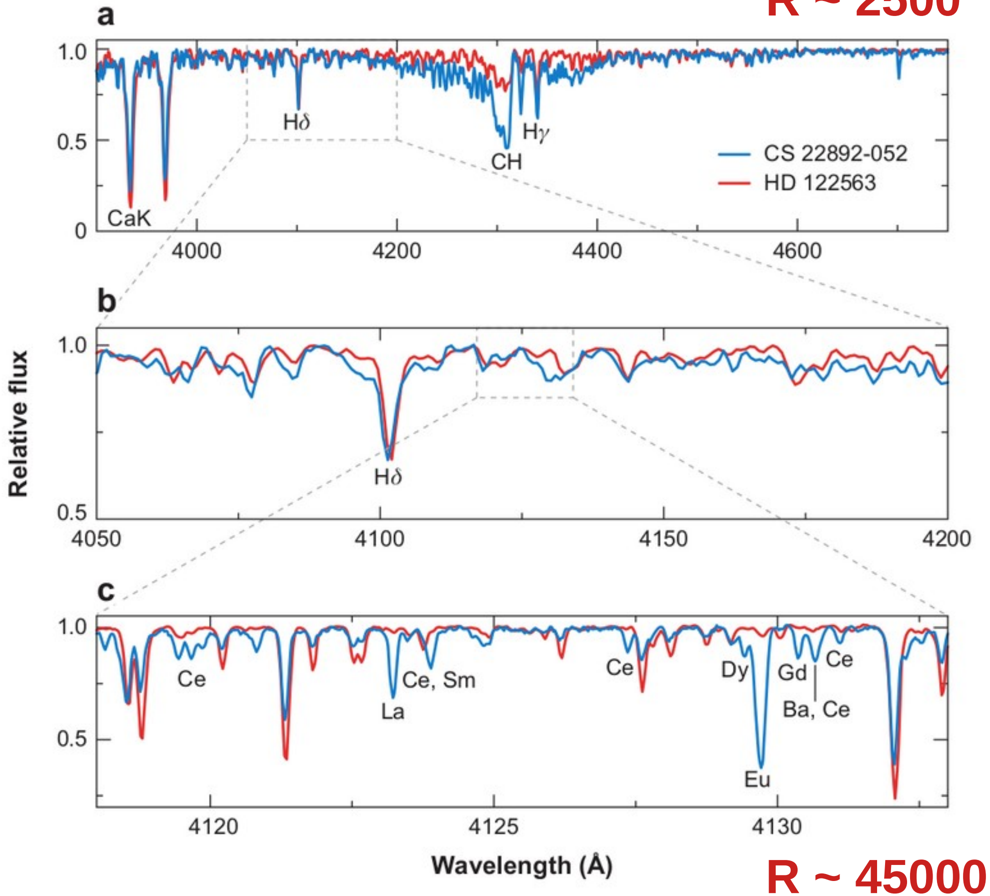
X-SHOOTER	UV-optical-NIR 300 - 2500 nm	echelle, slit and integral field spectroscopy	~5000-17000	no	full spectral coverage with one pointing; slit + IFU; RRM	VLT UT3
CRIRES	near-IR 0.95-5.3 µm	echelle, slit spectroscopy, spectro-polarimetry	~40,000-80,000	no	AO assisted, 29 wavelength settings, 0.2"x10" and 0.4"x10" slits, gas cells for precision RV measurements, linear and circular polarimetry below 2500 nm.	VLT UT3
HAWK-I	near-IR 0.85-2.5 µm	broand and narrow band imaging, fast photometry	-	-	pixel size of 0.106"; field: 7.5'x7.5', subwindow readout capability; GLAO; RRM	VLT UT4
MUSE	optical 465 - 930 nm	integral field spectroscopy	1770 @ 480nm 3590 @ 930nm	no	IFU size on sky 60"x60" with spaxel size 0.2" (WFM) or 7.5"x7.5" with spaxel size 0.025" (NFM); GLAO, LTAO, no AO; RRM.	VLT UT4
ESPRESSO	optical 380 - 788 nm	fibre-fed échelle spectroscopy	140,000, 190,000, or 70,000 (median)	no	2 fibres (1 object, 1 sky or simultaneous reference); RV precision < 1 m/s (with the ultimate goal of reaching 10 cm/s); 1-UT and 4-UT modes	VLT UT1, VLT UT2, VLT UT3, or/and VLT UT4
GRAVITY	near-IR 2.05 - 2.45 µm	spectro-interferometry	R ~ 20, 500, & 4000	no	4 beam combiner - delivers spectrally dispersed visibilities, differential and closure phases	VLTI - ATs VLTI - UTs

https://www.eso.org/sci/facilities/lpo/cfp/cfp109/instrument_summary.html

Choosing the instrument

- **Single object x Multi object** – UVES, ESPRESSO, X-Shooter **vs.** FORS2, FLAMES, MUSE (IFU actually)
- **Resolving power:** how well do we need to resolve the spectral lines?
  - $R = \lambda/\Delta\lambda = \nu/\Delta\nu = c/\Delta v$
  - Where $\Delta\lambda$, $\Delta\nu$, Δv give the resolution element in terms of wavelength, frequency or velocity
  - For R = 6000 @ 6000 A; $\Delta\lambda$ = 1 A, $\Delta\nu$ ~ 499.6 THz, Δv ~ 50 km/s
  - FORS2 (R = 260-5600); FLAMES Giraffe (R = 6000-28000); MUSE (R = 1770-3590); X-Shooter (R = 5000-17000); UVES (R up to 80-100k); ESPRESSO (R = 70, 140, 190k)

R ~ 2500



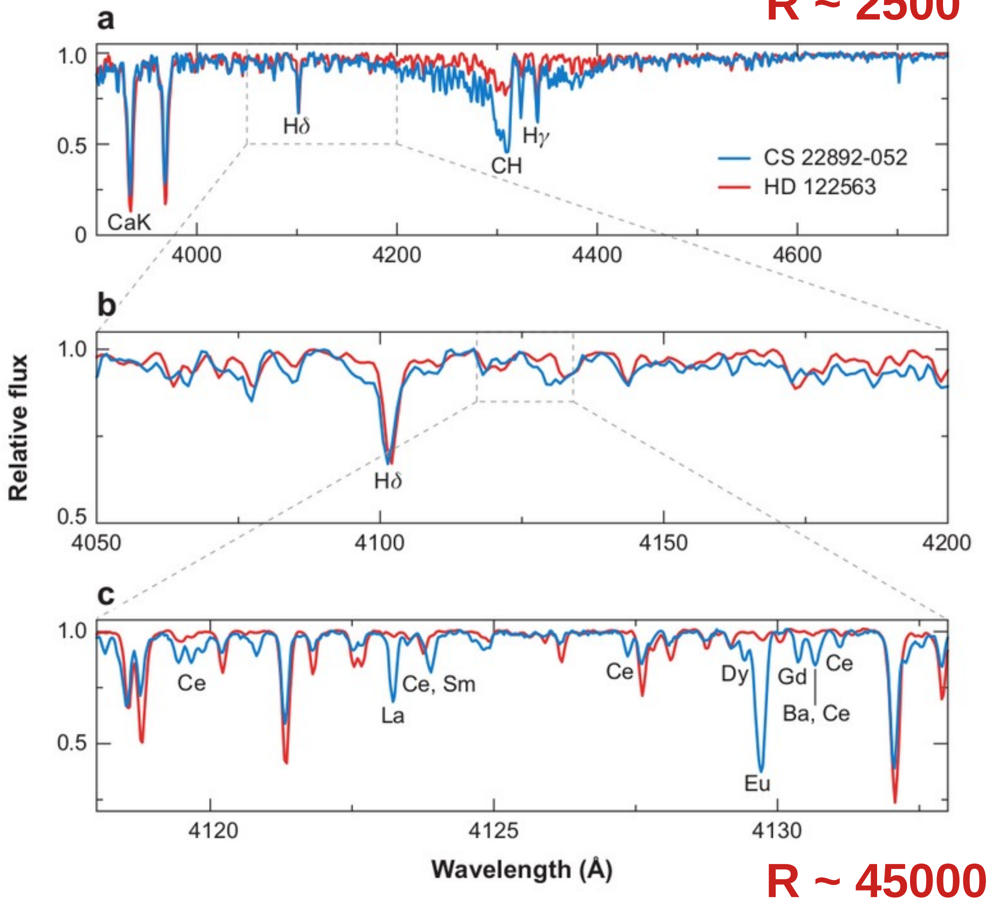
R ~ 45000

(Sneden et al. 2008)

Choosing the instrument

- **Wavelength range:**
  - FORS2: 330-1100 nm
  - FLAMES: 370-950 nm
  - UVES: 300 - 1100 nm
  - X-Shooter: 300 - 2500 nm
  - MUSE: 465 - 930 nm
  - ESPRESSO: 380 - 788 nm
- **Field of view and source distribution:**
  - FORS2: MOS with 6.8'x6.8'
  - FLAMES: 25' diameter
  - MUSE: Wide Field Mode 60"x60" with spaxel size 0.2"; Narrow Field Mode7.5"x7.5" with spaxel size 0.025"
- **Need AO?** - MUSE (e.g. the field is crowded)

R ~ 2500

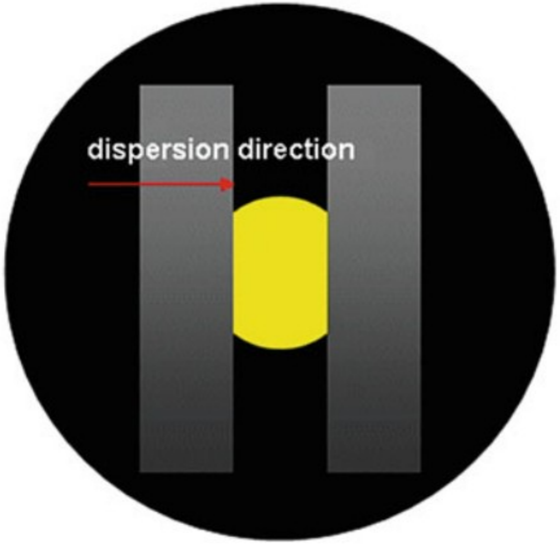


R ~ 45000

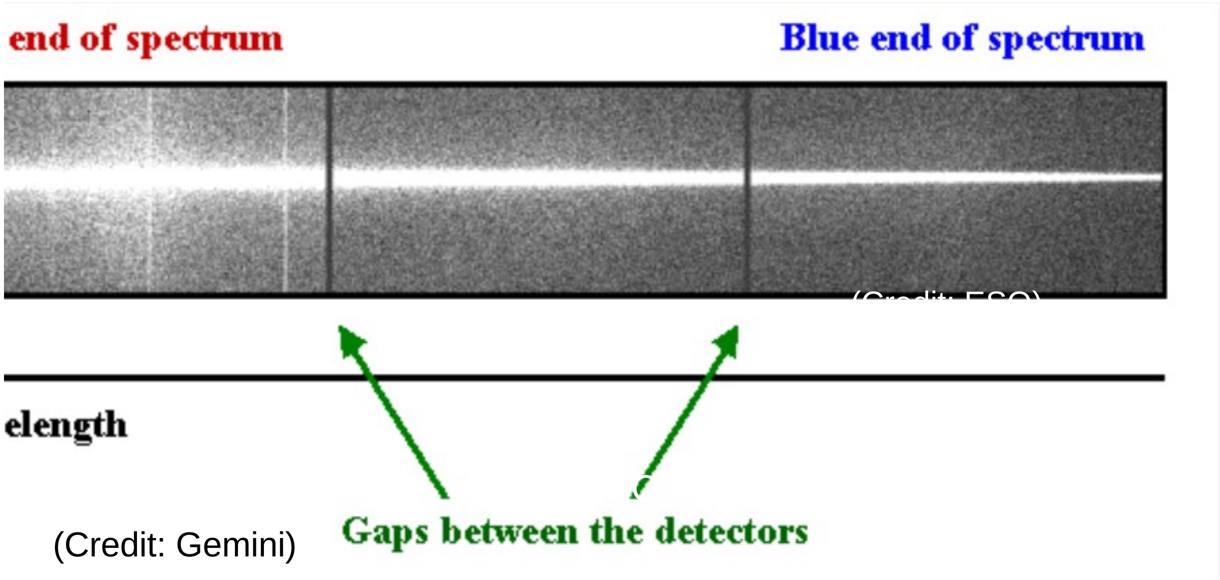
(Sneden et al. 2008)

Slit or fiber

- Using a long slit you can select the object but also sky regions for background correction
- Slit width << seeing causes loss of light
- The slid width connects to the resolution
- Slitless spectroscopy is possible (taking spectra of the whole field)



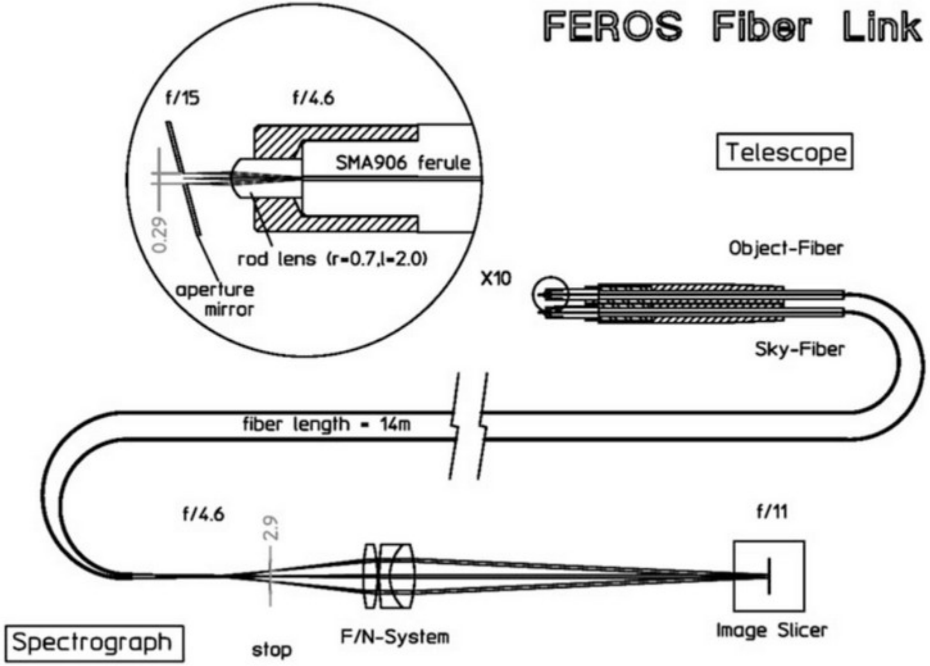
(Eversberg & Vollmann 2015)



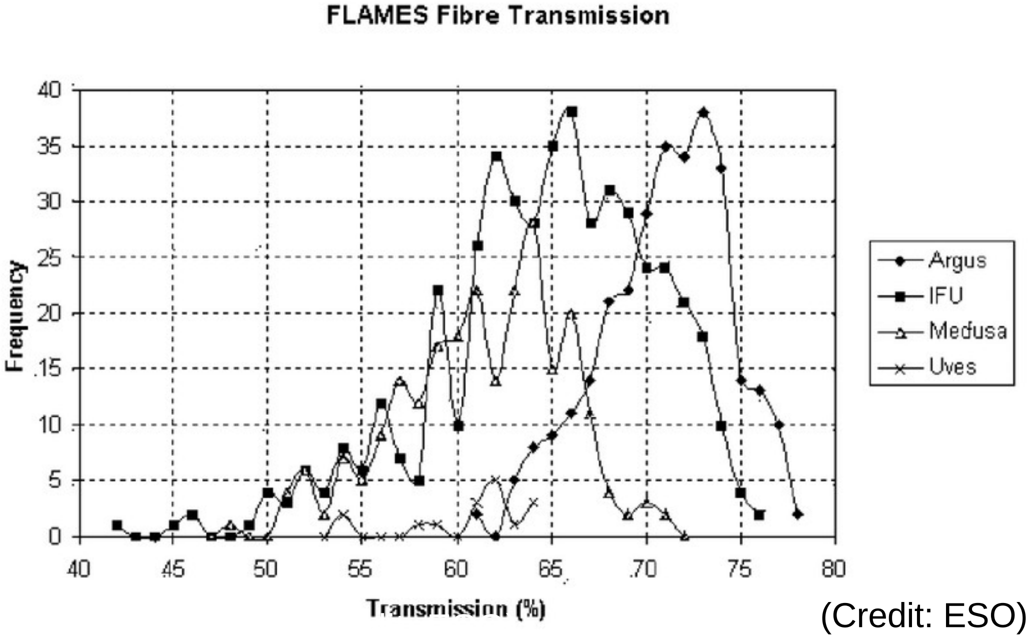
(Credit: Gemini)

Slit or fiber

- Spectrograph can be made to be very stable, not attached to the telescope
- Fiber apertures is fixed. Typically on sky ~1-2” (similar to the seeing)
- For background correction, separated fibers allocated to the sky (but transmission varies)
- Fiber attenuation is a function of the length and wavelength. Bad in the blue spectral region.



(Eversberg & Vollmann 2015)

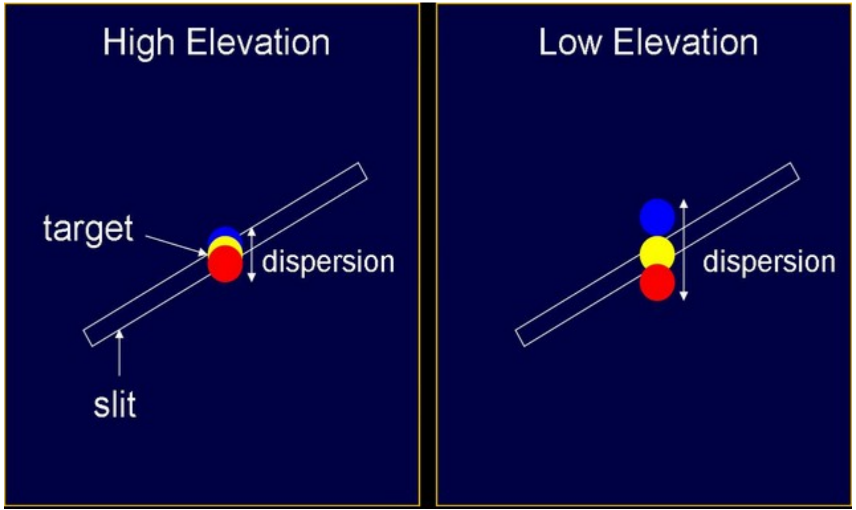


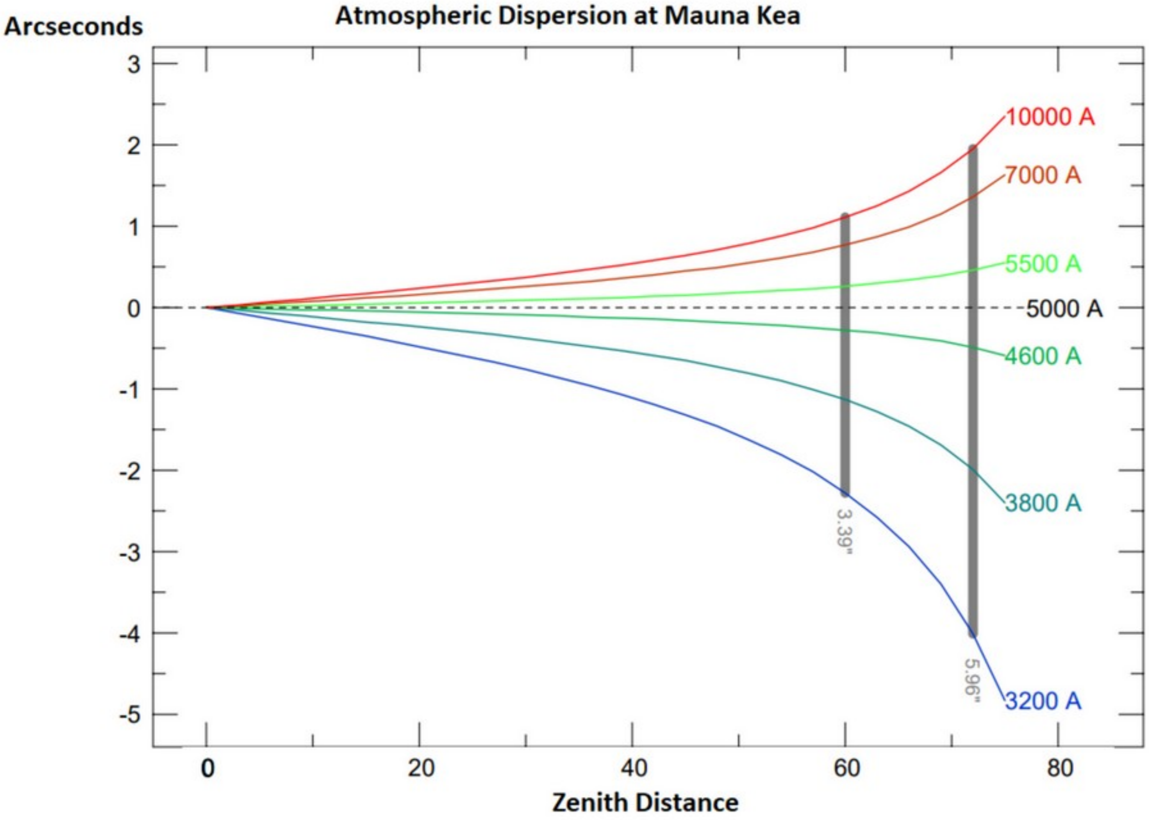
(Credit: ESO)

Figure 5: Distribution of the transmission of the FLAMES fibres at 600 nm. each fibre has been measured in laboratory.

Atmospheric dispersion

- The atmosphere disperses the light on the vertical direction
- The guiding system will be following the image in a certain filter (V has λ_c ~5556 A)
- Typical slit width or fiber aperture ~ 1”
- If the slit is not vertically aligned, certain colors may be lost

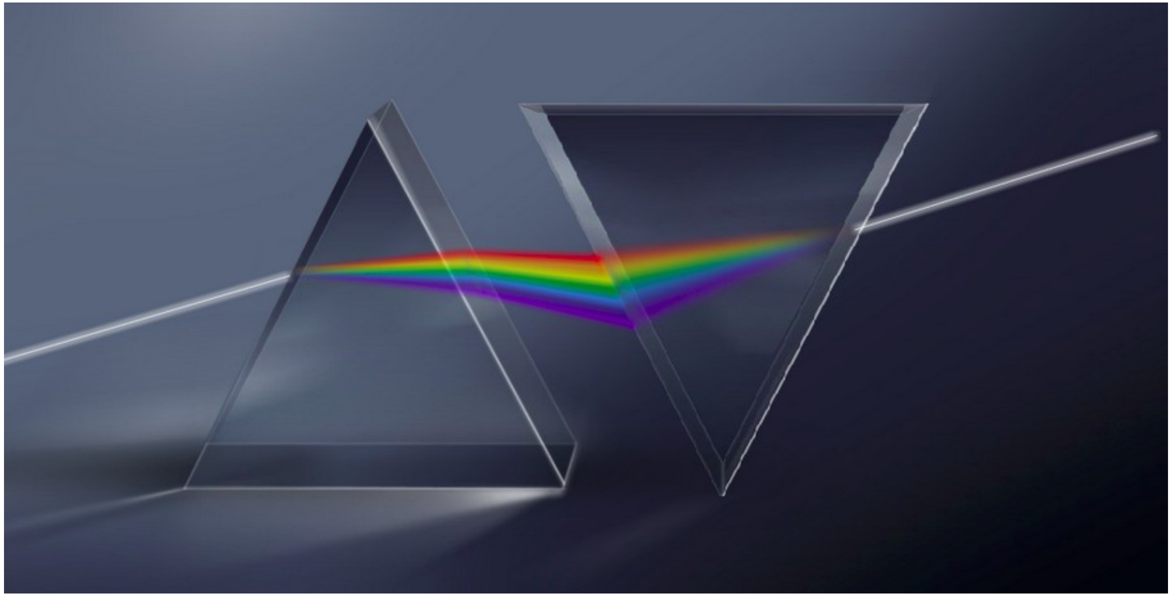




(Rakich et al. 2021)

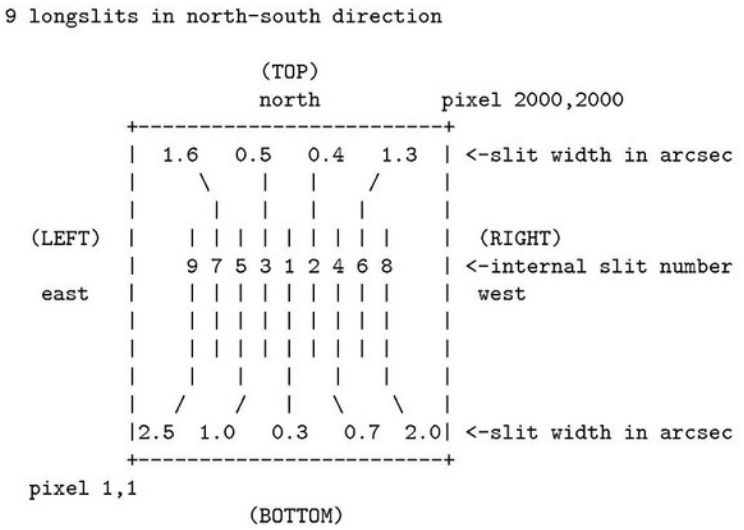
Atmospheric dispersion corrector

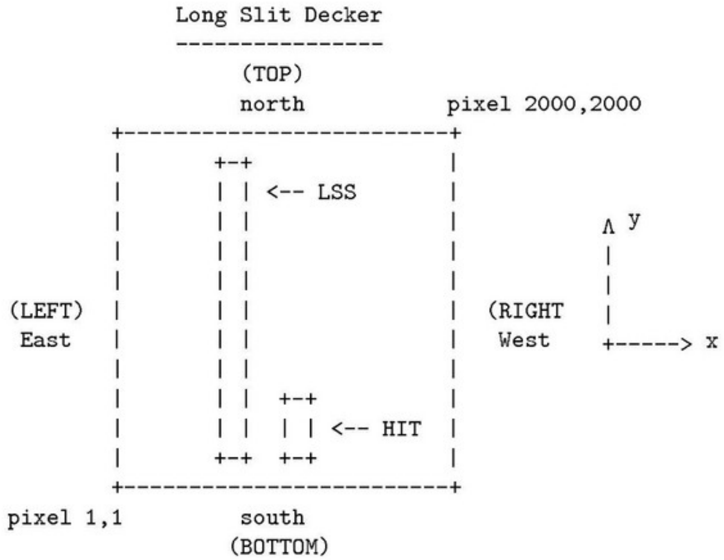
- Some spectrographs have an ADC
- It can (partially) correct for the dispersion caused by the atmosphere
- **With ADC: FORS2, UVES, ESPRESSO, MUSE (NFM only), X-Shooter (UV, VIS)**
- **No ADC: FLAMES, MUSE (in WFM), X-Shooter (NIR arm)**
- Need to create variable dispersion, depending on zenith angle
- Should not deviate the mean wavelength from its path
- Usually made of a system with 2 pairs of counter-rotating prisms



FORS2

- **FO**cal **R**educer and low dispersion **S**pectrograph (Appenzeller et al. 1998).
- Spectroscopic modes:
  - Long slit (LSS): 9 fixed width slits (0.3” to 2.5” x 6.8’)
  - Moveable slits (MOS): 19 pairs of arms (width > 0.3”)
  - Spectroscopic mask (MXU): up to 470 slits, of variable length, width and shape. Up to 10 masks can be mounted in the mask unit
  - Spectropolarimetry (PMOS)
- Two detectors: 1) MIT CCD, good red sensitivity, low fringing; 2) E2V CCD, good blue sensitivity, strong fringes > 650nm (only in visitor mode)
- Accurate positions needed for the mask (pre-imaging might be needed)

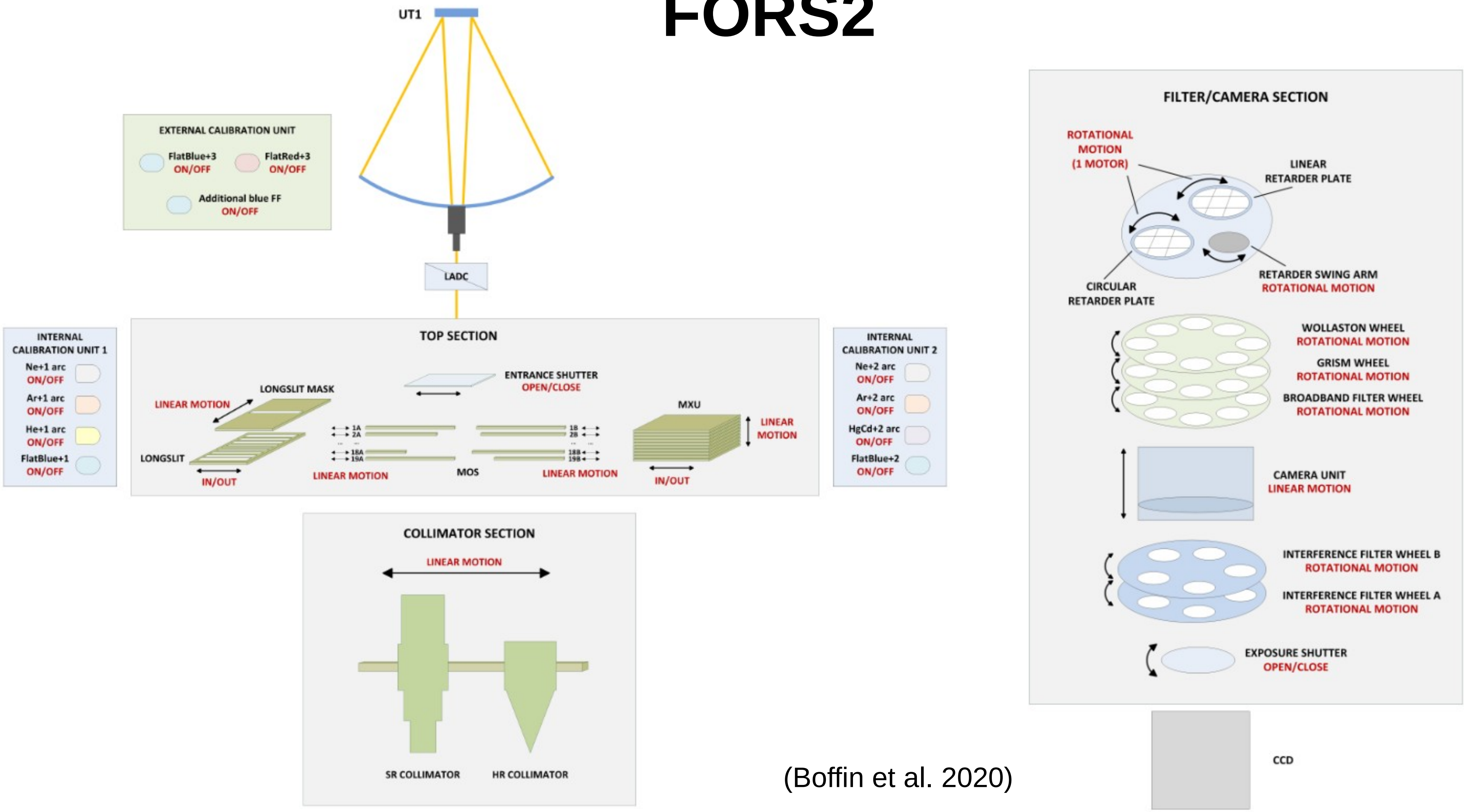




Questions?

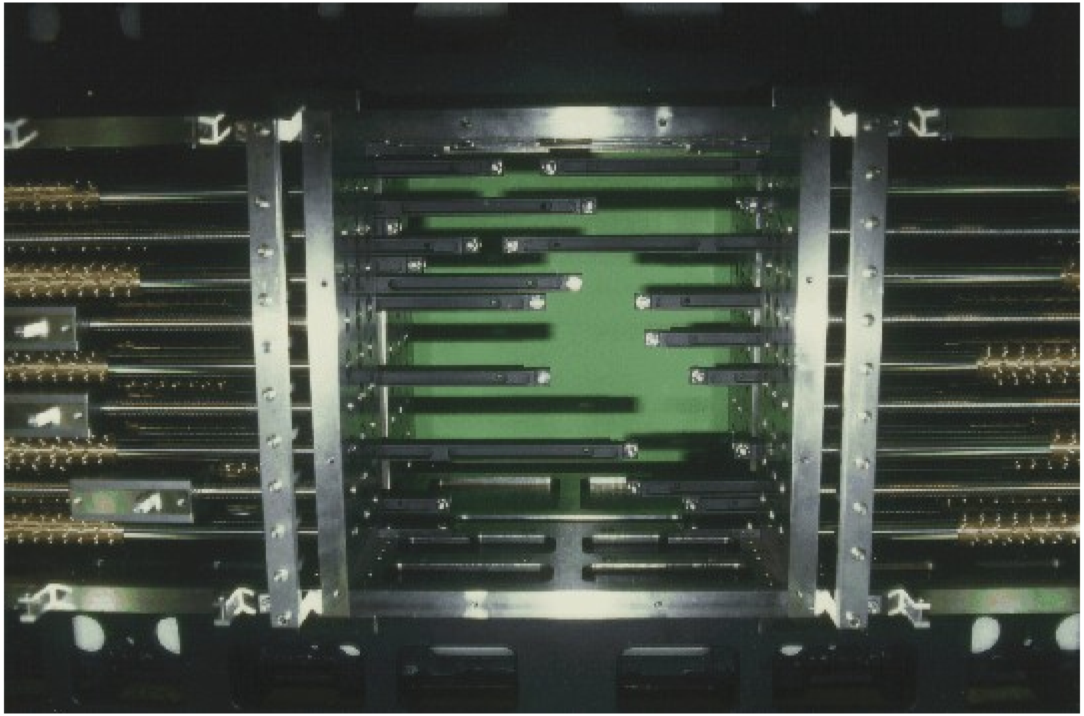
(Credit: Shutterstock)

FORS2



(Boffin et al. 2020)

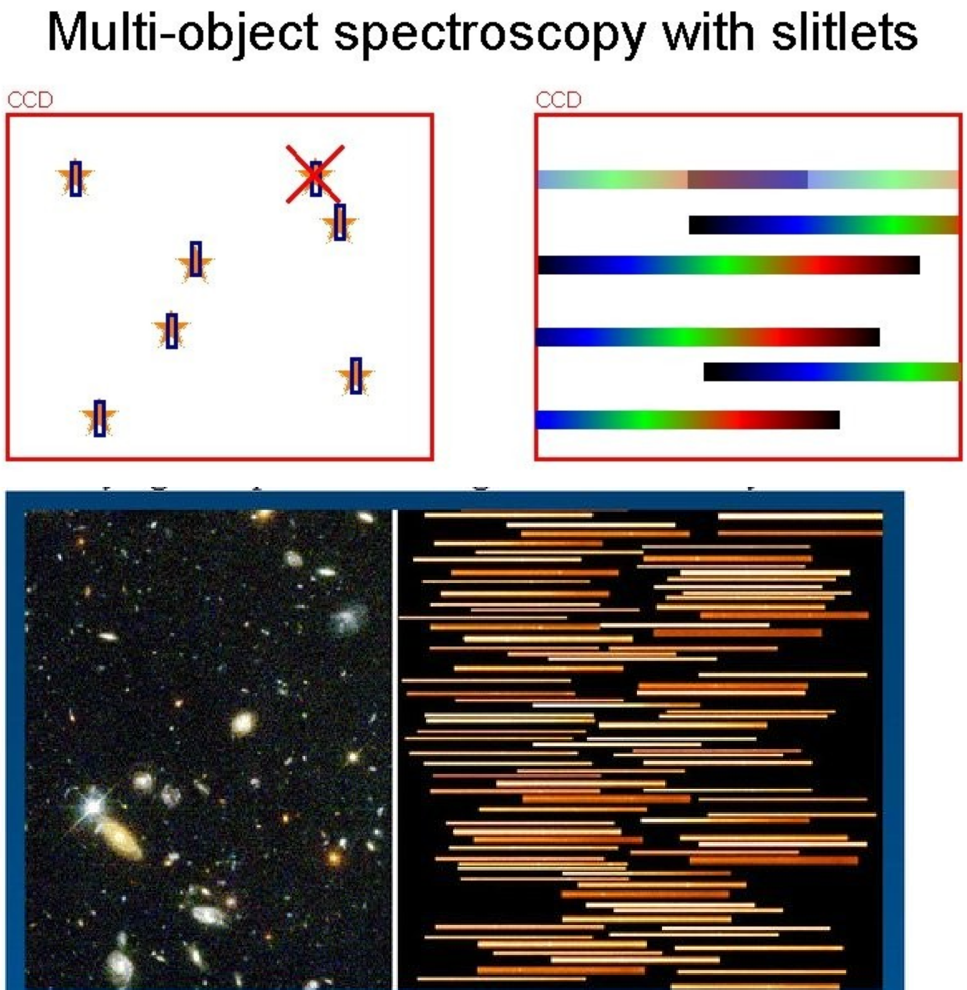
FORS2 MOS Slit Jaws



(Credit: ESO)

Mask design

- For FORS, masks design have to be prepared with the FIMS software
- Slits can be rectangular, circular or curved
- Alignment on the sky done with reference stars and pre-defined slits
- Positions have to be carefully selected to avoid overlap
- The wavelength coverage for each spectrum is different



FORS2 grisms

FORS2 standard grisms

The following grisms form the Standard Instrument Configuration. Response curves are given in the User Manual.

Grism name + ESO number	Lambda Central	Wavelength range	Dispersion	Order separation
	[nm]	[nm]	[Å/mm]	filter
standard:				
GRIS_600B+22	465	330 - 621	50	none
GRIS_300V+10 (1)	590	330 - (660)	112	none
GRIS_300V+10	590	445 - 865	112	GG435
GRIS_300I+11	860	600 - 1100	108	OG590
GRIS_150I+27 (1)	720	330 - (650)	225	none
GRIS_150I+27 (1)	720	445 - (880)	230	GG435
GRIS_150I+27	720	600 - 1100	230	OG590
holographic:				
GRIS_1400V+18	520	456 - 586	20.8	none
GRIS_1200B+97	435	366 - 511	24.0	none
GRIS_1200R+93	650	575 - 731	25.0	GG435
GRIS_1028z+29	860	773 - 948	28.3	OG590
GRIS_600RI+19	678	512 - 845	55	GG435
GRIS_600z+23	901	737 - 1070	54	OG590

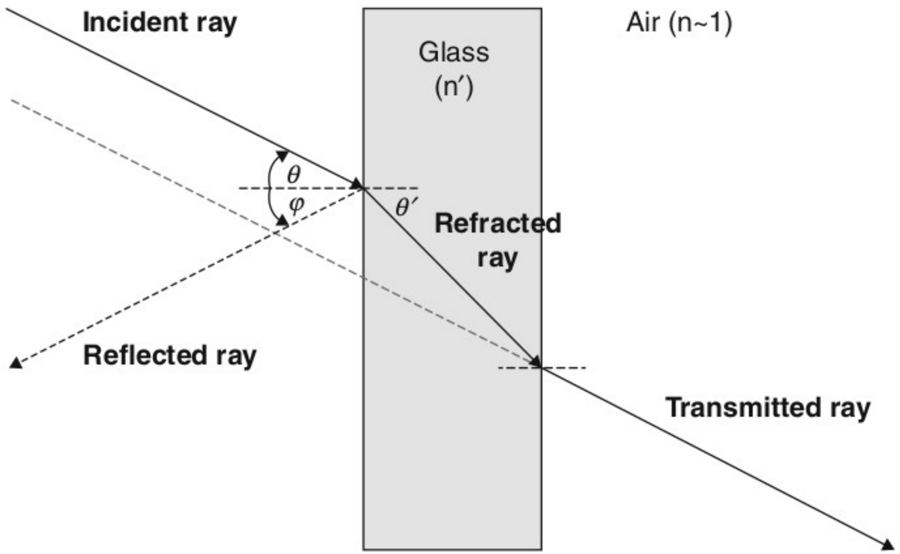
(Credit: ESO)

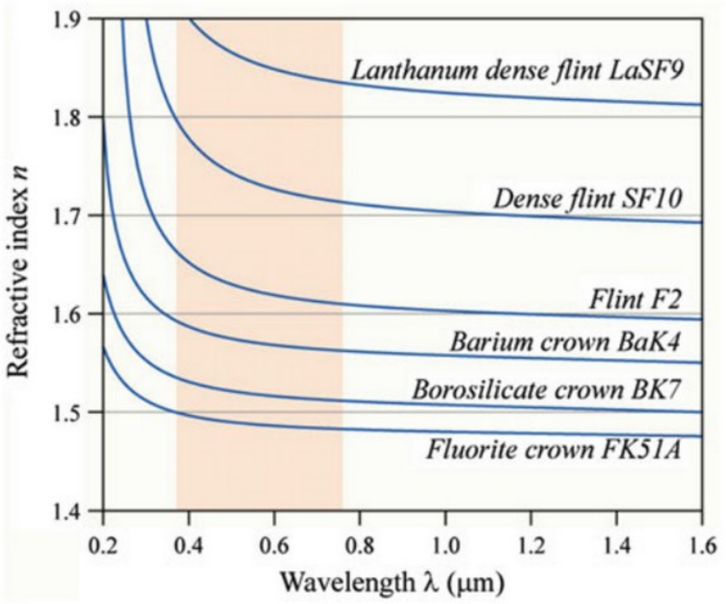
Dispersion elements

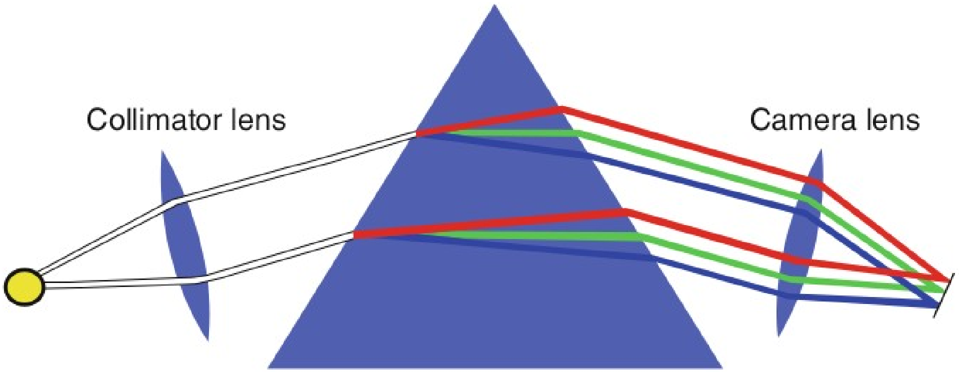
Prism

- Snell's law: $$\sin(\theta)/\sin(\theta') = n'/n$$

- Light changes velocity when changing media and the change is wavelength dependent (so is the refractive index and the final angle)

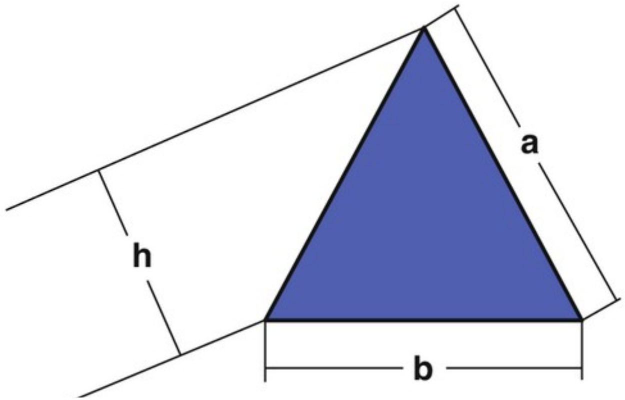






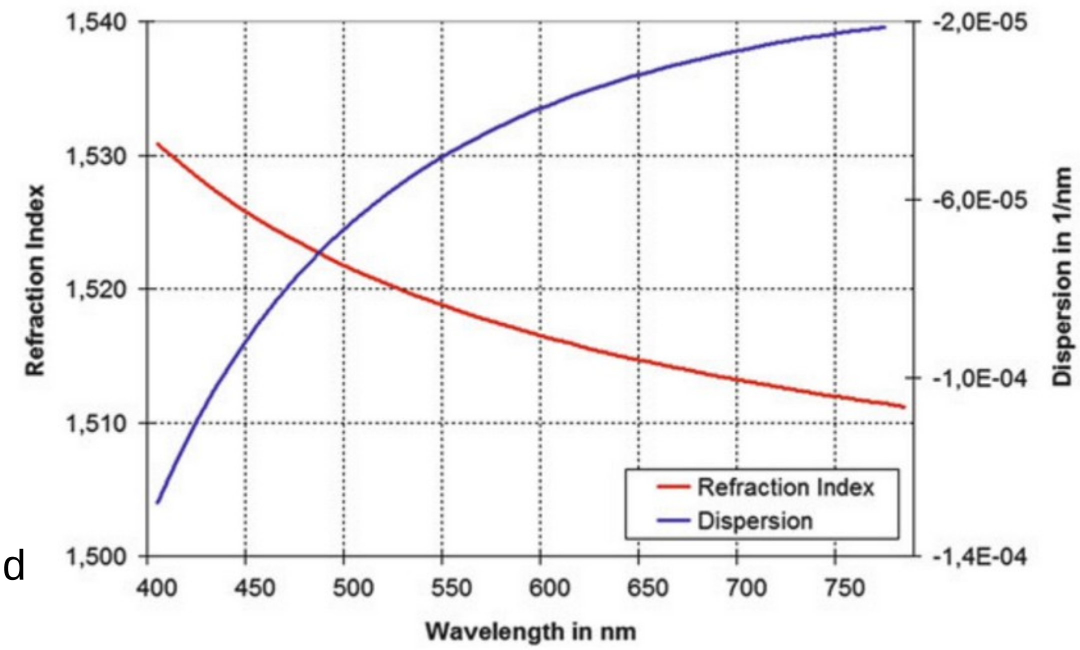
Prism

(Eversberg & Vollmann 2015)



- Prisms are cheap and can have high transmission
- Dispersion is relatively low
- Dispersion is non-linear
- Resolving power depends on the edge side length and the refraction index

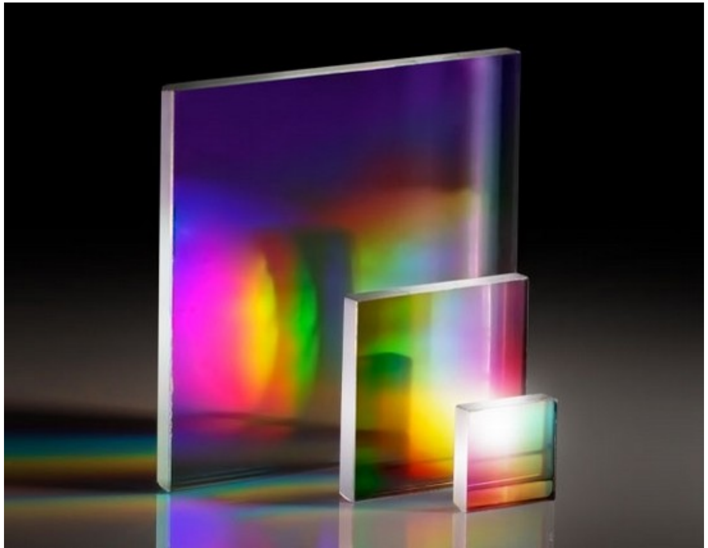
$$R = b \cdot \frac{dn}{d\lambda}$$



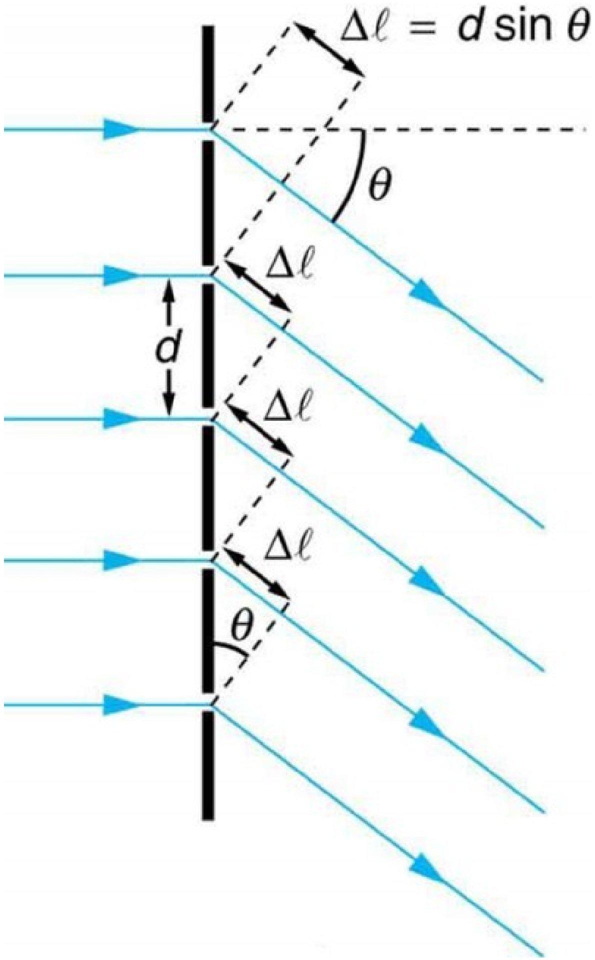
- **Objective prism surveys**
- Prism just in front of the telescope
- Simultaneous spectra for every source in the field
- But with overlap

Diffraction Grating

- Can be of transmission or reflection types
- Can be treated as a series of slits causing constructive and destructive interference
- Constructive interference only happens if the path difference is a multiple of the wavelength
- Grating equation: $m\,\lambda = d \sin\theta$ or $m\,\lambda = d\,(\sin\alpha + \sin\theta)$

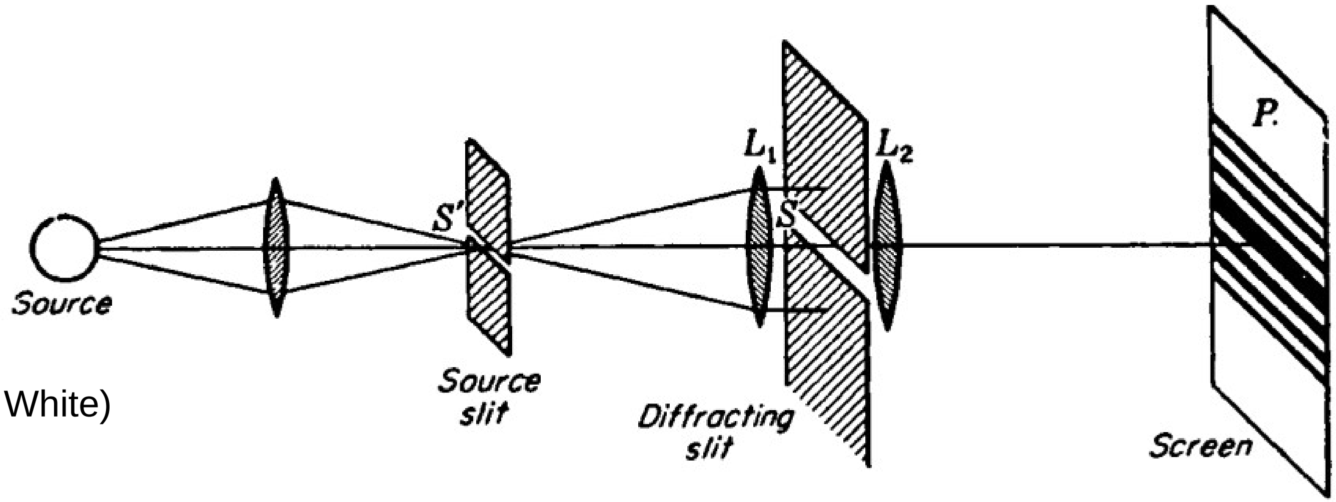


(Credit: Edmund Optics)

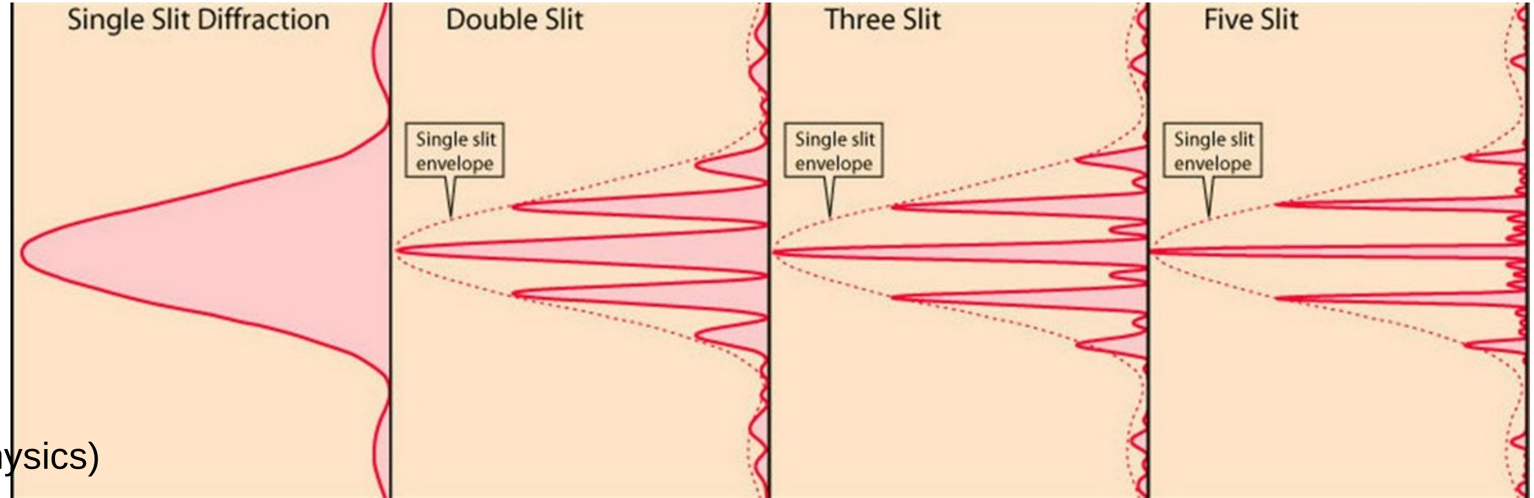


(Credit: Lumen learning)

Diffraction Grating



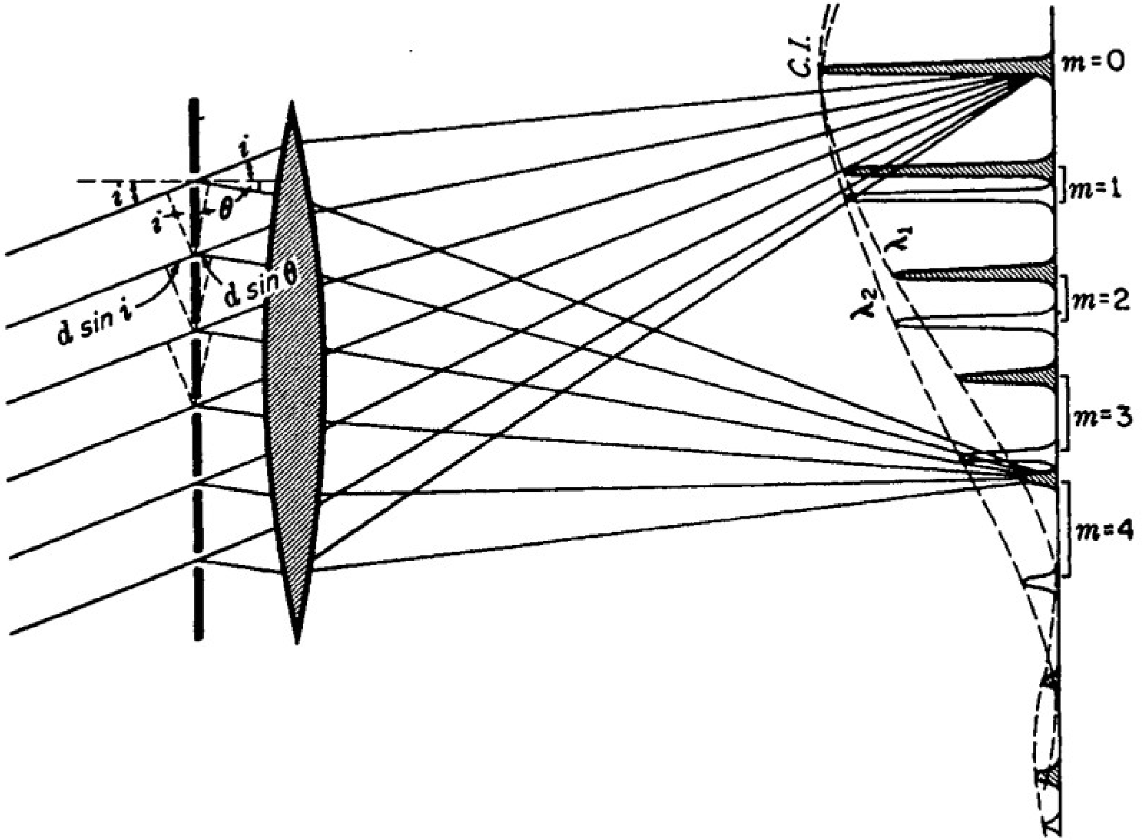
(Credit: Jenkins & White)



(Credit: Hyperphysics)

Diffraction Grating

- All wavelengths have order 0 at the same geometrical position
- Next orders, for two different wavelengths, are shifted from each other
- The higher the order, the more separated the wavelengths
- Eventually, the orders overlap (order blocking filters can be used)
- The single slit envelope that modulates the intensity is the blaze function
- The blaze function peaks at order zero, so a lot of the light is undispersed



(Credit: Jenkins & White)

Diffraction Grating

- Theoretical resolving power of a grating:

  $R = m\,N = m\,\rho\,W$

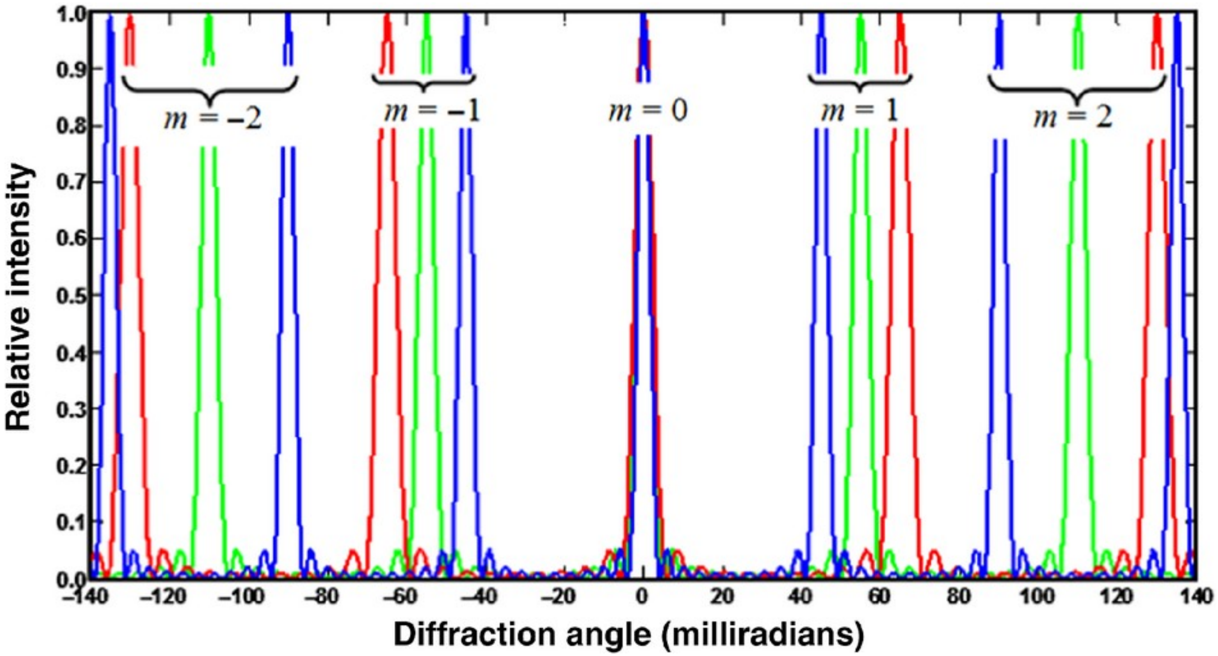
  (the order times the number of grooves; or order times the line density times the size)

- In practice (considering the width of each interference peak and how well one can be separated from the next):

  $R = \lambda\, m\, \rho\, W / s\, D_{tel}$

  (where s is the angular size of the slit and D_{tel} the diameter of the primary)

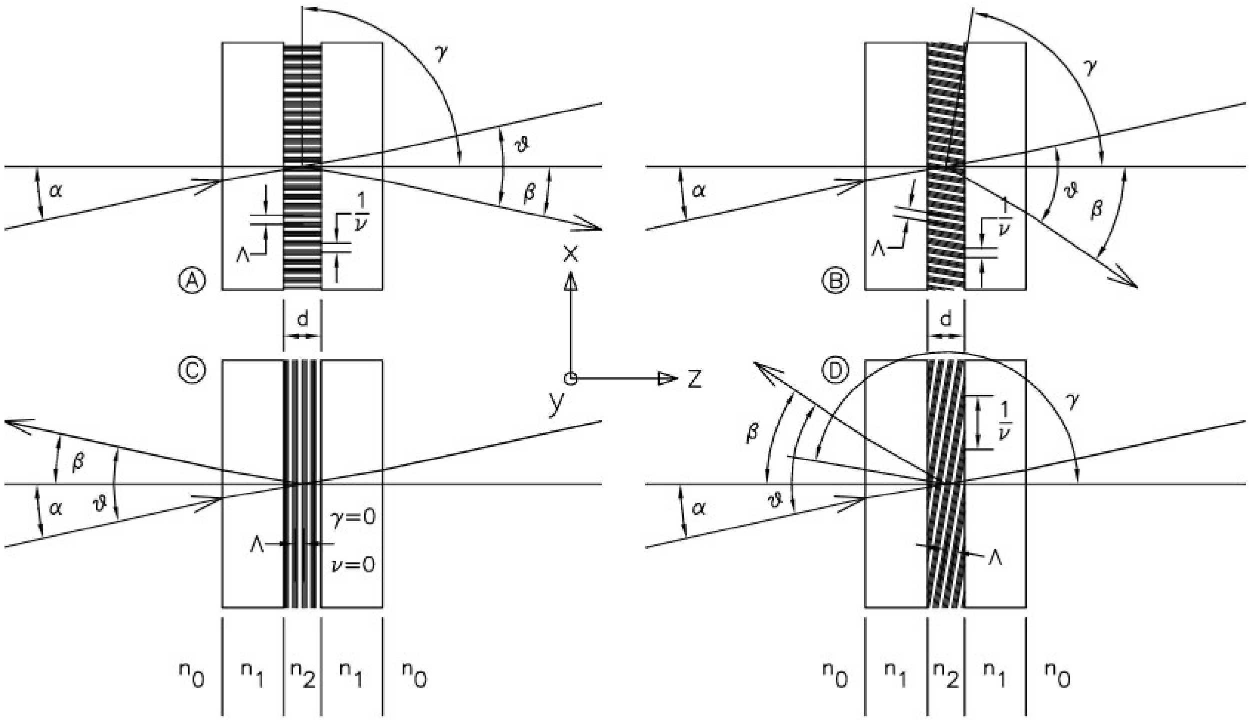
- For a larger telescope, we need larger gratings to get the same resolving power



(Credit: Harvey & Pfisterer 2019)

VPH Grating

- Creating a periodic structure of varying refractive index in a gelatin layer sealed between two optical windows
- Transmission or reflection
- Throughput is high
- Properties (e.g. groove density, bandwidth, polarization sensitivity) can be well adjusted
- Antireflection coatings on the glass layers can be applied
- Long lifetime

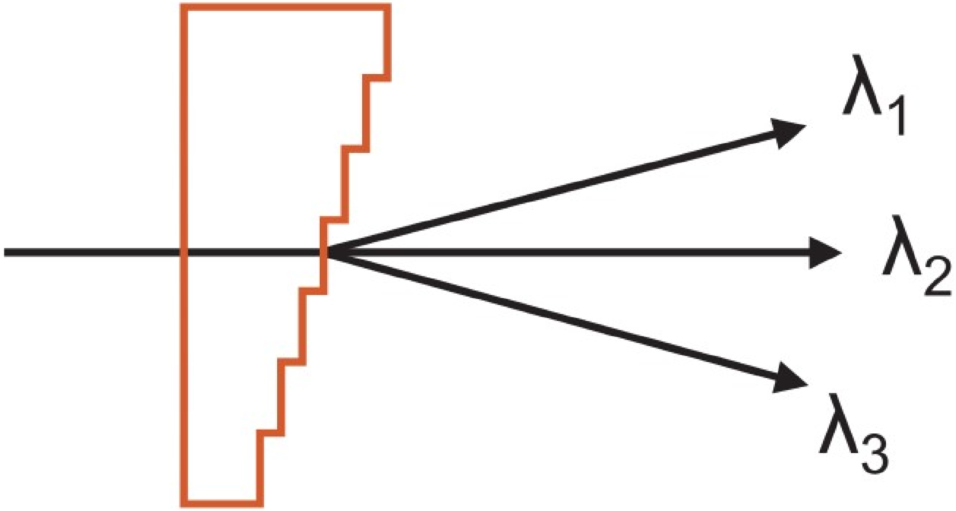


(Credit: Barden et al. 1998)

Grism

- Combination of prism and a grating
- One to compensate the diffraction angle of the other for a given wavelength
- Light can be dispersed but not deflected from the optical path
- The image is replaced by a spectrum
- Multiple grisms can then be exchanged, without affecting the direction of the beam

(Credit: Fraunhofer IAO)



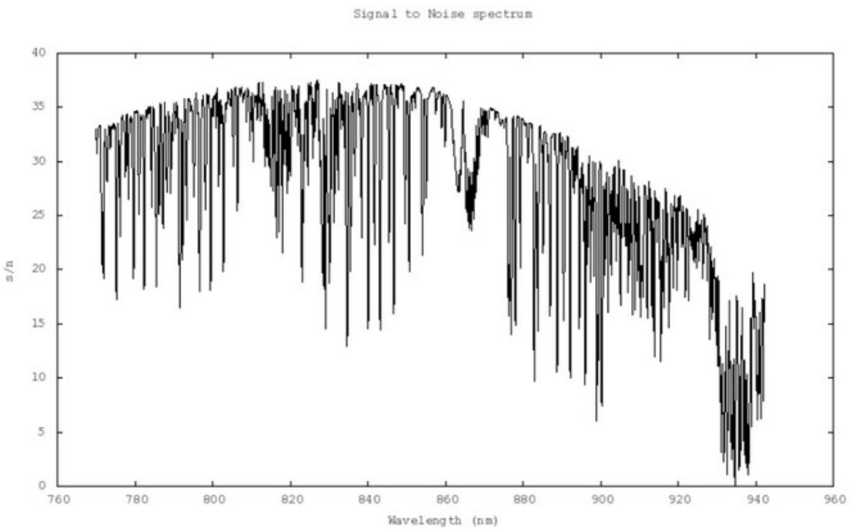
(Credit: Keller et al. 2015)

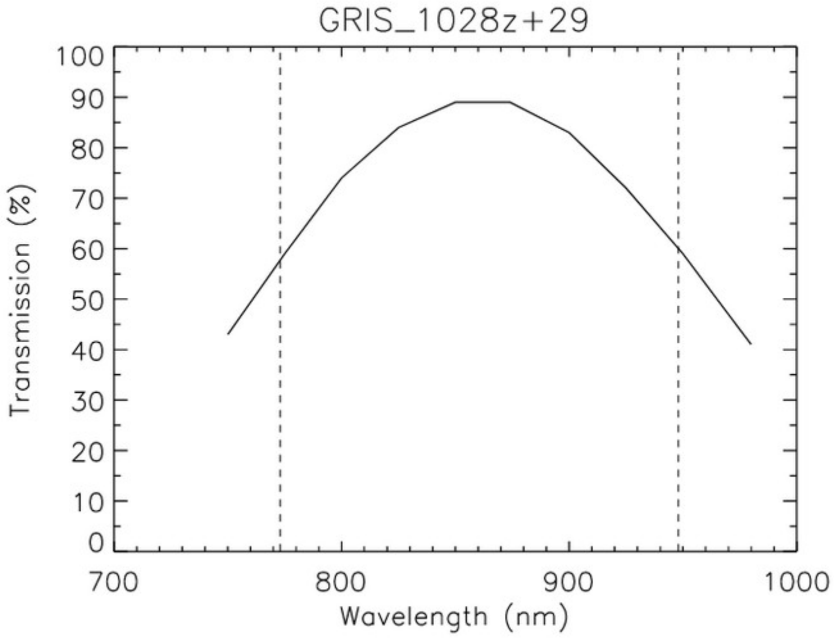
Questions?

(Credit: Shutterstock)

Strategy for our science case

- **If we decided** to use FORS we'd go for MXU mode
- The previous imaging for producing the slit mask
- ~860nm is a good region for metallicity determinatior of late-type stars
- Red CCD + Grism_1028z + narrow slit (0.4")
- Dispersion 0.084nm/px (R ~ 5000, 2px sampling)

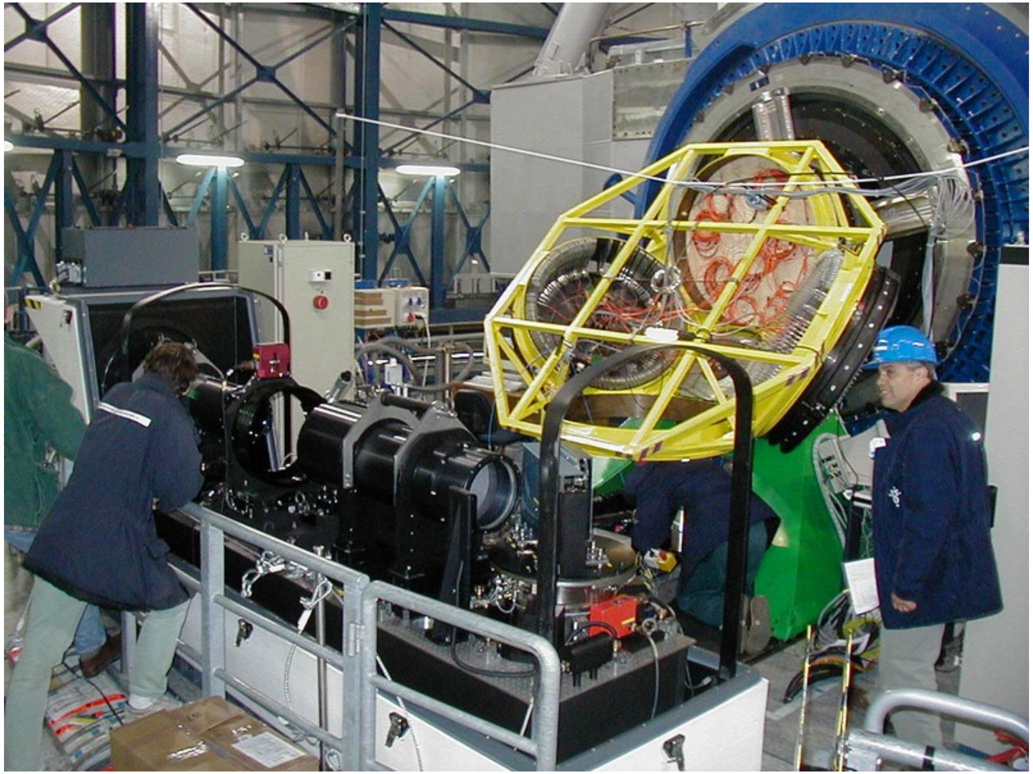




(Credit: ESO/FORS Manual)

FLAMES

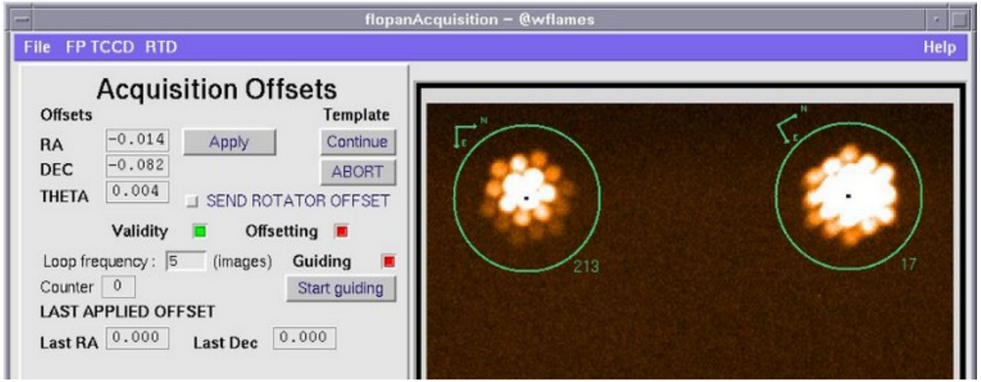
- **F**ibre **L**arge **A**rray **M**ulti **E**lement **S**pectrograph (Pasquini et al. 2002)
- Multi-fiber facility that can feed two spectrographs
- 25 arcmin field
- OzPoz fiber positioner: 2 plates (one observing, one being configured)
- Giraffe:
  - Medusa: 130 fibers, 1.2” on sky, R~5000-28000, 370-950nm
  - IFU mode: 15 units of 20 microlenses with 0.52” (aperture of 2 x 3 arcsecs)
  - ARGUS: 1 large IFU (22x14 microlenses, for 11.5 x 7.3 arcsec, or 6.6 x 4.2 arcsec)
- UVES: 8 fibers, R ~ 40000

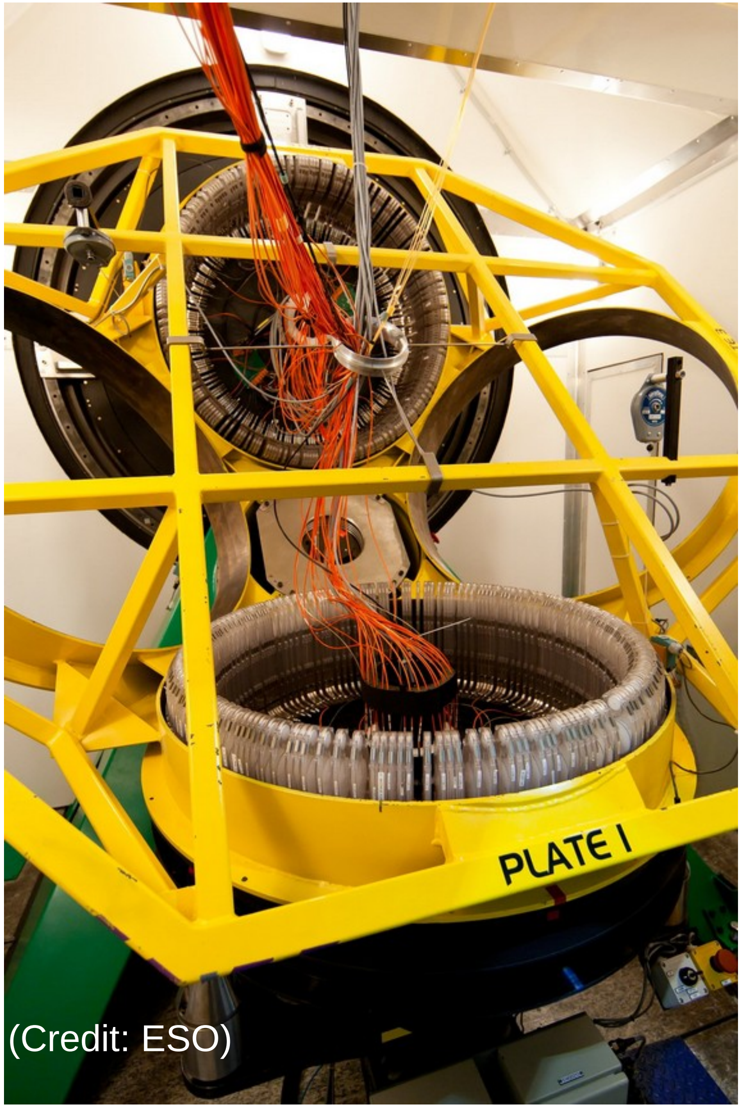


(Credit: ESO)

Oz Poz

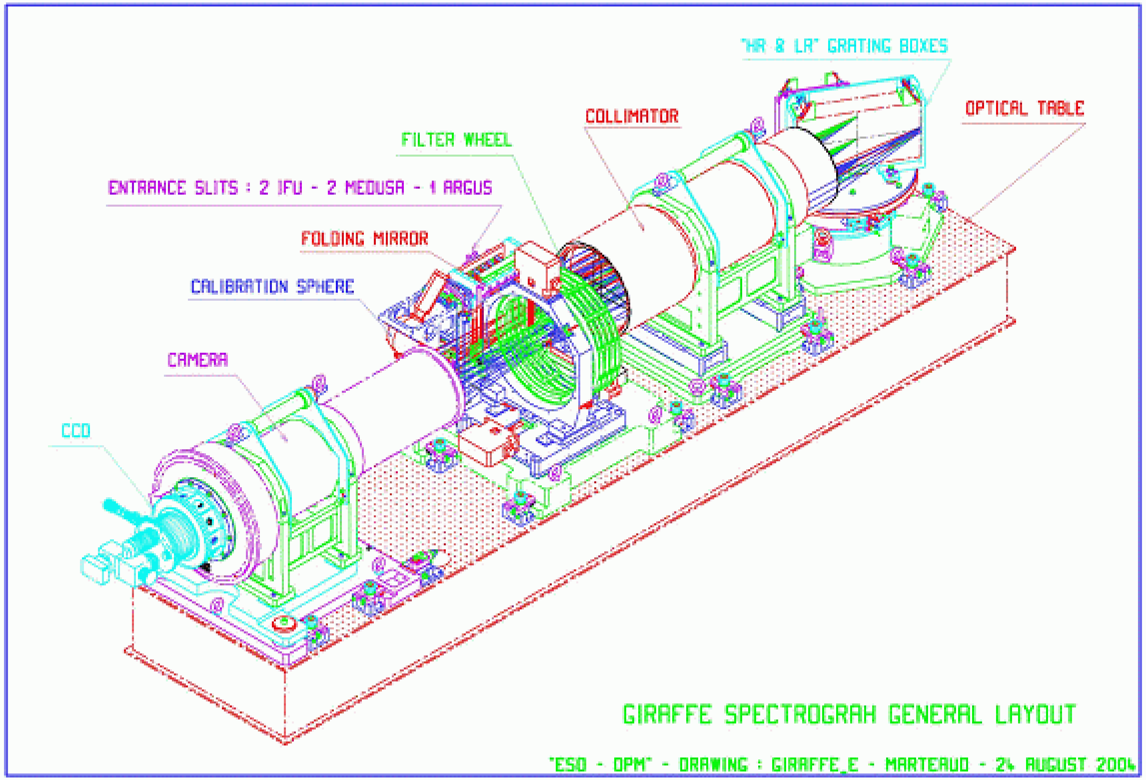
- Two metallic dishes where magnetic buttons with the fibers can be attached
- Positioning accuracy better than 0.08 arcsec
- Good astrometry of the field essential
- Dedicated FPOSS software for positioning
- Minimum separation of 11 arcsec (each button ~10arcsec)
- Exchange of plates in up to 180s
- Field Acquisition Coherent Bundles (FACBs): field orientation



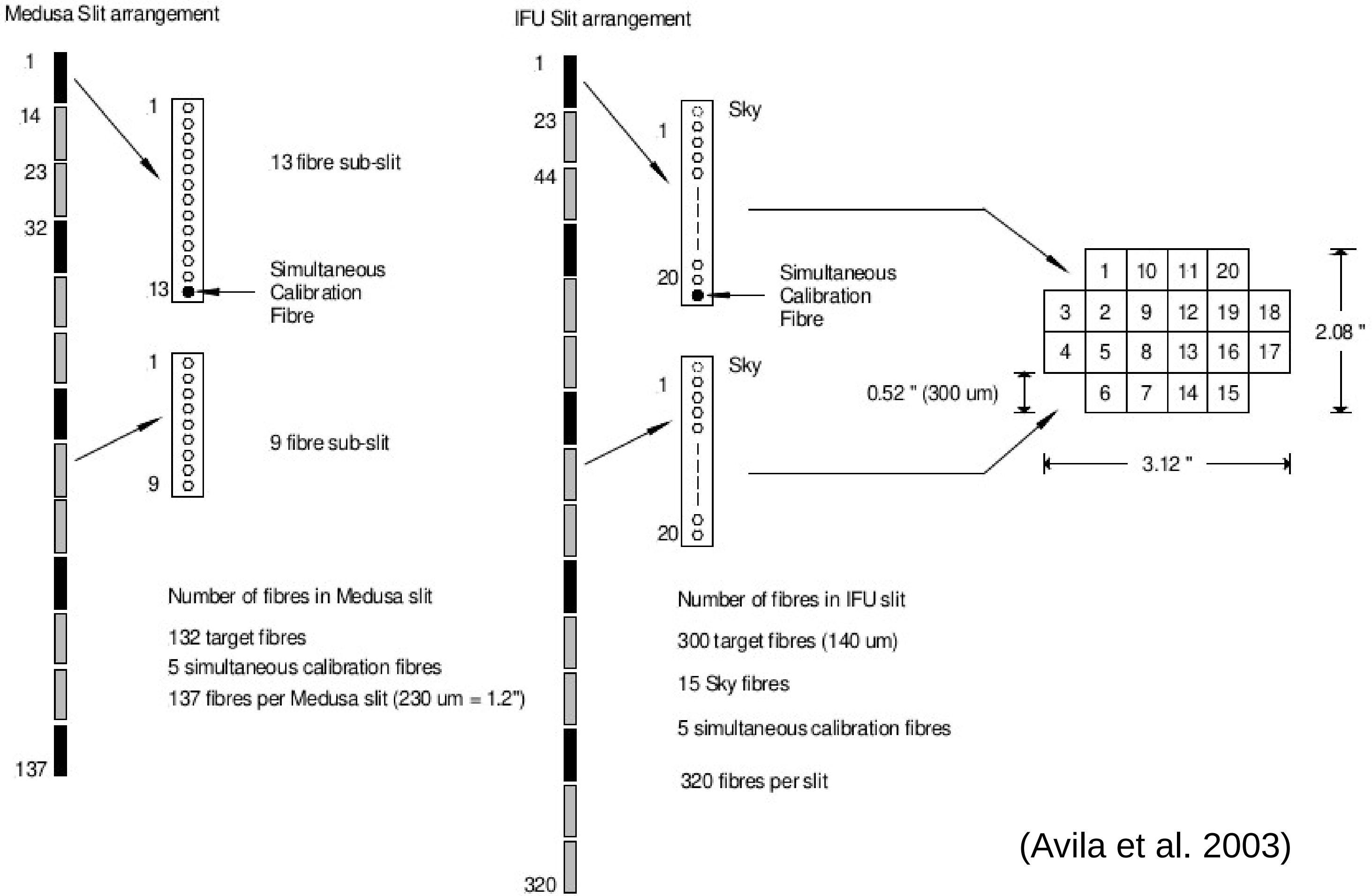


Giraffe

- Giraffe – long neck when standing
- Equipped with two gratings:
  - High-resolution 316 lines/mm, 63.5 blaze echelle grating
  - Low-resolution 600 lines/mm, 34.0 blaze grating
- Gratings can turn for access to different orders (one single order observed at a time)
- Plus, order selection interference filters are needed
- Several pre-defined setups for different spectral regions (with different resolution)
- Simultaneous calibration fibers are available (Th-Ar spectra)

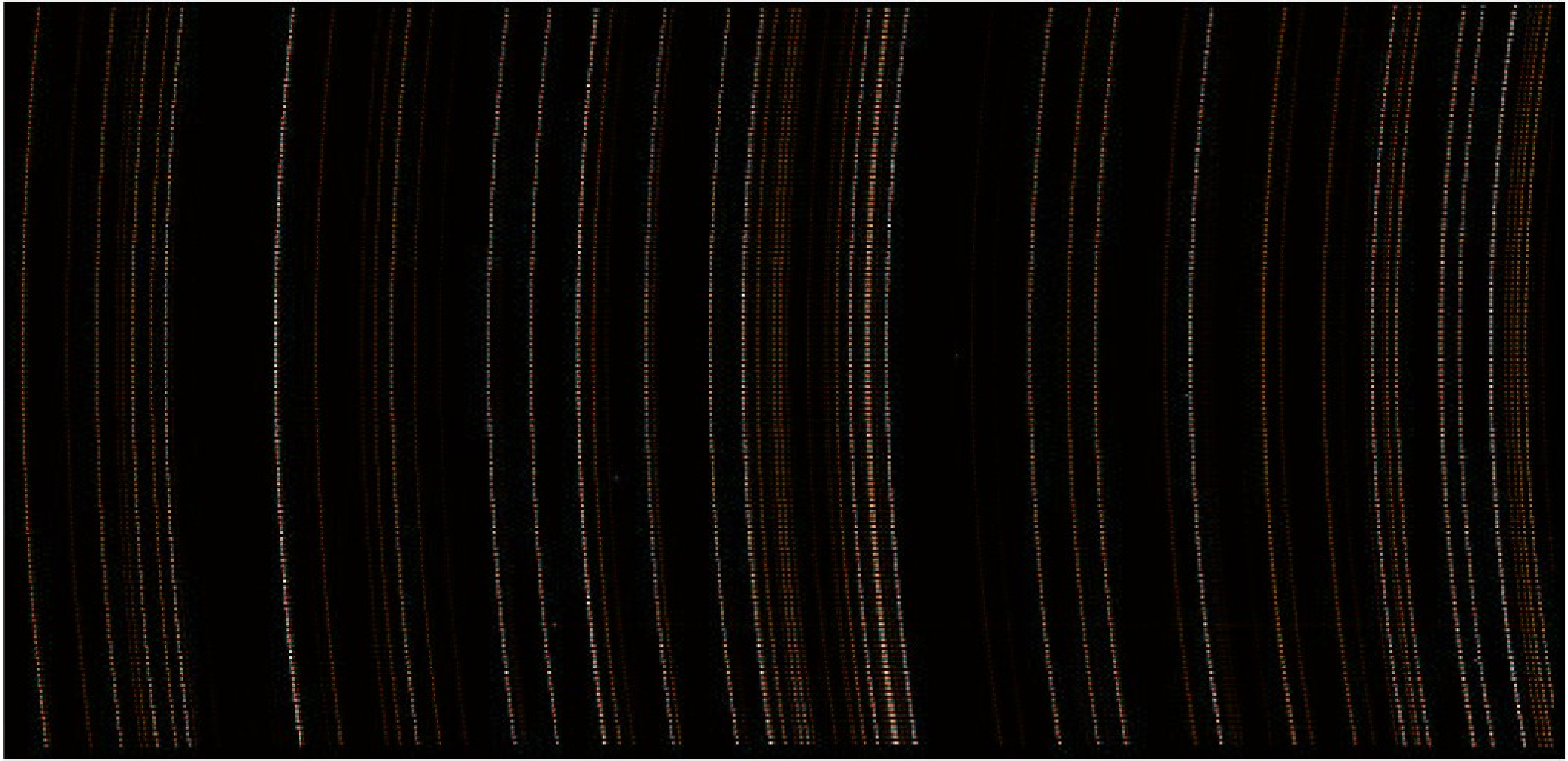


Fiber slit



(Avila et al. 2003)

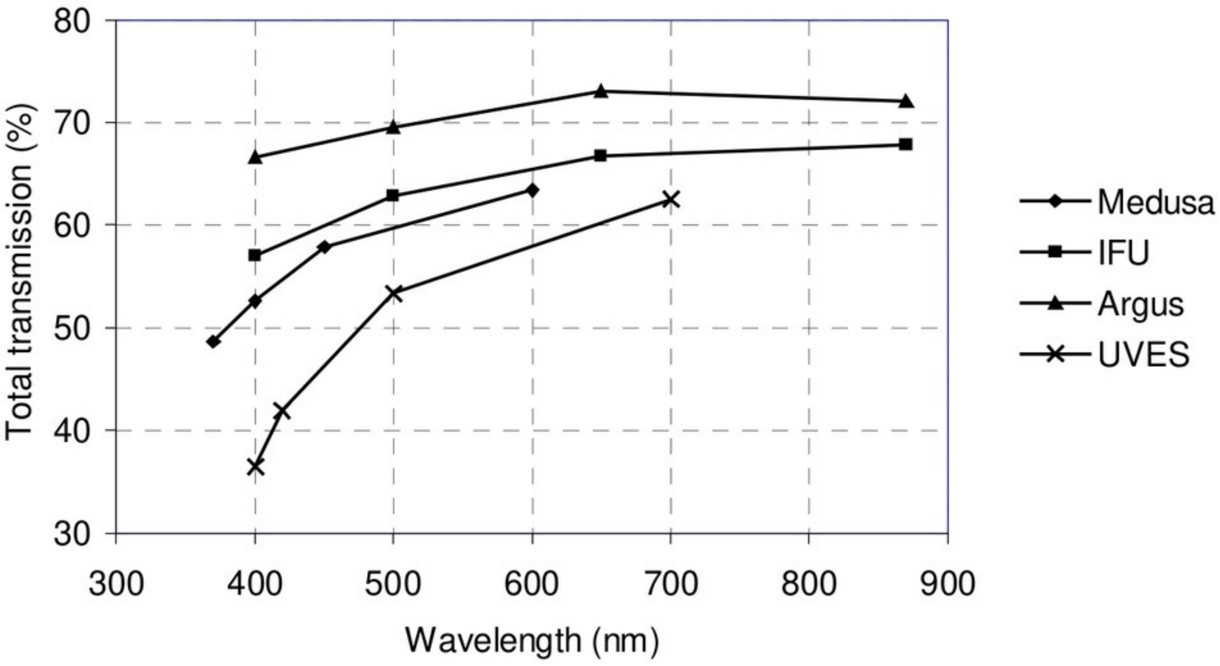
Spectral format



(Giraffe ThAr spectra)

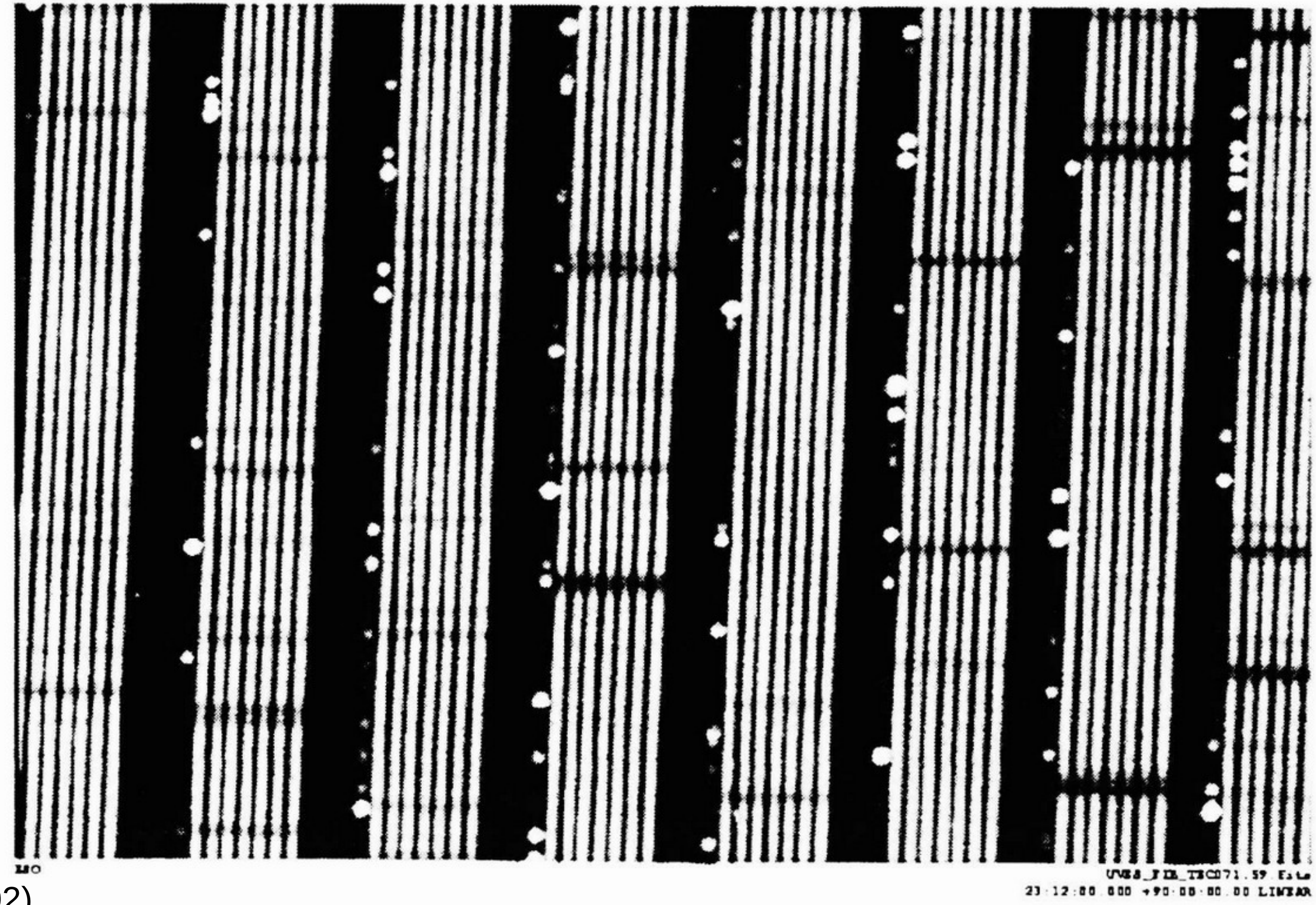
UVES fiber link

- 8 fibers of 55m connect FLAMES to UVES (on the opposite Nasmyt platform)
- + 1 fiber for simultaneous calibration (but only 8 can be used at a time)
- And at least one fiber should monitor the sky
- Fibers of 1 arcsec aperture (R ~ 40000)
- Only UVES red arm available:
  - U520 (414-621 nm)
  - U580 (476-684 nm)
  - U860 (660-1060nm)
- A mosaic of two 4096 ×2048 pixels CCDs
- One order is lost on the gap



(Avila et al. 2003)

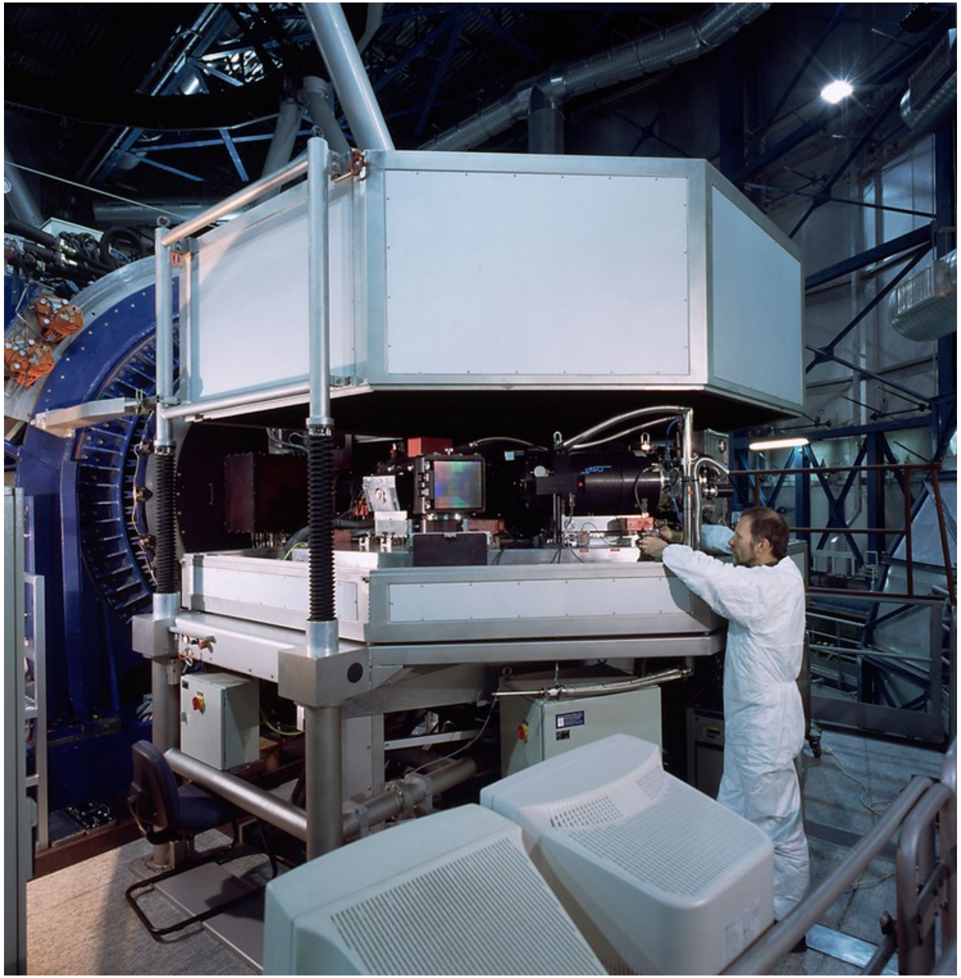
FLAMES UVES spectra



(Pasquini et al. 2002)

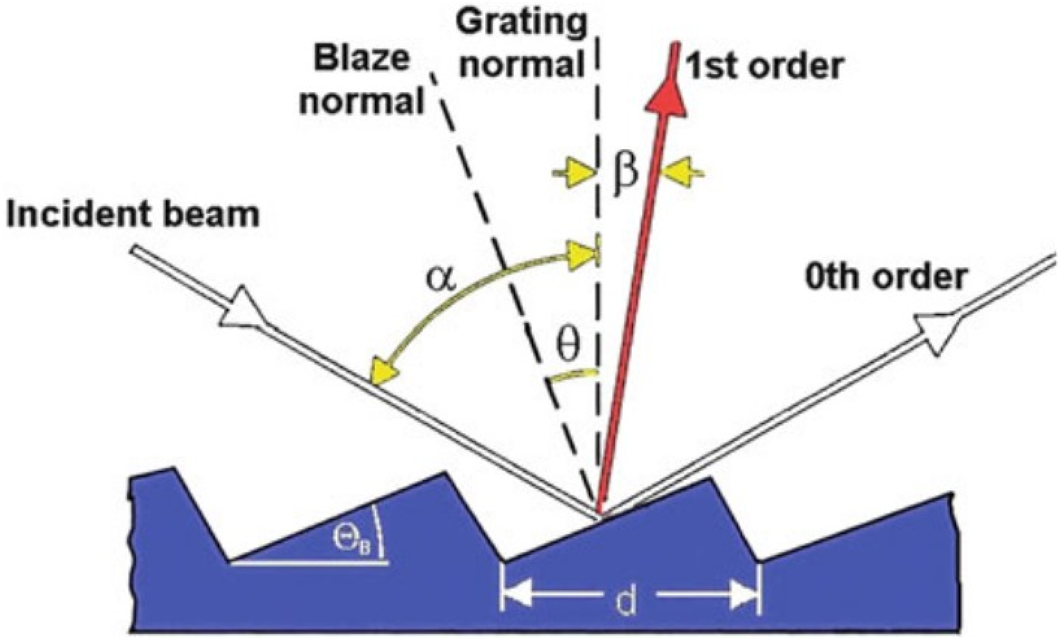
UVES

- **U**ltraviolet and **V**isual **E**chelle **S**pectrograph (Dekker et al. 2000)
- Cross-dispersed echelle (300-1100 nm)
- Beam splitter for two arms: 1) UV-Blue; 2) Visible-Red (can be used in parallel)
- 1 arcsec slit: R ~ 40 000
- Max resolution (adjusting the slit): R ~ 80000 (Blue) and ~110000 (Red)
- Image slicers available to reduce slit losses for very high resolution observations
- Iodine cell: simultaneous calibration for high radial velocity precision
- Stand-alone is a single object spectrograph



Echelle gratings

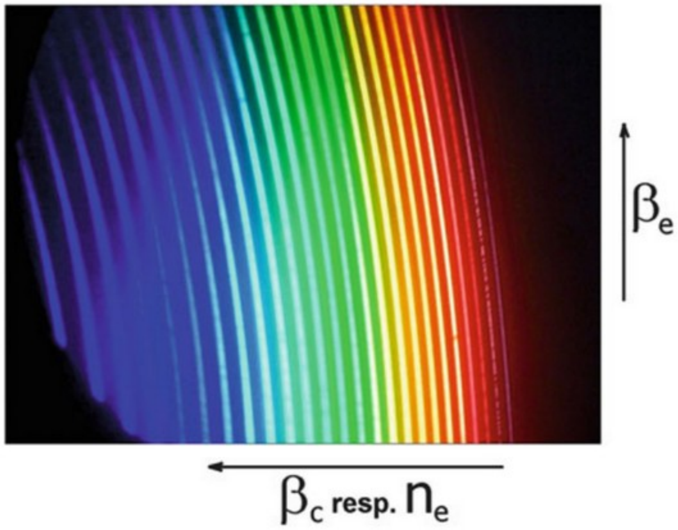
- Introducing an angle to the grooves, the peak of the blaze function can be moved to a higher order
- That's the blaze angle. The grating is blazed.
- Echelle gratings have large blaze angles (60-75 deg)
- Blaze function peaks at high-orders (50-100)
- The orders overlap, although they different wavelength range
- All orders are at the peak of the blaze function
- Cross-disperser needed to separate the orders (perpendicular to the echelle dispersion)

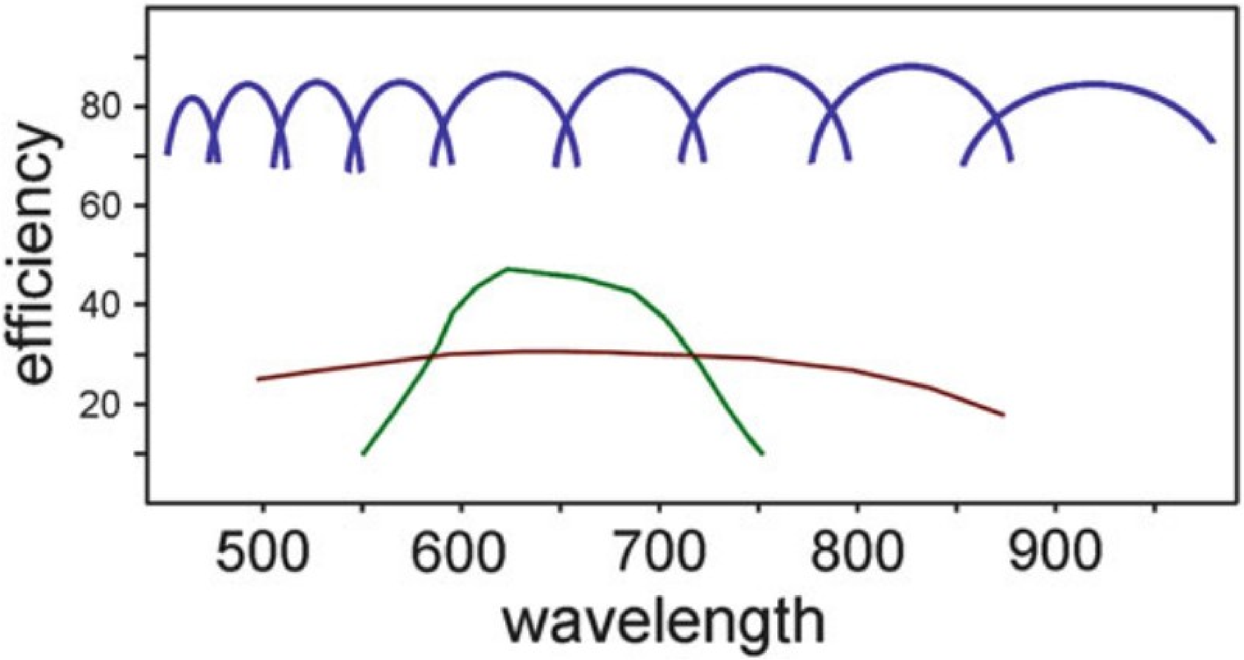


(Eversberg & Vollmann 2015)

Echelle spectra

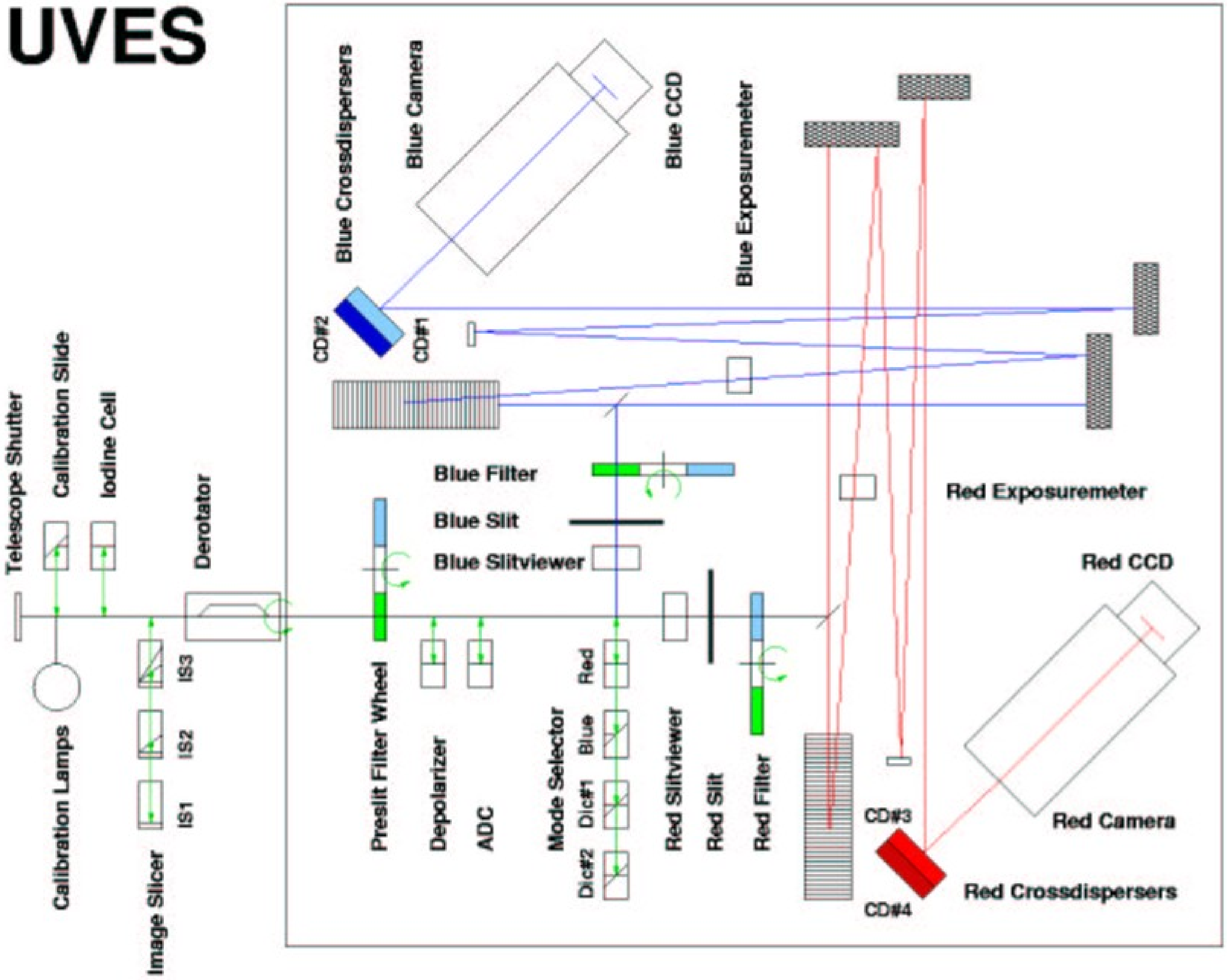
- Achieve very high-resolution with large wavelength coverage
- Blaze function curvature is very steep and hard to correct
- Accurate flux calibration not possible





(Eversberg & Vollmann 2015)

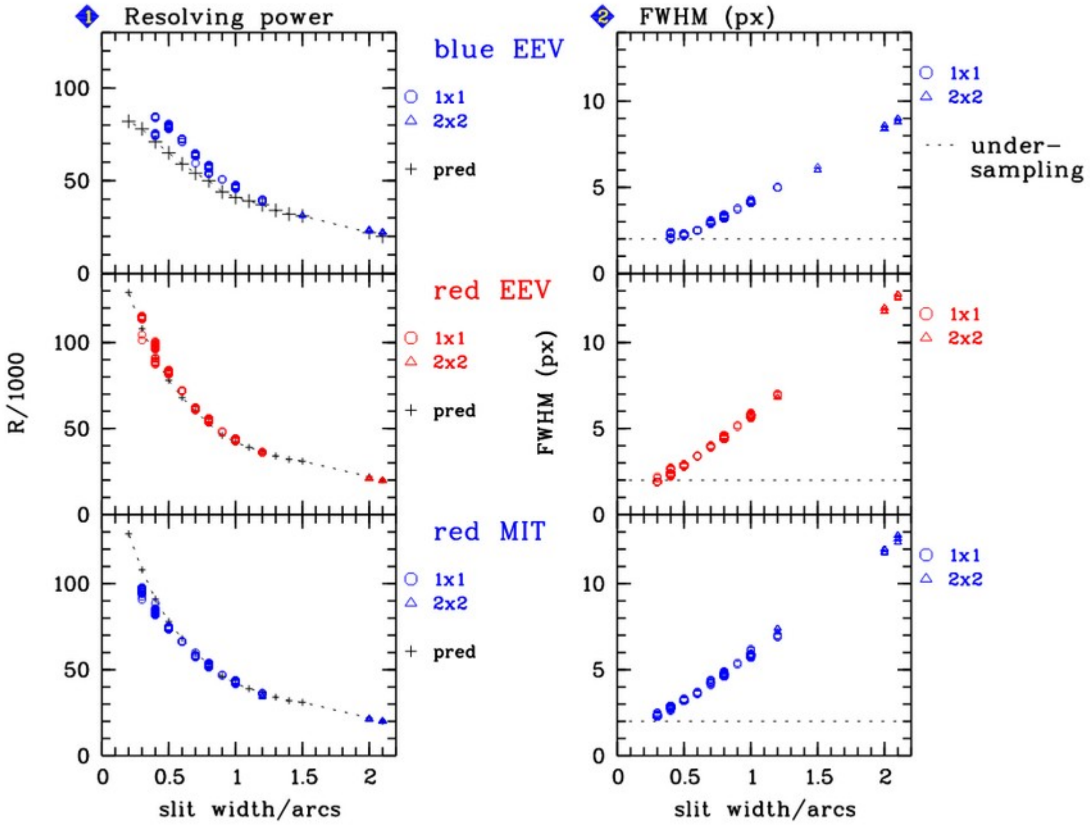
UVES



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

UVES

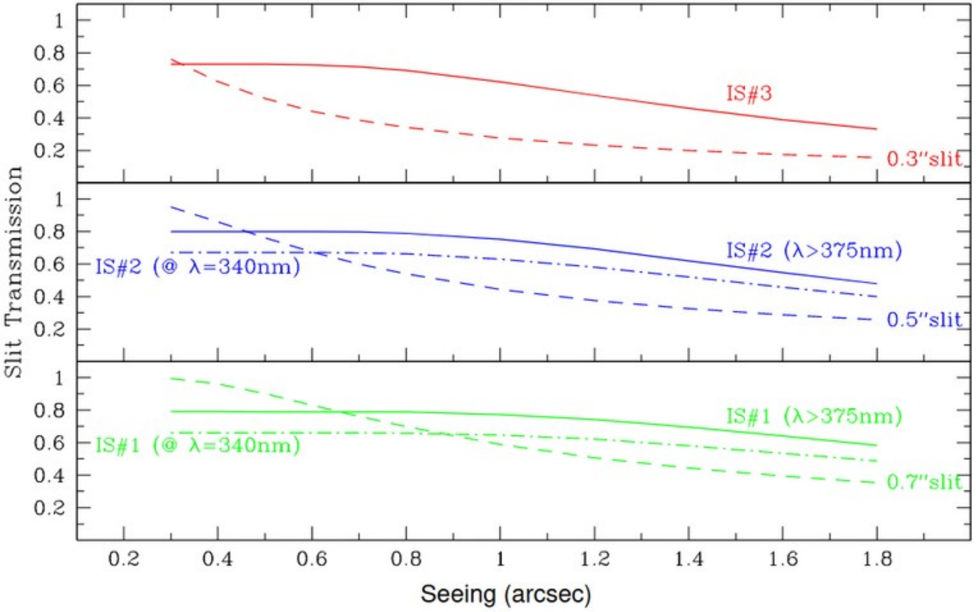
- Beam of 200 mm; echelle gratings of 214 ×840 ×125 mm; blaze angle (76◦).
- Filter wheel: color filters for maintenance and neutral density filters for bright objects
- ADC for zenith distances < 65 deg
- ADC is after the image slicers
- Depolarizer to correct for telescope induced polarization
- Slit viewer: 45” field; acquisition image saved; additional images on request
- Slit width: 0.15” to 20”; height up to 30”
- Interference filters for use with the red arm, for isolating orders with emission lines in extended objects (slit height up to 30”)

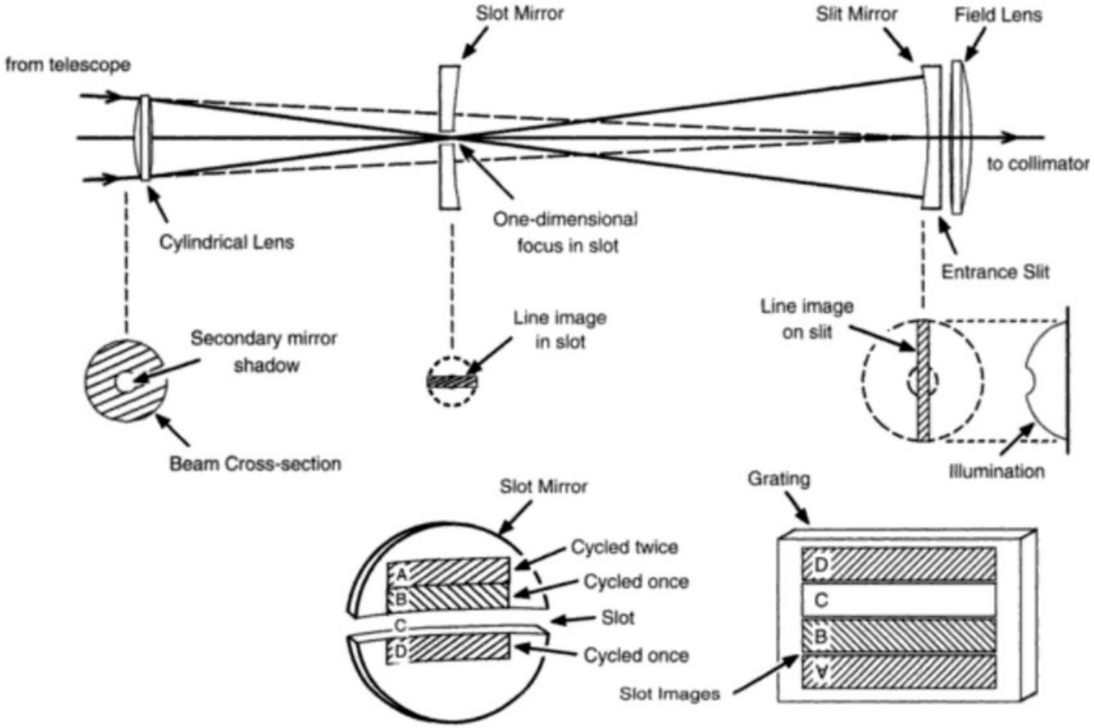


UVES standard settings							
Mode	Cross Disp.	Below slit filter	Min. Wav.	Central Wav. (nm)	Max. Wav.	Decker Height	Gap (nm)
Using dichroic							
DIC1	CD#1	HER_5	303	**346**	388	10.”	=
	CD#3	SHP700	476	**580**	684	12.”	5
DIC1	CD#2	HER_5	326	**390**	454	8.”	=
	CD#3	SHP700	458	**564**	668	11.”	2
DIC1	CD#1	HER_5	303	**346**	388	10.”	=
	CD#3	SHP700	458	**564**	668	11.”	2
DIC1	CD#2	HER_5	326	**390**	454	8.”	=
	CD#3	SHP700	476	**580**	684	12.”	5
DIC2	CD#1	HER_5	303	**346**	388	10.”	=
	CD#4	BK7_5	565	**760**	946	8.”	7
DIC2	CD#2	HER_5	326	**390**	454	8.”	=
	CD#4	BK7_5	565	**760**	946	8.”	7
DIC2	CD#2	HER_5	373	**437**	499	10.”	=
	CD#4	BK7_5	565	**760**	946	8.”	7
DIC2	CD#2	HER_5	373	**437**	499	10.”	=
	CD#4	OG590	660	**860**	1060	12.”	10
DIC2	CD#1	HER_5	303	**346**	388	10.”	=
	CD#4	OG590	660	**860**	1060	12.”	10
DIC2	CD#2	HER_5	326	**390**	454	8.”	=
	CD#4	OG590	660	**860**	1060	12.”	10
Using blue arm only							
BLUE	CD#1	HER_5	303	**346**	388	10.”	=
BLUE	CD#2	HER_5	373	**437**	499	10.”	=
Using red arm only							
RED	CD#3	SHP700	414	**520**	621	8.9”	1
RED	CD#3	SHP700	476	**580**	684	12.”	5
RED	CD#3	SHP700	500	**600**	705	12.”	5
RED	CD#4	OG590	660	**860**	1060	12.”	10

Image slicers

- Clever way to use the resolution of narrow slits without slit losses
- A series of mirrors that slice the seeing disk and rearrange on the slit
- UVES has 3 options of slicers (affected by atmospheric dispersion)

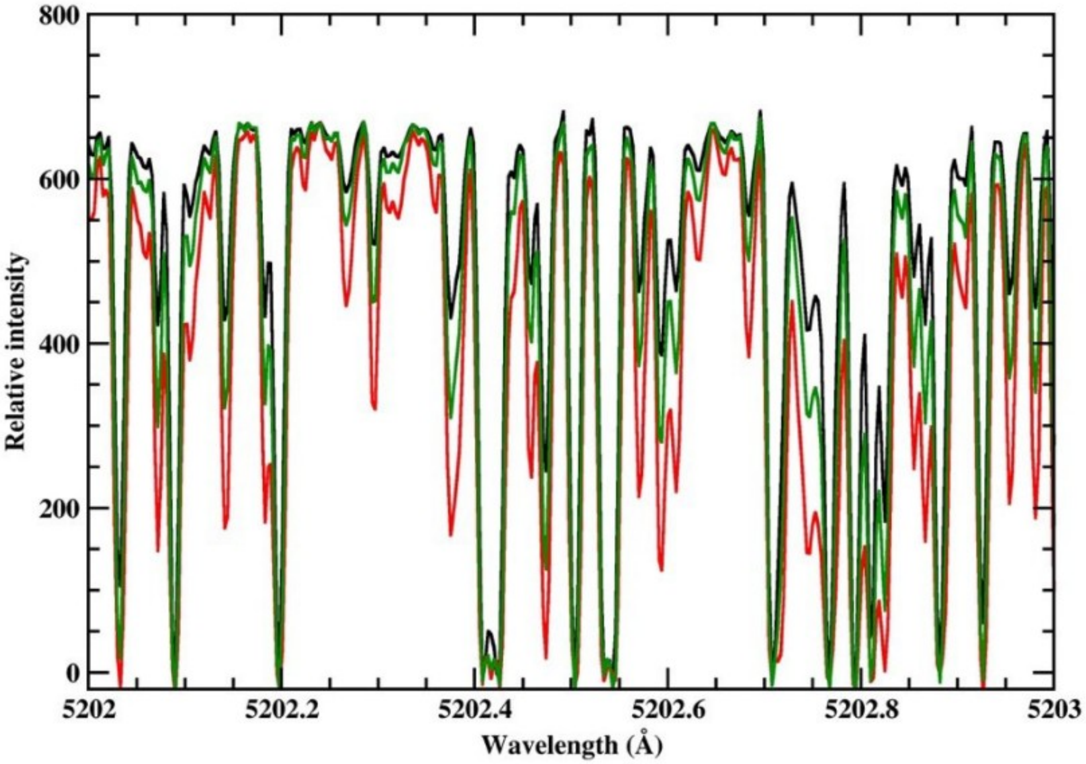




(Gray 2005)

Iodine cell

- A glass cell filled with heated I_2 gas
- Produce molecular absorption spectrum, containing many lines, on top of the observed spectrum
- Very accurate wavelength calibration in between 500-600 nm.
- RV calibration
- Red arm U600 (500-705 nm)
- Slit 0.3” for best accuracy
- Needs 1h of warming time

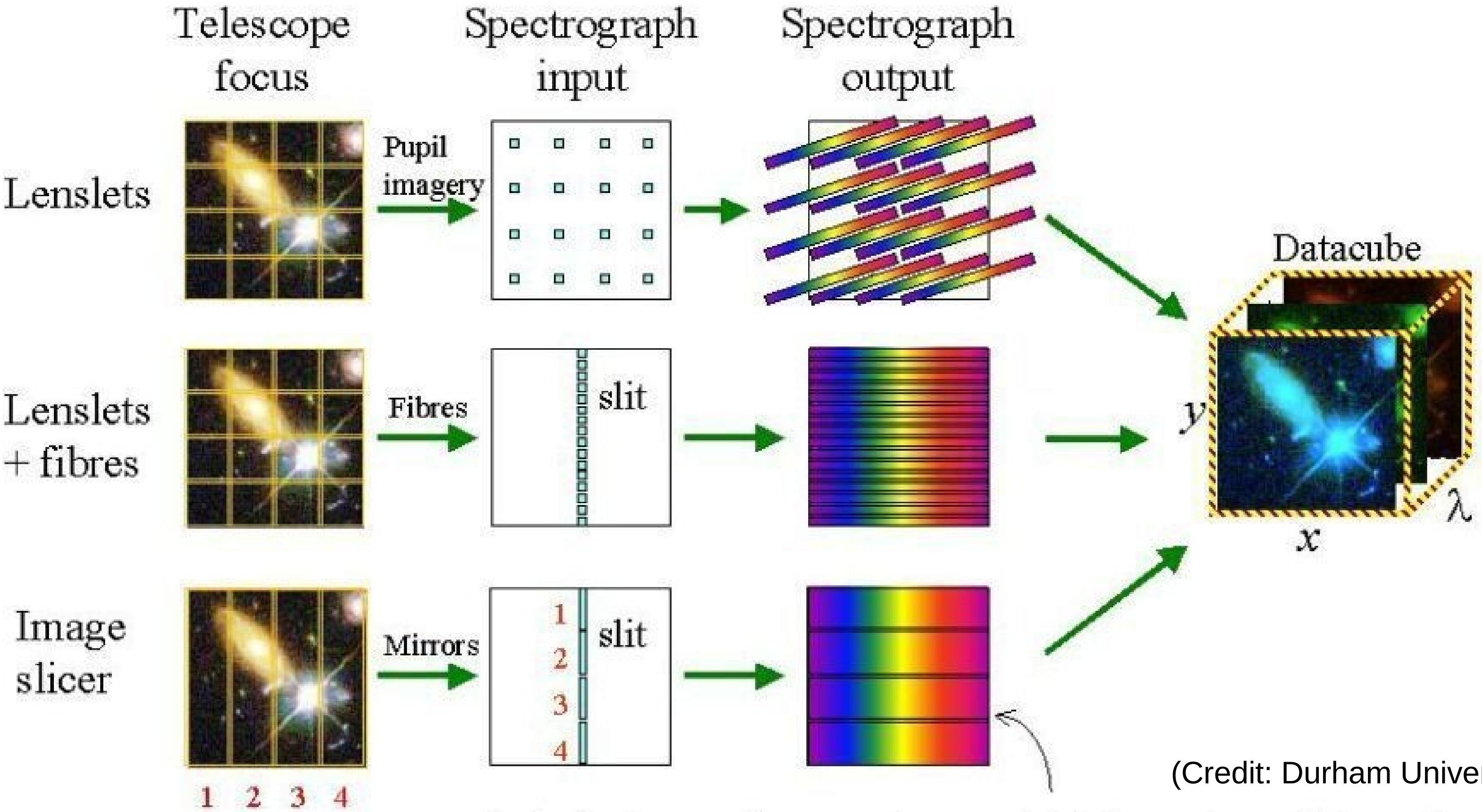


(Crause 2018)

Questions?

(Credit: Shutterstock)

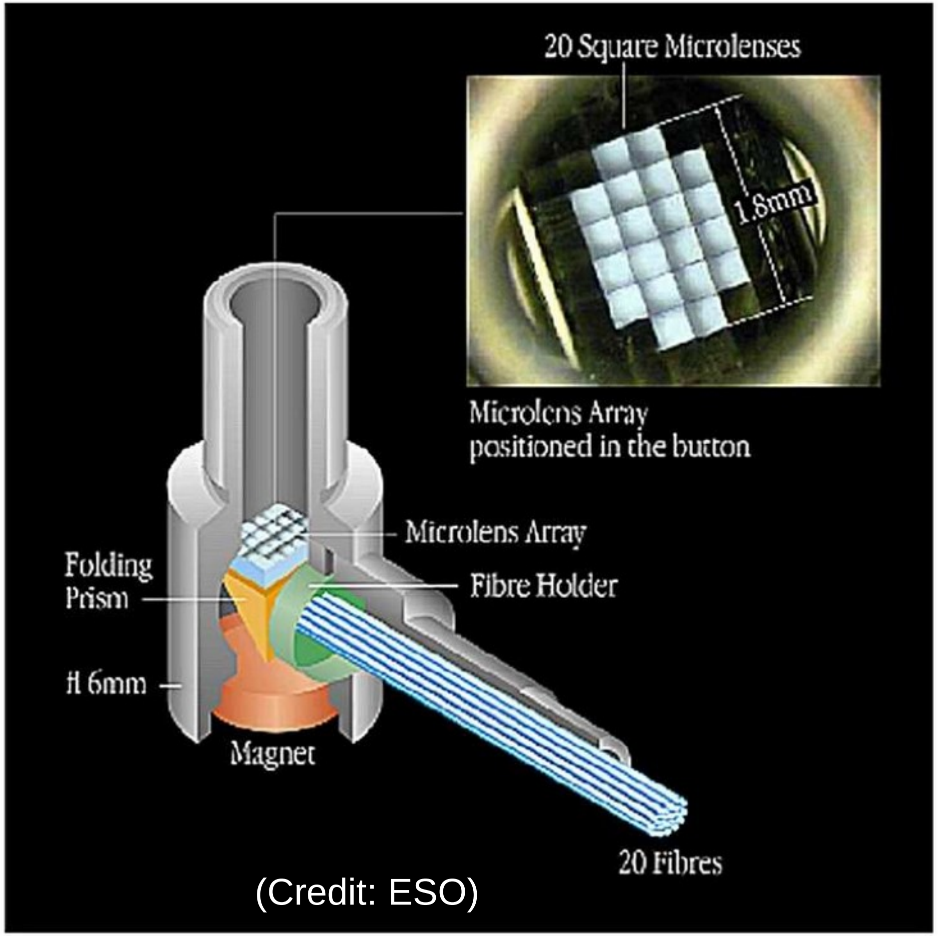
Back to FLAMES capabilities: Integral Field Spectroscopy



(Credit: Durham University)

FLAMES IFU Mode

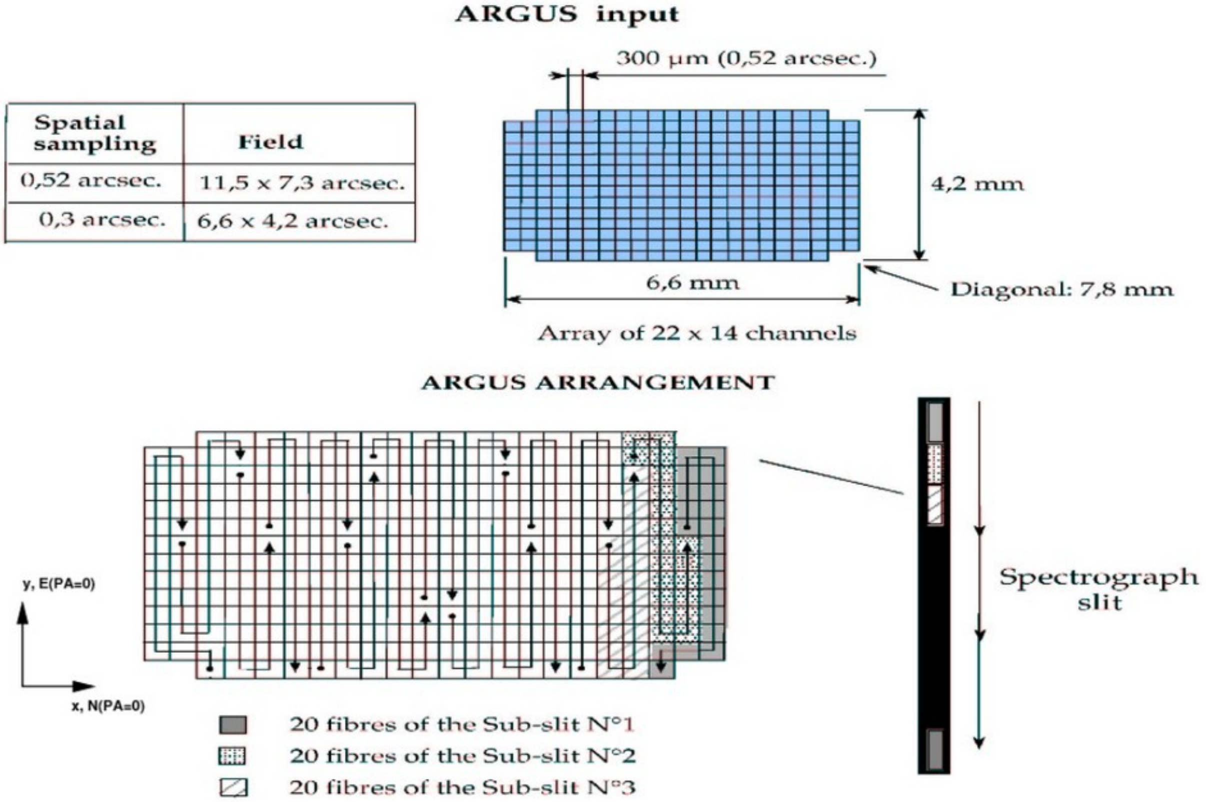
- 15 IFU units for objects + 15 units for sky (per OzPoz plate)
- 20 square microlenses of 0.52 arcsec side each (almost ∼ 3 ×2 arcsec).
- Sky units only have the central fiber
- Resolving power: 20k to 65k (because of the smaller apertures)
- UVES fibers can also be used when Giraffe is fed by the IFUs (and by ARGUS)



(Credit: ESO)

FLAMES Argus Mode

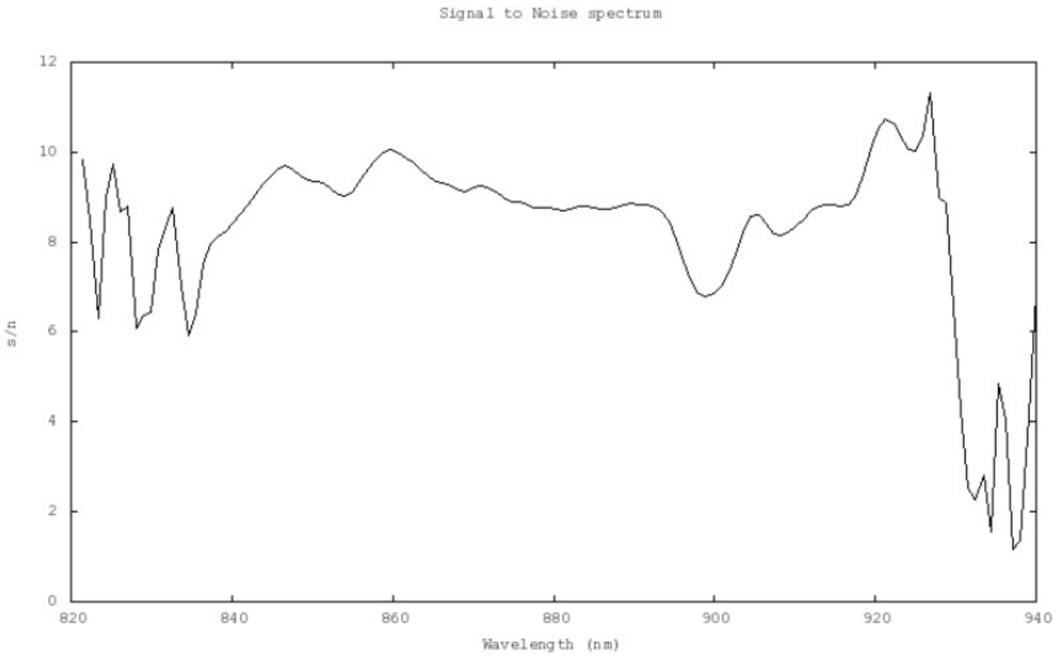
- 1 large IFU unit called Argus
- 15 single sky fibres available
- 22 by 14 microlenses. Fixed at the center of positioner plate 2.
- Operates in two scales:
  - Sampling of 0.52 arcsec/microlens (total ∼12” by 7”)
  - Sampling of 0.3 arcsec/microlens (total 6.6” by 4.2”).
- Bluer settings not possible with ARGUS (low transmission of light from the flat field lamps) – LR1 setting in visitor mode



Strategy for our science case

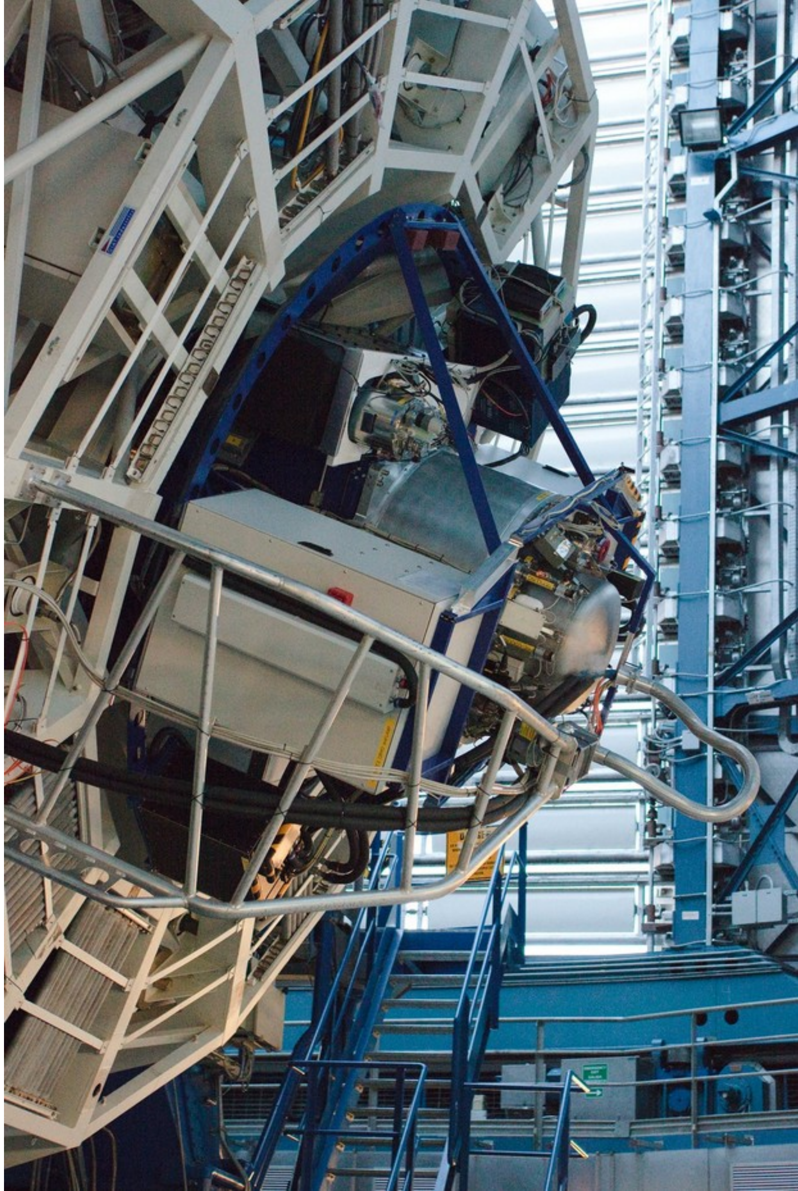
- **If we decided** to use FLAMES we'd go for Giraffe Medusa mode
- Our field is smaller (9 arcmin) than FLAMES field (25 arcmin)
- Minimum separation of fibers and target density should still be ok
- High-resolution of UVES or IFU/Argus not needed
- LR08: 820-940nm with R ~ 6500
- HR21: 848-900nm with R ~ 18000

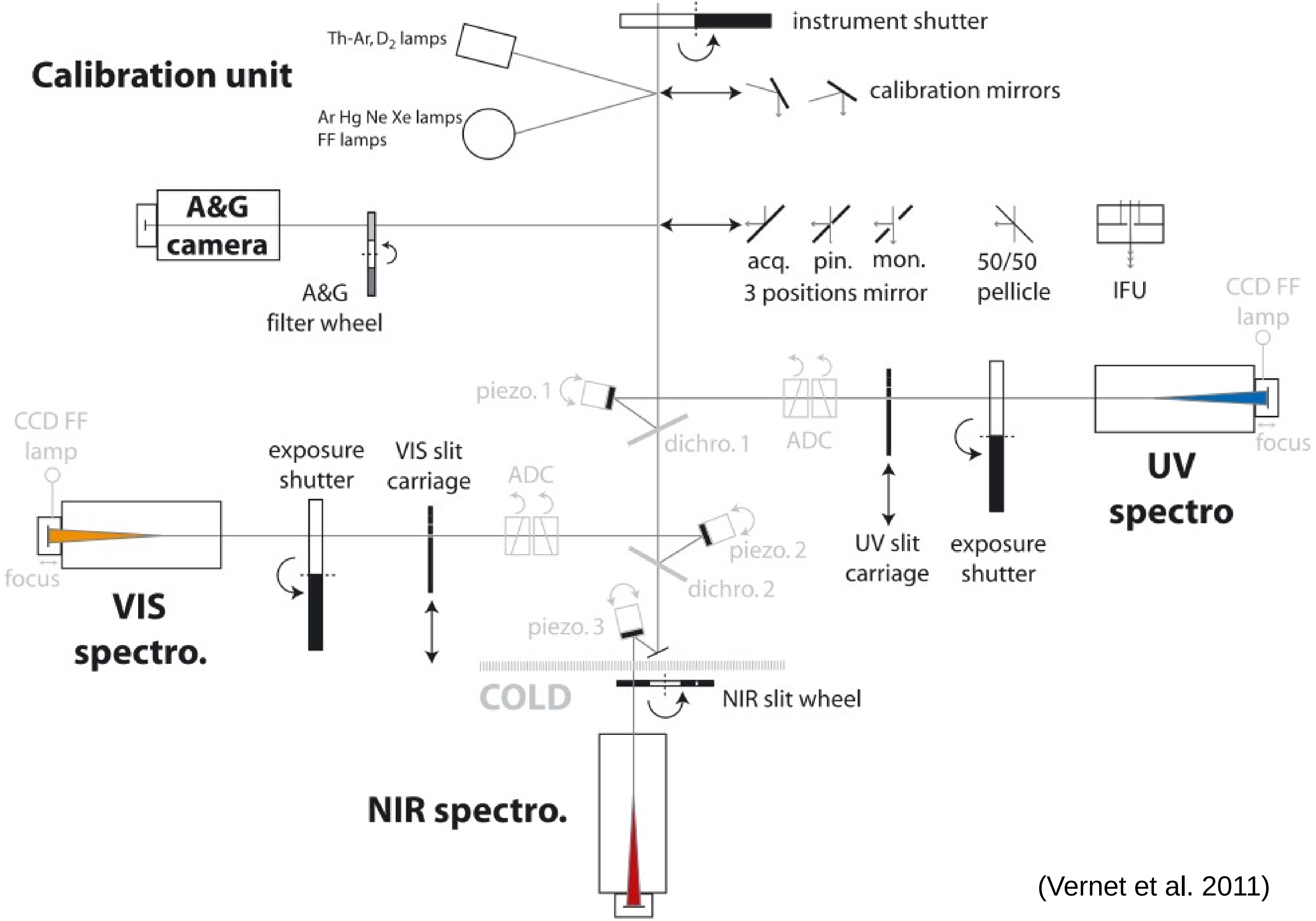
(FORS2 gave SNR~30-35 in the same region with similar resolution to LR08)



X-Shooter

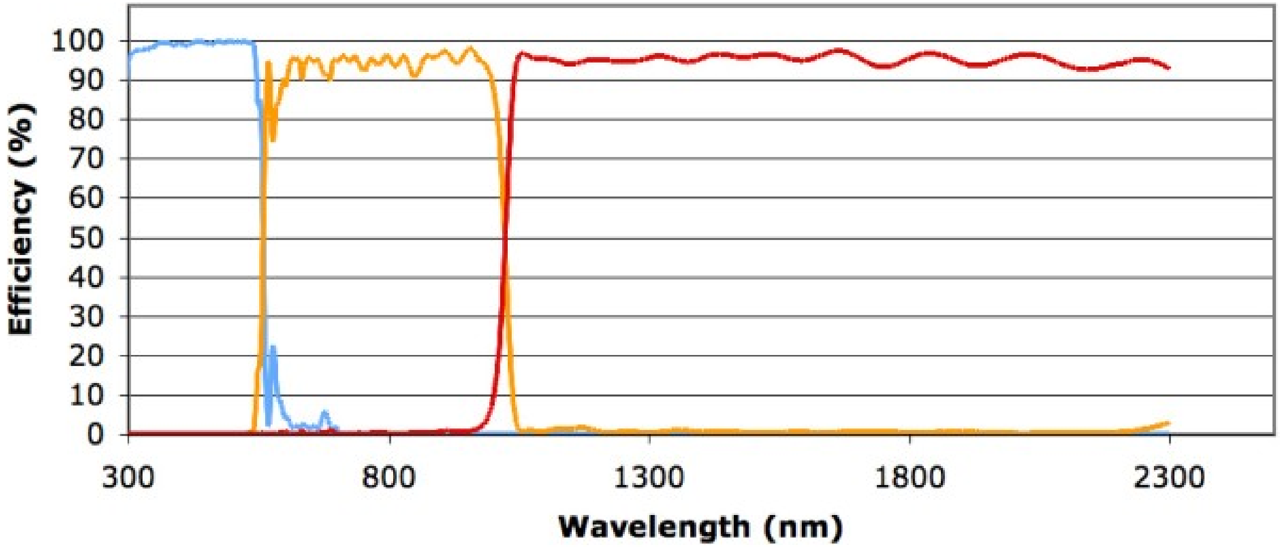
- **X-Shooter** (Vernet et al. 2011)
- Medium-resolution, multi-wavelength, single object, Cassegrain spectrograph
  - UVB arm (300-559.5 nm)
  - VIS arm (559.5-1024 nm)
  - NIR arm (1024-2480 nm)
- Three independent echelle spectrographs
- Each with a slit mask (series of fixed widths ~0.4” to 5” with 11” length)
- ADC for UVB and VIS arms
- Image slicer for IFU spectroscopy: 1.8''x4'' FoV.



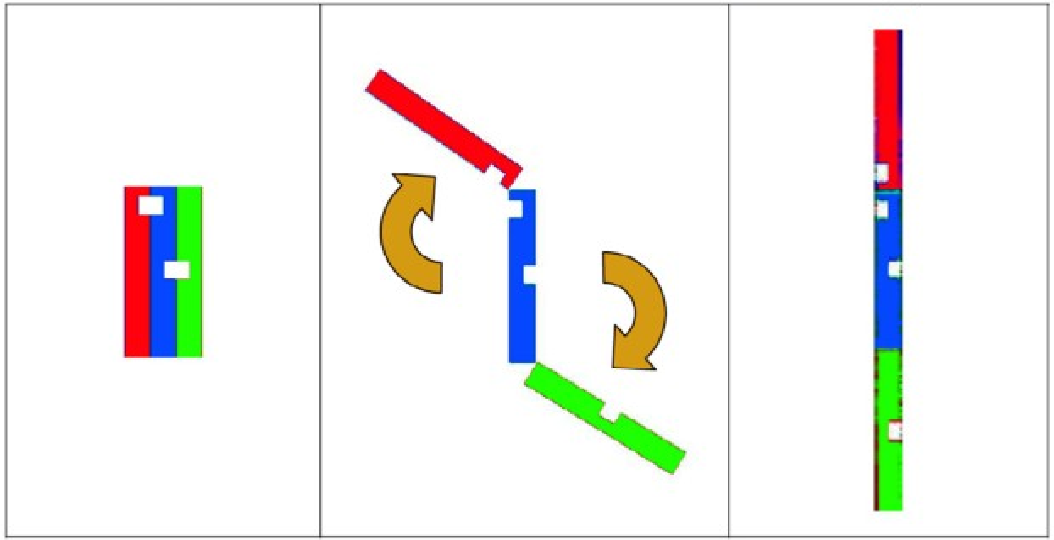


(Vernet et al. 2011)

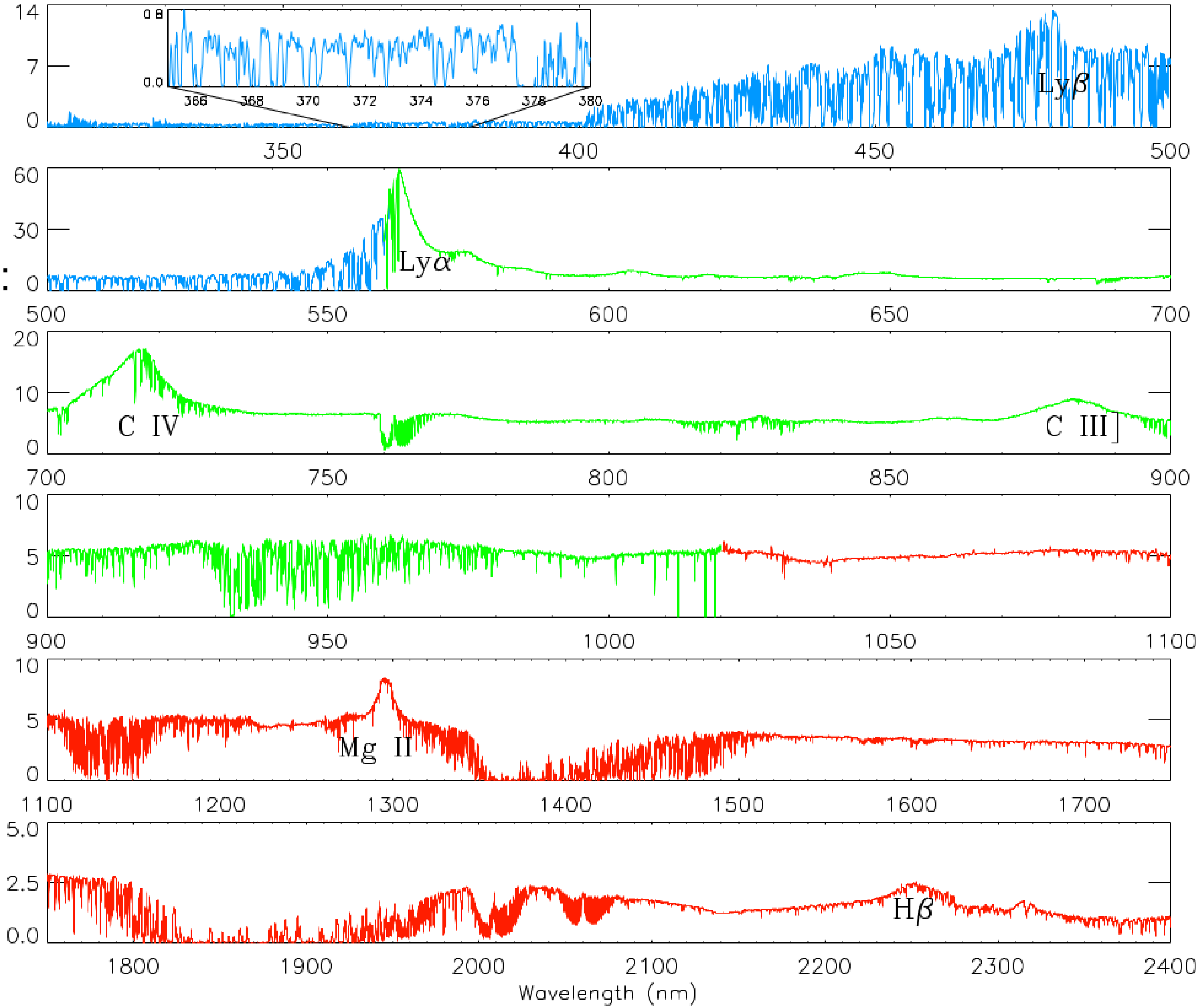
Dichroic efficiency:



Slicer geometry:

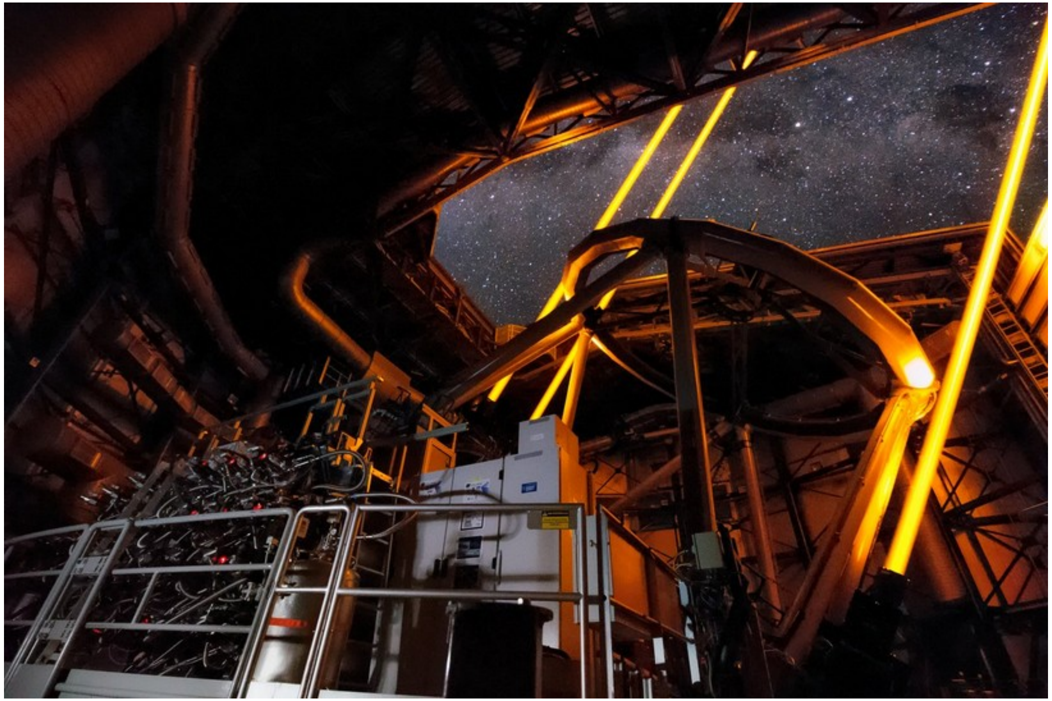


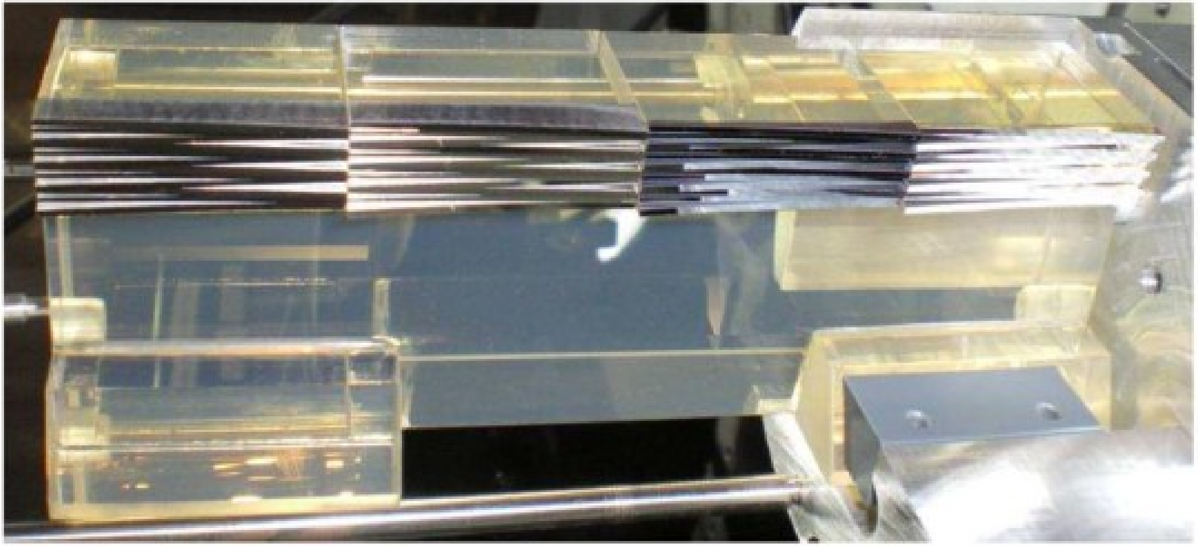
QSO spectrum:

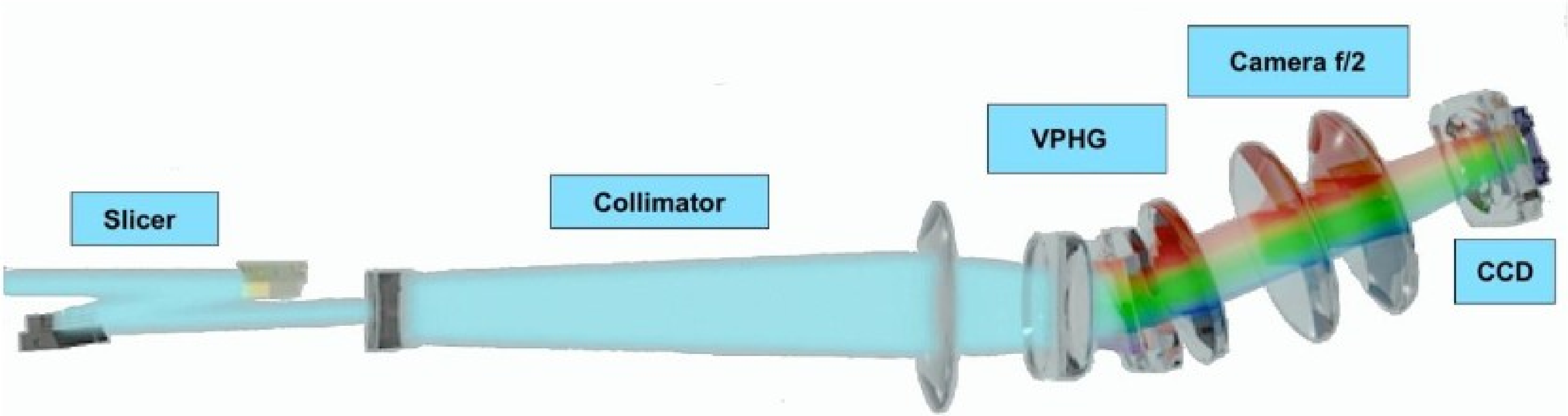


MUSE

- **M**ulti-**U**nit **S**pectroscopic **E**xplorer (Bacon et al. 2010)
- 24 IFU units with 48 slices each (1152 slitlets). Each unit with one spectrograph.
  - **Wide Field Mode (WFM)**: 59.9” by 60” FoV; each slitlet with 15"x0.2". Spatial resolution (FWHM) 0.3"- 0.4"
  - Narrow Field Mode (NFM): 7.42” by 7.43” FoV; each slitlet with 1.9"x0.02". Spatial resolution (FWHM) 0.025”
- Wavelength range: 480-930 nm (nominal); 465-930 nm (extended, in WFM with second order contamination > 900nm)
- Resolution:
  - 1770 (480 nm) – 3590 (930 nm) (WFM)
  - 1740 (480 nm) – 3450 (930 nm) (NFM)






Camera f/2
VPHG
Collimator
Slicer
CCD

2.1.2.5 Spectral format

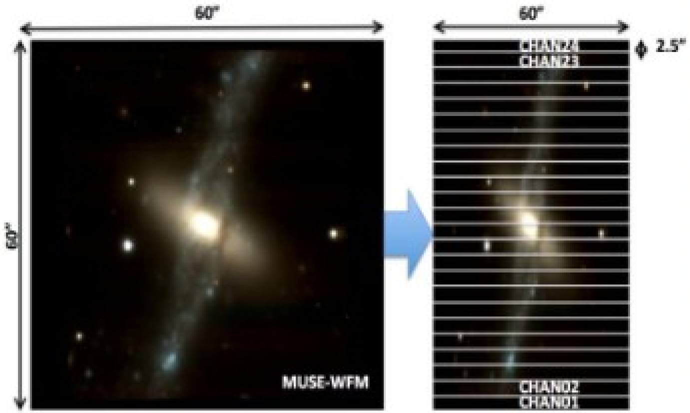
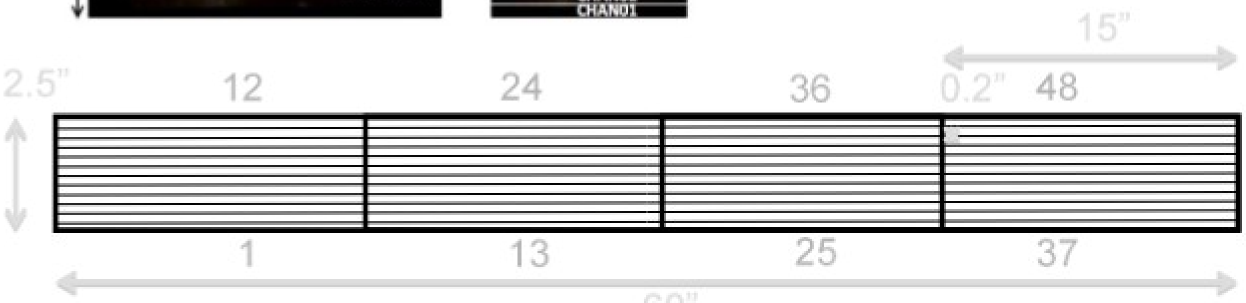
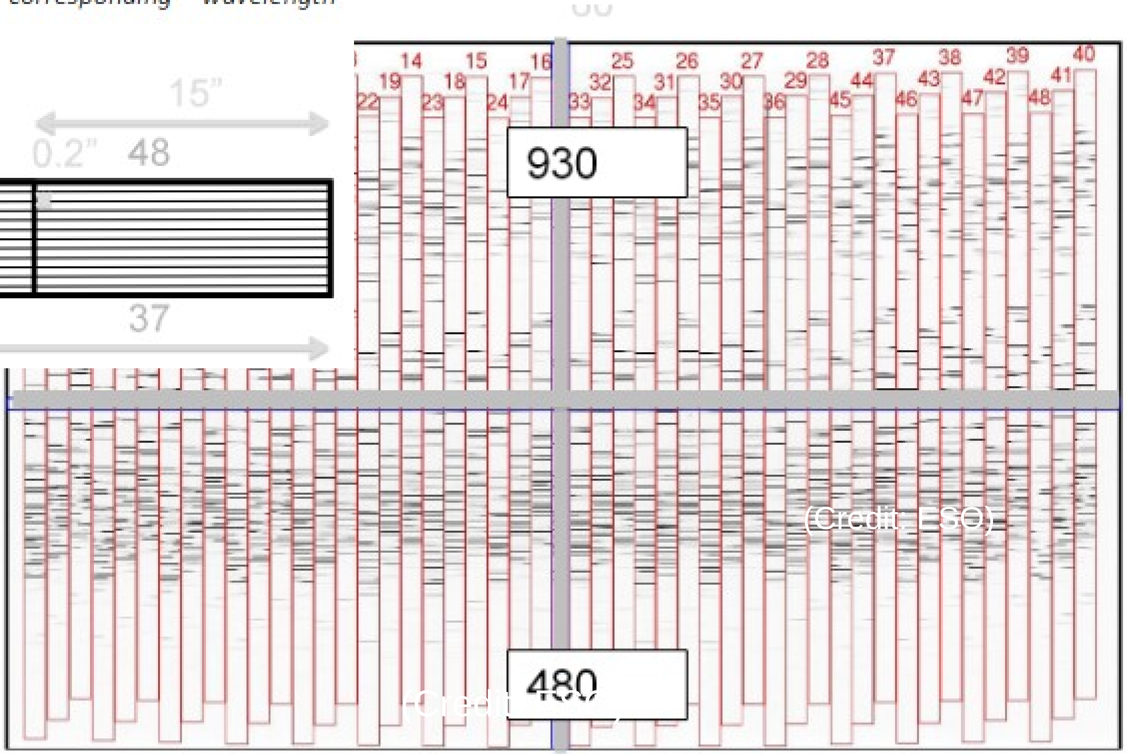


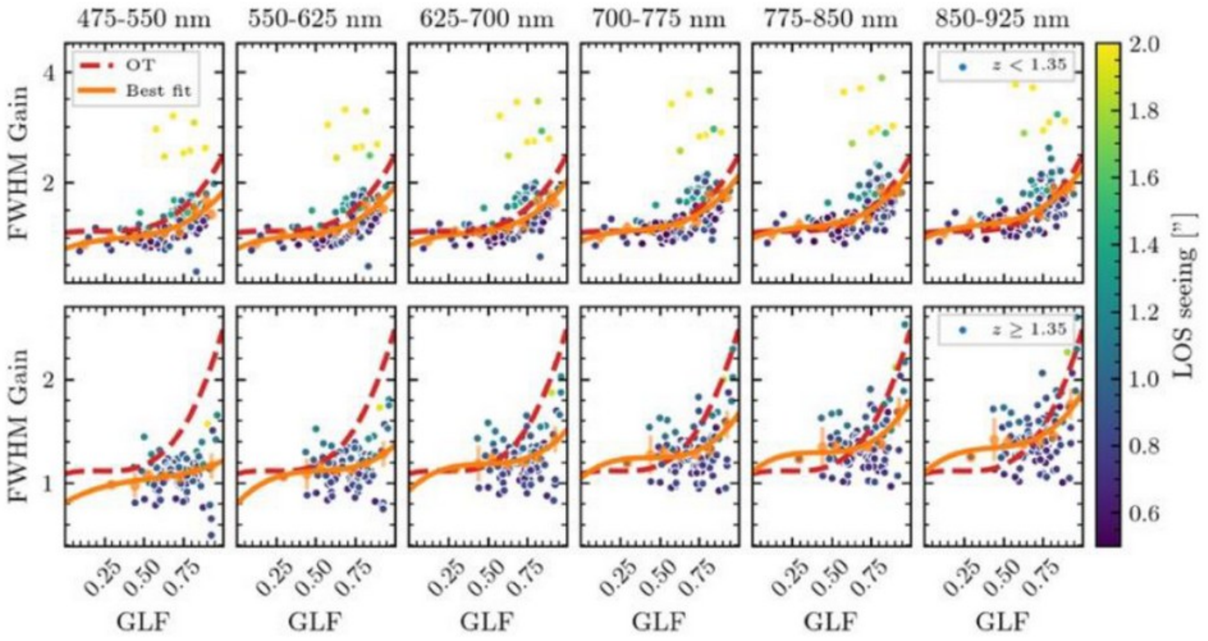
Figure 10: *Overview of the splitting of the field-of-view from the fore-optics to one of the MUSE detectors. Left: splitting of the MUSE FOV into 24 sub-fields entering each channel. Center: shape of the entrance slicer on sky, with 4 stacks of 12 slices (numbered in grey from 1 to 48) covering a 2.5" x 60" field. Bottom: location of each slice on the detector, with the corresponding wavelength range.*





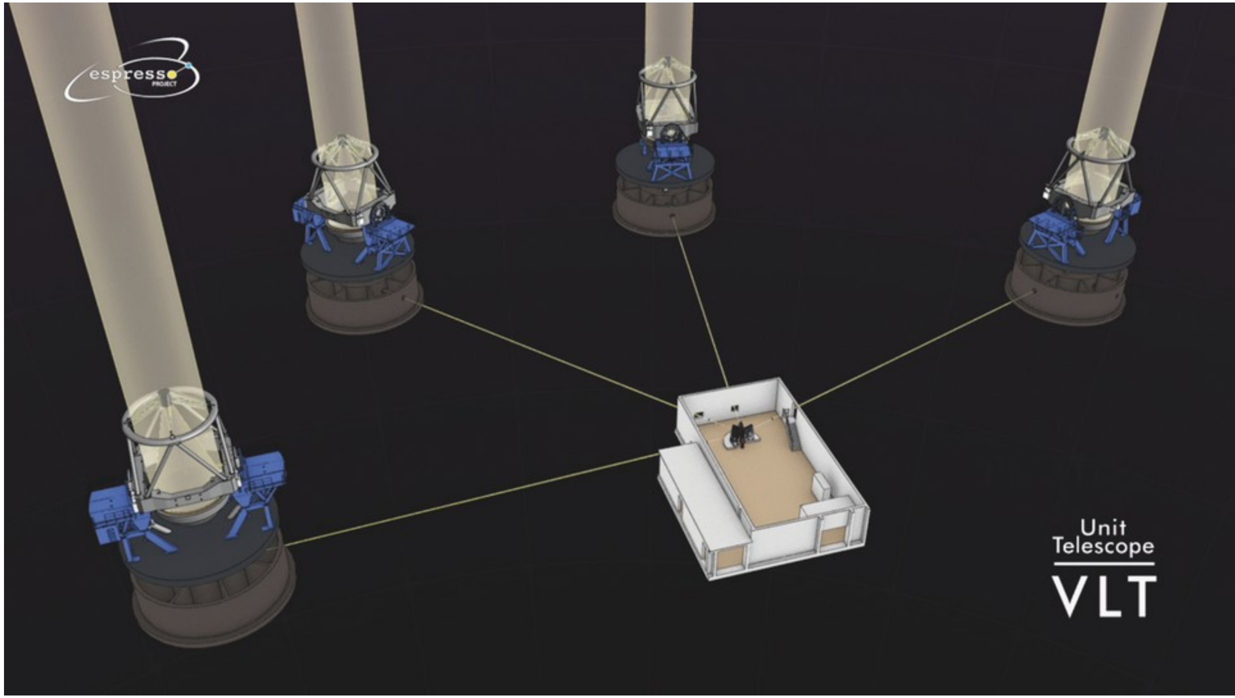
MUSE + AO

- Modes: noAO, Ground layer AO, and LTAO
- Maximum airmass 1.9
- In NFM optimal performance for <1.2 airmass
- AO improves the image quality, so if you need good image quality, AO increases the chance of observations being performed
- With sharper images, SNR increases
- AO telemetry data is saved and can be used to reconstruct the PSF in WFM-AO mode (Fusco et al. 2020)

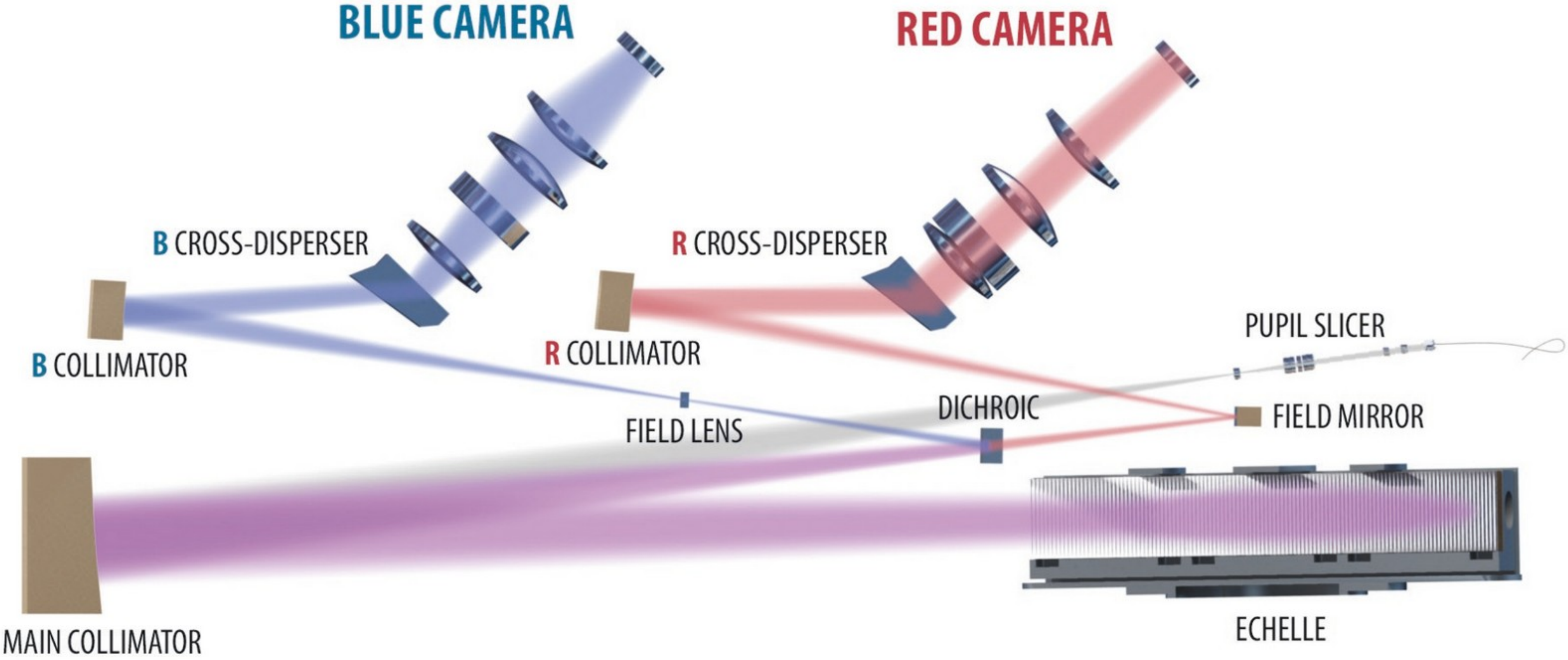


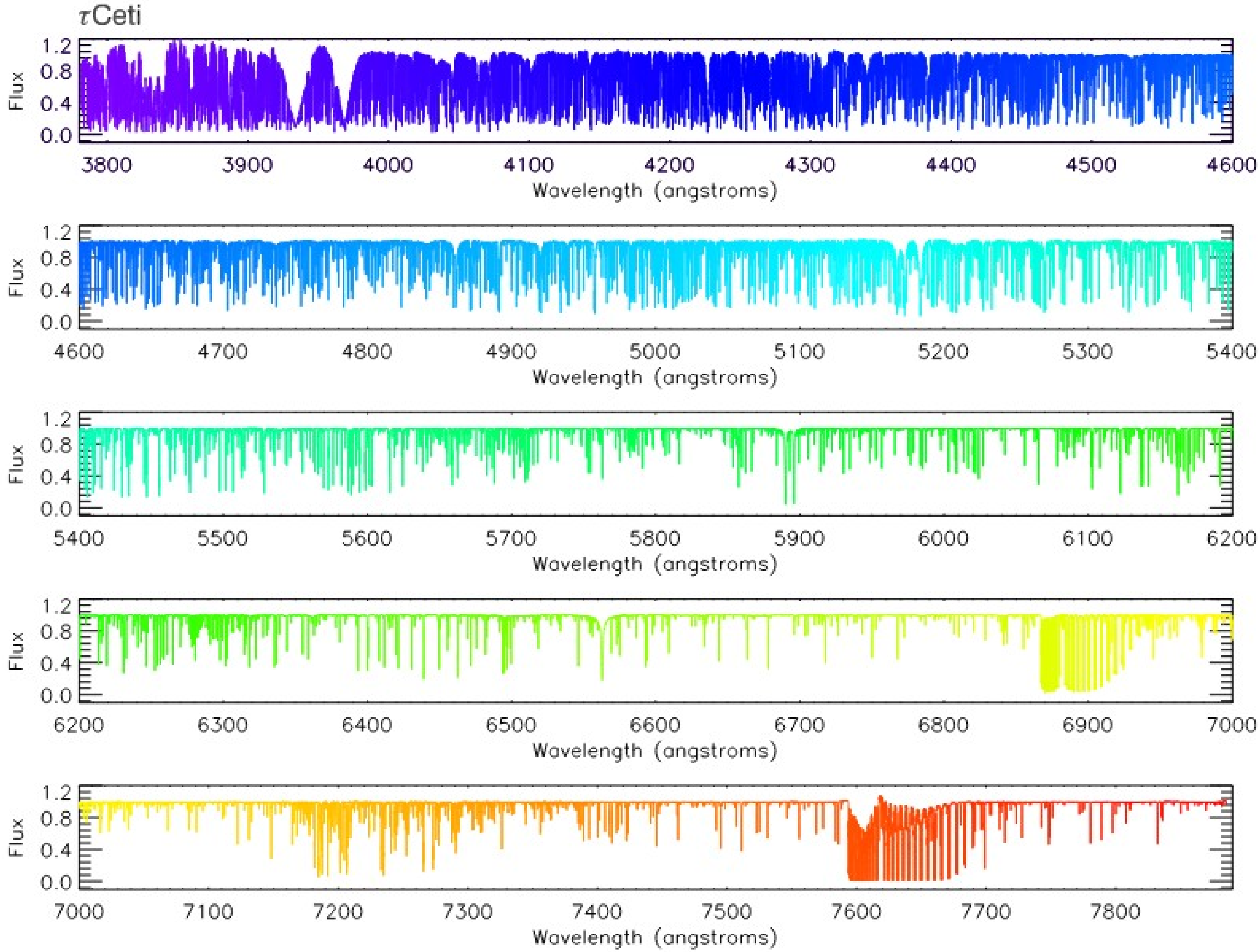
ESPRESSO

- **E**chelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations (Pepe et al. 2021)
- Ultra-stable fibre-fed échelle high-resolution spectrograph (R~140000, 190000, or 70000)
  - High-resolution with 1 UT and 1''.0 fiber
  - Very-high with 1UT and 0''.5 fiber
  - Medium with 4UTs and 4x1''.0 fibers
- Coude focus and can use the combined light of the four UTs (or with any UT)
- Coverage: 380–788 nm
- Wavelength calibration: combining ThAr-lamp with a white-light illuminated Fabry-Pérot.



ESPRESSO


BLUE CAMERA
RED CAMERA
B CROSS-DISPERSER
R CROSS-DISPERSER
B COLLIMATOR
R COLLIMATOR
PUPIL SLICER
FIELD LENS
DICHROIC
FIELD MIRROR
MAIN COLLIMATOR
ECHELLE


τCeti
Flux
Wavelength (angstroms)
3800
3900
4000
4100
4200
4300
4400
4500
4600
4700
4800
4900
5000
5100
5200
5300
5400
5500
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6200
6300
6400
6500
6600
6700
6800
6900
7000
7100
7200
7300
7400
7500
7600
7700
7800
0.0
0.4
0.8
1.2

Questions?

(Credit: Shutterstock)

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