EIRO Forum
Visible and IR Optics

J. KOSMALSKI

European Southern Observatory

16th of May 2024

What is ESO?

- an intergovernmental organisation established in 1962
  country Chile.
- 750 staff from more than 30 countries
- 3 Operating Observatories:
  - La Silla (since 1969) up to 4m class Telescopes
  - Paranal (since 1998) up to 8m class Telescopes
  - ALMA (since 2011)
- Currently building 39m E-ELT in Armazones (2028)

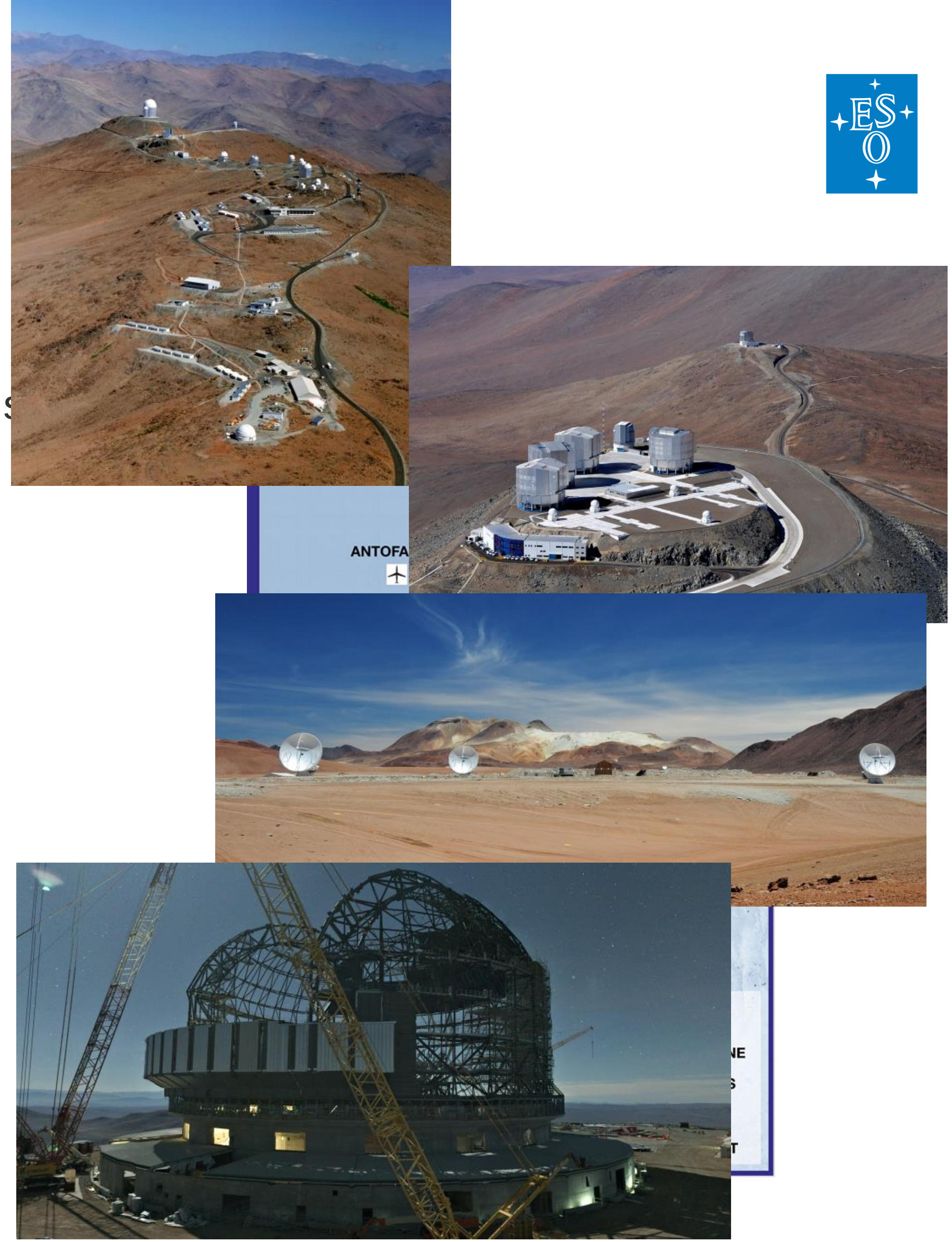


Table of Content

1. Design drivers
2. Instruments concepts and examples
    1. Imagers
    2. Spectrographs
        1. Low and Medium Resolution
        2. High Resolution
        3. 3D Spectroscopy

Design Drivers

The Telescope

1) Optical Interface:

    Exit Pupil Diameter and Position

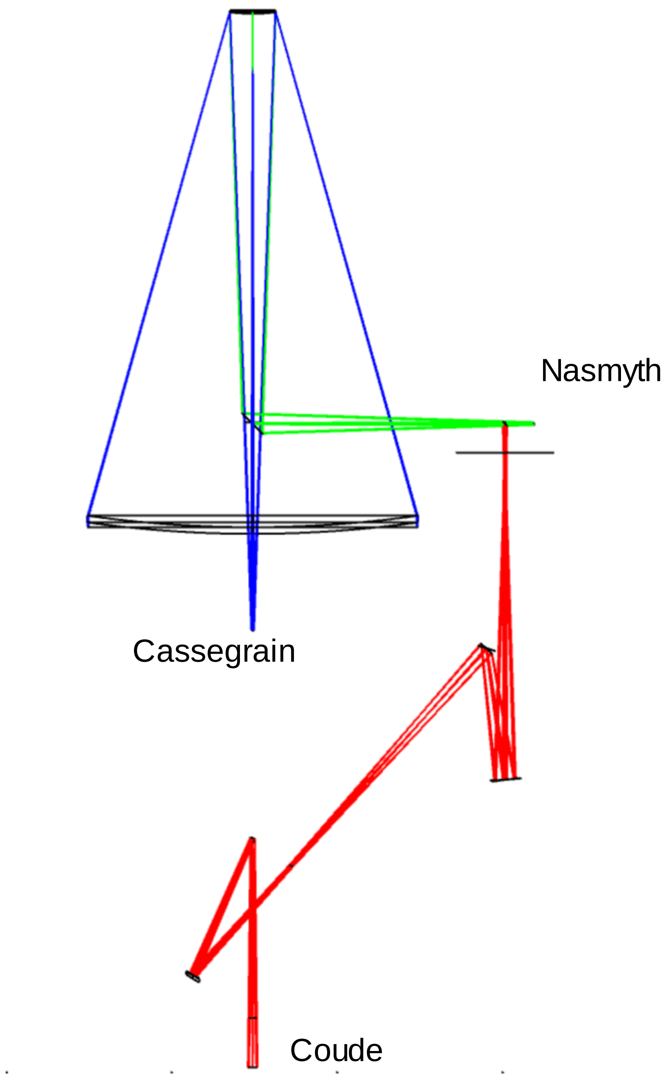
    F/#, plate scale (arcsec/mm), Field Curvature

2) Focal plane location:

    Instrument Volume

    Gravity Stable

    Field Derotation capability…



VLT focal stations

Design Drivers

What you would like to do with your instrument

1) Field of View (FoV) and spatial sampling

   Number of detectors

   Pixel Size → final F/#

2) Wavelength range

   Visible : variety of glasses available

   UV/IR: limited material

   IR: often implies Cryogenic instruments → mirror design preferred

3) Instrument functions:

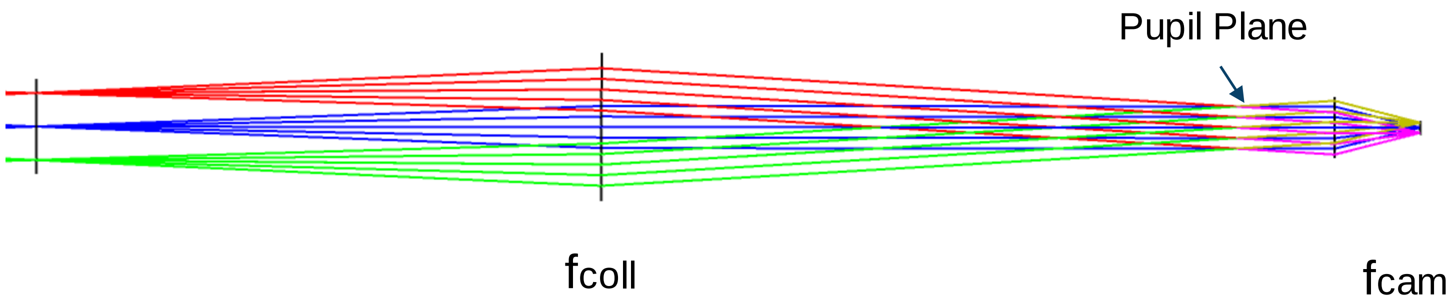
   Imagery, Spectroscopy, Polarimetry, Coronography

   Field derotation/ Atmospheric dispersion compensation

FOcal Reducer and low dispersion Spectrograph

Imager Main Function: Reformat the FoV to the detector size

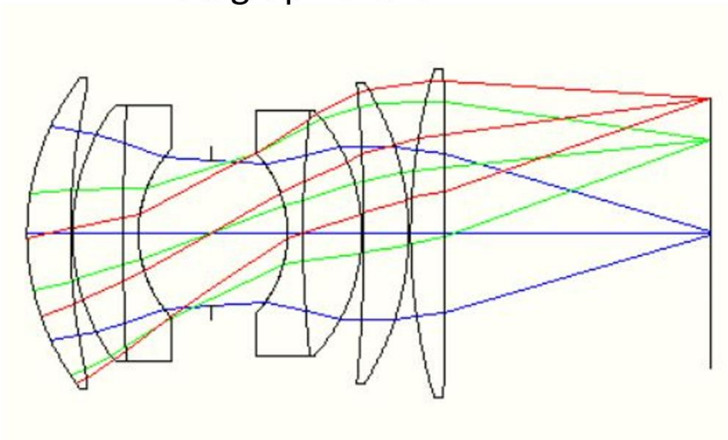
Classical approach: one collimator and one camera



Magnification is defined by fcam/fcoll
Instrument length and Volume by fcoll+Fcam
Pupil plane can be used to insert color filters, polarizer, gratings

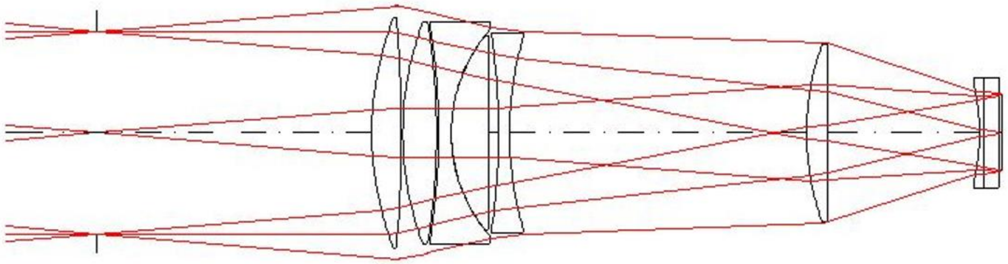
Why an astronomical camera is more difficult than a photographic Lens?

Photographic lens



Pupil inside → Helps to balance field dependant aberrations
Small wavelength range
Large vignetting allowed at the edge of the field
Large choice of material

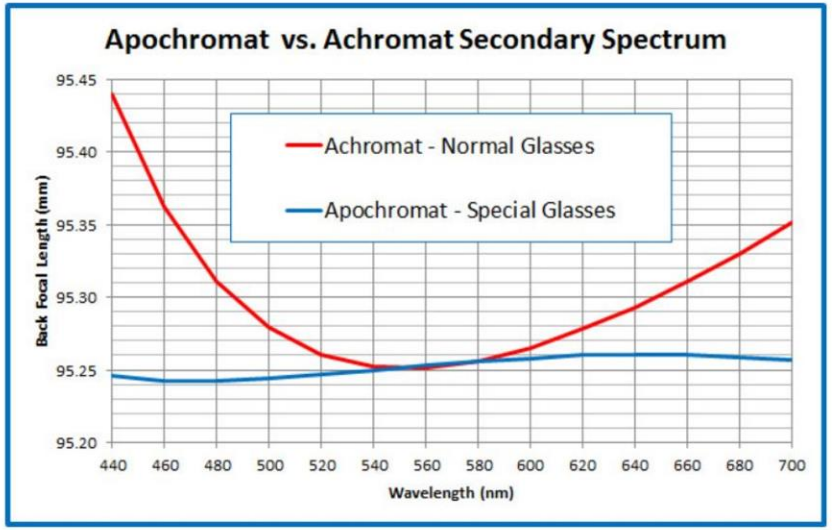
Astronomical camera



Pupil outside (far from front surface)
Large wavelength range
Limited choice of material (in size)

In an imager Color correction is mandatory

AXIAL CHROMATISM



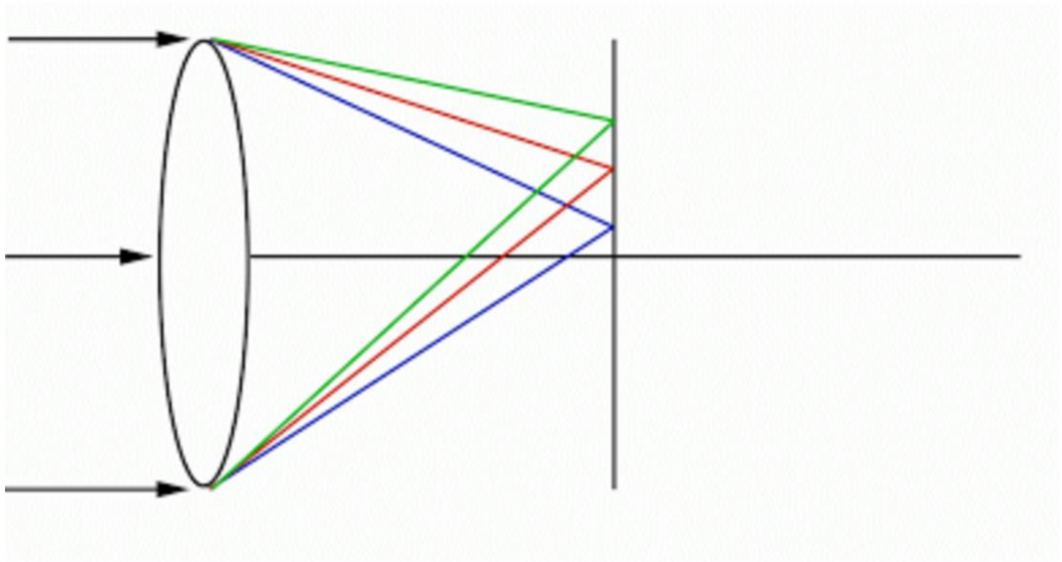
Special Glasses

CaF2
Schott FK54
Ohara SFPL53
….

Special glasses : high expansion coefficient
high Dn/DT
Fragile
Not available in large size (>400 mm)
Very expensive

Only some of the converging element requires special glasses

LATERAL CHROMATISM



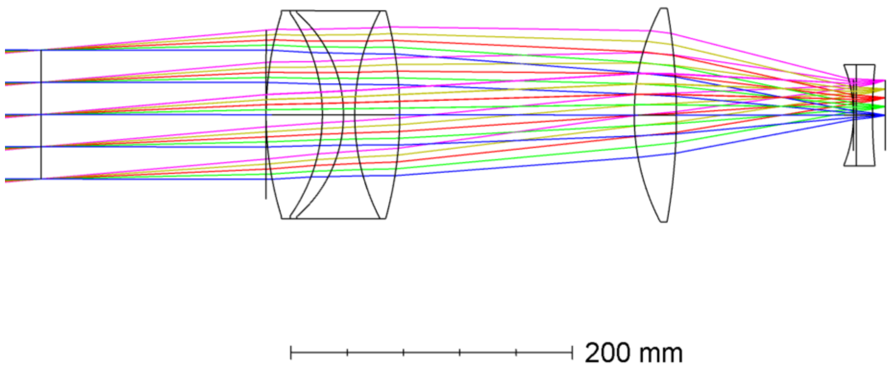
Lateral or Transverse Chromatic Aberration - Lens magnifies different wave lengths differently.

FORS

VLT Cassegrain instrument → limited length (2.5m)
FoV 7arcmin
2 scales 0.125arcsec/pix and 0.25arcsec/pix

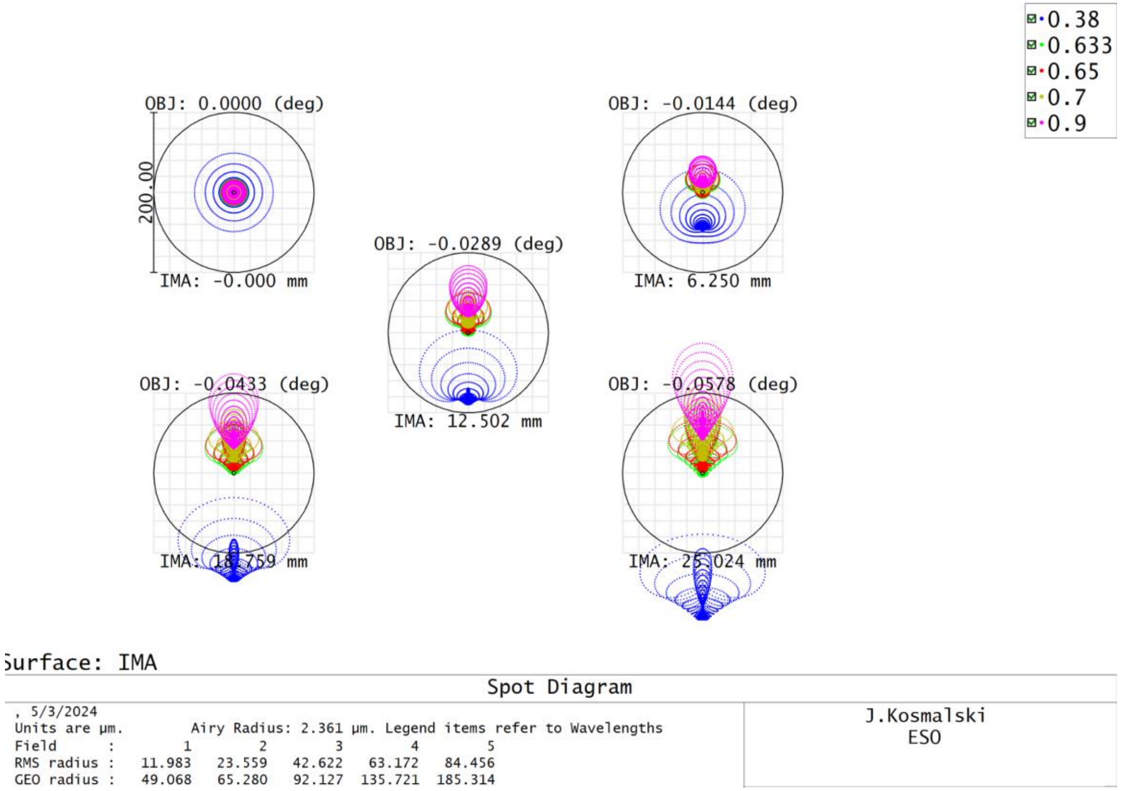
FORS camera

We want a color corrected instrument!
What is the trick to minimize the use of special glasses?



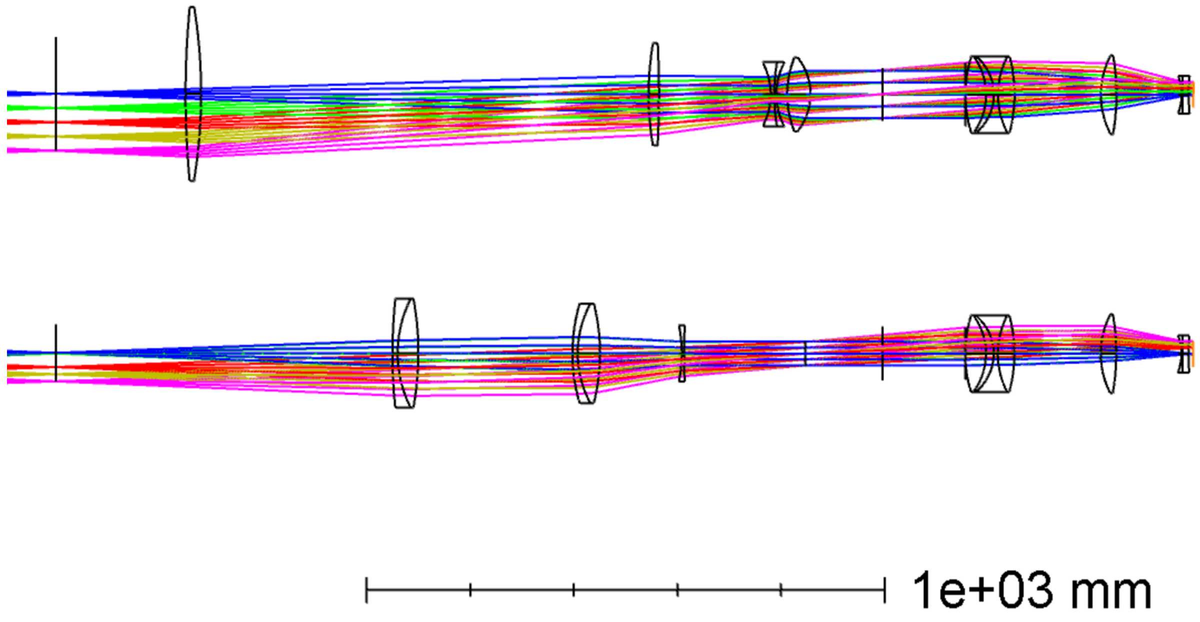
F/N	3.0
Focal Length	280 mm
Pupil	94 mm
Field of view (ϕ)	70 mm
Wavelengths	365 - 900

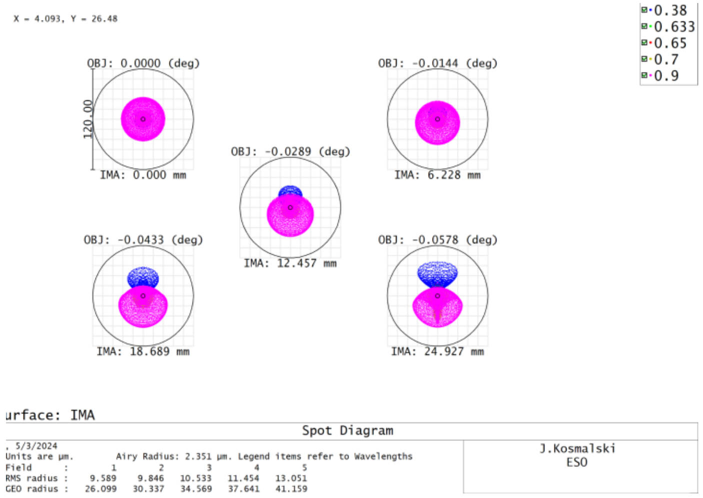
FORS Camera Stand Alone



Lateral Color not corrected

Perfect lateral color compensation with Coll



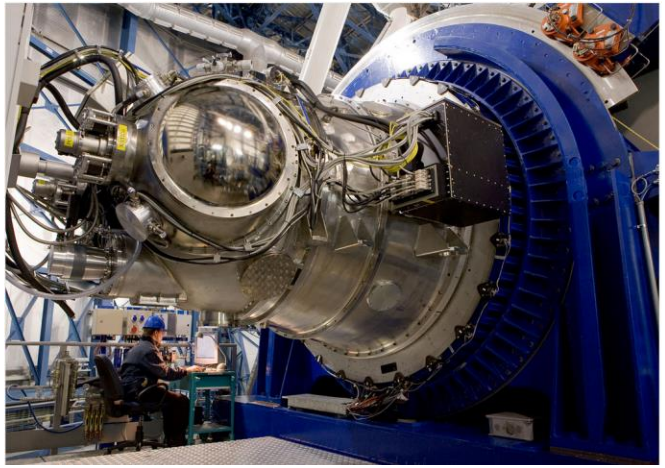


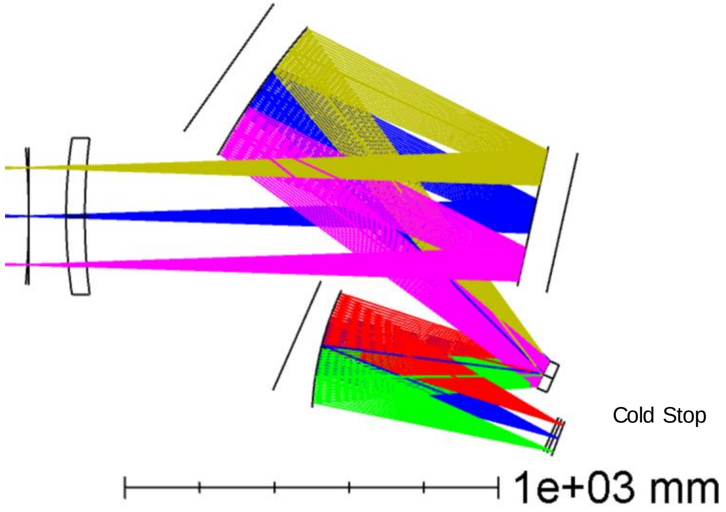
Collimators avoid the use of expensive glasses
Camera accommodates the change in pupil position

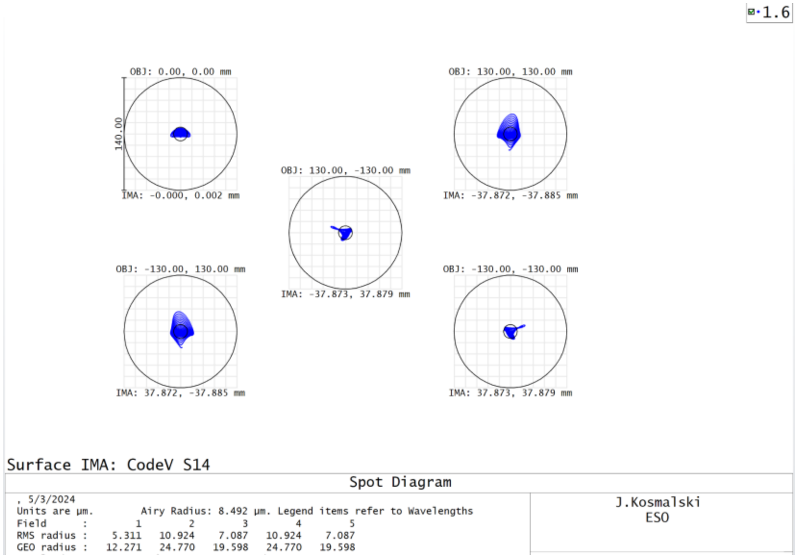
Another Imager Hawk-i

Nasmyth instrument

Field of view on the sky	7.5 x 7.5 arcmin
Field of view on the detector	76.2 x 76.2 mm²
Scale	0.1063 arcsec/ pixel or 1 arcsec = 169.4 µm
Final F/N	F/4.36
Wavelength range	850 – 2500 nm

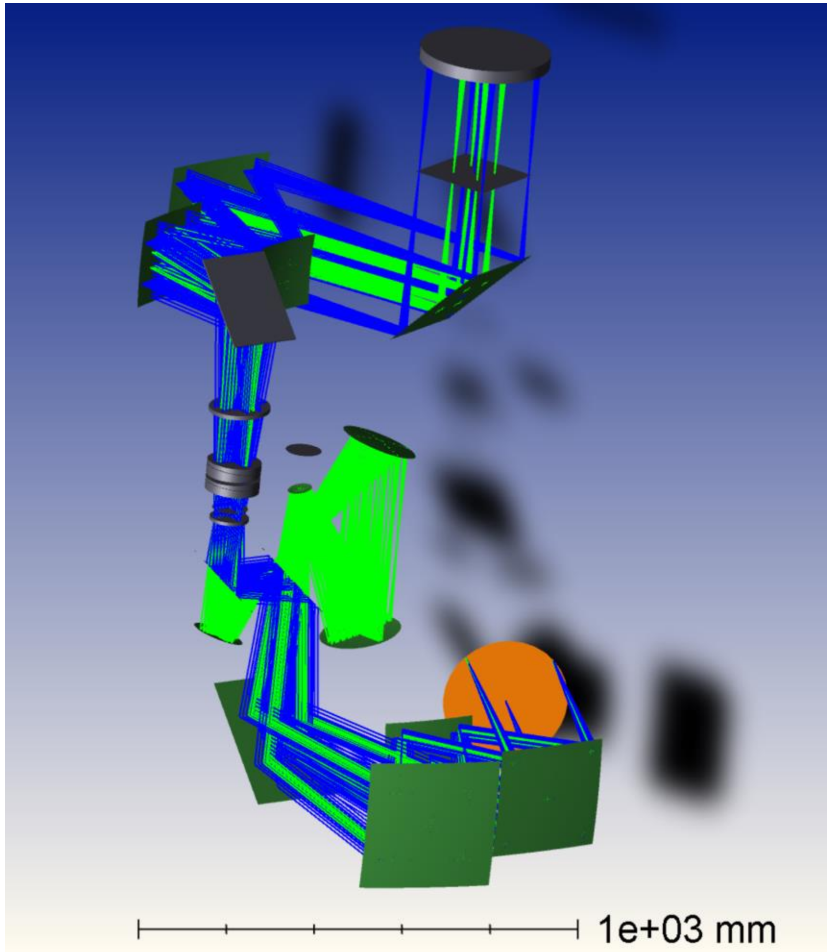






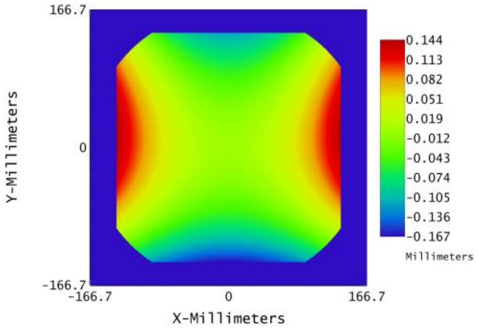
Compact Off-axis TMA (limited to 600mm diameter optics including mirror optical axis)
Field Lens acts as Entrance Windows of the cryostat (140K cold) and creates a clean pupil to reduce instrument back-ground
2by2 detector array

Some E-ELT-Imagers: Micado

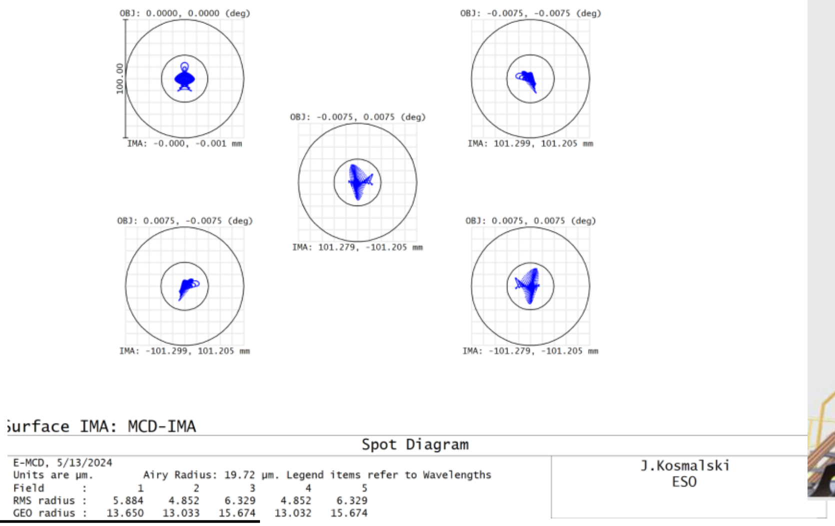


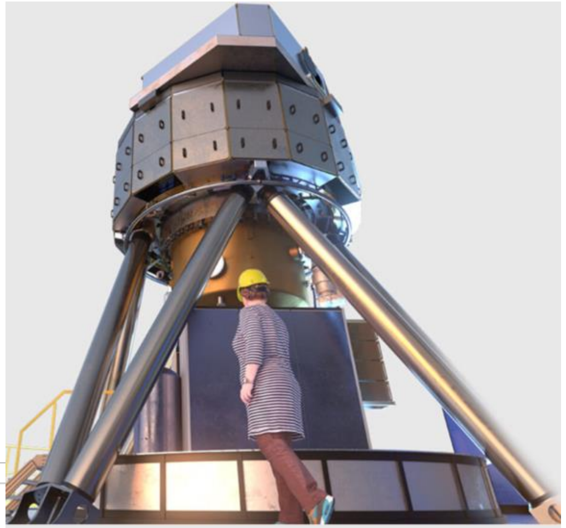
FoV 9x9arcmin FoV covering .8 to 2.4microns
F/20 camera
3x3 Detector array

→ Everything is bigger
→ Keeping the instrument within reasonable size requires the use of Freeform Optics to reach diffraction limited performances

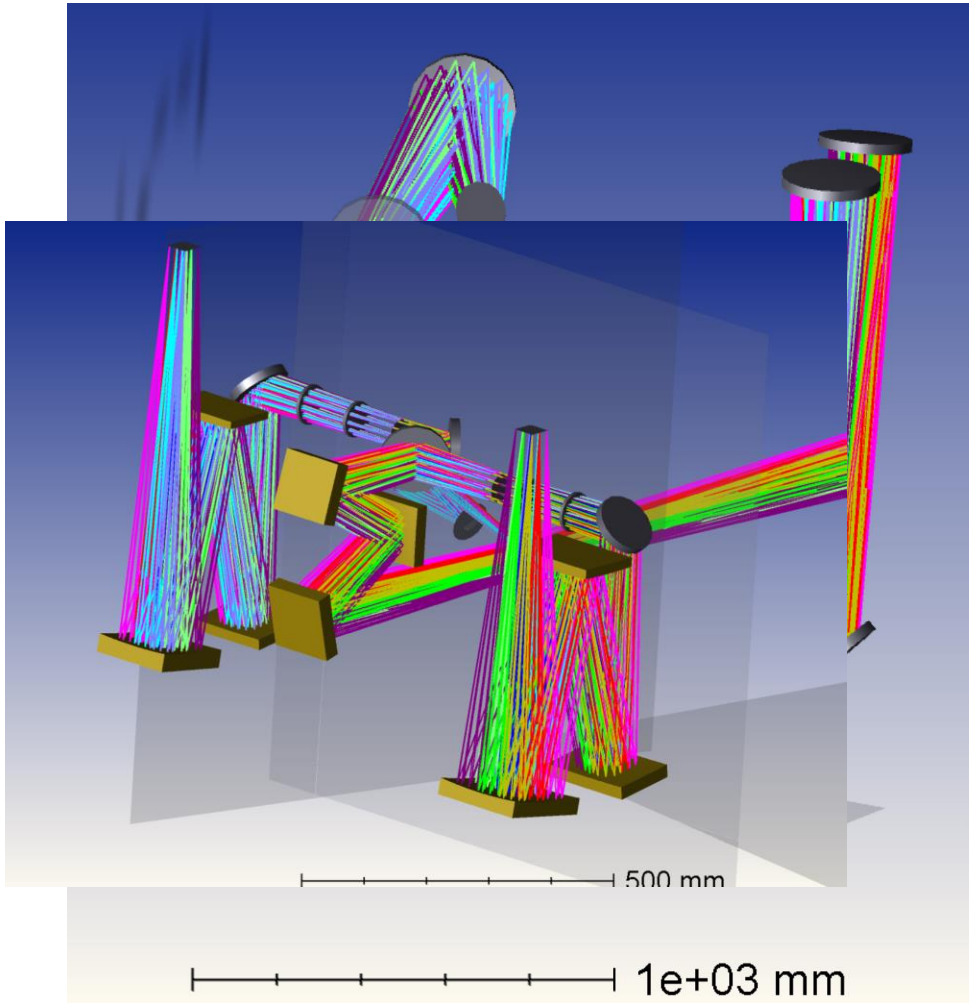


No radial symmetry of the mirror surface

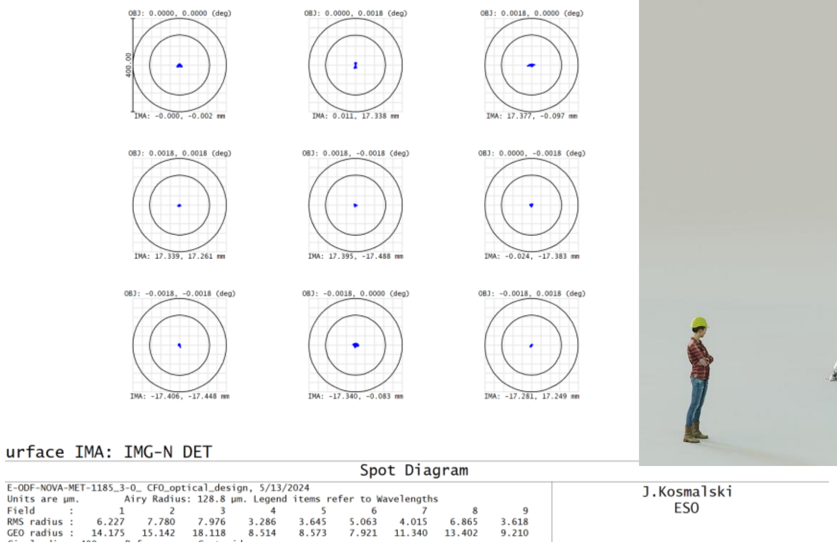




Some E-ELT-Imagers: METIS



13by13arcsec FoV, 2Arms covering (L, M) and N bands
F/14 camera
Diffraction limited
Very compact design allowed by using Freeform mirrors



Spectrographs

Used when you need access to wavelength information.
-Give you access to the chemical composition and kinetic of the object

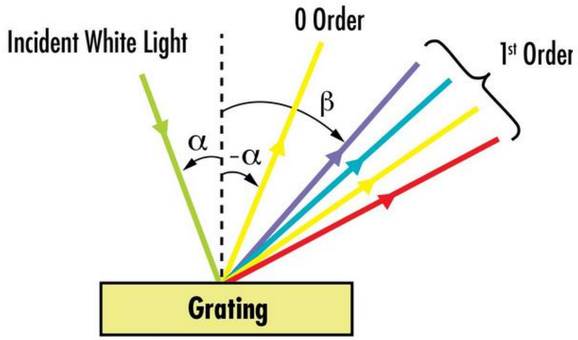
Identified Spectral lines impacted by the Doppler effect:
- Bluer region goes towards us
- Redder region goes away from us

→ This galaxy is clearly rotating

Need a dispersive element:
-simple prism → low dispersion
-Diffraction grating: Transmissive or reflective → low to high resolution
-Echelle grating: reflective → very high resolution

The grating equation

A diffraction grating is characterized by its line density



$$m\lambda = d\,(\sin\alpha + \sin\beta)$$

With m the order of diffraction
α incident angle
β diffracted angle
d the line density

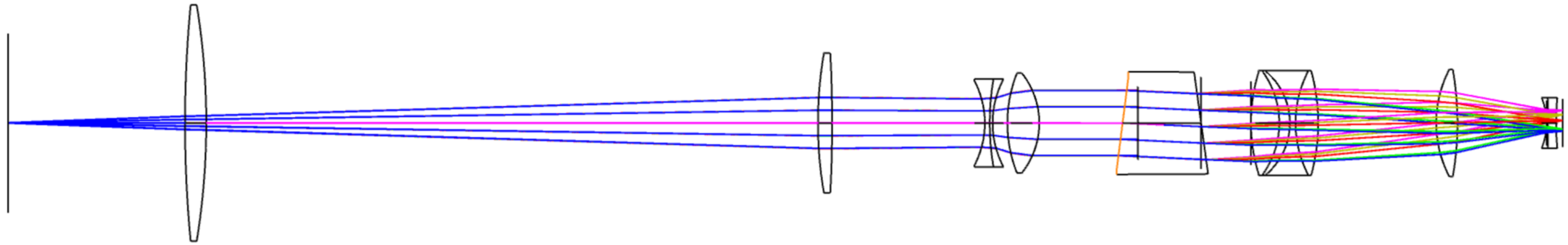
Red and blue are not diffracted with the same angle creating the spectral dispersion.

The Spectral Resolution is defined as $R = \frac{\lambda}{\Delta\lambda}$ where Δλ is the minimum distance between 2 wavelengths that you can separate on your detector.

Data Classification: ESO CONFIDENTIAL/INTERNAL/PUBLIC, ESO-XXXXXX v.X (doc nr, version)

Low Resolution Spectrograph

Back to FORS:
Obviously one dimension of the detector is taken by the dispersed light so FoV is limited to one long slit parallel to the grating lines.



In combination with a prism, line of sight can be preserved.

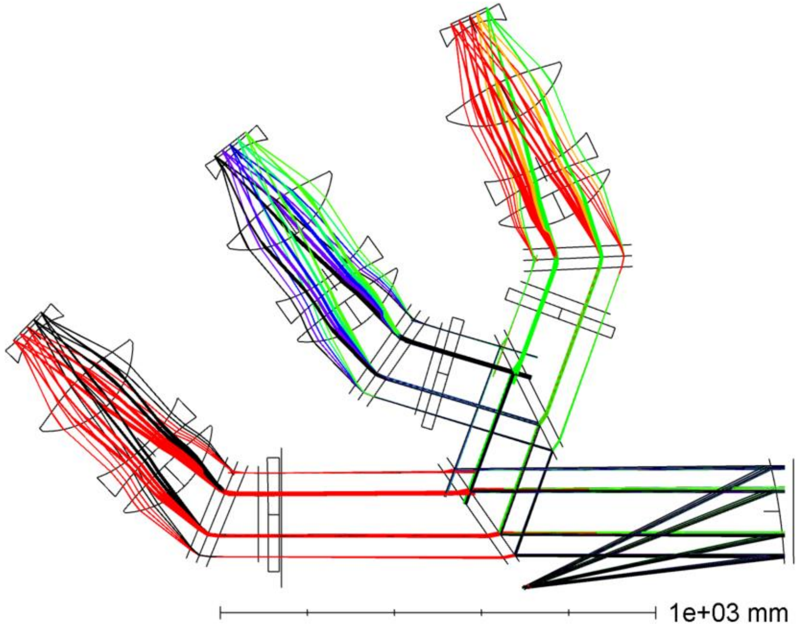
The Spectral Resolution is limited by the Slit width.
For FORS, resolution from 260 to 1600 can be achieved.

Medium/High Resolution Spectrograph

4 MOST Low Resolution Spectrograph

Fiber Fed Spectrograph
Continuous Spectral Coverage from 370 to 950nm
R> 5000
F/1.73

-Simple Spherical Collimator with corrector→ only possible because a curved slit design
-Fixed format spectrograph→ no need of axial color correction (tilted detector) only cheap glasses could be used

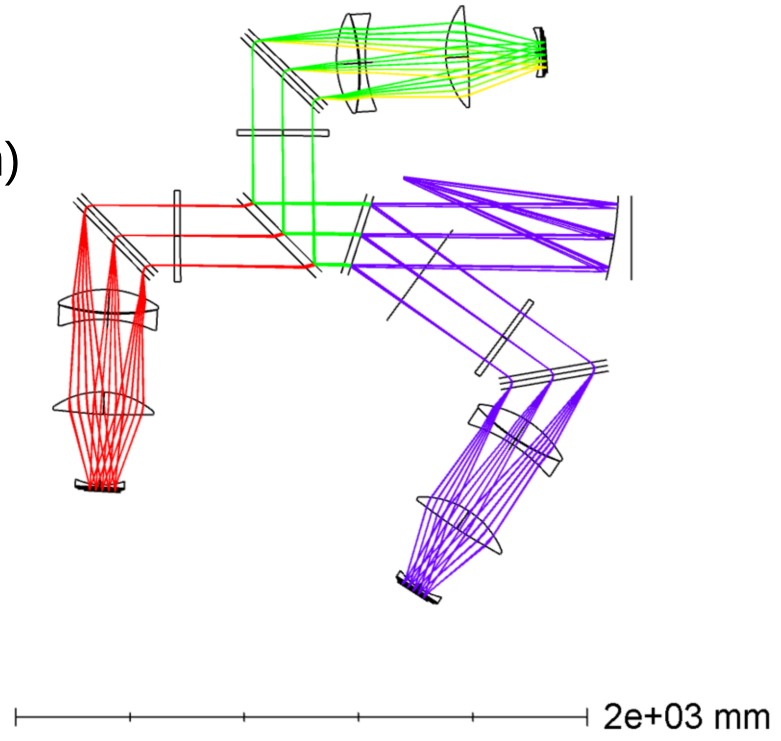


Medium/High Resolution Spectrograph

4 MOST High Resolution Spectrograph

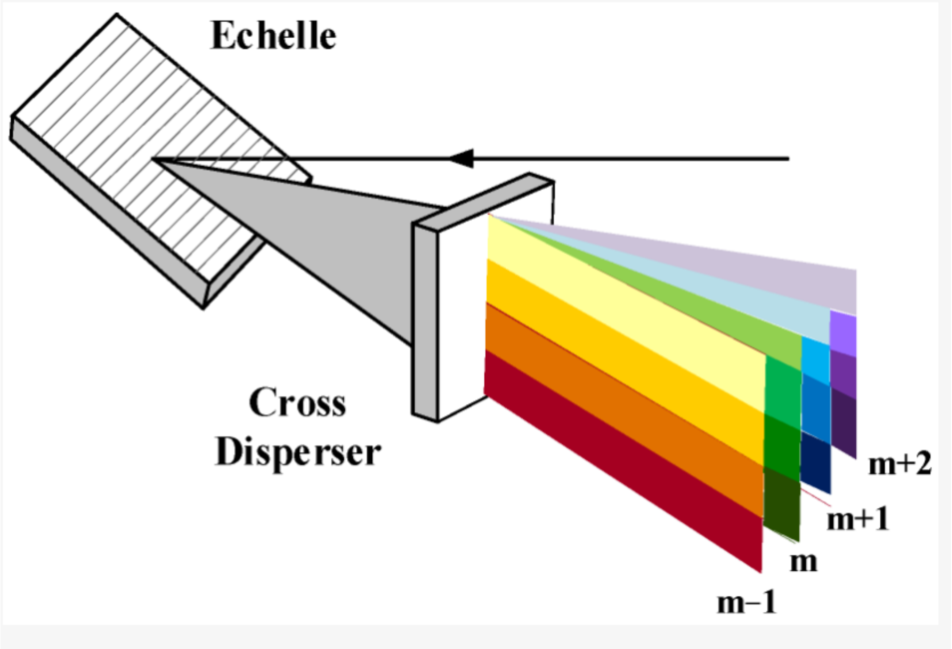
Fiber Fed Spectrograph
Discrete Spectral Coverage (393-436, 516-573 and 610-679nm)
R> 20000
F/1.73

-Simple Spherical Collimator with corrector→ only possible because a curved slit design
-Fixed format spectrograph→ no need of axial color correction (tilted detector) only cheap glasses could be used
But: we can observe that increasing the resolution increased significantly the size of the optics using "classical" gratings
-Difficult packaging (high angle on gratings)
-Only discrete coverage
→ To increase the Resolution/Spectral Coverage other design needs to be done



Echelle gratings

Using a grating with low line density at high incidence and high diffraction orders

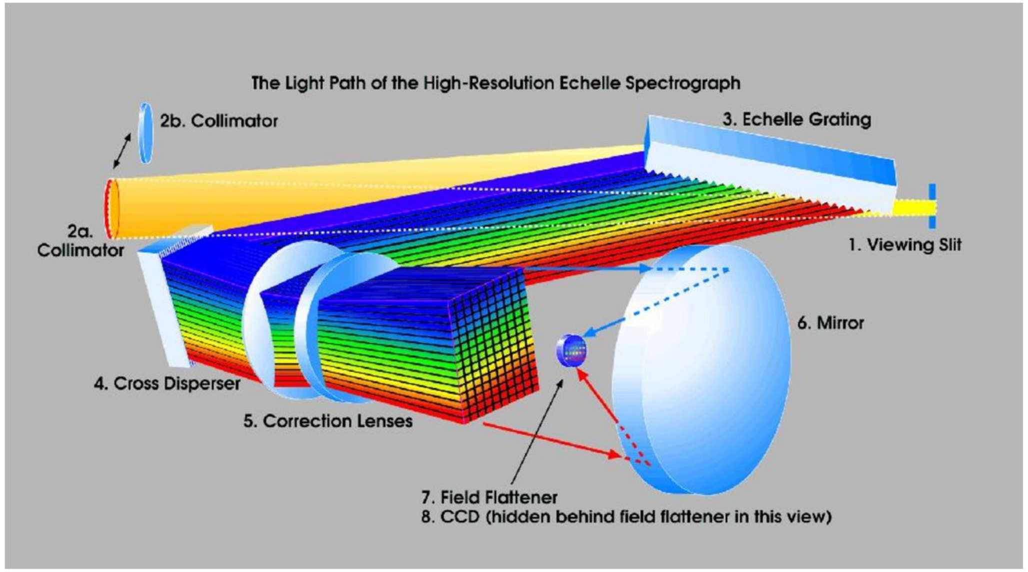


High diffraction orders are almost send at the same location
→ A cross dispersed helps to separate them on the detector

Now the spectral information covers a **2D space** → only a limited FoV is possible (determined by the inter-order separation on the detector

The white pupil concept

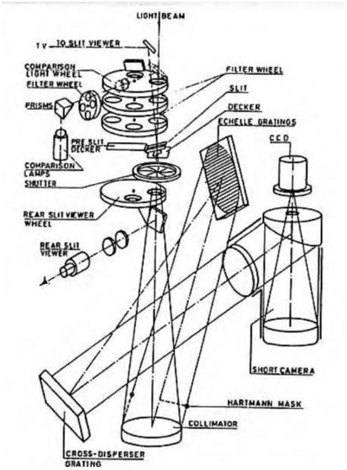
The Classical Approach for High resolution



KECK
High Resolution Spectrograph

- 1 Collimator followed by the Echelle+Cross disp.
- Large Schmidt camera 44inch
- Strong anamorphose and vignetting

CASPEC
@ ESO



Data Classification: ESO CONFIDENTIAL/INTERNAL/PUBLIC, ESO-XXXXXX v.X (doc nr, version)

The white pupil concept

-Proposed by **A. Baranne** in early 70’s

Use a Echelle Type of grating in Littrow with the collimator used in double path
A slit with overlapping diffraction orders is then created
Another transfert Collimator and Cross-disperser are needed

- Camera pupil size is almost a free parameter

- But slit length is limited by the orders separation

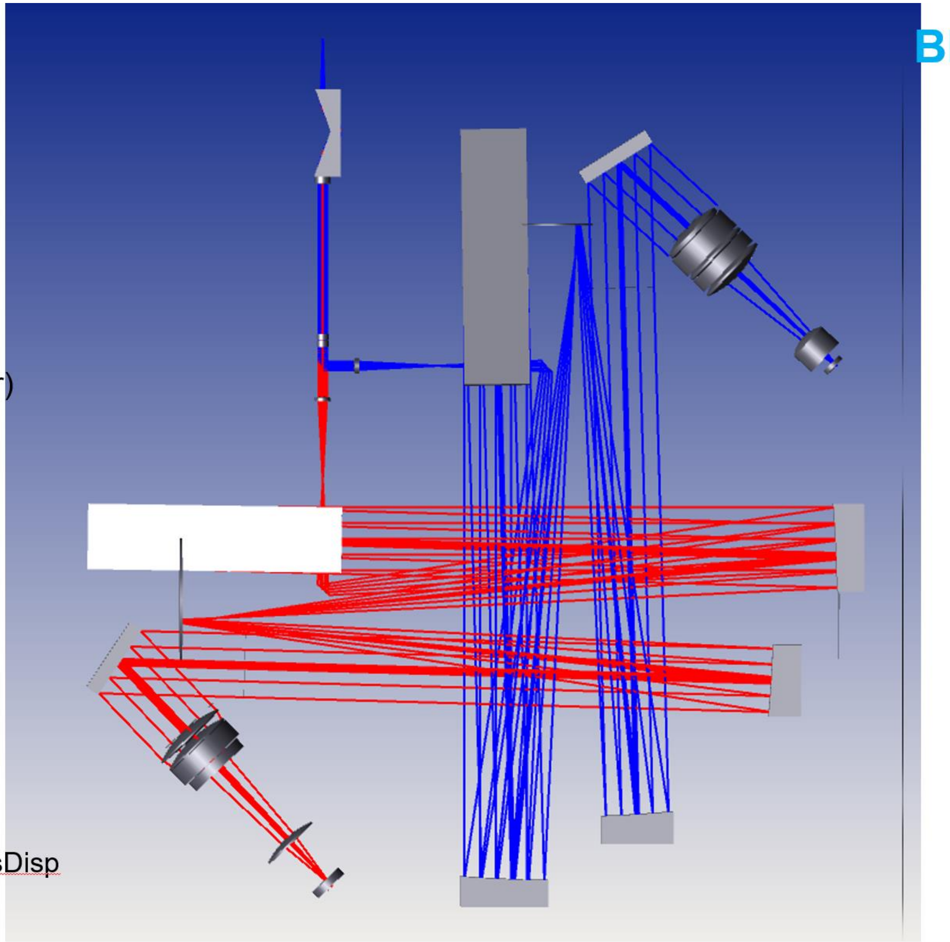
UVES: Ultraviolet and Visual Echelle Spectrograph

Preoptics:

-1 Optical Derotator
-ADC+filters
-2 Achromatic at F/10
-Selection mirrors

Other features:

-Slit Viewers
-Adjustable Slits (Dekker)



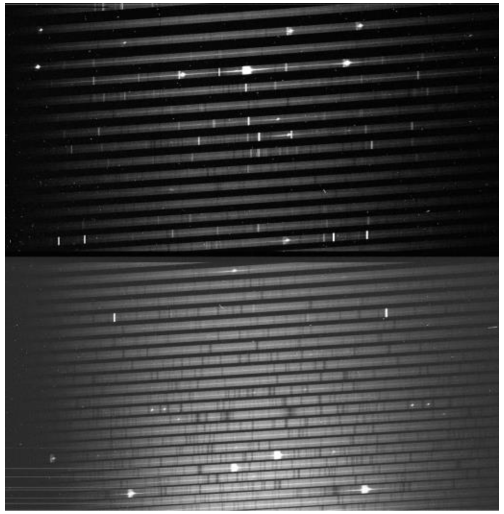
BLUE ARM:

7 lenses
EFL 360mm
200mm pupil
F/1.8 Achromatic Camera
R4 Echelle
0.3-0.5 micron
Covered using 2 Ex. CrossDisp
Usable FoV 7.5deg
(2k*2k equ.)

R~100 000

Red ARM:

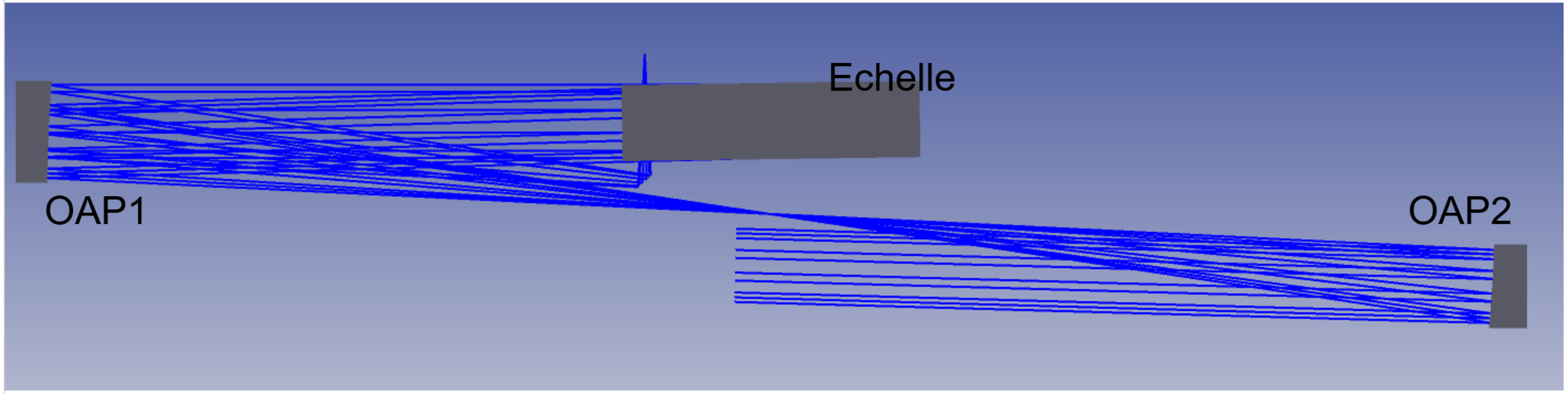
6 lenses (but 2 doublets)
EFL 500mm
200mm pupil
F/2.5 Achromatic Camera
R4 Echelle
0.42-1 micron
Covered using 2 Ex. CrossDisp
Usable FoV 12deg
(4kx4k)



Echellogram

UVES design tricks

Main and Transfer Collimators combination!



1)Perfect compensation of vertical coma and Astig of OPA1 in double path by OPA2.
2)Perfect compensation of horizontal coma between OAP1 and OAP2

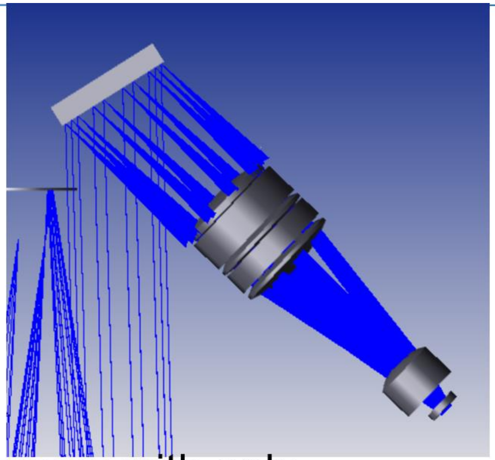
→Unbeatable Image Quality performances
→ No Ghost
→Only problem is Field Curvature (Cylindrical Cryostat window to correct this)

UVES design tricks

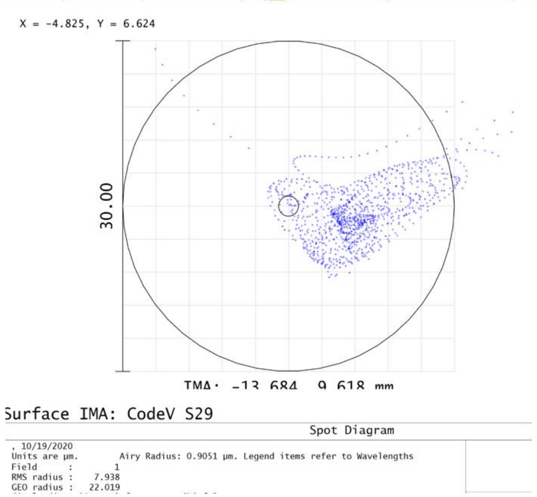
Vignetting of the Cameras:

- Camera far from the pupil
- Glass blanks larger than 200mm not existing

Up to 25% vignetting

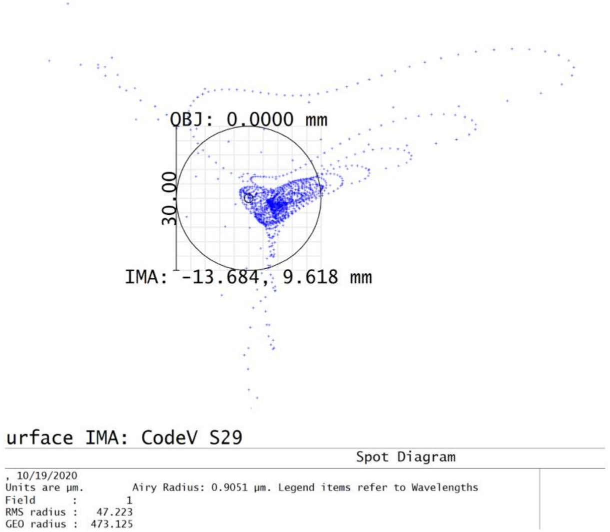


Making a clever use of this vignetting allows very good images with only spherical and much thinner lenses



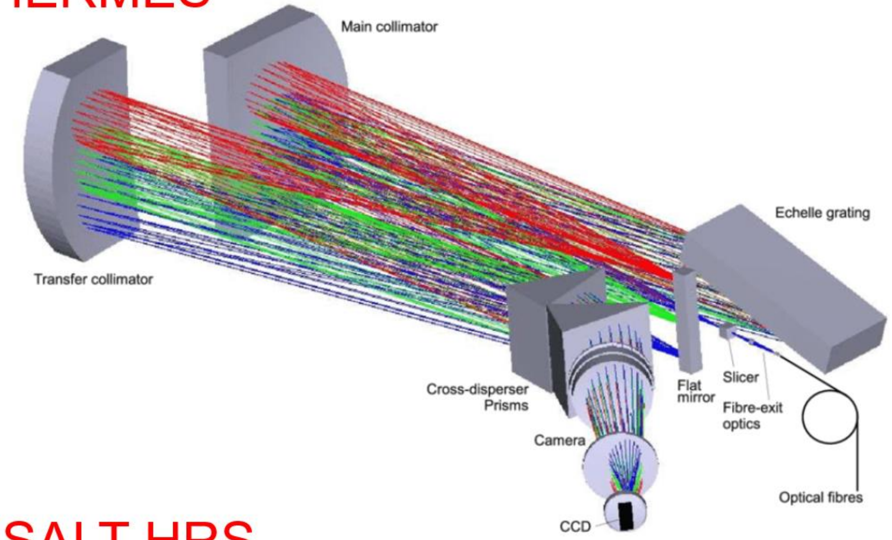
RMS spot size

1 pix with Vignetting
vs **6pix** without !

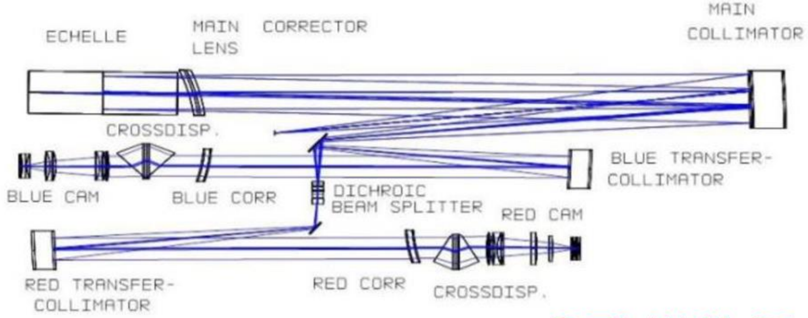


COPIED Many times with variations of collimator:

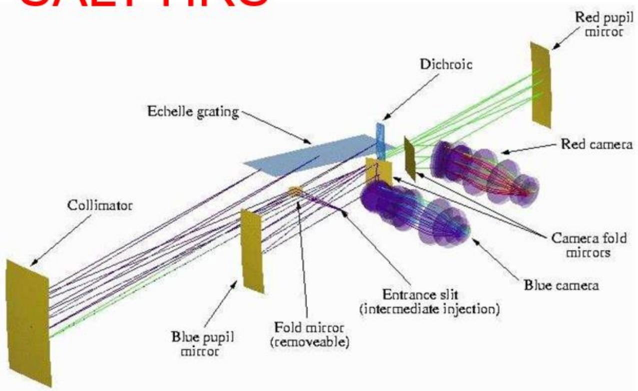
HERMES



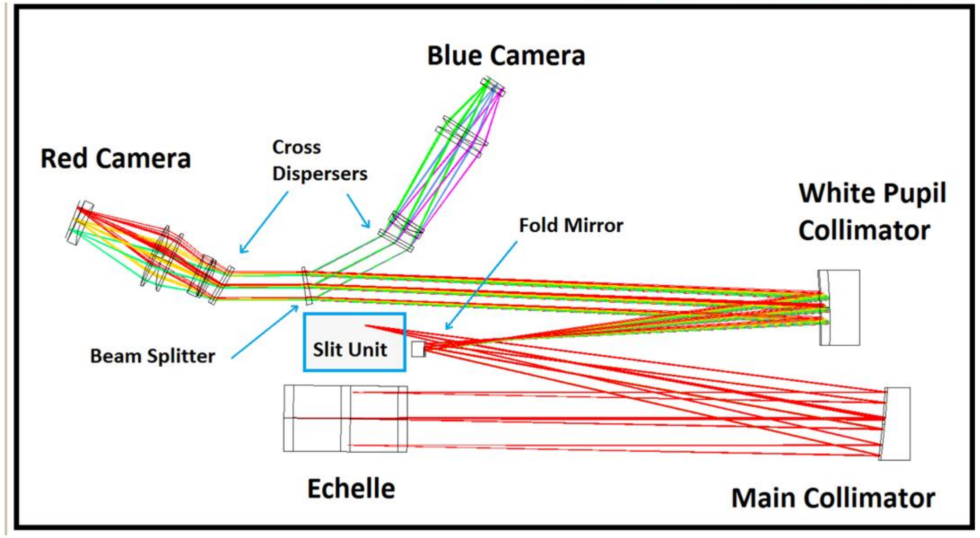
LBT PEPSI



SALT HRS



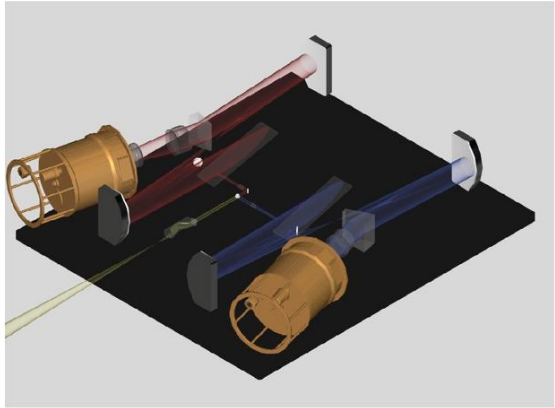
GEMINI GHOST



FEROS, HARPS, ESPADON, SPIROU, FOCES… the list is long

STELES

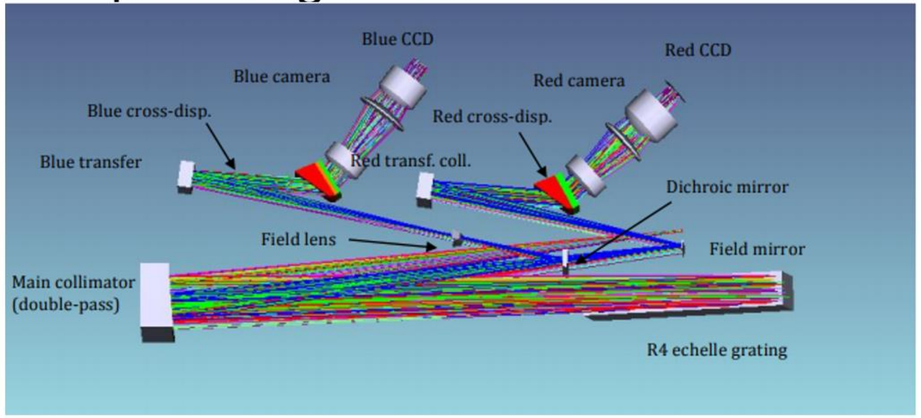
Spherical Transfert Collimator with Camera Compensation



ESPRESSO

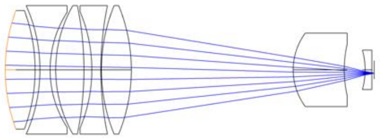
Spherical Trans Coll+ field flattener

Pupil slicing

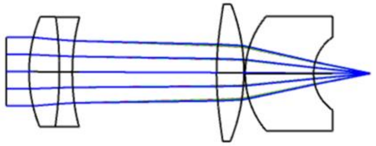


Huge benefit of fixed format detector for the camera designs

UVES Blue

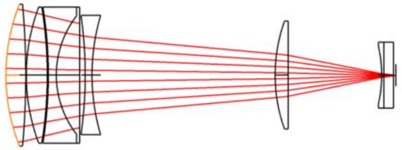


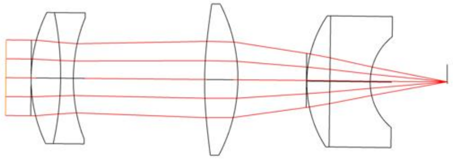
VS



ESP Blue

UVES Red



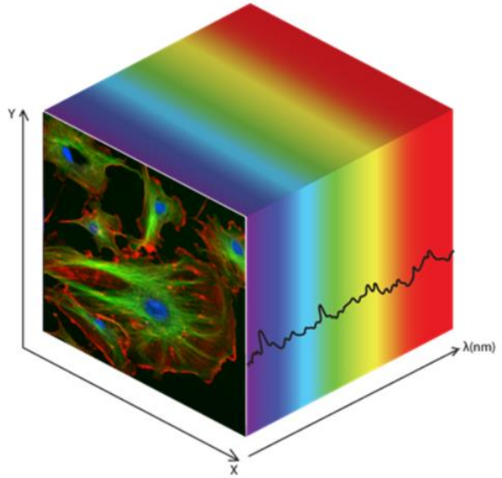


ESP Red

3D or Integral Field Spectrographs

So far, we have seen one dimension of the FoV has to be sacrificed to do spectroscopy!

How can we get the spectral information over a 2D spatial FoV ?



Hyperspectral data cube

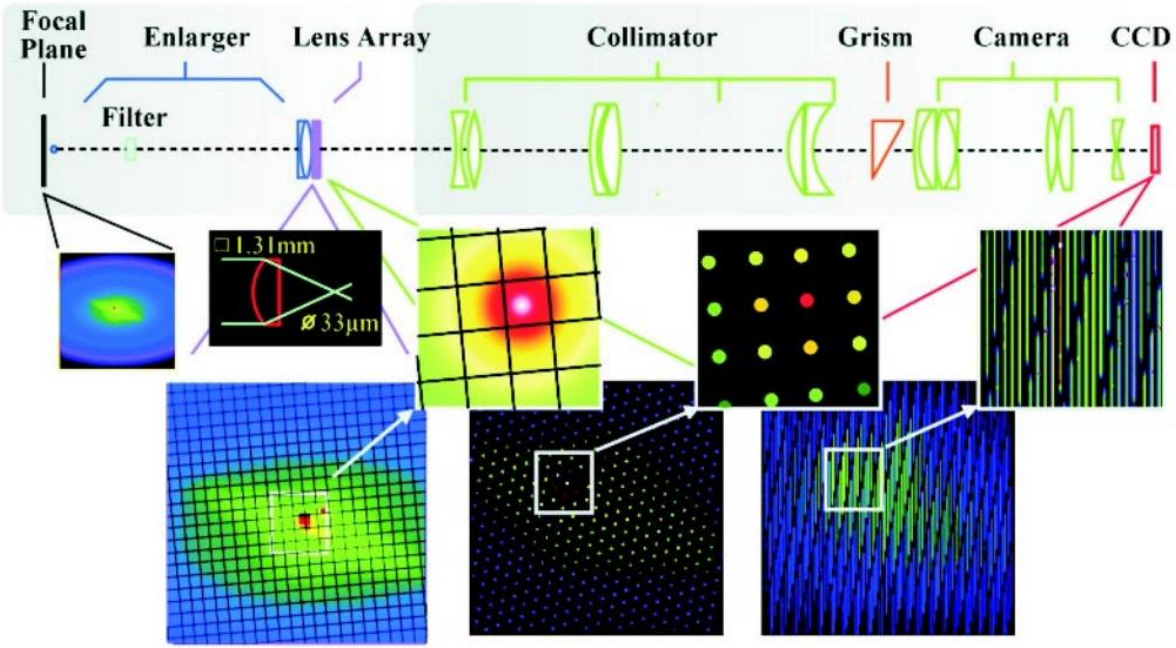
<u>Classical approach</u>:

Do multiple long slit exposures changing the Telescope pointing

→ Not really efficient in term of Telescope use.
→ Atmospheric conditions can vary a lot between exposures. (calibration issues)

Using Lenslet arrays

Used in many first generation IFS: OASIS, TIGER, **SAURON**

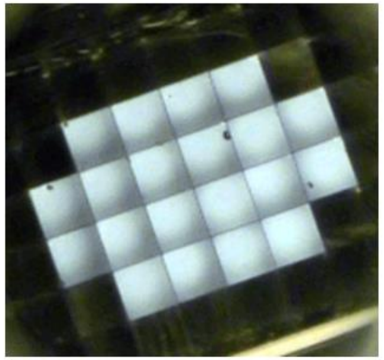


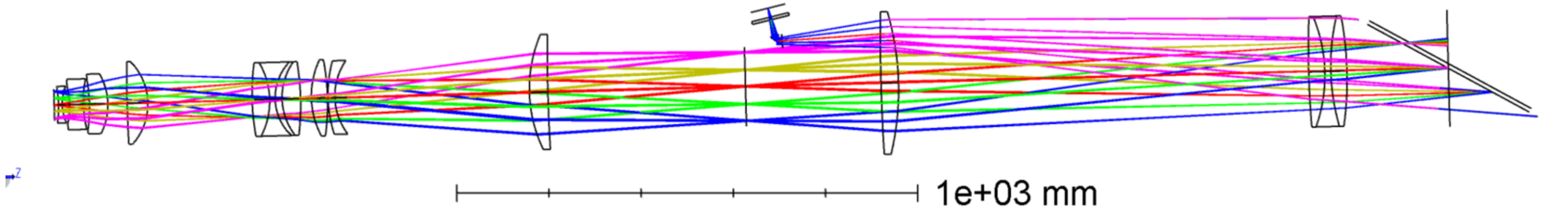
Spectra overlapp avoided by tilt the lenslet pattern wrt the dispersion axis

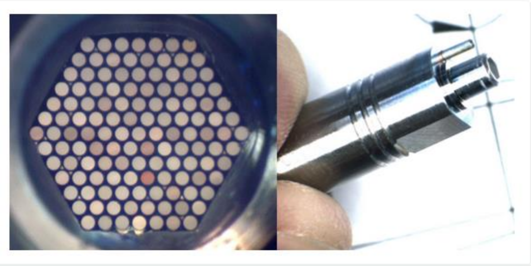
Strong limitation of the Spectral Resolution
Not ideal filling factor of your detector.

Using Fiber bundle

Hexagonal Fiber bundle or Lenslet array combined with Fibers
-Used in GIRAFFE
- -Collimator used in double path
- -No Cross disperser: order selection using waveband filters
- -R 7500 to 30000 for 350nm to 950nm

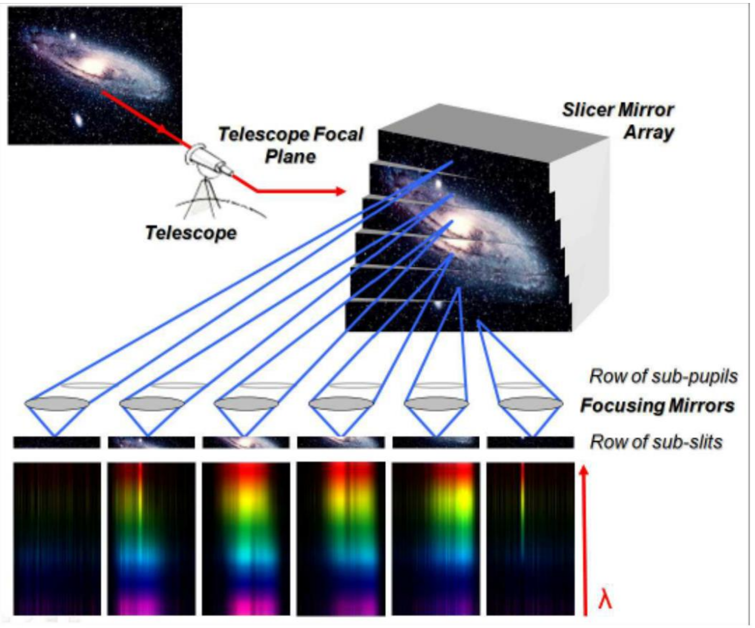






→ Fibers can be rearranged in a long slit: gain in filling factor
→ Fiber injection losses: 10-20%

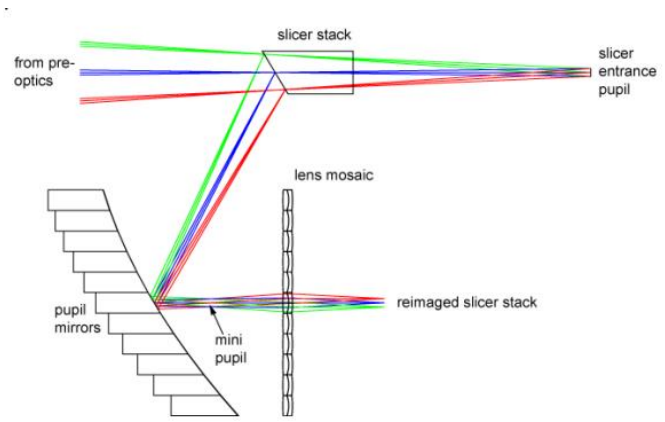
Using advanced Image Slicer

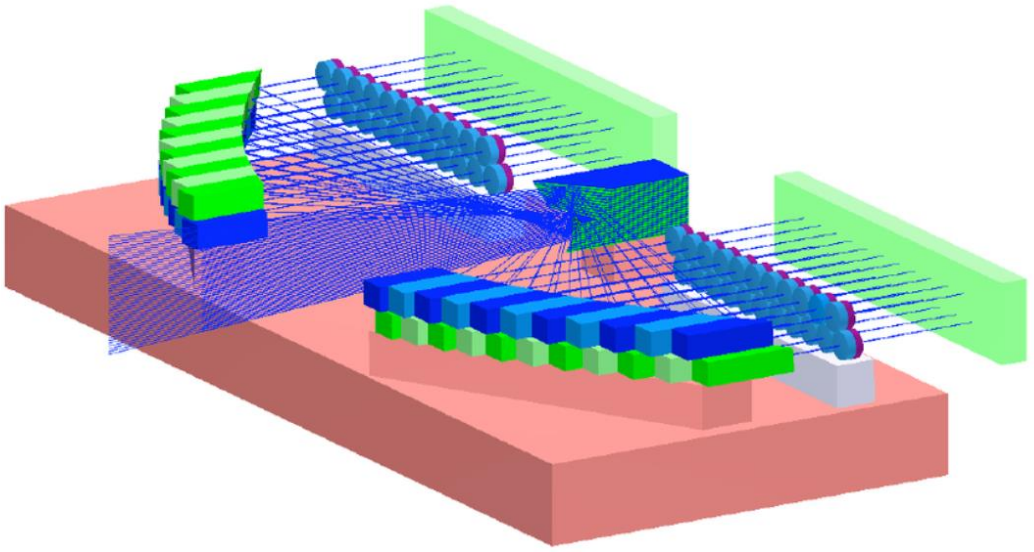


3 functions:

- Slice the input image
- Reimage all subpupils into a common location for the spectrograph
- Demagnify each slice and rearrange them into a slit

Advanced image slicer example: Swift



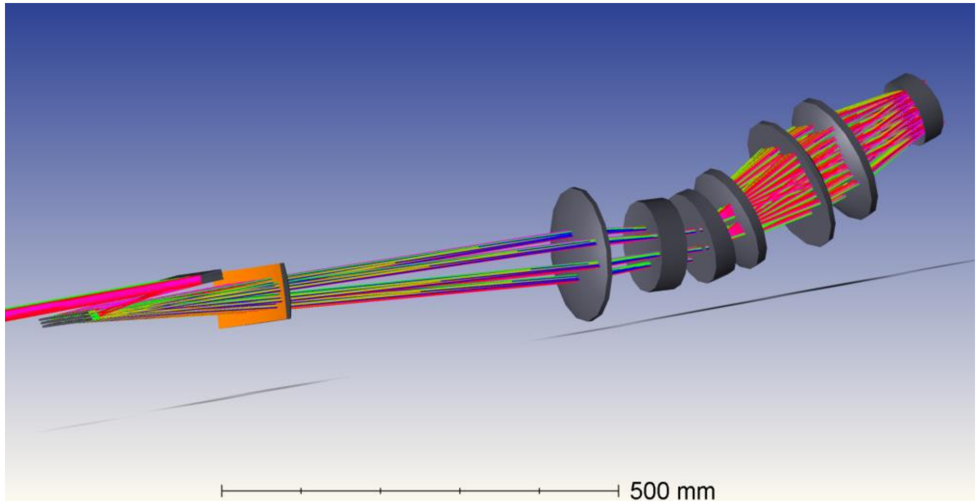


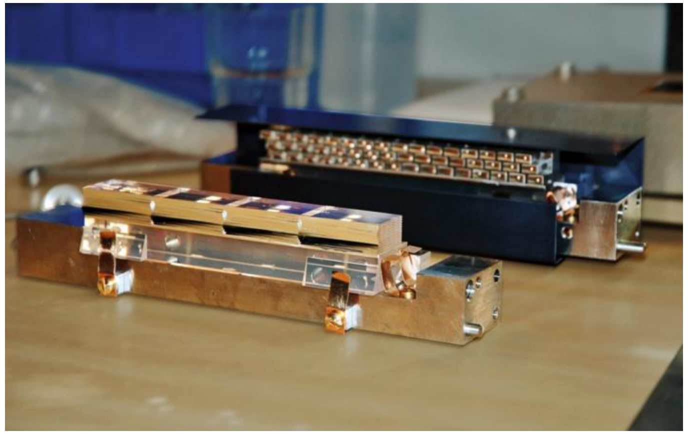
44 Flat slices (→ polished individually) No power needed as input pupil is at finite distance

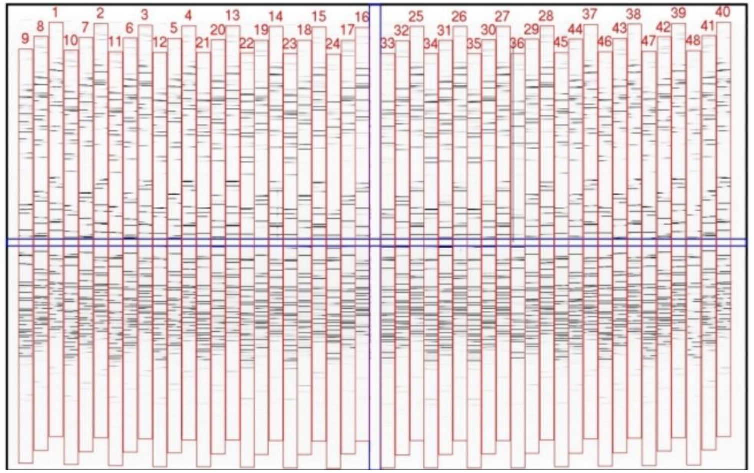
An array of flat mirror to redirect the beam towards the spectrograph

A mini lens array to reimage the slice and sub-pupils

Advance image slicer example 2: MUSE





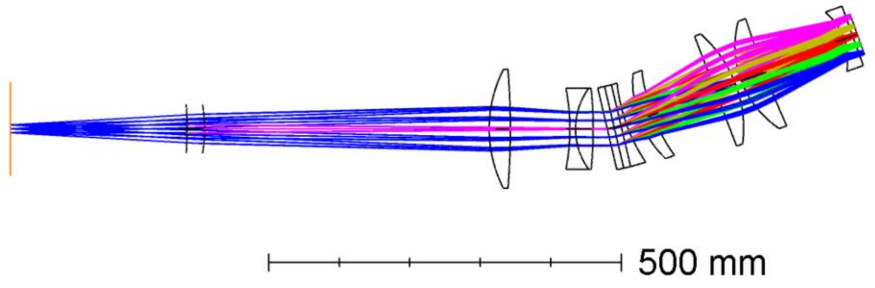


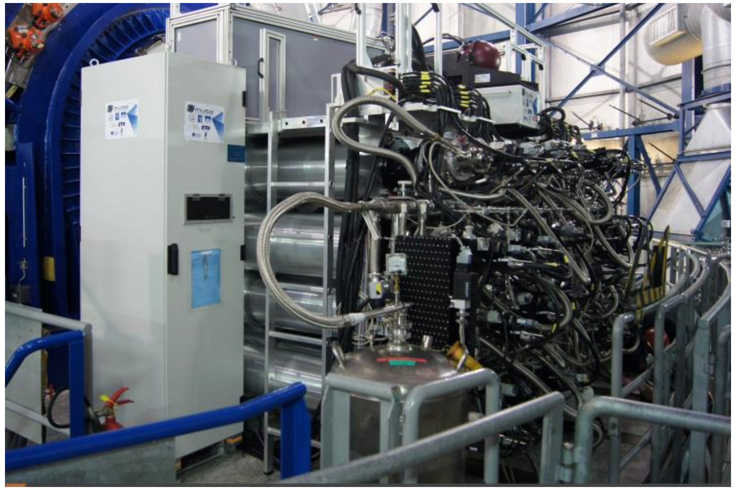
4 identical stacks of 12 spherical slices (can be polished simultaneously)
1 array of 48 spherical mirrors that combines the slices and subpupils reimaging.

Advance image slicer example 2: MUSE

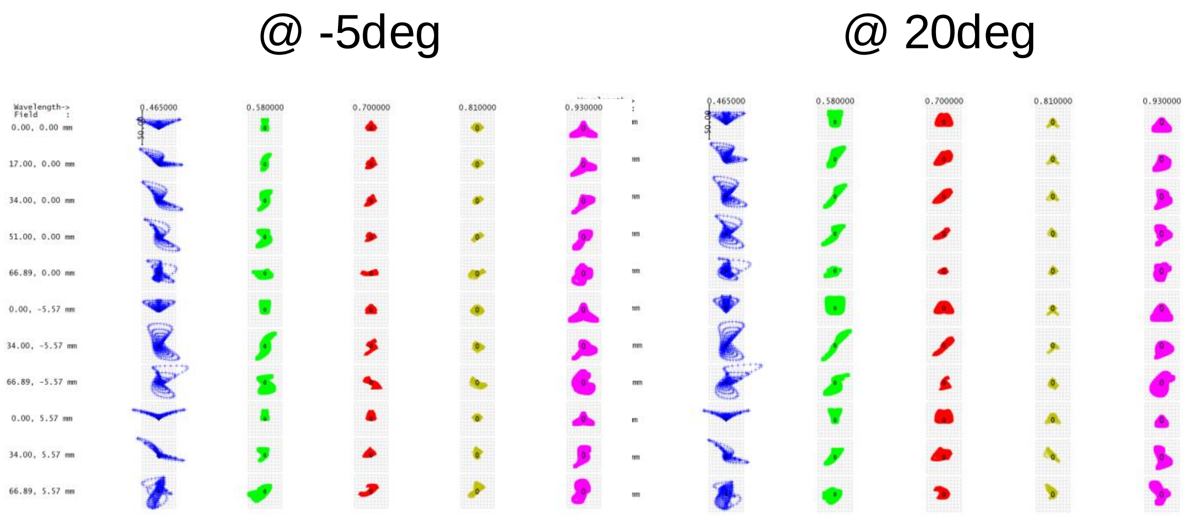
There are 24 slicers and spectrographs in the instrument to cover a large 1x1arcmin FoV

- → Important to minimize costs of the optics
- → Try to avoid any refocus over the temperature range (-5 to 15deg) of the F/2 cameras





- → Fixed format: no lateral or axial color correction needed
- → Cross optimization of collimator and camera allows the use of only 3 different glasses (cheap glasses)
- → One glass has negative Δn/ΔT balancing
- → Passive Athermalization of the design
  dZ/DT= -0.819µm by degree



Conclusion

We have seen many instruments covering Imagers, Low to high Resolution spectrographs and 3D spectrographs with some designs tricks to reduce costs, delivery time without impacting the instruments performances.

But there are many more in the Astronomical landscape that would require each a dedicated presentation:

- Telescopes designs
- Adaptive optics systems
- Interferometers
- ….

Thank you!

Johan Kosmalski

jkosmal@eso.org

@ESOAstronomy

@esoastronomy

@ESO

european-southern-observatory

@ESOobservatory

Connect with ESO