Spectroscopy

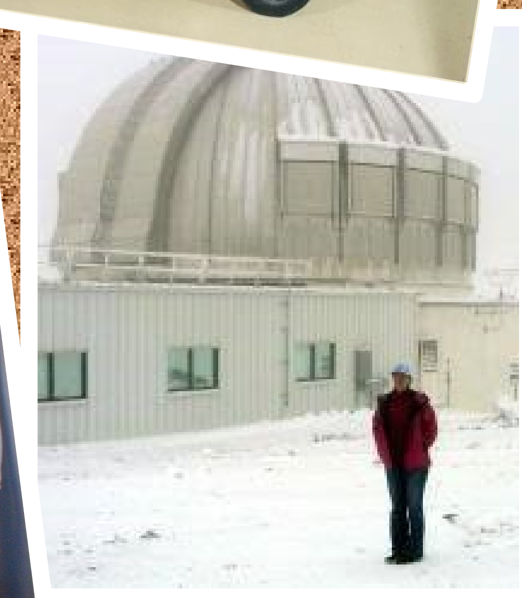
Suzanne Ramsay (sramsay@eso.org)

David Dunlap Instrumentation School,
July 2019

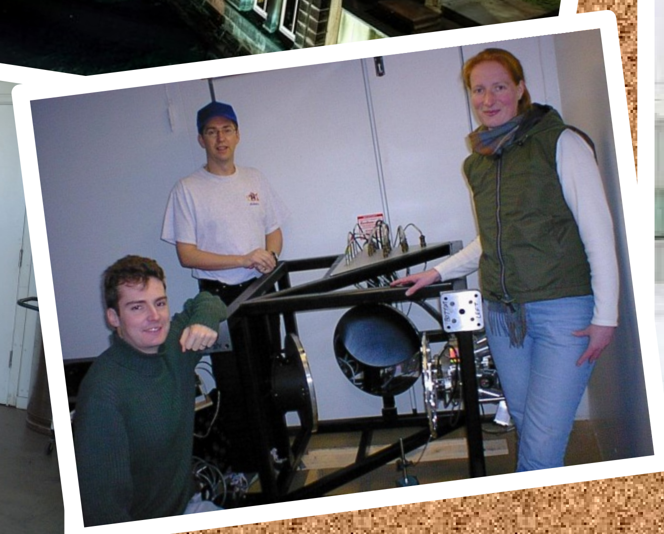
Outline of the talk

- Who am I?
  - A career in pictures
- Spectroscopy
  - Refresh: Spectrograph basics
  - Dispersion technologies in use today
  - Variations on the simple spectrograph
    - Multi-object; Integral field; Cross-dispersed; Ultra-stable
  - Back of the envelope spectrograph design
- Real life example(s): spectrographs for an Extremely Large Telescope

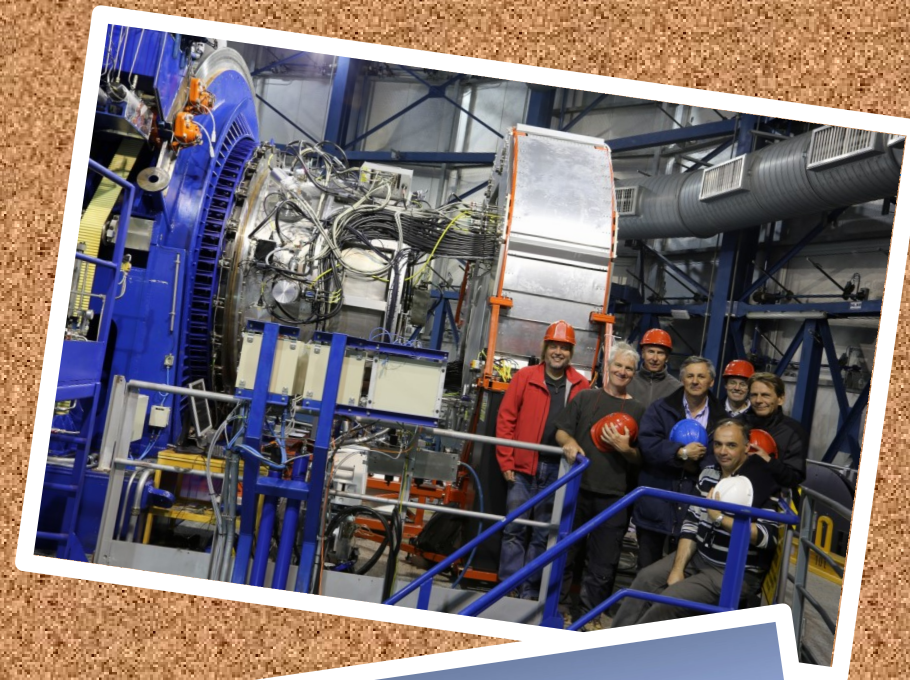
A career in pictures

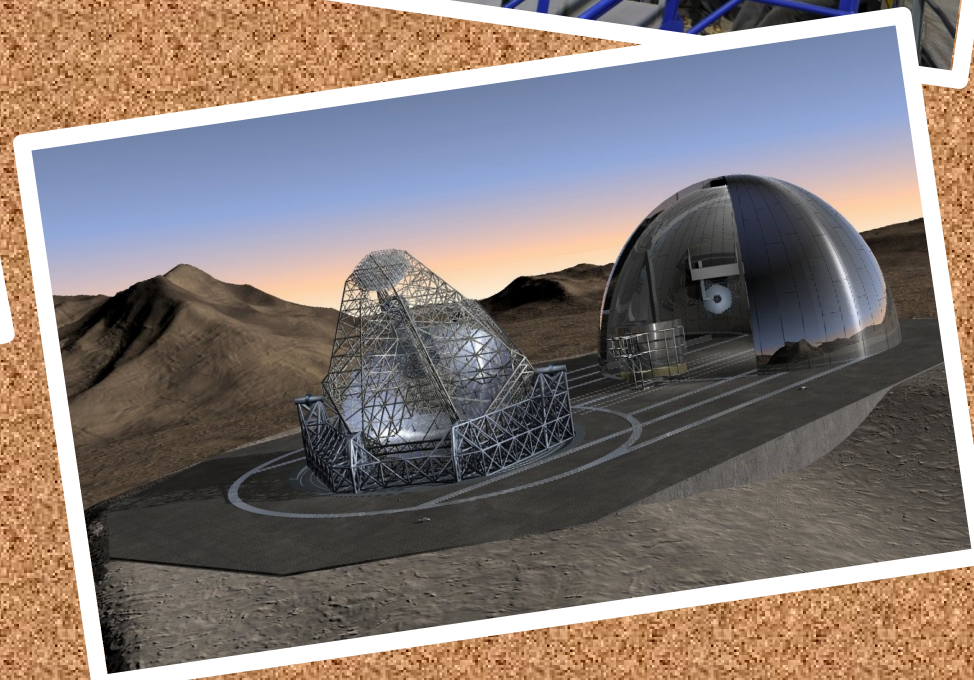



NO EXIT




NOVA
METIS
-size optomechanical design of METIS, the Mid-infrared ELT Imager and Spectrograph

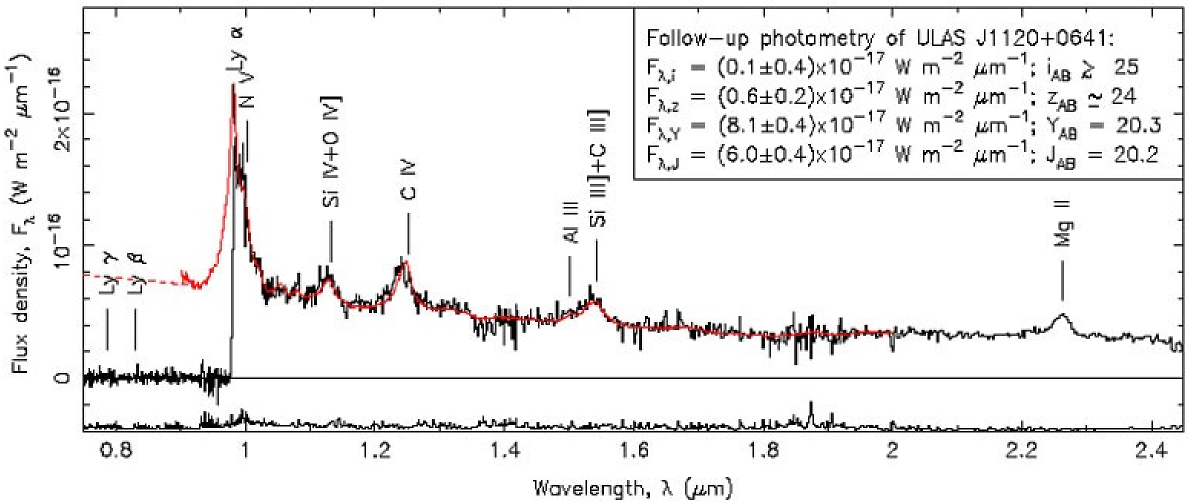




Spectroscopy

Why spectroscopy?

- Imaging informs us about what is out there and provides basic information
  - Imaging in multiple filters provides e.g. basic information about stellar temperatures or photometric redshifts
- To take the next step and start to understand the detailed astrophysics, we need to take spectra



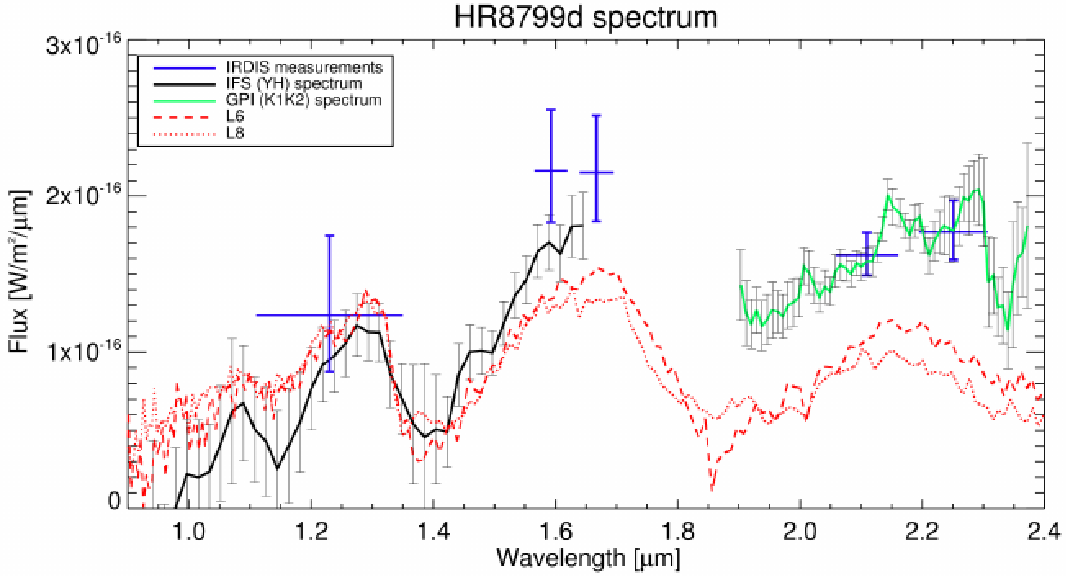
Z= 7.085 quasar; Mortlock et al. 2011

Why spectroscopy?

- Imaging informs us about what is out there and provides basic information
  - Imaging in multiple filters provides e.g. basic information about stellar temperatures or photometric redshifts
- To take the next step and start to understand the detailed astrophysics, we need to take spectra

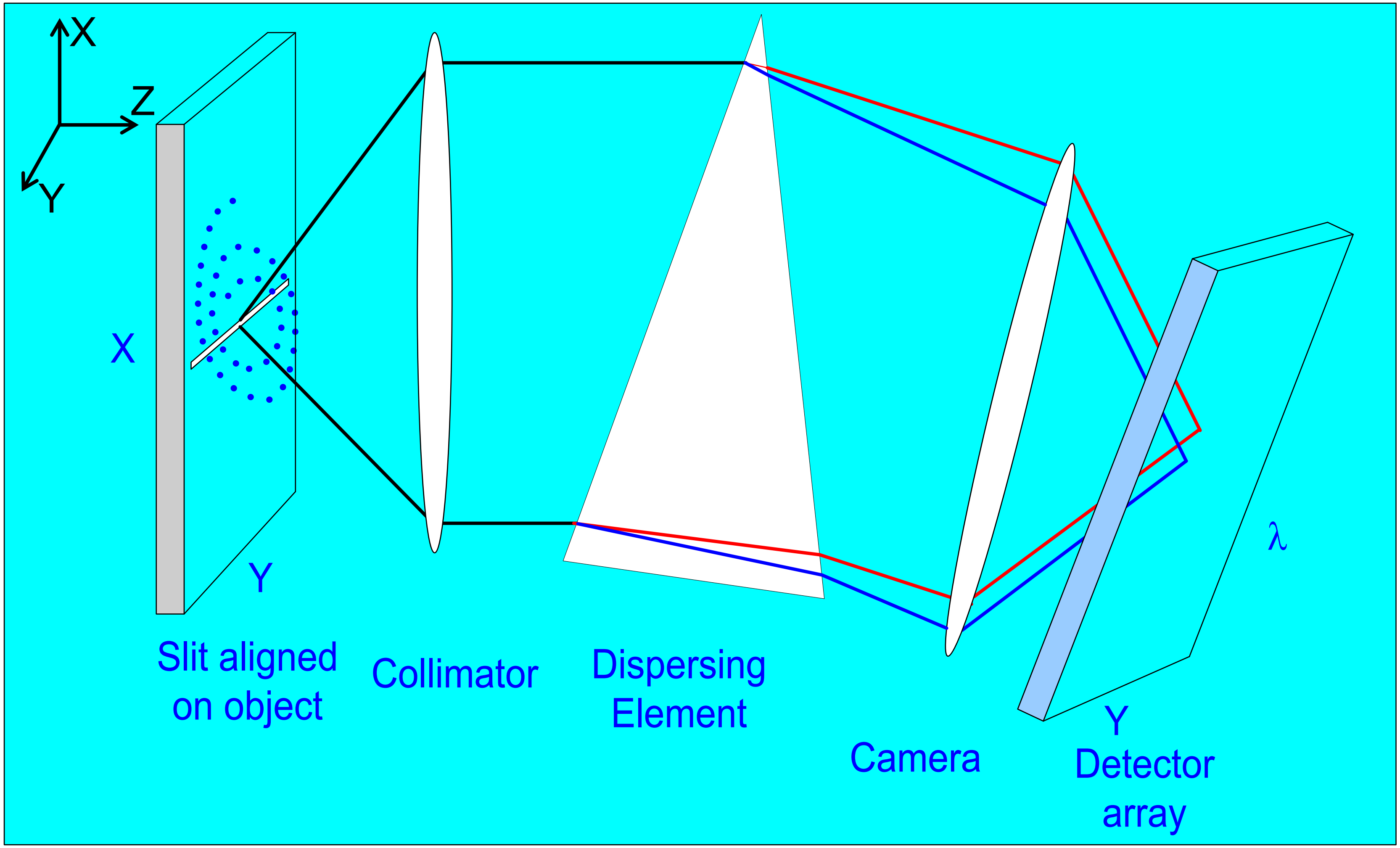
Why spectroscopy?

- Imaging informs us about what is out there and provides basic information
  - Imaging in multiple filters provides e.g. basic information about stellar temperatures or photometric redshifts
- To take the next step and start to understand the detailed astrophysics, we need to take spectra



Exoplanet spectrum compared with models of brown dwarfs, Zurlo et al. 2015

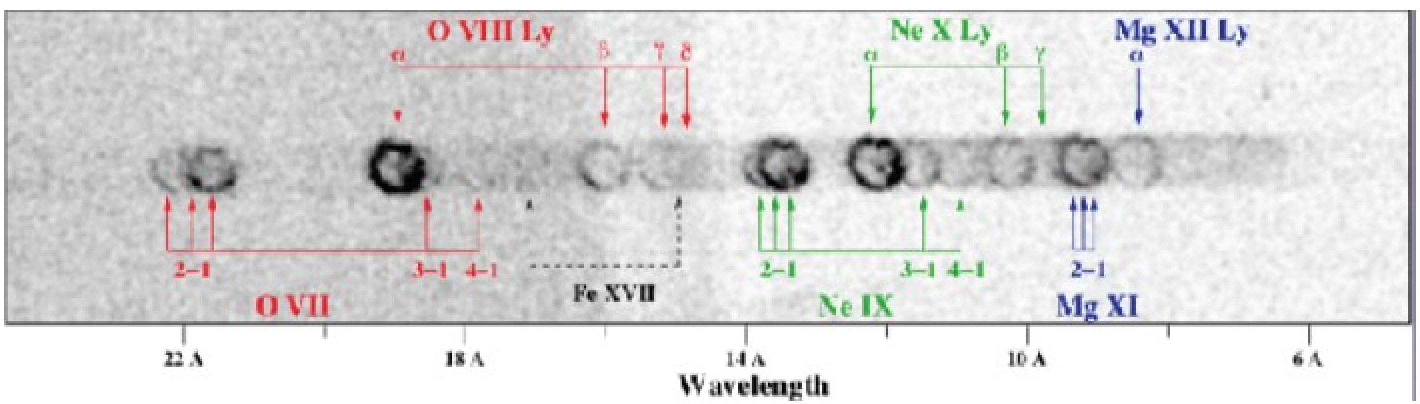
Basic Spectrometer layout

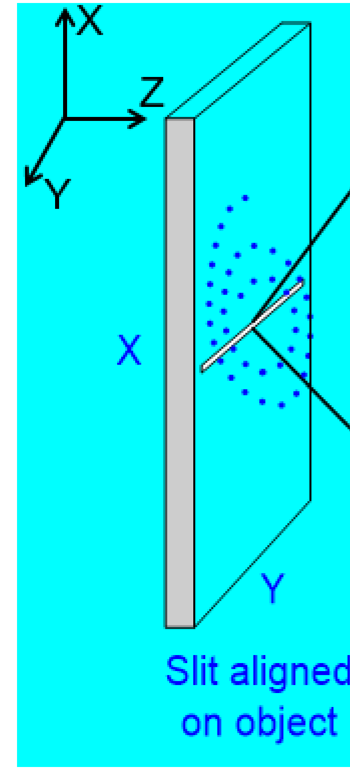


entrance aperture/slit + collimator + dispersing component
(if possible at a pupil)

Entrance slit

- The entrance slit is the ‘field stop’ for the spectrograph
  - It restricts the angles at which light enters the spectrograph
  - Controls stray-light, avoids overlap of the spectra on the detector
- ‘Slitless’ spectroscopy works well for isolated sources and low background radiation (Hubble Space Telesope, Chandra)





Flanagan et al. 2007

- At ground based observatories, the background radiation is much brighter than the astronomical targets

Optical/NIR background emission for ground-based observatories

VIRCAM raw data

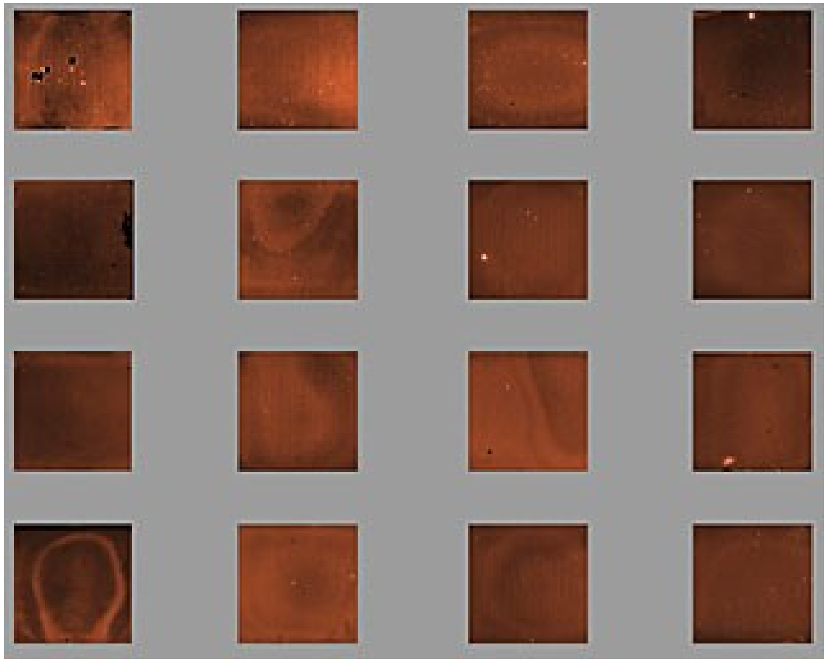
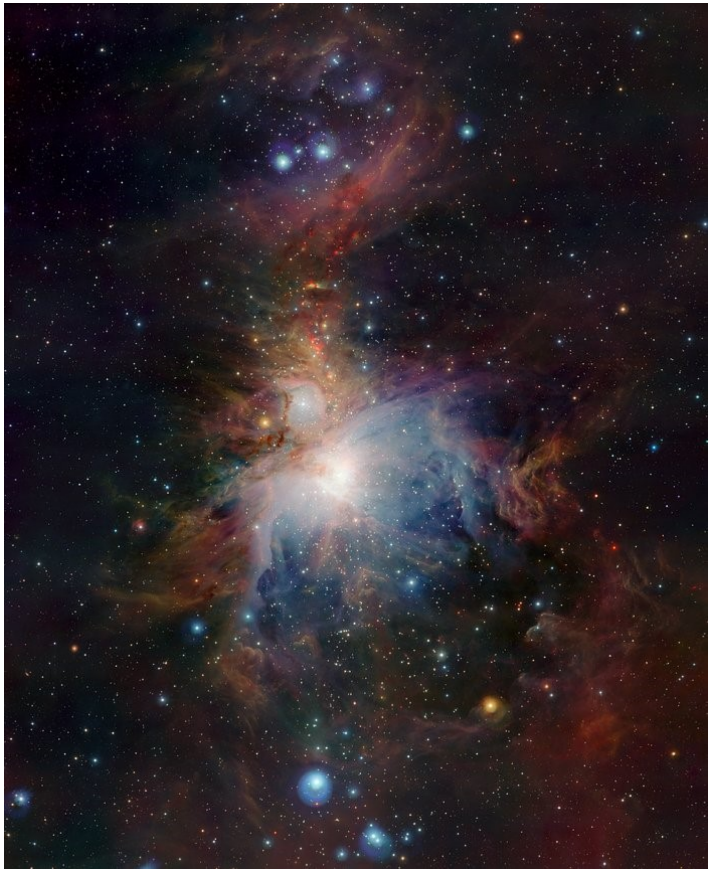


Image of the Orion (Nebula Messier 42)
Z,J,Ks filters used
1degree x 1.degree field
10minutes per filter

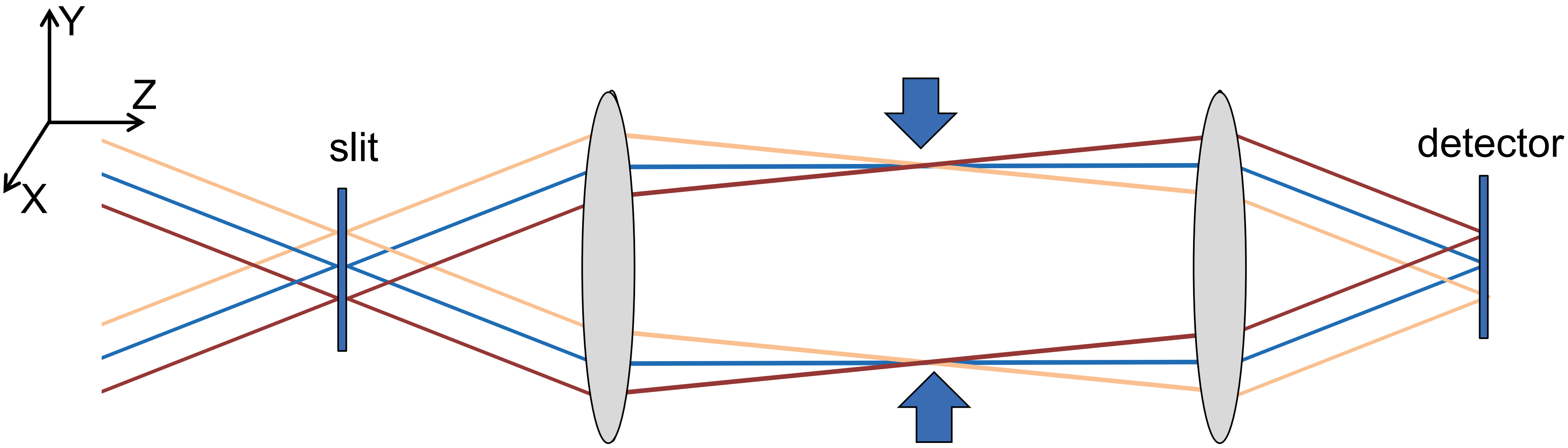
Processed image



Credit: ESO/J.Emerson/VISTA
Processing: Cambridge Astronomical Survey Unit

The pupil in any optical system

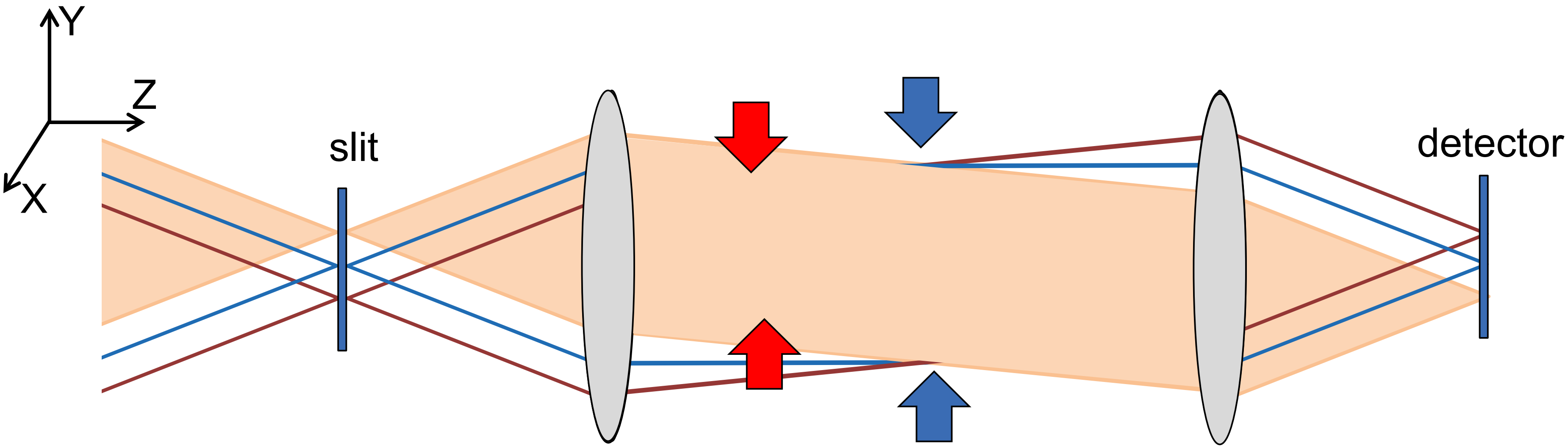
- The rays from any position along the spectrograph slit fill the pupil



- The pupil is the narrowest point along the optical train
  - A pupil or aperture stop placed here restricts the amount of light entering the optical system.
  - Gratings or filters are placed as closed as possible to the filter. Any non-uniformities in their coatings or optical quality are experienced by each point along the slit equally>>more uniform results

Vignetting

- The rays from any position along the spectrograph slit fill the pupil



- The pupil is the narrowest point along the optical train
  - A pupil or aperture stop placed here restricts the amount of light entering the optical system.
  - Gratings or filters are placed as closed as possible to the filter. Any non-uniformities in their coatings or optical quality are experienced by each point along the slit equally>>more uniform results
  - The beam is “vignetted” if something blocks the light

Conservation of étendue

- Etendue (also called throughput) must be conserved to build an efficient instrument
- At any given aperture, étendue is the product of the area of the aperture (A) and the solid angle of the rays accepted (Ω)
- In particular, for an astronomical instrument:

$$A\Omega_{tel} = A\Omega_{det}$$

Using a few assumptions and simple geometrical optics, we can calculate some important instrument parameters…..but we will get to that later….

F-number

- Focal ratio or F-number (F/#)
  - The ratio of the diameter of a lens to its focal length
  - “Fast” optics: small f-number (f/2, f/3)
  - “Slow” optics: large f-number (VLT telescope: f-17)

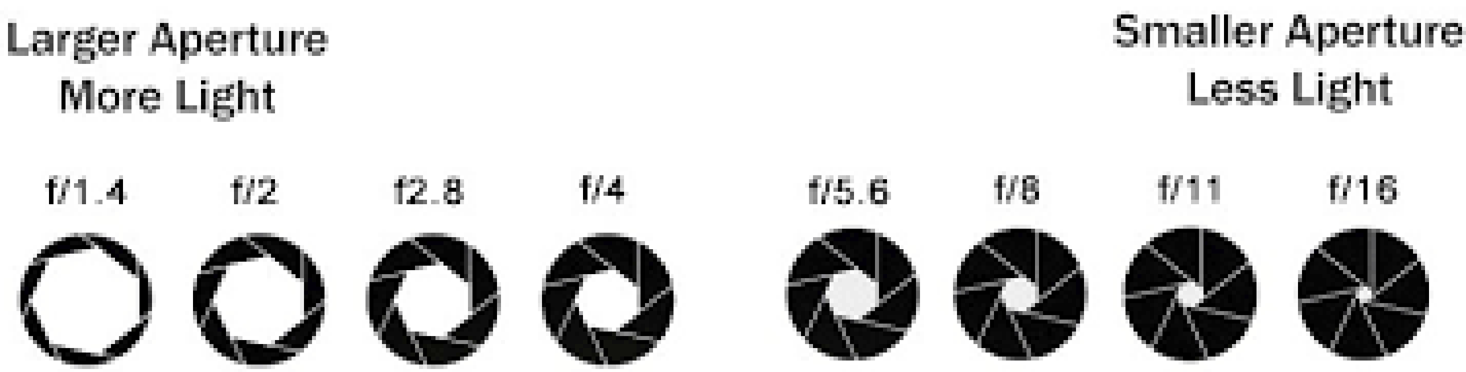
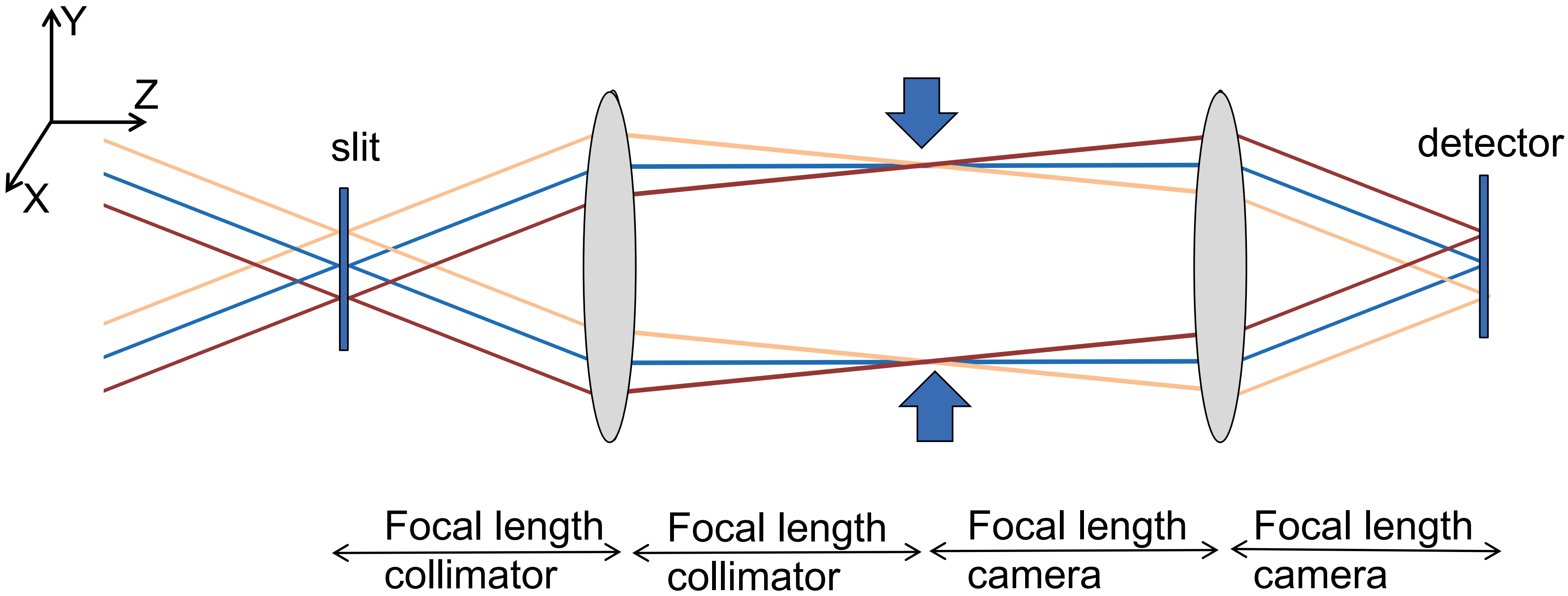


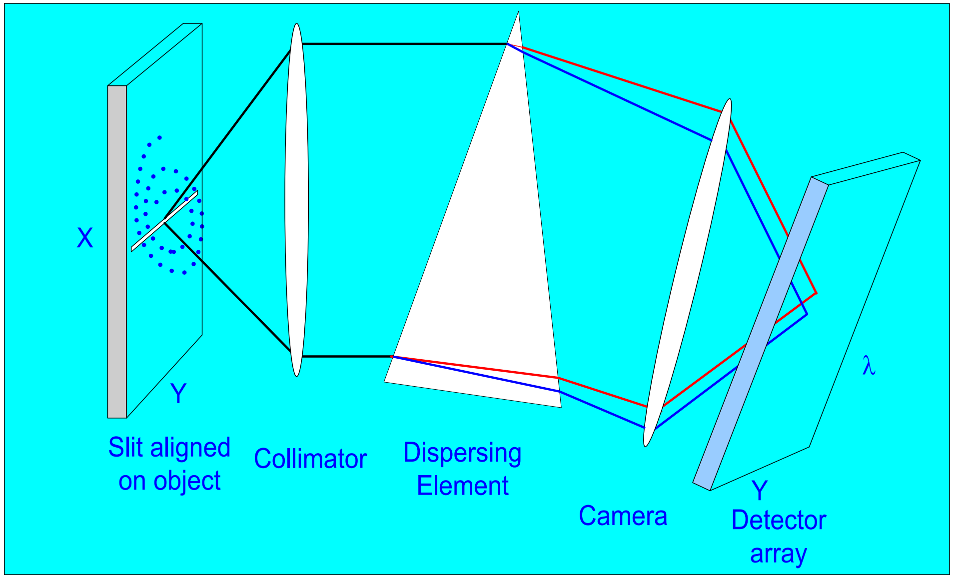
Image Credit: robin@lenscraft.co.uk
https://lenscraft.co.uk/landscape-photography-tutorials/tutorial-what-is-an-f-stop/

The pupil in any optical system

- The rays from any position along the spectrograph slit fill the pupil



Dispersing elements

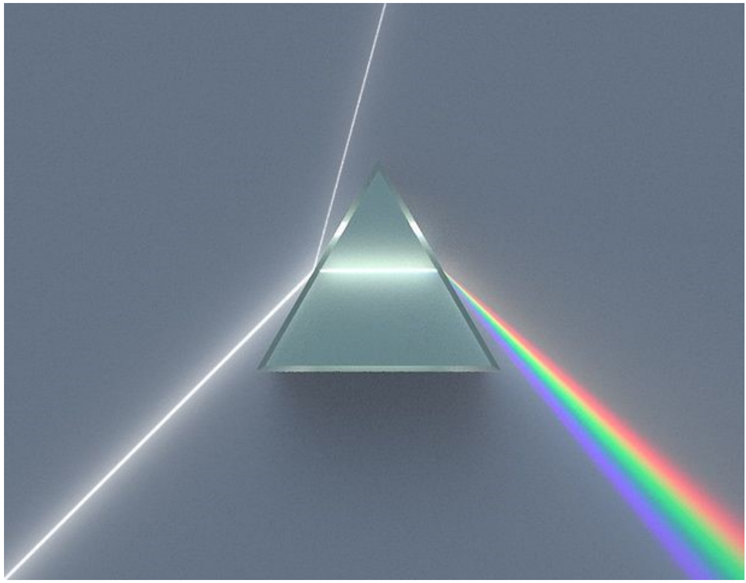


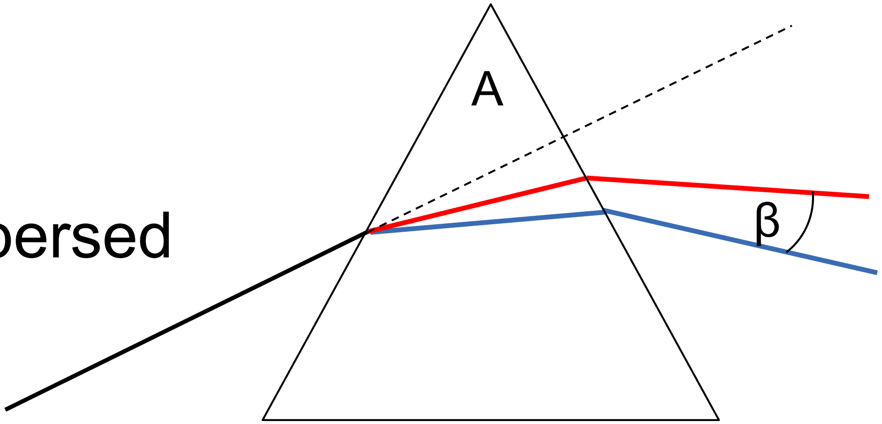
Prisms

- The starting point for thinking about spectroscopy is often the example of white light dispersed by a prism
- Angular dispersion by a prism

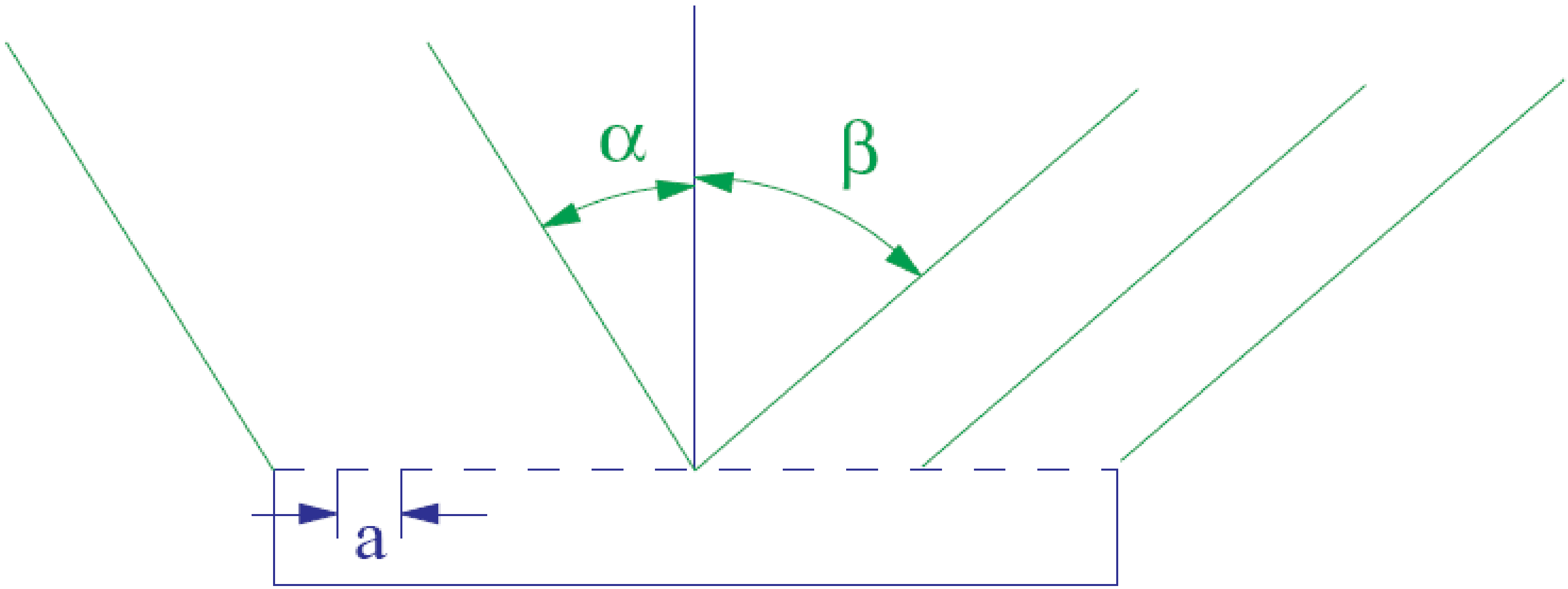
$$\frac{\partial \beta}{\partial \lambda} = A \frac{\partial n}{\partial \lambda}$$

- Hard to get high spectral resolution from a prism
  - Applications for cross-dispersed spectroscopy, see later





Diffraction by a grating



Grating equation

$$m\frac{\lambda}{a} = \sin\alpha + \sin\beta$$

Angular dispersion

$$\frac{d\beta}{d\lambda} = \frac{m}{a\cos\beta}$$

m=grating order
a=groove spacing

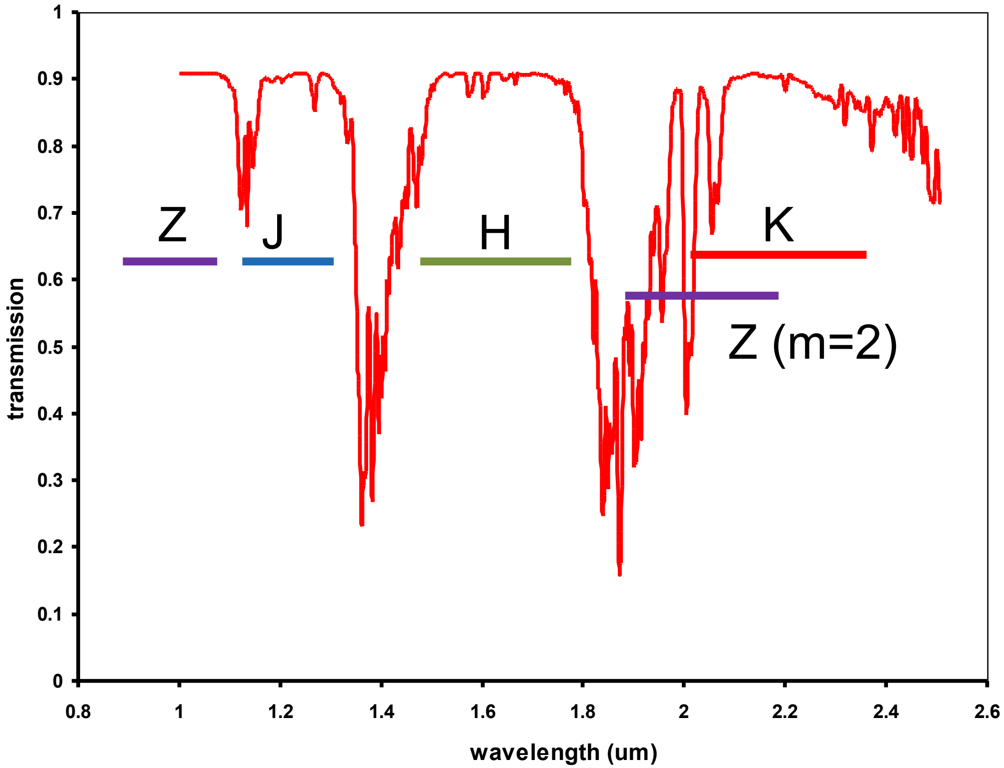
α=angle of incidence
β=angle of diffraction

typical a ~ few μm
Few hundred grooves/mm

Diffraction by a grating

$$m\frac{\lambda}{a} = \sin\alpha + \sin\beta$$

For the same α, β there is more than one combination of m, λ
>> different wavelengths from different orders will overlap at the detectors



Near-infrared windows/bands:

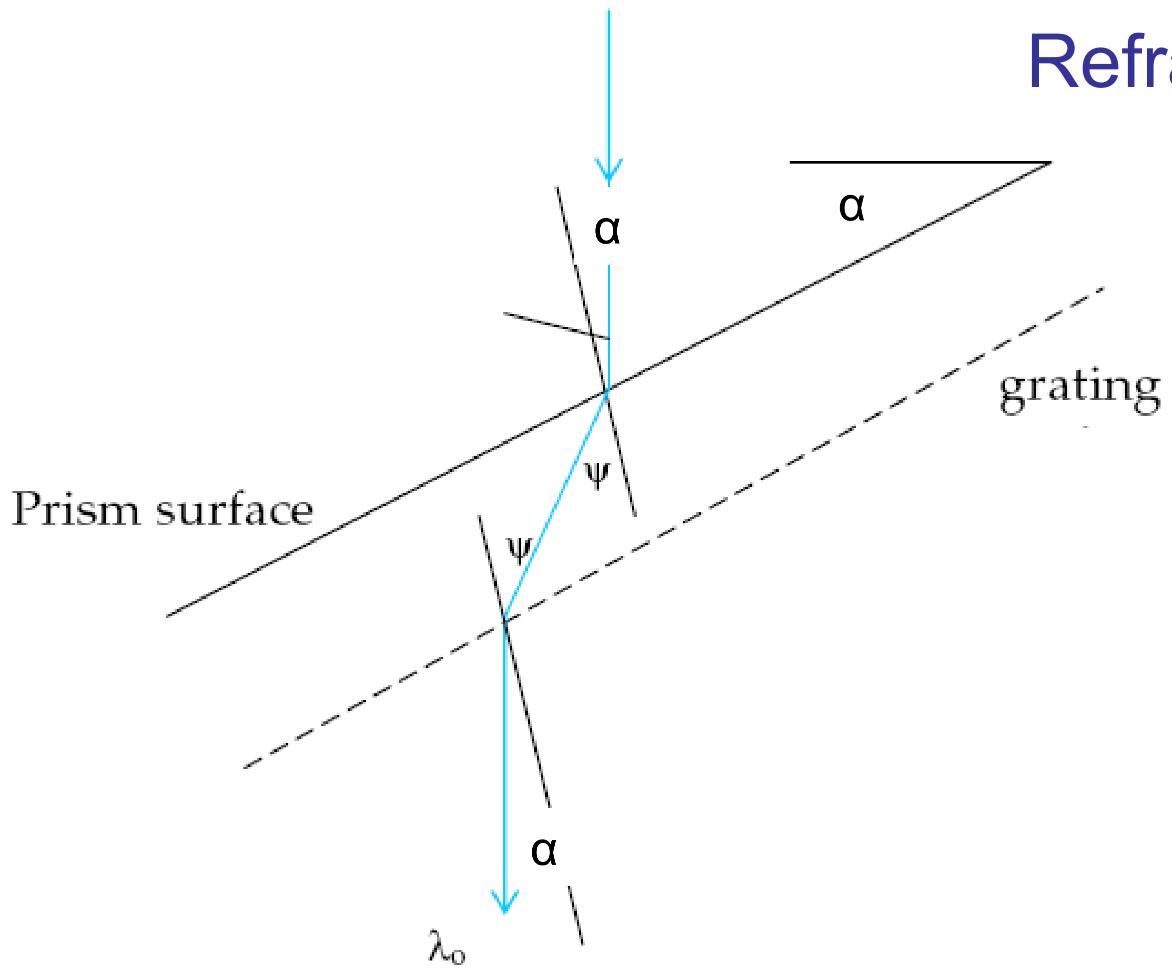
Z – 0.93 μm – 1.015 μm – 1.10 μm
J – 1.17 μm - 1.25 μm – 1.33 μm
H – 1.49 μm - 1.64 μm – 1.780 μm
K – 2.03 μm - 2.2 μm – 2.370 μm

Z-band in second order:

Z (m=2) – 1.86 μm – 2.20 μm

Solution? Order sorting:
Use it: cross-dispersion
Loose it: blocking filters

Grisms



Refraction in the prism:

$$\sin\Psi = n\sin\alpha$$

n from the grating(*):

$$= d(\sin\alpha - \sin\beta)$$

rism' equation:

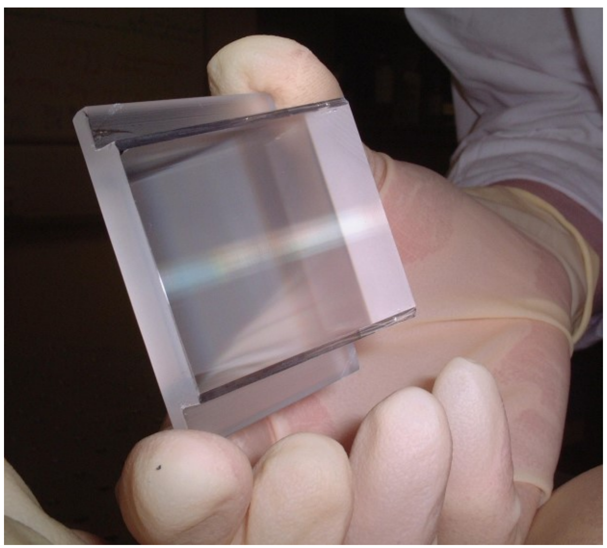
$$= (n-1)d\sin\alpha$$

NB: dependence on the refractive index of the glass

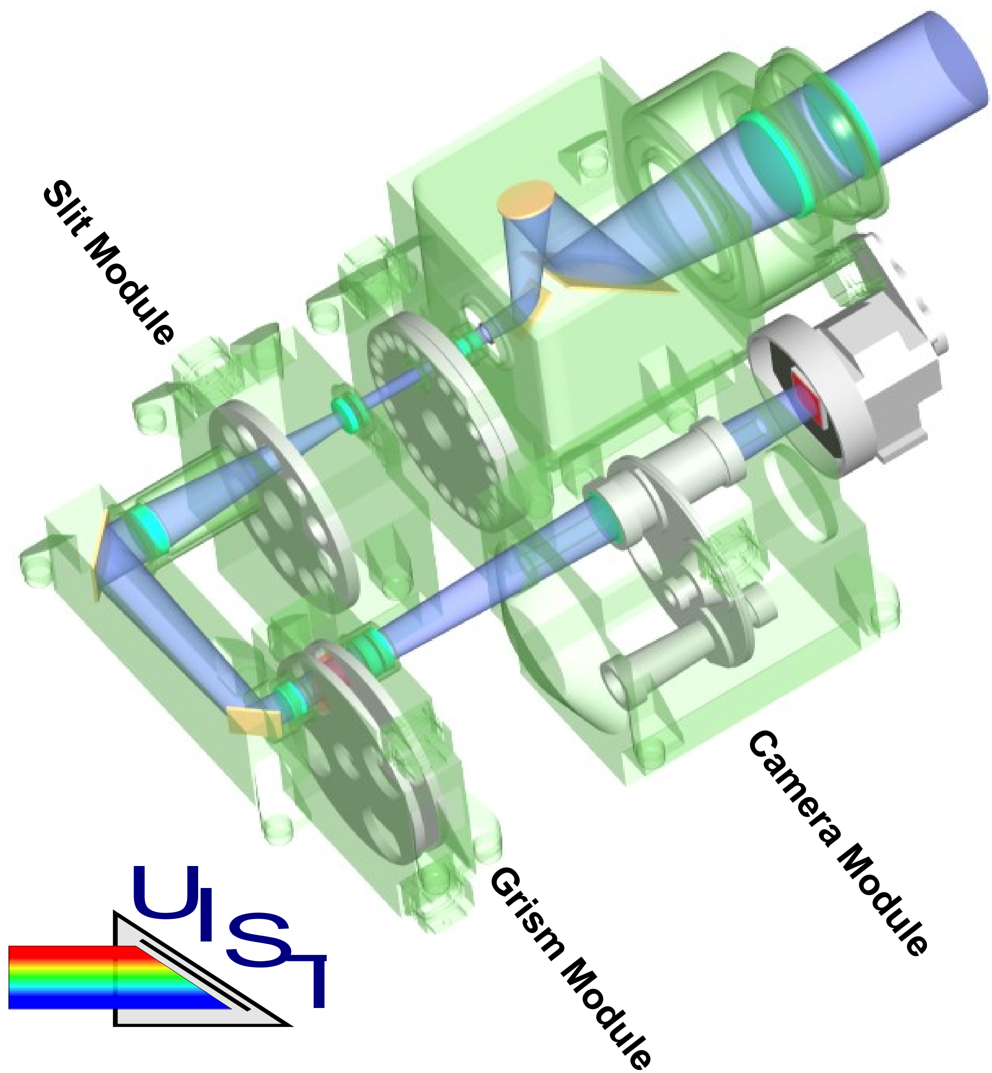
(*) grating equation for a grating used in transmission

Grisms

- Advantages
  - Compact
  - simplified instrument layout
  - *Potential* for higher R for a given beam size

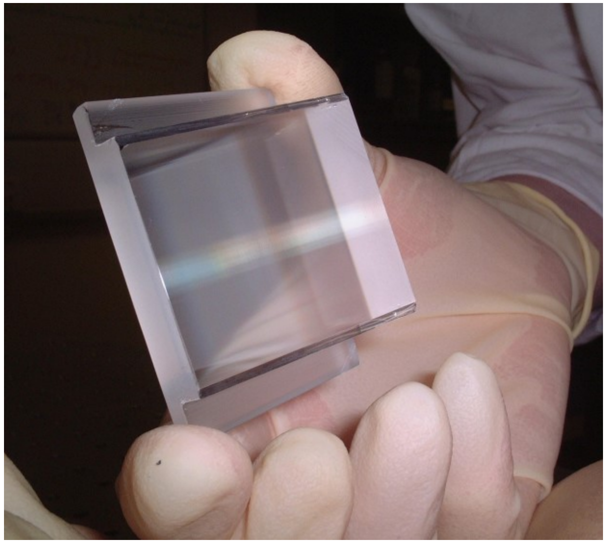


A fused silica grism (from Hyperfine), grating replicated onto the front surface



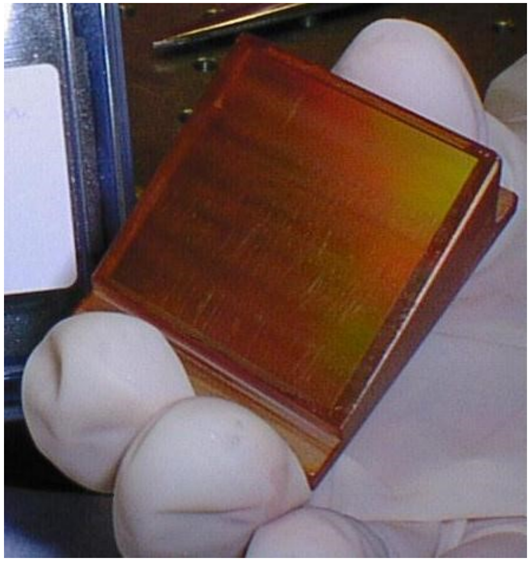
Grisms

- Advantages
  - Compact
  - simplified instrument layout
  - *Potential* for higher R for a given beam size



A fused silica grism (from Hyperfine), grating replicated onto the front surface

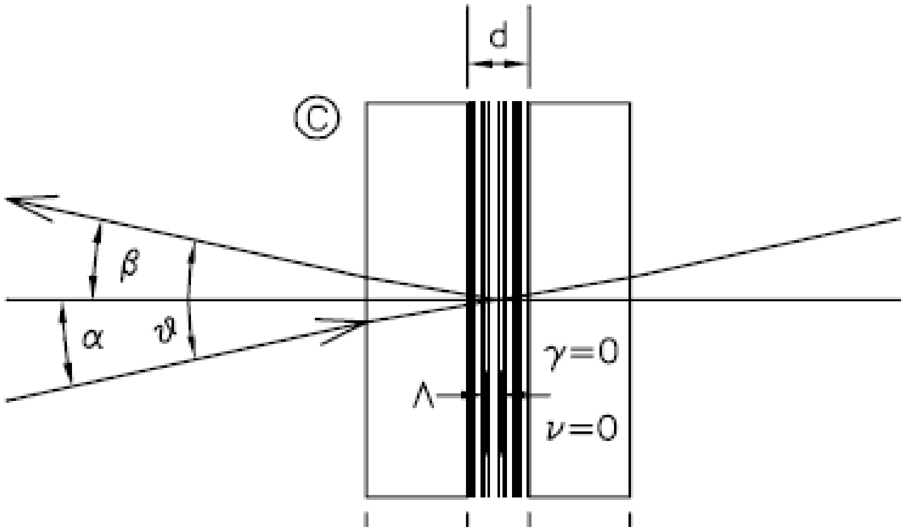
- Disadvantages:
  - difficult materials
    - Fused silica, n=1.45 (NIR)
    - (HST) CaF_2, n=1.45 (NIR)
    - KRS5, n=2.4 (NIR)
  - Relatively low transmission (60%)

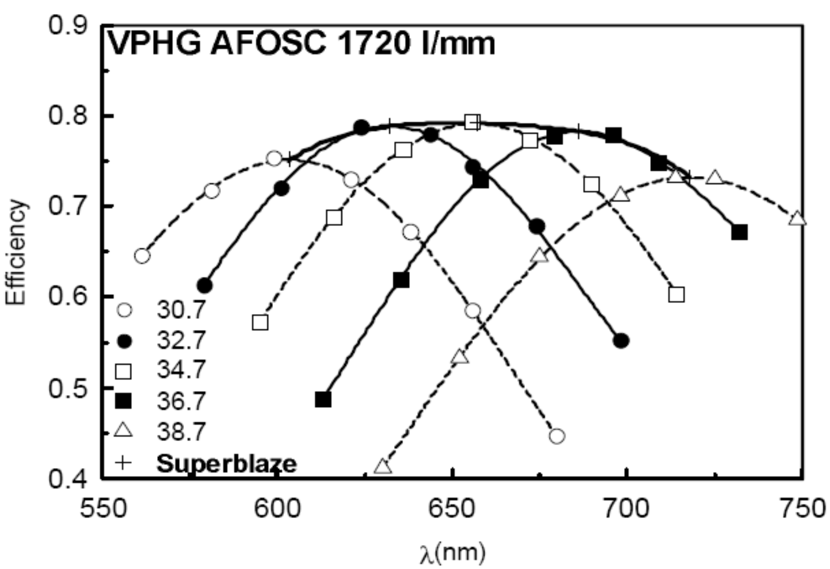


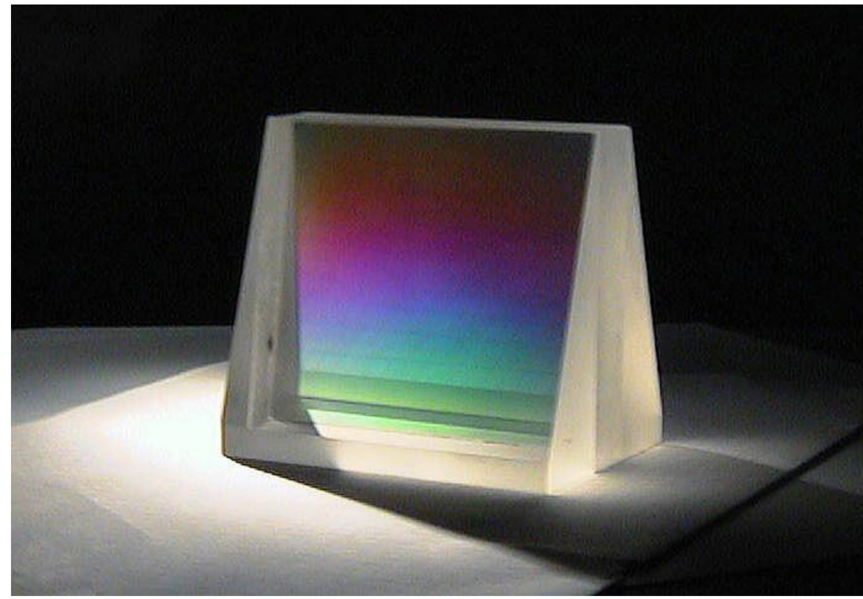
A grism made from KRS5, mechanically ruled grating (from Zeiss, Jena)

Volume Phase Holographic gratings

$$m\nu\lambda = \sin(\alpha) - \sin(\beta)$$







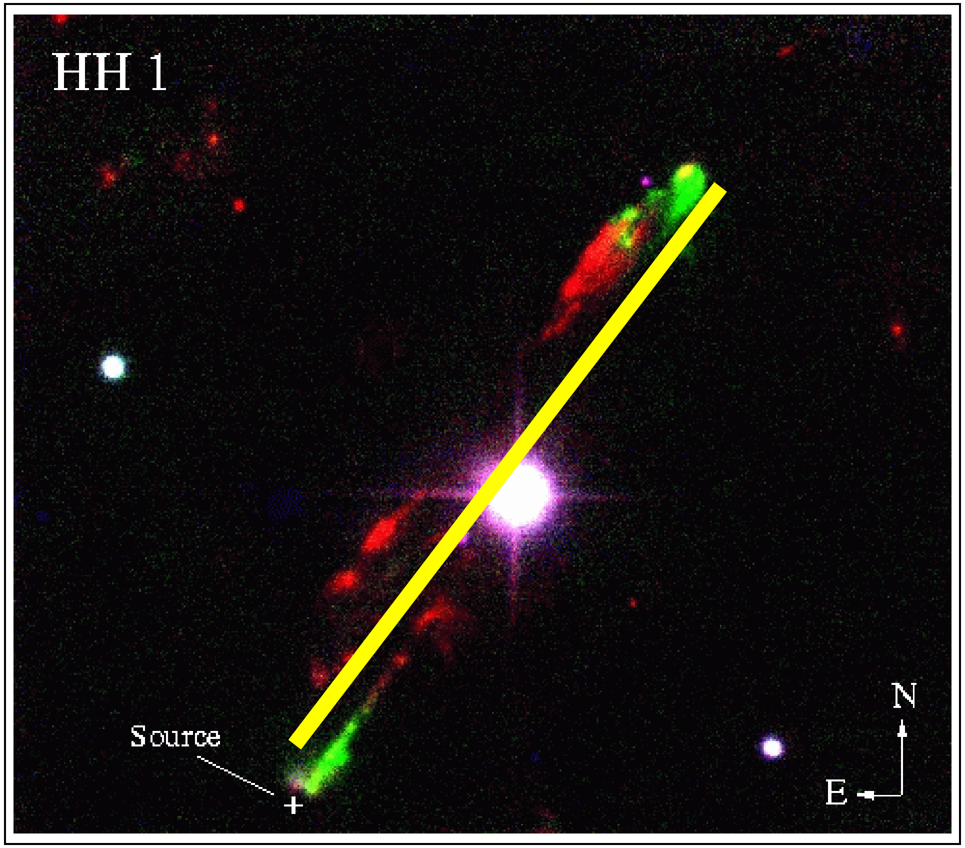
Use for astronomy proposed about 20 years ago (Barden et al 1998); now standard for modern opt-IR spectrographs.

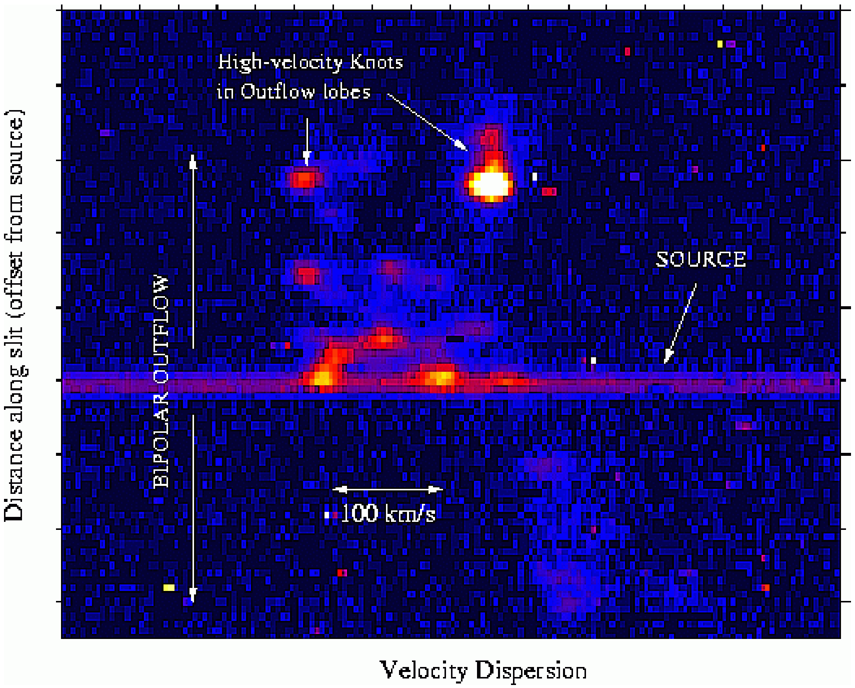
Very high efficiency.

Variations on the classical spectrograph

The long slit: strengths/weaknesses

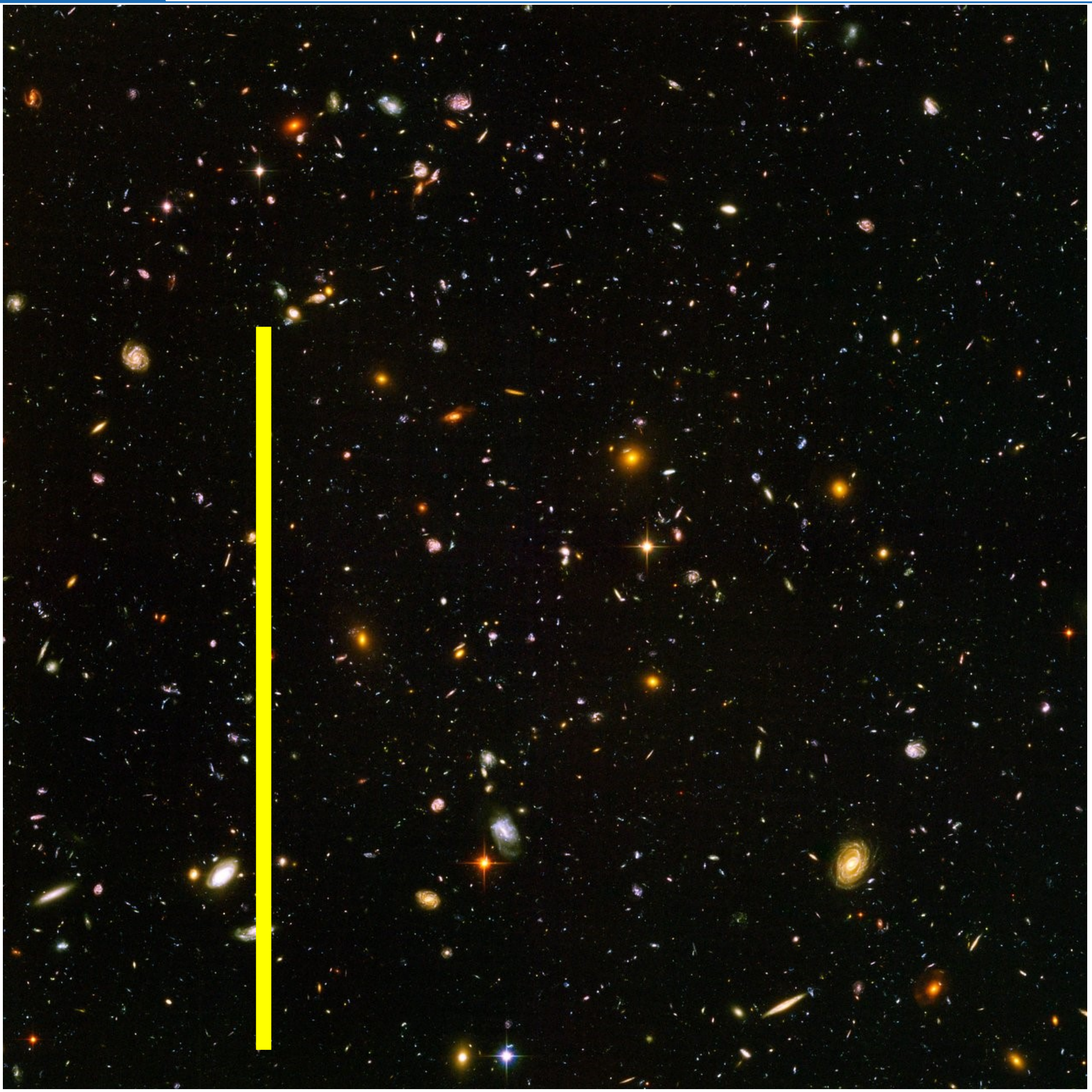
- With typical plate scales of 0.2arsec/pixel and 2048 x 2048 pixel detectors, modern spectrometers have slit lengths of 120arcmin
- Some very beautiful astronomical objects will fill this slit, but many not!





Data courtesy UK Infrared Telescope, Tom Ray and Chris Davis

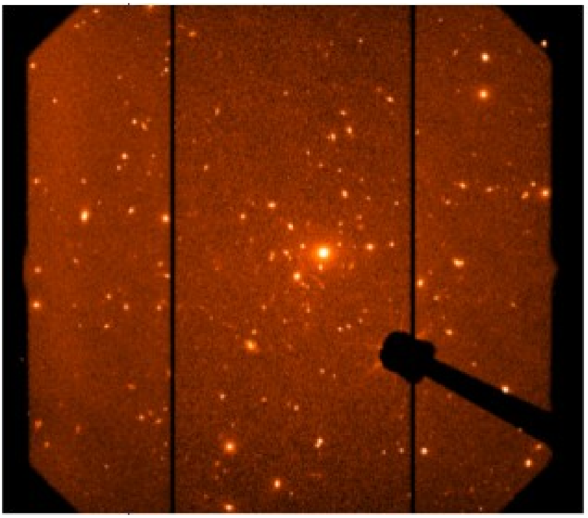
A more typical set of objects

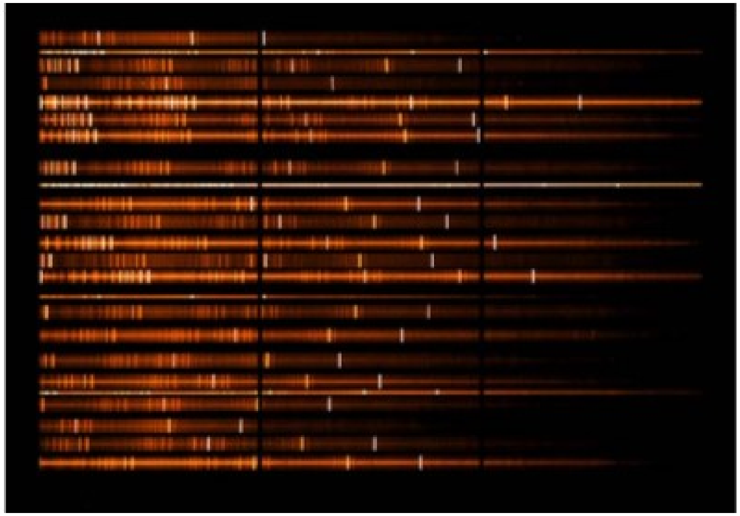


- This is the Hubble Ultra-Deep field, filled with almost 10,000 galaxies at of all ages (all redshifts)
- The image is 3.1arcmin x 3.1 arcmin
- Multi-object spectroscopy offers a more efficient solution for observing a field like this
- (but not 10s of thousands of objects….100s of objects)

Multi-object spectroscopy (1)

- Multi-object spectroscopy with slit masks





Pre-imaging may be required to map or identify objects

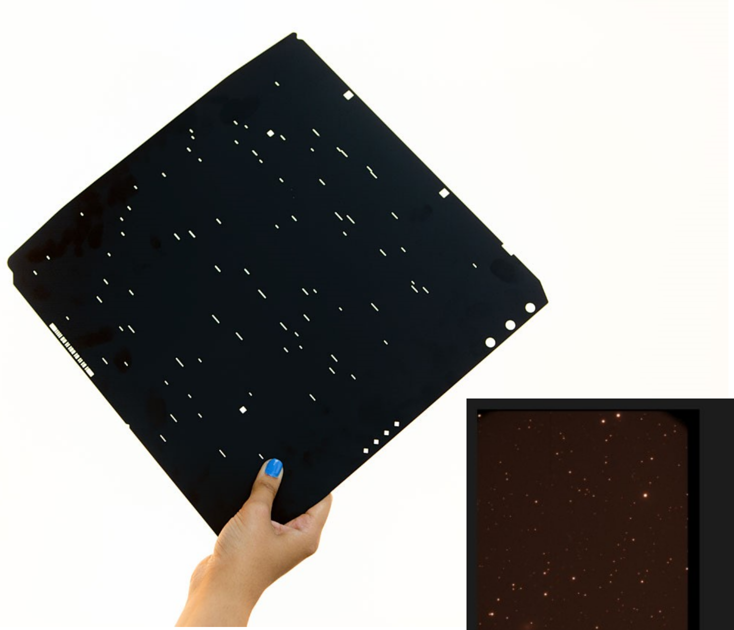
A slit mask is made with slitlets for each target and inserted into the instrument focal plane

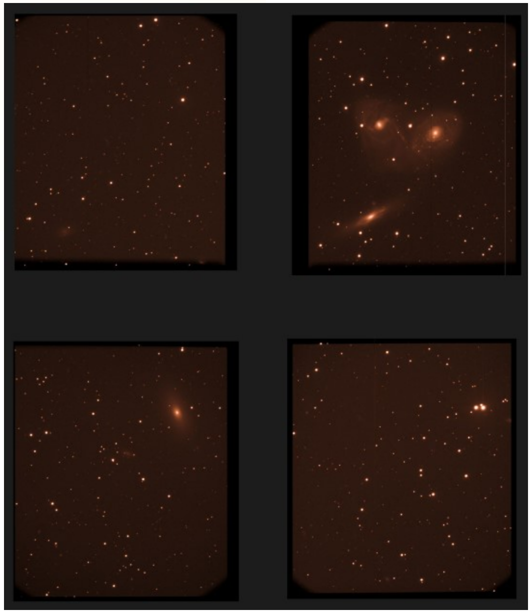
Spectra of the multiple objects are obtained with excellent useage of the array and some restrictions on the object selection

Images are from the Gemini multi-object spectrograph

Multi-object spectroscopy (2)

- VIMOS at ESO’s 8-m Very Large Telescope

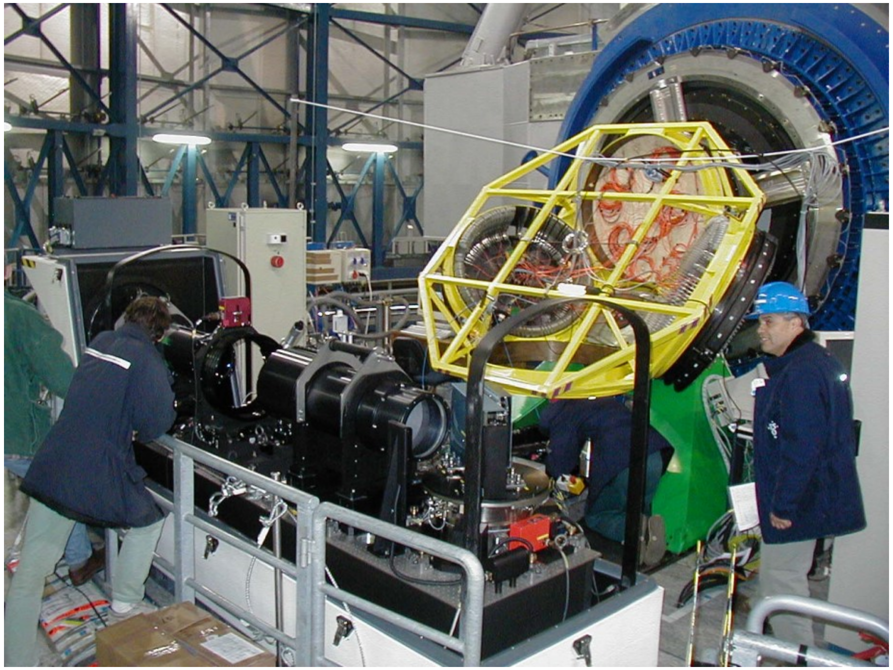




Slit (mask) spectrographs are sensitive to faint objects. VIMOS was designed with galaxy surveys in mind. e.g. VIPERS (vipers.inaf.it)

Multi-object spectroscopy (3)

- Multi-object spectroscopy with fibres: FLAMES



The OzPoz fibre coupled to the GIRAFFE or UVES spectrographs are ideally suited to surveys of stars e.g. the GAIA-ESO survey to 10^5 sources (www.gaia-eso.eu)

Back to our galaxy field

- MOS spectrographs can survey wide areas taking integrated light spectra of hundreds of objects
- But astronomers are also interested in the details of the assembly and evolution of these galaxies
- For this, spatially resolved observations of these small objects is desired
- >> integral field or 3D spectroscopy is ideal for this….

Integral Field Spectroscopy

- Integral field or 3D spectroscopy

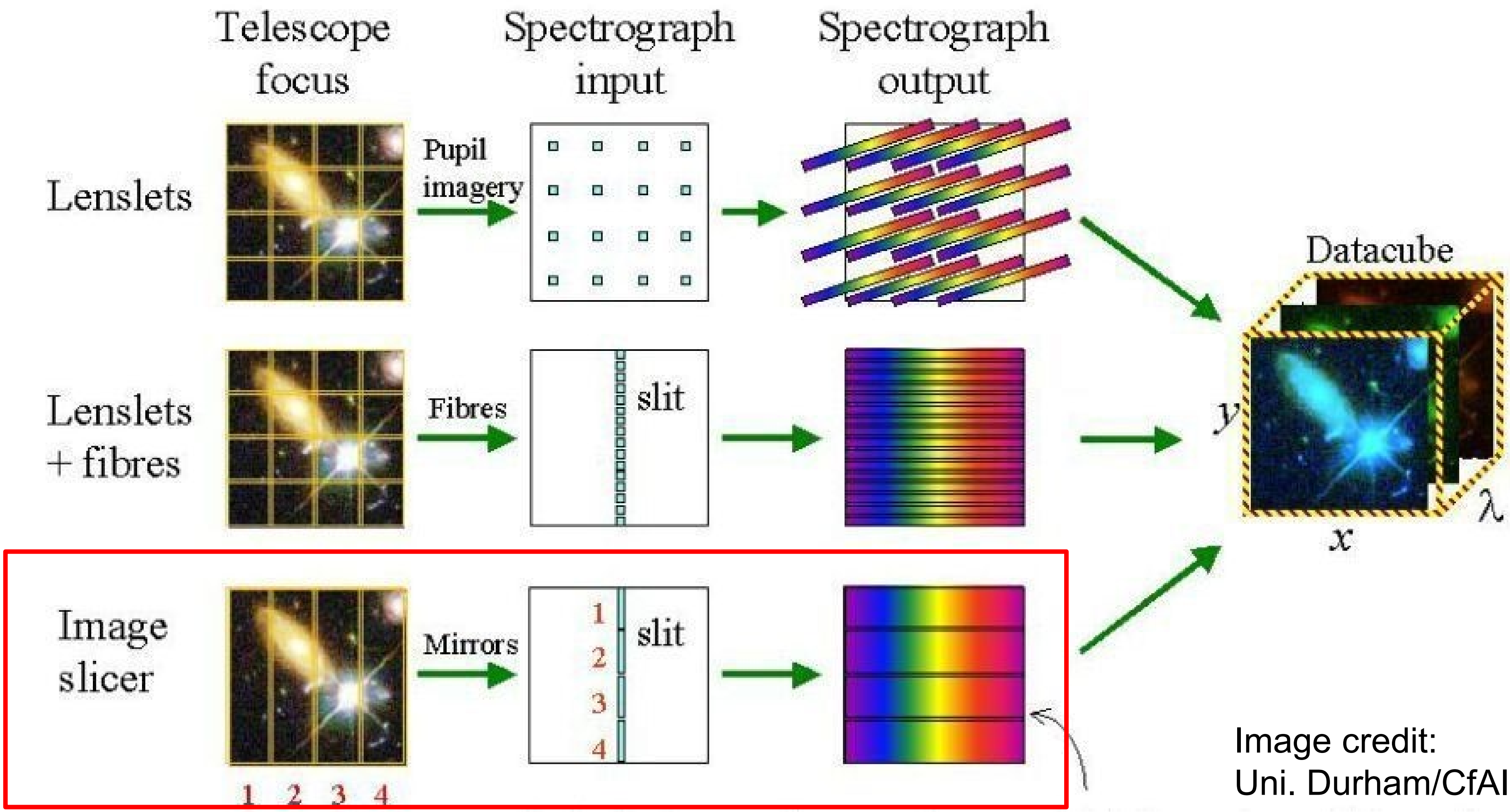


Image credit:
Uni. Durham/CfAI

Data cube from the UIST IFU

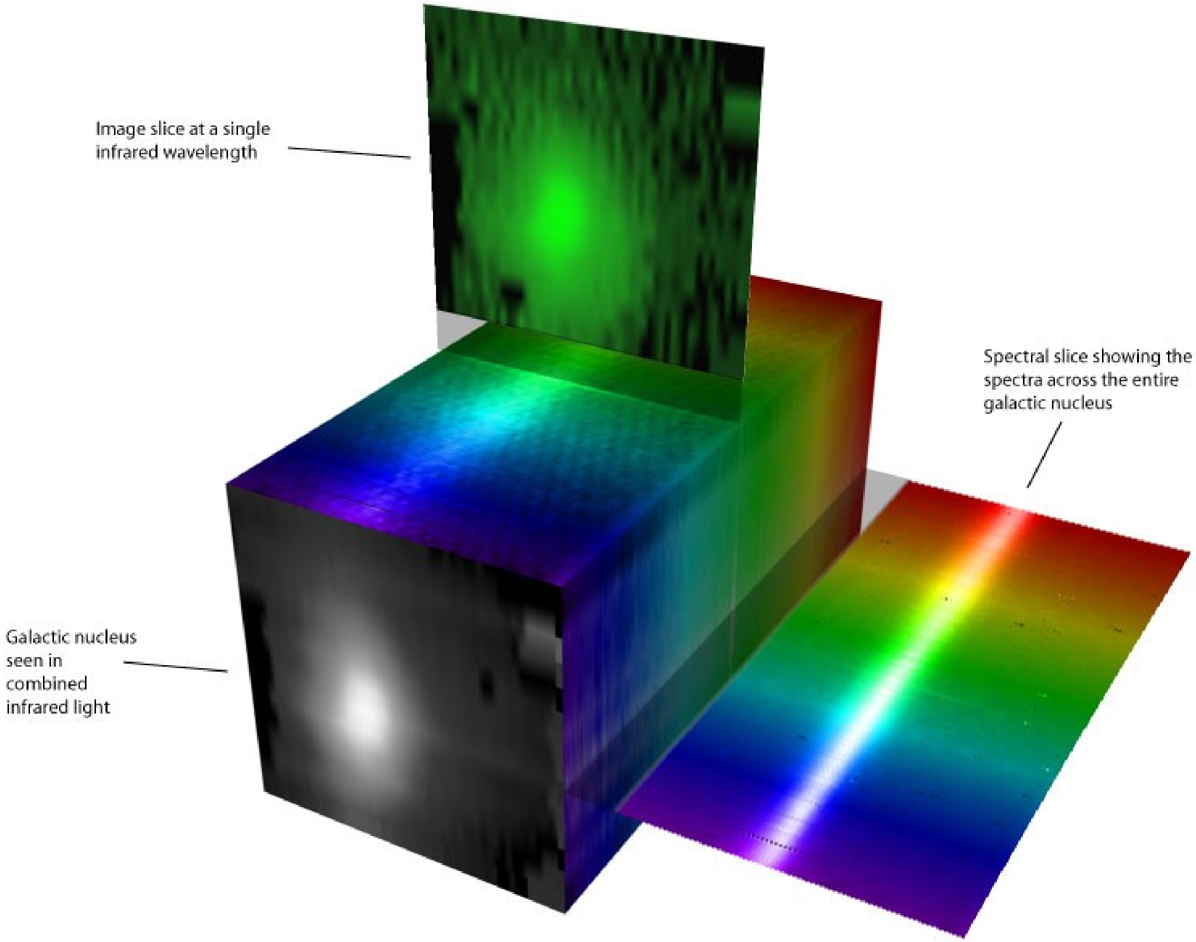
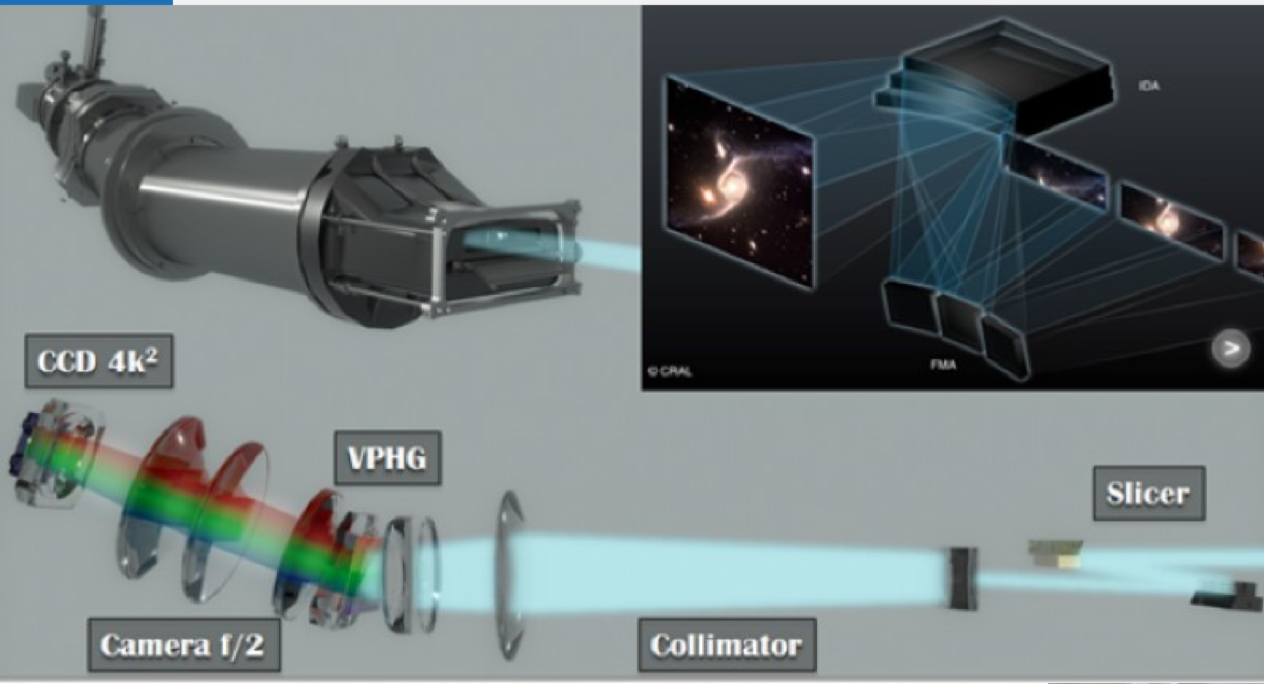
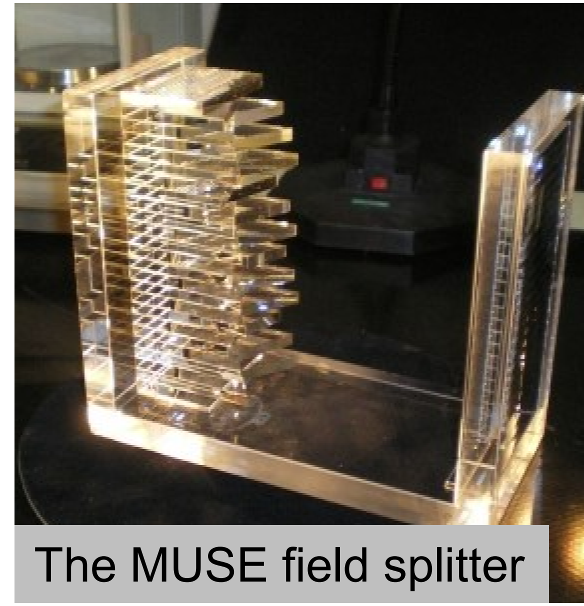


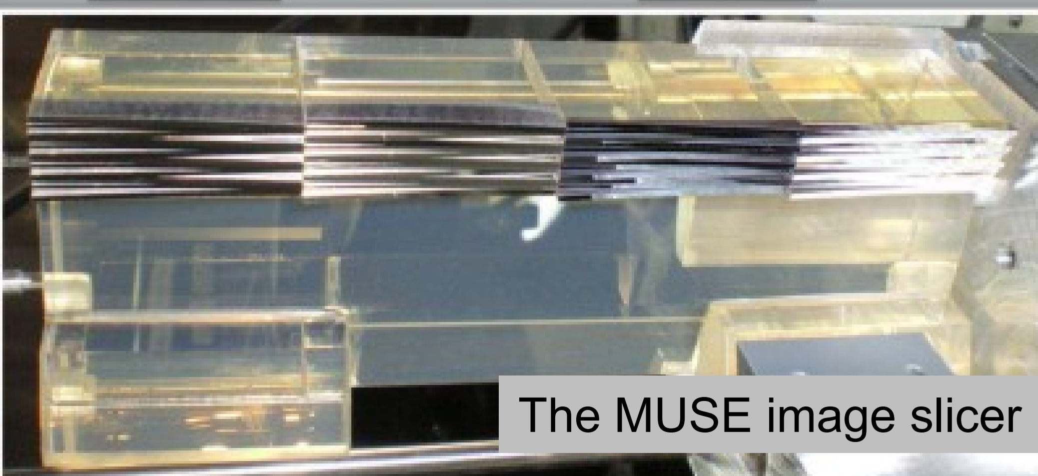
Image: Stephen Todd, ROE and Douglas Pierce-Price, JAC

MUSE at the VLT





The MUSE field splitter



The MUSE image slicer

MUSE at the VLT

The Pillars of Creation as observed by HST
http://hubblesite.org/image/3471/news_release/2015-01

The Pillars of Creation as observed by MUSE. Three colour images extracted from the datacube.

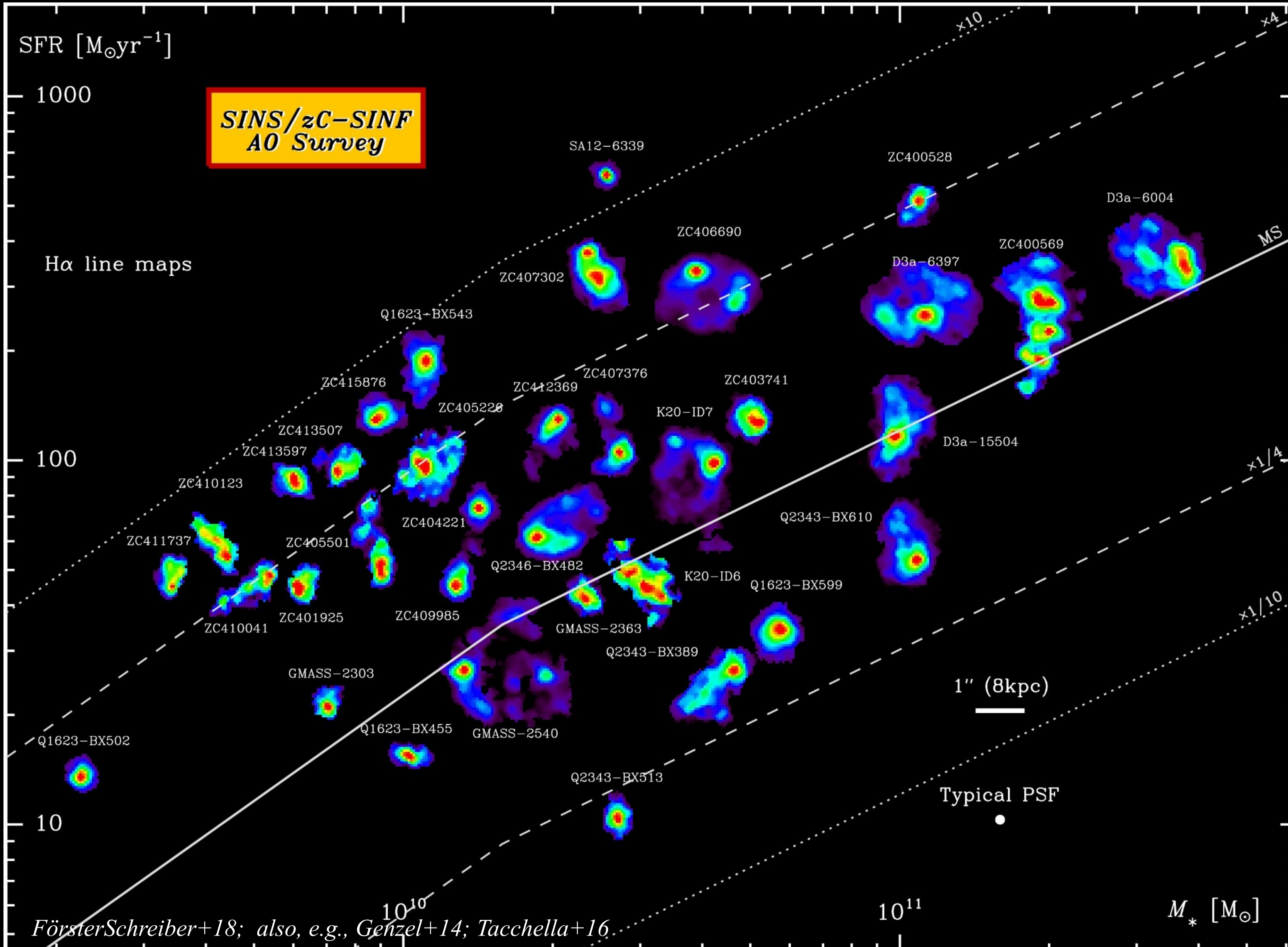
Mcleod et al (2015)

The MUSE ultra-deep field

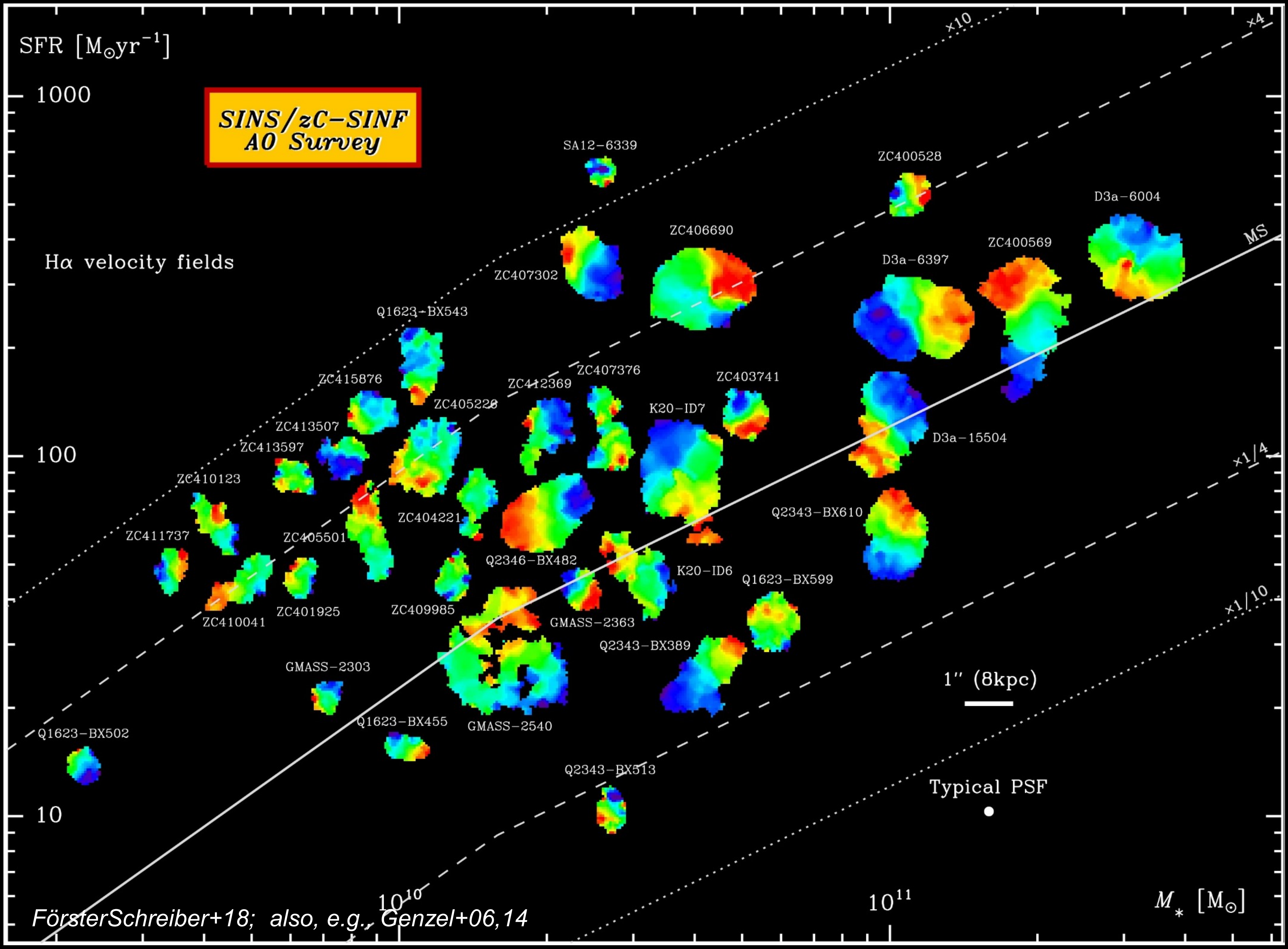
There is a spectrum for every pixel in this image!

10h exposure; 9 x the MUSE 1arcmin field of view.

1600 galaxies of which 72 not detected by HST (Lyman-alpha emitters).



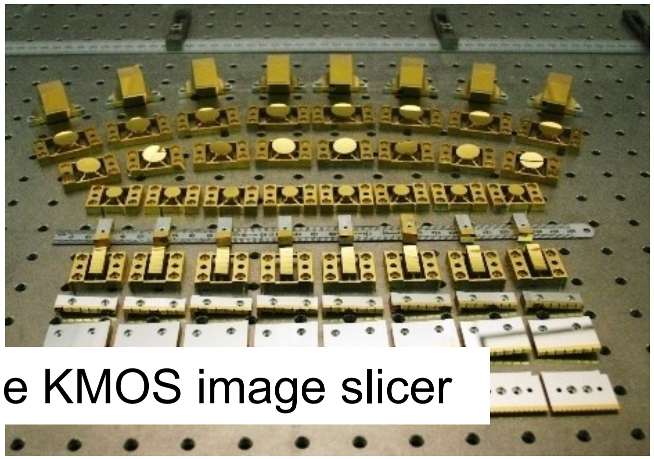
FörsterSchreiber+18; also, e.g., Genzel+14; Tacchella+16



FörsterSchreiber+18; also, e.g., Genzel+06,14

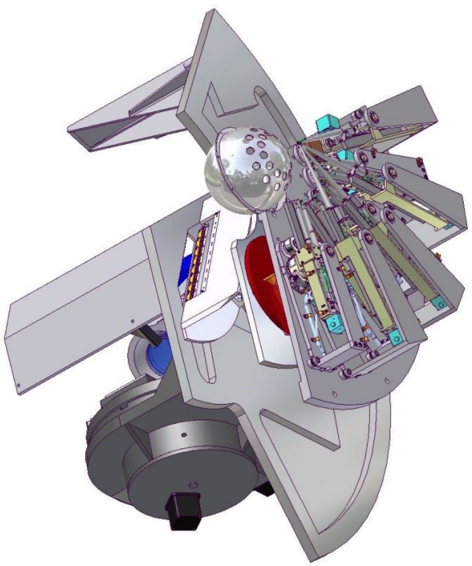
Multi-IFU spectrographs

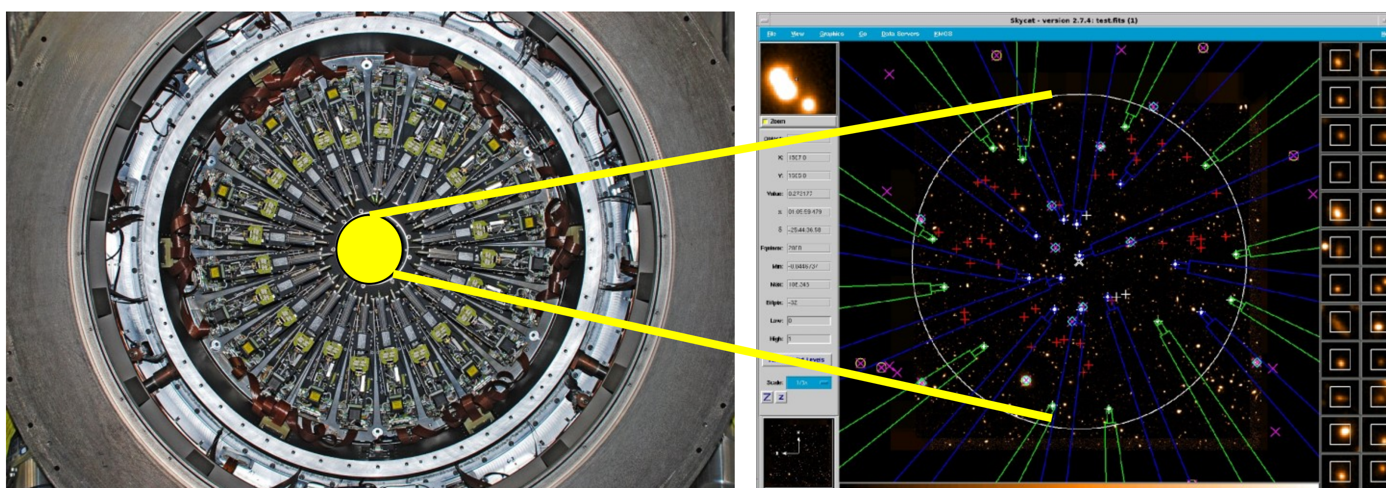
- Multi-IFU spectroscopy in the NIR with KMOS

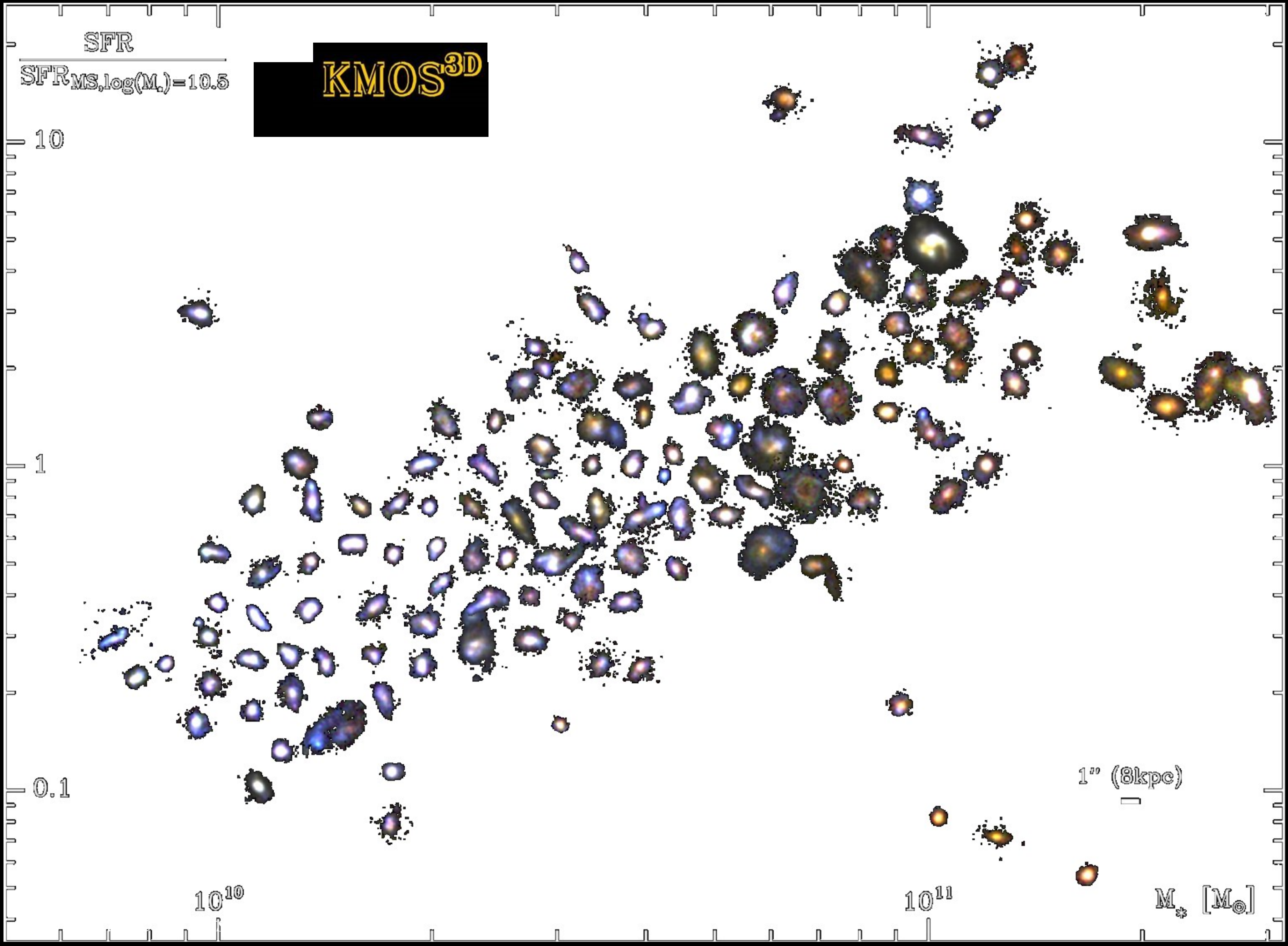


The KMOS image slicer

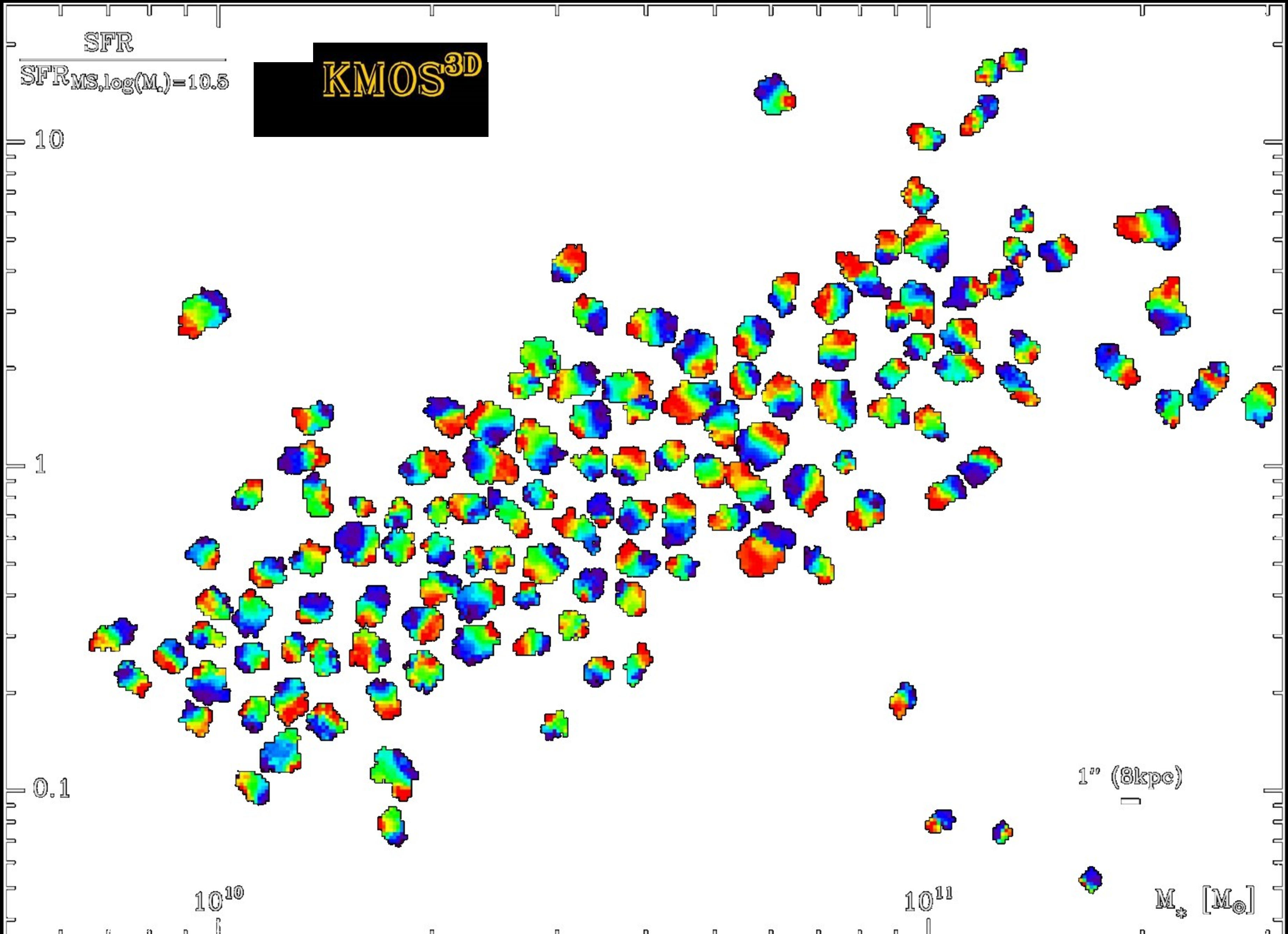
24 pick-off arms select targets over the VLT 7arcmin field of view then direct the beam to 24 IFUs and 3 spectrographs.







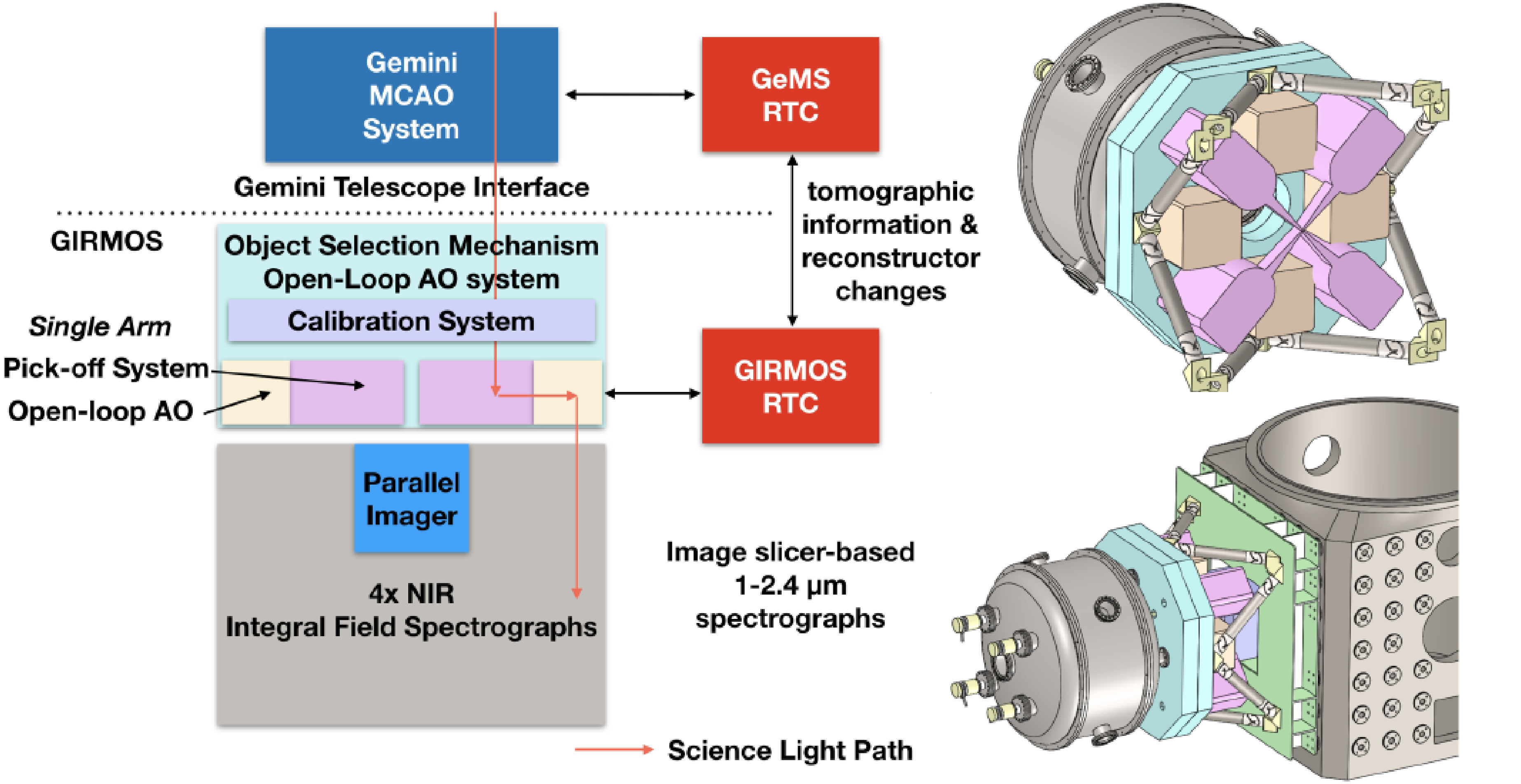
SFR / SFR_MS,log(M*)=10.5
KMOS3D
10
1
0.1
1" (8kpc)
10^10
10^11
M* [M⊙]



$\frac{SFR}{SFR_{MS,\log(M_*)=10.5}}$
KMOS^{3D}
10
1
0.1
1" (8kpc)
10^{10}
10^{11}
M_* [$M_\odot$]

GIRMOS

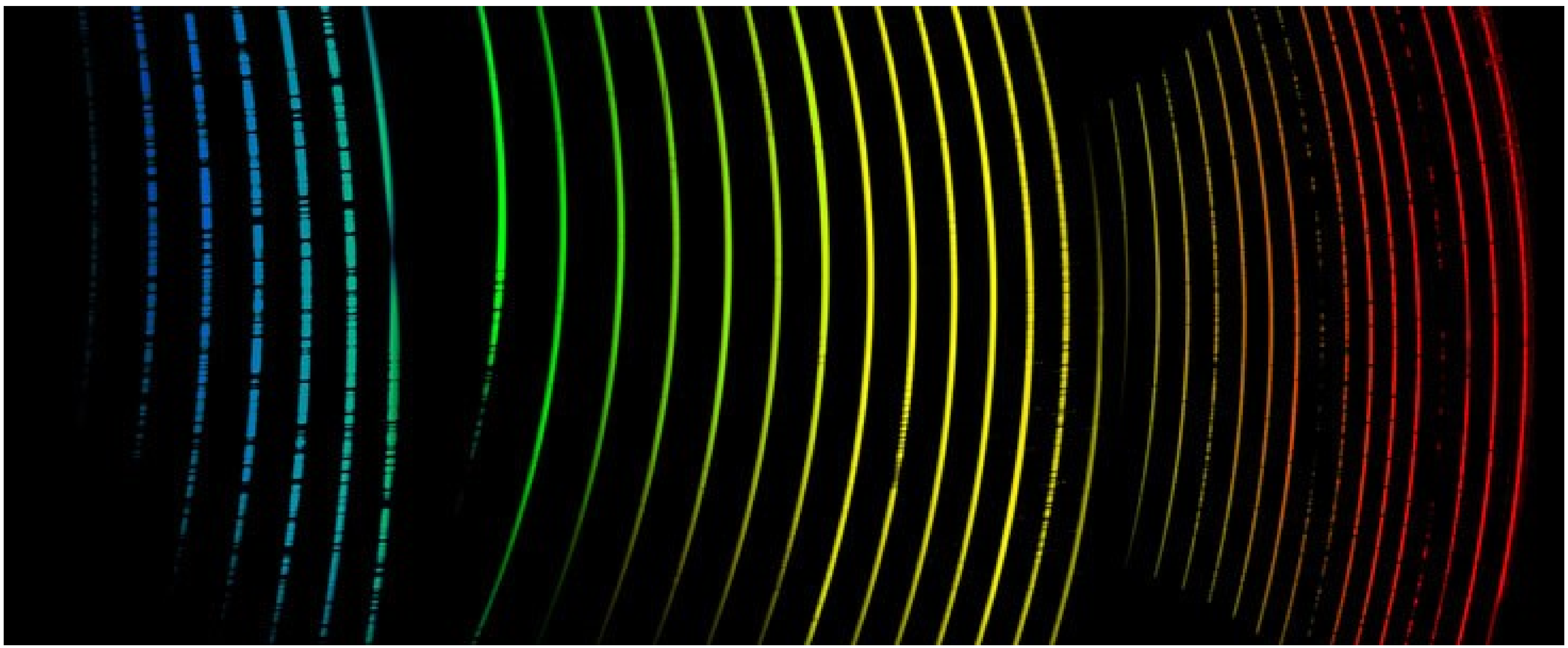
- Sivanandam et al. 2018 (arXiv:1807.03797)



Cross-dispersed spectrographs

- For the widest wavelength range and small objects: cross-dispersed spectroscopy

wavelength

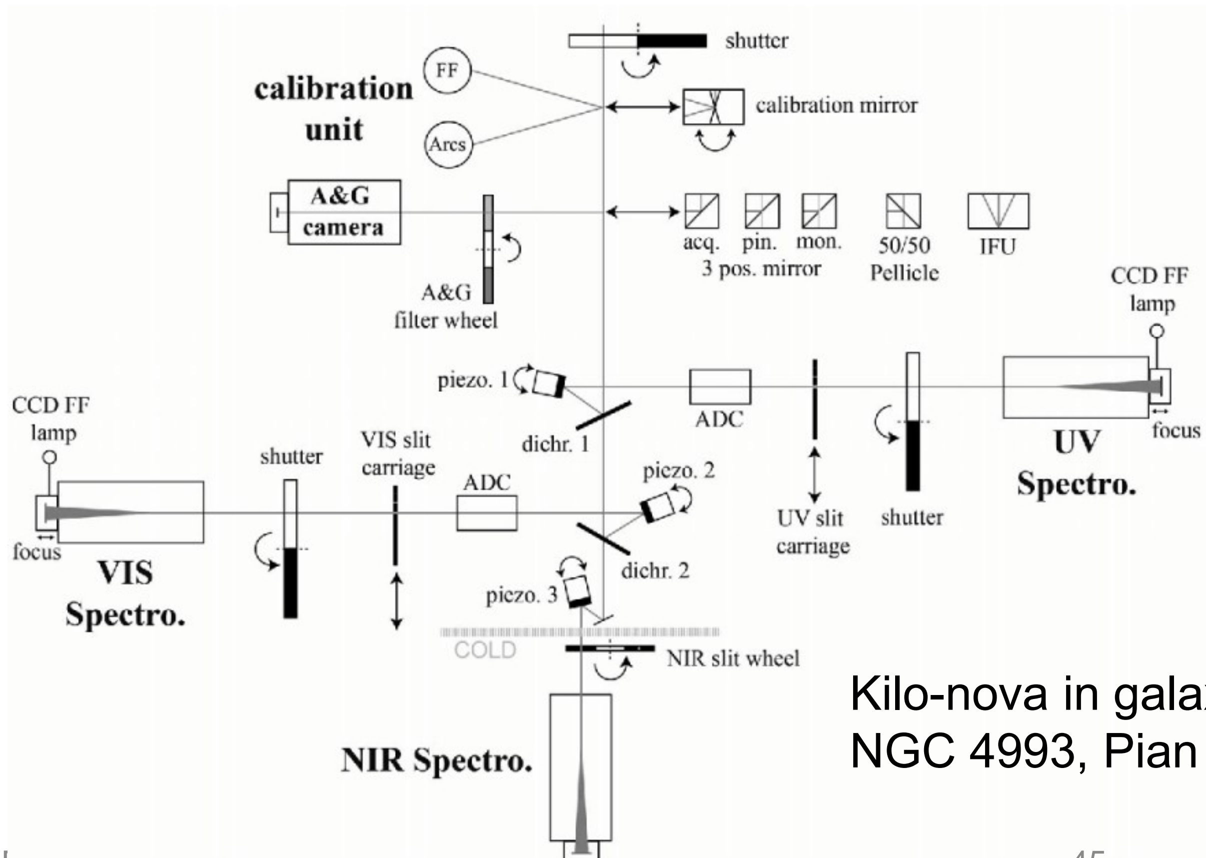


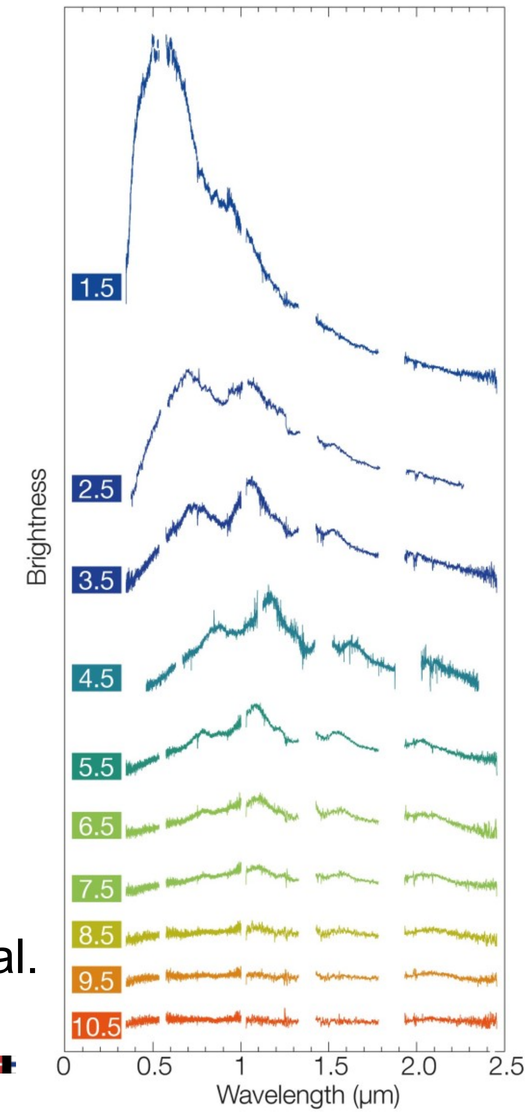
Cross-dispersed orders of the gratings

Cross-dispersed spectrographs

Cross-dispersed spectroscopy with X-shooter

X-shooter was designed specifically for quick follow up of transient sources, in particular gamma ray bursts and supernovae.

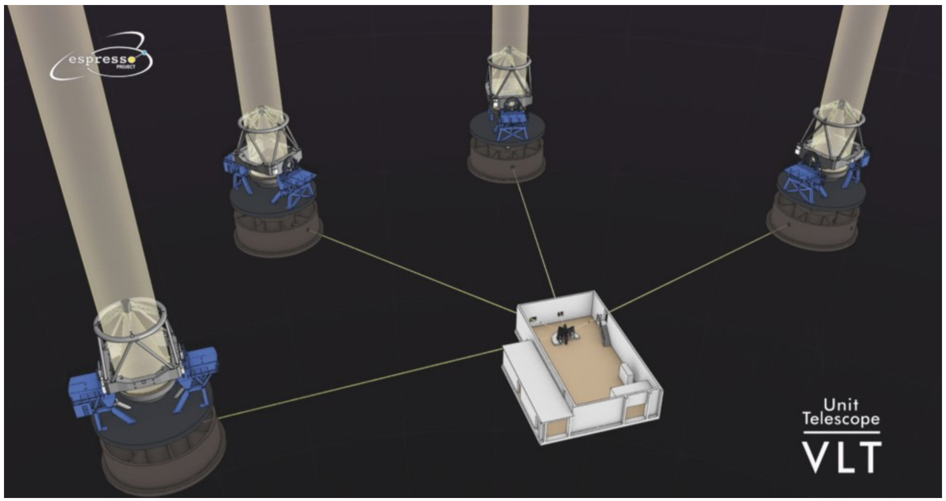


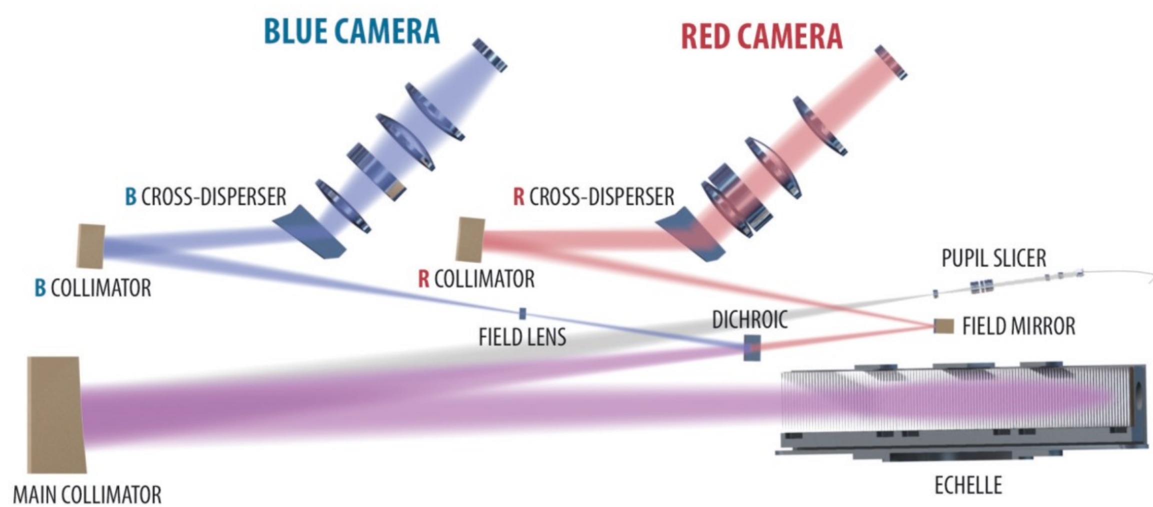


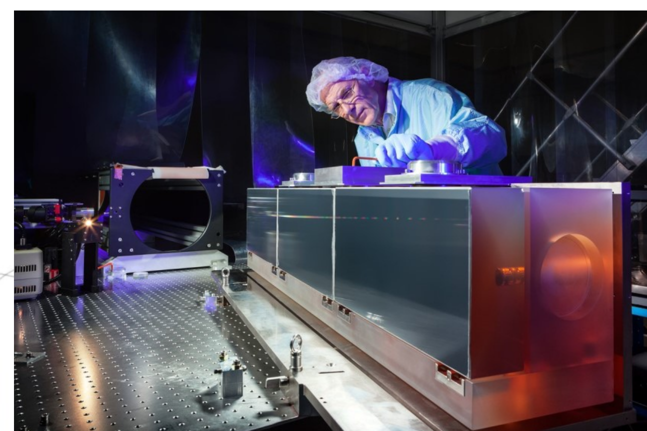
Kilo-nova in galaxy NGC 4993, Pian et al.

Ultra-stable spectrographs

- Typical science case: long term measurement of radial velocities of planets: < m/s precision required







Worked example

Spectrograph Design for instrument scientists

Conservation of étendue

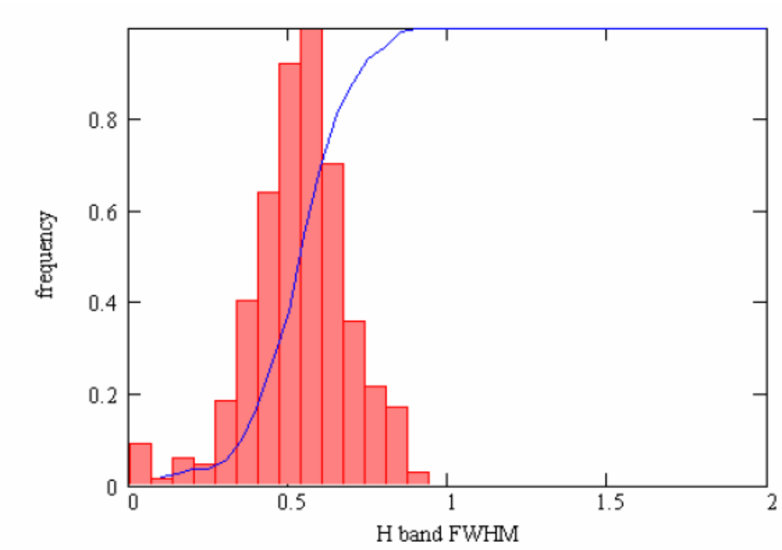
- Etendue (also called throughput) must be conserved to build an efficient instrument
- At any given aperture, étendue is the product of the area of the aperture (A) and the solid angle of the rays accepted (Ω)
- In particular, for an astronomical instrument

$$A\Omega_{tel} = A\Omega_{det}$$

Using a few assumptions and simple geometrical optics, we can calculate some important instrument parameters…..

Back-of-the-envelope instrument for the ESO VLT (1)

- Scientific goal
  - Detection and characterisation of galaxies (in clusters) at redshift z=1-2 (peak period of star formation)
  - Velocities resolution ~10kms^{-1} to measure rotation curves
  - Spatial/angular resolution set by the seeing limit at the telescope



H median FWHM = 0.53 arcsec

- Scientific requirements
  - z=1-2 >> most diagnostic lines fall in the 0.8-2.4μm wavelength range
  - Best seeing ~0.4arcsecs in K band (2.0-2.4 μm) >> 0.2arcsec per pixel
  - Spectral resolving power set by the vel. res'n to R $\left(\frac{\lambda}{\delta\lambda}\right) \cong 3000$

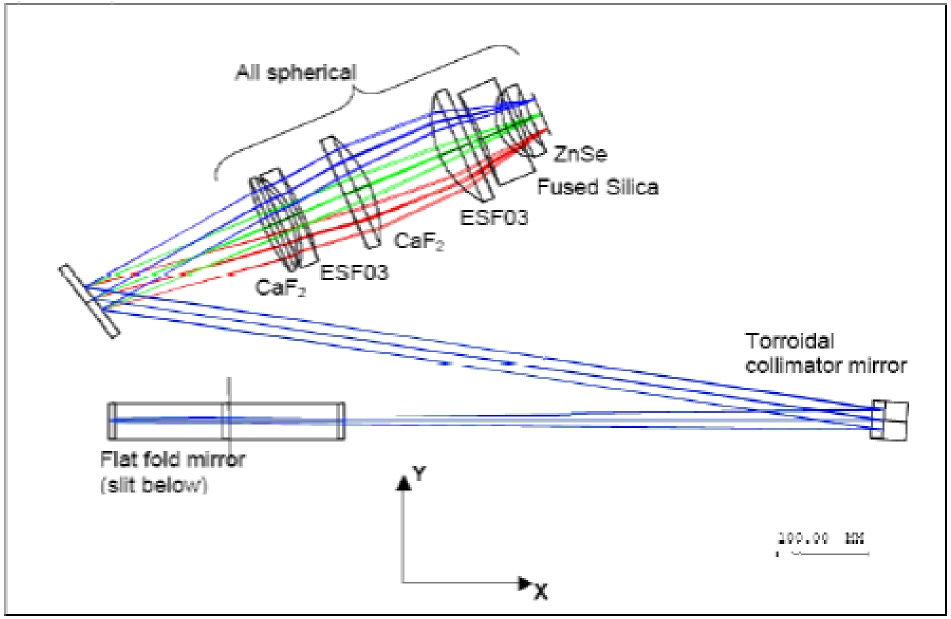
Back-of-the-envelope instrument (2): camera focal ratio

- Conservation of étendue and the detector pixel size determines the camera f-number:

$$D_{tel}\theta_{tel} = d_{pix}\theta_{cam}$$

$$\theta_{cam} = \frac{d_{pix}}{f\_number}$$

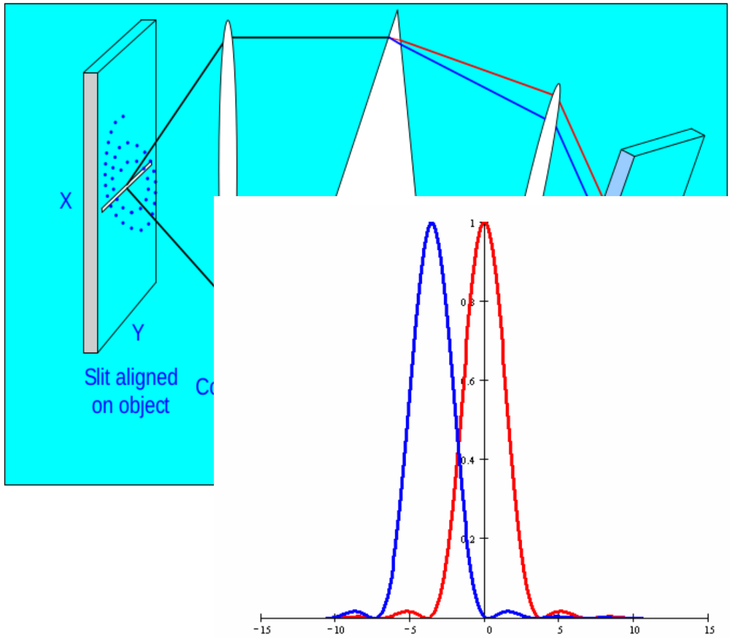
- θ_{tel}=0.2arcsecs, D_{tel}=8.2m
- d_{pix}=18μm
- Camera should be f/2.3
- Such a fast camera is hard but not impossible



Optical layout of the KMOS spectrograph

Spectral resolving power

- With the f-number of the camera defined and the spectral resolution defined by the astronomers, the pupil size can be calculated
- To resolve two spectral lines at the array $\Delta\theta = \Delta\lambda \frac{\delta\theta}{\delta\lambda}$
- $\frac{\delta\theta}{\delta\lambda}$ comes from the grating equation
  $m\lambda = d\sin(\theta i) + \sin(\theta r) \gg \frac{\delta\theta}{\delta\lambda} = \frac{m}{d\cos(\theta)}$
- Using $\Delta\theta = \theta_{cam} = {}^{d_{pix}}/_{focal\ length}$ and the definition of resolving power $R = \frac{\lambda}{\delta\lambda}$



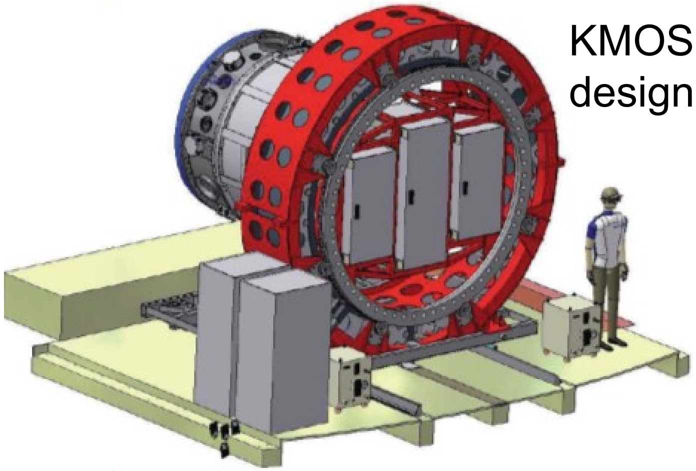
$$R = \frac{2f\tan\theta r}{d_{pix}}$$

f=focal length

Back-of-the-envelope instrument (4): Pupil/beam size

- For KMOS, set R~4000 over 2 pixels to Nyquist sample the spectral lines
- Set θr = 45degrees for a first estimate
- Then f~72mm and the beam size for an f/2.3 camera is ~31mm
- In practice the KMOS beam is 33mm diameter
- With these key numbers, a first idea of the size and technical difficulty of the instrument may be estimated but doesn't give the whole story!

$$R = \frac{2f \tan \theta r}{d_{pix}}$$



KMOS design

KMOS on the VLT1 Nasmyth platform

A back of the envelope instrument for the ELT

- 0.2arcsecs/pixel, 15μm pixels, 39-m telescope
- ~f/0.4 on the ELT
- Alternatively, define the camera to be f/2
- The seeing disk is imaged onto ~150 μm at the detector or 10 pixels
- Such oversampling implies larger focal plane>>larger instruments>>increased detectors costs>>power consumption etc….
- The tendency towards larger arrays of smaller pixels on larger telescopes is a real challenge for instrument design!

At the diffraction limit

- Diffraction limited instruments:
  - H-band diffraction limited FWHM = 10mas
  - 0.005 arcsecs/18 μm pixel
  - ~f/19 on the ELT
- Aside from the scientific benefits, using adaptive optics can help reduce image sizes to the point where instruments are easier to build
- For an instrument to operate at the diffraction limit of a telescope set the pixel field of view:

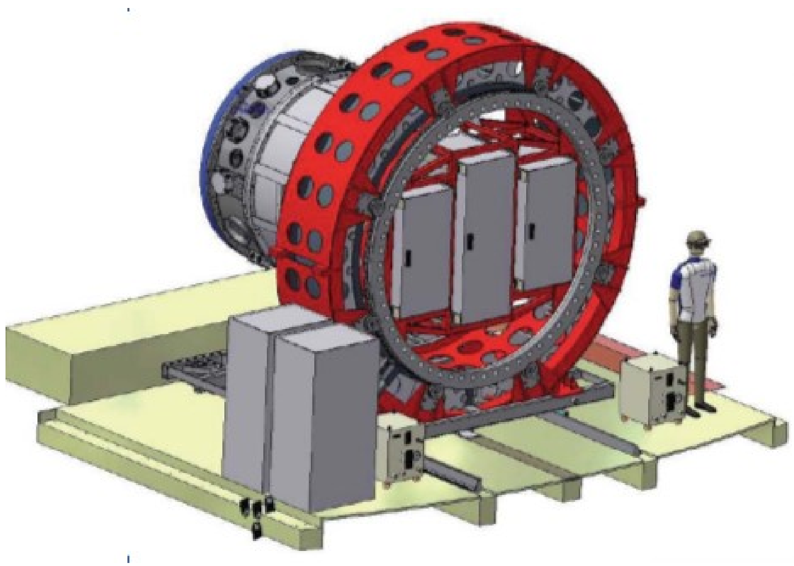
$$\theta_{tel} = \frac{1.22\lambda}{D_{tel}} \quad \text{then} \quad \frac{d_{pix}}{f\_number} \sim \lambda$$

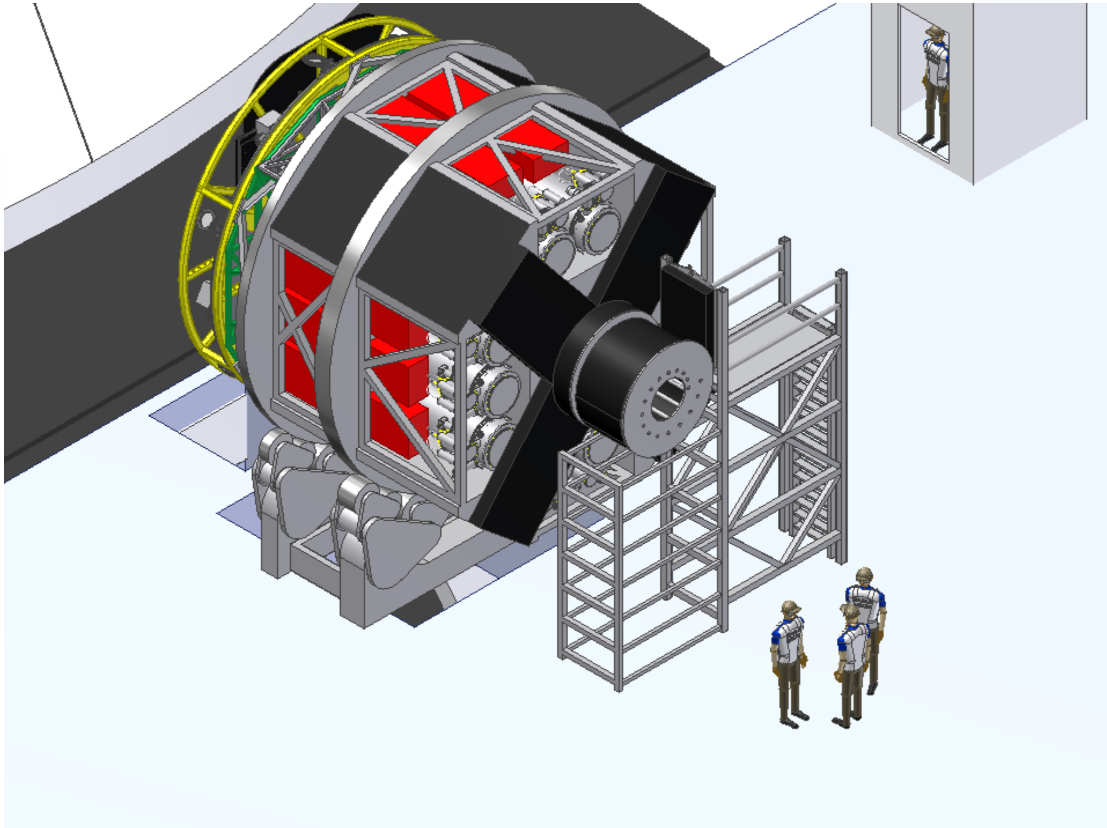
- A diffraction limited instrument can go on any telescope!

The challenge of building instruments for an ELT

- Instrument size typically increases with telescope size
  - VLT f-ratio: f/15 plate scale: 0.582mm/arcsec
  - E-ELT f-ratio: f/17.7 plate scale: 3.3mm/arcsec
- Some things get easier
  - Relaxed positioning tolerances
  - KMOS pick-off arms position to 0.2arcsecs = 120µm on VLT; would be 660µm on E-ELT
- Some things get harder….

KMOS vs EAGLE





KMOS: 0.2arcsec pixels on 8-m telescope, 7arcmin field of view
EAGLE concept: 40mas pixels on a 39-m telescope, 7arcmin field of view
These instruments have the SAME AΩ product/étendue and can select the same numbers of objects (20-24).

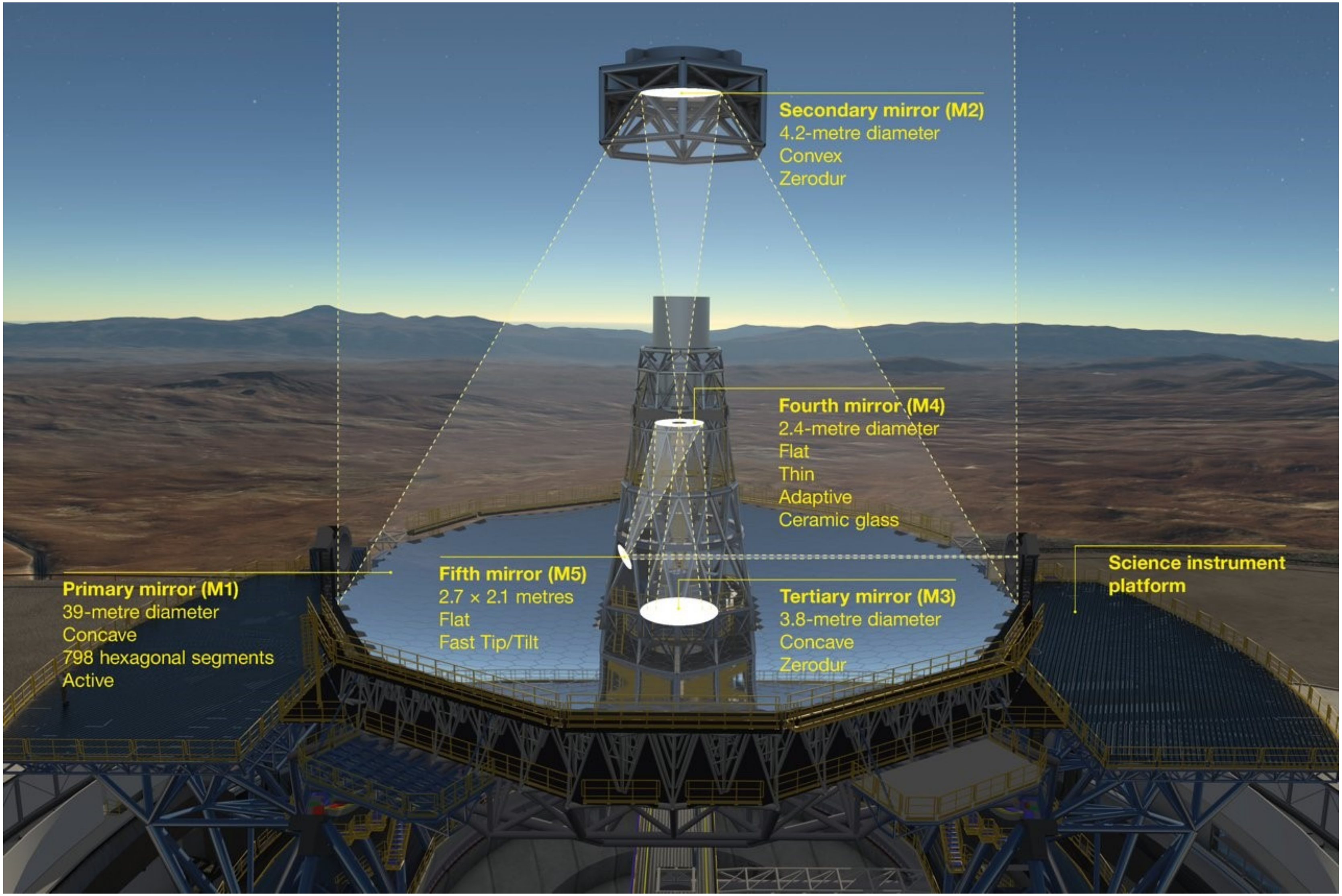
ESO’s Extremely Large Telescope and its instruments

https://xkcd.com/1294/

ESO's Extremely Large Telescope

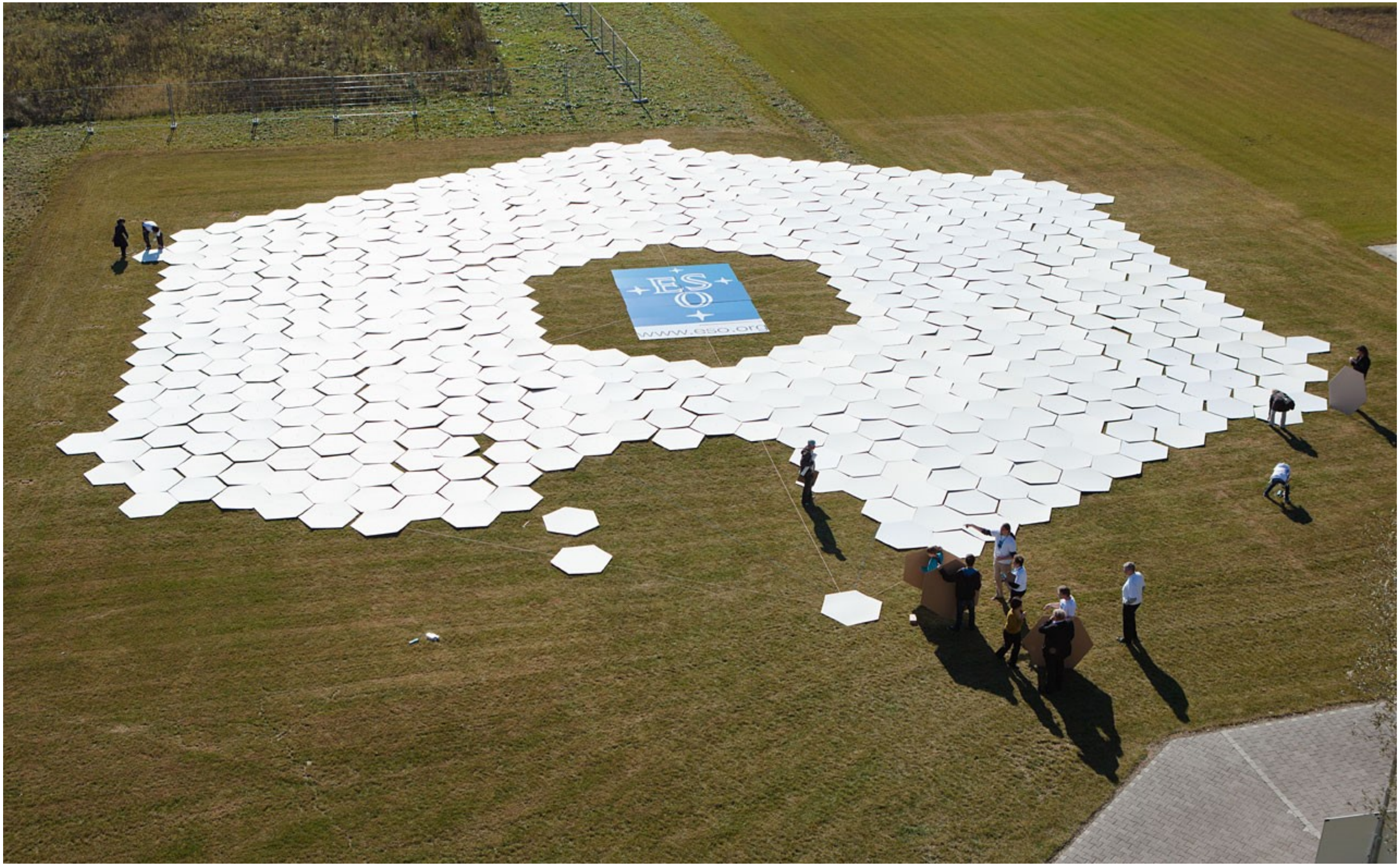
https://xkcd.com/1294/

ELT optics



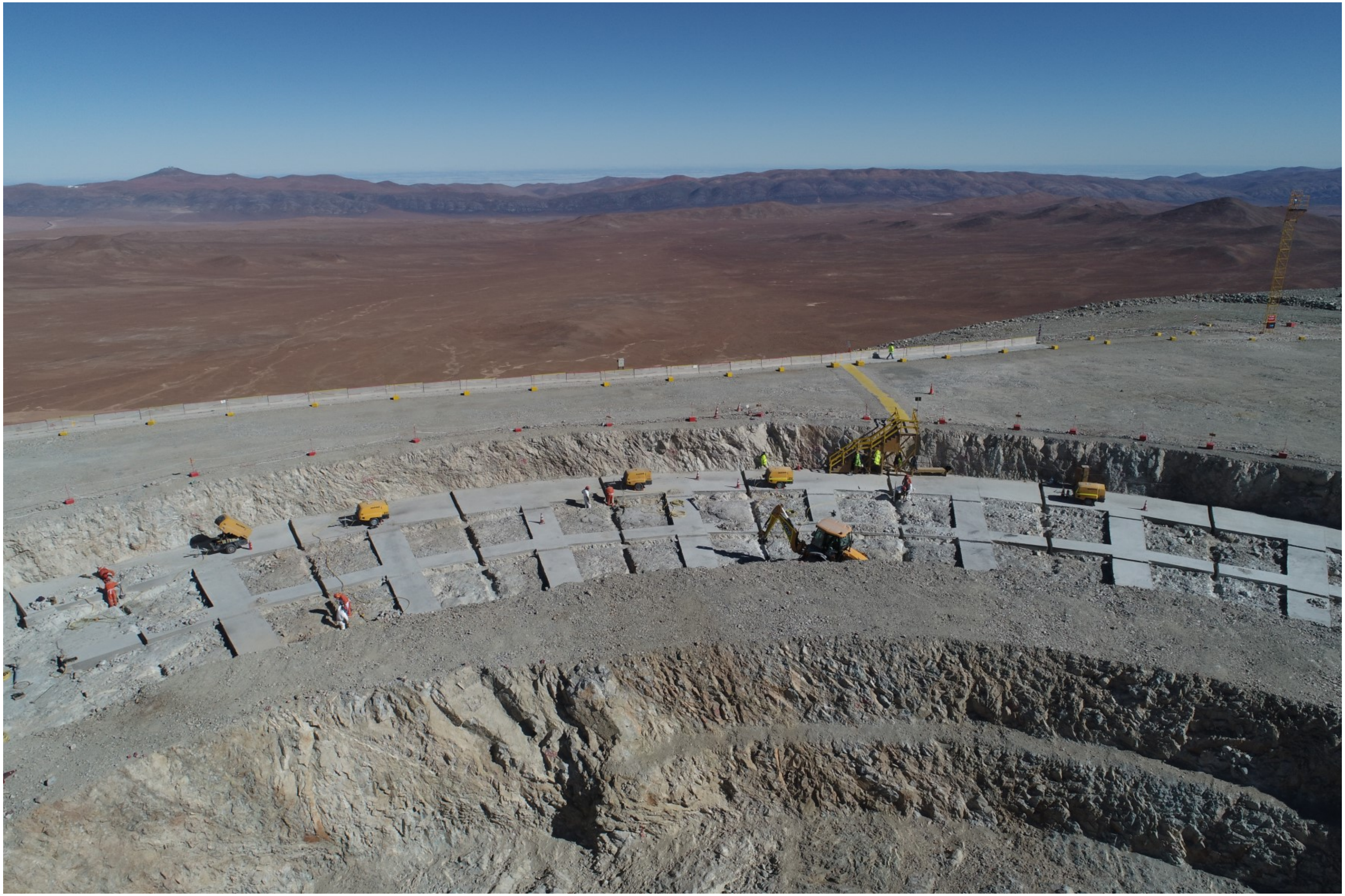
Secondary mirror (M2)
4.2-metre diameter
Convex
Zerodur
Fourth mirror (M4)
2.4-metre diameter
Flat
Thin
Adaptive
Ceramic glass
Science instrument platform
Primary mirror (M1)
39-metre diameter
Concave
798 hexagonal segments
Active
Fifth mirror (M5)
2.7 × 2.1 metres
Flat
Fast Tip/Tilt
Tertiary mirror (M3)
3.8-metre diameter
Concave
Zerodur

ESO open house 2011

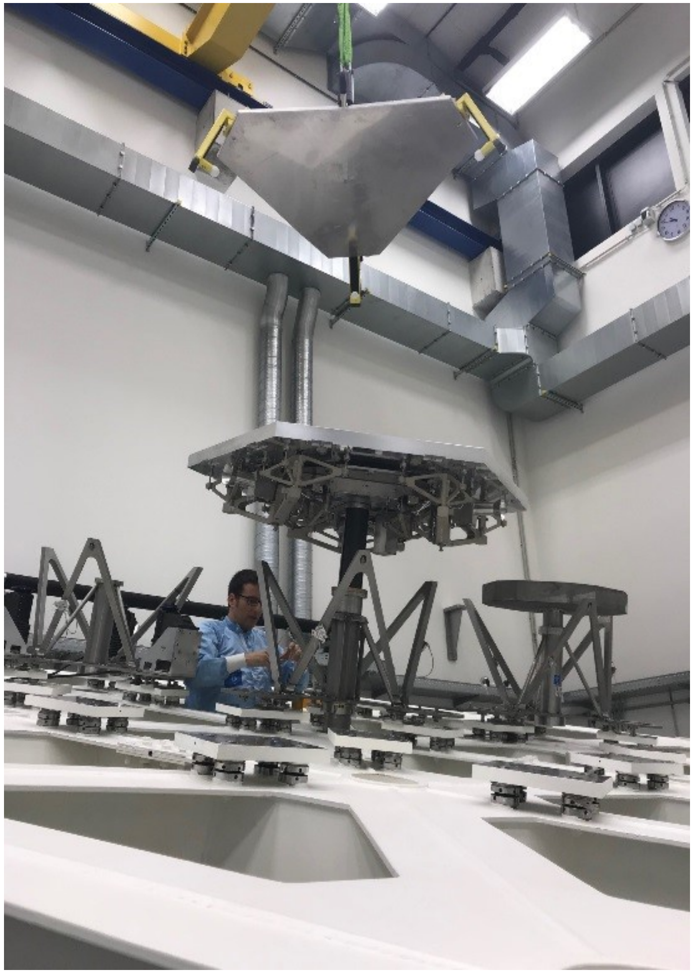


The ELT Site: Cerro Armazones

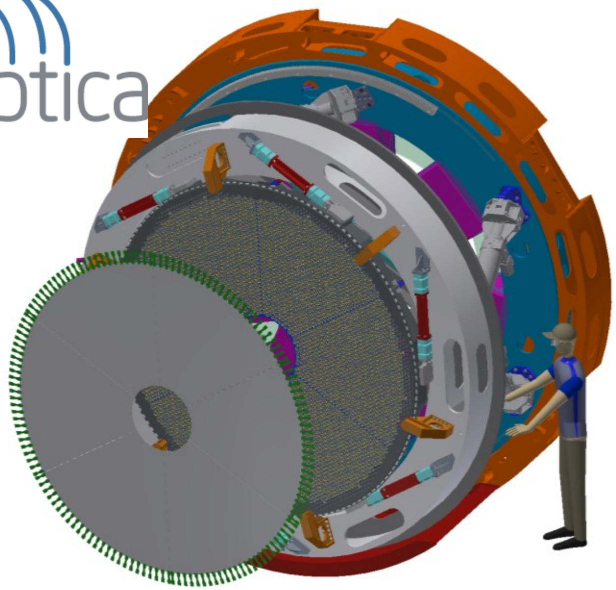
ELT site: construction

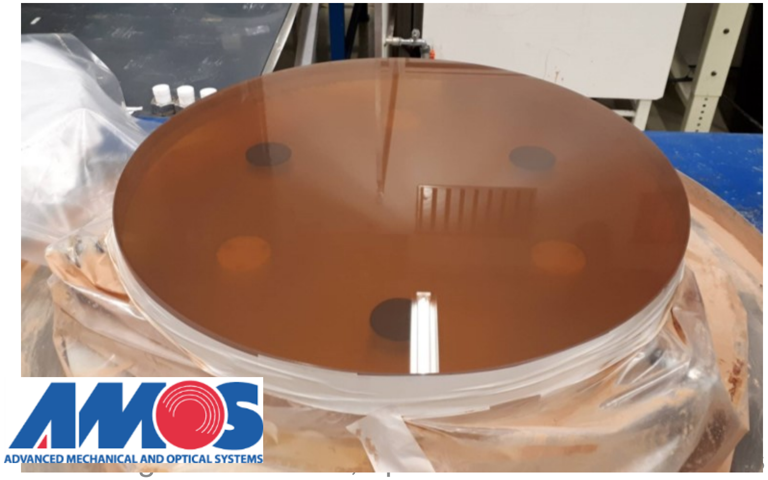


M1 Mirror Blanks

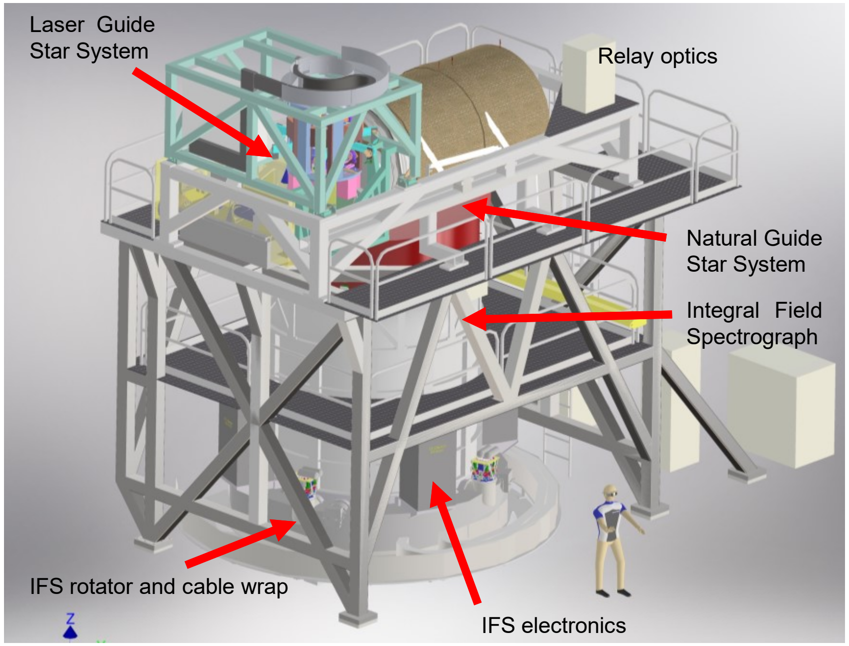


M4 deformable mirror

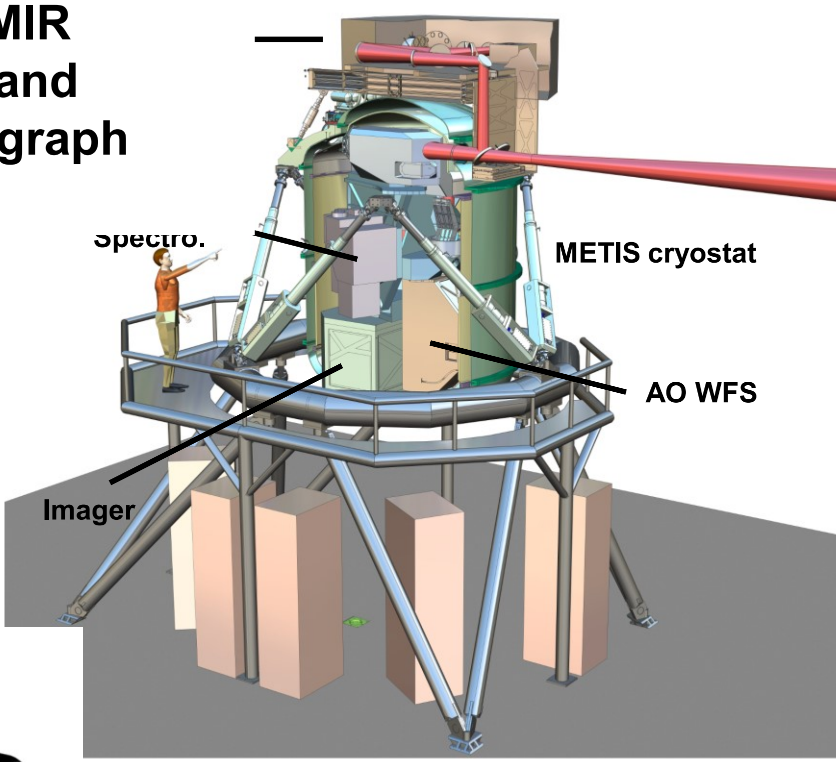




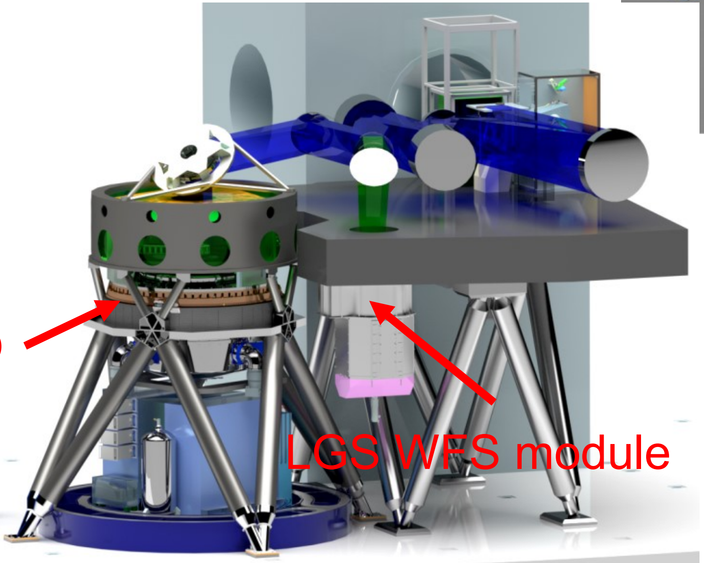
ELT instruments



METIS MIR imager and spectrograph +AO

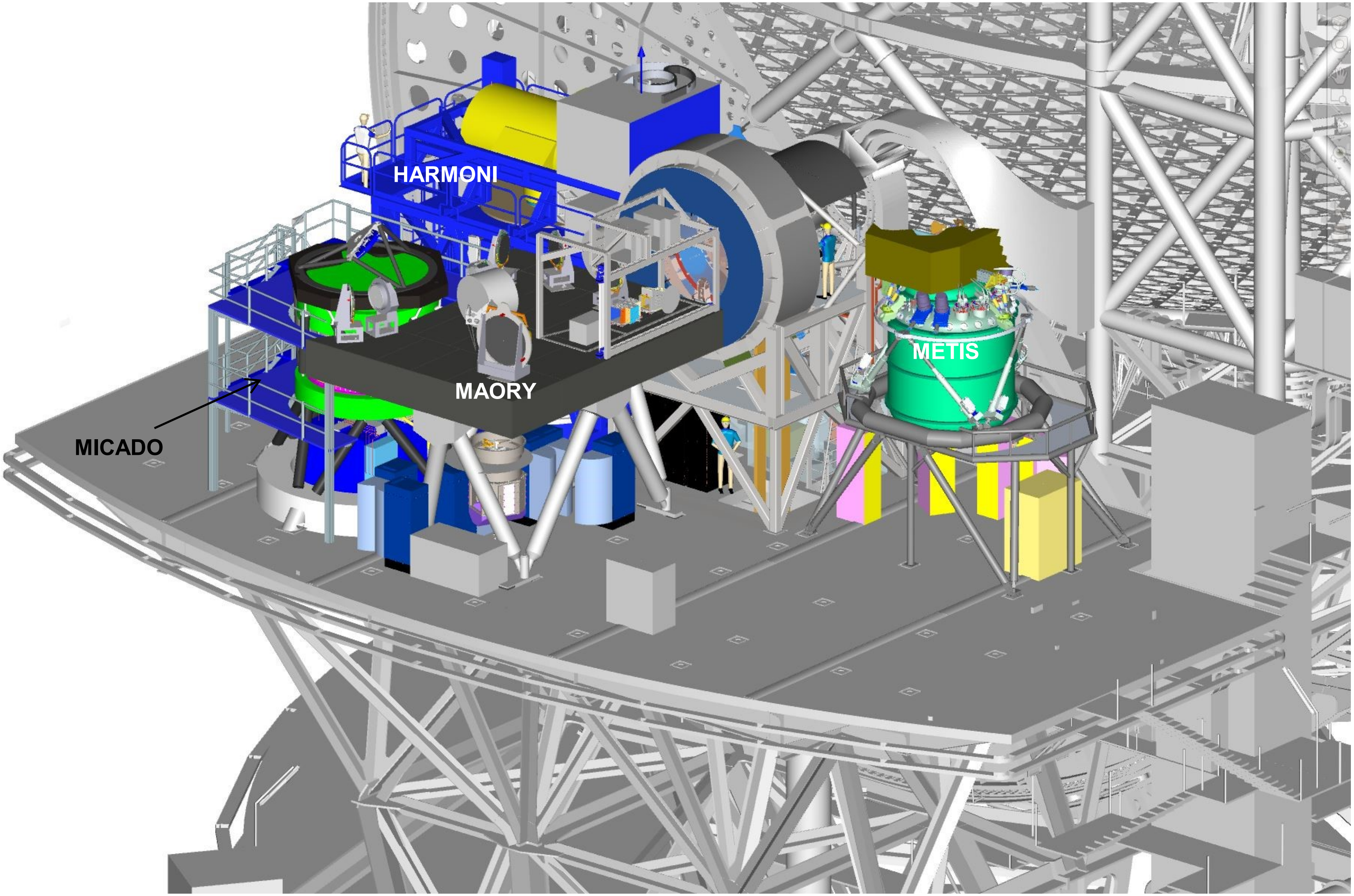


HARMONI optical to NIR 3D spectrograph+AO

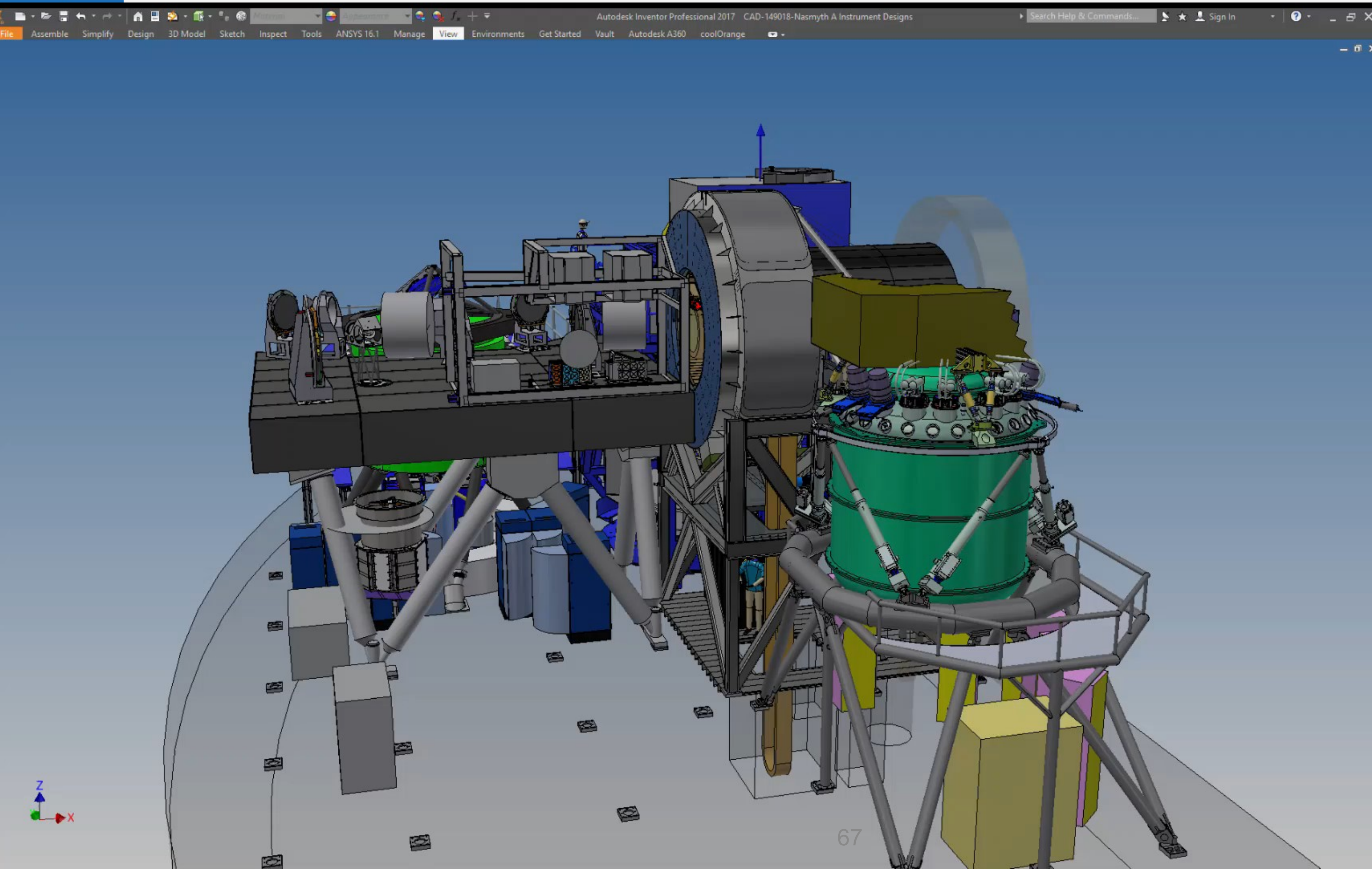


MICADO NIR imager and slit spectrograph with the MAORY MCAO module

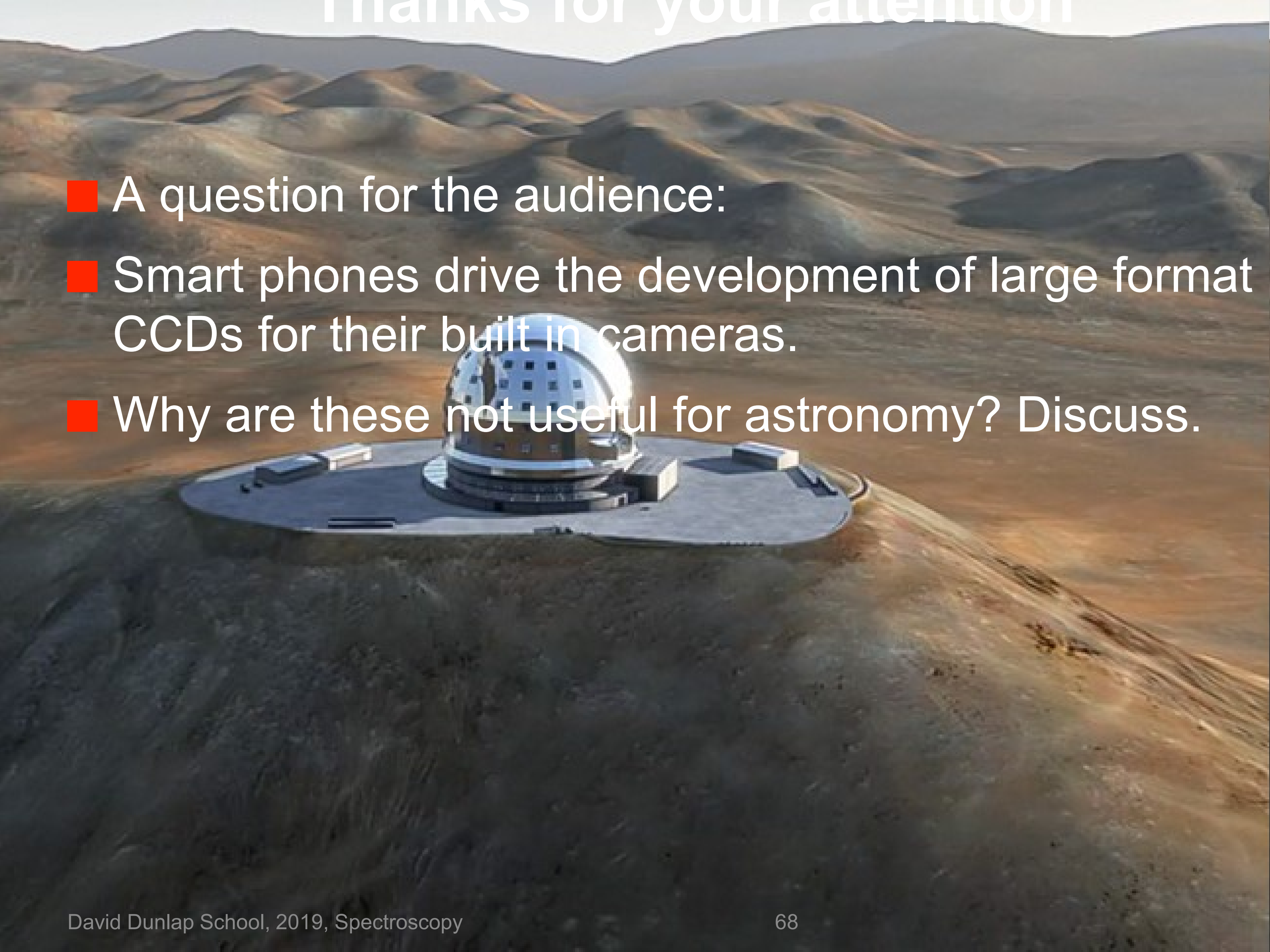
Instruments on Nasmyth A



Instruments on Nasmyth A



Thanks for your attention



- A question for the audience:
- Smart phones drive the development of large format CCDs for their built in cameras.
- Why are these not useful for astronomy? Discuss.

Links and acknowledgements

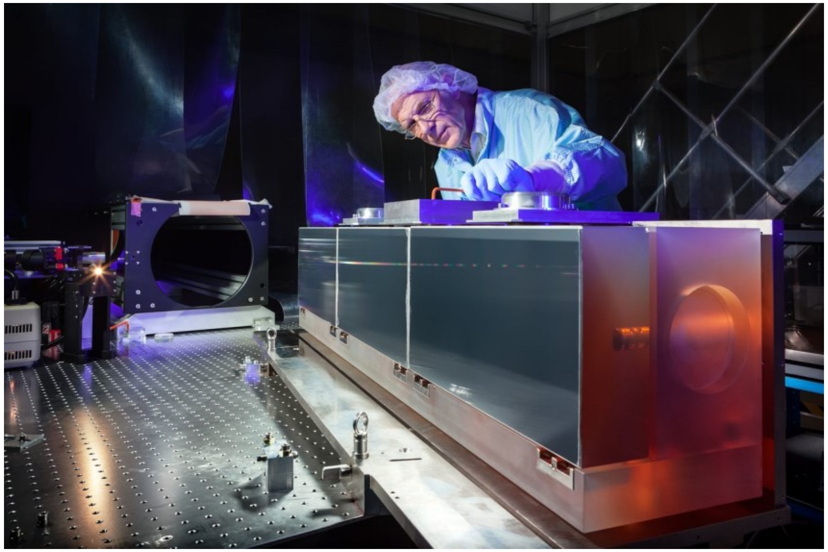
- AO open/closed loop GIF (slides #): www.mpg.mpia.de/AO/INTRO/AOWFSintro.html
- VISIR detector image from Mills, Beuville & Corrales (spie.org/newsroom/3786-evolution-of-long-wavelength-astronomy-sensors)
- KMOS-3d survey: see Wisnioski, E et al (2015), ApJ, 799, 209

What sets the resolving power of a spectrograph?

- Theoretical limit set by the number of rulings
  - Back to school calculation of this from a standard optics book
- Actually for spectrographs with moderate resolving power then the slit width sets the resolving power
  - Later – come to the example of small movements with the slit introducing a fake radial velocity signal

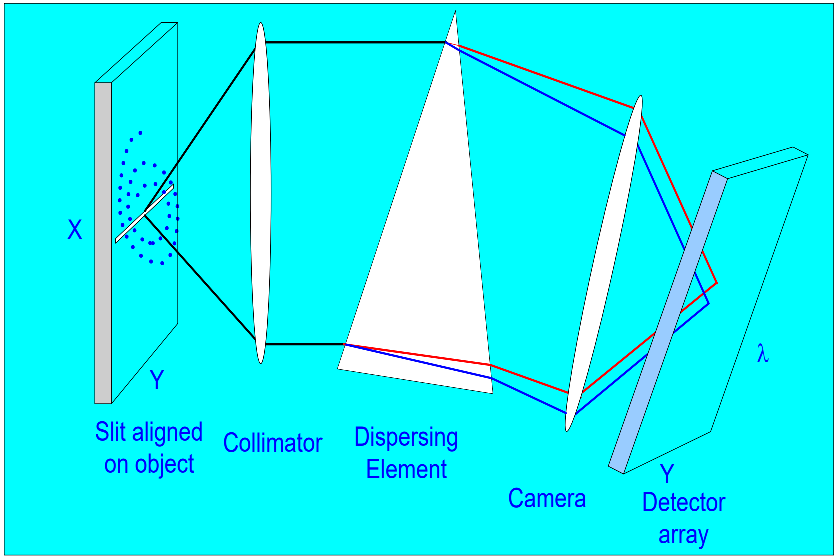
Large high resolving power gratings

- The grating for the ESPRESSO spectrograph



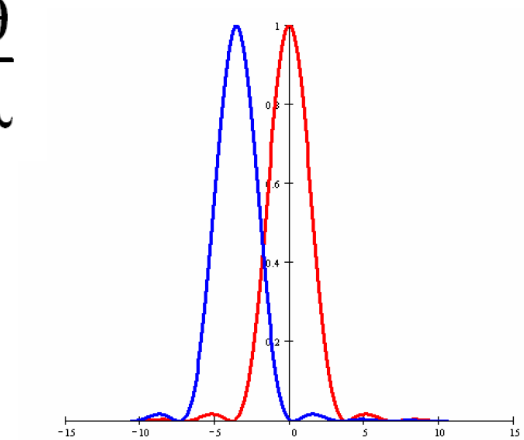
https://www.eso.org/public/images/potw1537a/

Spectral resolving power, R



Angular separation of two wavelengths at the detector

$$\Delta\theta = \Delta\lambda \,.\, \frac{d\theta}{d\lambda}$$



From conservation of étendue:

$$\theta_p = \frac{D_T\theta_T}{d_p}$$

Wavelengths are resolved when these are equal, so:

$$\boxed{R = \frac{\lambda}{\Delta\lambda} = \frac{d_p}{D_T\theta_T} \,.\, \lambda \frac{d\theta}{d\lambda}}$$

NB: max R depends on Pupil size, telescope D and angular size of the object.