An Introduction
to
Ground-based
Astronomical Instrumentation

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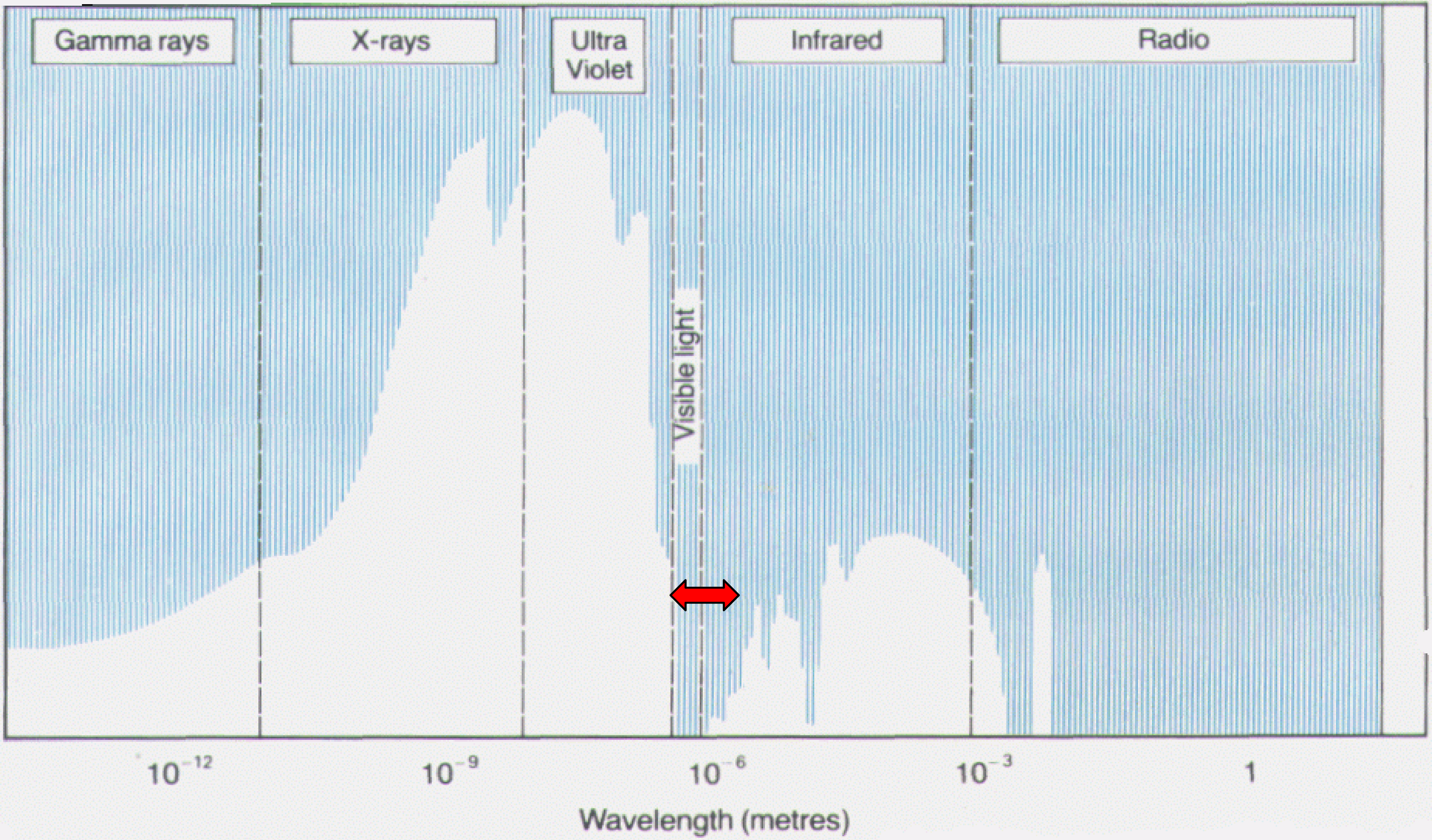
Outline of the talk

- Starting points for instrument design
- Design basics
- Novel instruments for optimising scientific return
- Prospect for future instrumentation

Or……

- One important concept
- Two tricks with geometry
- Some nice pictures……

Astronomy from the ground



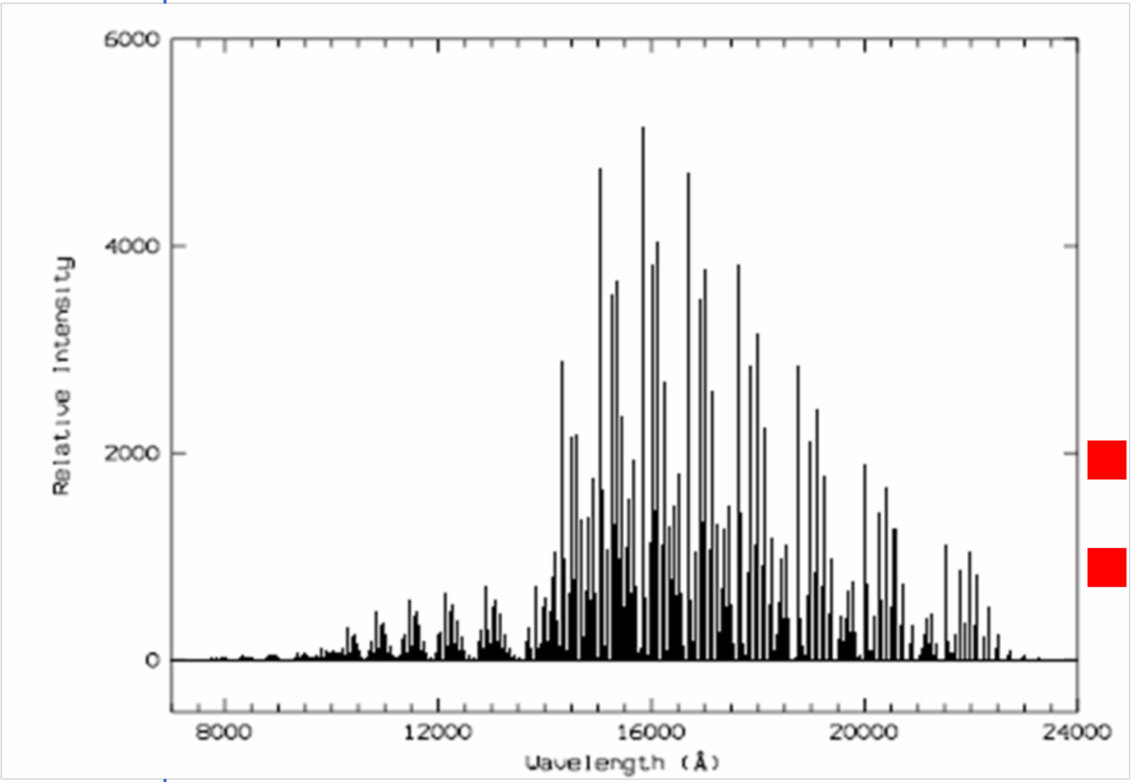
Sensitivity/detectability

- Sources of noise in ground based observations

$$noise \approx \sqrt{Object + SkyBgrd + TelBgrd + DetReadNoise^2 + DarkCurrent}$$

- Det Read Noise, Dark Current
- Object = Typical object: magnitude ~ 18-20
  - rarely the dominant noise source
  - ~ a few photons/s for spectroscopy with Dtel=8m
- Sky background
  - V (0.55μm) =21.8 (new moon)
  - K (2μm)=13 for sky background
  - Typical objects in the IR are 1% or less of the sky

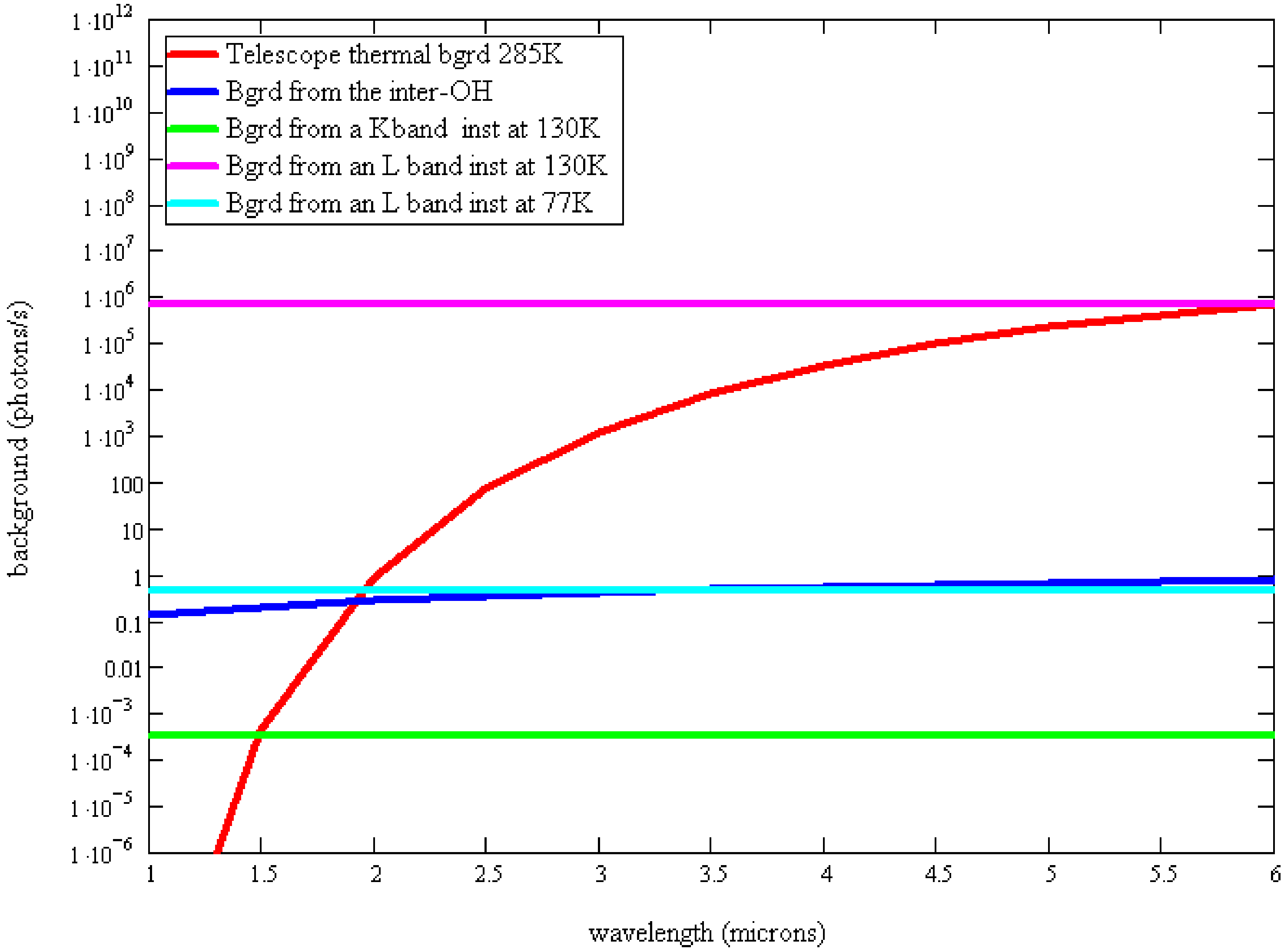
The OH emission spectrum:



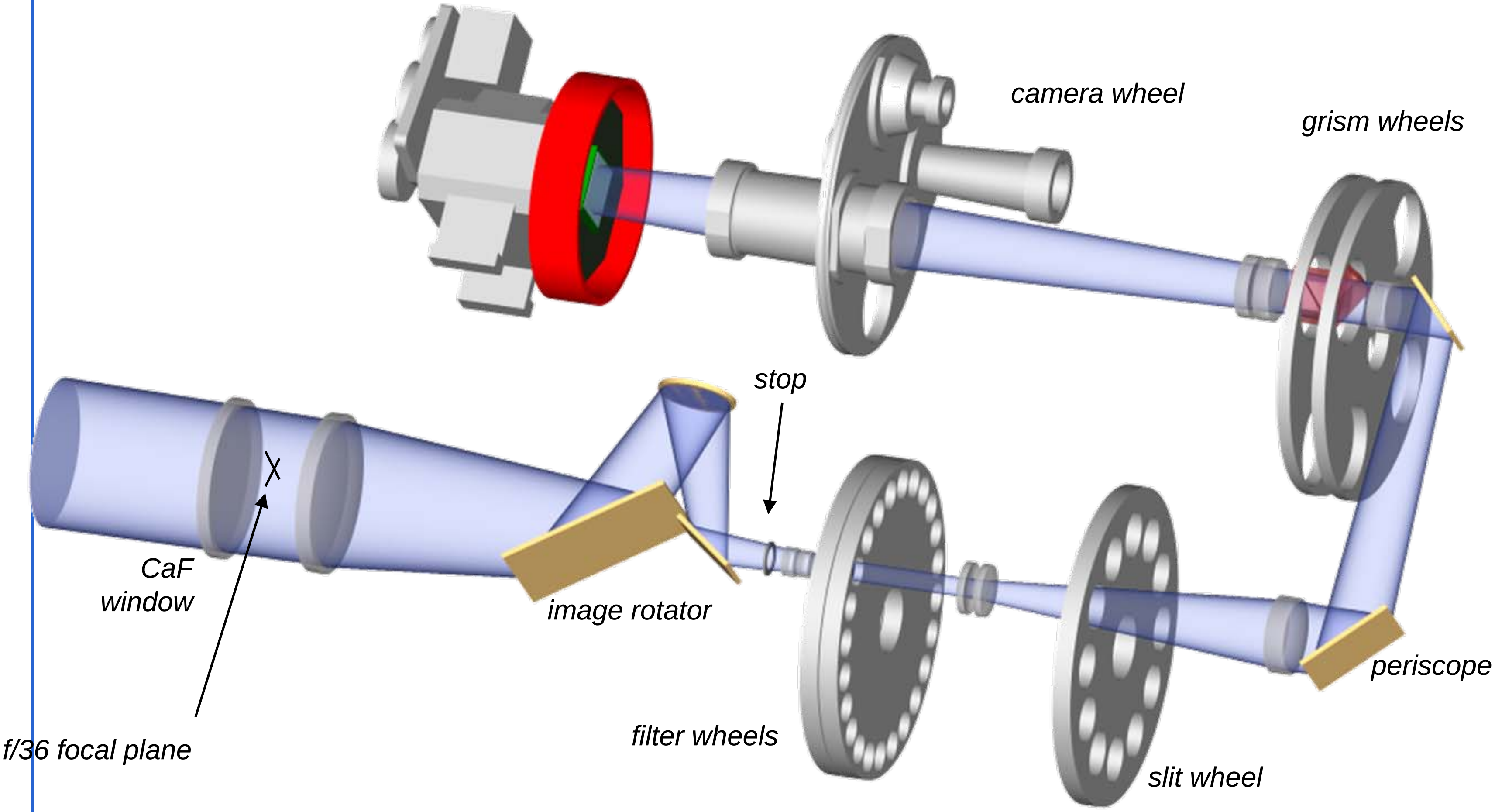
- Lines are bright
  - 2500 photons per second per arcsec with an 8-m telescope, 1000 times target source flux
- Variable
- BUT, the continuum between them is very dark
  - 0.1photons per second

OH spectrum from Rousselot et al. (2000, A&A, 354,1134).

Thermal background emission

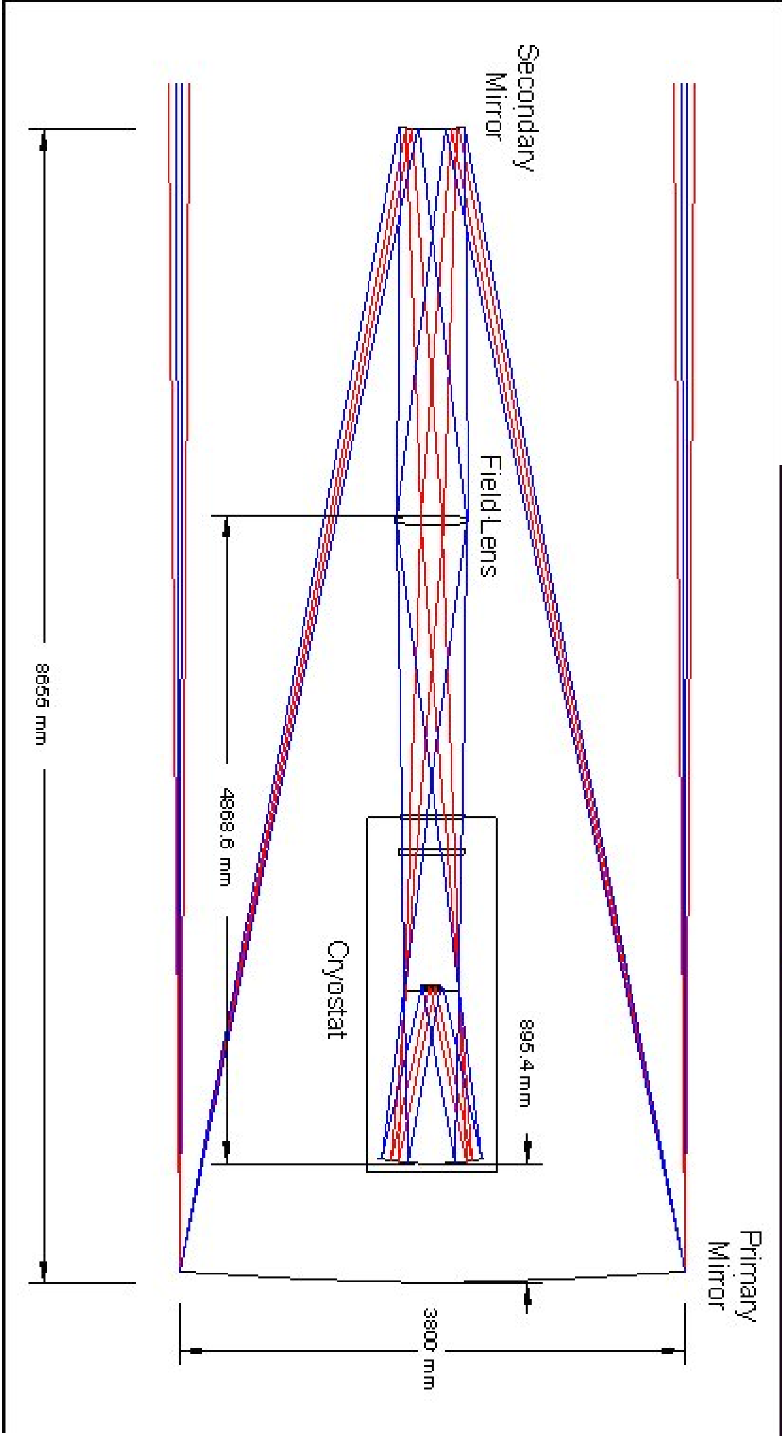


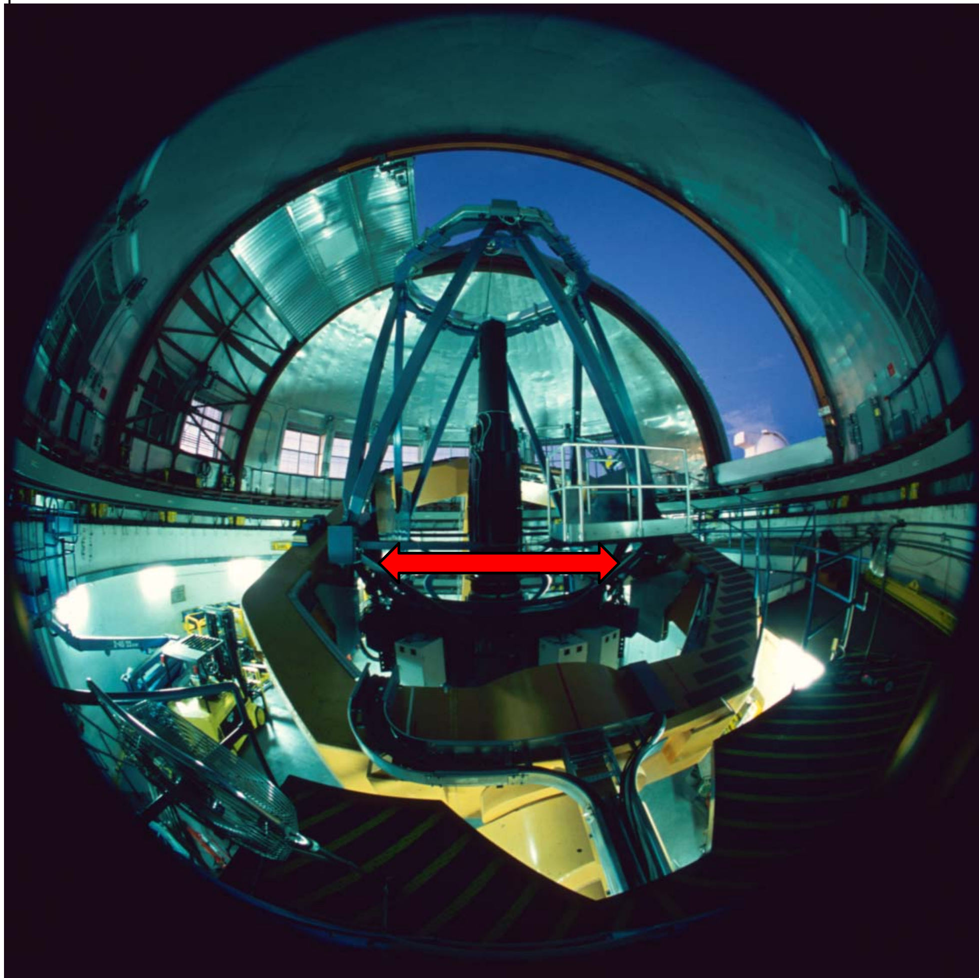
A word about the cold stop



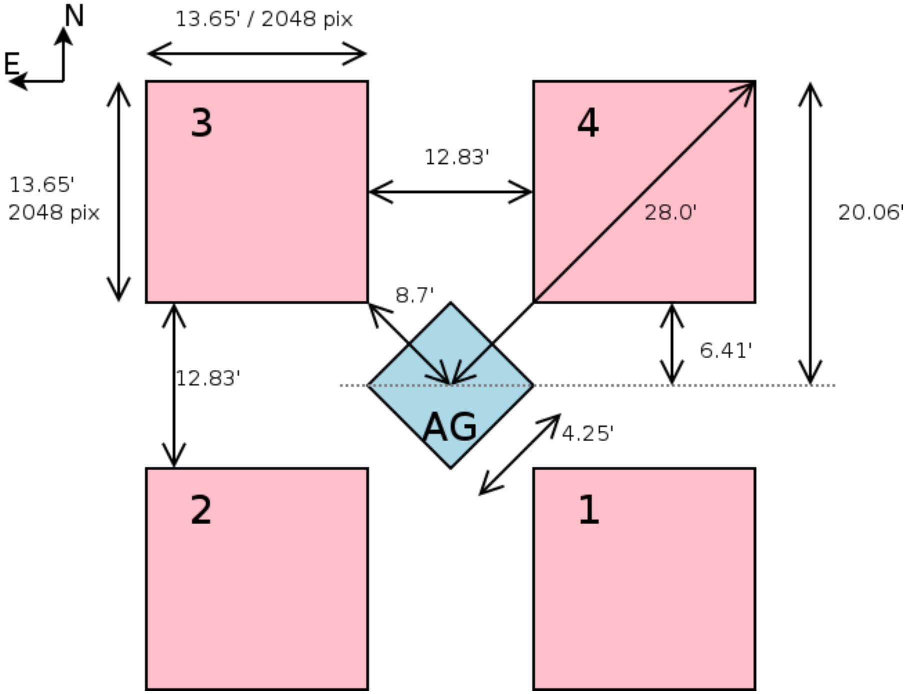
opto-mechanical layout

The survey camera WFCAM on the UK Infrared Telescope





WFCAM

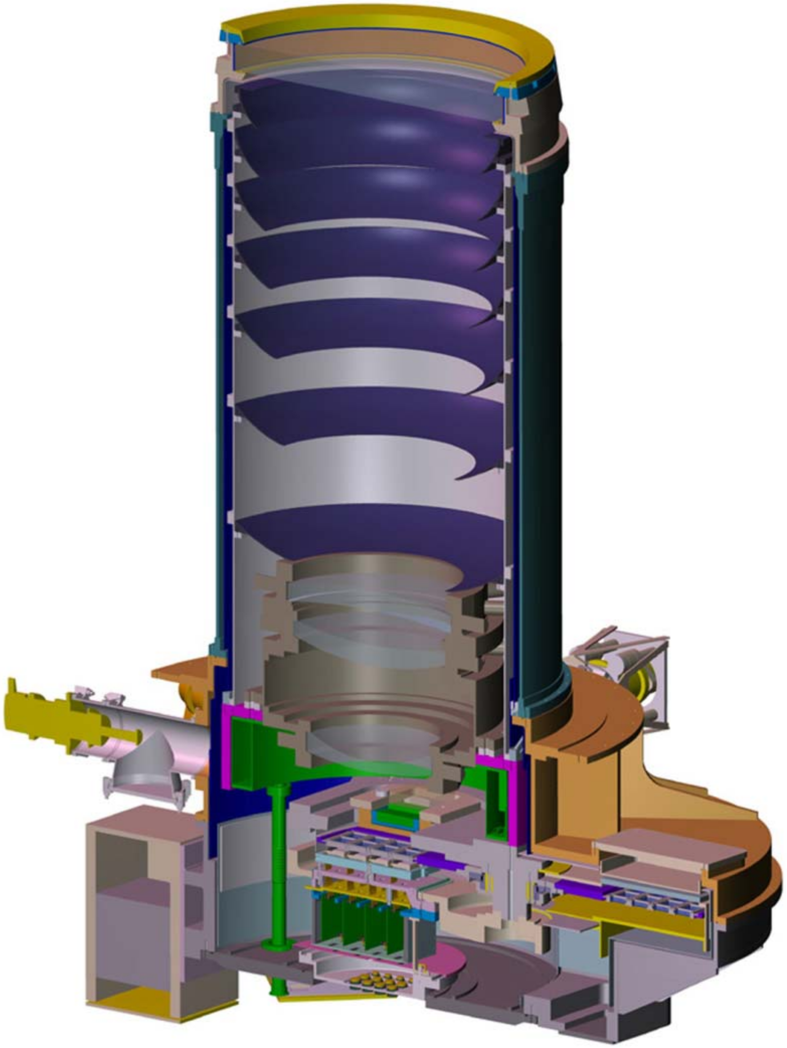


The focal plane layout :

4 Rockwell Hawaii-II (HgCdTe 2048x2048)

4 separately pointed observations cover a filled square of sky covering 0.75 square degrees with 0.4 arcsecond pixels.

VISTA plus the IR camera



Conservation of Etendue

- Etendue or throughput must be conserved in an efficient instrument
- At any given aperture, it is the product of the area of the aperture (A) and the solid angle of the rays accepted (Ω)
- In particular……

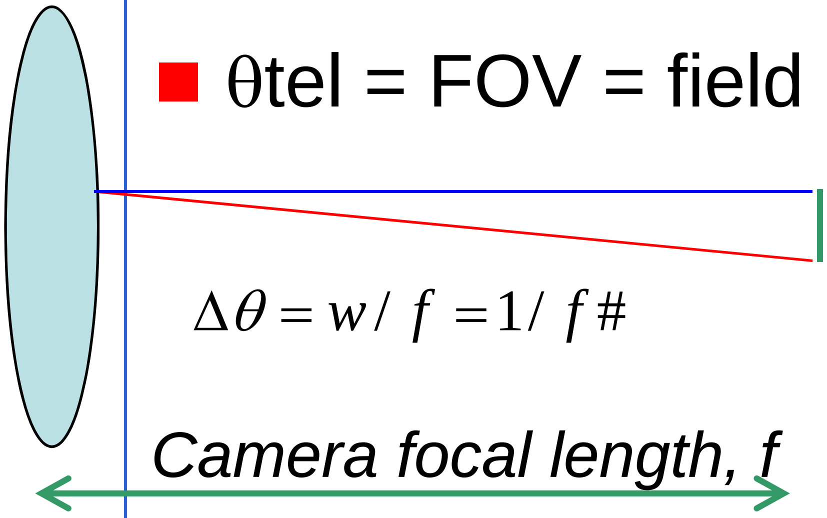
$$A\Omega_{\mathrm{tel}} = A\Omega_{\mathrm{detector}}$$

A very practical application.....

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

$$Dtel\,\theta_{\mathrm{tel}} = dpix\,\theta_{\mathrm{cam}}$$

- θtel = FOV = field of view in arcsec



Pixel width

$$\Delta\theta = w / f = 1 / f\#$$

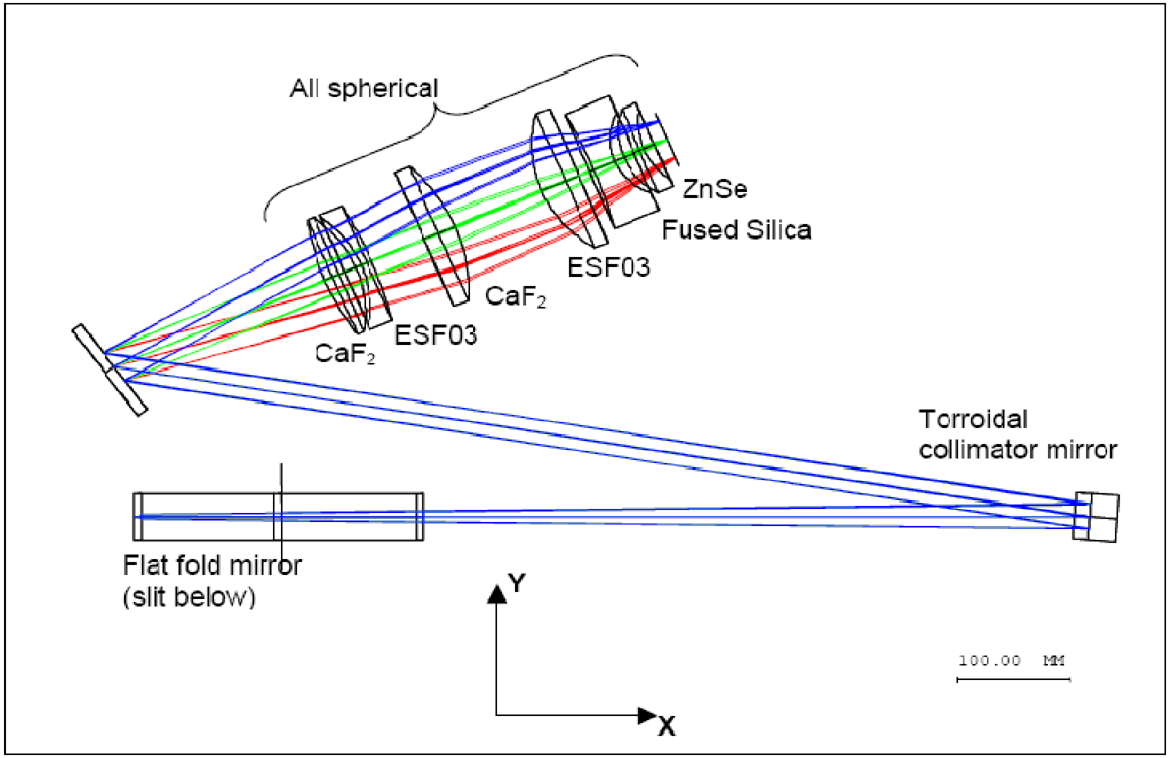
Camera focal length, f

$$\boxed{\frac{\mathrm{D}\cdot\mathrm{FOV}}{206265} = \frac{\mathrm{pixel\_width}}{\mathrm{f\_number}}}$$

A very practical application

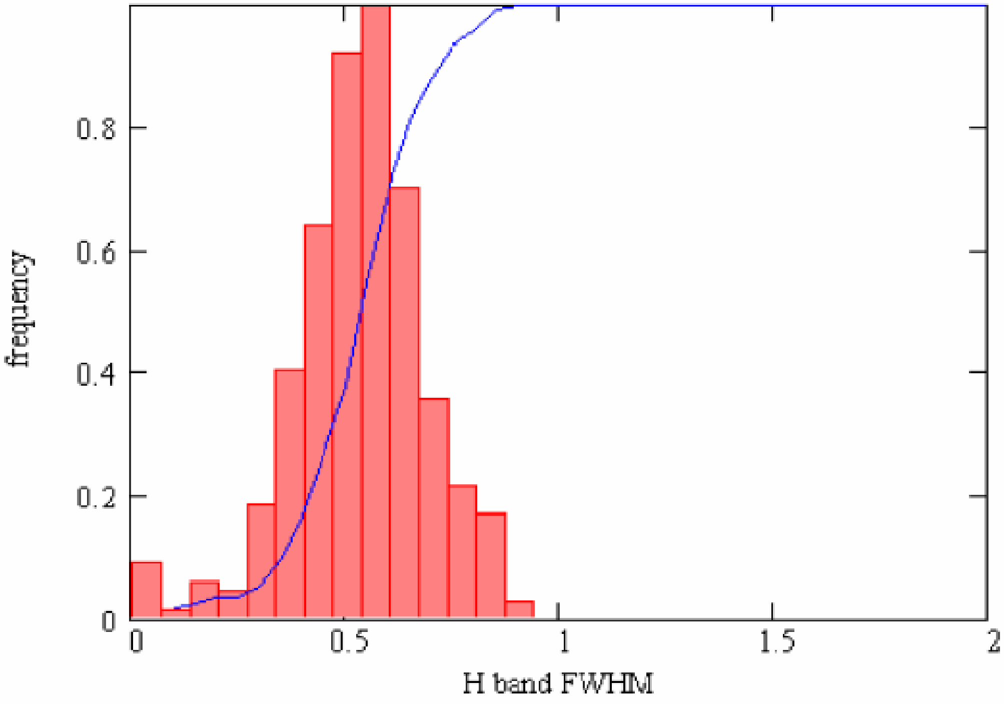
- KMOS
- FOV=0.2arcsecs

$$\frac{D \cdot \mathrm{FOV}}{206265} = \frac{\text{pixel\_width}}{\text{f\_number}}$$



KMOS Design choices: pixel FoV

- pixel FoV depends on
  - Size of images
  - the science case
- For maximum sensitivity
  - Match slit to seeing
- KMOS has designed for the best seeing at VLT



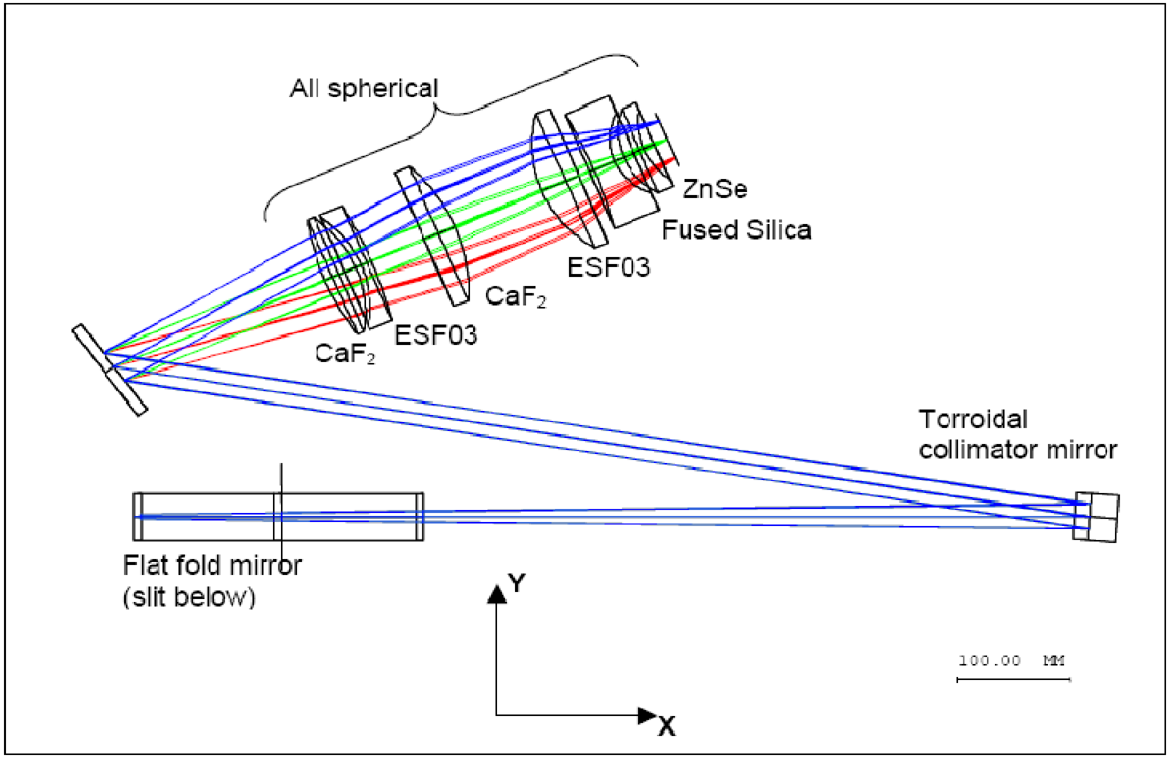
H median FWHM = 0.53 arcsec

- Pixel scale selected is 0.2arcsec for Nyquist sampling of the seeing

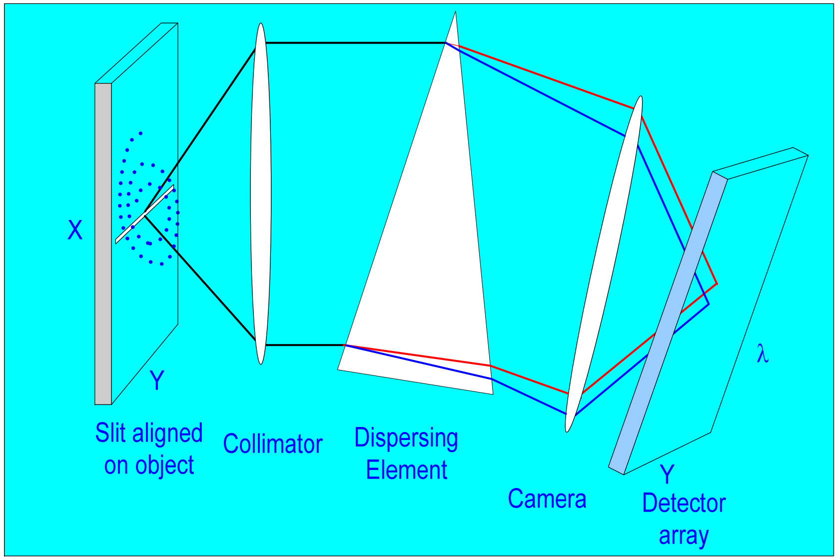
A very practical application

- KMOS
- At the seeing limit
- FOV=0.2arcsecs
- 18μm pixels
- f2.3 on the 8m VLT

$$\frac{D \cdot FOV}{206265} = \frac{pixel\_width}{f\_number}$$



Spectral resolving power, R



Grating equation

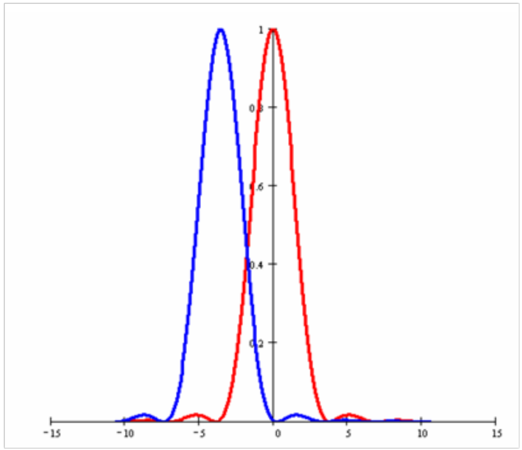
$$m \cdot \lambda = d(\sin(\theta i) + \sin(\theta r))$$

Angular dispersion

$$\frac{\partial \theta}{\partial \lambda} = \frac{m}{d \cdot \cos(\theta)}$$

Angular separation of two wavelengths at the detector

$$\Delta\theta = \Delta\lambda \cdot \frac{d\theta}{d\lambda}$$

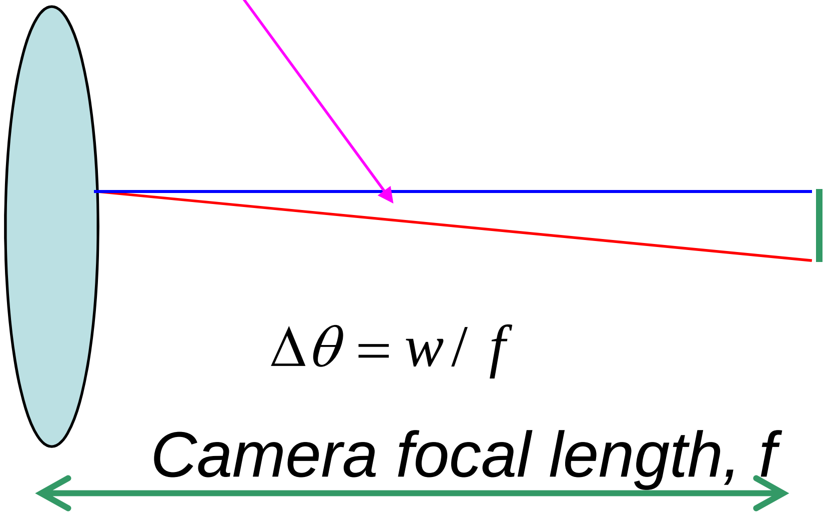


Spectral resolving power, R = λ/Δλ

Relating R to instrument design parameters:

$$R = \frac{\lambda}{\Delta\lambda} = \frac{2f}{w}\tan(\theta_r)$$

$$\Delta\theta = \Delta\lambda \cdot \frac{d\theta}{d\lambda}$$



$$\Delta\theta = w/\ f$$

Camera focal length, f

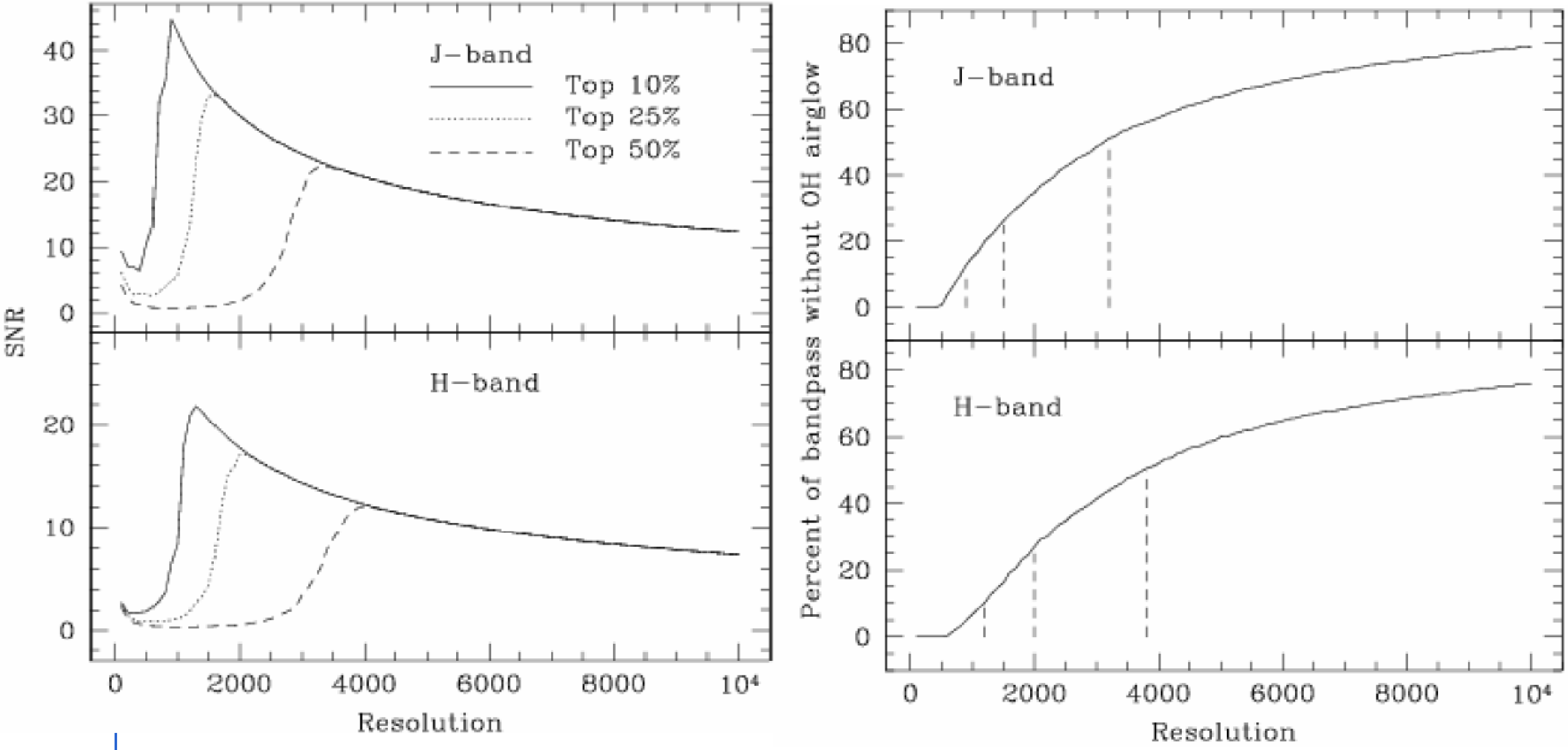
Pixel size, w

NB: often w = two pixels for Nyquist sampling of the spectral line width

KMOS – design choices, gratings

- Key requirements for KMOS on spectral resolving power:
  - Ideally, coverage of a complete transmission window simultaneously
    - E.g. K band from 1.95μm to 2.45μm, 2048 pixel detector
    - R~4500
  - high enough to resolve OH lines

Resolving the OH background



Spectral resolving powers of >2000, preferably around 4000 are a good choice.

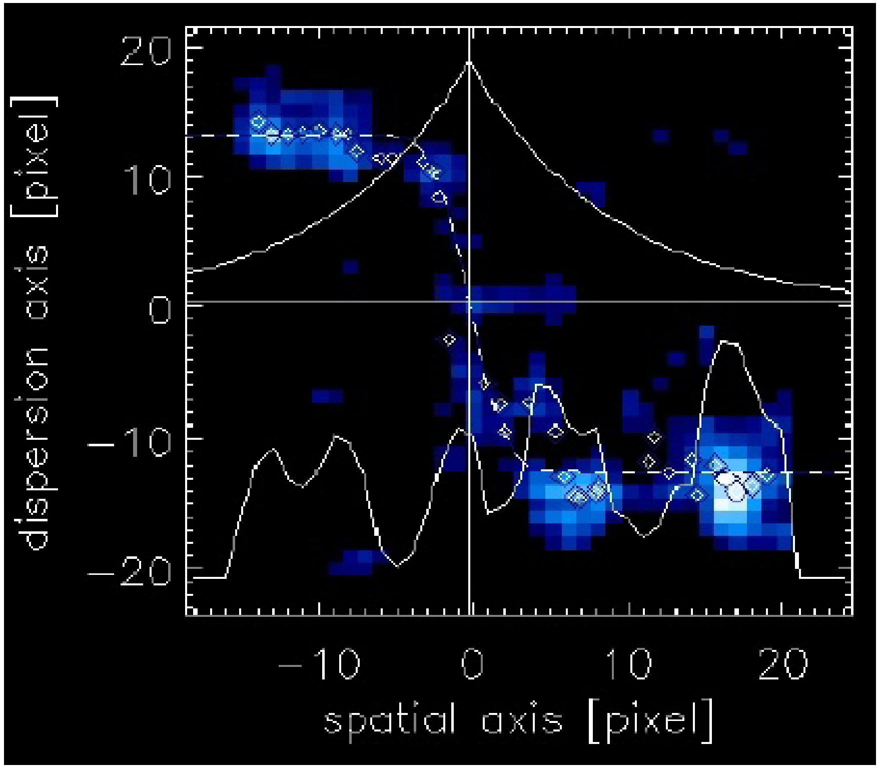
From Martini & DePoy 2000, Proc SPIE 4008, 695

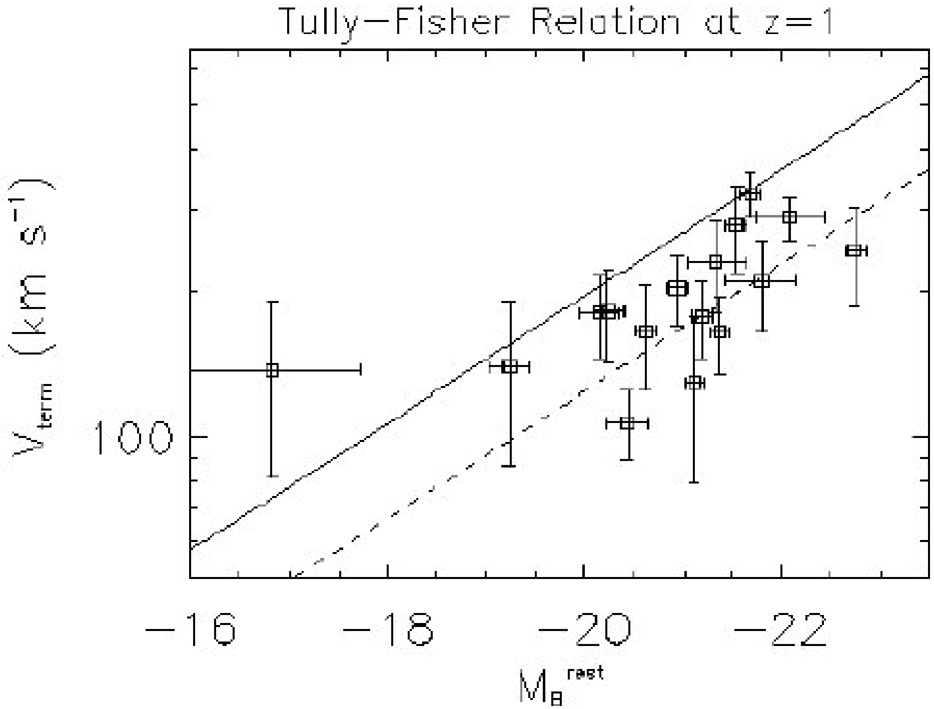
KMOS – design choices, gratings

- Key requirements for KMOS on spectral resolving power:
  - high enough to resolve OH lines
  - Ideally, coverage of a complete transmission window simultaneously
  - Allowing velocity resolution of 10km/s for experiments on the Tully-Fischer relation in galaxies

KMOS – galaxy dynamics

- Key requirements for KMOS on spectral resolving power:





KMOS Design choices - gratings

- Key requirements for KMOS on spectral resolving power:
  - high enough to resolve OH lines
  - Ideally, coverage of a complete transmission window simultaneously
  - Allowing velocity resolution of 10km/s for experiments on the Tully-Fischer relation in galaxies
  - Resulting choice: $\lambda/d\lambda > 3000$

KMOS gratings again…..

- For a grating spectrometer :

$$R = \frac{\lambda}{\delta\lambda} = \frac{2 \cdot f \cdot \tan(\theta r)}{w}$$

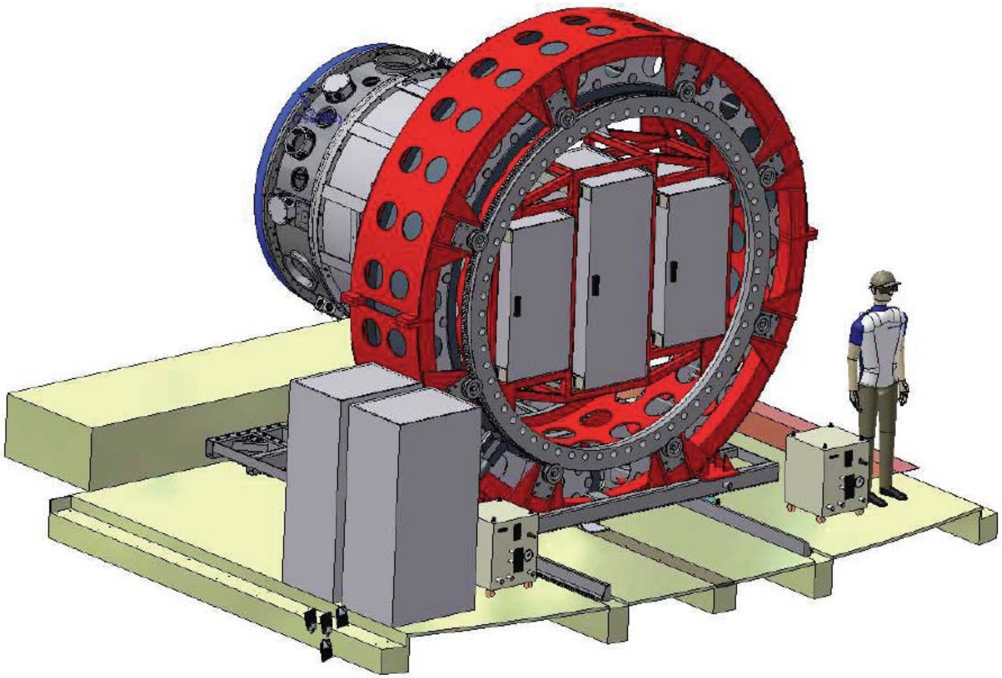
  - f is the focal length of the camera,
  - w is the size of the slit at the detector (two 18μm pixels for KMOS)
  - θr the blaze angle for the grating (45º).
  - f ~ 70mm and beam size ~31mm for R=4000
  - In practice, KMOS beam size is 33mm

Instrument scaling laws

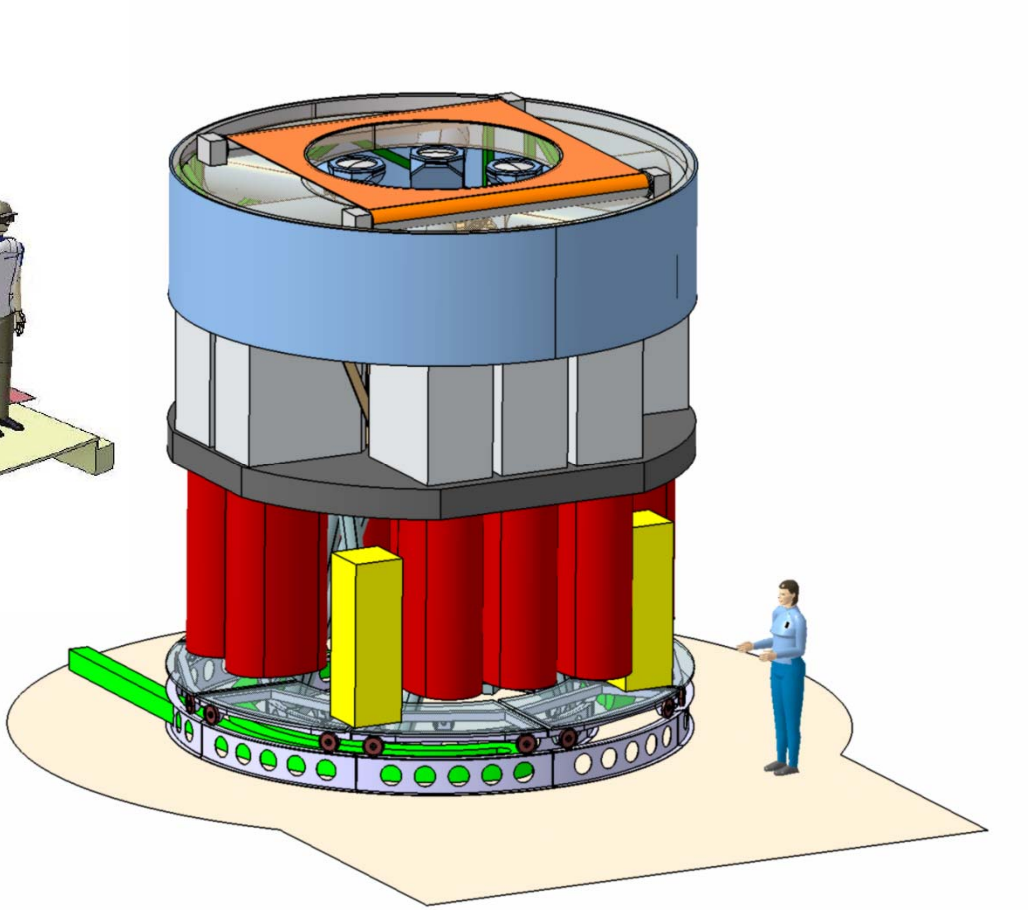
- Instruments sizes scale with the telescope

KMOS vs EAGLE

- KMOS for the 8-m VLT



- EAGLE for the 42m E-ELT



Instrument scaling laws

- Instruments sizes scale with the telescope
- Diffraction limited instruments
  - Set the field of view to match the diffraction limit:

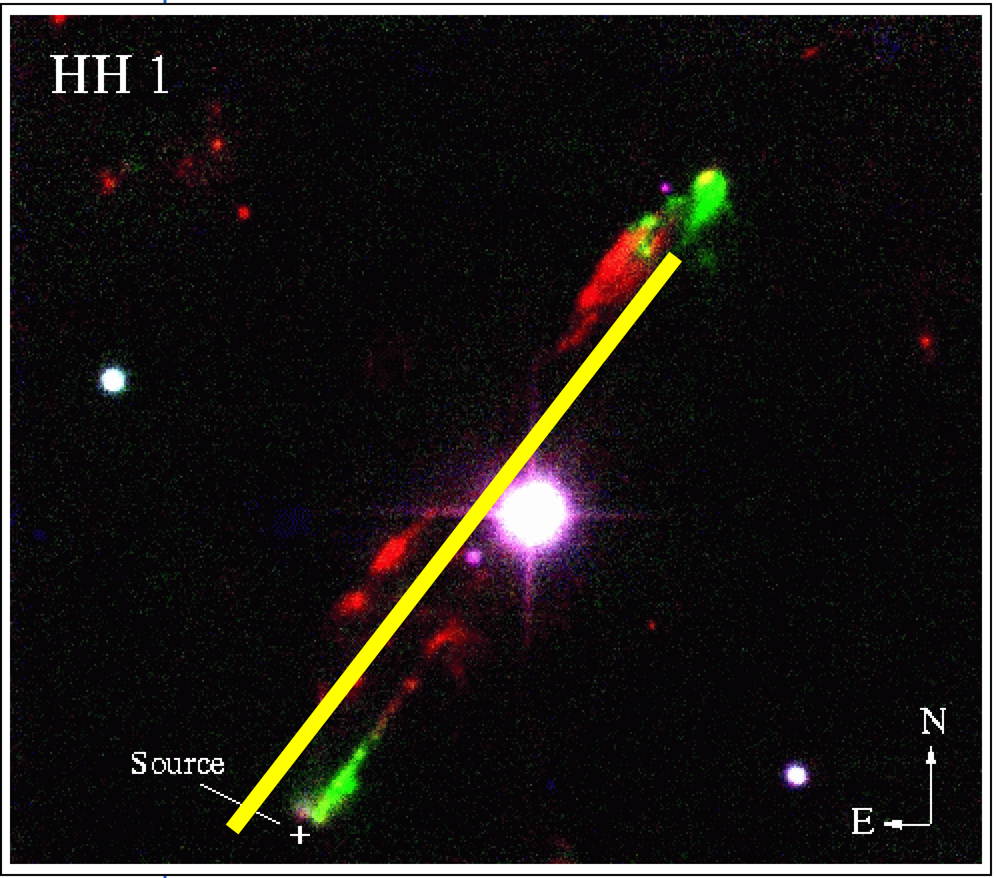
$$\mathrm{FOV} = \frac{1.22\lambda}{\mathrm{D}}$$

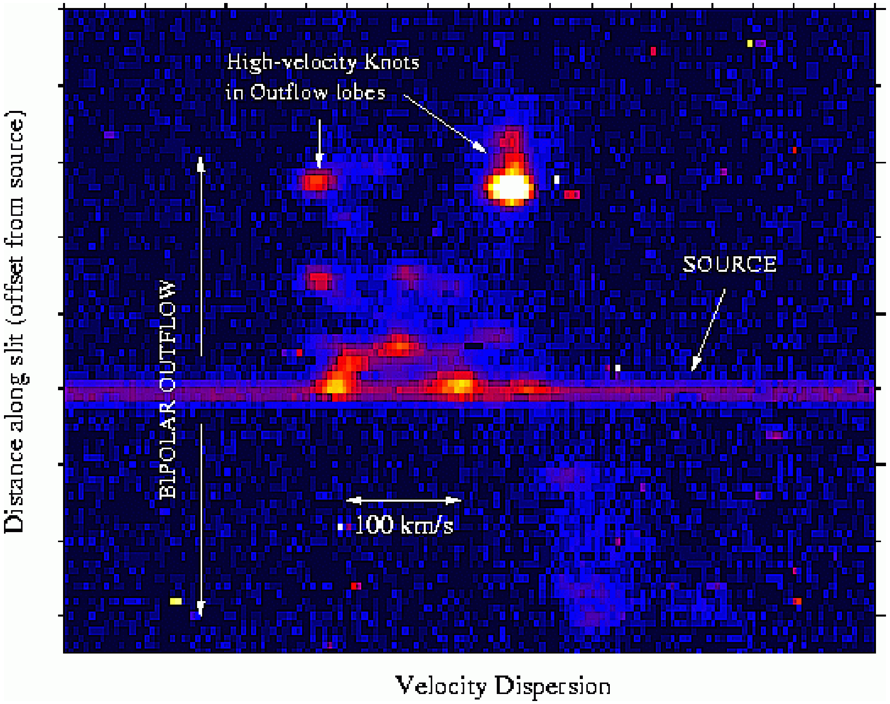
$$\boxed{\frac{\mathrm{pixel\_width}}{\mathrm{f\_number}} \propto \lambda}$$

  - A diffraction limited instrument can go on any telescope

long slit spectrograph: strengths/weaknesses

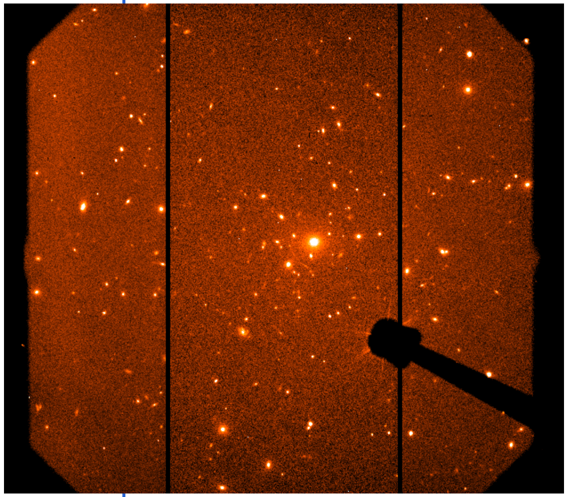
- *With typical plate scales of 0.2arsec/pixel and 2048 x 2048 pixel detectors, modern spectrometers have slit lengths of 2arcmin.*



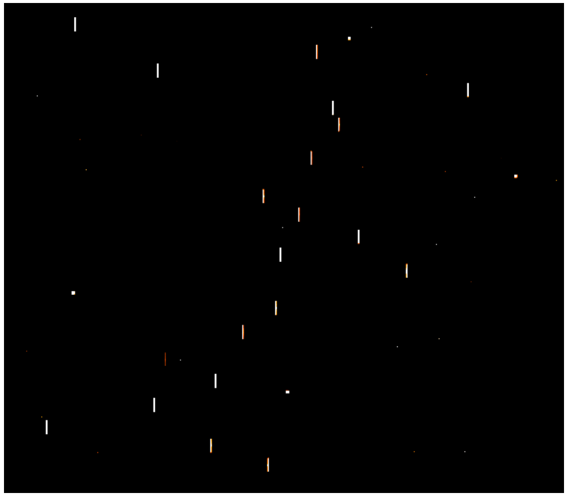


Data courtesy UK Infrared Telescope, Tom Ray and Chris Davis

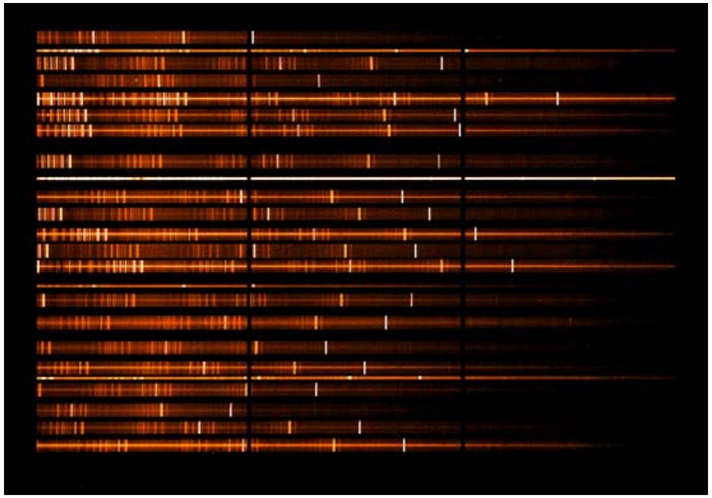
Long slit versus multi-object spectroscopy (MOS)



An image of a field of stars and galaxies is used to set positions for slitlets in a mask…



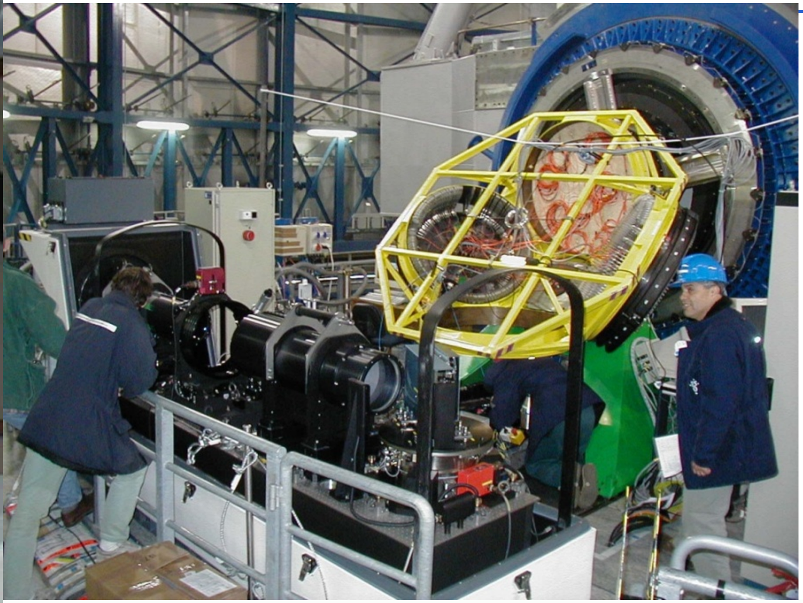
the multi-object slit mask is inserted at the telescope focal plane…..

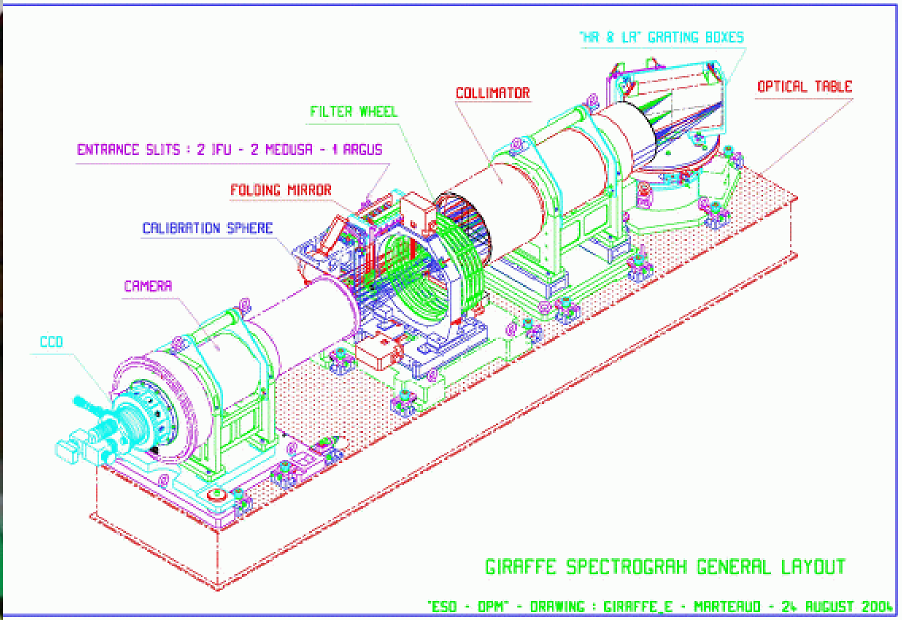


and spectra of the selected sources measured at the detector.

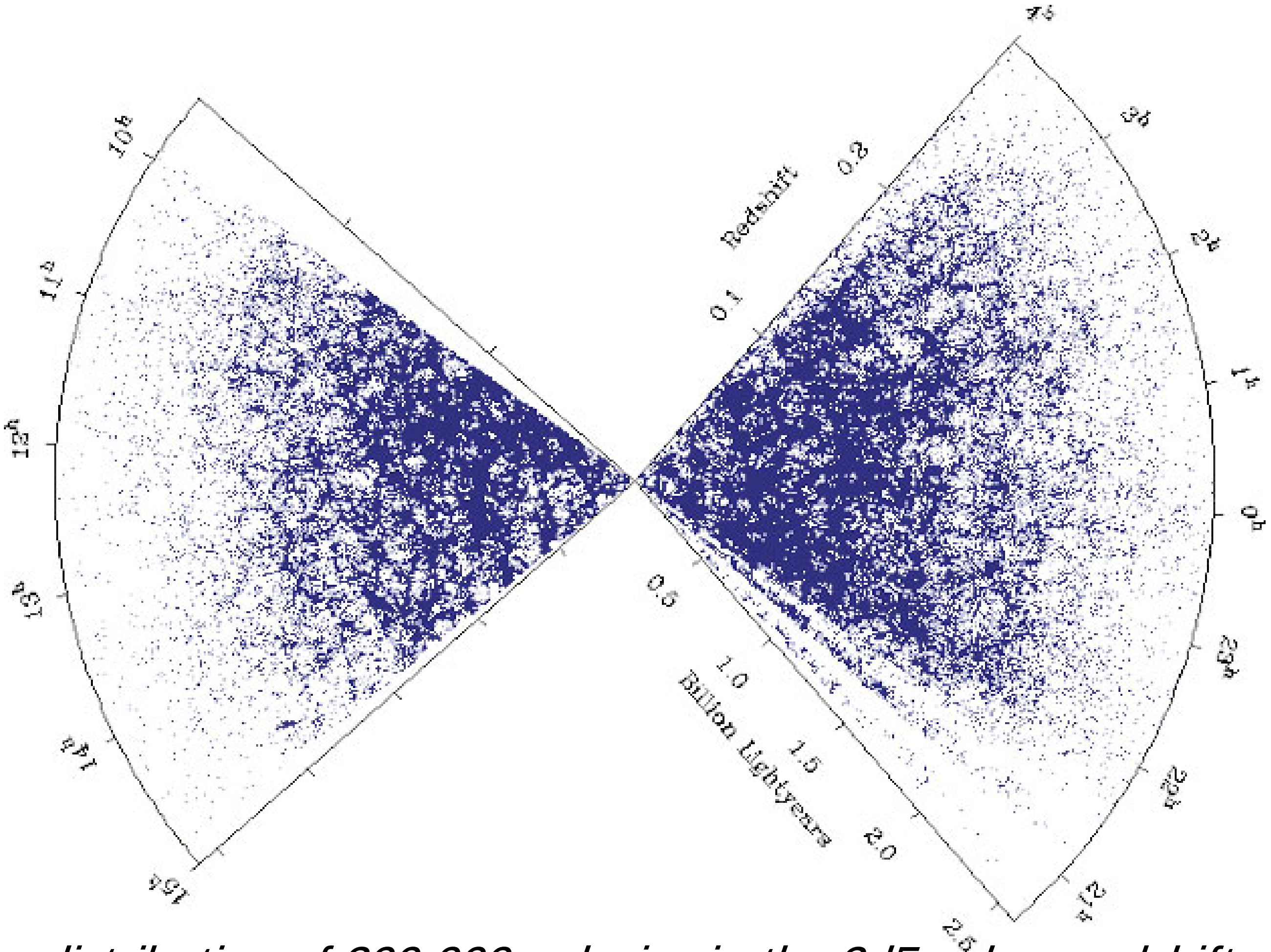
Images from the Gemini Multi-object Spectrograph

GIRAFFE on the VLT



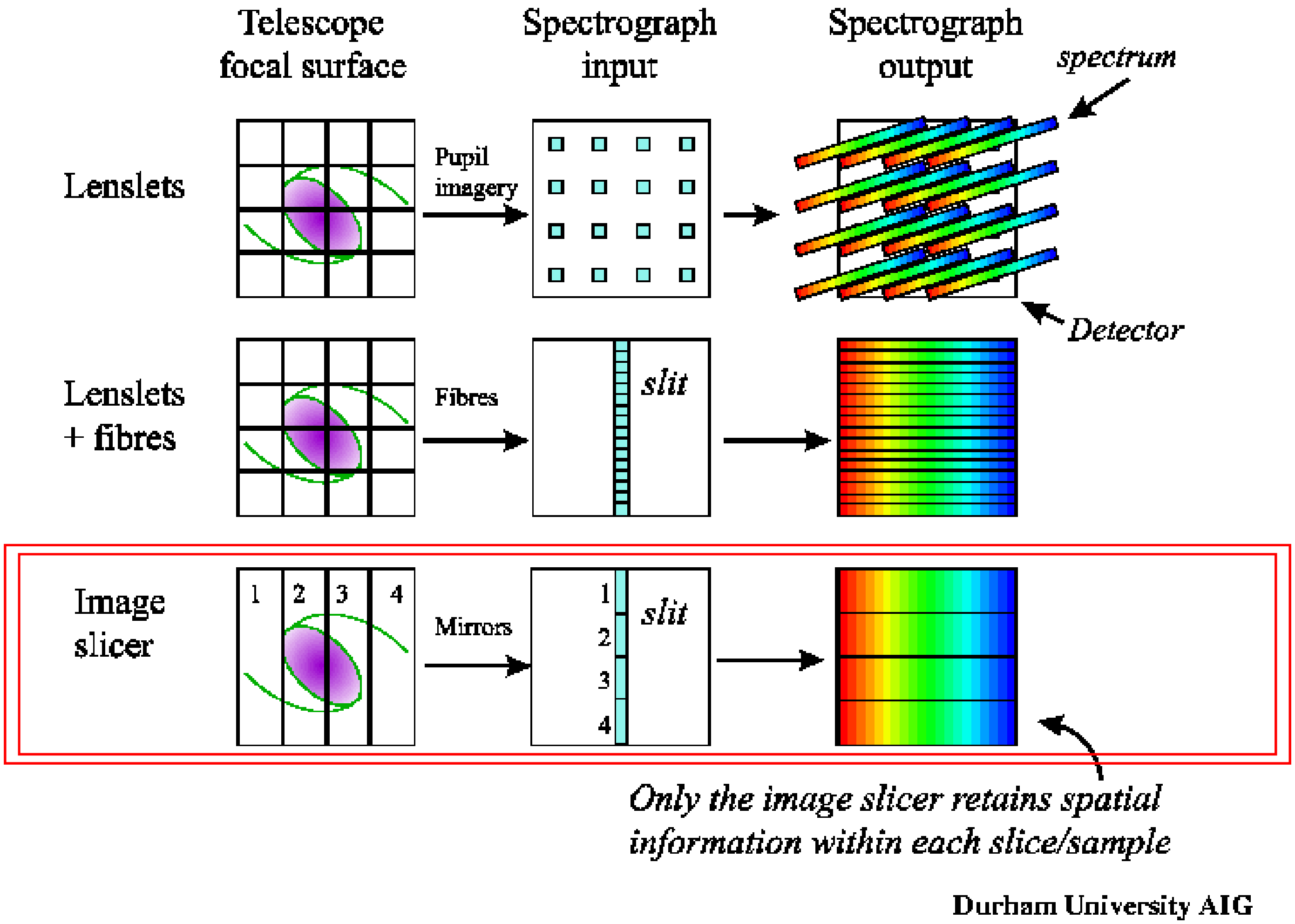


A fibre-fed MOS spectrograph: 2DF



- *The distribution of 200,000 galaxies in the 2dF galaxy redshift survey*
- *2dF is an optical multi-object spectrograph with a two-degree field of view and the ability to observe 400 objects simultaneously*

Techniques for 3D spectroscopy



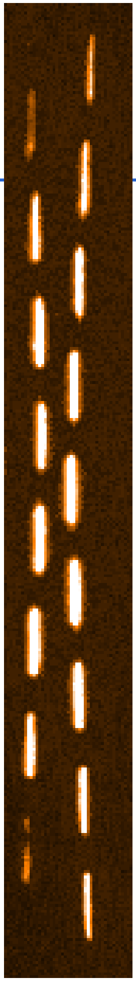
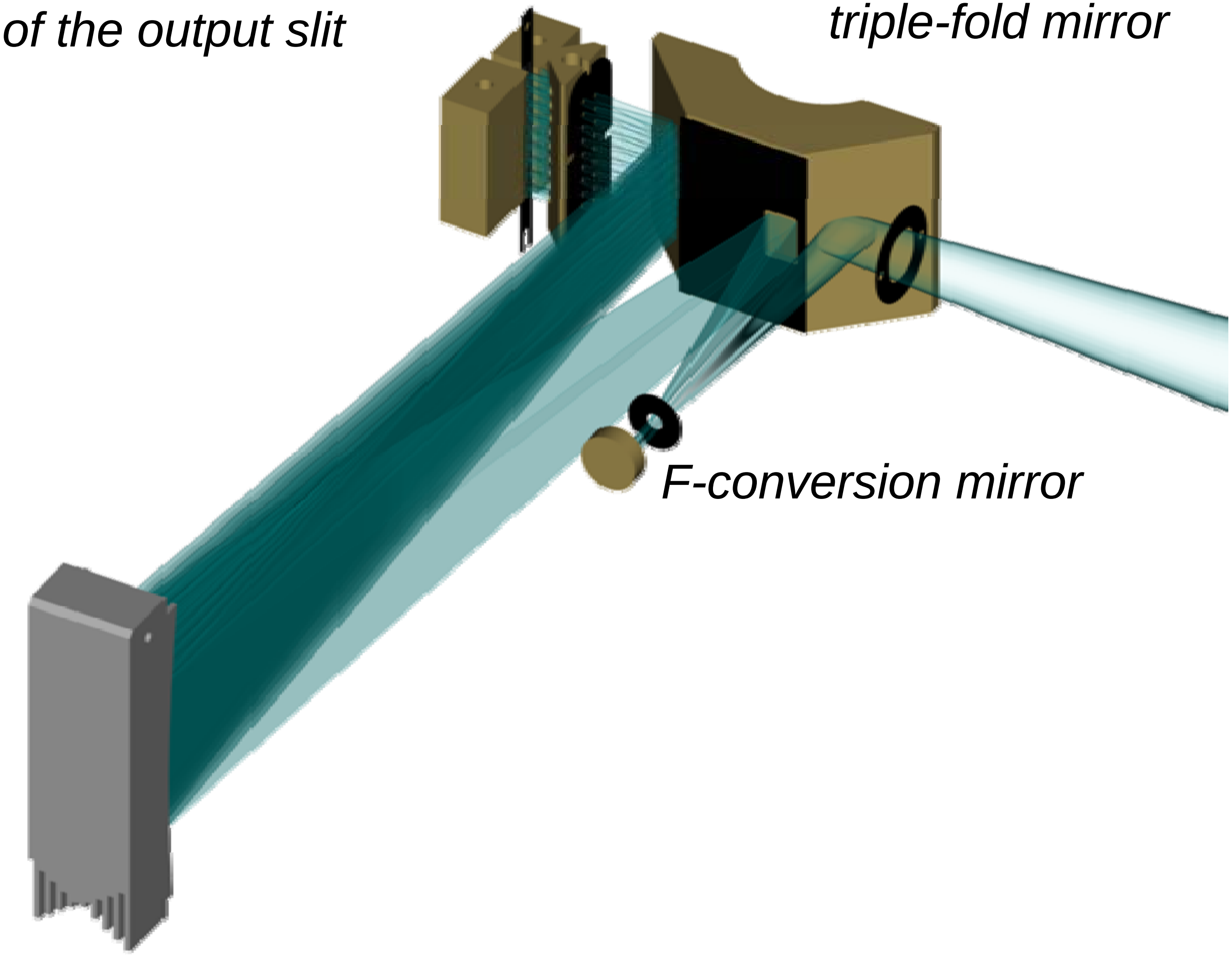
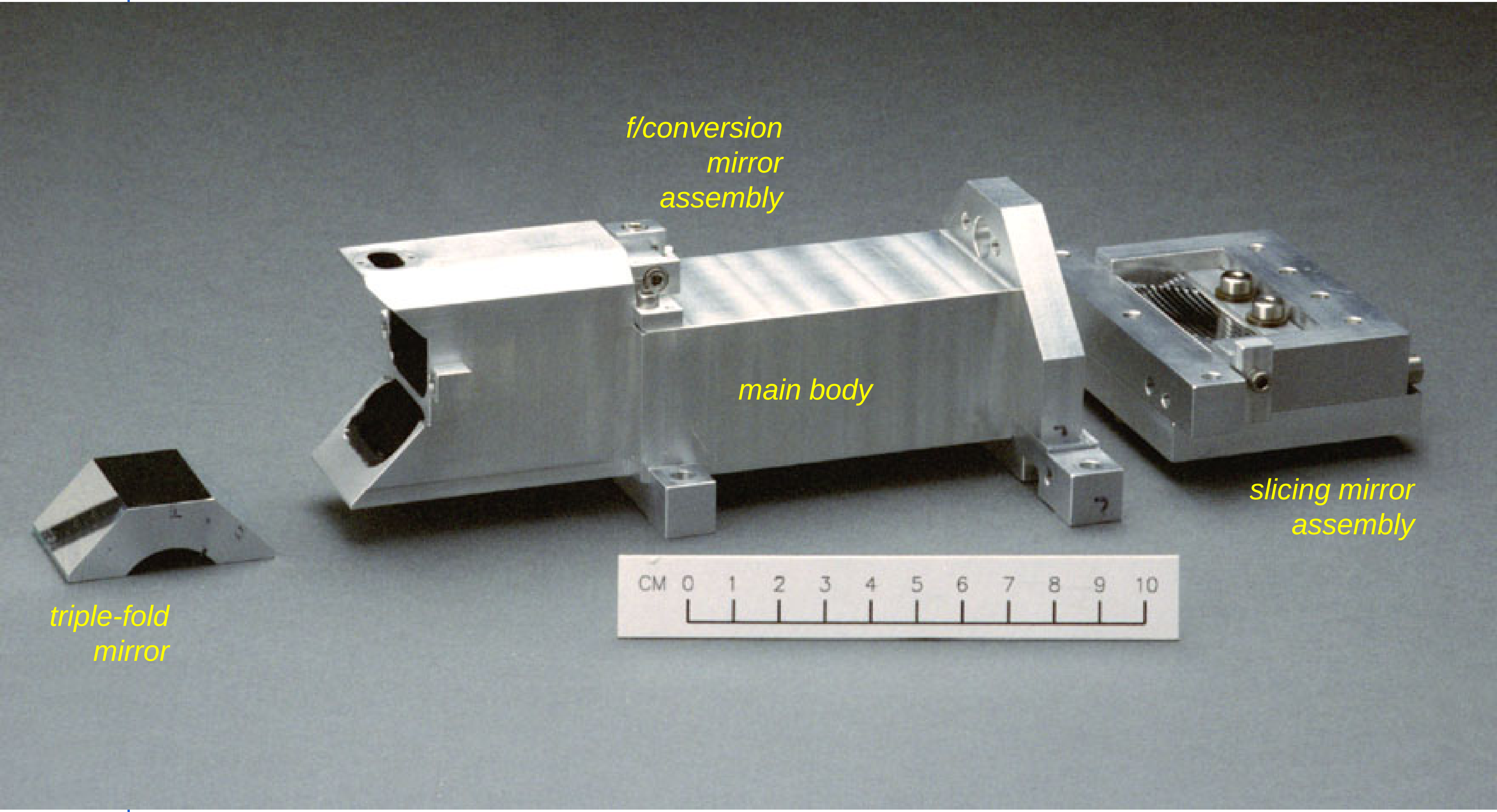


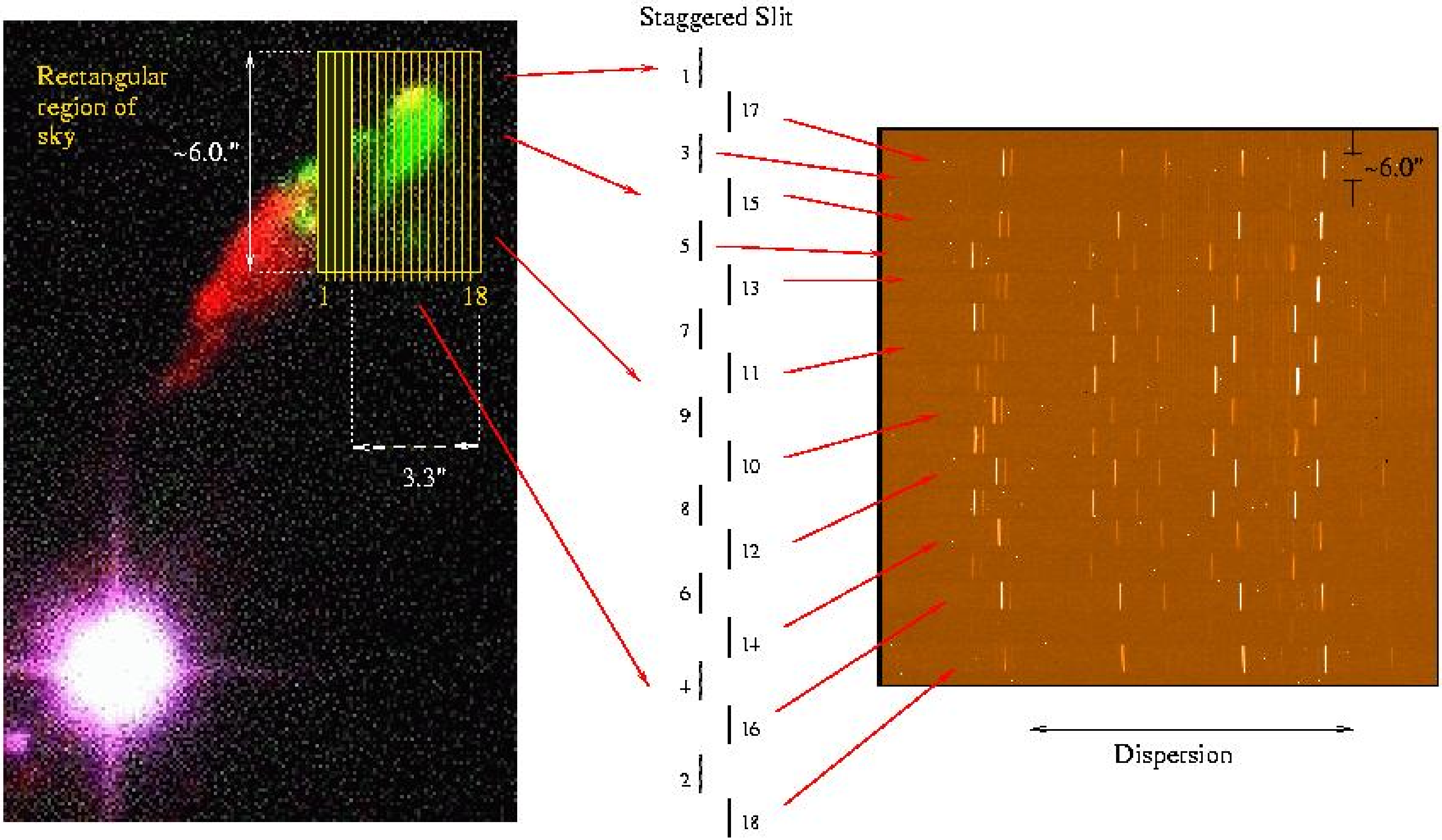
Image of the output slit



The UIST integral field unit

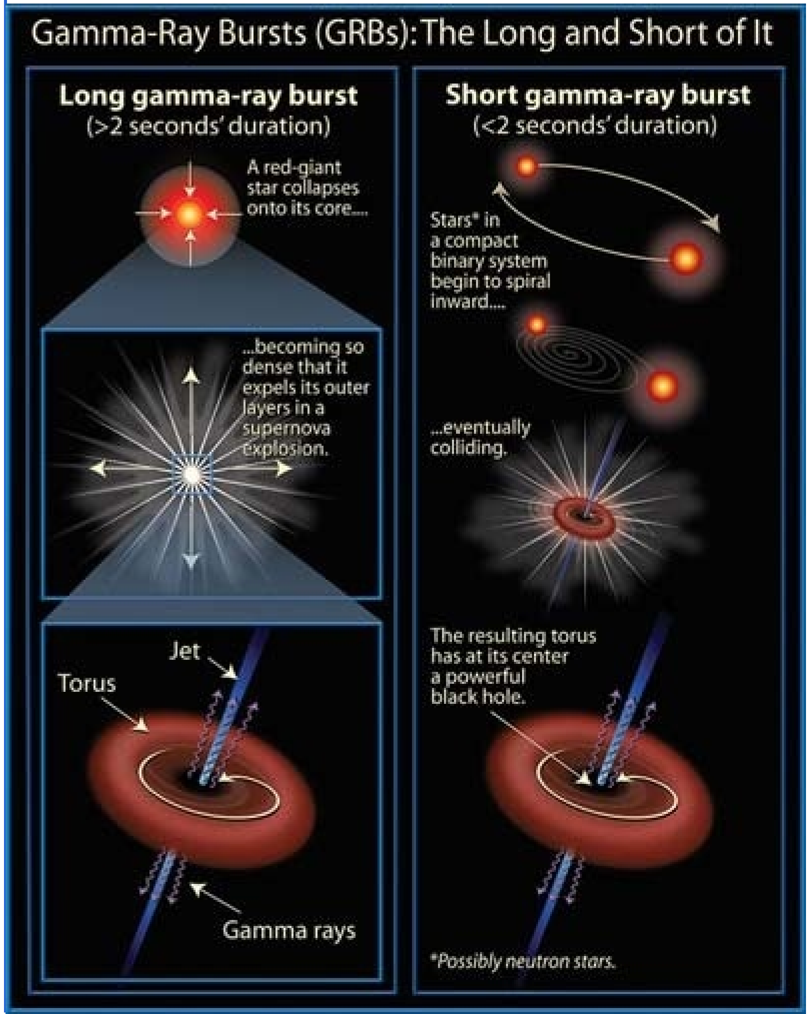


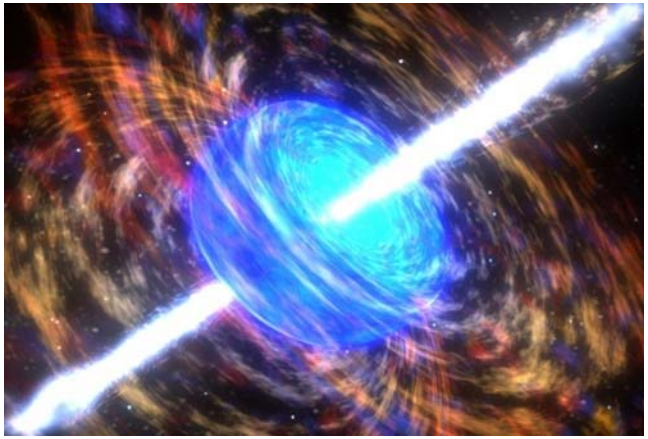
Integral field spectroscopy: data



X-shooter

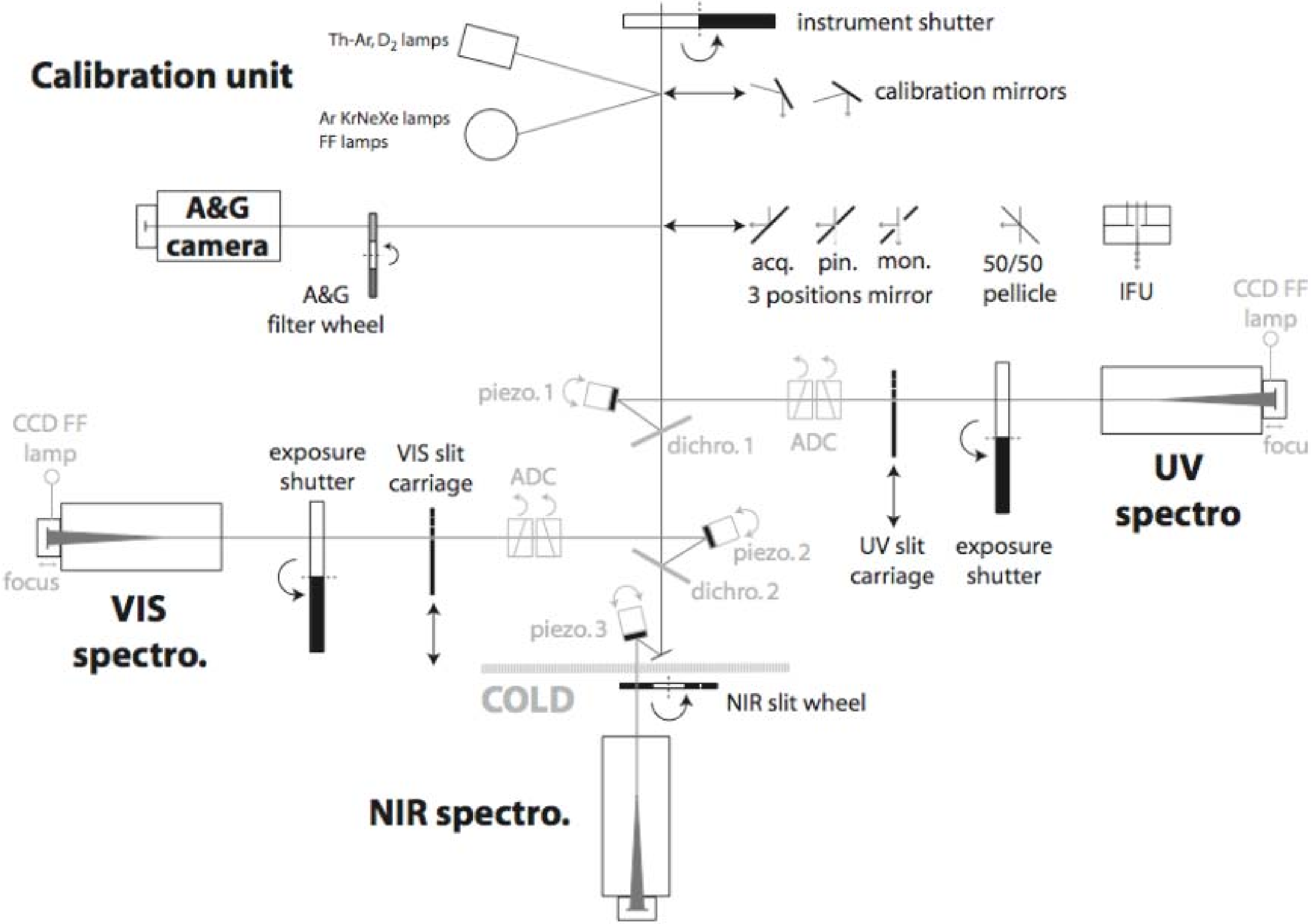
- Catching gamma ray bursts in the act



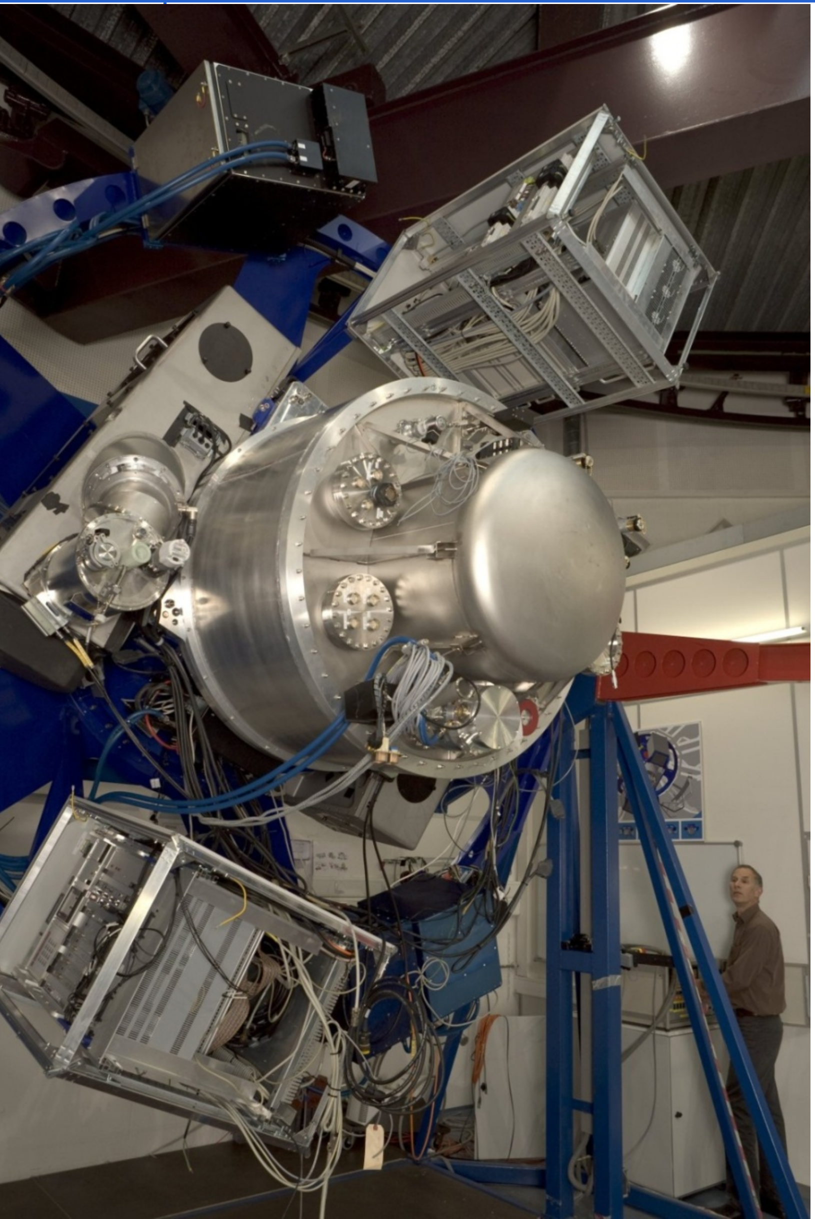


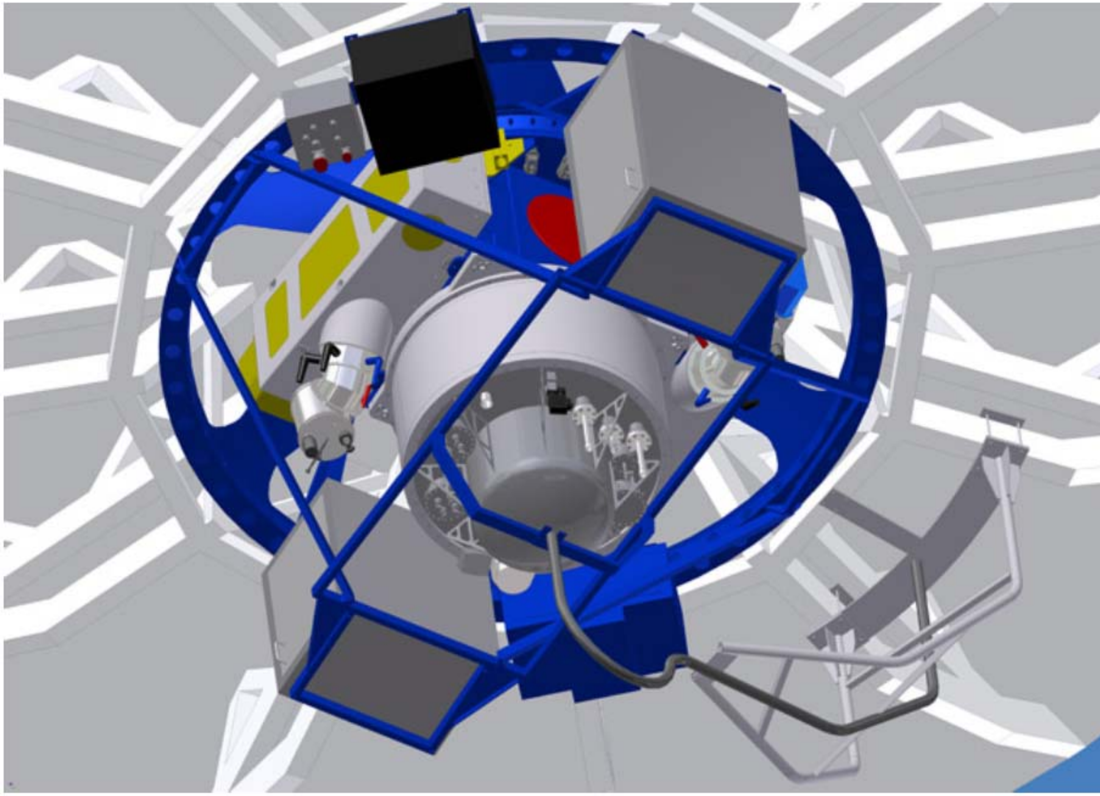
- Instrument requirements
  - Broad wavelength coverage
  - Fast set-up
  - Efficiency
  - Small field of view

X-shooter


instrument shutter
Calibration unit
Th-Ar, D_2 lamps
Ar KrNeXe lamps
FF lamps
calibration mirrors
A&G camera
A&G filter wheel
acq.
pin.
mon.
3 positions mirror
50/50 pellicle
IFU
CCD FF lamp
piezo. 1
dichro. 1
ADC
UV slit carriage
exposure shutter
focu
UV spectro
CCD FF lamp
exposure shutter
VIS slit carriage
ADC
piezo. 2
dichro. 2
focus
VIS spectro.
piezo. 3
COLD
NIR slit wheel
NIR spectro.

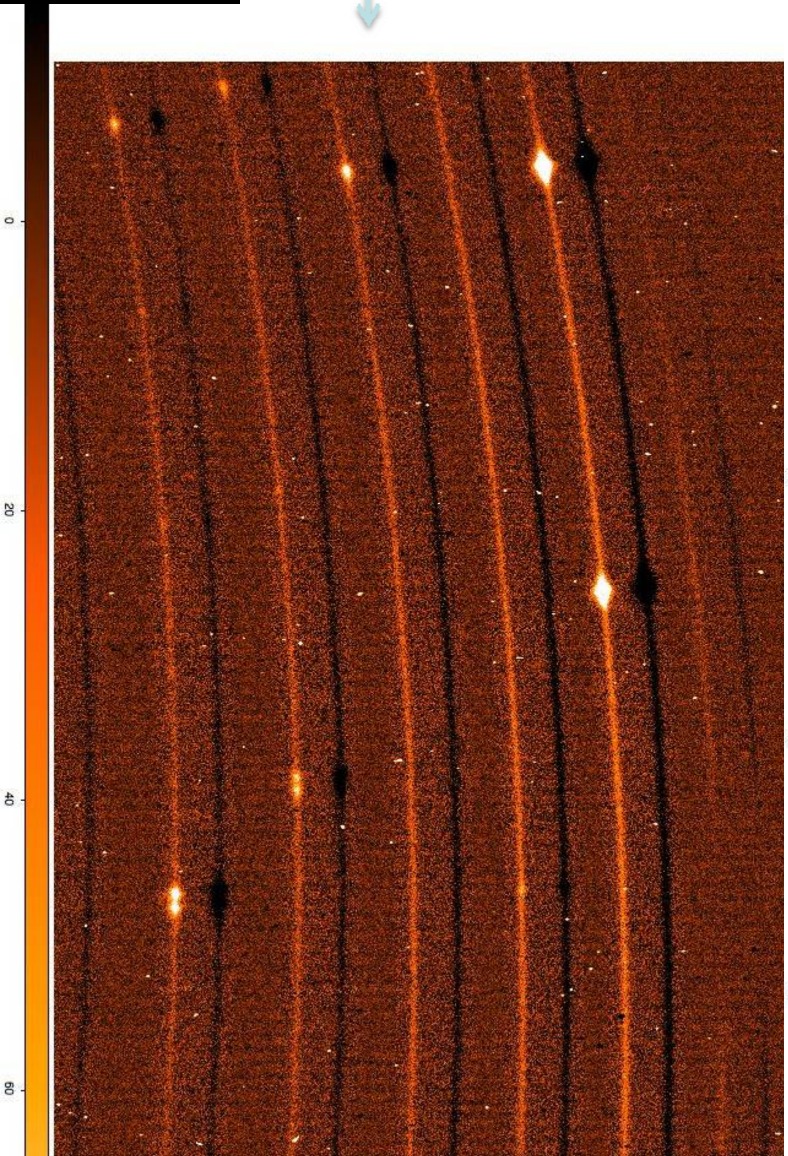
X-shooter

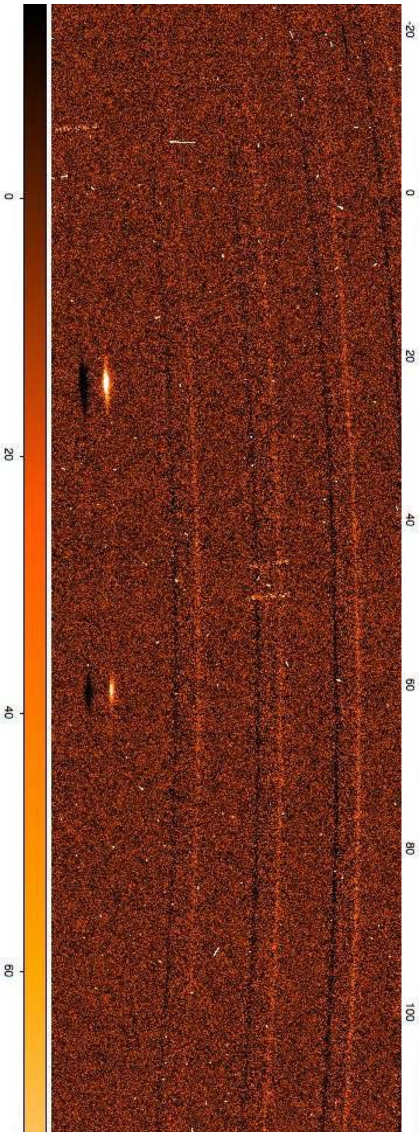


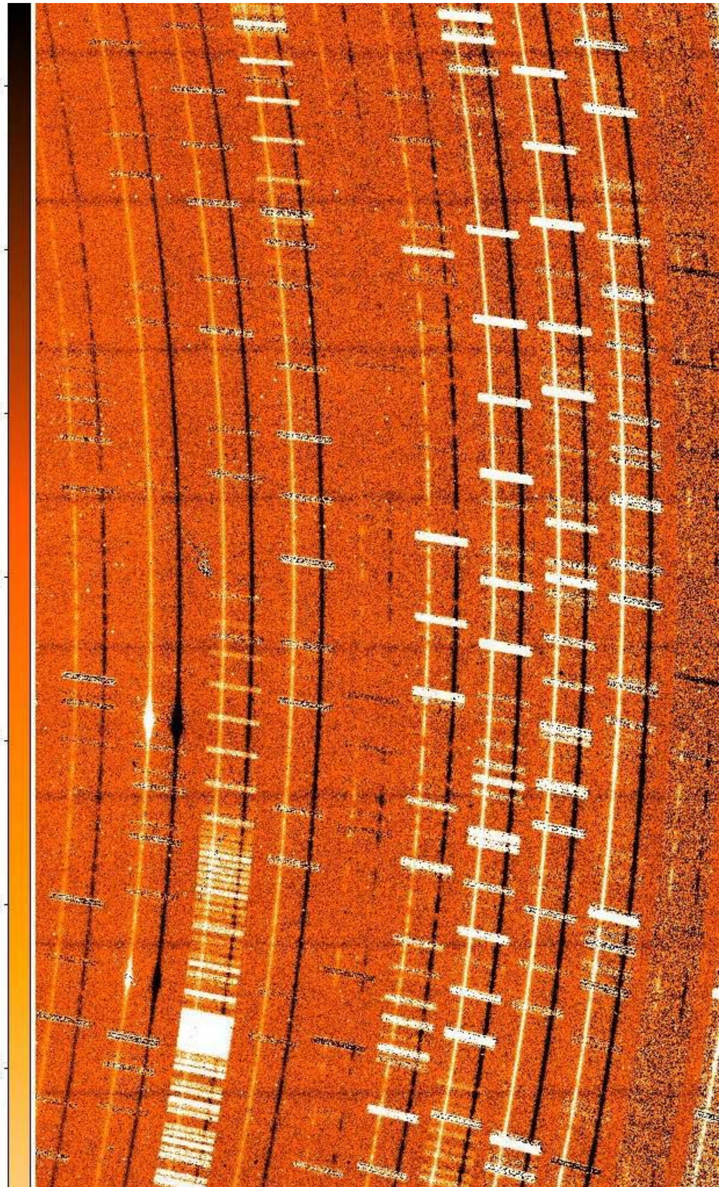


4 x1200s exposure on a starburst galaxy, night 16-17 March, courtesy Comm Team

UVB: 320-559nm, R= 5100, VIS:560-1040nm, R=8800, NIR: 1040-2300, R=5600

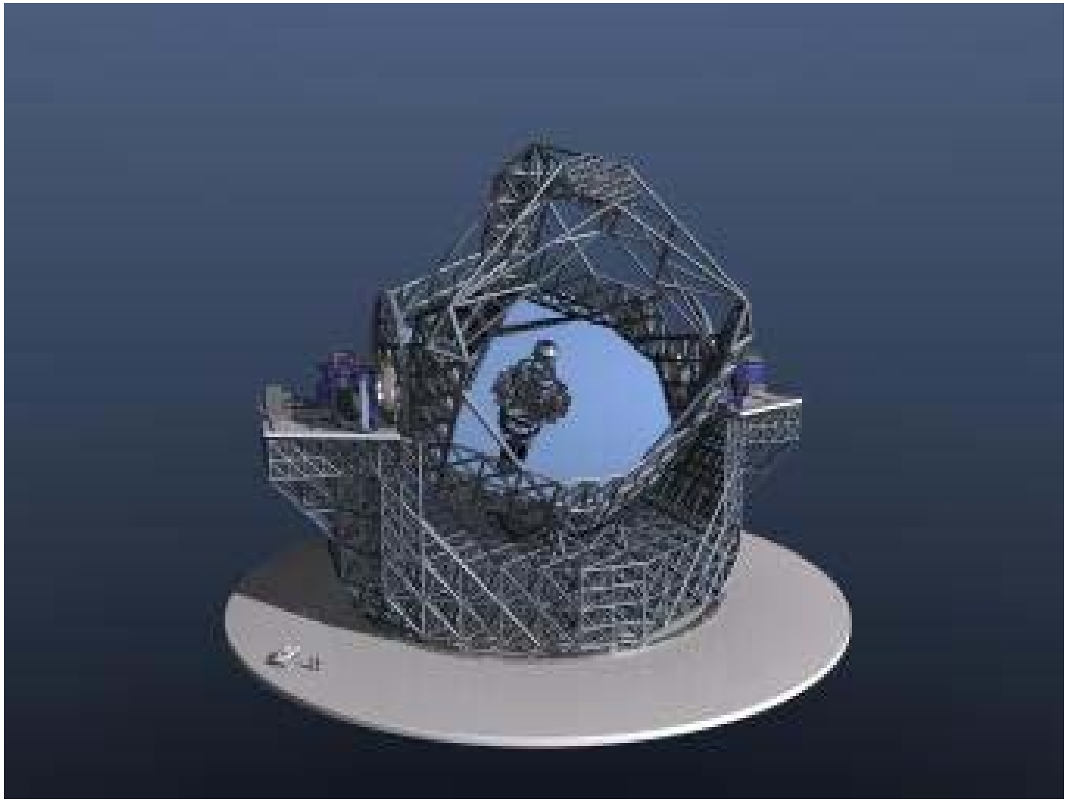






Future Instrumentation

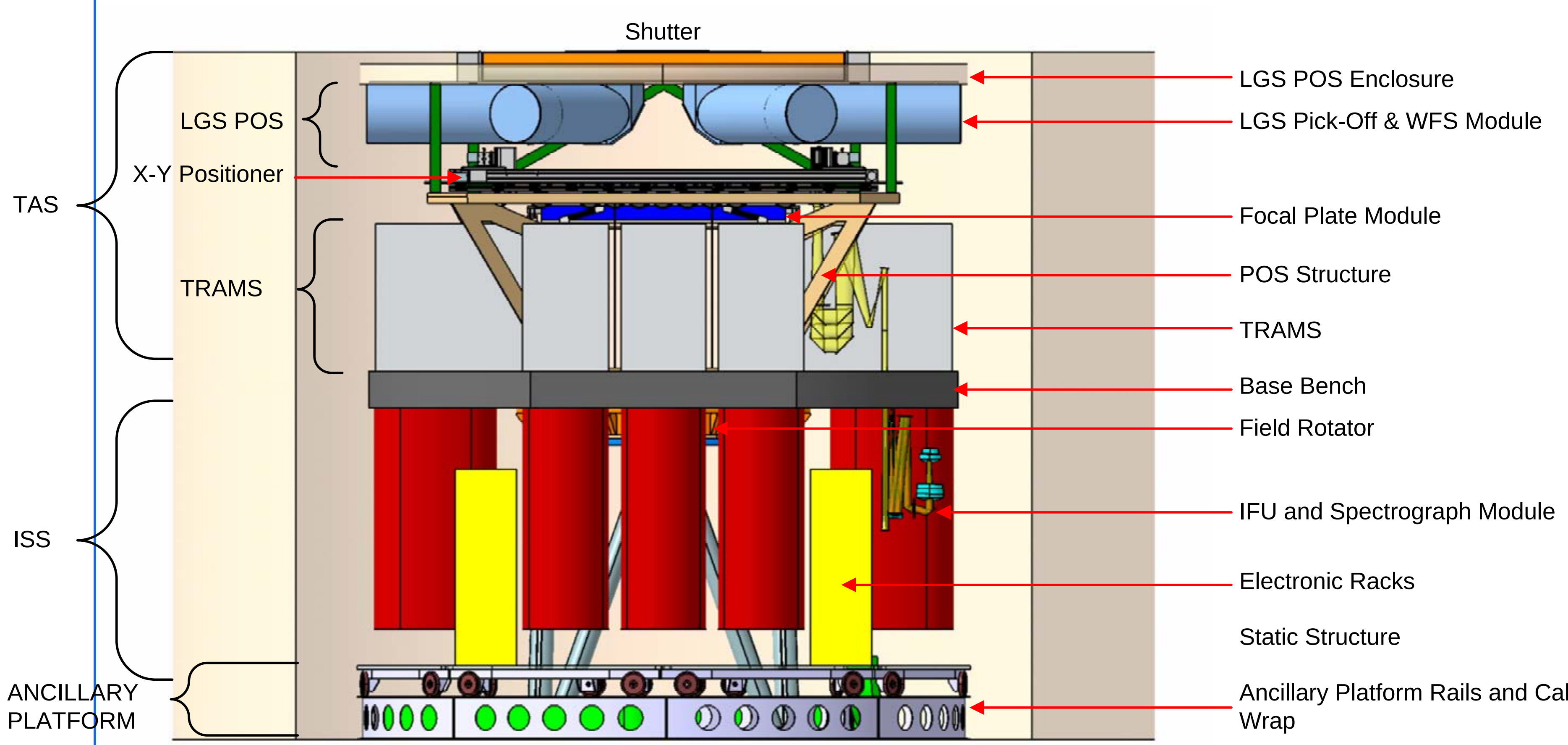
- Studies are underway for the next generation of telescopes (>30m)
- The E-ELT, being designed at ESO is 42m



Implications of the aperture size

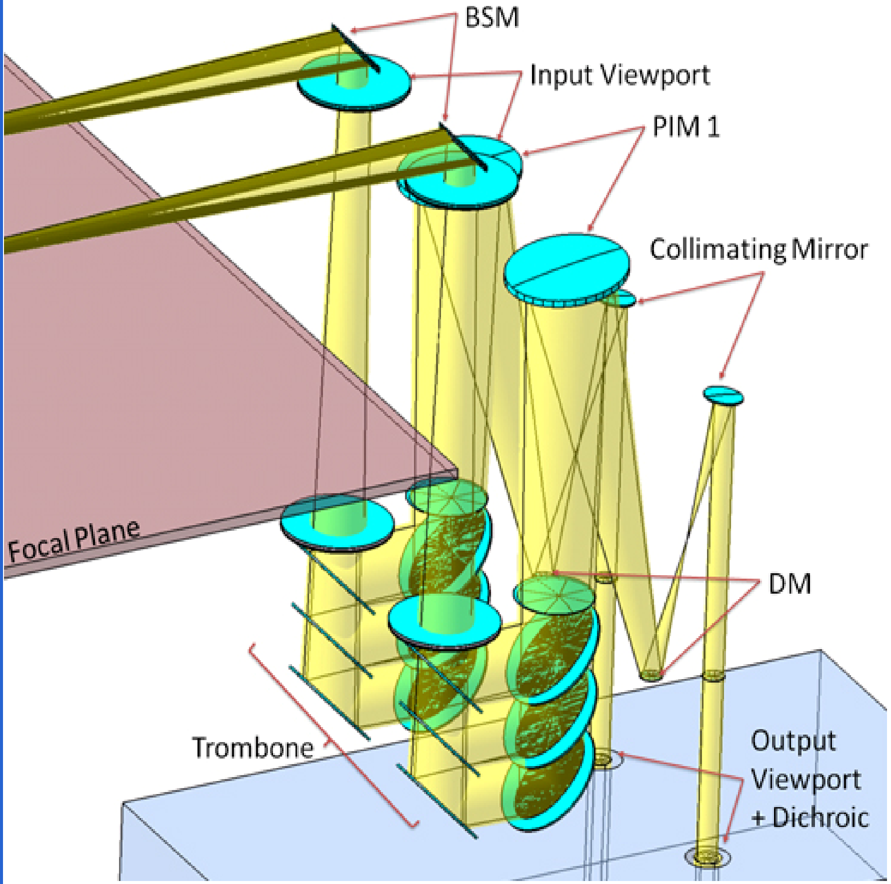
- Huge gains in sensitivity
  - from photon collecting power
  - from increased in spatial resolution
- Higher spatial resolution leads to astrophysics on smaller physical scales
- For the instrument builders….some challenges
  - D=42m, FOV=0.8arcsec, pix=18μm
  - Camera f-ratio = 0.2
  - Or 9 pixels per seeing disk for an f-1 camera
- Adaptive optics to the rescue…….

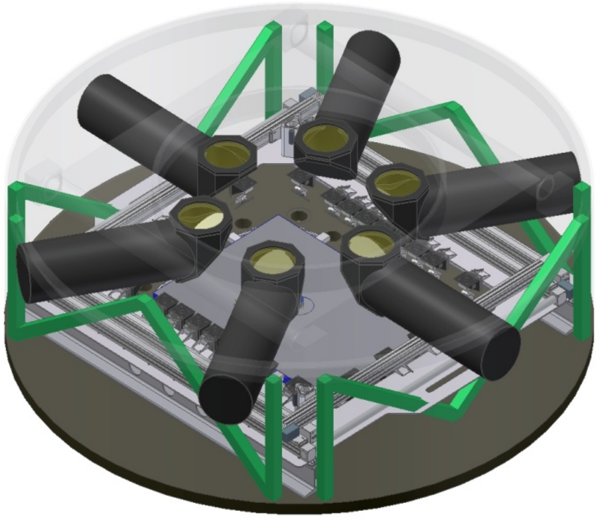
EAGLE


Shutter
TAS
LGS POS
X-Y Positioner
TRAMS
ISS
ANCILLARY
PLATFORM
LGS POS Enclosure
LGS Pick-Off & WFS Module
Focal Plate Module
POS Structure
TRAMS
Base Bench
Field Rotator
IFU and Spectrograph Module
Electronic Racks
Static Structure
Ancillary Platform Rails and Cal
Wrap

EAGLE Adaptive Optics

- 6 laser guide star pick-offs





- Adaptive correction of each selected field

EAGLE science:
Galaxy archaeology