

# Instrumentation for optical/IR groundbased astronomy

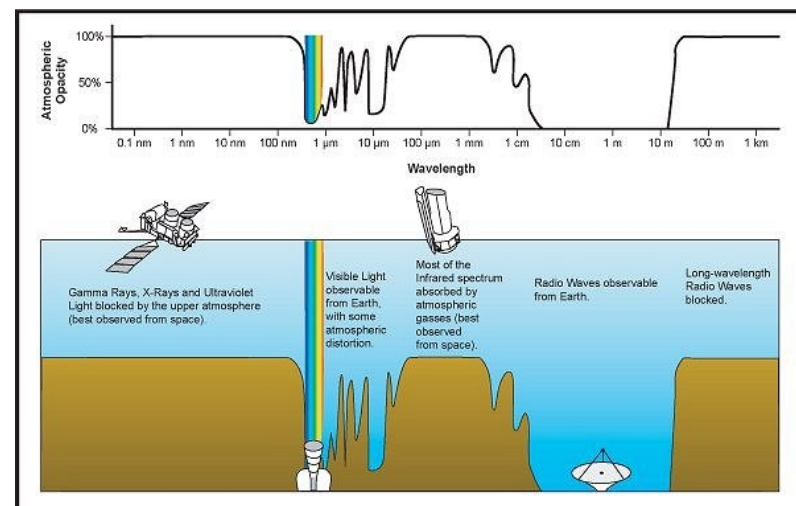


**EIROFORUM school, June 2021**

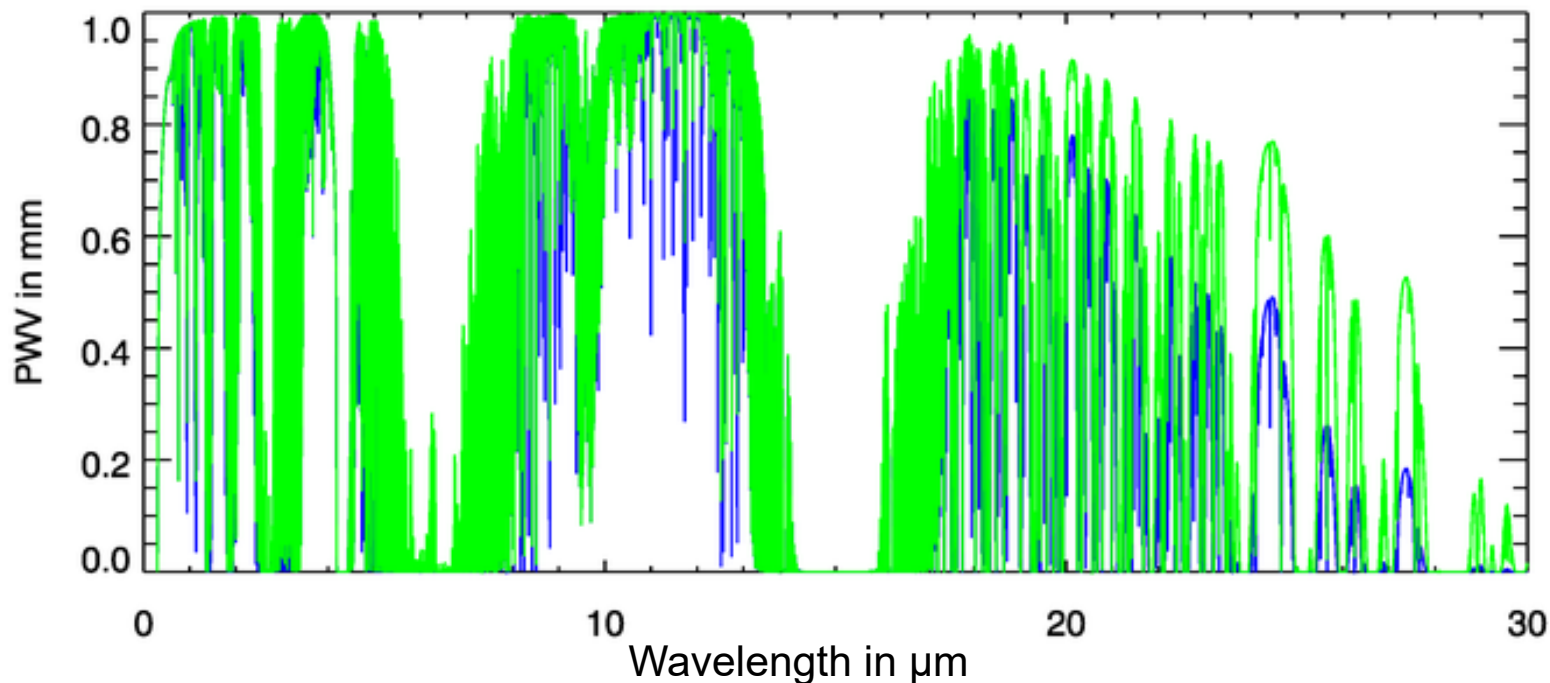
Suzanne Ramsay ([sramsay@eso.org](mailto:sramsay@eso.org))

# Outline of the talk

- Scope: optical to MIR >> 350nm to 28μm
  - No photonic instruments and no interferometry
- Astronomy from the ground
  - Background radiation
  - Atmospheric transmission
  - Atmospheric turbulence
- Adaptive optics
- Detectors for ground-based instruments
- Instrument design for instrument scientists
- State-of-the art instruments today



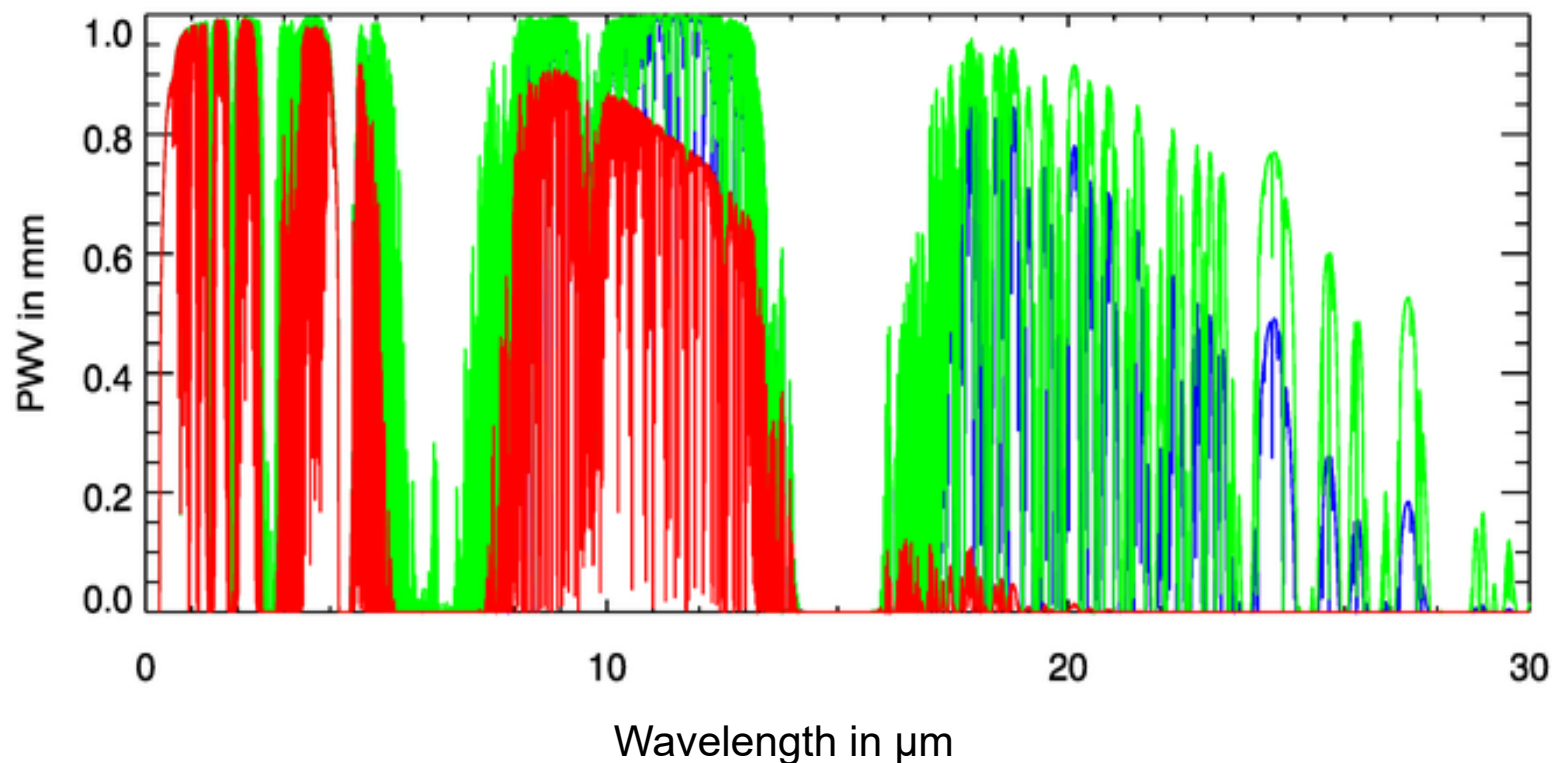
# Astronomy from mountain tops



Optical to mid-infrared (MIR) atmospheric transmission for ESOs  
Paranal site using precipitable water vapour value of 2.5mm (median,  
blue) and 1.0mm (best conditions, green).

*Atmospheric transmission calculations from the Cerro Paranal Advanced Sky model, Skycalc, at [www.eso.org](http://www.eso.org).  
See Noll et al. 2012, A&A, 543, A92 and Jones et al. 2013, A&A, 560, A91*

# Astronomy from ... Noordwijk



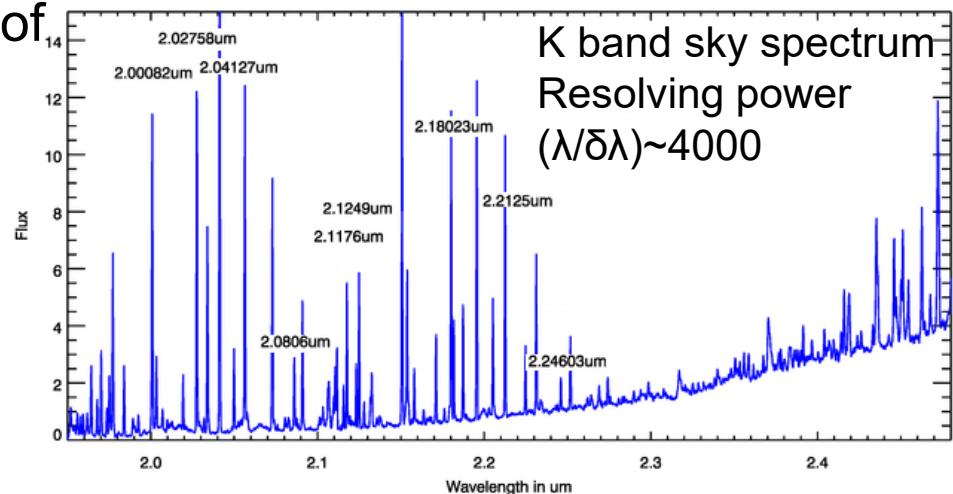
Typical atmospheric transmission for Holland using an assumed precipitable water vapour value of 20mm.

# Background radiation: airglow

- Earth's atmosphere also emits thermal and non-thermal radiation
- Airglow is the important, non-thermal component
  - Mainly OH emission lines
  - Variable in time (minutes)
  - Much brighter than the astronomical targets: 1000s of photons/s versus a few photons/s
  - Must be measured and subtracted as part of observation calibration



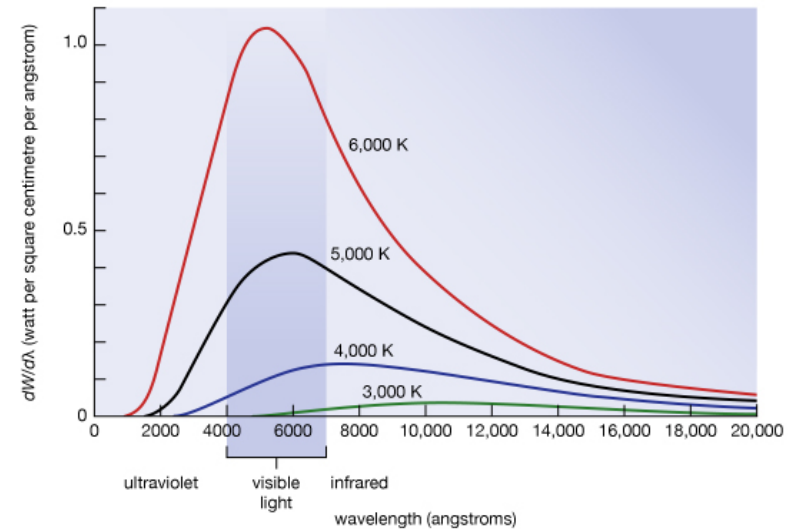
Gravity Waves in the atmospheric airglow  
APOD 140901. Copyright: Jeff Dai 2014





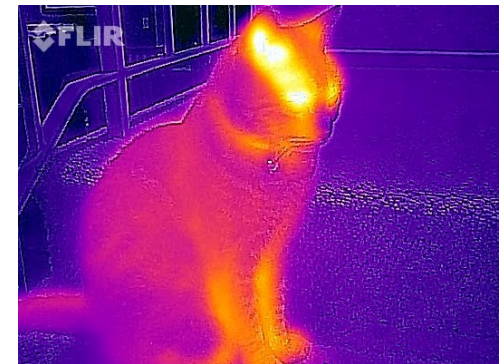
# Background radiation: thermal emission

- Wien's displacement law:  
 $\lambda_{\text{max}}/T \sim 2900 \mu\text{mK} \gg \text{room temperature bodies peak at } 10 \mu\text{m}$
- Blackbody radiation from the surroundings dominates at wavelengths longer than  $\sim 2 \mu\text{m}$
- Optical instruments are typically not cooled, apart from their detectors
- Instruments in the NIR (1-5  $\mu\text{m}$ ) are typically cooled to 70-130K (detectors to 30-70K)
- Instruments in the MIR (5-28  $\mu\text{m}$ ) are typically cooled to 30-40K (detectors to  $\sim 10\text{K}$ )



© Encyclopædia Britannica, Inc.

*Image credit: Encyclopedia Britannica*



**A kitten in the infrared**

# Atmospheric turbulence

- Earth's turbulent atmosphere blurs astronomical images
- Increasing telescope size increases photon flux but does not improve angular resolution as it theoretical should

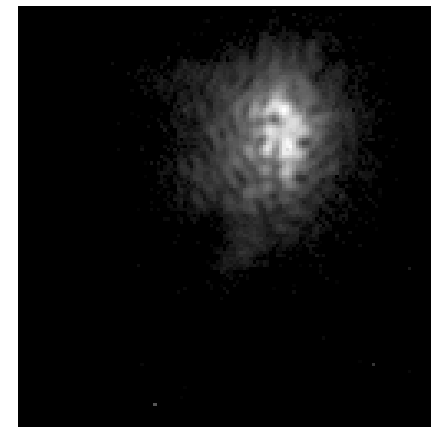
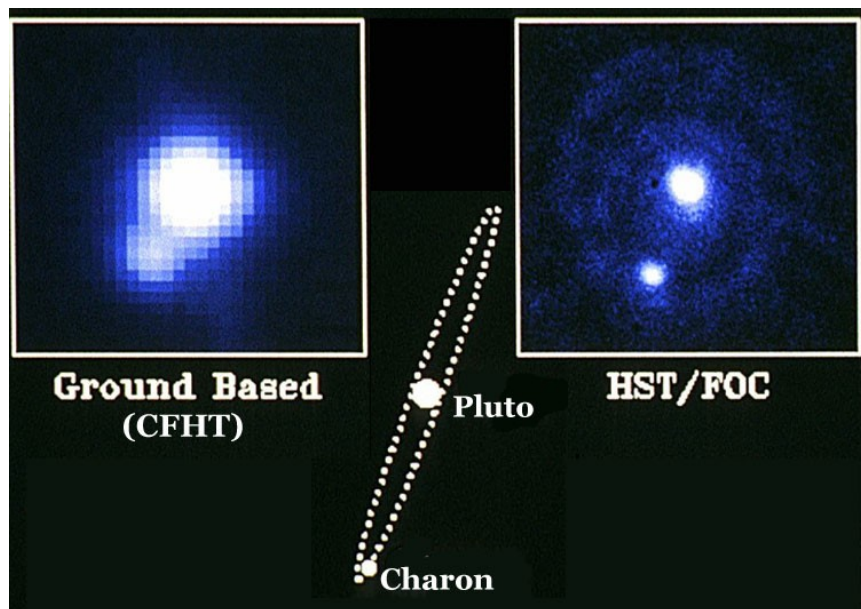


Image of a star in natural seeing  
GIF c/o MPIA/Hippler (edited)

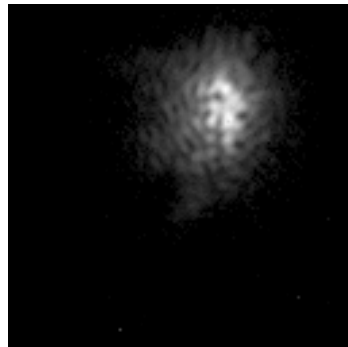


- Pluto and Charon imaged in 1990 by the HST (2.4m) and by the Canada France Hawaii Telescope (3.6m)
  - Maximum separation is 0.9arcsecs (typical not-bad ground based “seeing”)

# Adaptive optics (1)

- A crucial development in the last 30 years has been “adaptive optics”
- Basic Concept: measure and correct the atmospheric wavefront distortions
  - Proposed by Babcock 1953 but the technology was not available (computing power)

Natural seeing and  
AO loop closed  
GIF c/o  
MPIA/Hippler



No. 58 – December 1989

## Successful Tests of Adaptive Optics

*F. MERKLE, ESO*

*P. KERN, P. LÉNA, F. RIGAUT, Observatoire de Paris, Meudon, France*

*J. C. FONTANELLA, G. ROUSSET, ONERA, Châtillon-Sous-Bagneux, France*

*C. BOYER, J. P. GAFFARD, P. JAGOUREL, LASERDOT, Marcoussis, France*

## PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 65

October 1953

No. 386

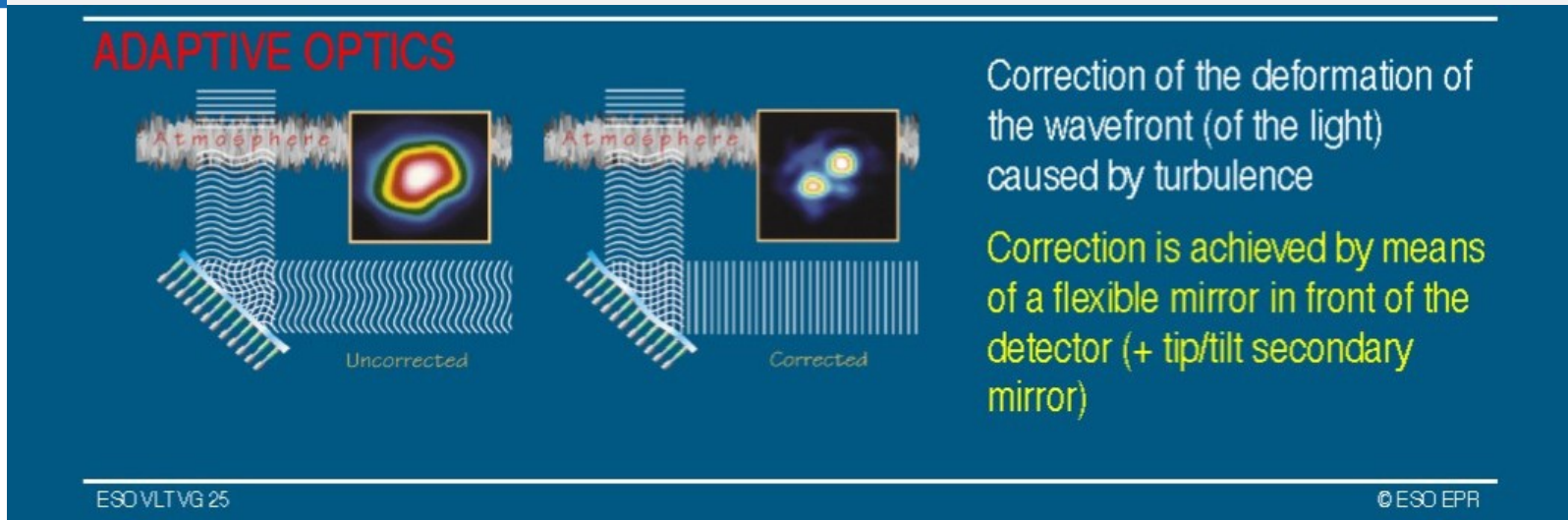
### THE POSSIBILITY OF COMPENSATING ASTRONOMICAL SEEING

H. W. BABCOCK

Mount Wilson and Palomar Observatories  
Carnegie Institution of Washington  
California Institute of Technology



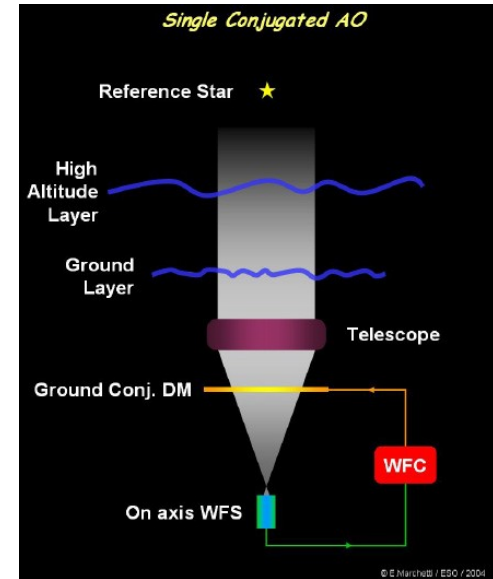
# Adaptive optics (2)



- Atmospheric turbulence is statistically described using a *Kolmogorov model* with characteristic size scale  $r_0$
- $r_0 \propto \lambda^{6/5}$  where  $r_0$  may be thought of as the equivalent telescope size over which the wavelength is flat. Seeing is related directly ( $0.98\lambda/r_0$ )  
At  $0.5\mu\text{m}$ ,  $15\text{cm } r_0 \gg 0.75\text{arcsecs}$  seeing.
- The equivalent characteristic timescale  $\tau_0 \propto \lambda^{6/5}$  is the time take for turbulence to blow across the telescope aperture. This gives the correction timescale: few 100Hz in the optical to few Hz in the MIR

# Adaptive optics (3)

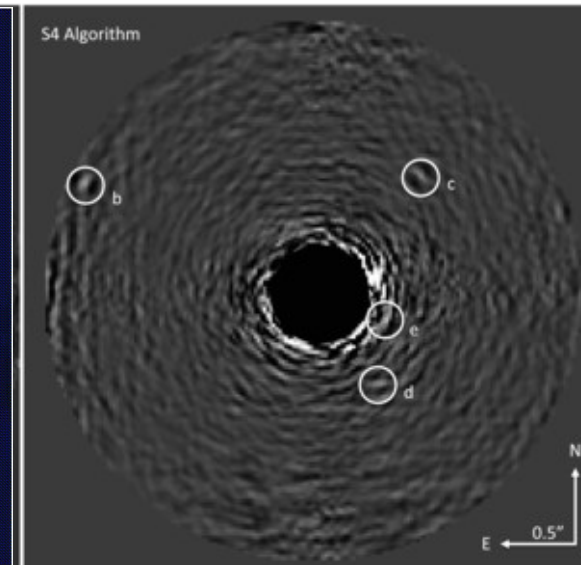
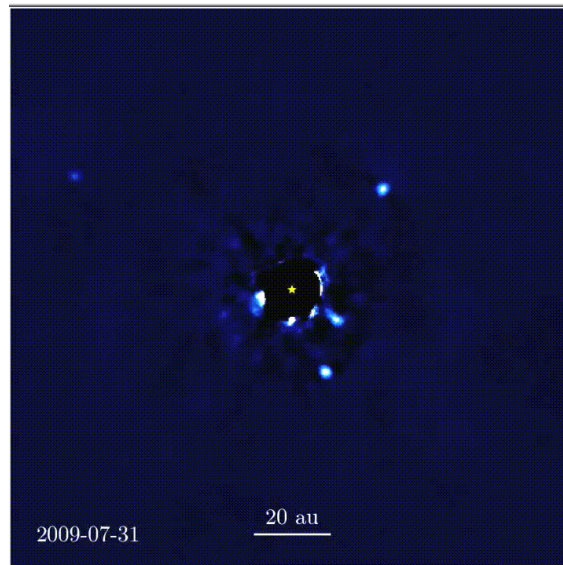
- The simplest AO systems measure wavefront errors using the scientific target
  - Perfect correction along the line of site
  - Since a bright star is required (R magnitude~15) the number of targets is limited (few percent of the sky)
  - Still the best choice for some science e.g. exoplanets



Results from VLT SPHERE  
on the multi-exoplanet  
system HR 8799

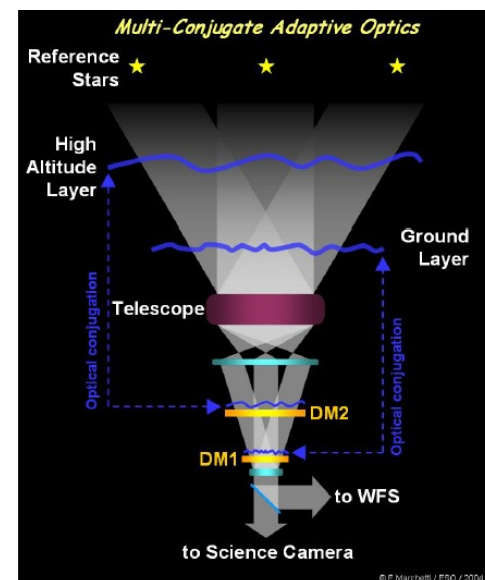
Figure 2 from B. R. Oppenheimer et al. 2013 ApJ 768

Animation By Jason Wang, et al -  
<https://www.youtube.com/watch?v=KVgKidAuf4o>, CC BY 3.0,  
<https://commons.wikimedia.org/w/index.php?curid=55463078>



# Adaptive optics (4a)

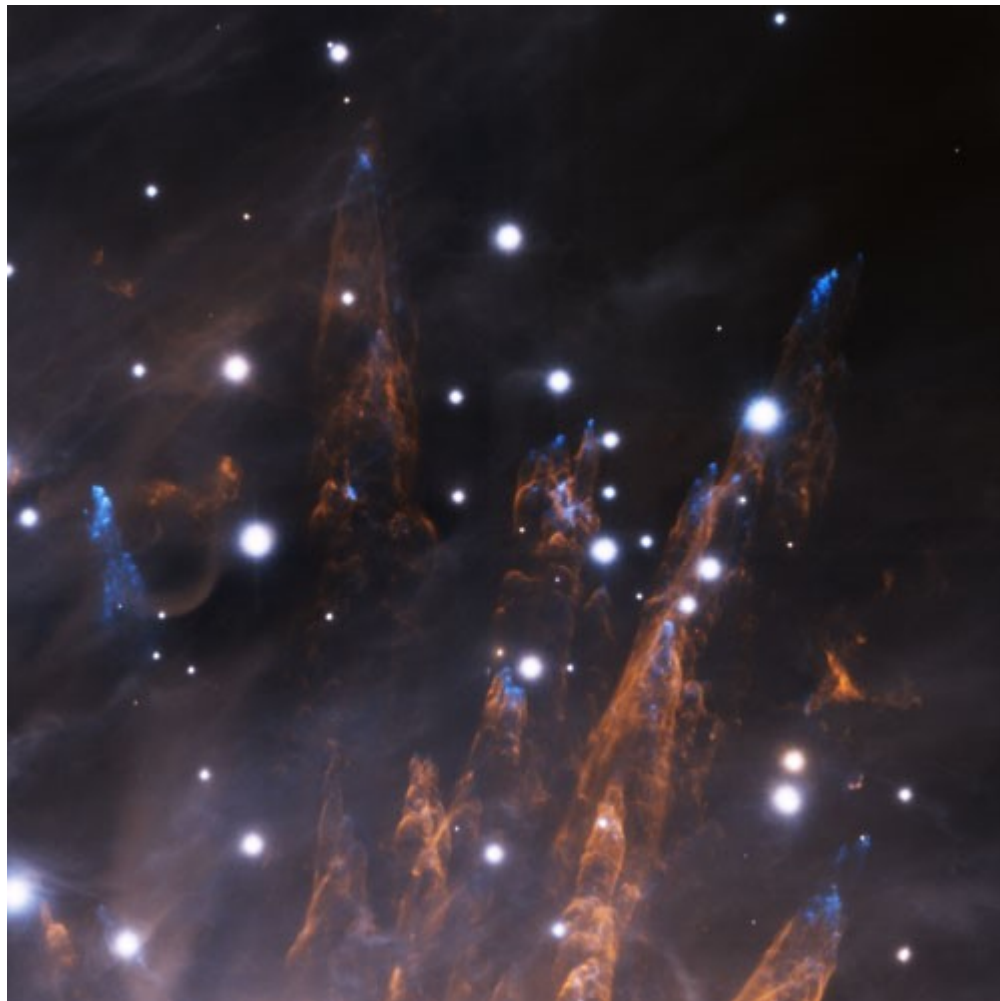
- Two key developments in AO
- Increase the corrected field using multiple guide stars and/or more than one deformable mirror
  - Tomography
  - Multi-conjugate adaptive optics



# Gemini GEMs MCAO system

- The “Orion Bullets” imaged in the NIR with GEMs – a multiconjugate AO system. Seeing of  $\sim 1$  arcsec in the optical, corrected image FWHM of  $\sim 0.1$  arcsec in the NIR.

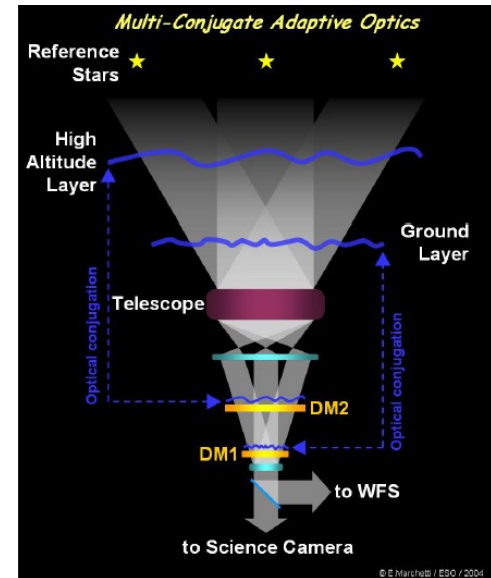
Image credit: Gemini/AURA  
Bally et al. 2015 A&A, 579,130





# Adaptive optics (4b)

- Two key developments in AO
- Increase the corrected field using multiple guide stars
  - Tomography
  - Multi-conjugate adaptive optics



- Extend the sky available for AO using artificial laser guide stars
  - Lasers launched from the telescope excite the sodium layer at 90km in the Earth's atmosphere

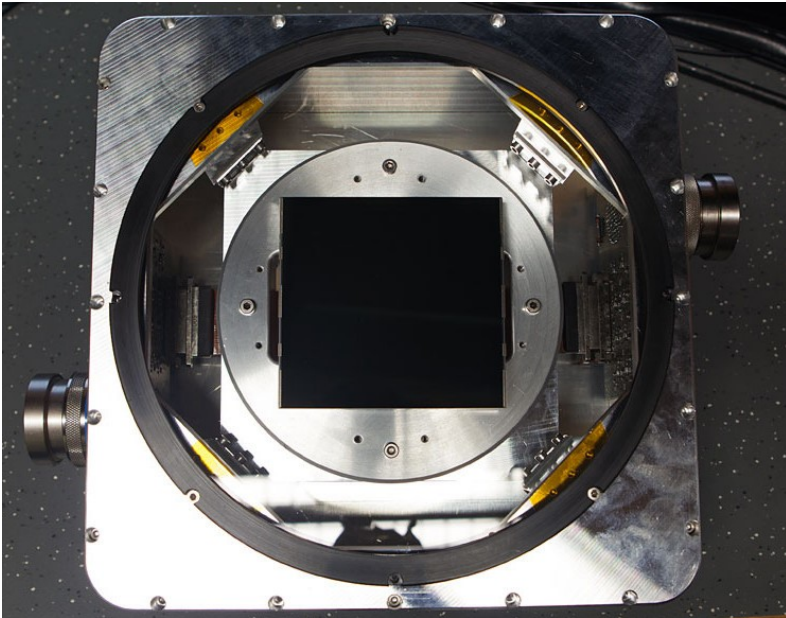


# Detectors for astronomy (1)

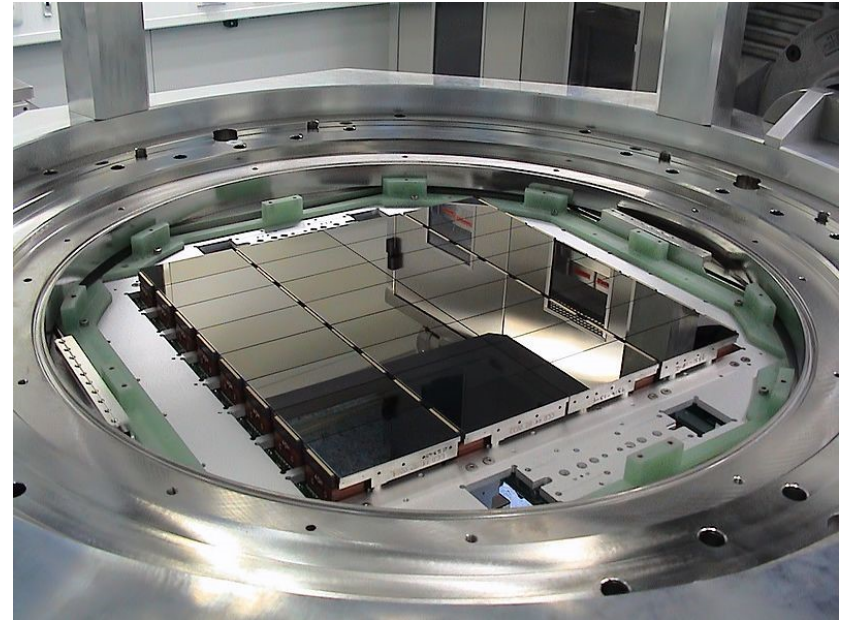
- Selection of the detectors is a critical part of defining the instrument
  - The choice sets many of the design parameters (see later)
  - The choice often drives the costs and risks in the instrument!
  - The costs of the detectors leads to some novel instrument designs that maximise the use of the detectors (see even later)
- Scientific priorities define the requirements but in general for ground based instruments the main the considerations are
  - High quantum efficiency
  - Low noise (read-out noise)
  - Large well depth (infrared)
  - As many pixels as possible/affordable!
  - Read-out speed important for specialist applications: AO wavefront sensor detectors, high time resolution astrophysics ( $\mu\text{s}$  to  $\text{ms}$ )

# Detectors (2)

## ■ CCD detectors for visible wavelengths



ESPRESSO/ESO VLT. High spectral resolution, highly stable spectrograph  
Single CCD of 9000 x 9000 10 $\mu$ m pixels from Teledyne-e2v

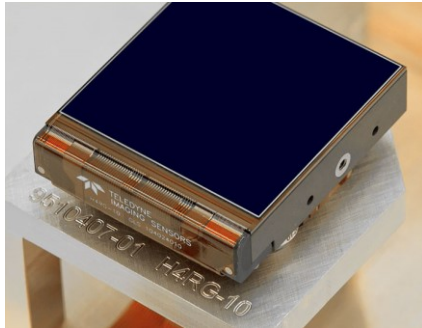


OMEGACAM/VLT Survey Telescope (VST)  
32 CCDs of 2000 x 4000 10 $\mu$ m pixels  
from Teledyne-e2v

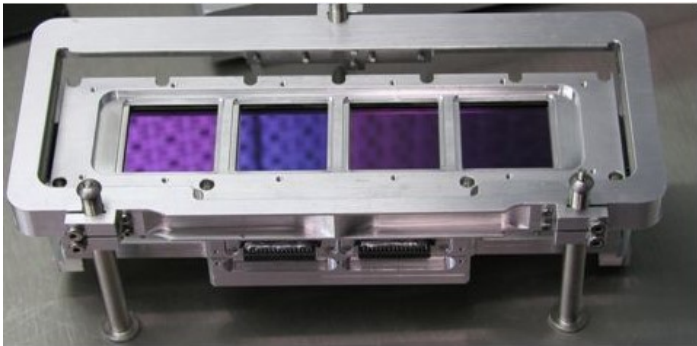
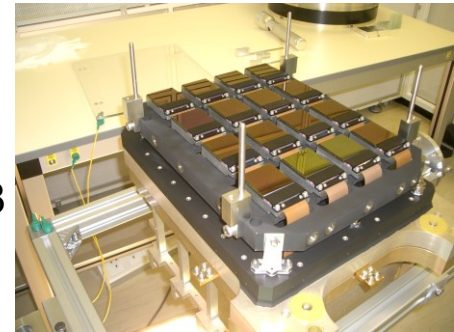
# Detectors (3)

## ■ Detectors for infrared wavelengths

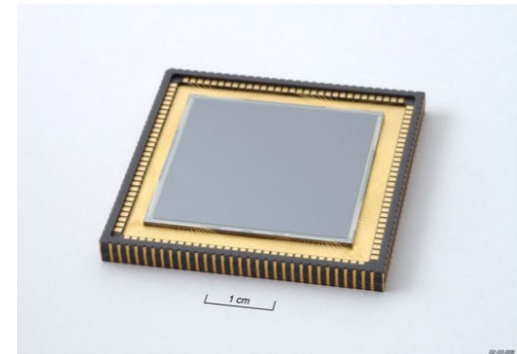
Teledyne Hawaii-4RG  
HgCdTe detector  
4096 x 4096 10-15 $\mu$ m  
pixels. Operating  
temperature  $\sim$ 30-80K.



VIRCAM/VISTA 0.8-  
2.5 $\mu$ m 16 Raytheon  
'VIRGO' HgCdTe  
detectors of 2048 x 2048  
20 $\mu$ m pixels Operating  
temperature:  $\sim$ 70K



The VLT/CRIRES NIR echelle spectrograph ( $R \sim 10^5$ )  
has/had an array of 4 1024 x 4096 InSb 'ALADDIN'  
detectors from Raytheon 0.8-5 $\mu$ m range.  
It is being upgraded with new detectors.



The VLT/VISIR has an array of four  
1024 x 1024 Si:As IBC 'Aquarius'  
detectors from Raytheon 3-28 $\mu$ m range.  
Operating temperature  $\sim$ 9K



# Detectors (4)

## ■ VIRCAM raw data

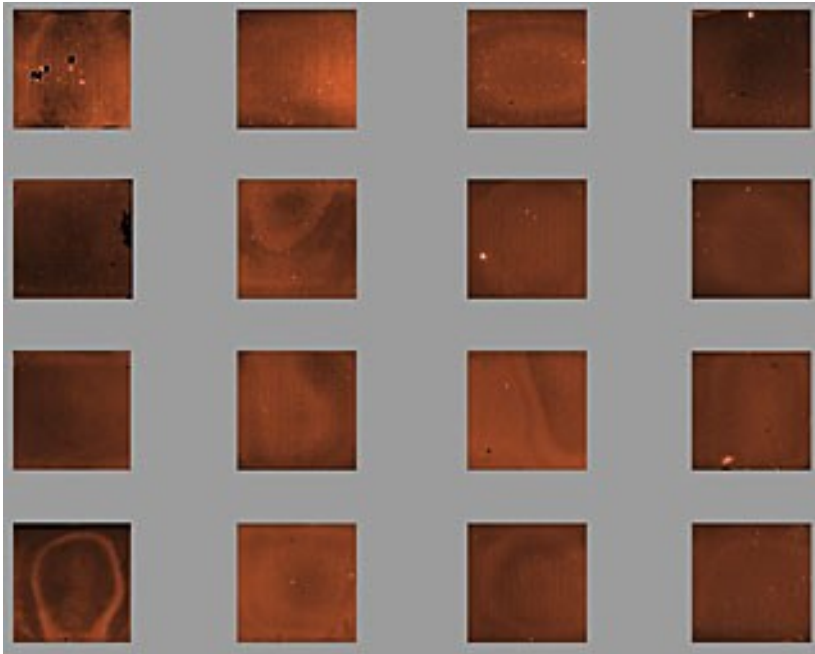
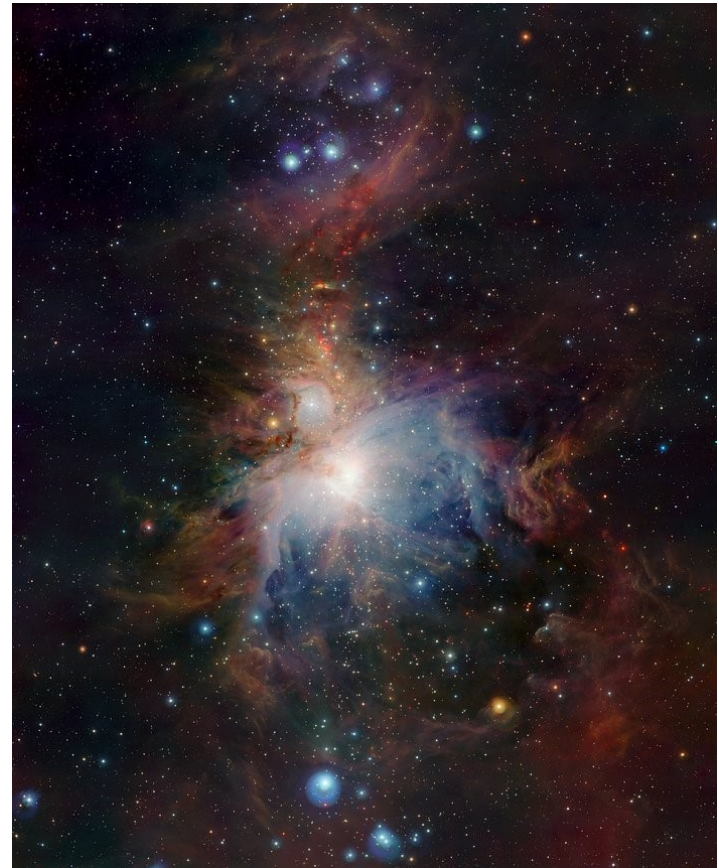


Image of the Orion (Nebula Messier 42)  
Z,J,Ks filters used  
1degree x 1.degree field  
10minutes per filter

## ■ Processed image



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

# 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 ( $\Omega$ )
- 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.....*

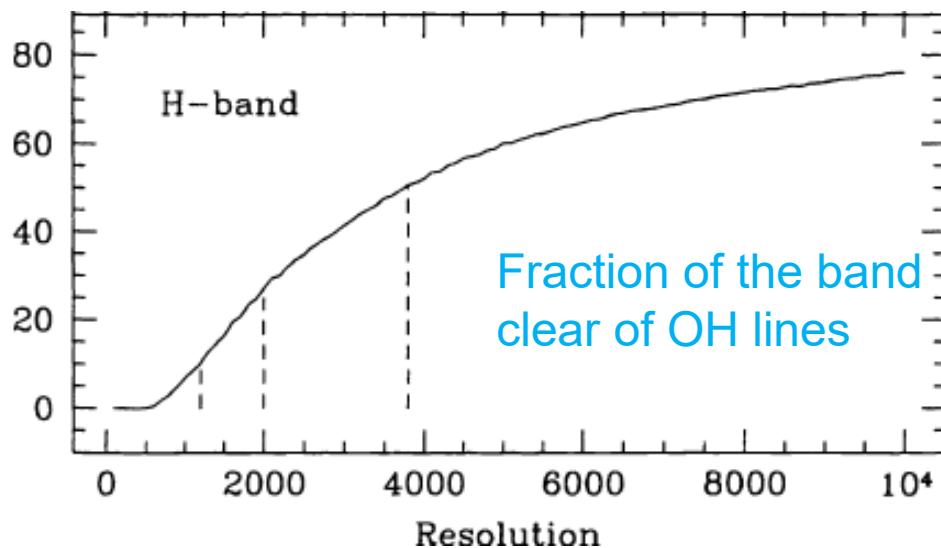


# Back-of-the-envelope instrument for the ESO VLT (1)

## Scientific goal

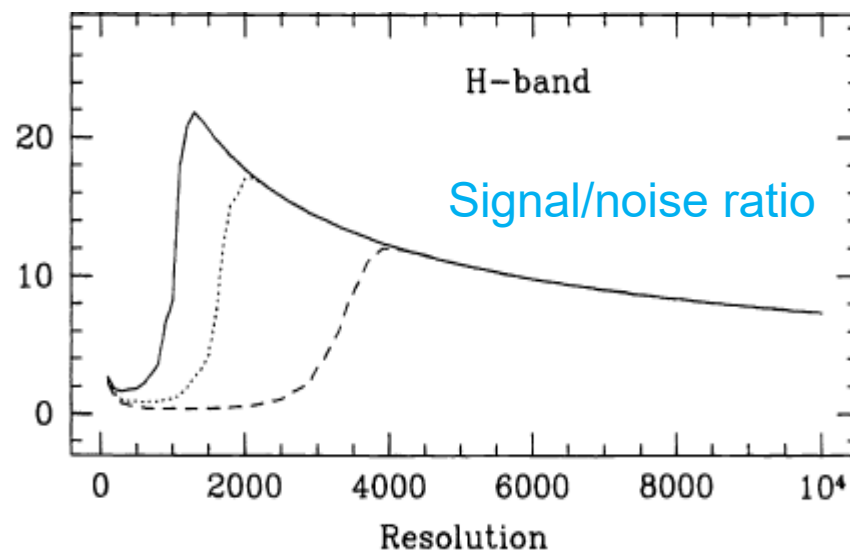
- Detection and characterisation of galaxies (in clusters) at redshift  $z=1-2$  (peak period of star formation)
- Velocities resolution  $\sim 10 \text{ km s}^{-1}$  to measure rotation curves
- Spatial/angular resolution set by the seeing limit at the telescope

*Martini & DePoy, 2000, SPIE*



## Scientific requirements

- $z=1-2 \gg$  most diagnostic lines fall in the  $0.8-2.4 \mu\text{m}$  wavelength range
- Best seeing  $\sim 0.4 \text{ arcsecs}$  in K band ( $2.0-2.4 \mu\text{m}$ )  $\gg 0.2 \text{ arcsec}$  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

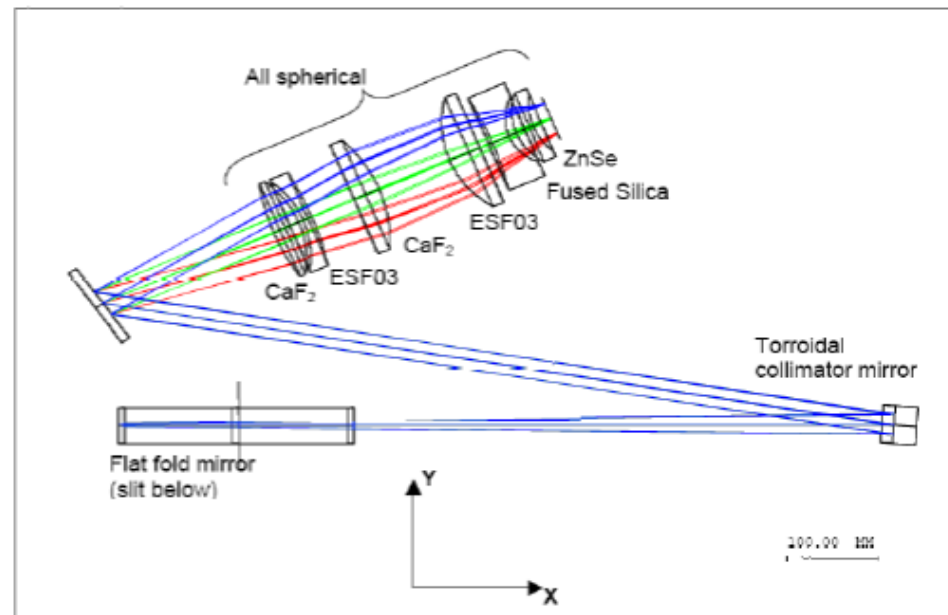
- Conservation of étendue and the detector pixel size determines the camera f-number:

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

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

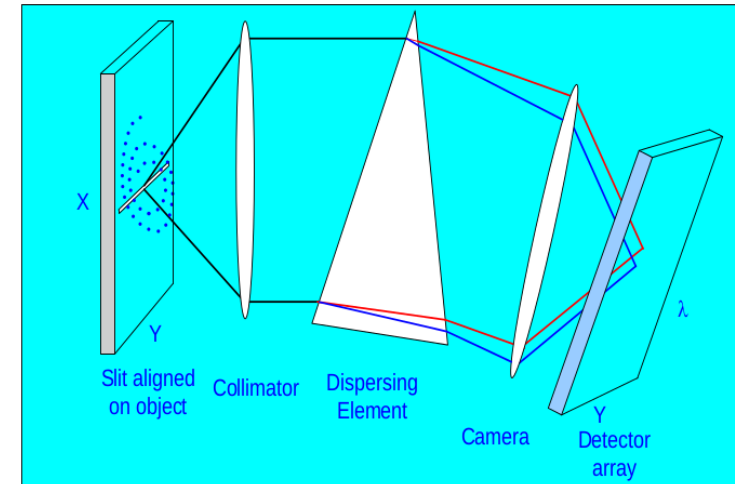
- $\theta_{tel}=0.2\text{arcsecs}$ ,  $D_{tel}=8.2\text{m}$
- $d_{pix}=18\mu\text{m}$
- Camera should be f/2.3
- Such a fast camera is hard but not impossible

*Optical layout of the  
KMOS spectrograph*



# Back-of-the-envelope instrument (3): Pupil/beam size

- 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  $\Delta\theta = \theta_{cam} = \frac{d_{pix}}{focal\ length}$  and the definition of resolving power  $R = \frac{\lambda}{\delta\lambda}$

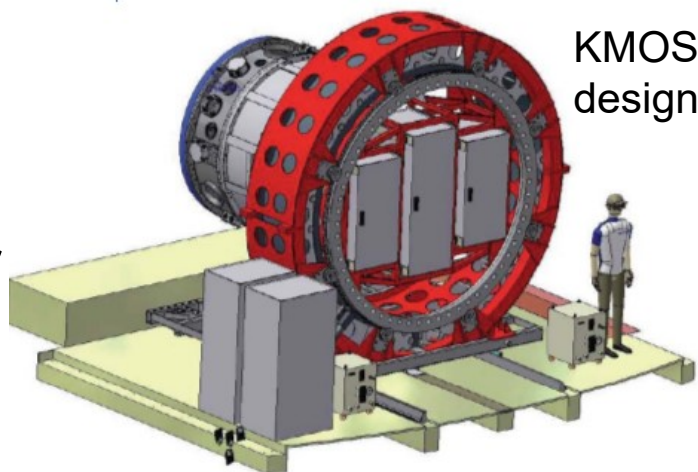
$$R = \frac{2f \tan \theta_r}{d_{pix}}$$

$f$ =focal length

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

- For KMOS, set  $R \sim 4000$  over 2 pixels to Nyquist sample the spectral lines
- Set  $\theta r = 45^\circ$  for a first estimate
- Then  $f \sim 72\text{mm}$  and the beam size for an  $f/2.3$  camera is  $\sim 31\text{mm}$
- In practice the KMOS beam is  $33\text{mm}$  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!

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





# A back of the envelope instrument for the ELT

- 0.2arcsecs/pixel, 15 $\mu$ m pixels, 39-m telescope
- $\sim f/0.4$  on the ELT
- Alternatively, define the camera to be  $f/2$
- The seeing disk is imaged onto  $\sim 150\text{ }\mu\text{m}$  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  $\mu\text{m}$  pixel
- $\sim f/19$  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

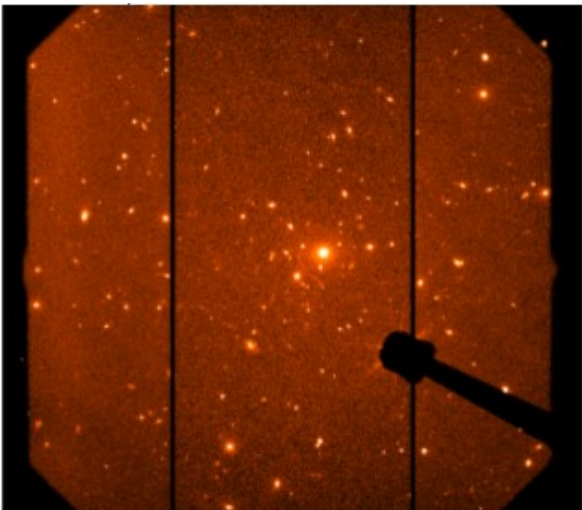
## ■ For an instrument to operate at the diffraction limit of a telescope set the pixel field of view:

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

## ■ A diffraction limited instrument can go on any telescope!

# Ground-based instruments today (1)

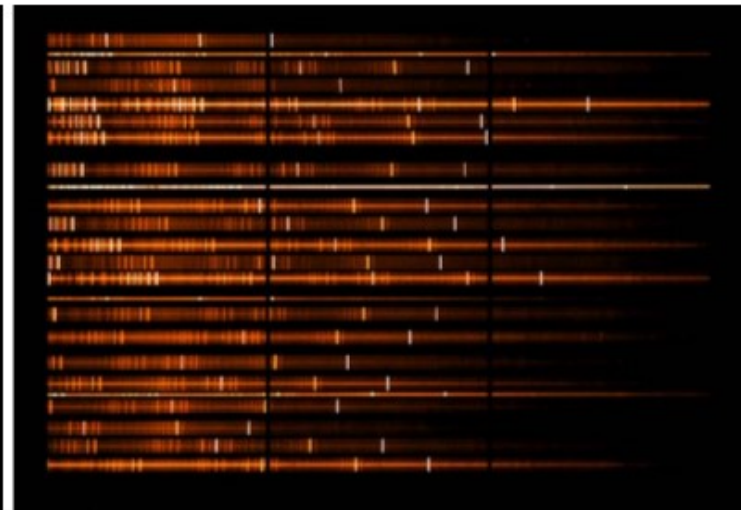
## ■ Multi-object spectroscopy with slit masks



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

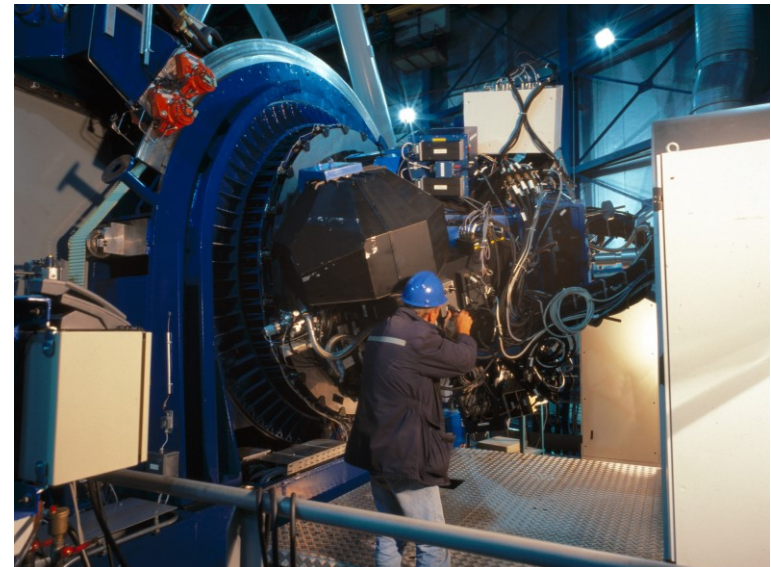
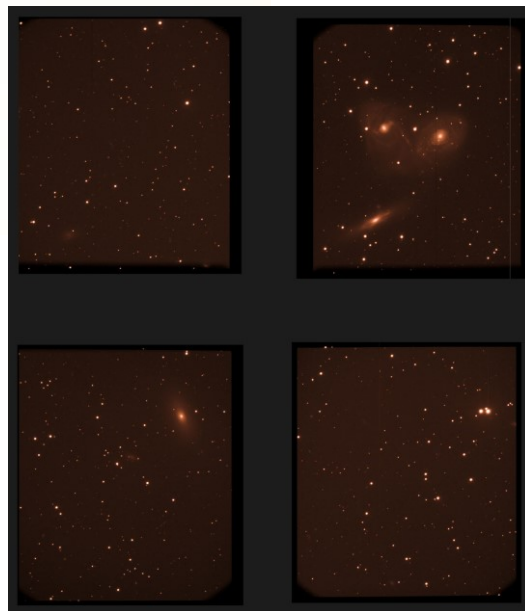
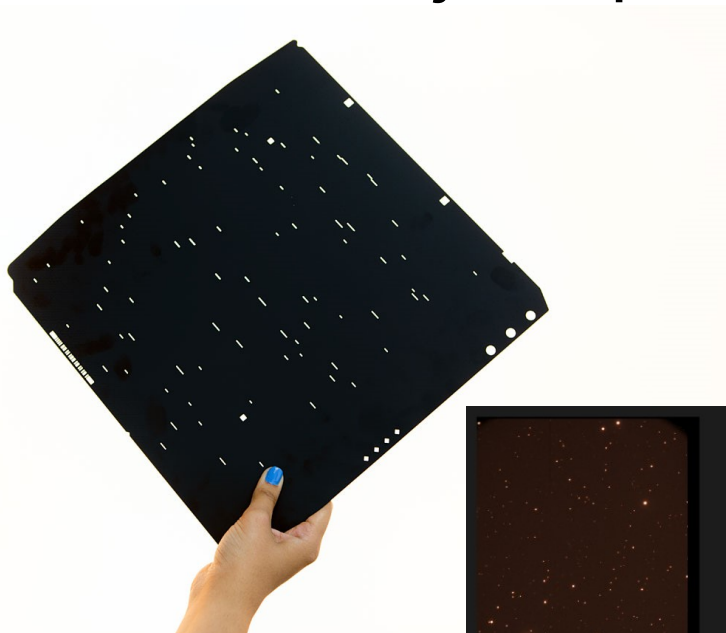


Spectra of the multiple objects are obtained with excellent usage of the array and some restrictions on the object selection

*Images are from the Gemini multi-object spectrograph*

# Ground-based instruments today (2)

## ■ Multi-object spectroscopy: VIMOS at VLT

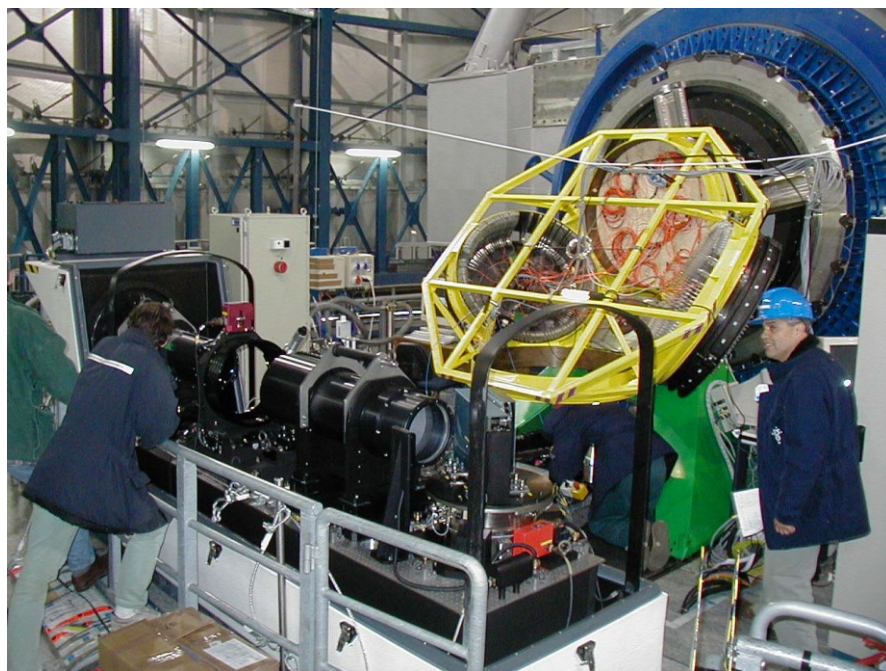


Slit (mask) spectrographs are sensitive to faint objects. VIMOS was designed with galaxy surveys in mind. e.g. VIPERS ([vipers.inaf.it](http://vipers.inaf.it))



# Ground-based instruments today (3)

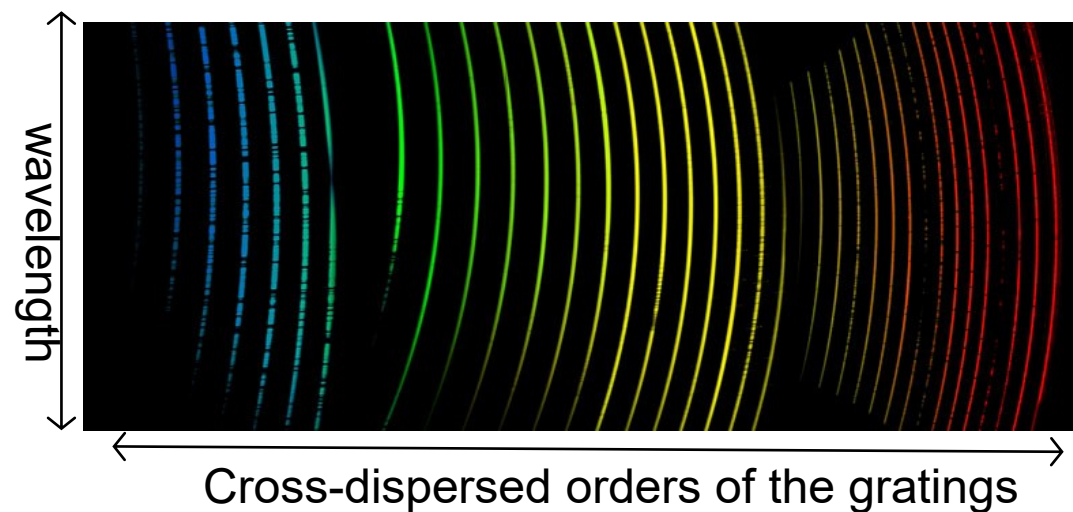
## ■ Multi-object spectroscopy with fibres: FLAMES



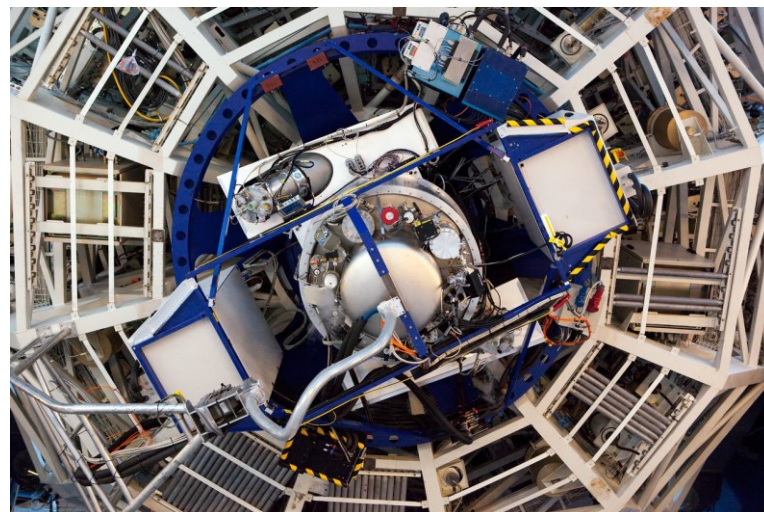
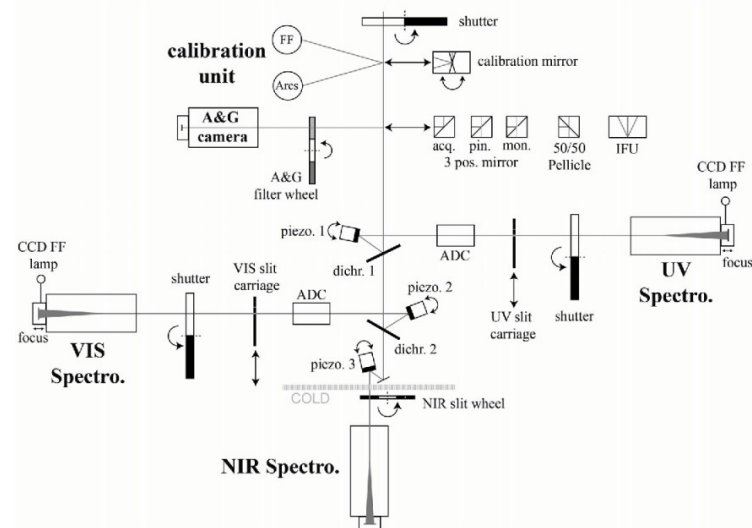
The OzPoz fibre coupled to the GIRAFFE or UVES spectrographs are ideally suited to surveys of stars e.g. the GAIA-ESO survey to  $10^5$  sources ([www.gaia-eso.eu](http://www.gaia-eso.eu))

# Ground-based instruments today (4)

- The widest wavelength range: 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.





# Ground-based instruments today (5)

## ■ Integral field or 3D spectroscopy

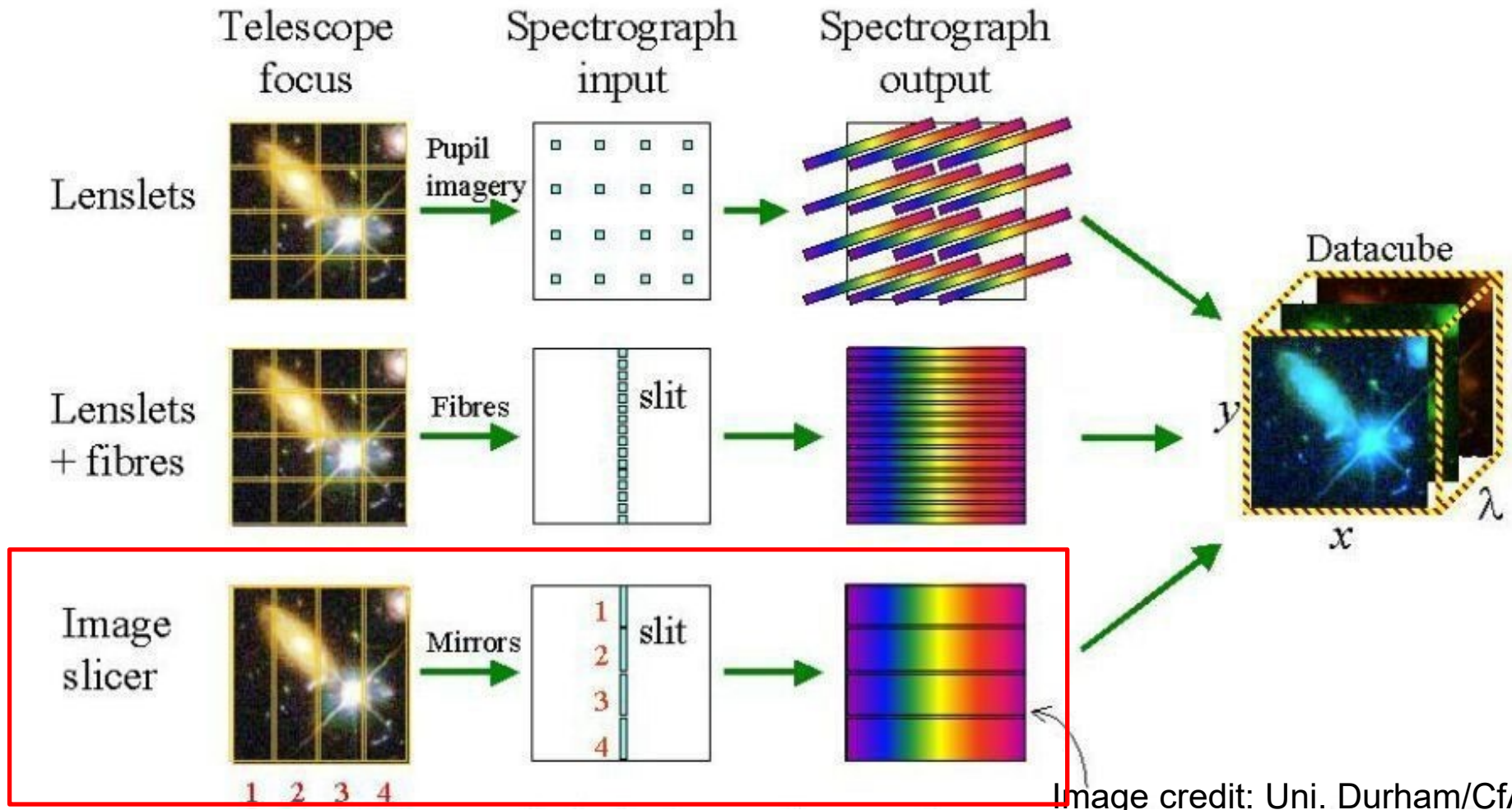
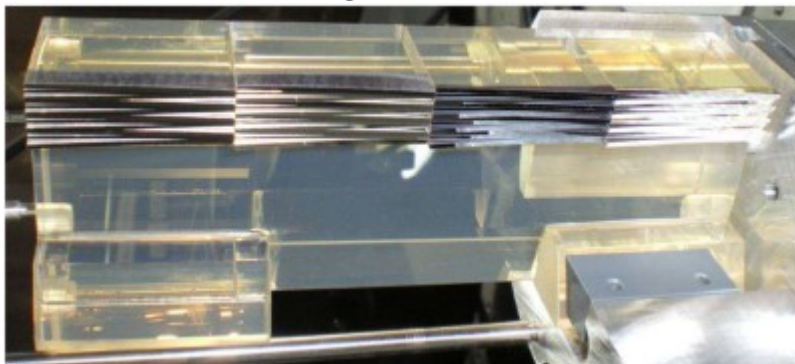


Image credit: Uni. Durham/CfAI

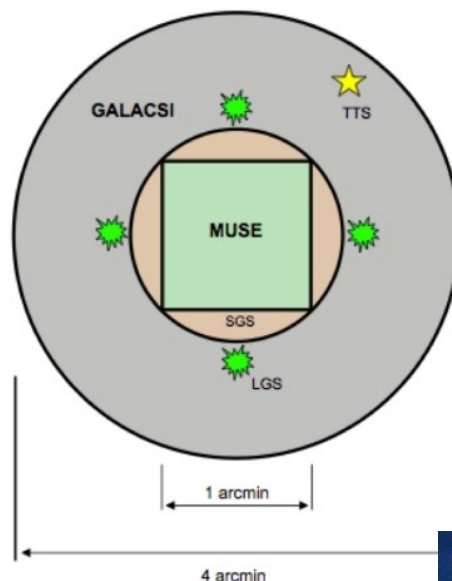
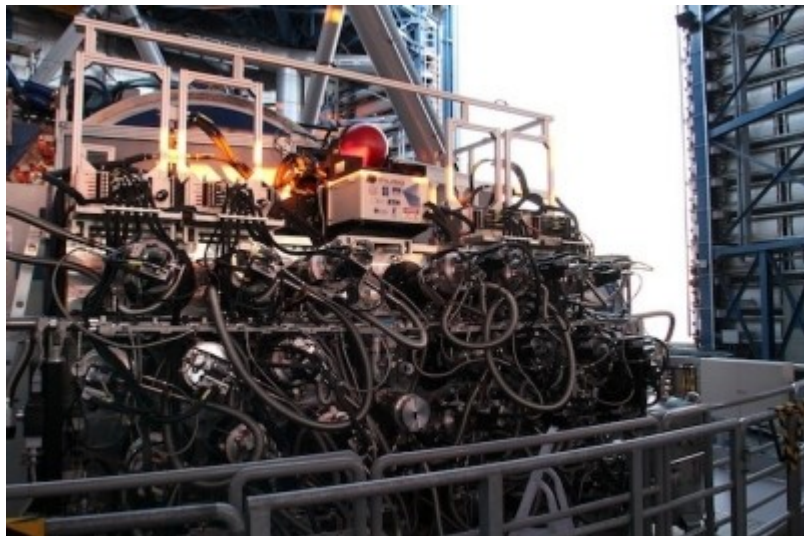
# Ground-based instruments today (6)

## ■ Widefield and AO assisted optical IFU: MUSE

The MUSE image slicer



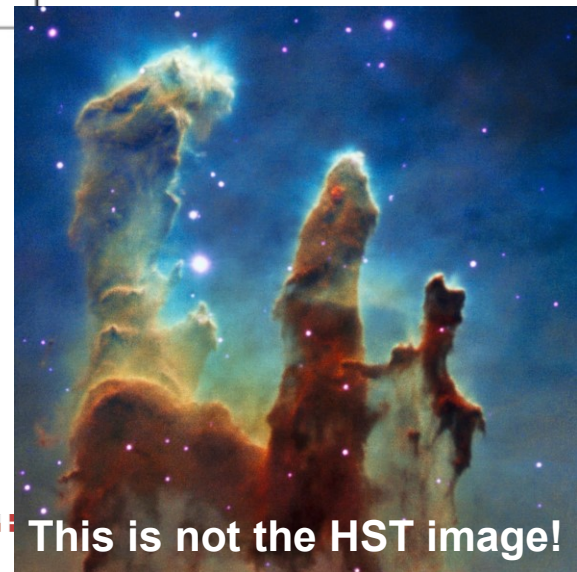
MUSE at the VLT: 24 spectrographs



Schematic of MUSE  
With the GALACSI  
wavefront sensor  
module. LGS=laser  
guide star locations.  
Correction of the  
atmosphere is by a  
deformable mirror that  
replaces the telescope  
secondary mirror.

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

McLeod et al (2015)

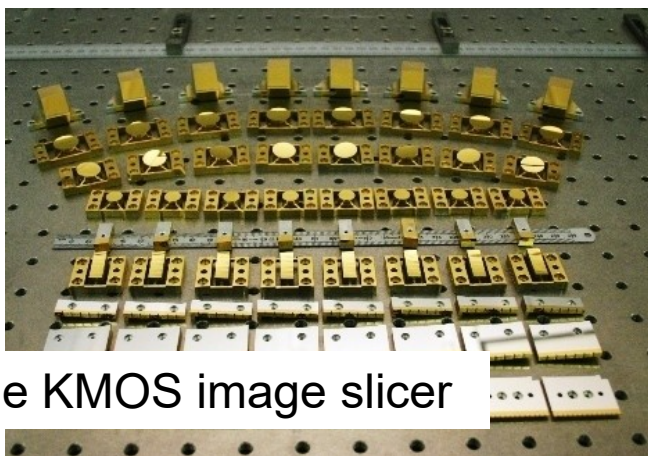


This is not the HST image!

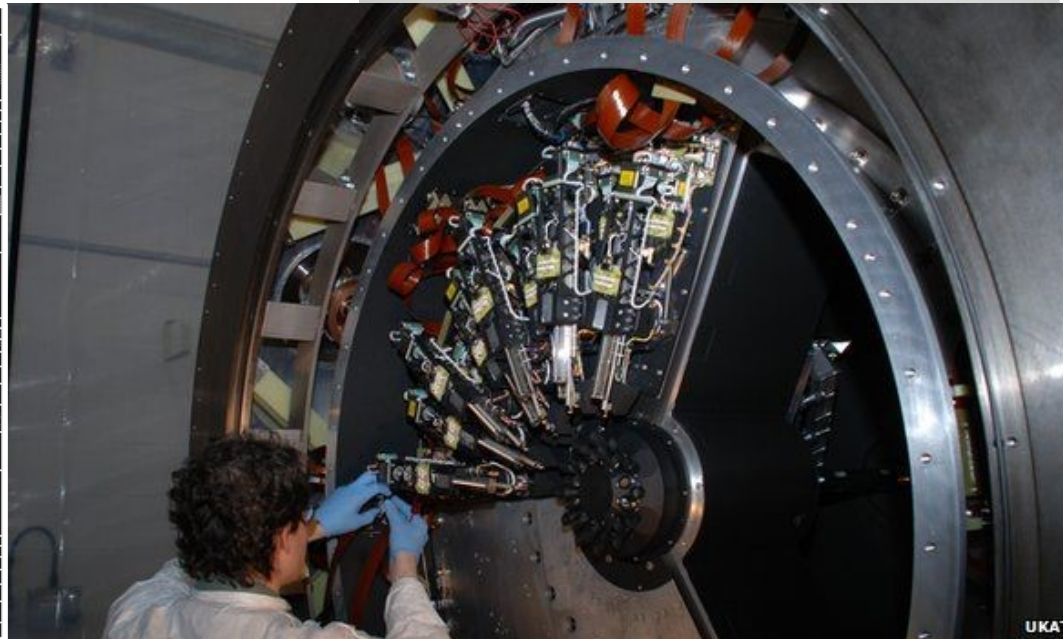
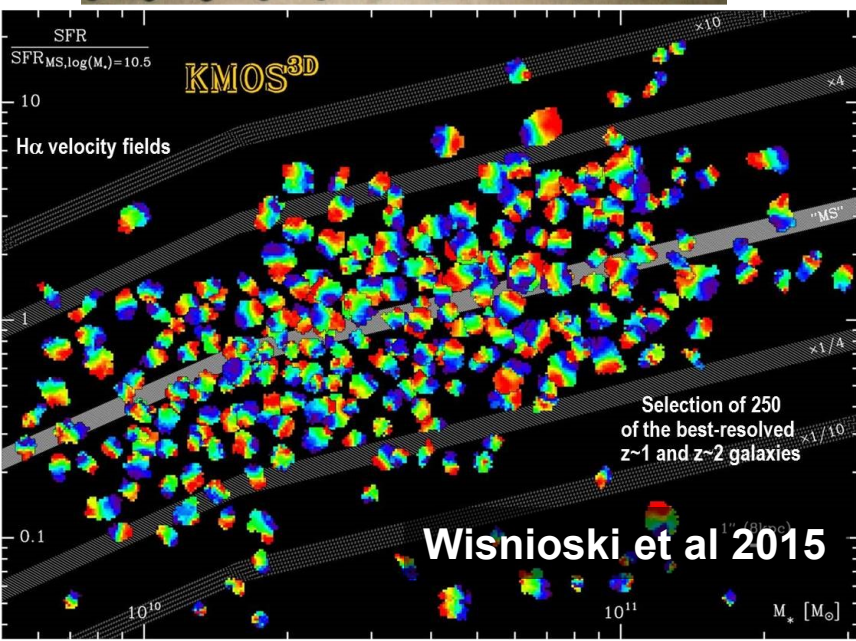


# Ground-based instruments today (7)

## ■ Multi-IFU spectroscopy in the NIR with KMOS

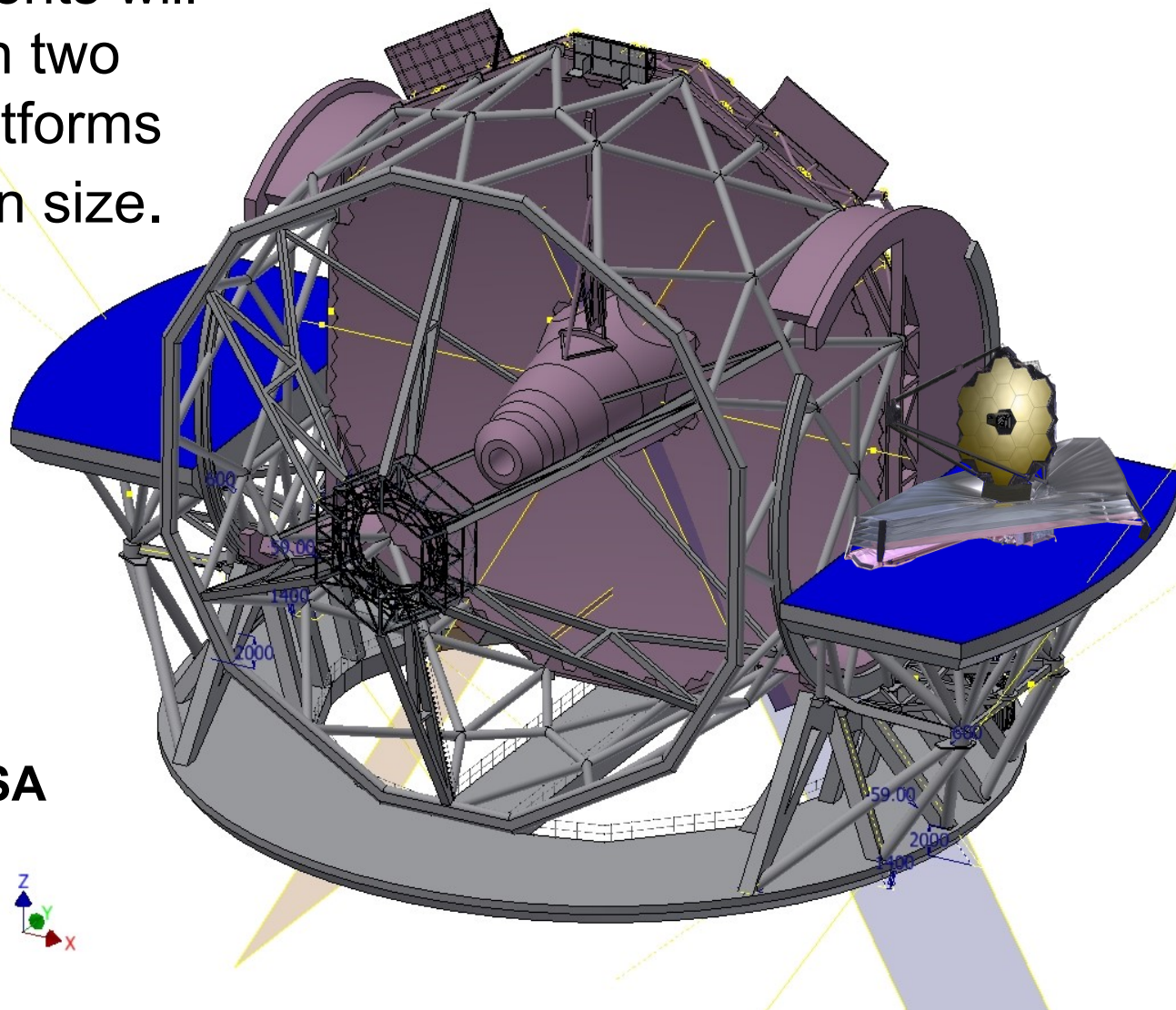


24 pick-off arms select targets over the VLT 7arcmin field of view then direct the beam to 24 IFUs and 3 spectrographs.



# Ground based instruments tomorrow

- ELT instruments will be hosted on two Nasmyth platforms 12m x 29m in size.



**JWST sun-shield**  
**21m x 14m**  
**Image credit/NASA**





# 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

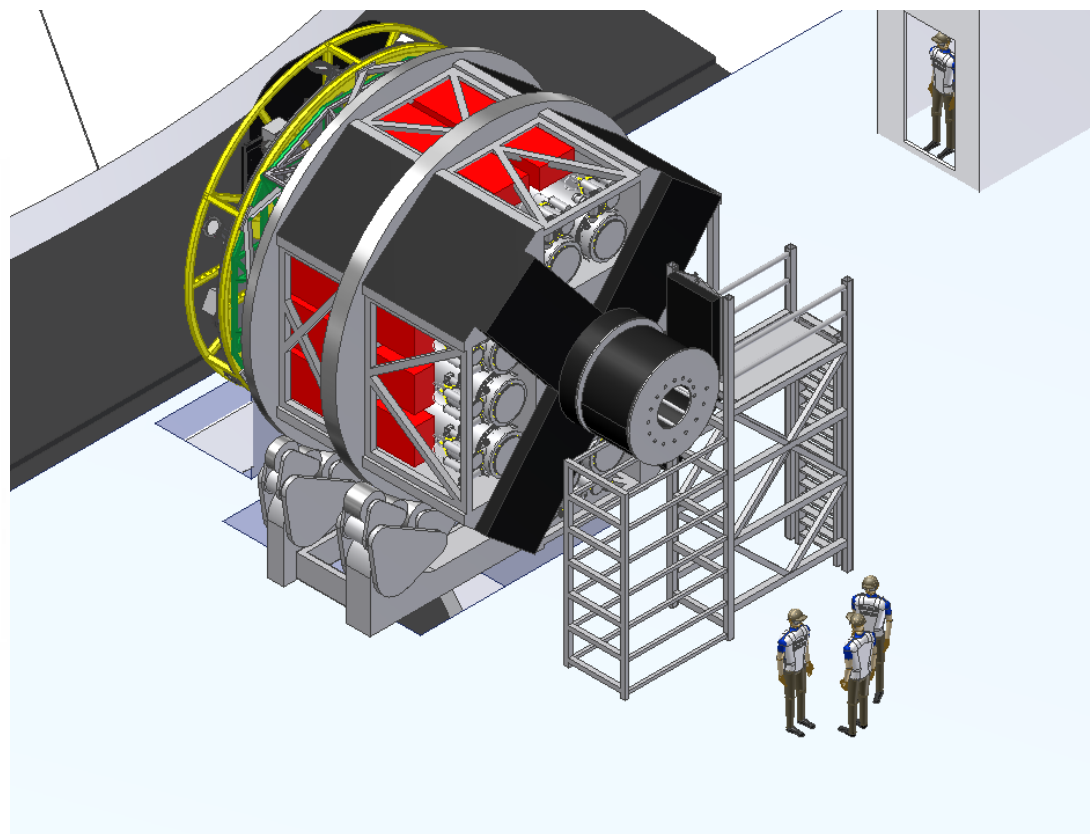
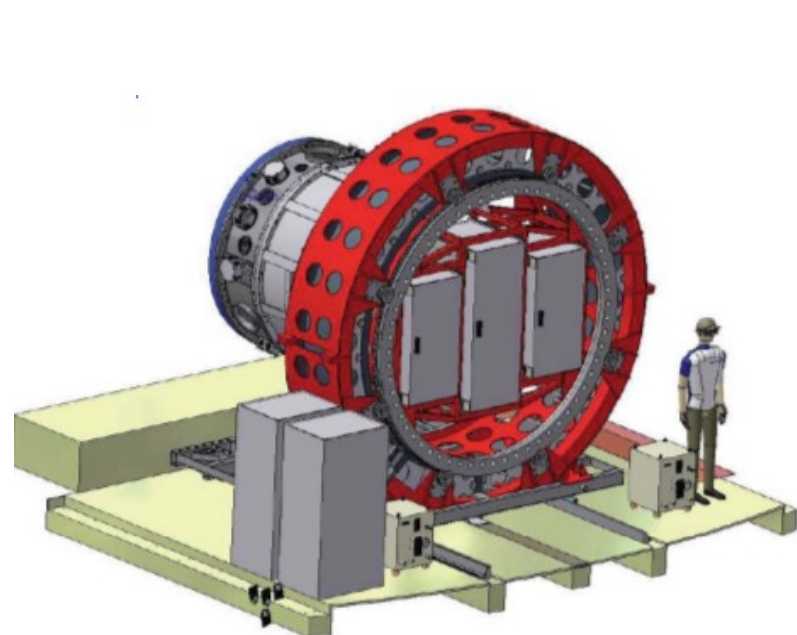
- Relaxed positioning tolerances
- KMOS pick-off arms position to 0.2arcsecs = 120 $\mu$ m on VLT; would be 660 $\mu$ m on E-ELT

- 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

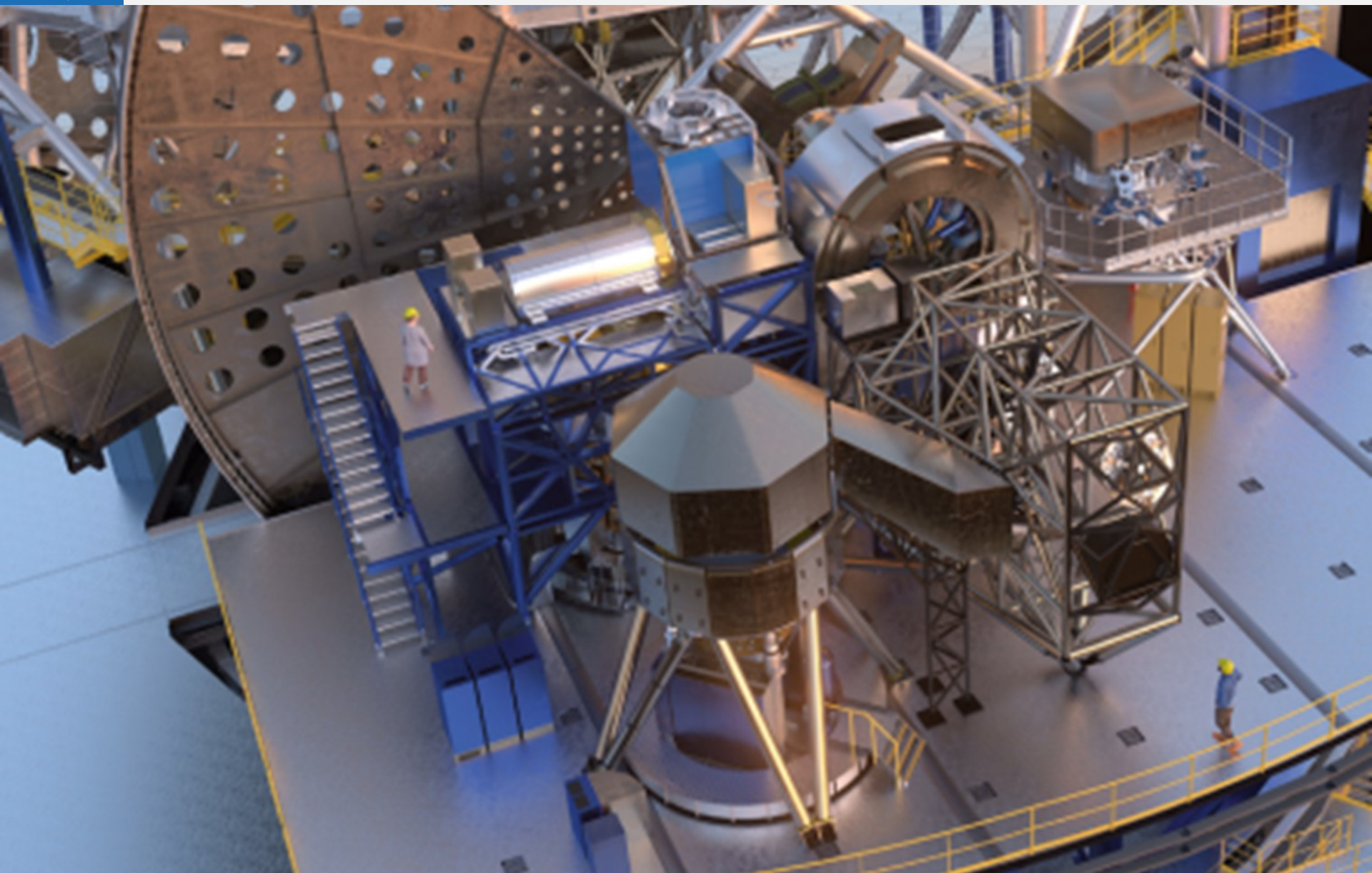
These instruments have the **SAME  $A\Omega$  product/étendue** and can select the same numbers of objects (20-24).



## MICADO NIR imager and slit spectrograph with the MAORY MCAO module



# 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.

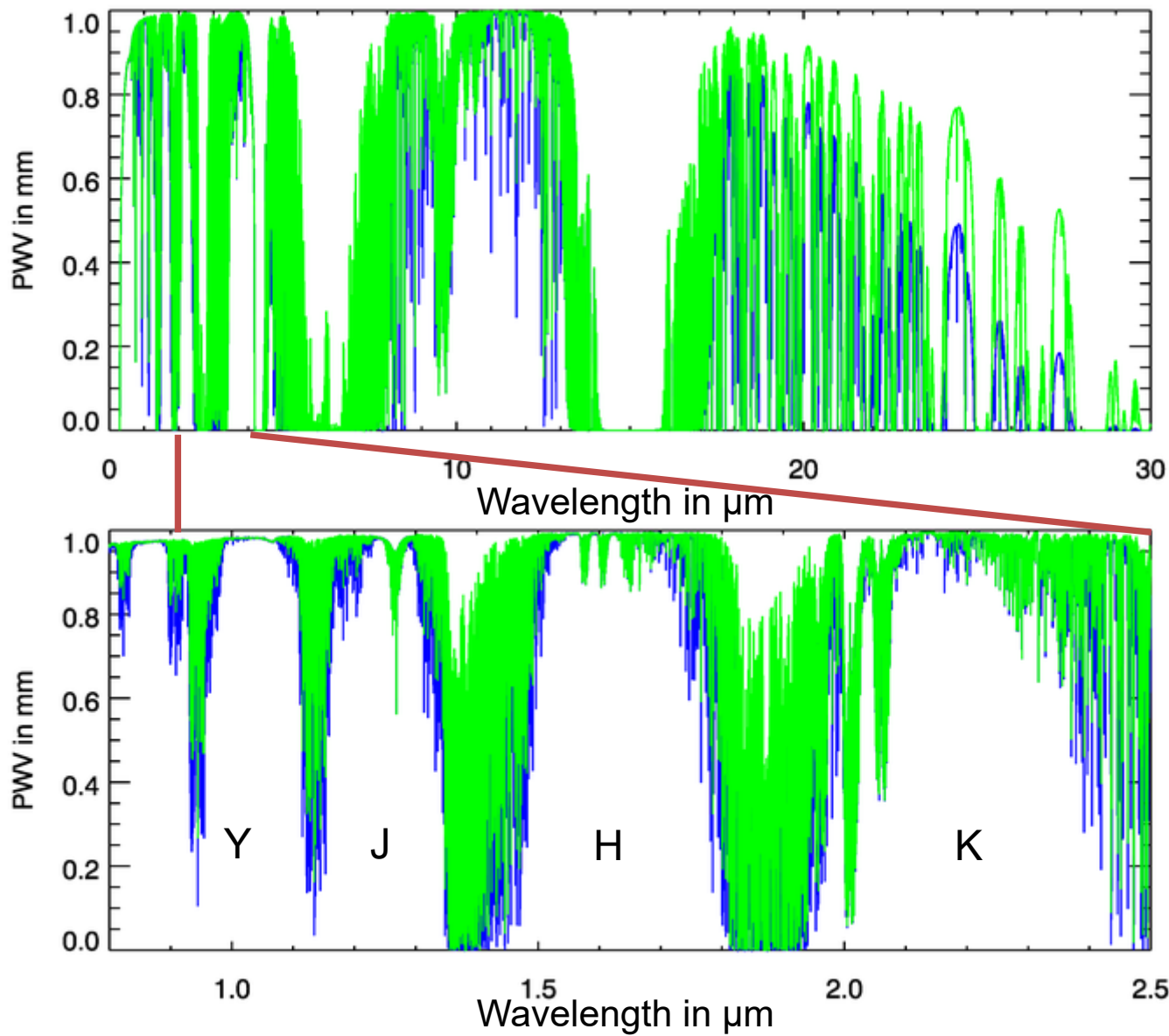
Why are these not useful for astronomy?  
Discuss.

# Links and acknowledgements

- AO open/closed loop GIF (slides #):  
[www.mpg.mpia.de/AO/INTRO/AOWFSintro.html](http://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



# Near infrared atmospheric windows



# ELT instruments

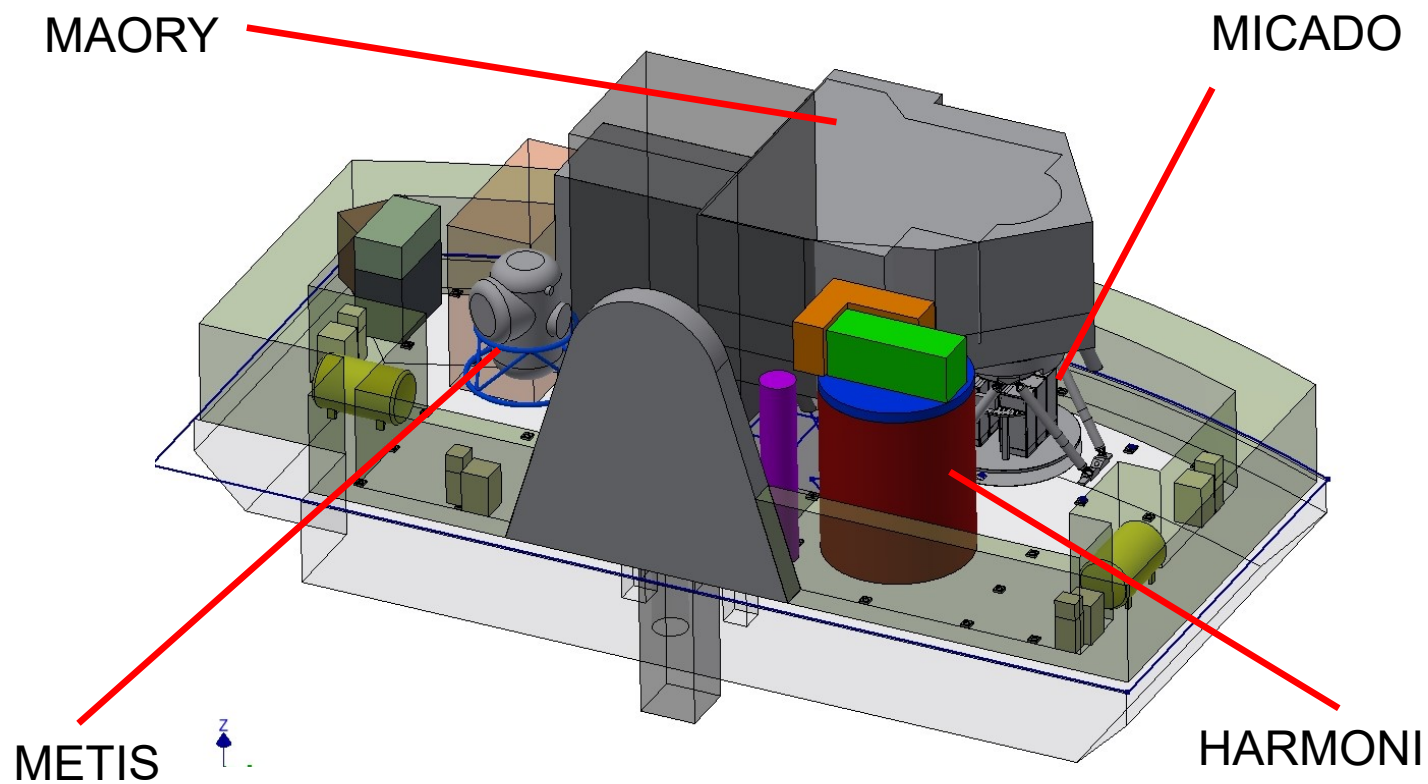


Image provided by Gerd Jakob (ESO)