Instrumentation for optical/IR groundbased astronomy

EIROFORUM school, June 2017

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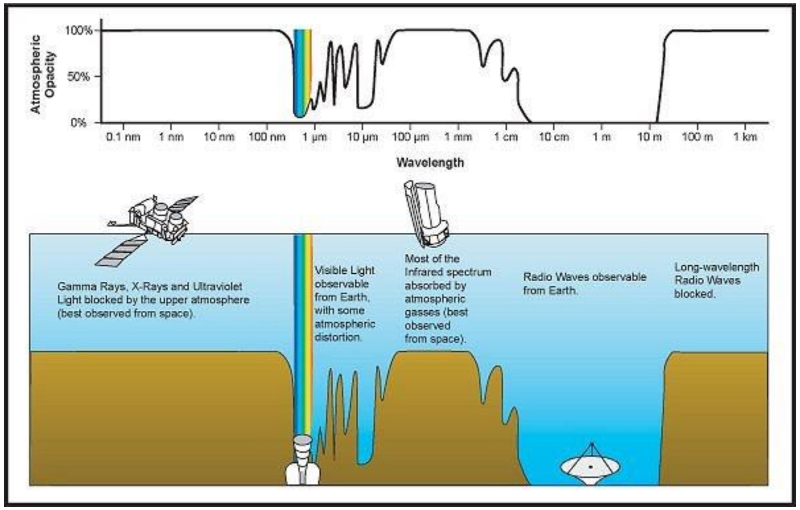
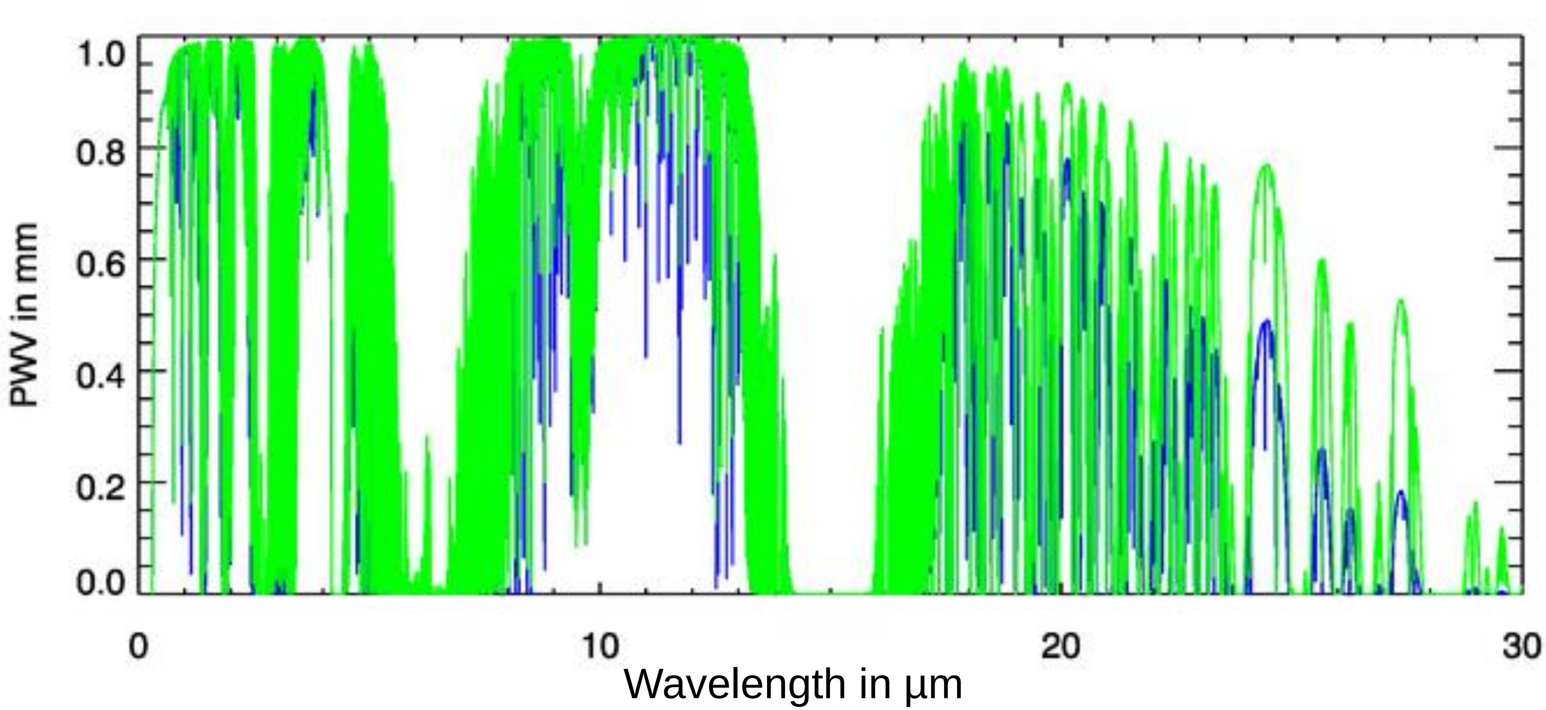
Outline of the talk

- 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

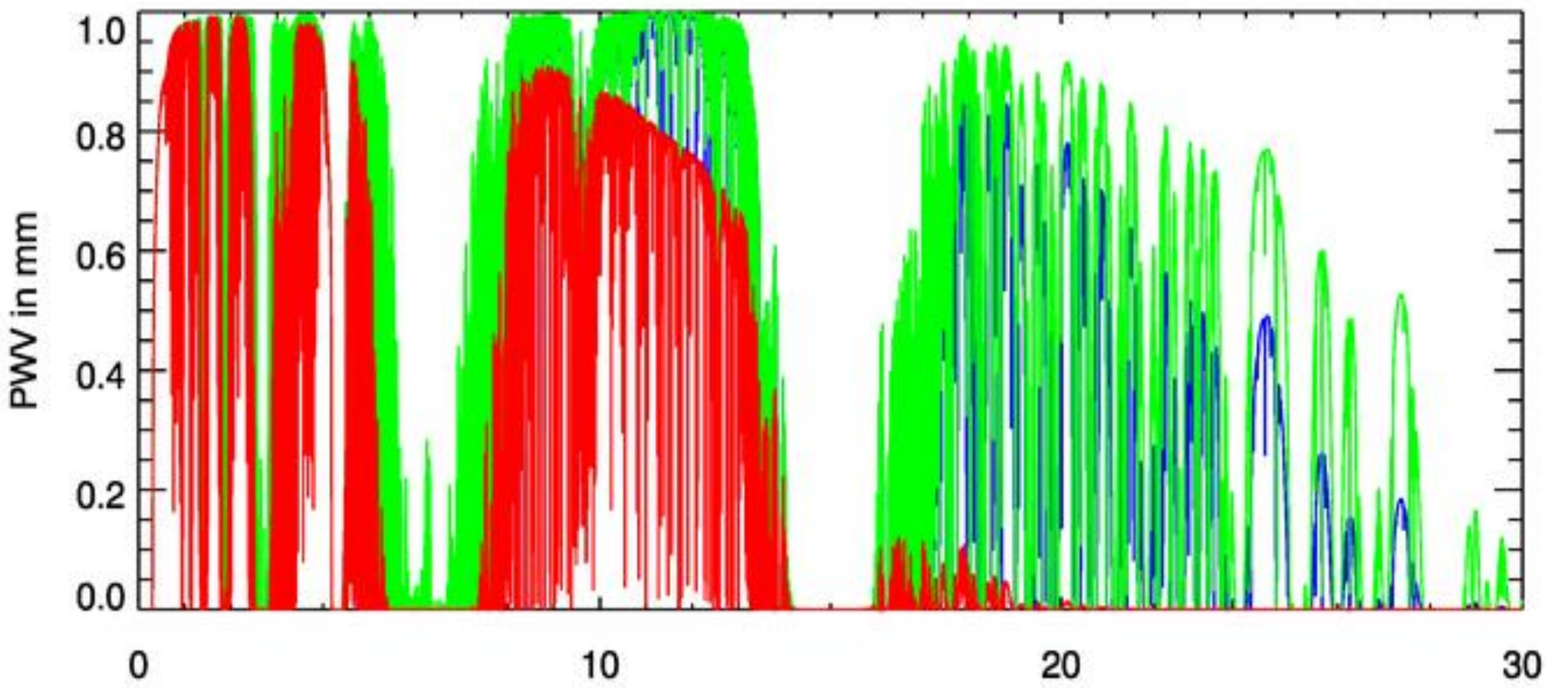
Astronomy from mountain tops



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. See Noll et al. 2012, A&A, 543, A92 and Jones et al. 2013, A&A, 560, A91

Astronomy from … Hamburg



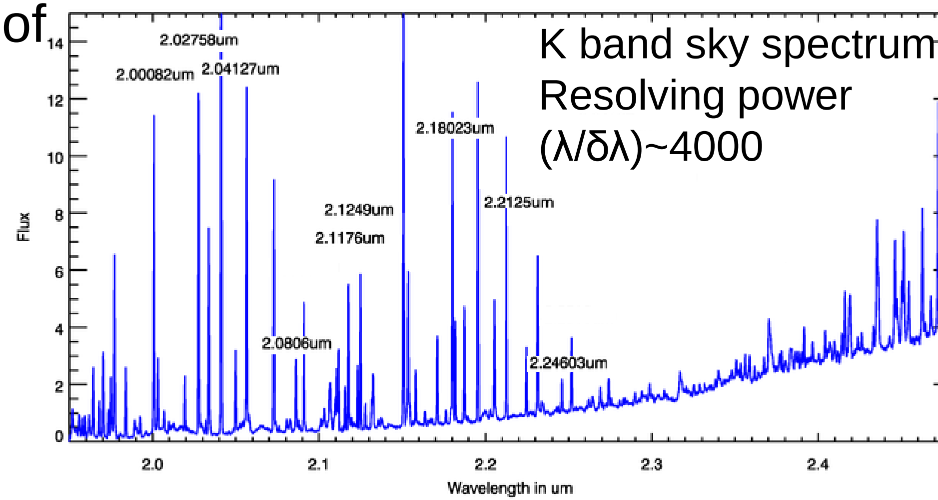
Wavelength in µm

Typical atmospheric transmission for Germany 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: $\lambda_{max}/T \sim 2900\ \mu mK$ >> room temperature bodies peak at 10 µm
- Blackbody radiation from the surroundings dominates at wavelengths longer than ~2µm
- Optical instruments are typically not cooled, apart from their detectors
- Instruments in the NIR (1-5µm) are typically cooled to 70-130K (detectors to 30-70K)
- Instruments in the MIR (5-28µm) are typically cooled to 30-40K (detectors to ~10K)

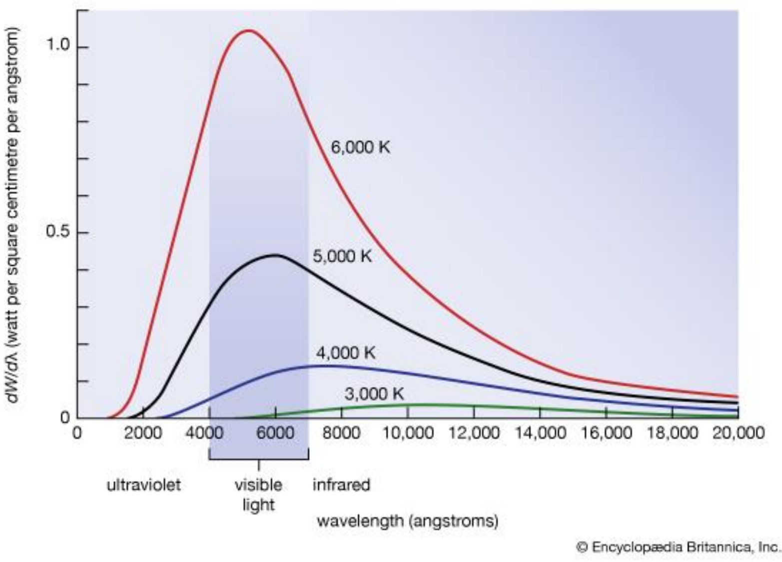
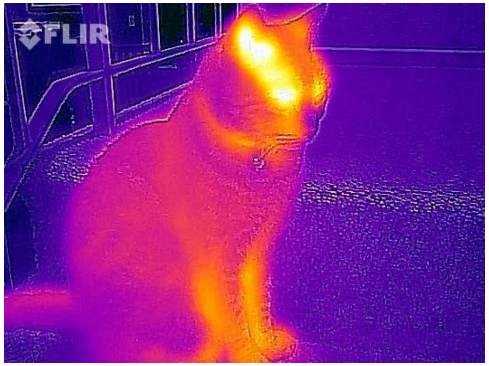


Image credit: Encyclopedia Britannica



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

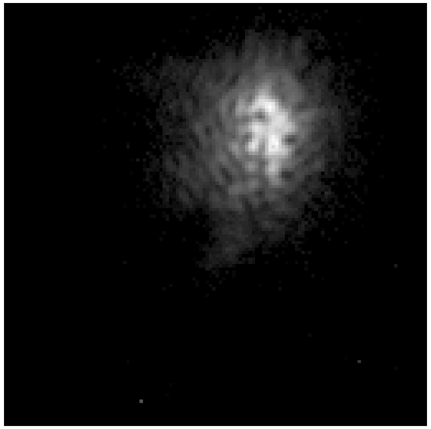
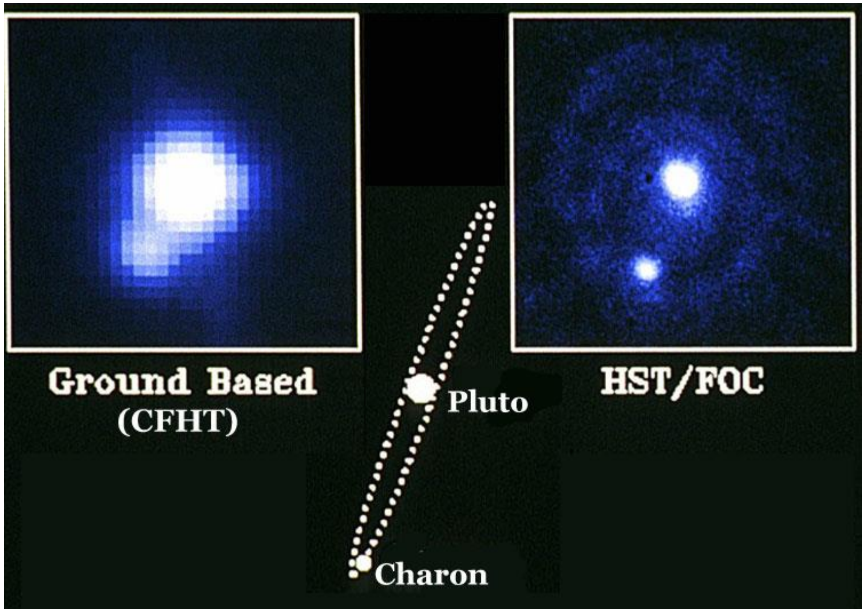


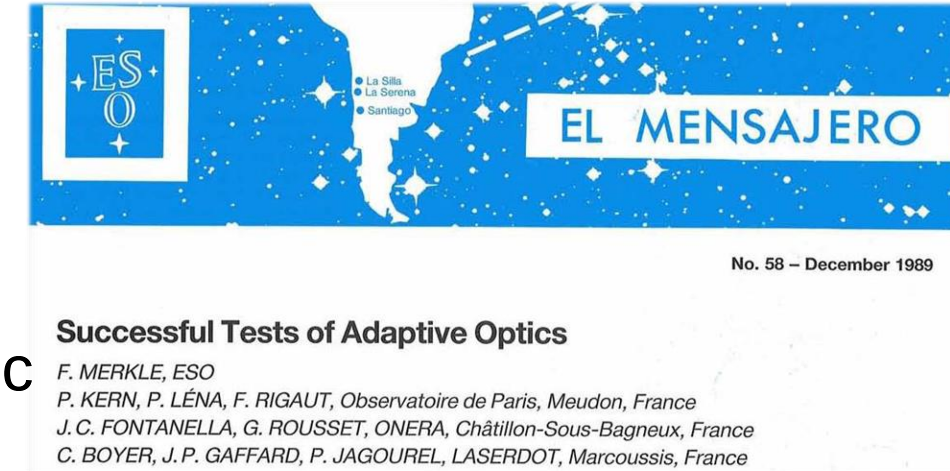
Image of a star in natural seeing
GIF c/o MPIA/Hippler (edited)



- 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 25years 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)



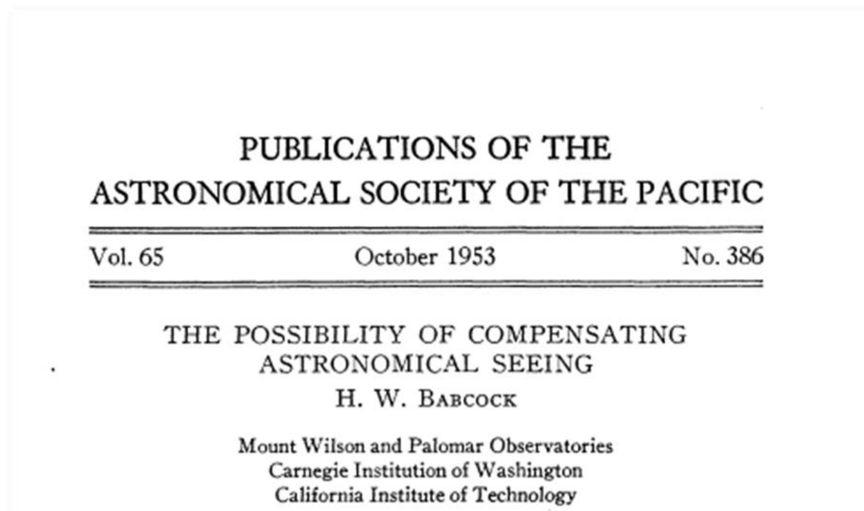
EL MENSAJERO

La Silla
La Serena
Santiago

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



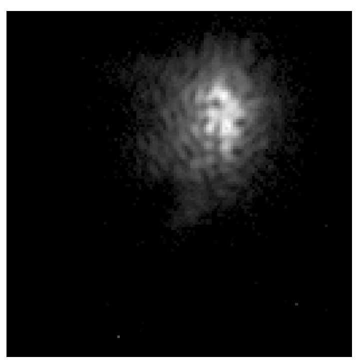
PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

Vol. 65 | October 1953 | No. 386

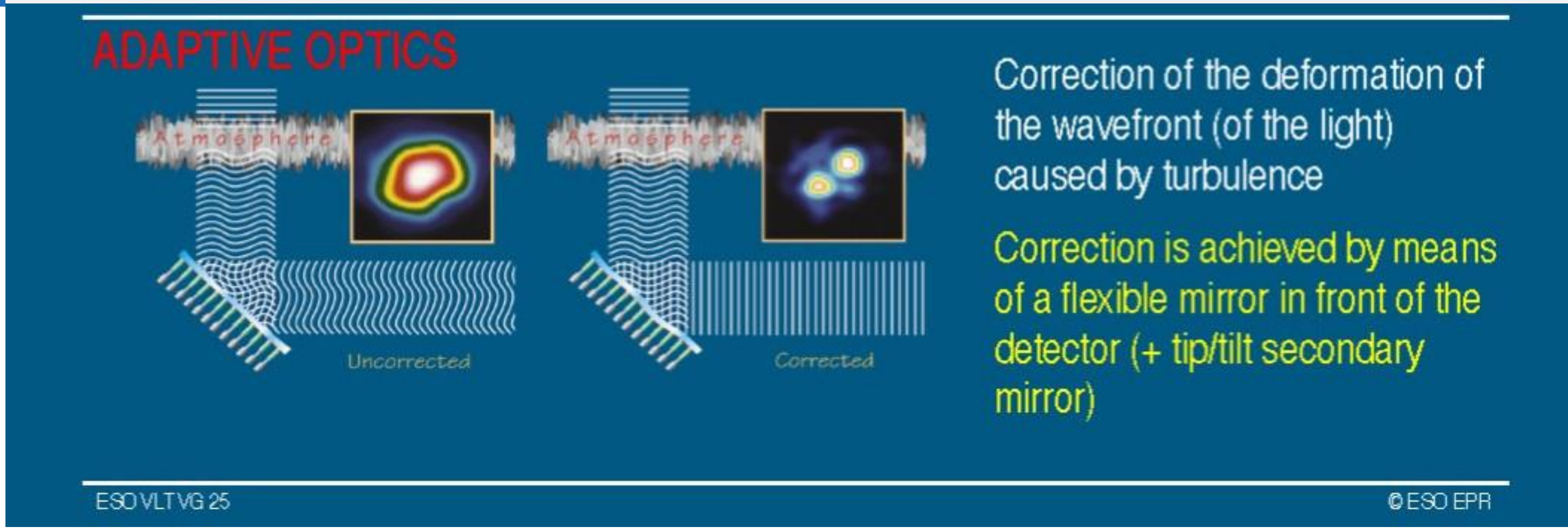
THE POSSIBILITY OF COMPENSATING
ASTRONOMICAL SEEING
H. W. BABCOCK

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

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



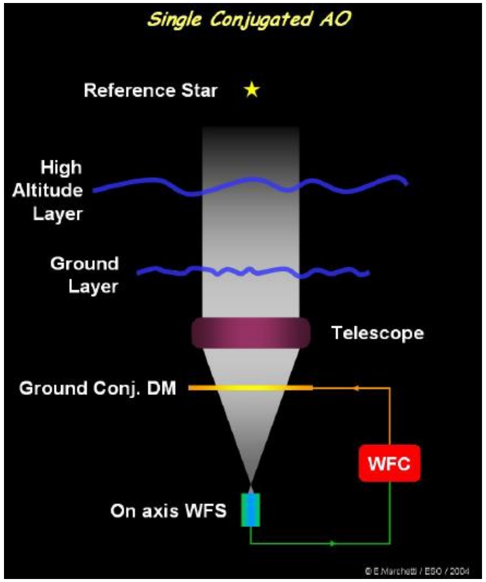
Adaptive optics (2)



- 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 0.5um, 15cm r_0 >> 0.75arcsecs 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 correcetion 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 the VLT SPHERE instrument on the multi-exoplanet system HR 8799

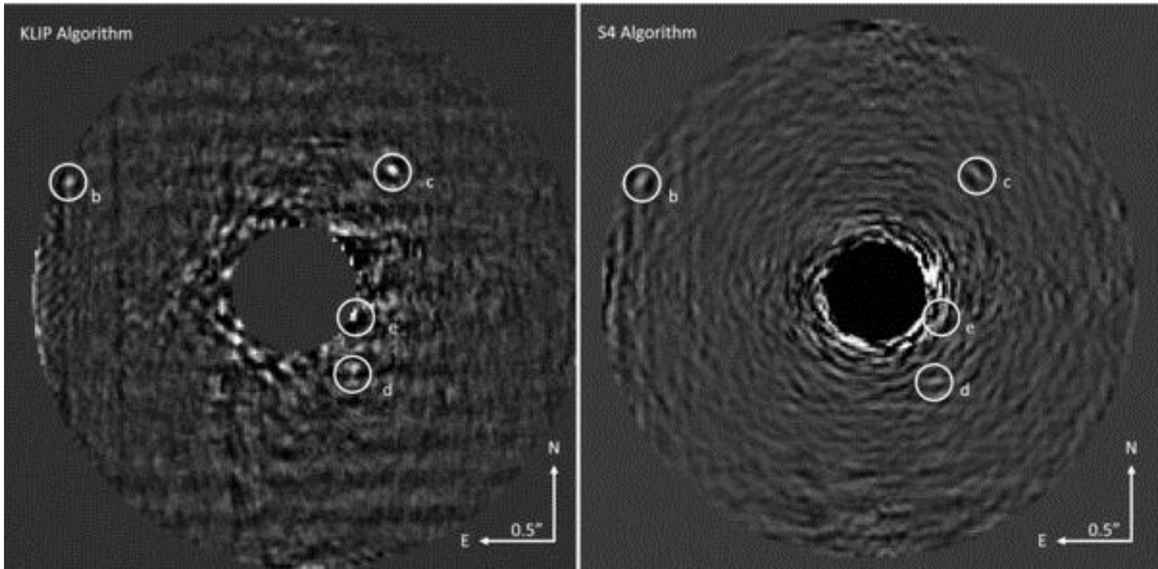
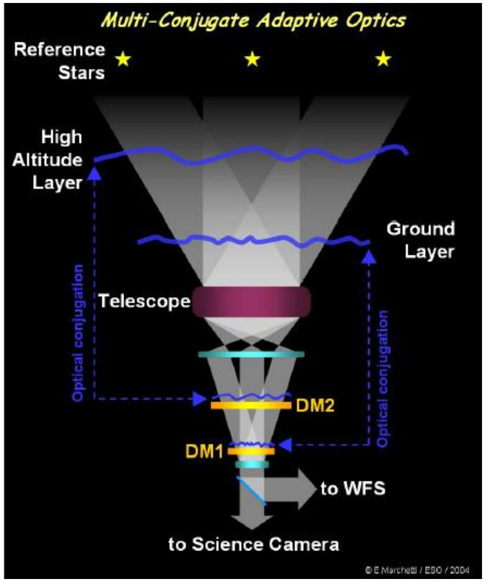


Figure 2 from B. R. Oppenheimer et al. 2013 ApJ 768

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 ~1arcsec in the optical, corrected image FWHM of ~0.1arcsec in the NIR.

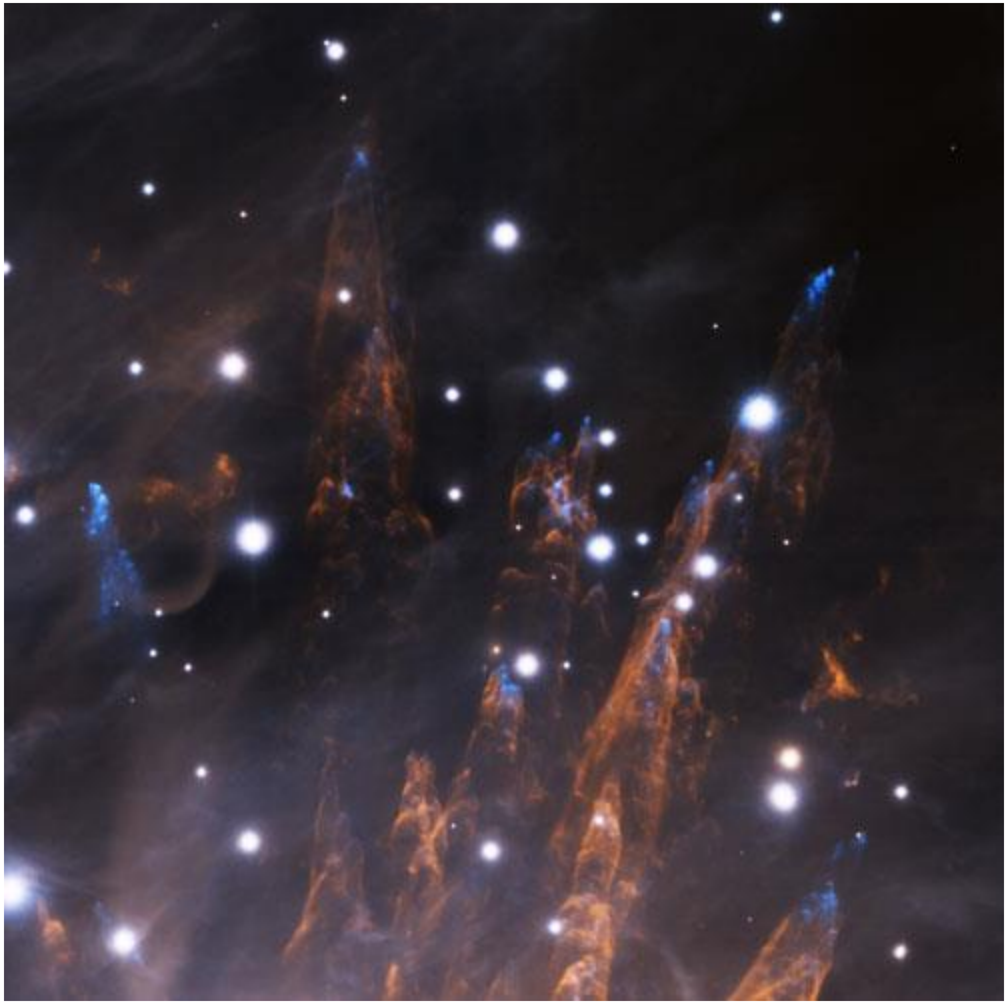
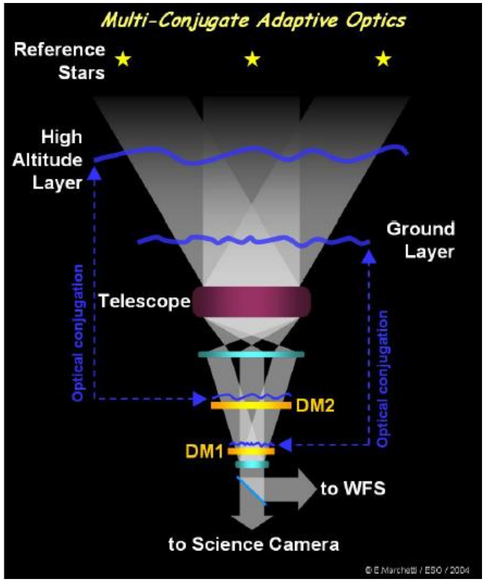


Image credit: Gemini/AURA
Bally et al. 2015 A&A, 579,130

Adaptive optics (4b)

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



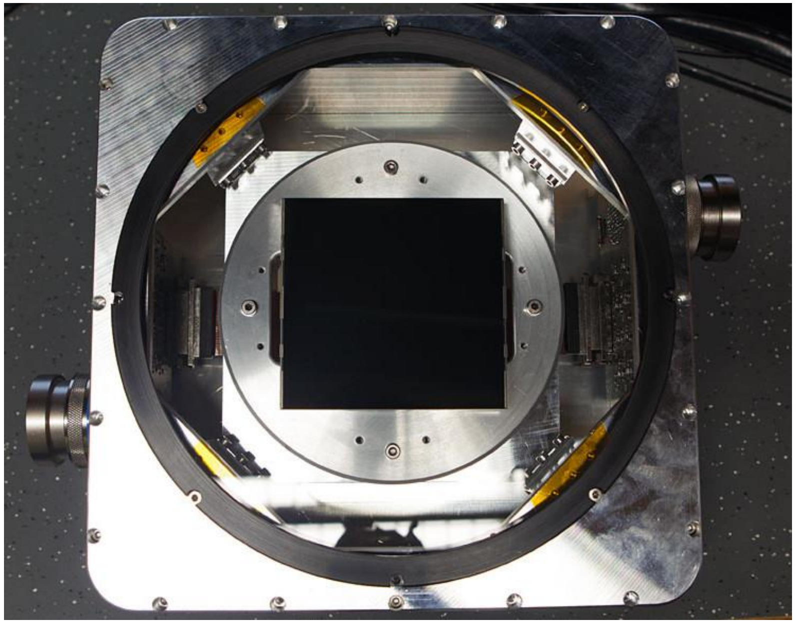
- Extend the sky available for AO using artificial laser guide stars
  - Lasers launched from the telescope excite the sodium layer at 90km in the Earth’s atomsphere

Detectors for astronomy (1)

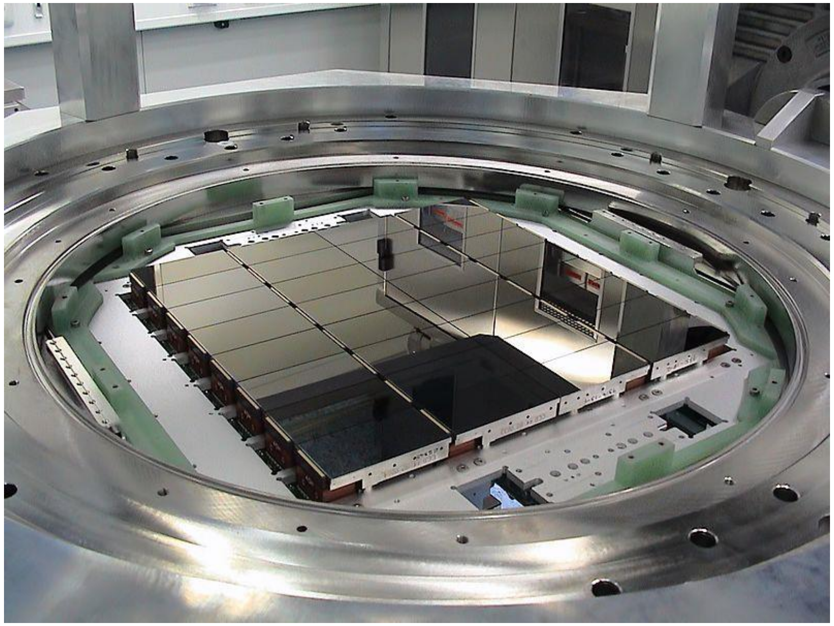
- Selection of the detectors is a critical part of defining the instrument
  - The choice sets many of the design parameters (see later)
  - The choice often drives the costs and risks in the instrument!
  - The costs of the detectors leads to some novel instrument designs that maximise the use of the 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 (μs to ms)

Detectors (2)

- CCD detectors for visible wavelengths



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



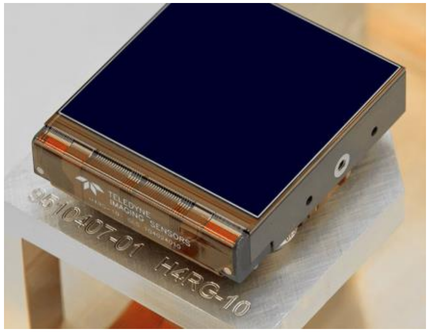
OMEGACAM/VLT Survey Telescope (VST)
32 CCDs of 2000 x 4000 10µm pixels from Teledyne-e2v

See also LSST focal plane, Casali lecture

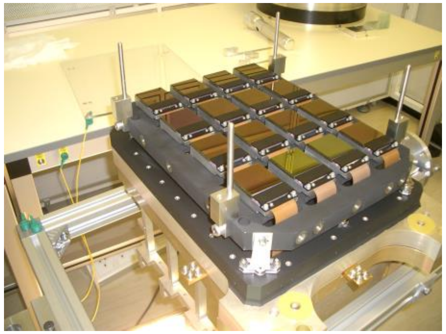
Detectors (3)

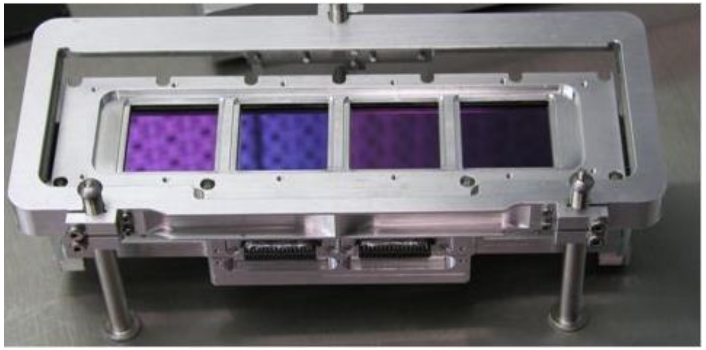
Detectors for infrared wavelengths

Teledyne Hawaii-4RG HgCdTe detector 4096 x 4096 10-15µm pixels. Operating temperature ~30-80K.

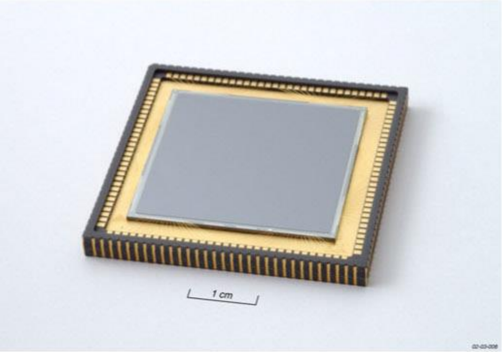


VIRCAM/VISTA 0.8-2.5µm 16 Raytheon 'VIRGO' HgCdTe detectors of 2048 x 2048 20µm pixels Operating temperature: ~70K





The VLT/CRIRES NIR echelle spectrograph ($R \sim 10^5$) has/had an array of 4 1024 x 4096 InSb 'ALADDIN' detectors from Raytheon 0.8-5µm 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 3-28µm range. Operating temperature ~9K

Detectors (4)

- VIRCAM raw data

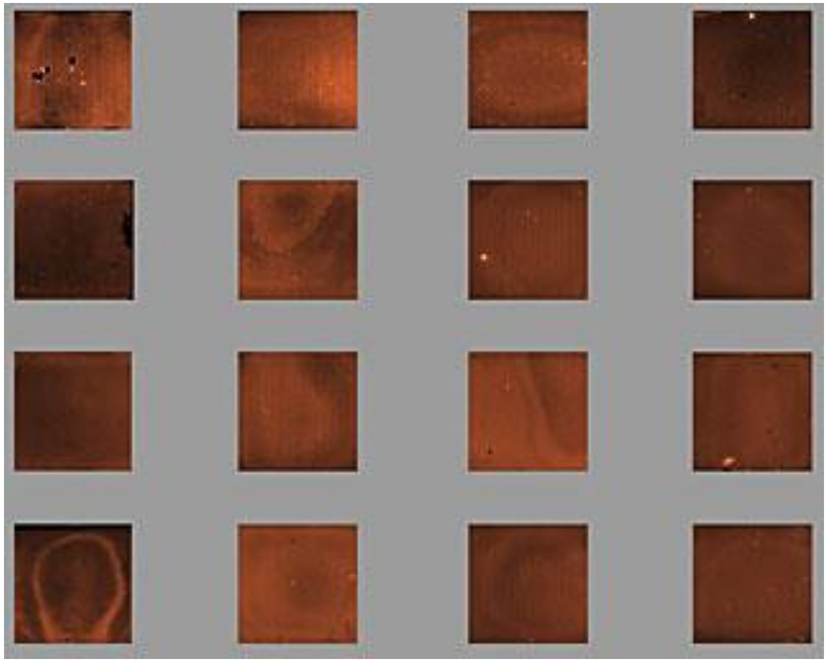


Image of the Orion (Nebula Messier 42)
Z,J,Ks filters used
1degree x 1.degree field
10minutes per filter

- 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 (Ω)
- In particular, for an astronomical instrument

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

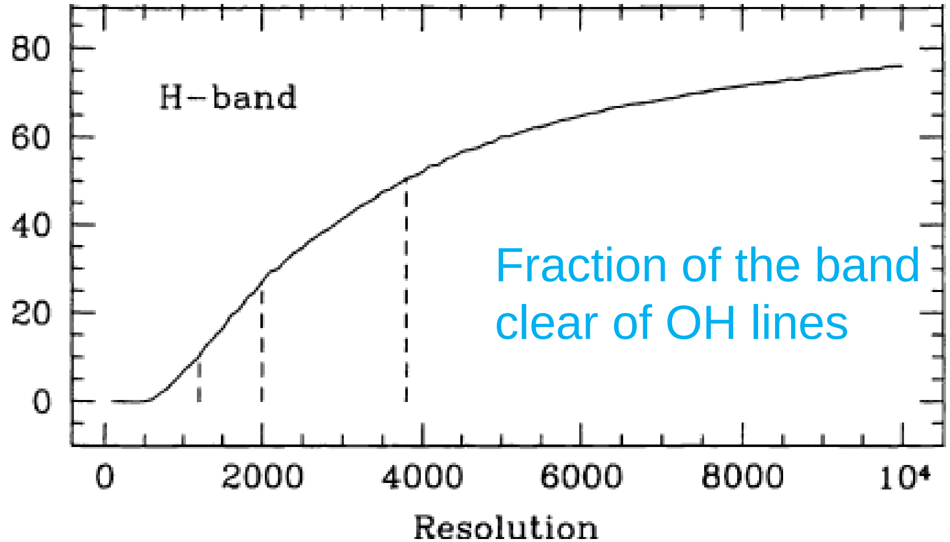
Using a few assumptions and simple geometrical optics, we can calculate some important instrument parameters…..

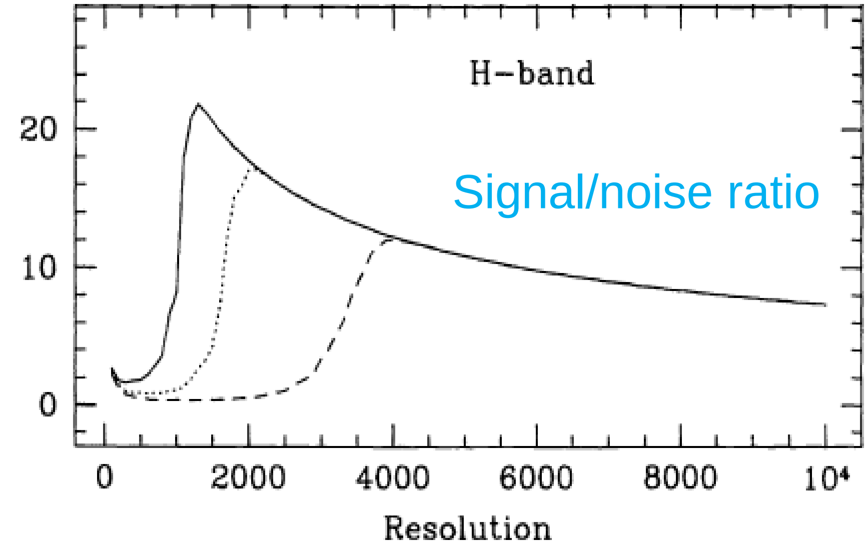
Back-of-the-envelope instrument for the ESO VLT (1)

- **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

- **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 ($\frac{\lambda}{\delta\lambda}$) ≅ 3000

Martini & DePoy, 2000, SPIE





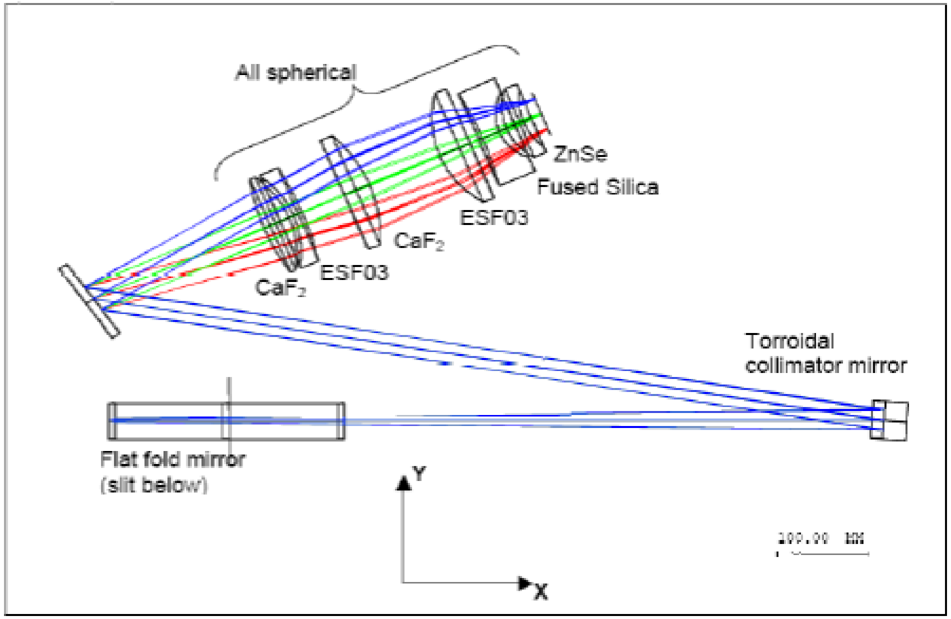
Back-of-the-envelope instrument (2): camera focal ratio

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

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

$$\theta_{cam} = \frac{1}{f\_number}$$

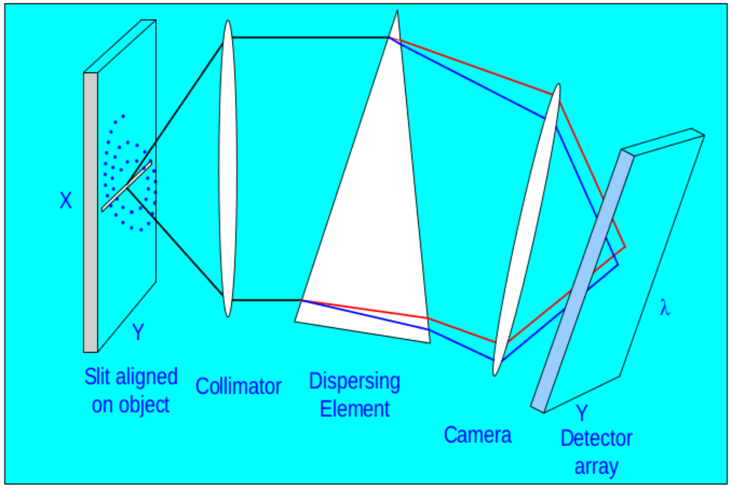
- θ_{tel}=0.2arcsecs, D_{tel}=8.2m
- d_{pix}=18µm
- Camera should be f/2.3
- Such a fast camera is hard but not impossible



Optical layout of the KMOS spectrograph

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

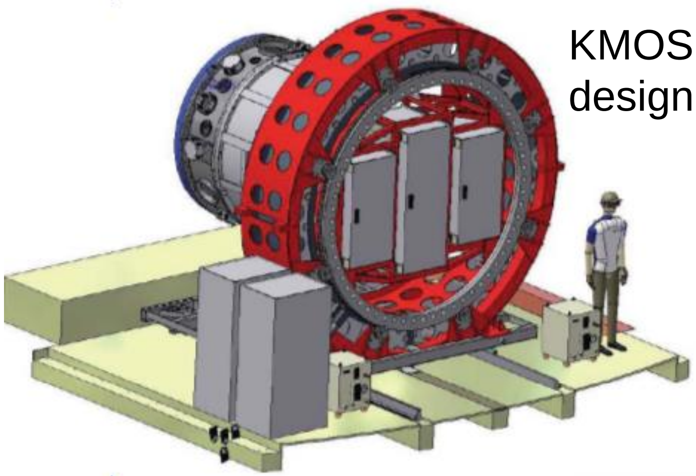
$$R = \frac{2f\tan\theta r}{d_{pix}}$$

f=focal length

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

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

- 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!



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

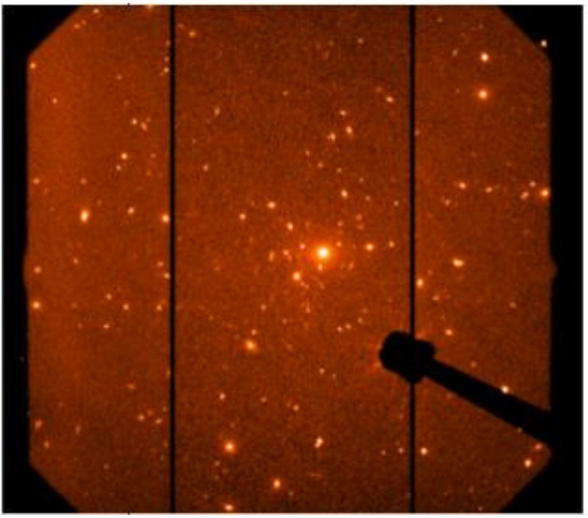
- Diffraction limited instruments:
  - H-band diffraction limited FWHM = 10mas
  - 0.005 arcsecs/18 µm pixel
  - ~f/19 on the ELT
- Aside from the scientific benefits, using adaptive optics can help reduce image sizes to the point where instruments are easier to build
- For an instrument to operate at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

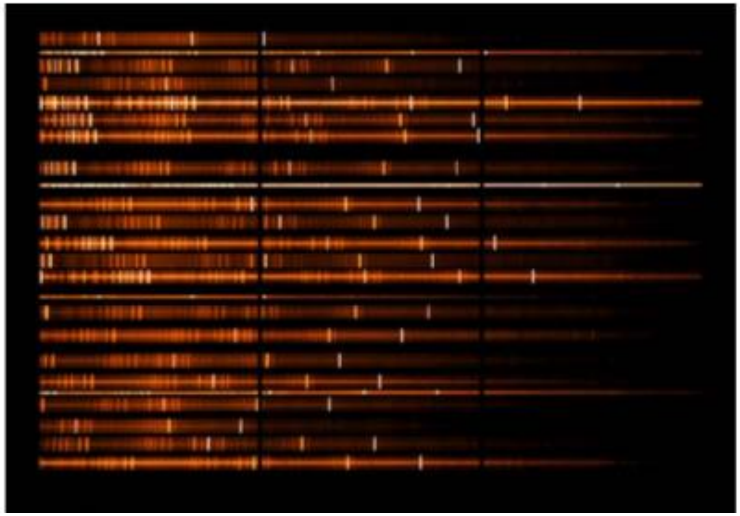
$$\theta_{tel} = \frac{1.22\lambda}{D_{tel}} \quad \text{then} \quad \frac{d_{pix}}{f\_number} \sim \lambda$$

- A diffraction limited instrument can go on any telescope!

Ground-based instruments today (1)

- Multi-object spectroscopy with slit masks





Pre-imaging may be required to map or identify objects

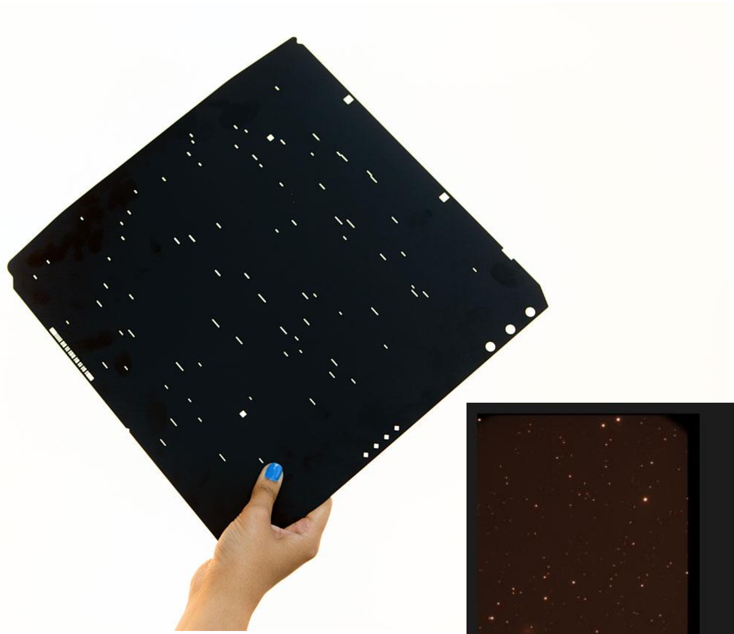
A slit mask is made with slitlets for each target and inserted into the instrument focal plane

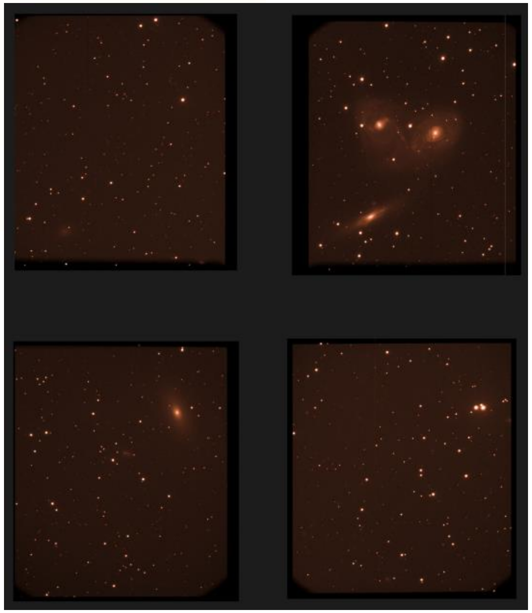
Spectra of the multiple objects are obtained with excellent useage of the array and some restrictions on the object selection

Images are from the Gemini multi-object spectrograph

Ground-based instruments today (2)

- Multi-object spectroscopy: VIMOS at VLT

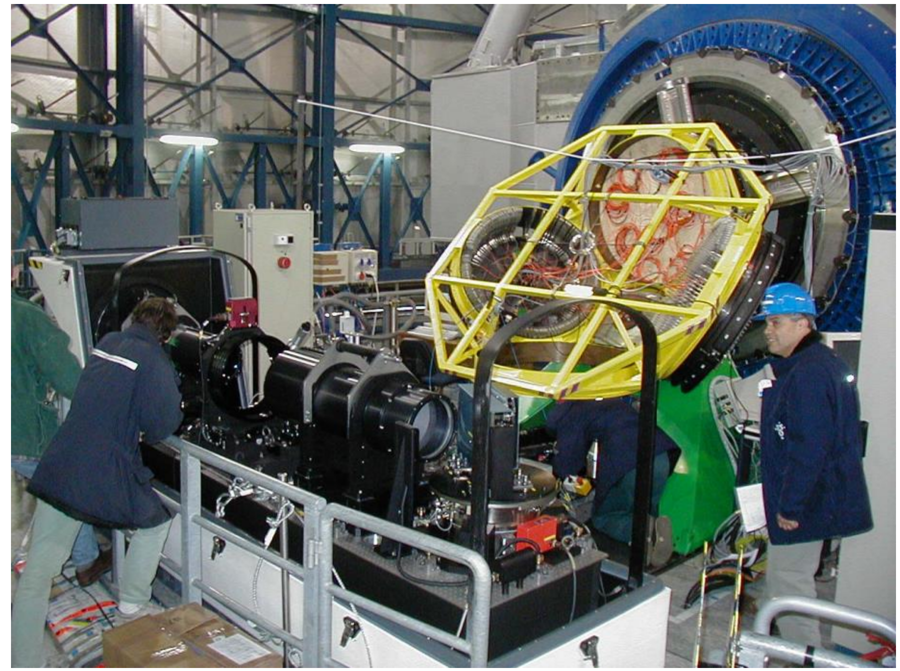




Slit (mask) spectrographs are sensitive to faint objects. VIMOS was designed with galaxy surveys in mind. e.g. VIPERS (vipers.inaf.it)

Ground-based instruments today (3)

- Multi-object spectroscopy with fibres: FLAMES

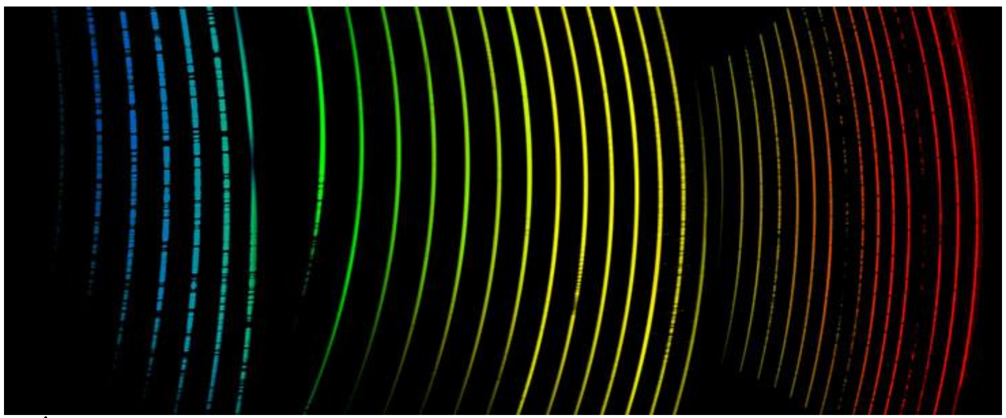


The OzPoz fibre coupled to the GIRAFFE or UVES spectrographs are ideally suited to surveys of stars e.g. the GAIA-ESO survey to 10^5 sources (www.gaia-eso.eu)

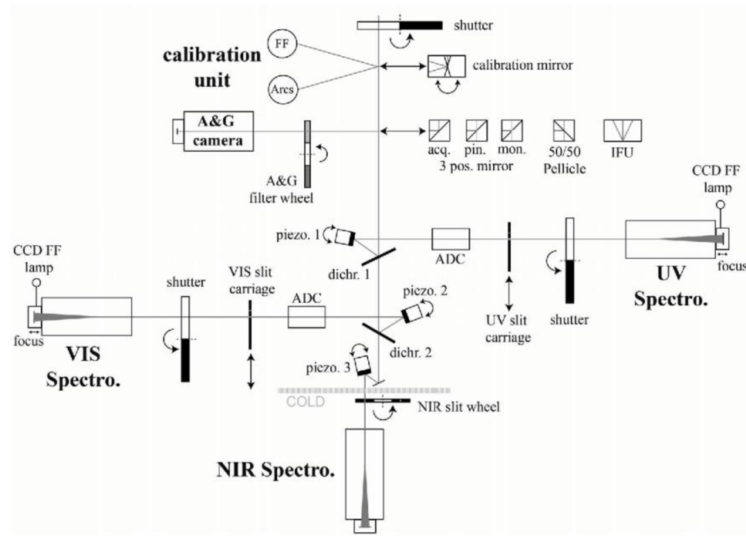
Ground-based instruments today (4)

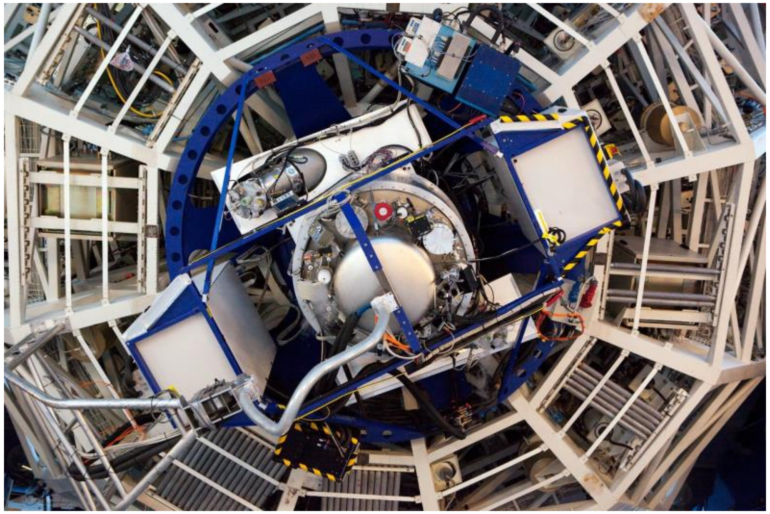
- The widest wavelength range: cross-dispersed spectroscopy with X-shooter

wavelength



Cross-dispersed orders of the gratings





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

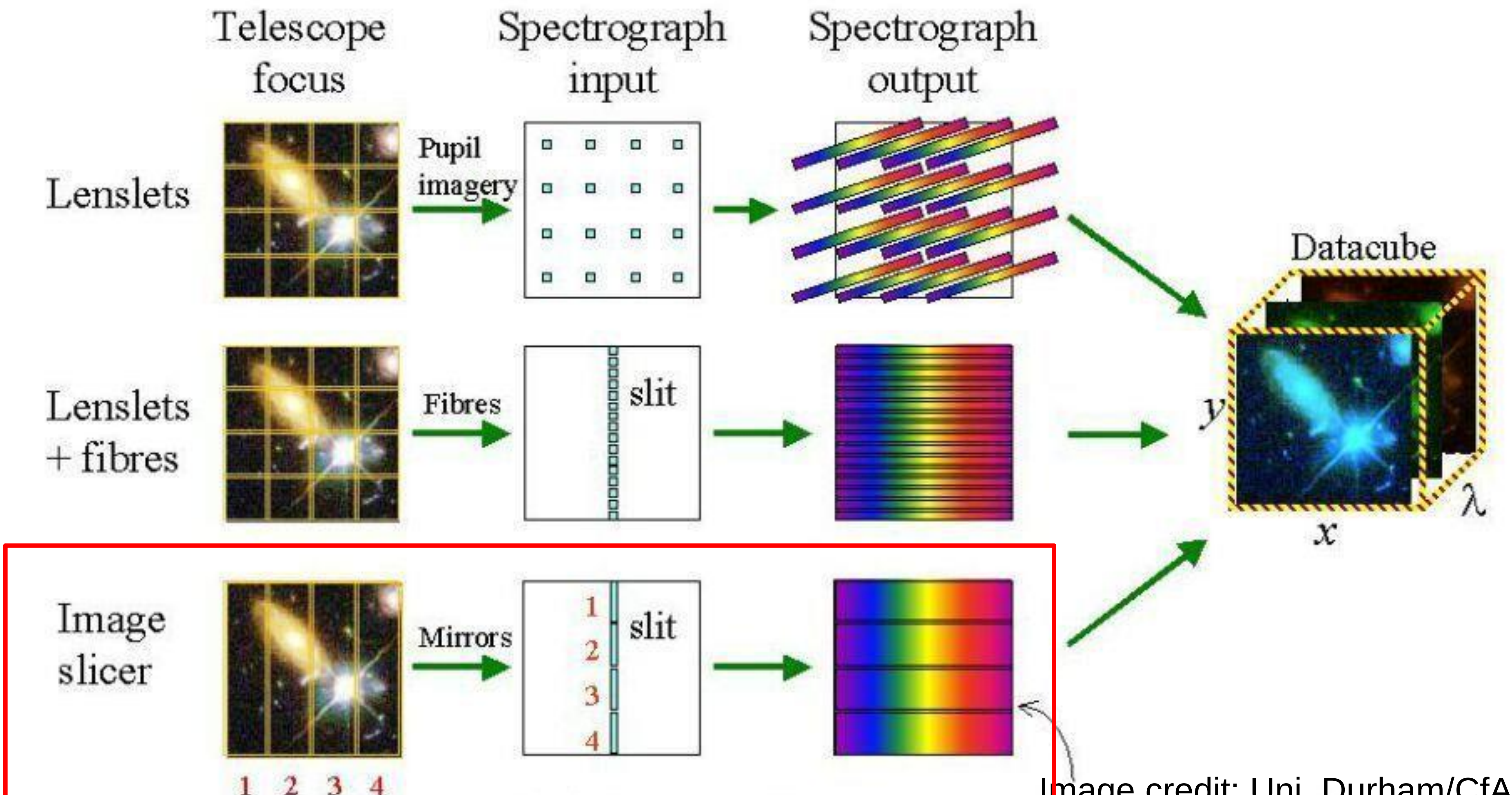
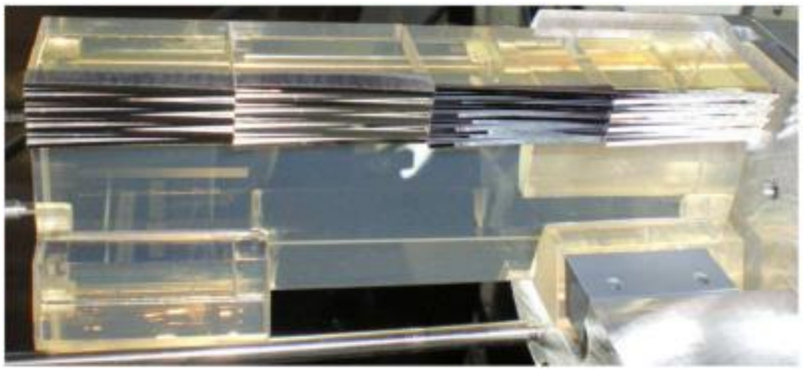


Image credit: Uni. Durham/CfAI

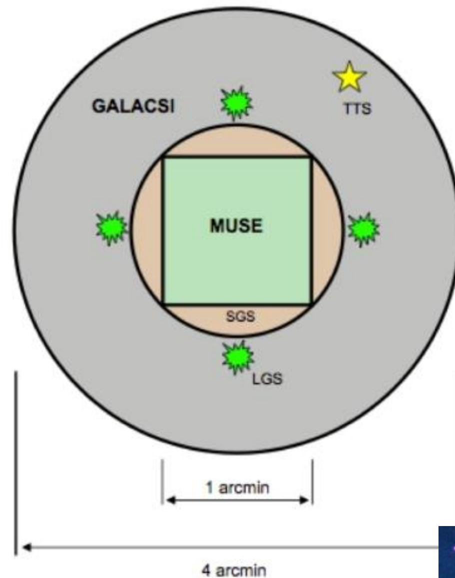
Ground-based instruments today (6)

Widefield and AO assisted optical IFU: MUSE

The MUSE image slicer



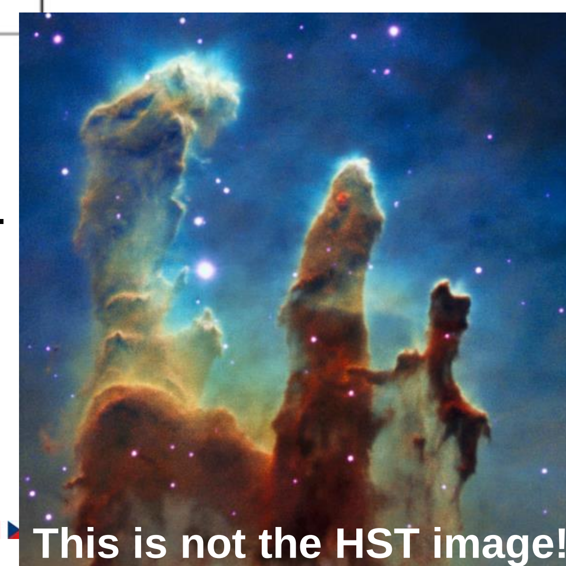
MUSE at the VLT: 24 spectrographs



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.

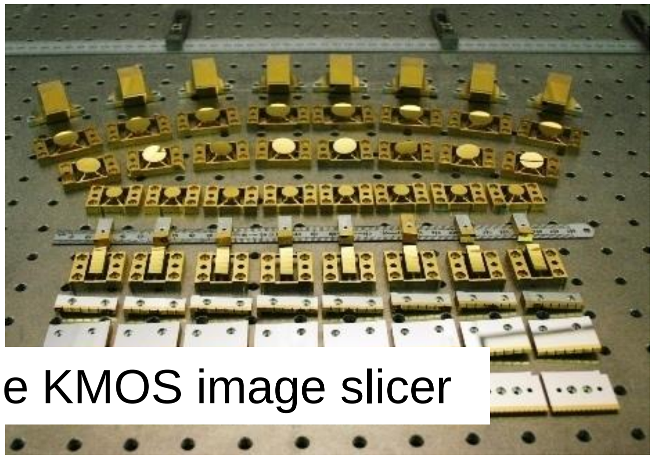
The Pillars of Creation as observed by MUSE. Three colour images extracted from the datacube.

Mcleod et al (2015)



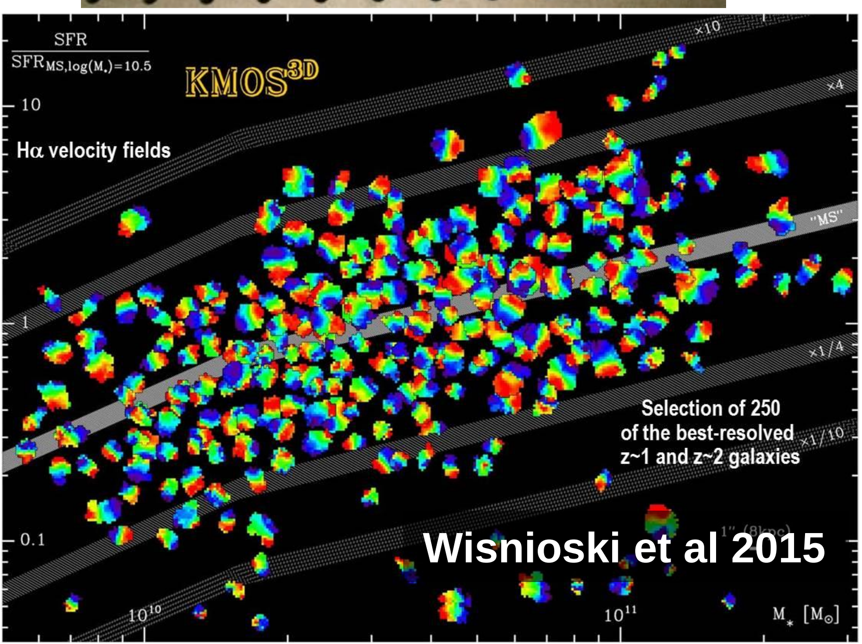
Ground-based instruments today (7)

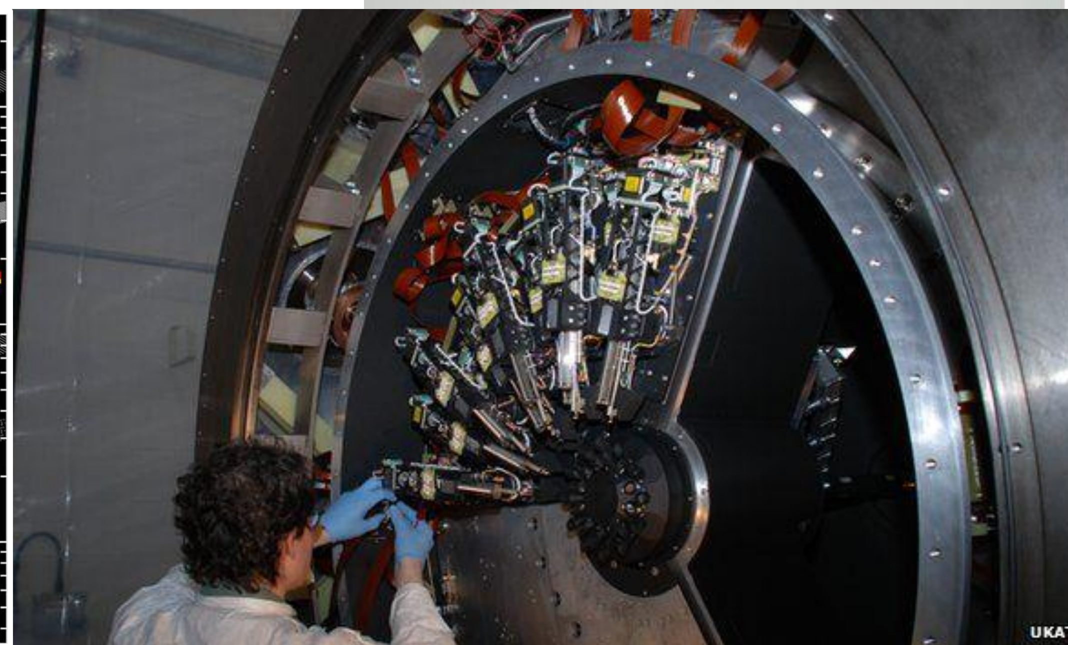
- Multi-IFU spectroscopy in the NIR with KMOS



The KMOS image slicer

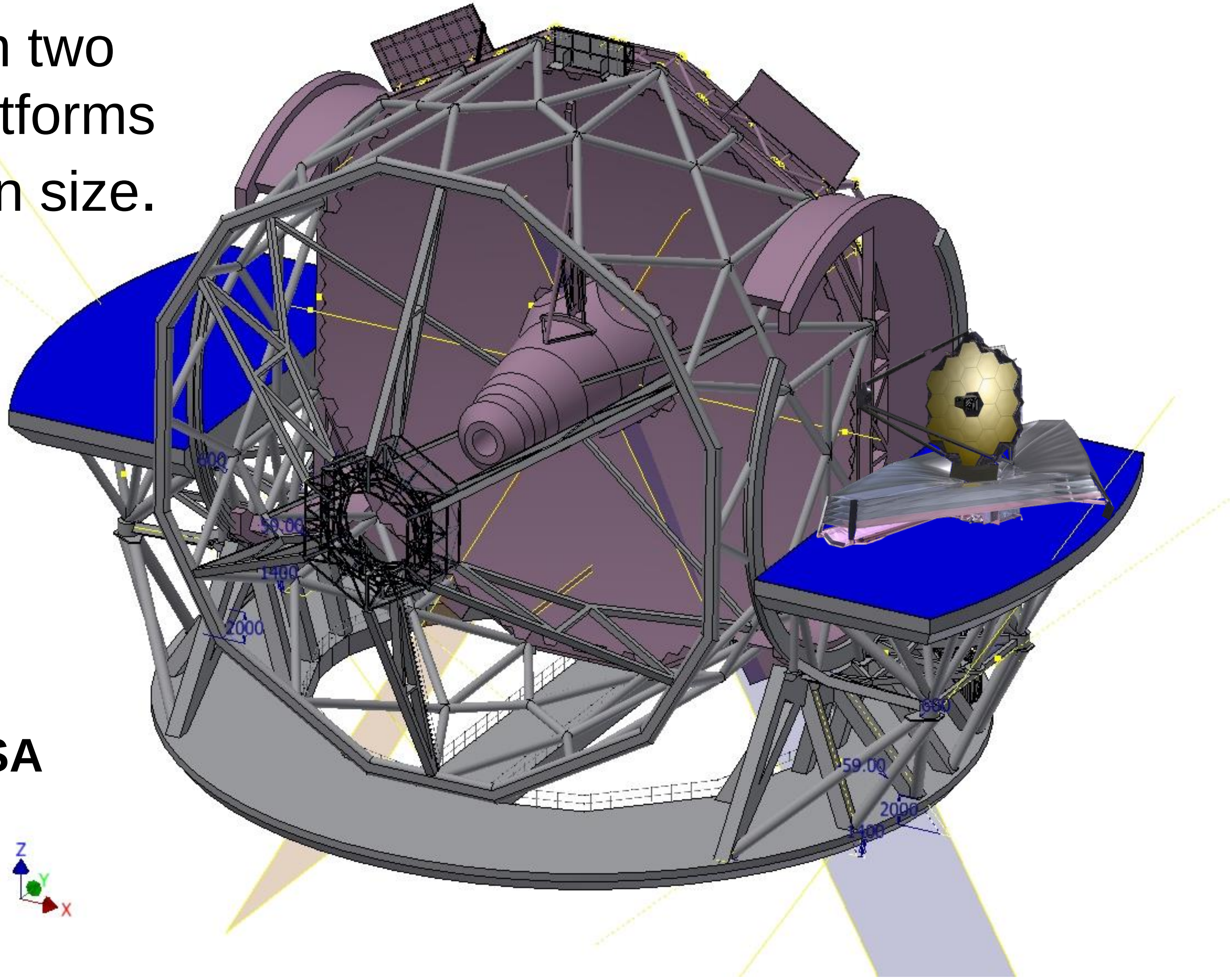
24 pick-off arms select targets over the VLT 7arcmin field of view then direct the beam to 24 IFUs and 3 spectrographs.





Ground based instruments tomorrow

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

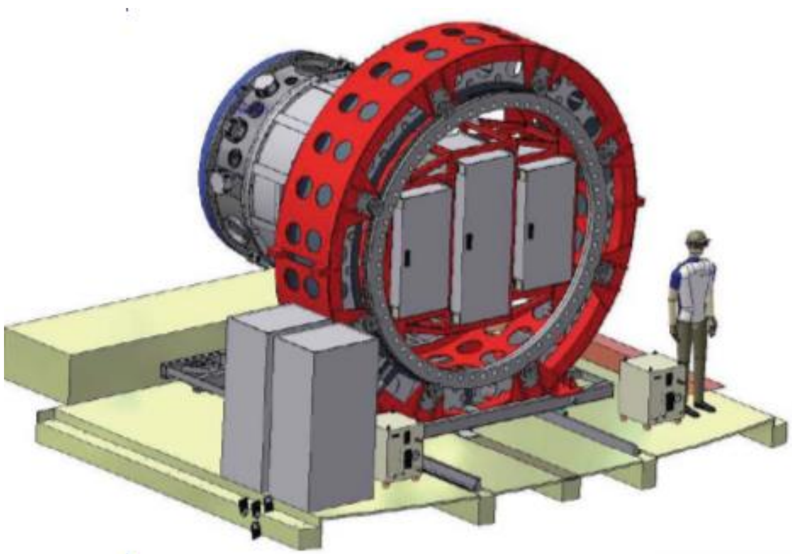


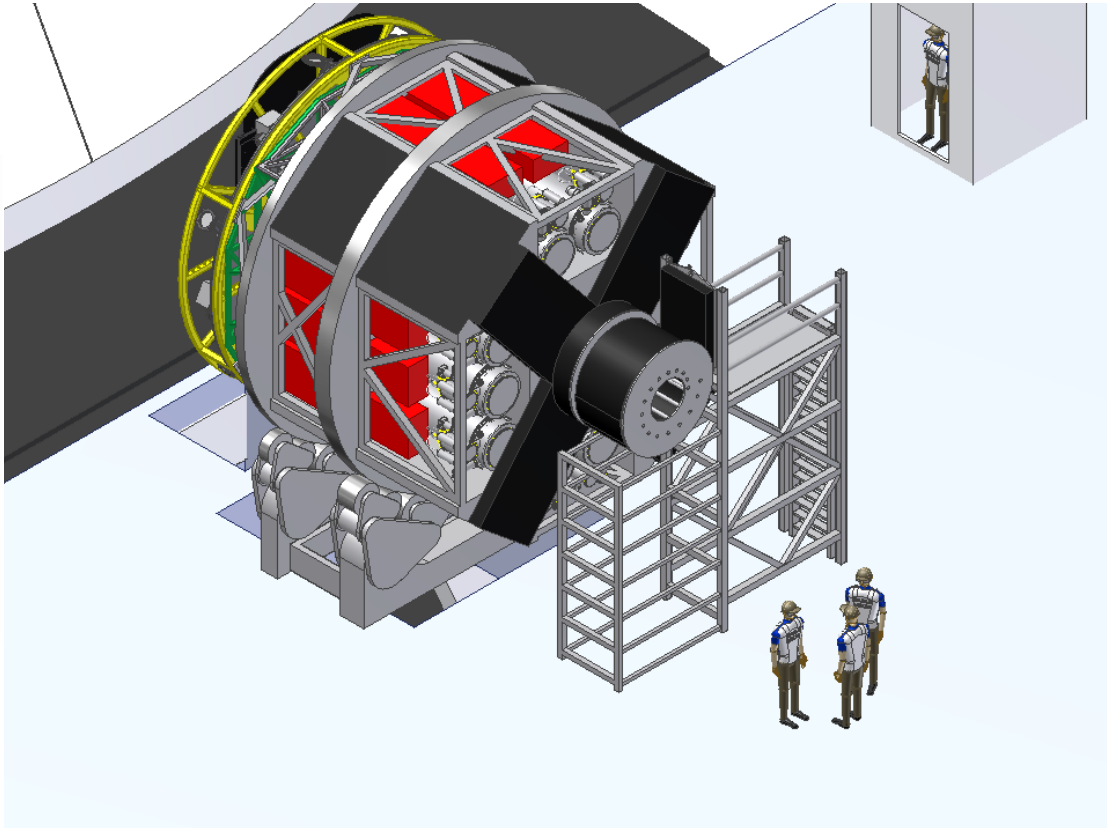
JWST sun-shield
21m x 14m
Image credit/NASA

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 = 120µm on VLT; would be 660µm on E-ELT
- Some things get harder….

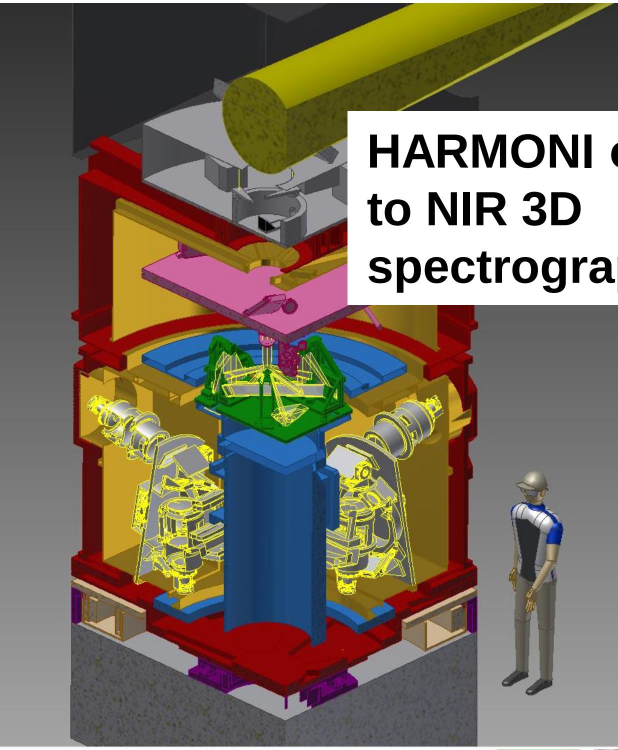
KMOS vs EAGLE



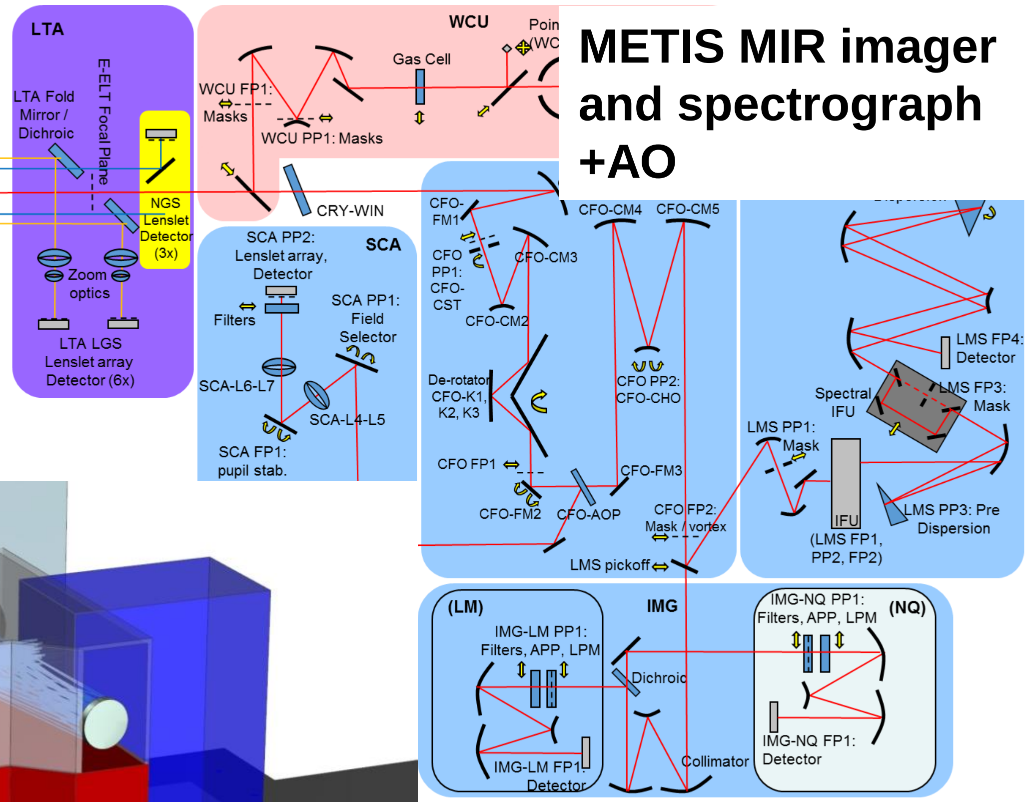


KMOS: 0.2arcsec pixels on 8-m telescope, 7arcmin field of view
EAGLE concept: 40mas pixels on a 39-m telescope, 7arcmin field of view
These instruments have the SAME AΩ product/étendue and can select the same numbers of objects (20-24).

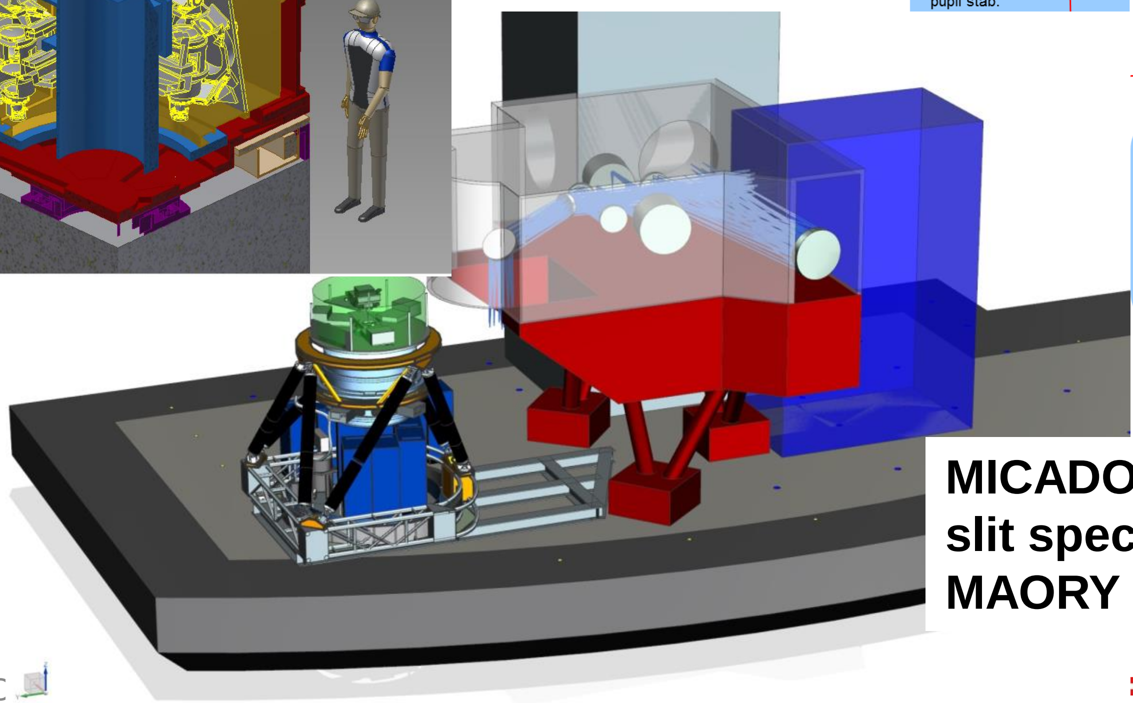
ELT instruments



HARMONI optical to NIR 3D spectrograph+AO



METIS MIR imager and spectrograph +AO



MICADO NIR imager and slit spectrograph with the MAORY MCAO module

Thanks for your attention

A question for the audience:

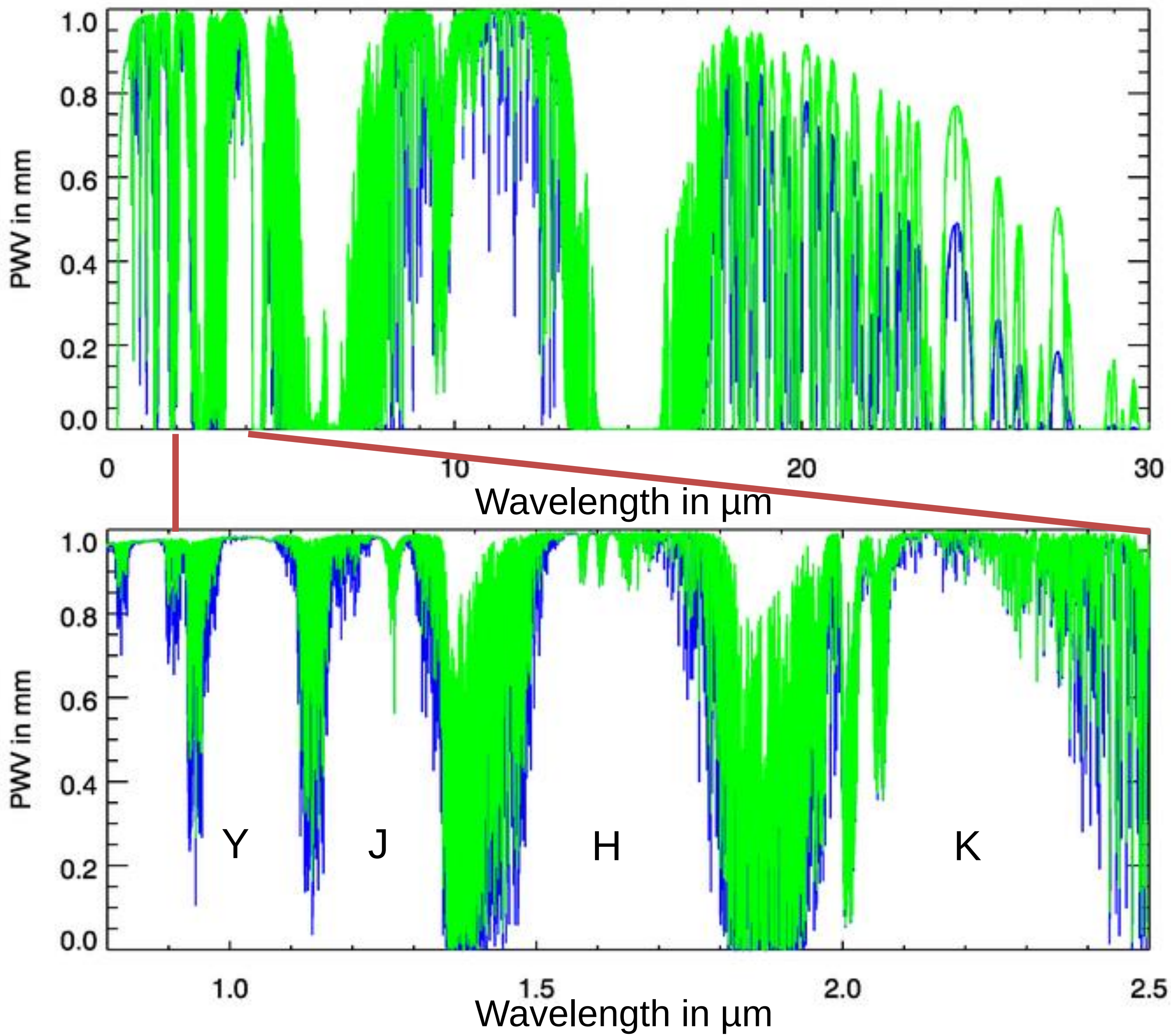
Smart phones drive the development of large format CCDs for their built in cameras.

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

Near infrared atmospheric windows



ELT instruments

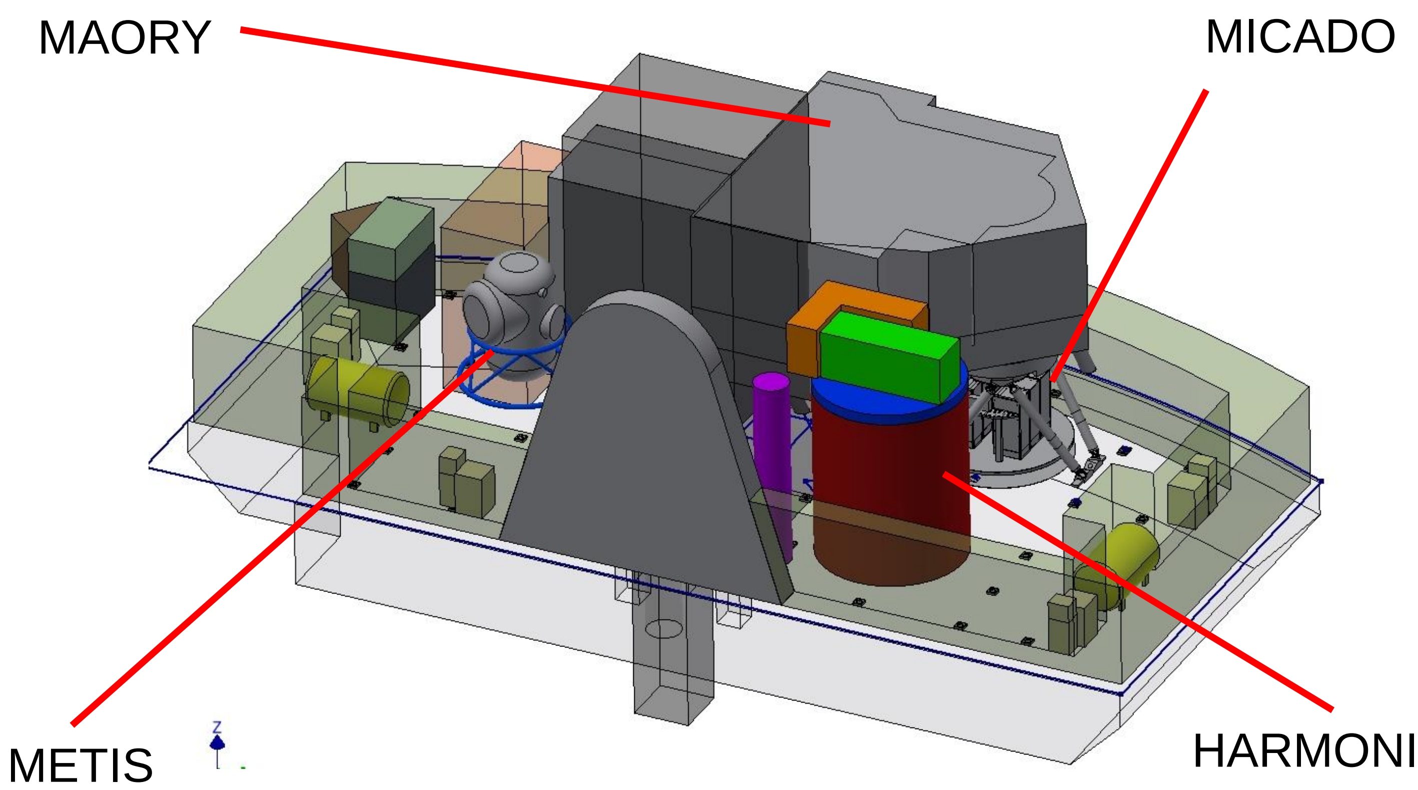


Image provided by Gerd Jakob (ESO)