Observational Astrophysics II

Active and Adaptive optics

Kitchin pp. 89-100

Fidelity of the astronomical observations

The reproduction of the surface brightness within the field of view (FoV) in the telescope focal plane is crucial

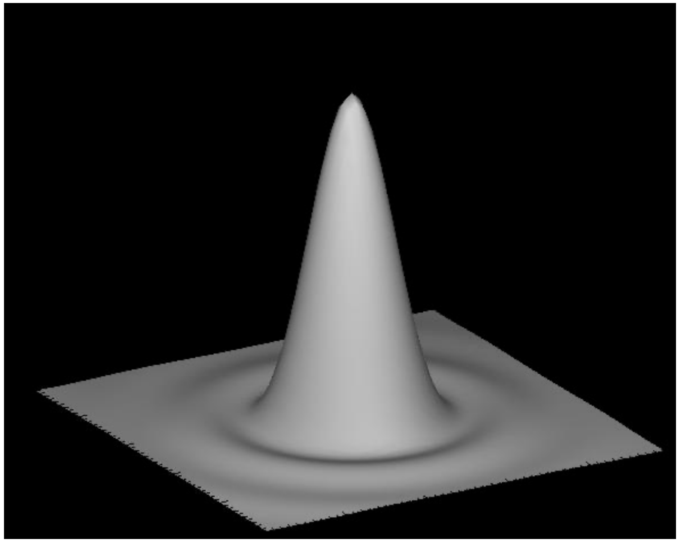
There are the pre-requisites for that:

- Assumption of the collimated (parallel) beam from a distant point source
- Performance of the optical system

None of them will hold automatically

Point Spread Function

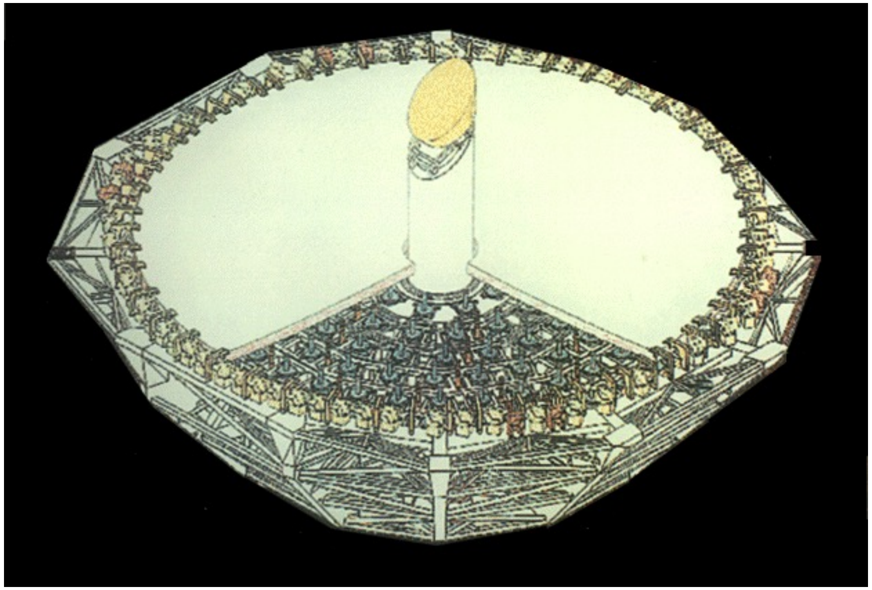
- The image of a distant point source made by any telescope is not a point. We call it PSF.
- PSF is the intensity distribution in the focal plane produced by a point source at infinity.
- Ideal PSF with for a circular mirror is a Bessel function:
- Active optics system is used to maintain the shape of optical elements.

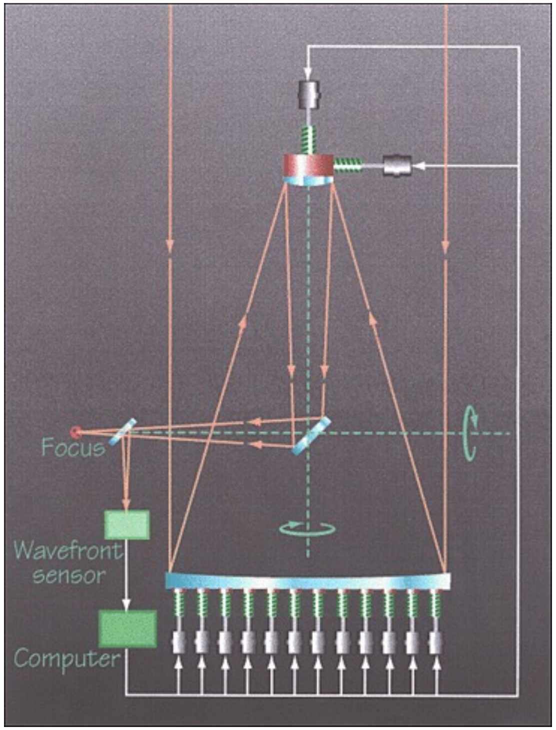


Active optics

Large thin mirrors are shaped by support system: VLT mirror is 8.2m in diameter

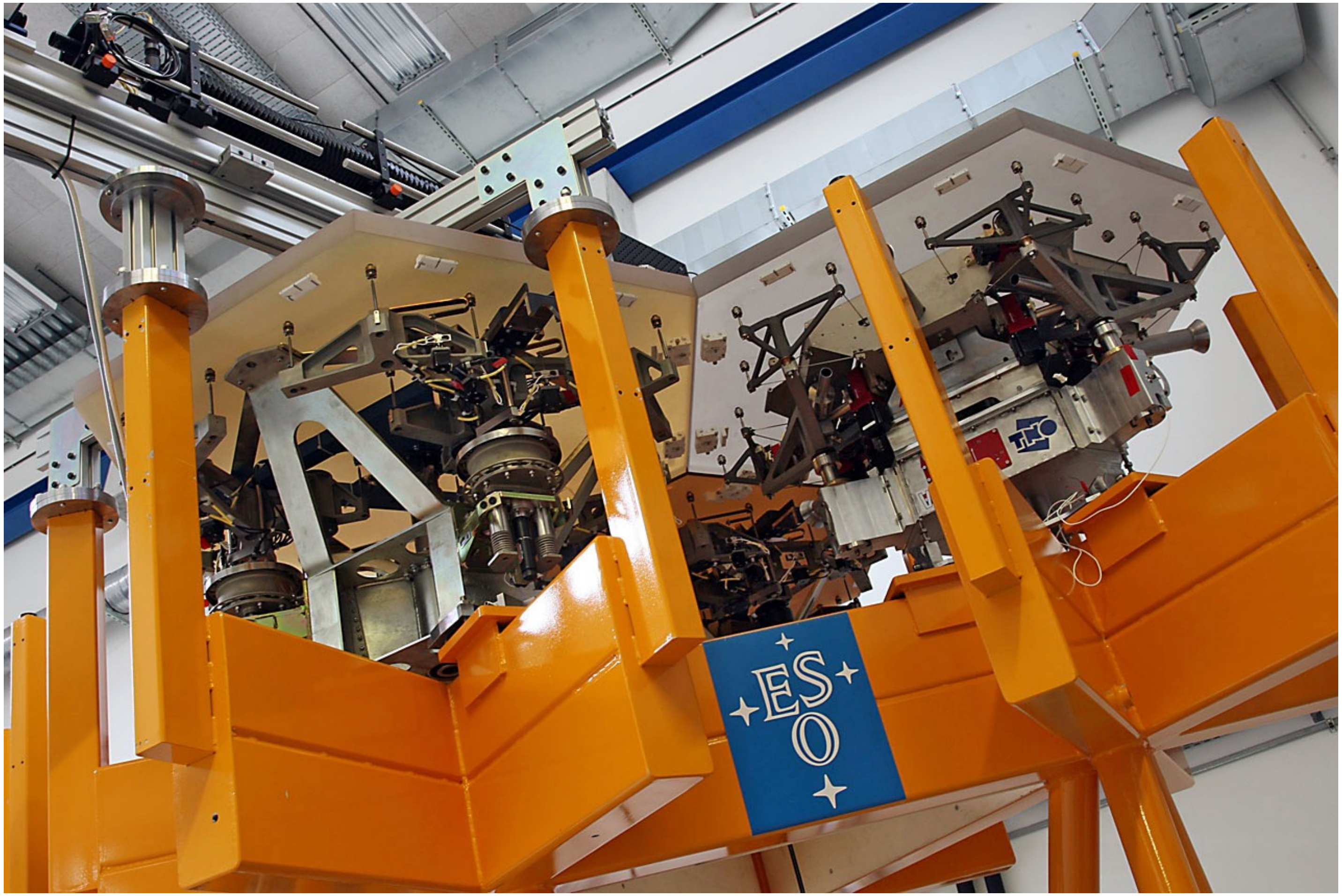
and only 18 cm thick!





- Compensate for thermal and orientation distortions
- Close loop operation during adjustment
- Database of corrections
- Low frequency: 30 s cycle
- VLT: 150 actuators

Active optics: ELT segments

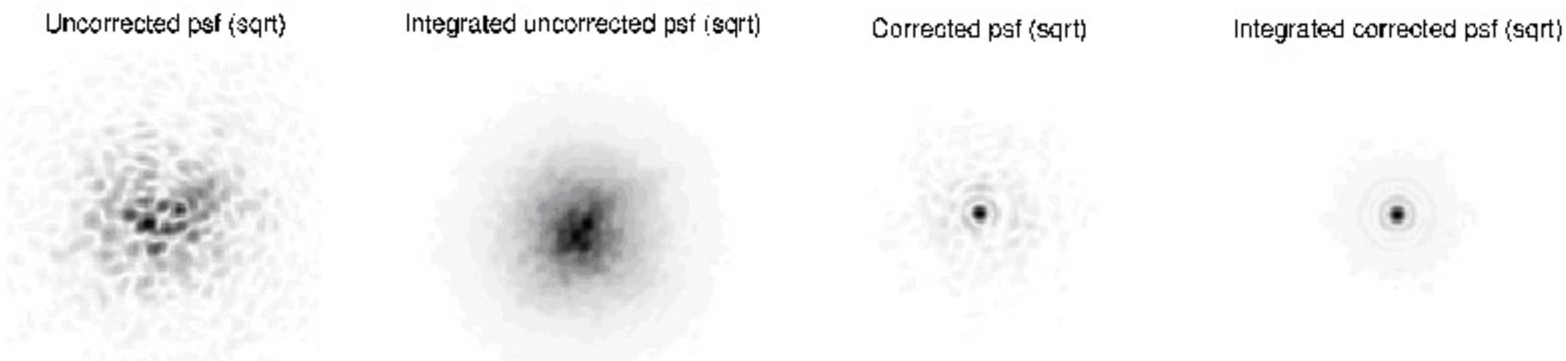


Active optics (cont'd)

- Active optics operates using a database of corrections.
- Corrections are recorded by observing point sources at different altitudes and wind loads.
- During calibration mirror shape is adjusted to match the theoretical PSF for a given telescope (closed loop).
- During science operation the corrections are read from the database and applied (open loop operation).

Adaptive optics

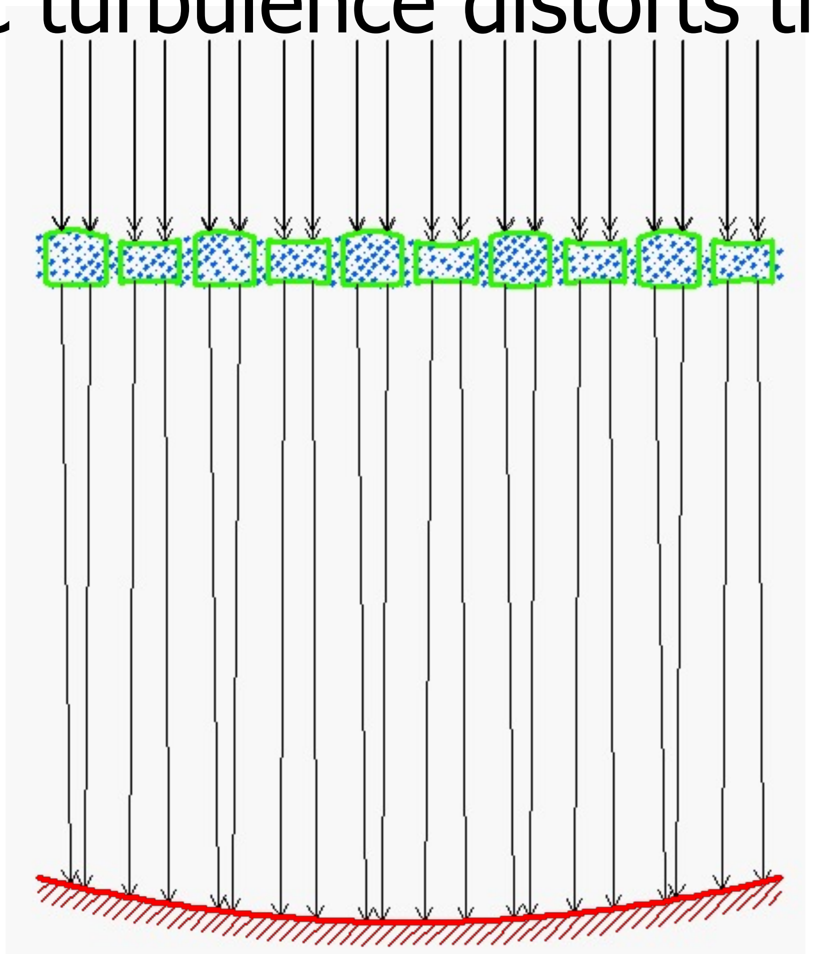
Seeing corrections (PSF):



The *Strehl ratio* is the ratio of peak intensities in the aberrated and ideal point spread functions in the focal plane (Born and Wolf 1999).

Why do we need adaptive optics?

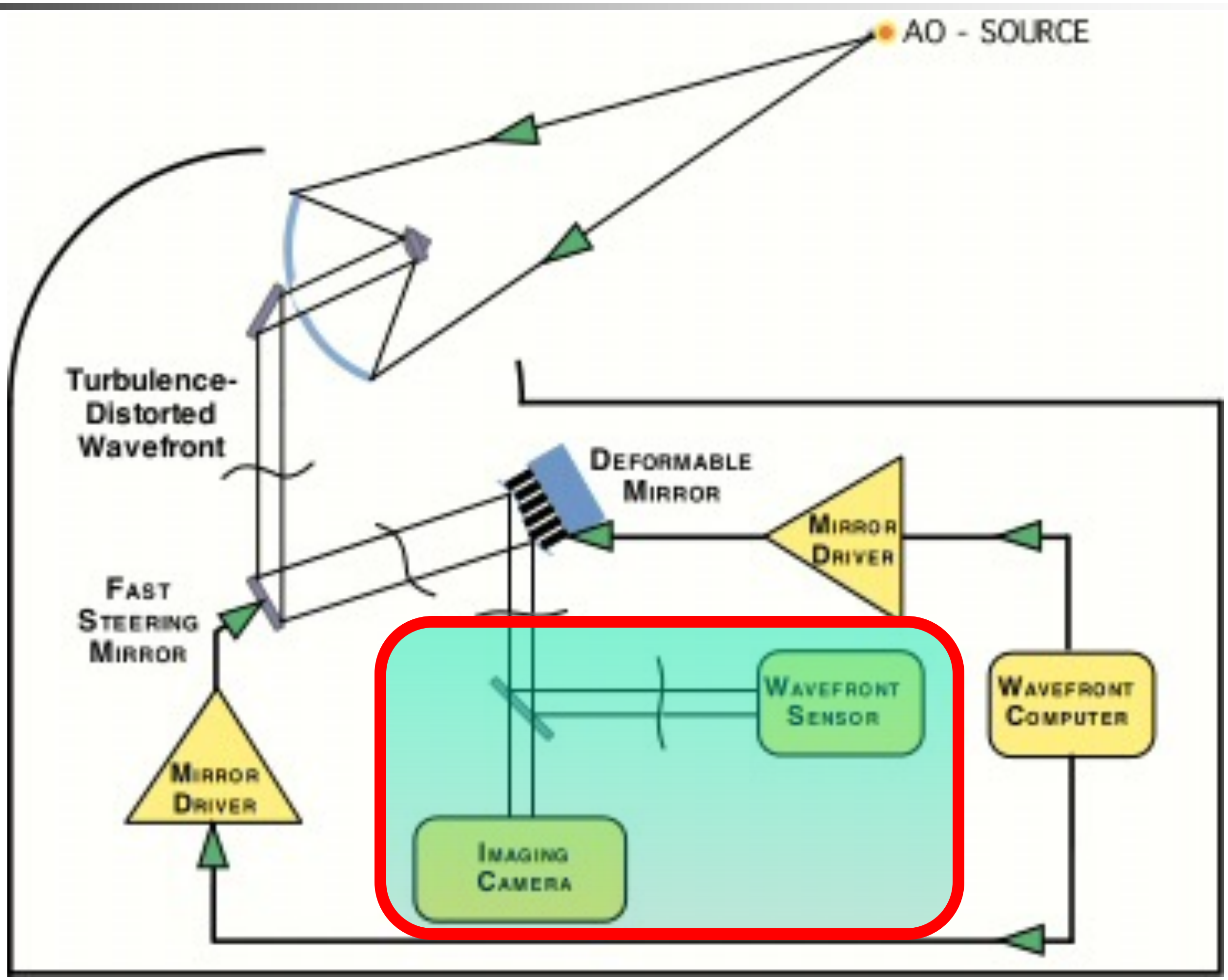
Atmospheric turbulence distorts the wave front.



Three ways of looking at the focal plane image:

1. Non-collimated beams (speckles)
2. Curved wavefront (phase shifts)
3. Changing intensity distribution

How adaptive optics work?



A bit of theory…

- Amplitude of turbulence spectrum $\Phi(k) \propto k^{-2/3}$ where $k = 2\pi / r$ (Kolmogorov spectrum)
- Refraction index changes in the atmosphere are given by: $\delta n = -7.8 \cdot 10^{-2} \dfrac{P\delta T}{T^2}$ (Oboukhov's law)
- Typical variations of temperature are of the order of 10 mK and thus refraction changes ≈10^{-8}
- Phase shift is: $\phi(r) = \dfrac{2\pi}{\lambda} \int \delta n(r,z)dz$

… and some more …

We are interested in accumulated phase difference between two points on the sky separated by **angular** distance α and therefore $\Delta\phi$ is proportional to the scale of perturbation in the power 5/3:

$$\Delta\phi(\alpha) = \frac{2\pi}{\lambda}\int \delta n(r)dr/\alpha \propto$$

$$\propto \frac{2\pi}{\lambda\alpha}\int r^{2/3}dr = \frac{2\pi}{\lambda\alpha} r^{5/3} = (r/r_0)^{5/3}$$

where r_0 is Fried radius defined as the radius where the phase shift is 1 radian. Fried radius shows:

- size of the isoplanatic patch
- the aperture size which can reach diffraction limit

… and some more …

- Fried radius is related to the wavelength:

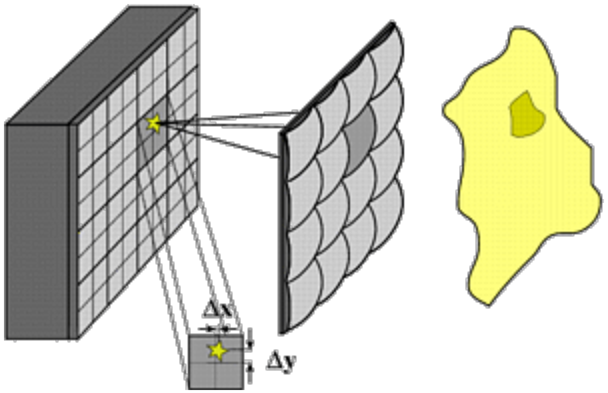
$$r_0 \propto \lambda^{6/5}$$

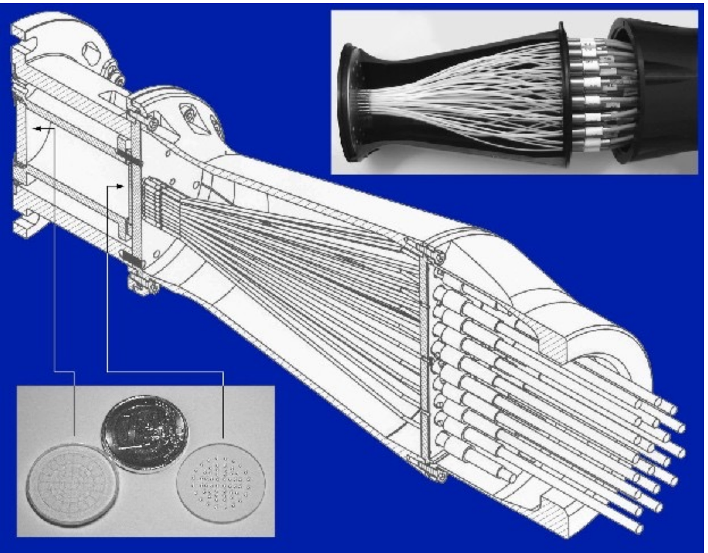
because diffraction width of telescope PSF is λ/D. Alternatively, Fried radius gives the maximum diameter of the telescope that reaches diffraction limit:
$$\mathrm{FWHM} \approx \lambda/r_0$$

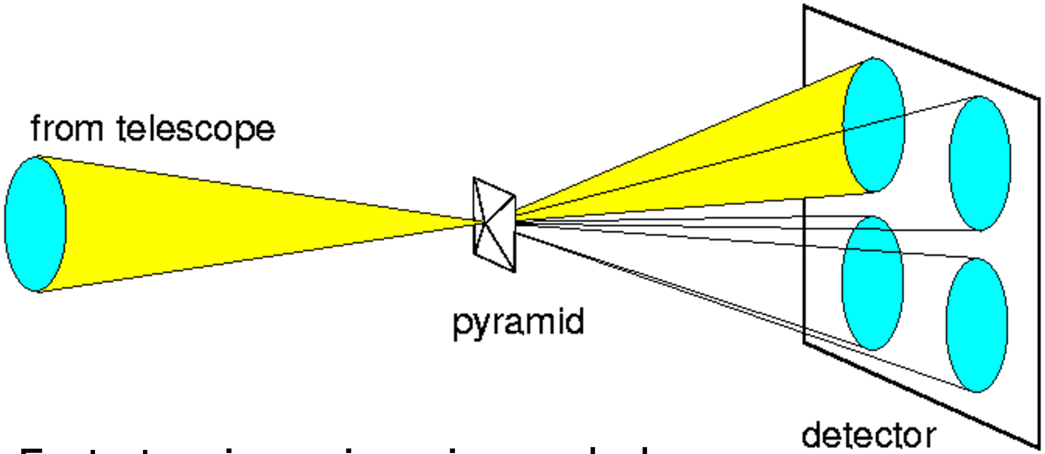
- Time scales: *0.001 seconds*
- Typical r_0 are around *10 cm in the visible light*
- How would one measure r_0?

Wavefront sensor

- Shack-Hartmann
- Curvature sensor
- Pyramid WFS





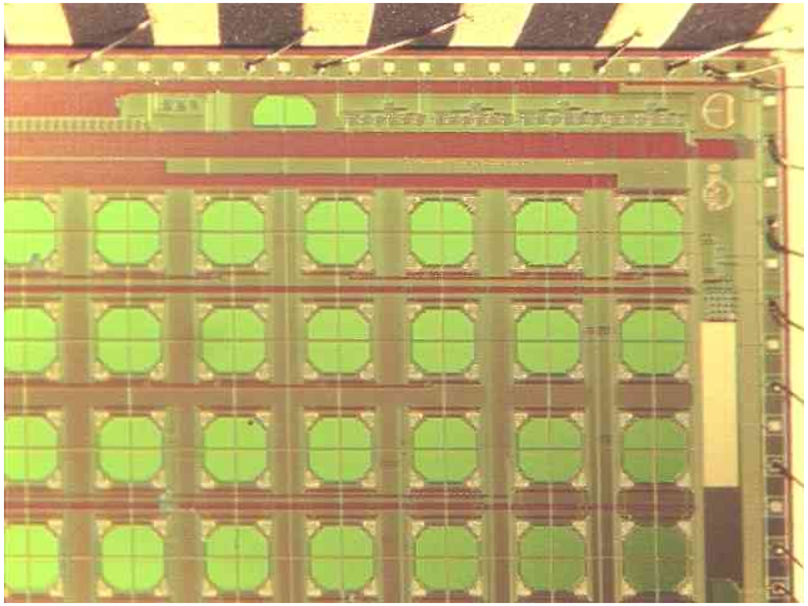


Fast steering mirror is needed
to get all pixels in focus

Sensor implementation

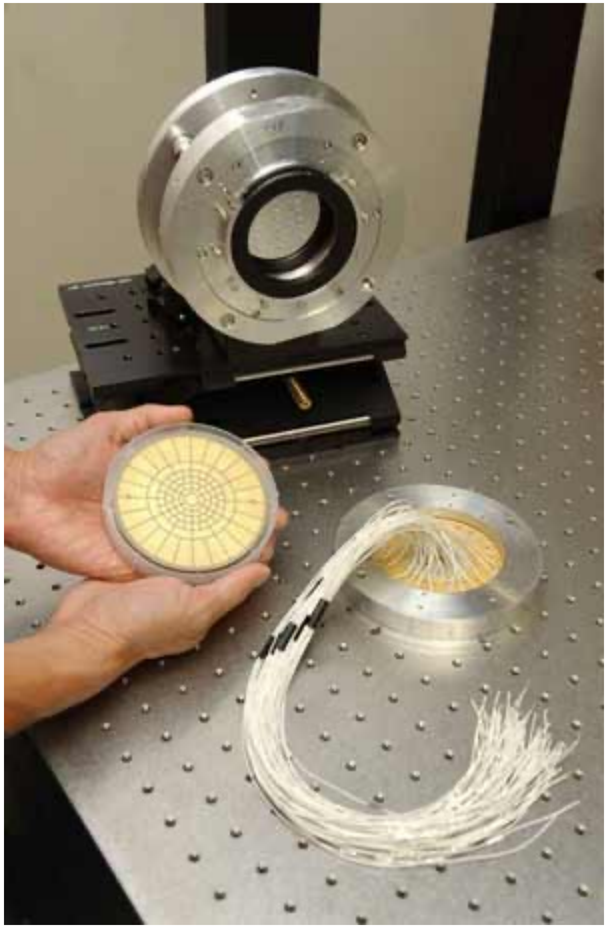
Wavefronts must measured many at 100 kHz rate!

Sensor chip on a printed-circuit board.



Photograph of a corner of the 1cmx1cm wavefront-sensor chip implemented in standard CMOS. The green elements are the position-sensitive detectors.

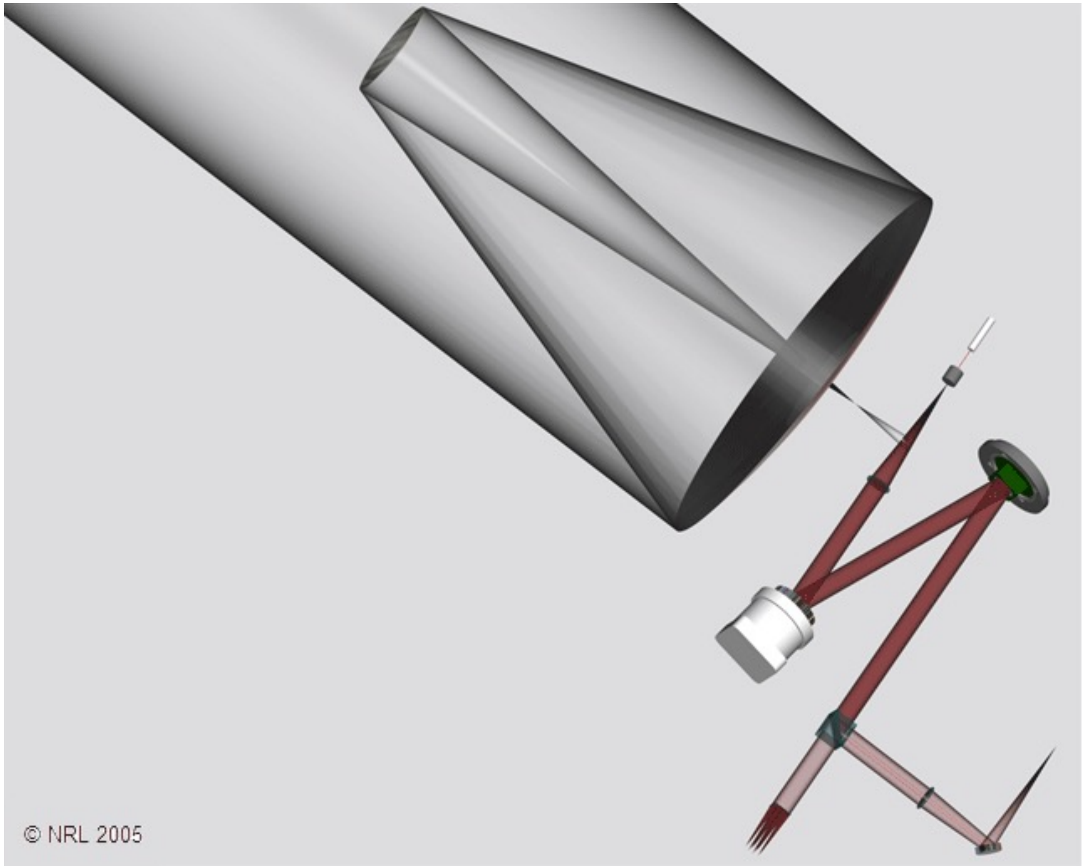
Deformable mirror



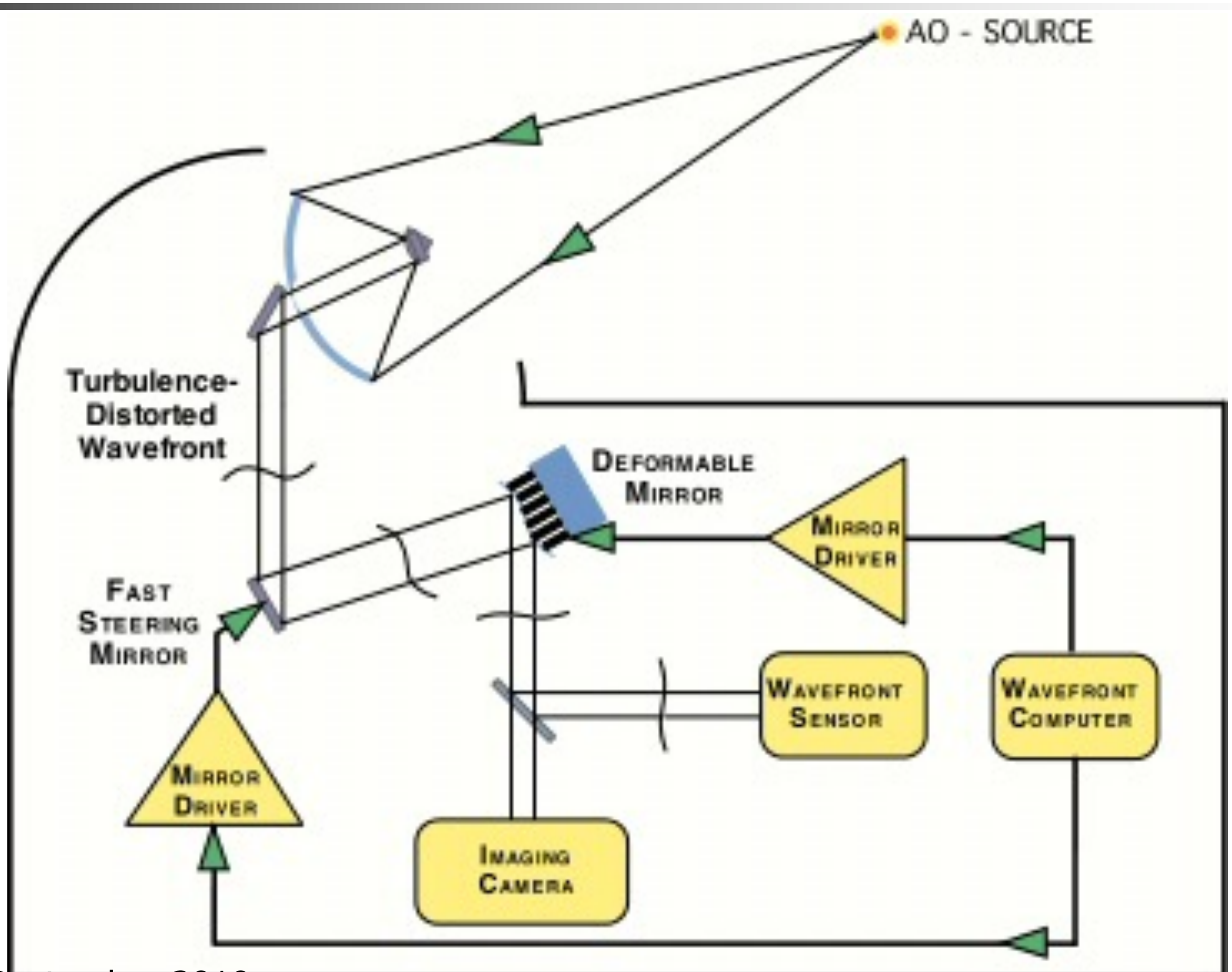
Various Zernike mode corrections performed with 37 actuator mirror

Calibrations

Looking for a zero-point of DM:

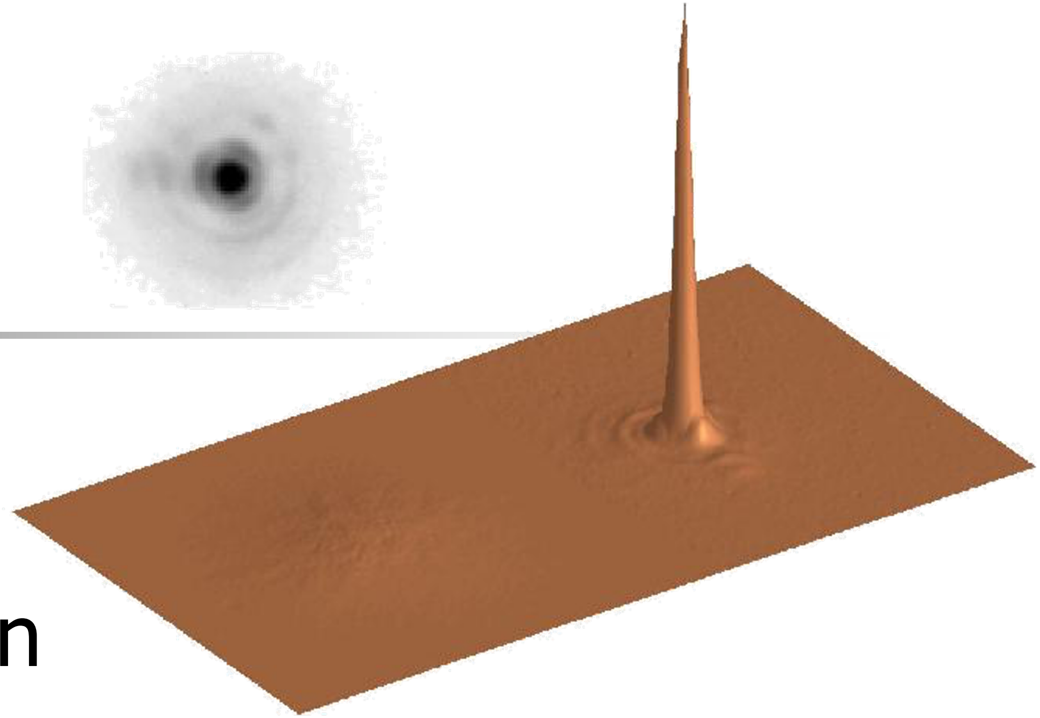


Closing the loop

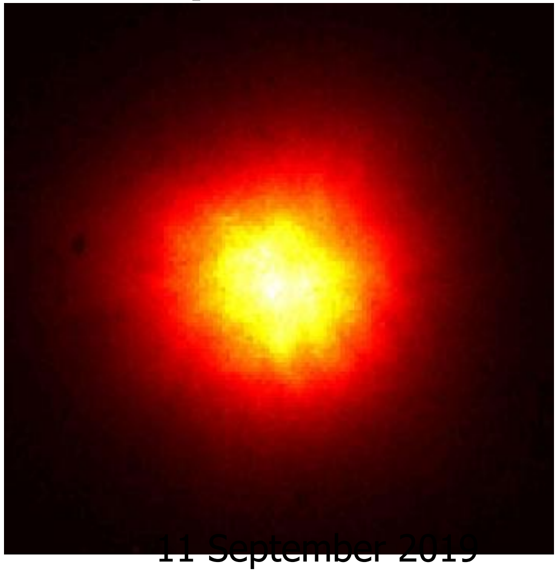


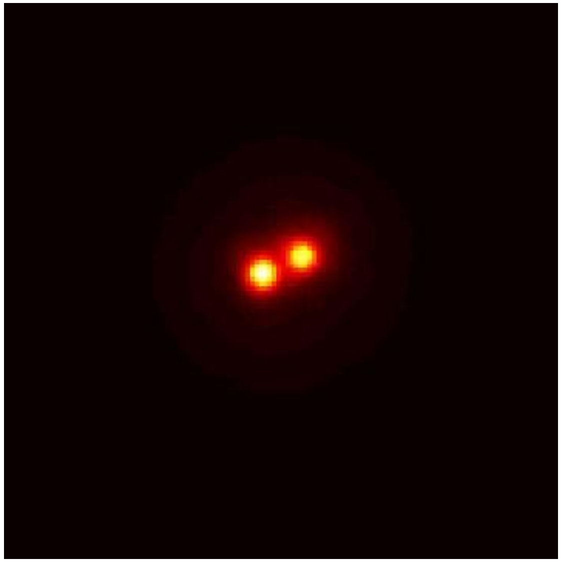
Laser Guide Star

Final result



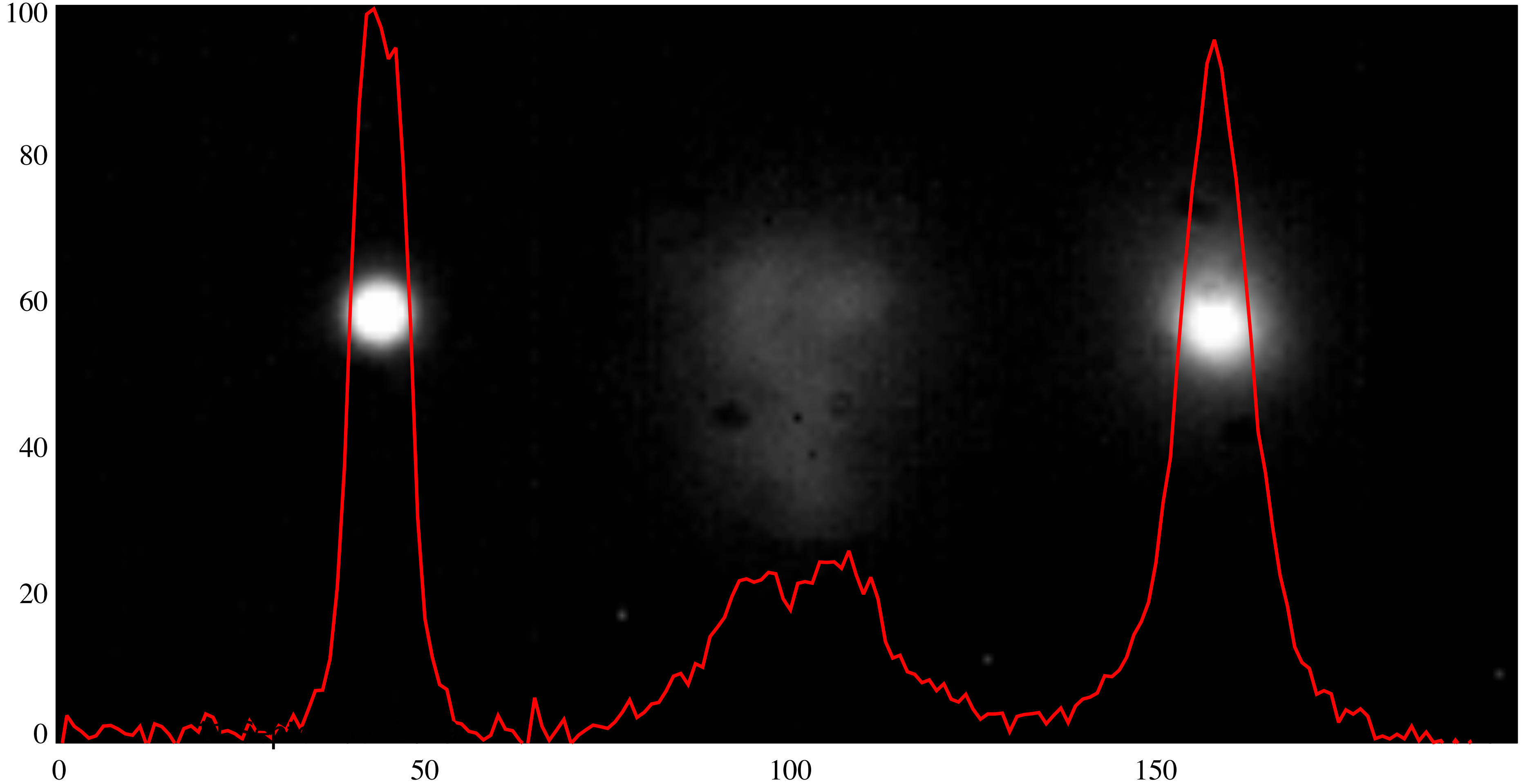
VLT NACO:
PSF and resolution improvements



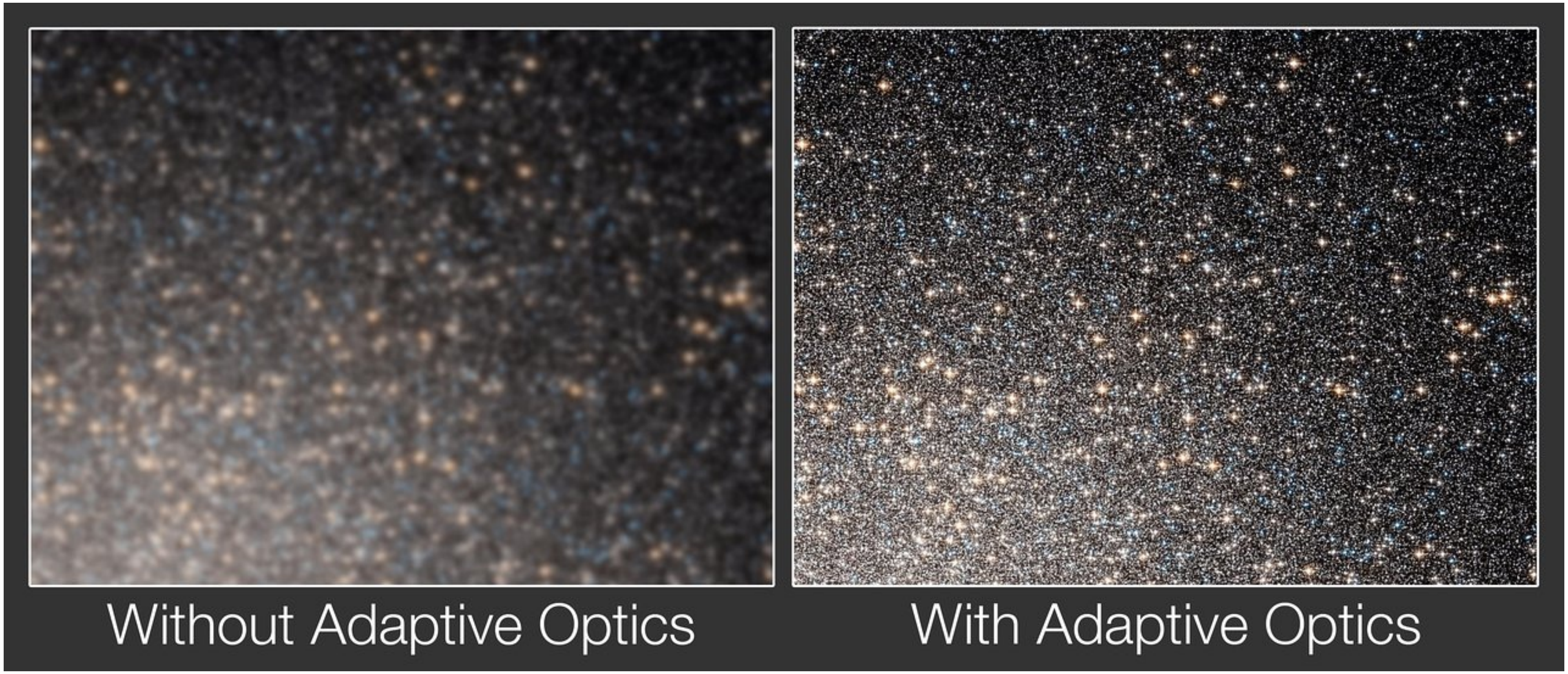


Another example

CRIRES+ AO system performance:

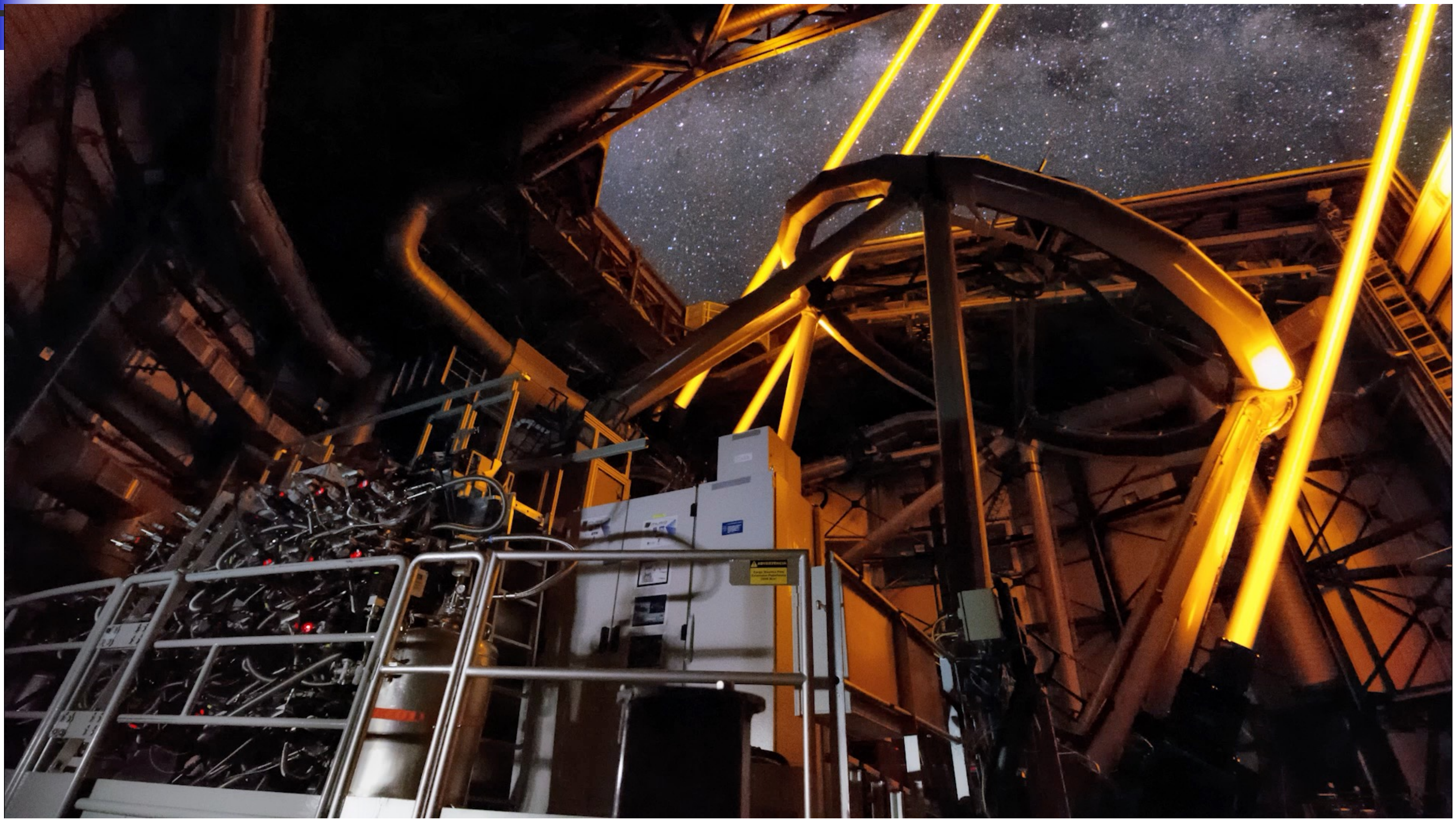


AO over wide field of view



ESO VLT MUSE instrument at the new AO facility

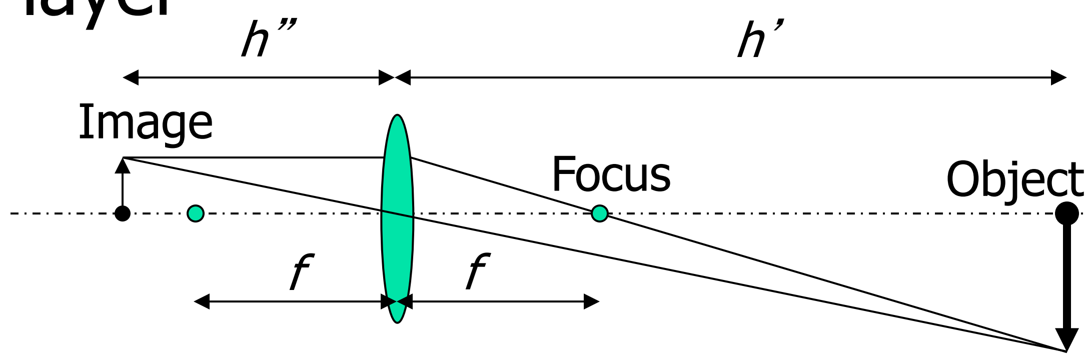
AO tomography



Multi-Conjugate Adaptive Optics

- Main problem of AO: assumption of a single thin turbulent layer
- Fundamental formula of a lens:

$$\frac{1}{f} = \frac{1}{h'} + \frac{1}{h''}$$

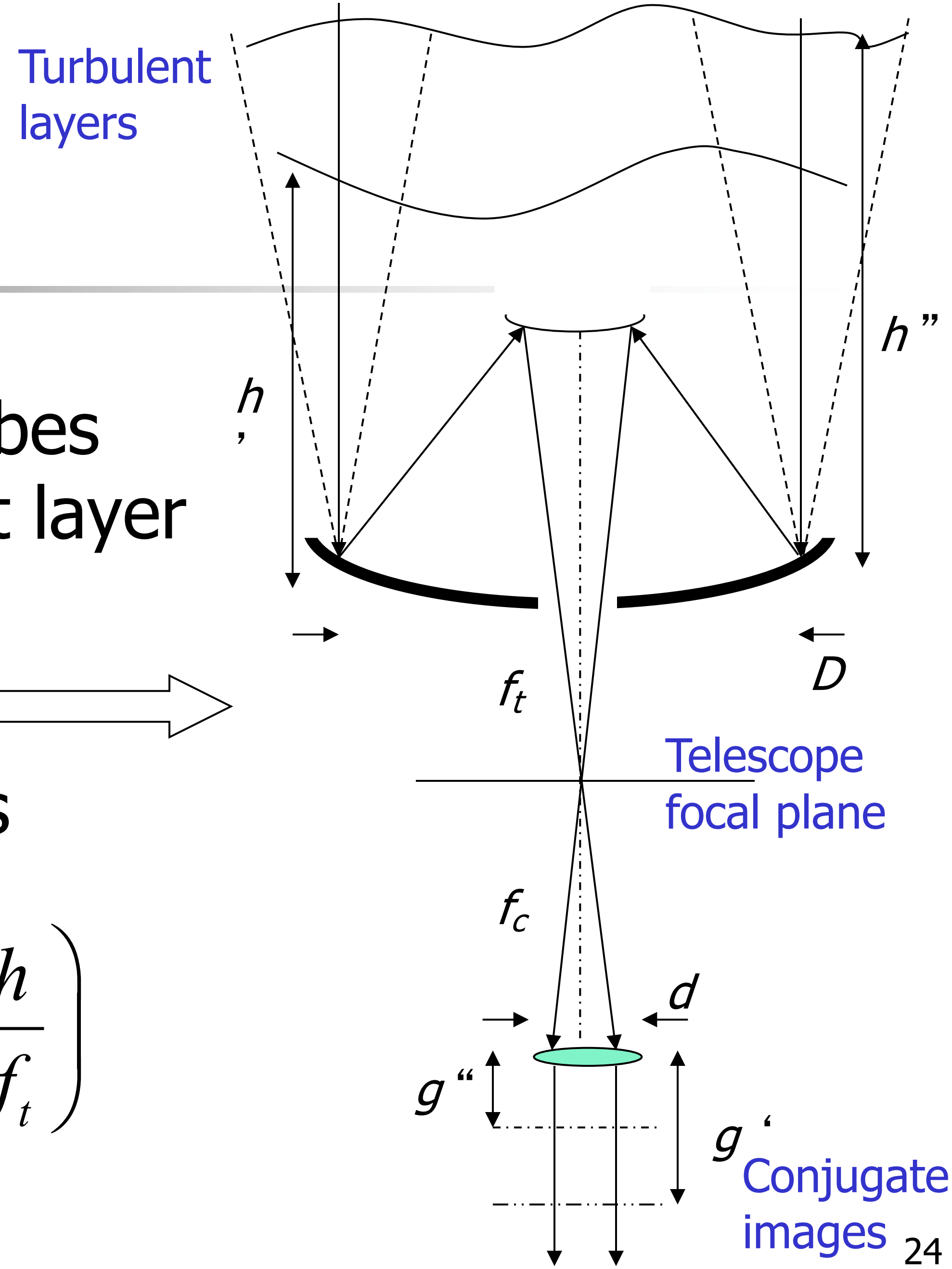


- Thus, we can create the image of one turbulent layer on one deformable mirror
- This allows to have multi-layer AO

MCAO

- Single guide star probes only part of turbulent layer
- Here is how it may look for two layers:
- Conjugate distance is given by:

$$\frac{g}{f_c} = \left(1 + \frac{d}{D}\right) - \left(\frac{d}{D}\right)\left(\frac{h}{f_t}\right)$$



Home work

- Look on the web for the most advanced multi-conjugate AO systems using laser-guide star. What telescopes and what instruments are using these systems and why?
- Derive the formula for conjugate distances remembering that: $f_c / f_t = d / D$