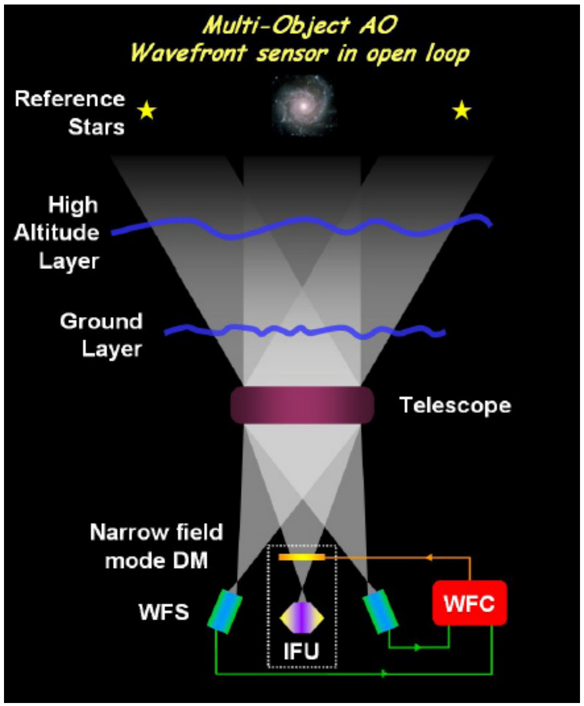
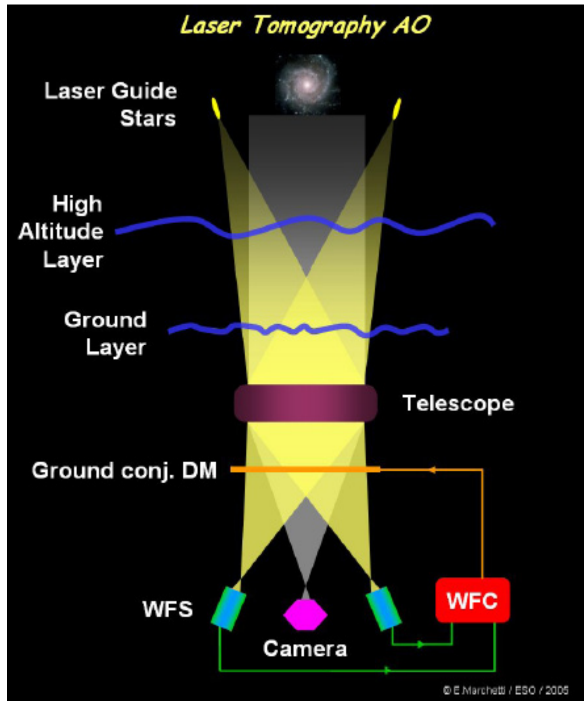
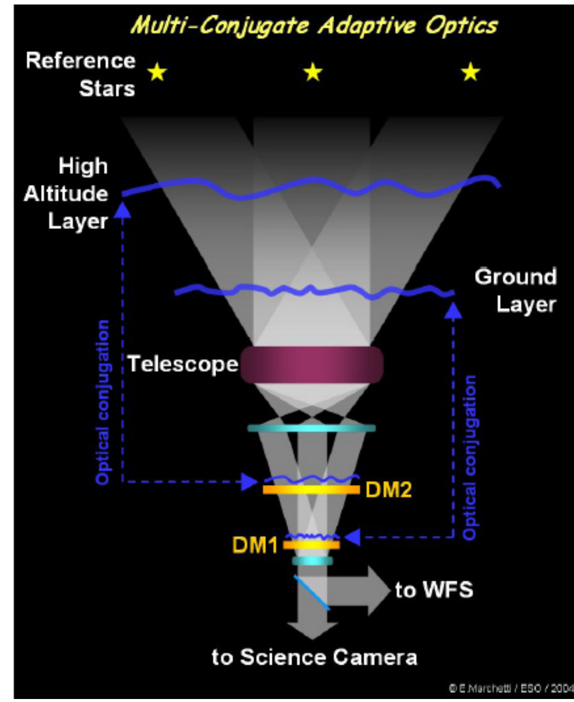
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

11th Lecture: 1 December 2010







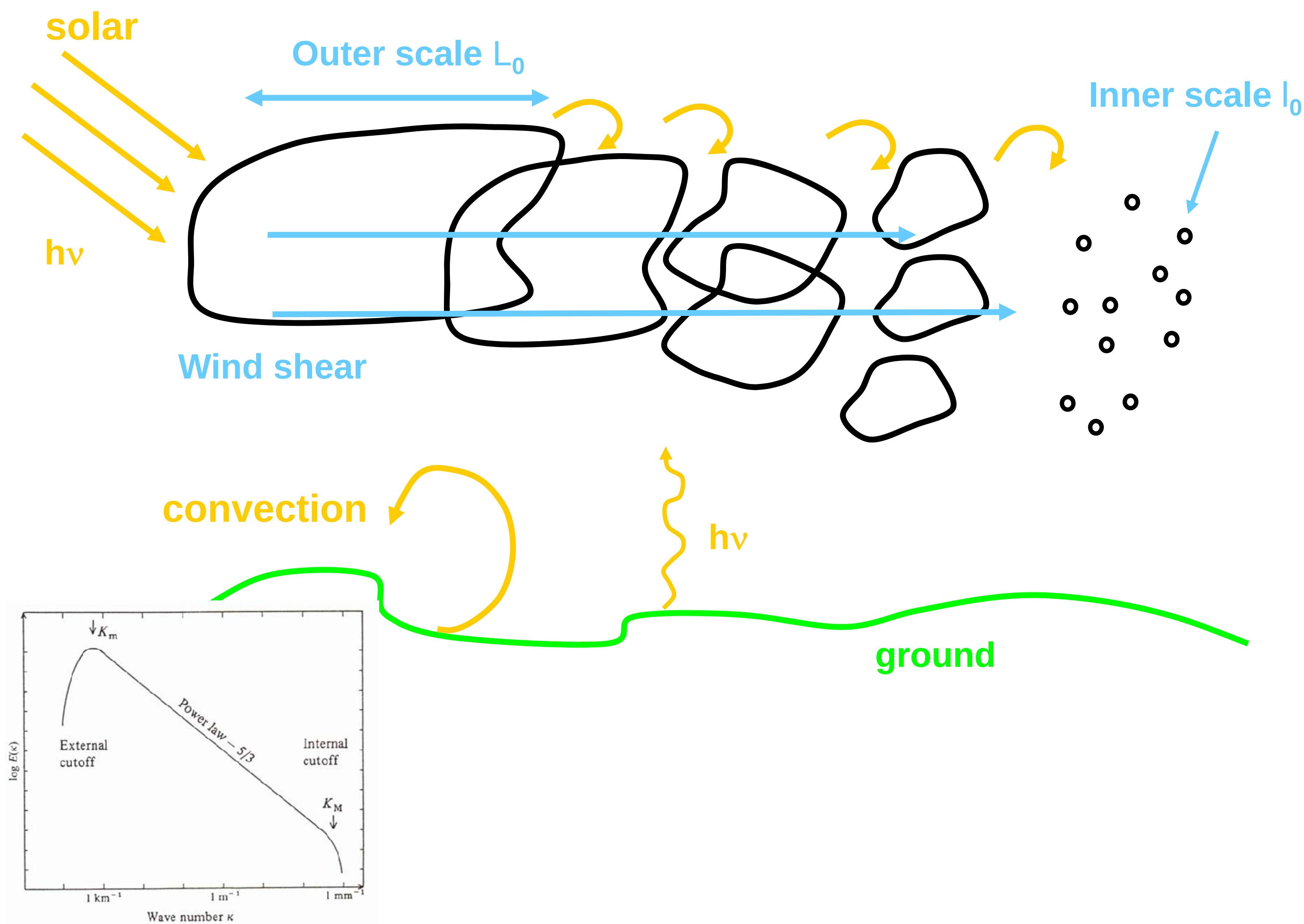
Based on:

"Adaptive Optics in Astronomy" (Cambridge UP) by F. Roddier (ed.),
Claire Max's lecture course on AO http://www.ucolick.org/~max/289C/
and ESO: http://www.eso.org/projects/aot/DSM/AO_modes.html

Content:

Reminder: Atmospheric Turbulence

Kolmogorov Turbulence



r_0, seeing, τ_0, θ_0

The Fried parameter $r_0(\lambda) = 0.185\lambda^{6/5}\left[\int_0^\infty C_n^2(z)dz\right]^{-3/5}$ is the radius of the spatial coherence area.
It is the average turbulent scale over which the RMS optical phase distortion is 1 radian. *Note that r_0 increases as $\lambda^{6/5}$*.

$\Delta\theta = \frac{\lambda}{r_0} \sim \lambda^{-1/5}$ is called the seeing. At good sites r_0 (0.5μm) ~10 - 30 cm.

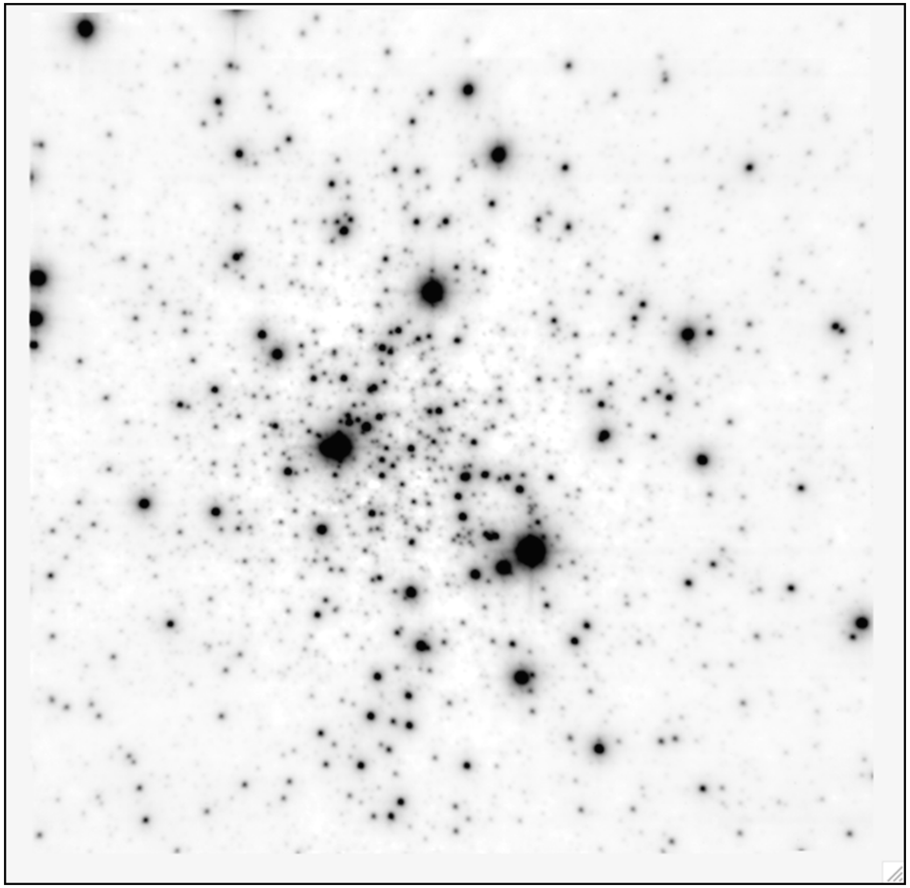
The atmospheric coherence (or Greenwood delay) time is: $\tau_0 = 0.314\frac{r_0}{\bar{v}}$
It is the maximum time delay for the RMS wavefront error to be less than 1 rad (where v is the mean propagation velocity).

The isoplanatic angle $\theta_0 = 0.314\cos\zeta\frac{r_0}{\bar{h}}$ is the angle over which the RMS wavefront error is smaller than 1 rad.

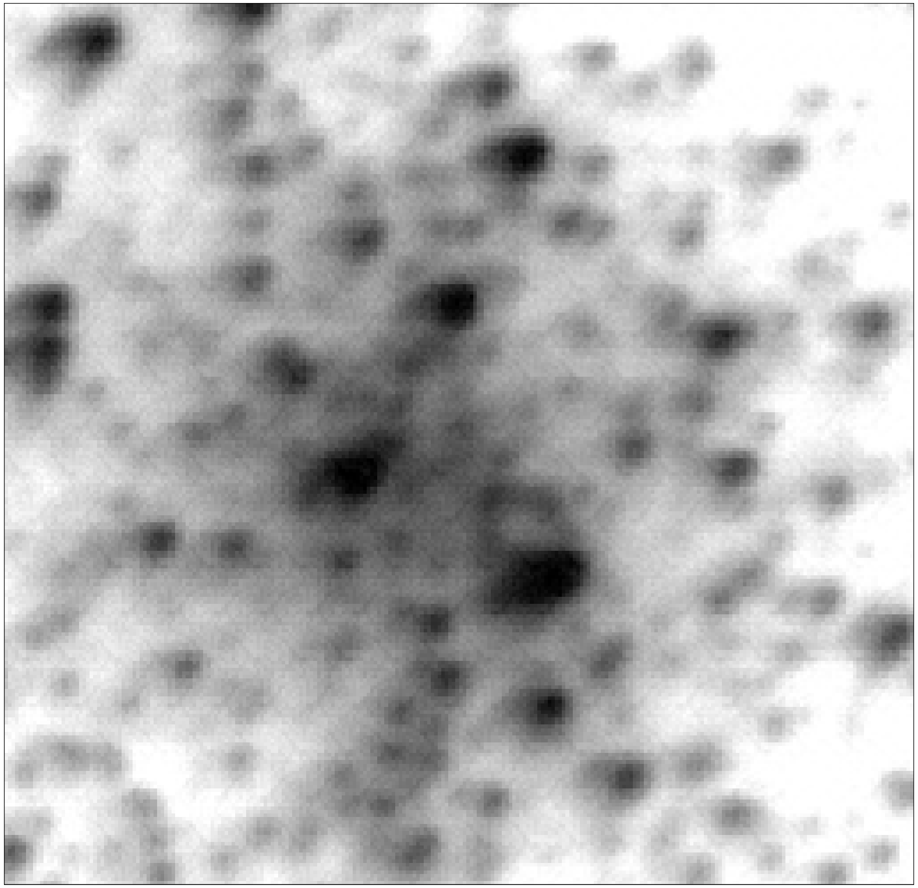
Why Adaptive Optics?

Improvement in Resolution and Sensitivity

1. Angular resolution: $\theta = \frac{\lambda}{r_0} \rightarrow \theta = \frac{\lambda}{D} \quad \Rightarrow \text{gain} = \frac{D}{r_0}$
2. Point source sensitivity: $S/N \sim \mathrm{D}^2 \quad \Rightarrow \text{gain in } t_{\mathrm{int}} \sim \frac{1}{D^4}$



PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM

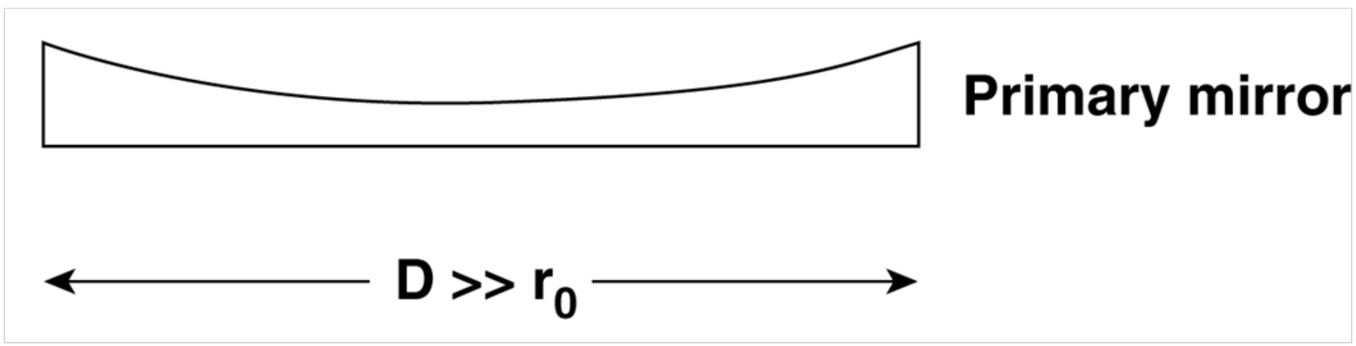


WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

Basic AO Principle

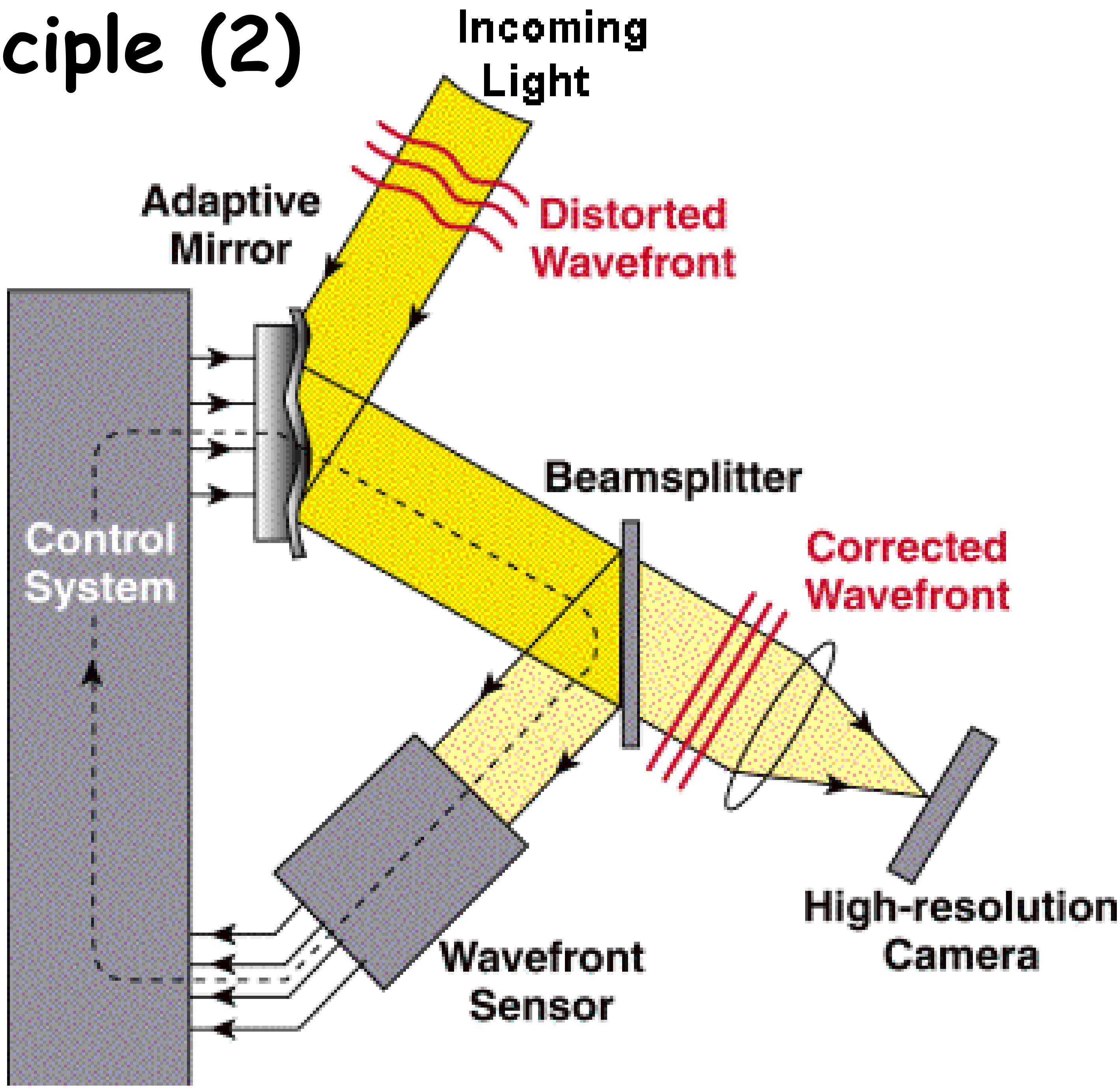
AO Principle

1. Maximum scale of tolerated wavefront deformation is r_0 → subdivide the telescope aperture into r_0's
2. Measure the wavefront deformations.
3. Correct the wavefront deformations by "bending back" the patches of size r_0.



The number of subapertures is $(D/r_0)^2$ at the observing wavelength → can easily require hundreds to thousands of actuators for very large telescopes.

AO Principle (2)

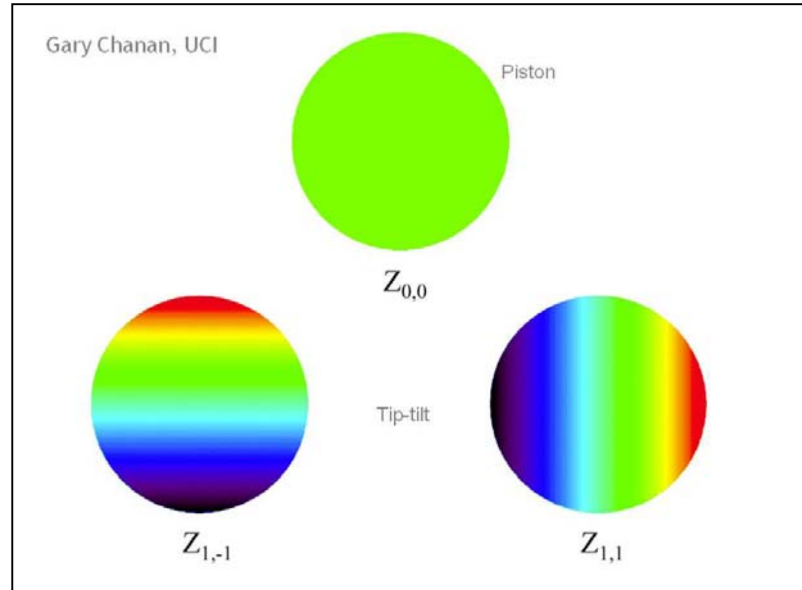


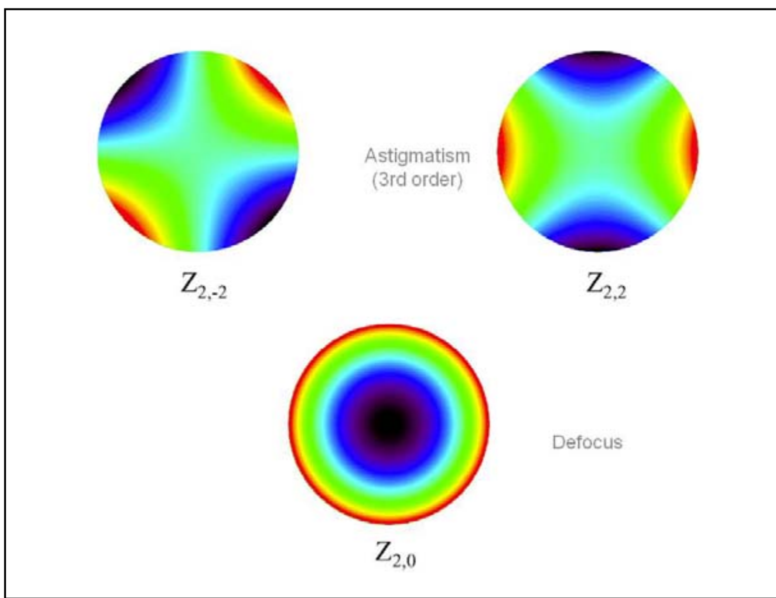
Wavefront Description: Zernike Polynomials

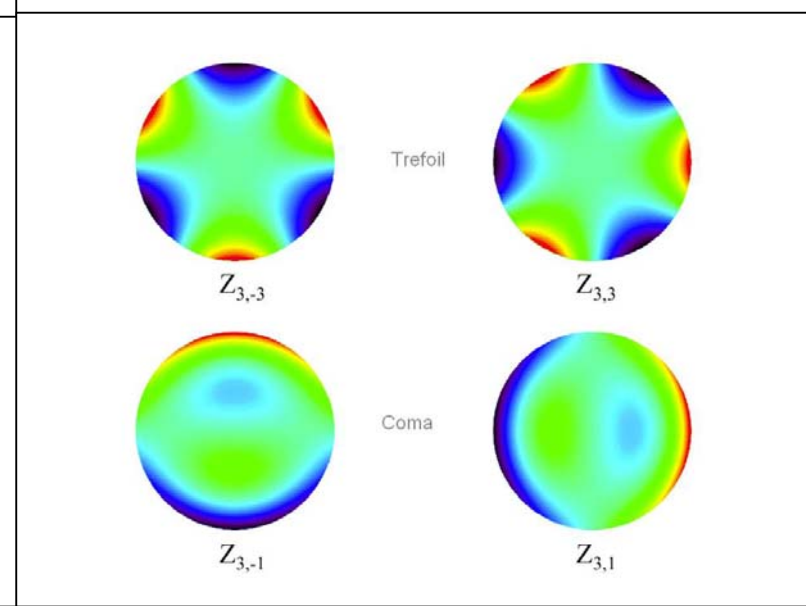
Expansion into a series of orthogonal terms:

$$\varphi(r,\theta) = \Sigma\, a_{m,n} Z_{m,n}(r,\theta)$$

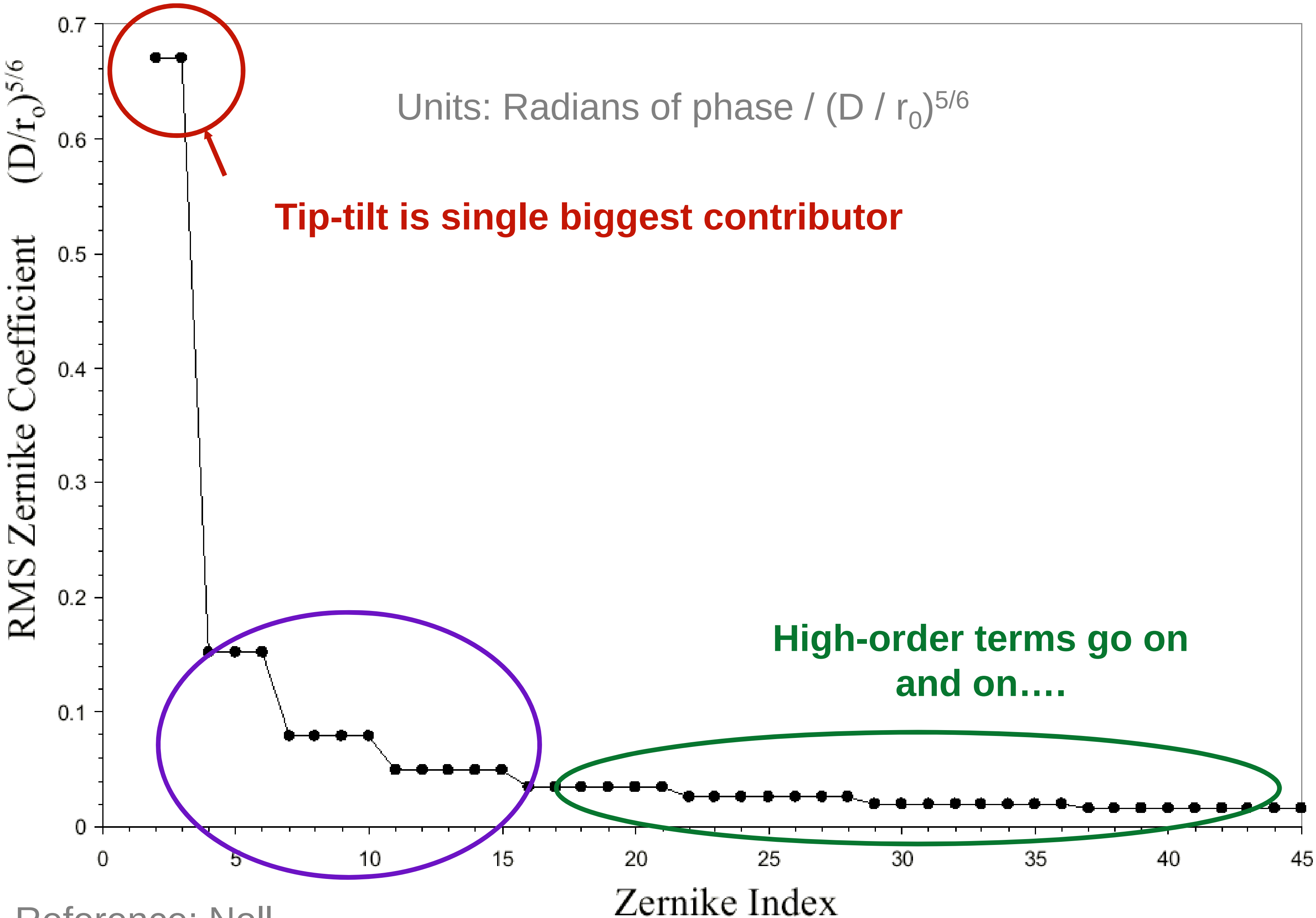
$Z_{0,0} = 1$		piston
$Z_{1,-1} = 2\, r \sin\theta$	}	tip/tilt
$Z_{1,1} = 2\, r \cos\theta$		
$Z_{2,-2} = \sqrt{6}\, r^2 \sin 2\theta$		astigmatism
$Z_{2,0} = \sqrt{3}\,(2r^2 - 1)$		focus
$Z_{2,2} = \sqrt{6}\, r^2 \cos 2\theta$		astigmatism







Tip-Tilt and higher order Terms (1)

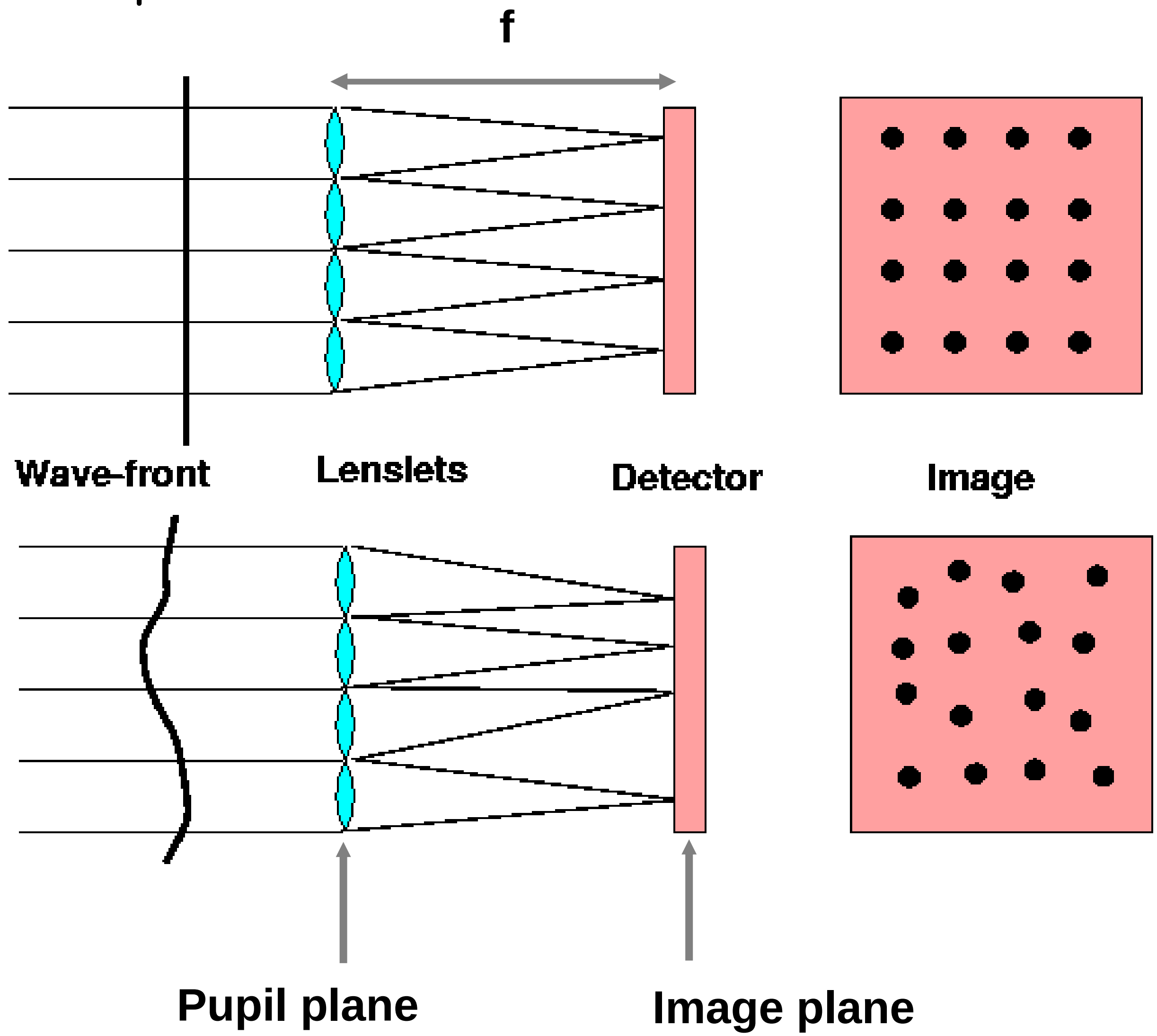


Reference: Noll

AO – Key Components

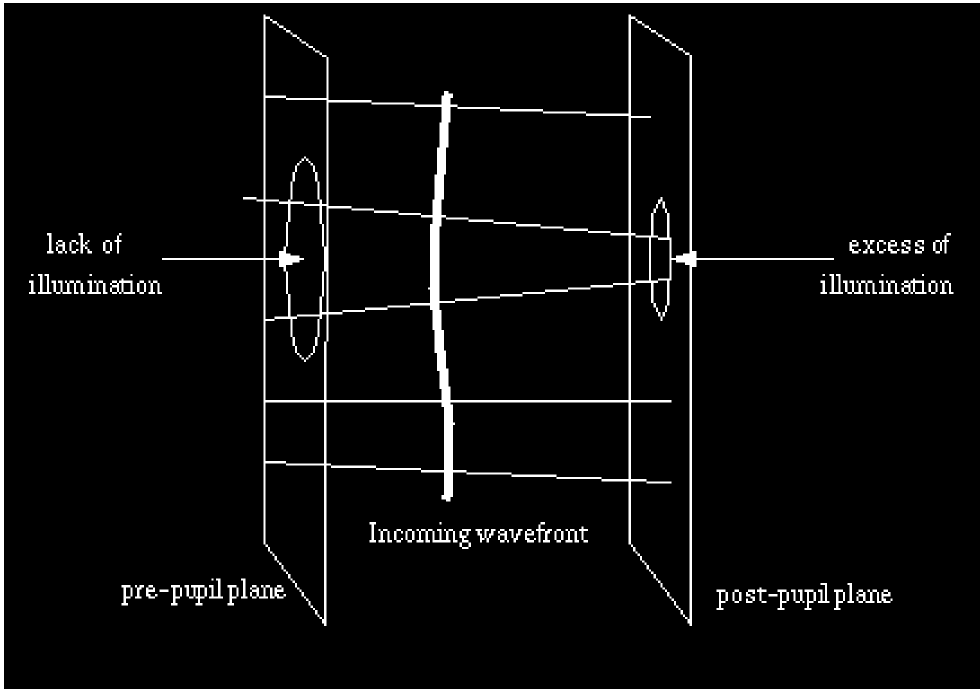
Wavefront Sensors – Shack Hartmann

Most common principle is the Shack Hartmann wavefront sensor measuring sub-aperture tilts:



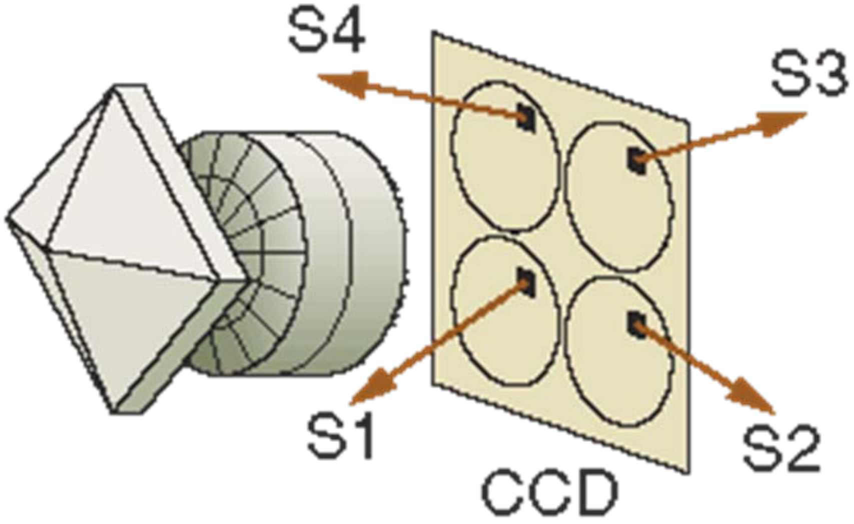
WFs: Curvature and Pyramid Sensors

Other common principles are the



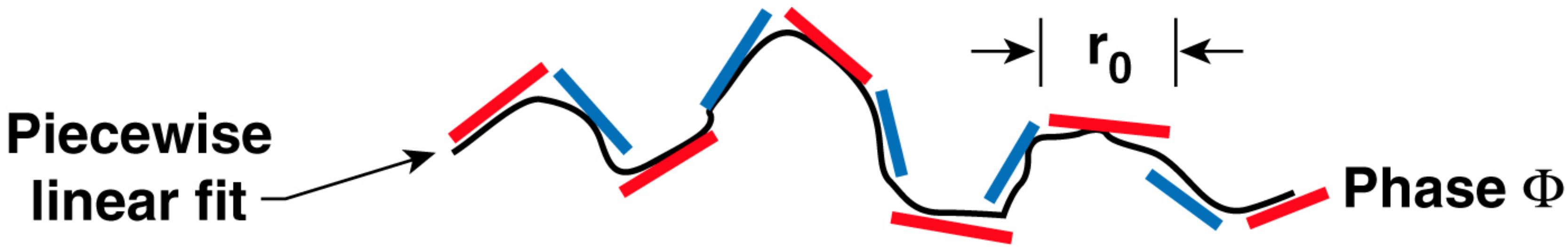
curvature sensor →

and the pyramid sensor →

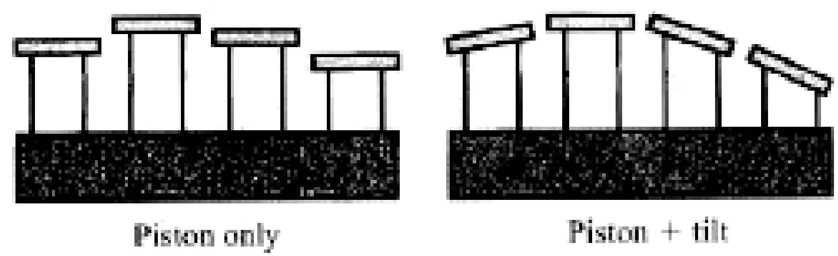


Deformable Mirrors

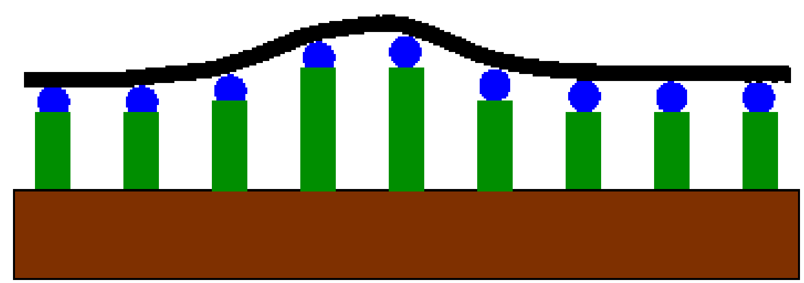
Basic principle: piece-wise linear fit of the mirror surface to the wavefront. r_0 sets the number of degrees of freedom.



Two general types: segmented mirrors



and continuous face-sheet mirrors:



Note that the (piezo) actuator stroke is typically only a couple of micrometers → requires separate tip-tilt mirror.

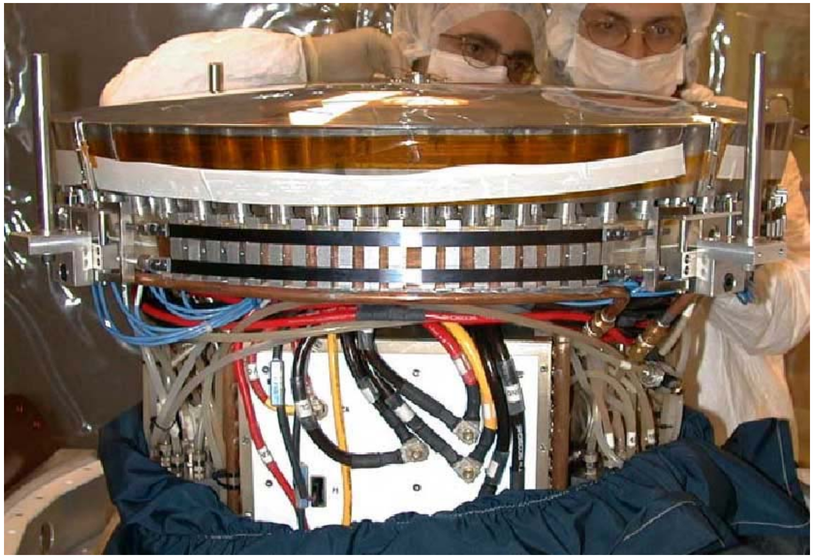
Adaptive Secondary Mirrors

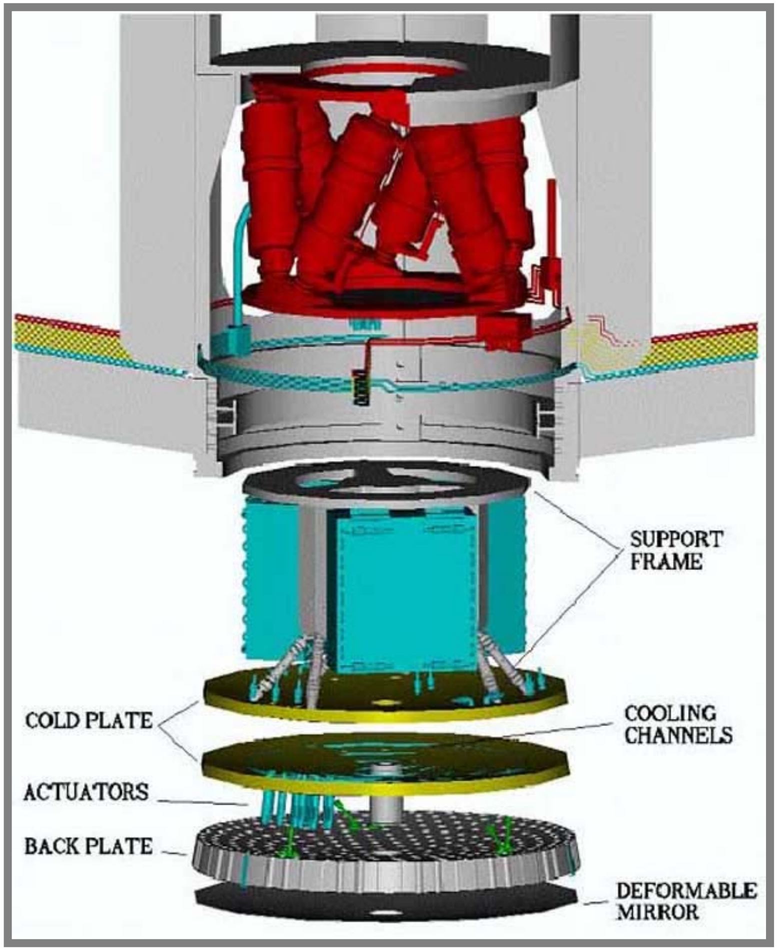
Concept: integrate DM into the telescope → adaptive secondary mirrors.

Advantages:

- no additional optical system needed → lower emission, higher throughput
- large surface → higher actuator density
- larger stroke → no tip-tilt mirror needed

...but also more difficult to build, control, and handle.





DM for MMT Upgrade

AO Correction Error Terms

Typical AO Error Terms

- **Fitting errors** from insufficient approximation of the wavefront (finite actuator spacing, influence function of actuators, etc.).

$$\sigma_{fit}^2 \approx 0.3\left(\frac{D}{r_0}\right)^{5/3}$$

- **Temporal errors** from the time delay between measurement and correction (computing, exposure time).

$$\sigma_{temp}^2 \approx \left(\frac{t}{\tau_0}\right)^{5/3}$$

- **Measurement errors** from the WFS (S/N!)

$$\sigma_{measure}^2 \sim S / N$$

- **Calibration errors** from aberrations in the non-common path between sensing channel and imaging channel.

$$\sigma_{calibration}^2 \sim ???$$

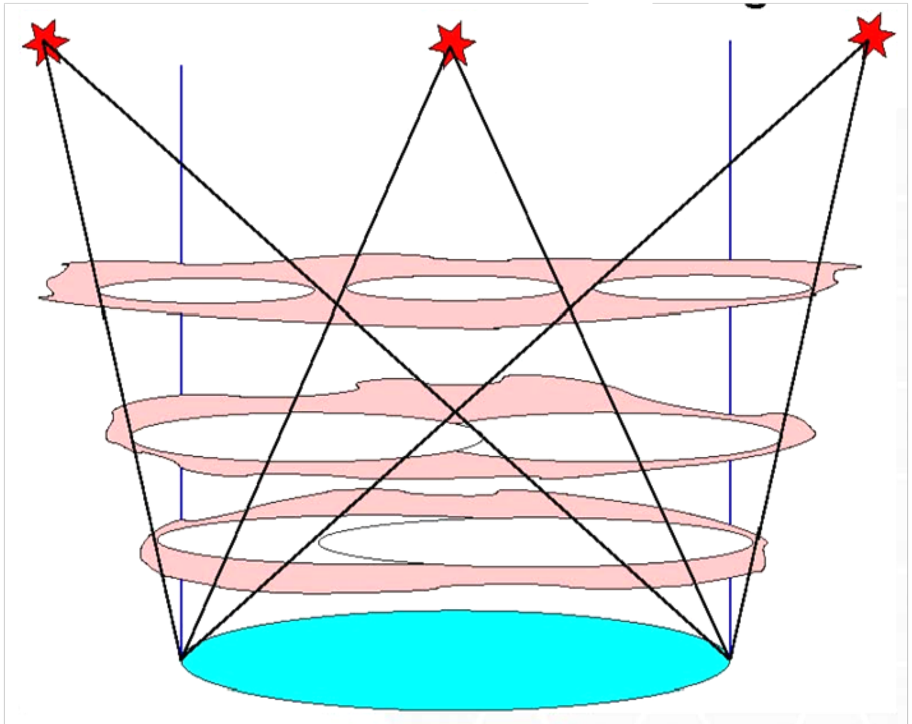
- **Angular anisoplanatism** from sampling different lines of sight through the atmosphere.

$$\sigma_{aniso}^2 \approx \left(\frac{\theta}{\theta_0}\right)^{5/3}$$

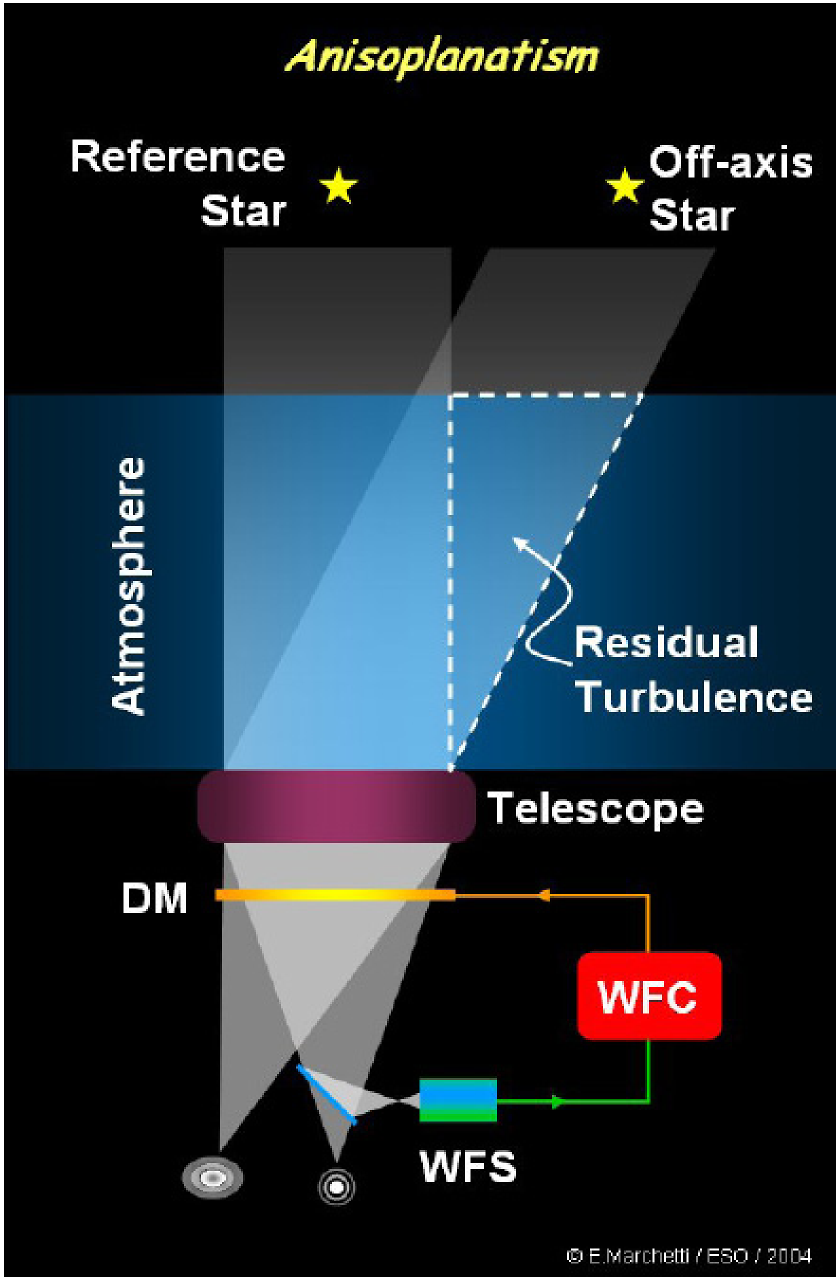
Angular Anisoplanatism

Angular anisoplanatism is a severe limitation to:

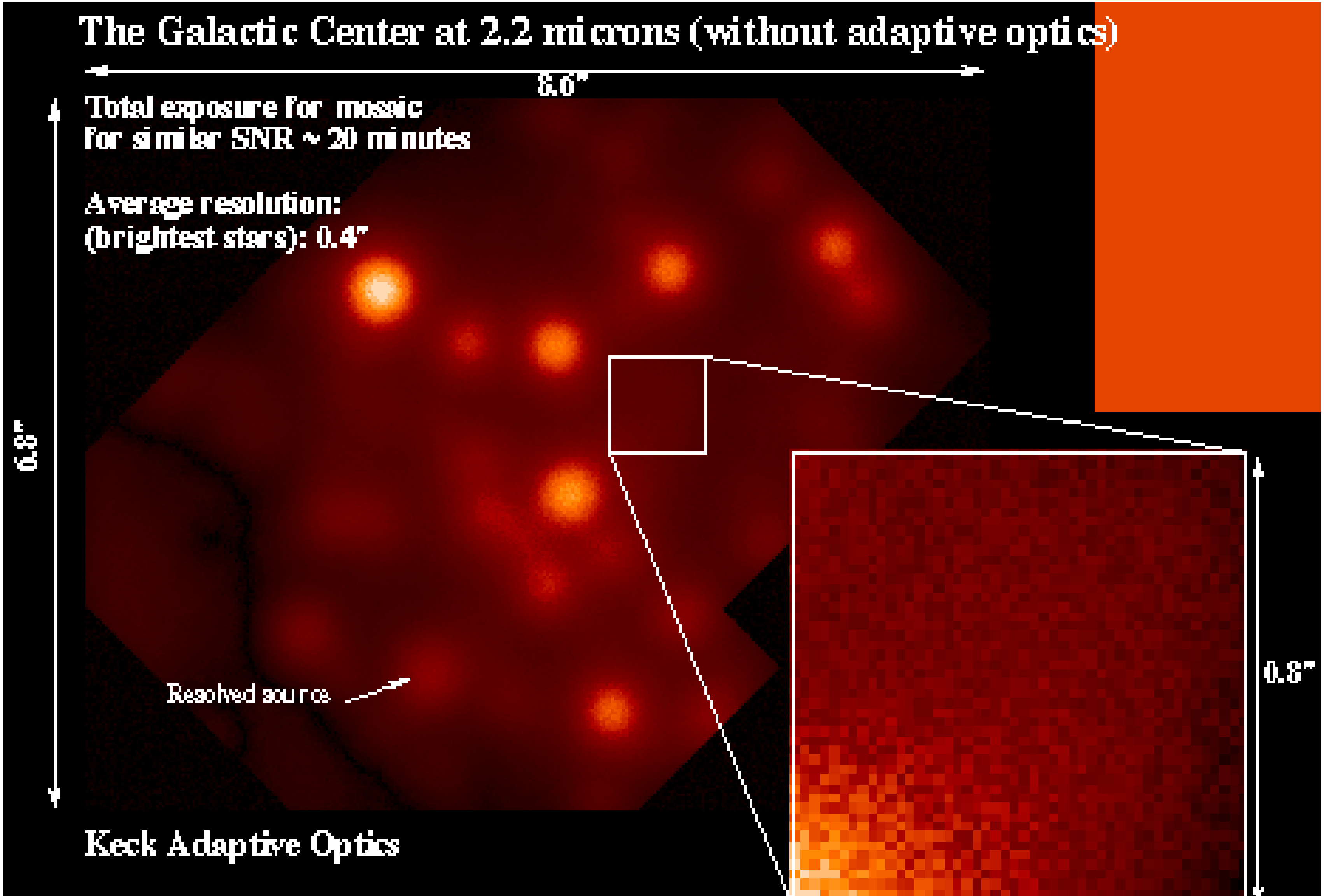
- wide-field imaging
- sky coverage (finding a guide star within the isoplanatic angle)



Multi-LGS allows to fight cone effect AND increase FOV



"Typical" Correction and Residuals

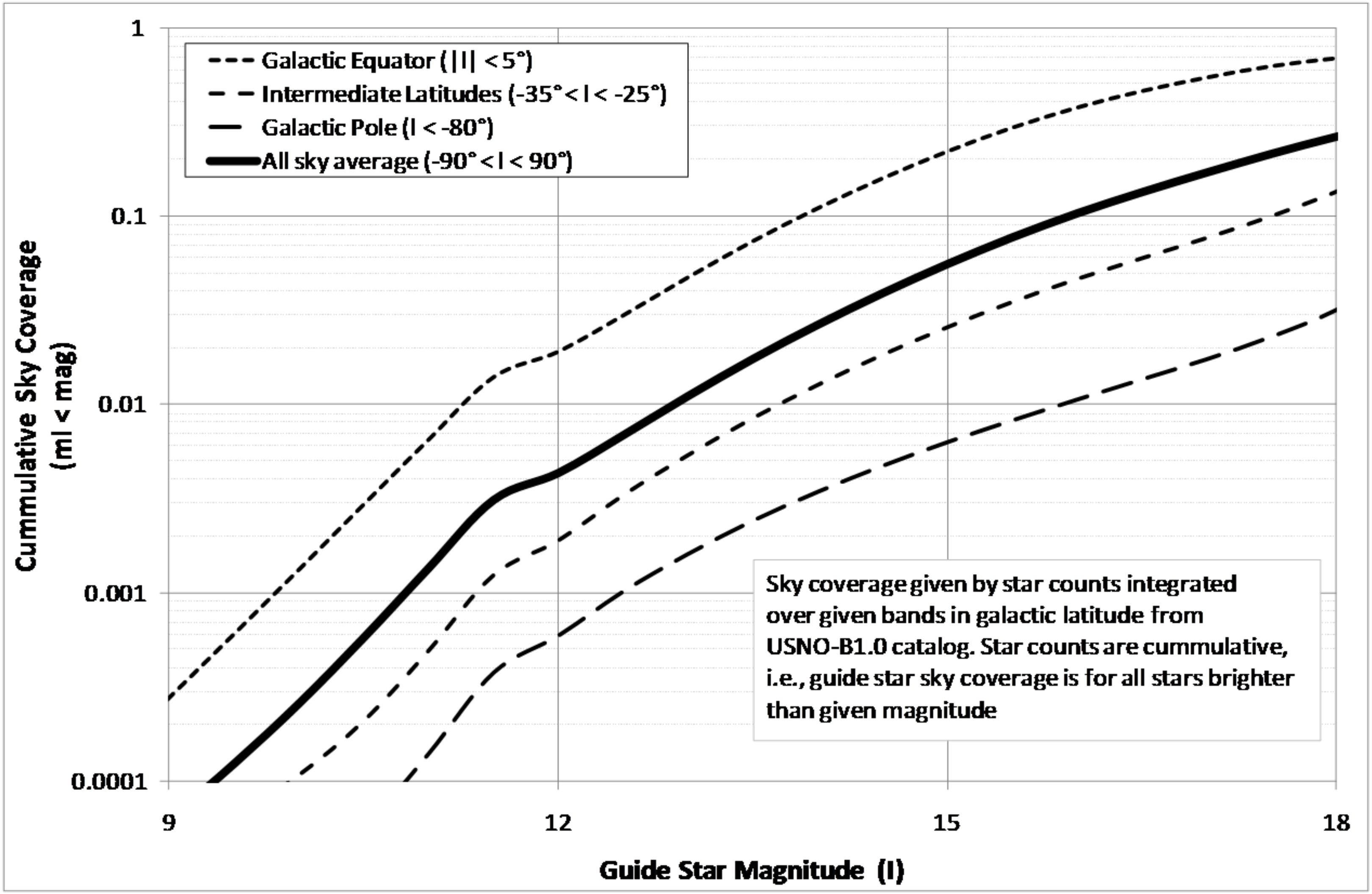


http://cfao.ucolick.org/pgallery/gc.php

Laser Guide Stars

Sky Coverage

To sense the wavefront one needs a bright reference/guide star within the isoplanatic angle.



Cumulative sky coverage, i.e., the chance of finding stars brighter than given magnitude, for a random target as a function of I-band magnitude using the USNO-B1.0 catalogue.

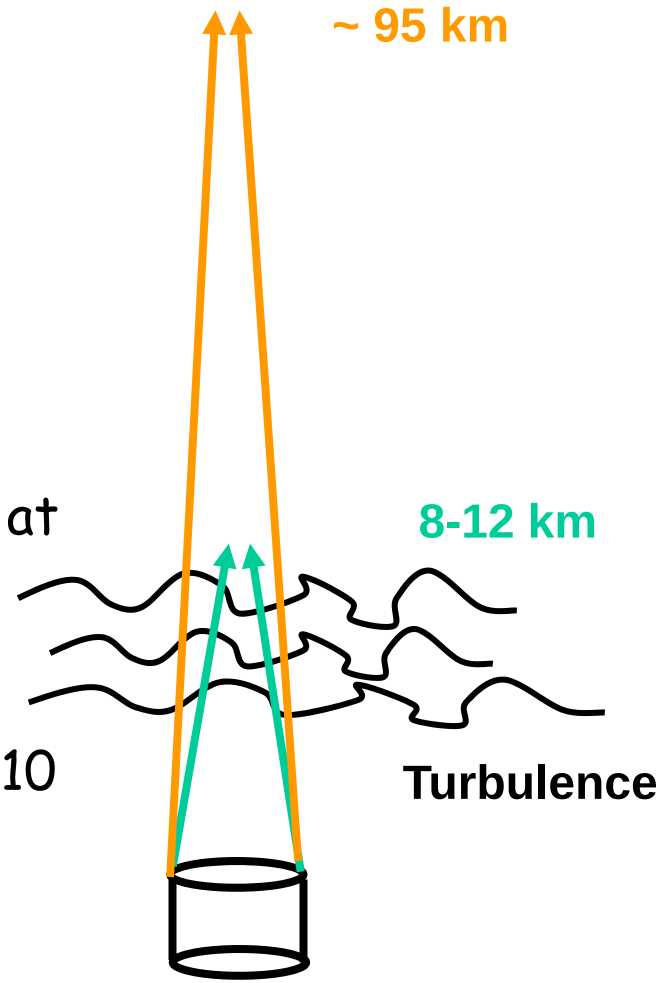
Laser Guide Stars

Solution to the sky coverage problem:
create your own guide star.

Two principle concepts:

- Sodium LGS – excite atoms in "sodium layer" at altitude of ~ 95 km.

- Rayleigh beacon LGS – scattering from air molecules sends light back into telescope, h ~ 10 km

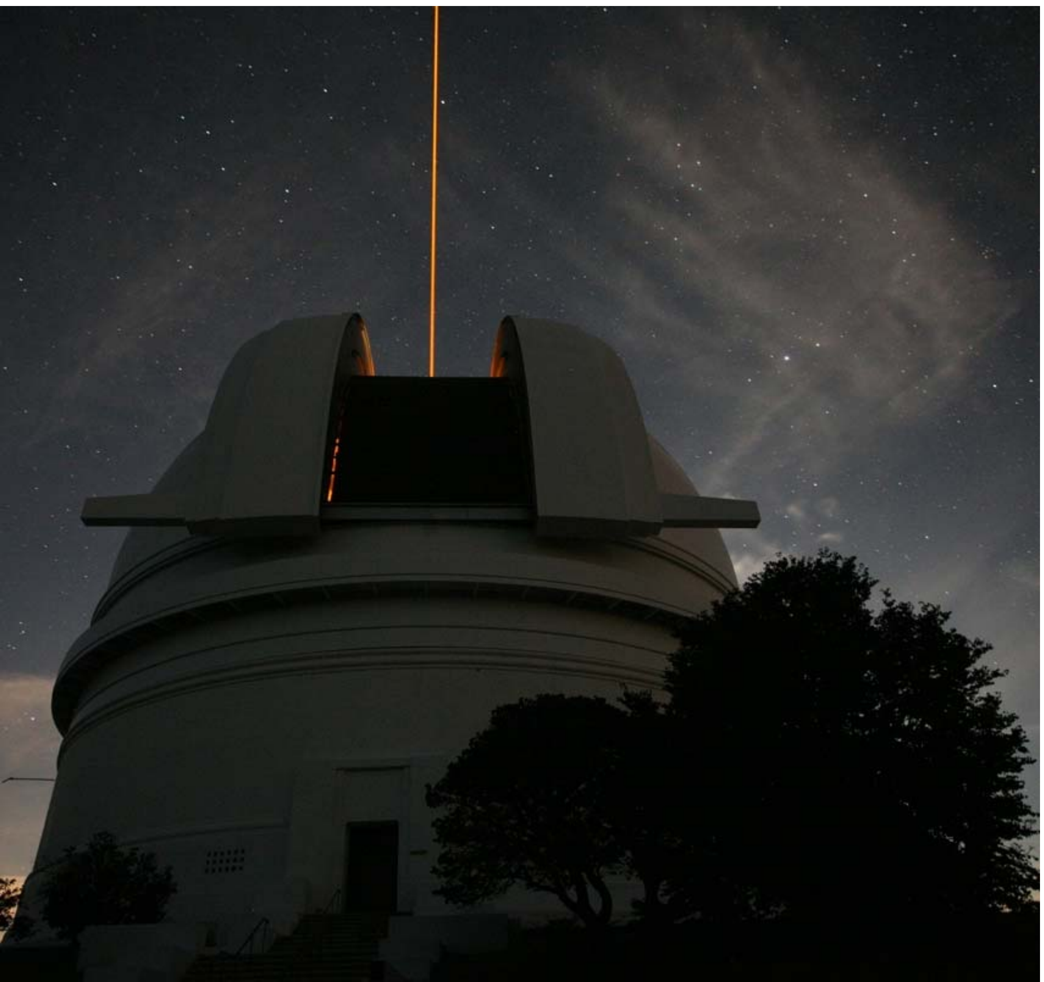


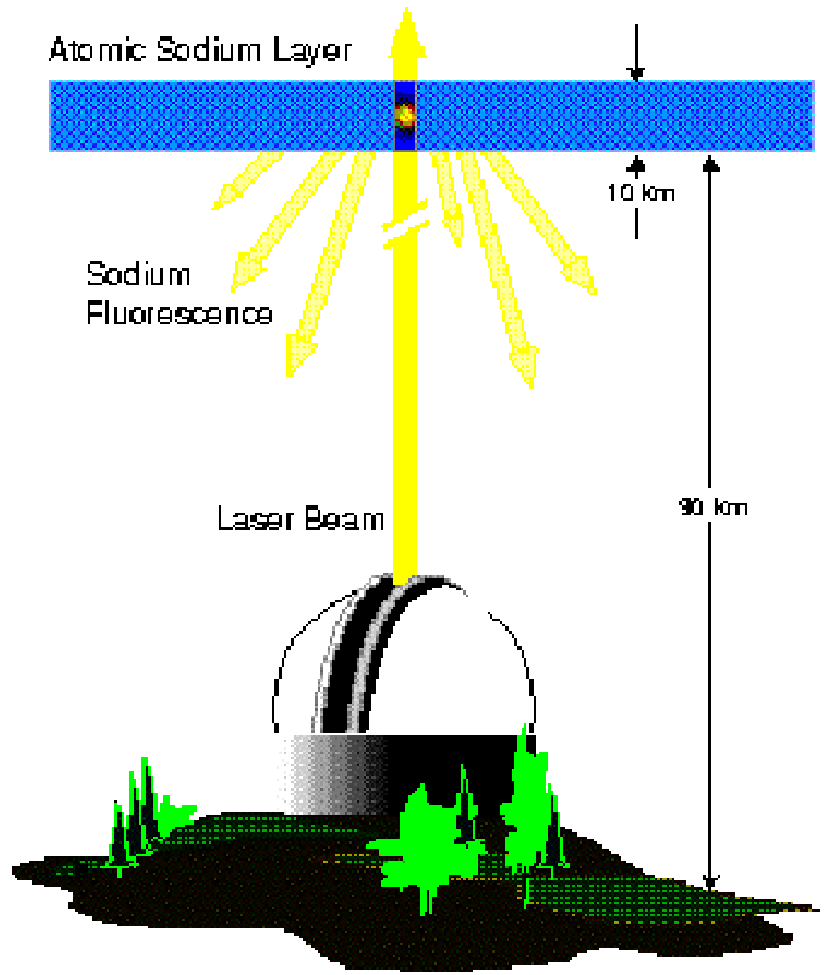
Since the beam travels twice (up and down) through the atmosphere, tip-tilt cannot be corrected → LGS-AO still needs a natural guide star, but this one can be much fainter (~18mag) as it is only needed for tip-tilt sensing.

Sodium Beacons

Layer of neutral sodium atoms in mesosphere (height ~ 95 km, thickness ~10km) thought to be deposited as smallest meteorites burn up.

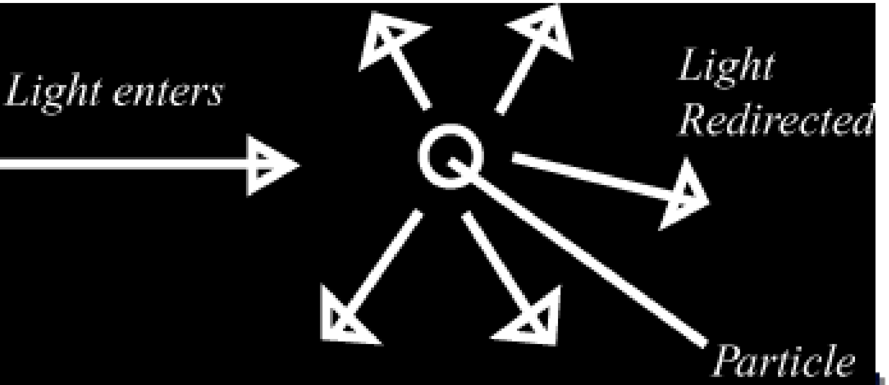
Resonant scattering occurs when incident laser is tuned to D2 line of Na at 589 nm.

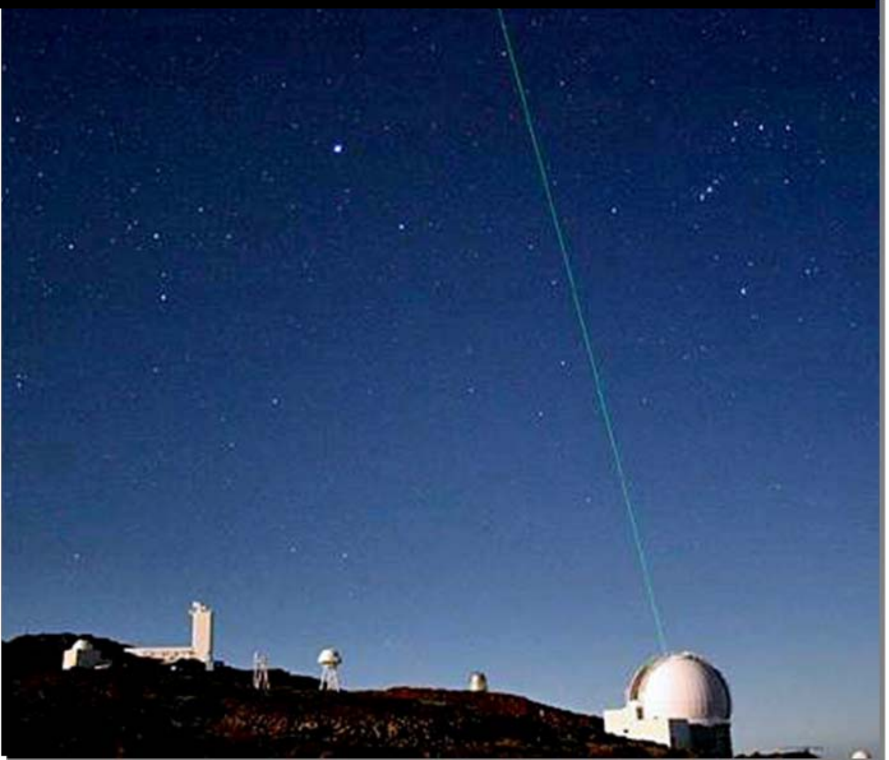




Rayleigh Beacons

Due to interactions of the electromagnetic wave from the laser beam with molecules in the atmosphere.





Advantages:

- cheaper and easier to build
- higher power
- independent of Na layer

Disadvantages:

- larger focus anisoplanatism
- laser pulses → timing

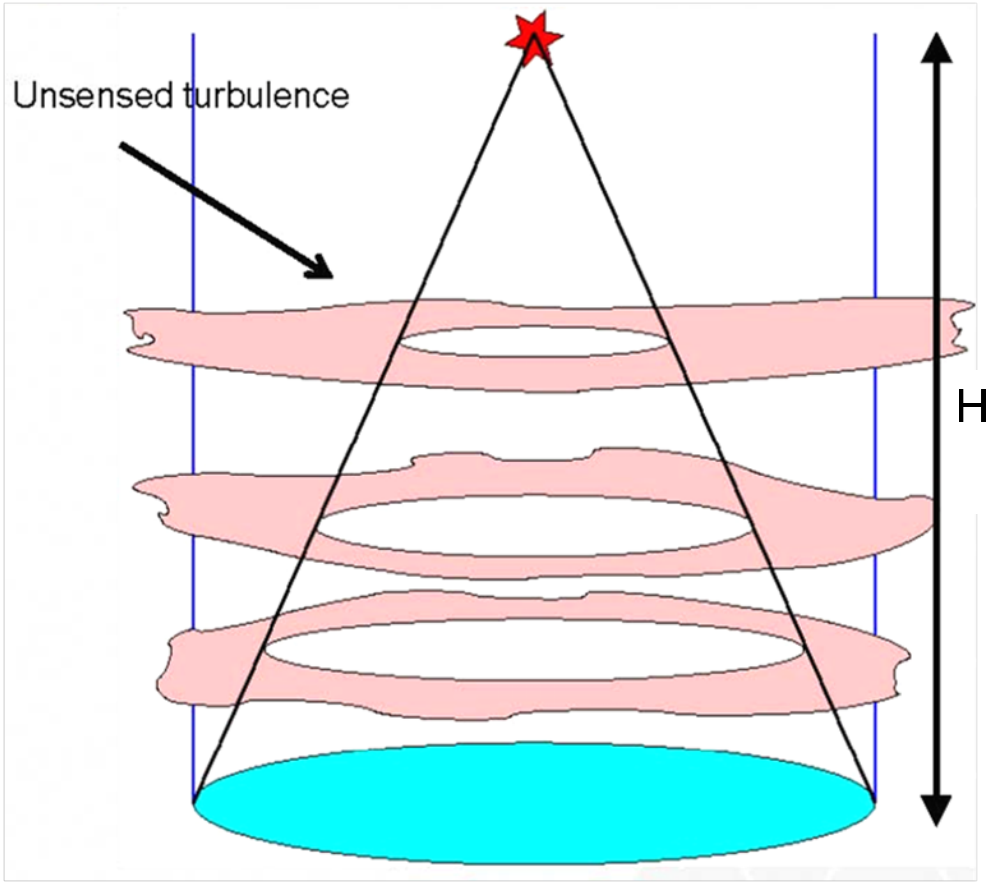
Focus Anisoplanatism

The LGS is at finite distance H above the telescope and does not sample all turbulence and not the same column of turbulent atmosphere ("cone effect"):

The contribution to the wavefront error contribution from focus anisoplanatism is: $\sigma_{FA}^2 = \left(\frac{D}{d_0}\right)^{5/3}$

where $d_0 \sim \lambda^{6/5}$ depends only on wavelength and turbulence profile at the telescope site.

→ very large telescopes need multiple LGSs due to this cone effect.



More Types of AO

Ground Layer AO – GLAO

- Useful if ground layer (= ground + dome + mirror seeing) is the dominant component

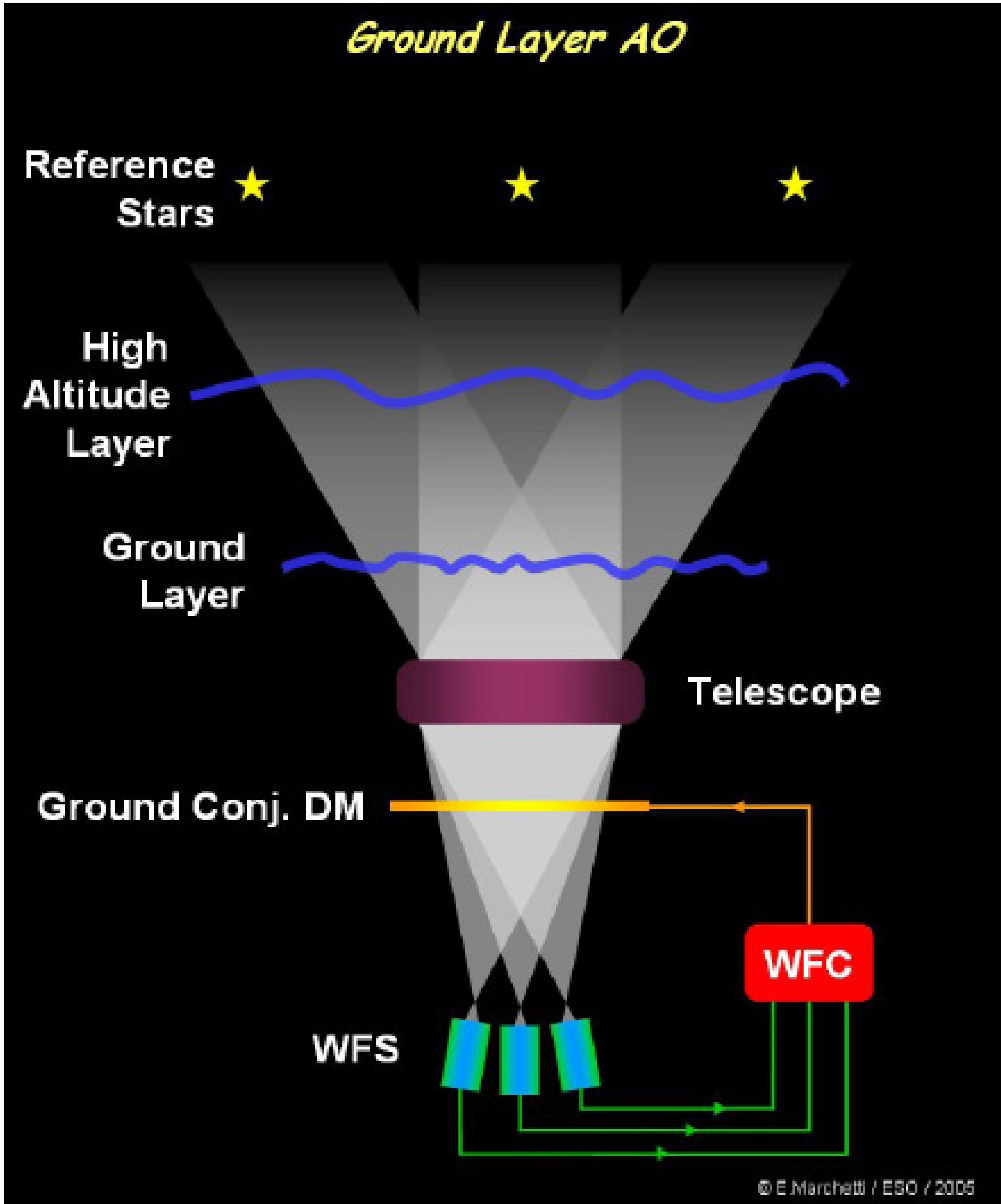
- Uses several WFS and guide stars within a large FOV (several arcmin).

- WFS signals are averaged → control one DM

- Reduction of FWHM ~ factor of two (only!)

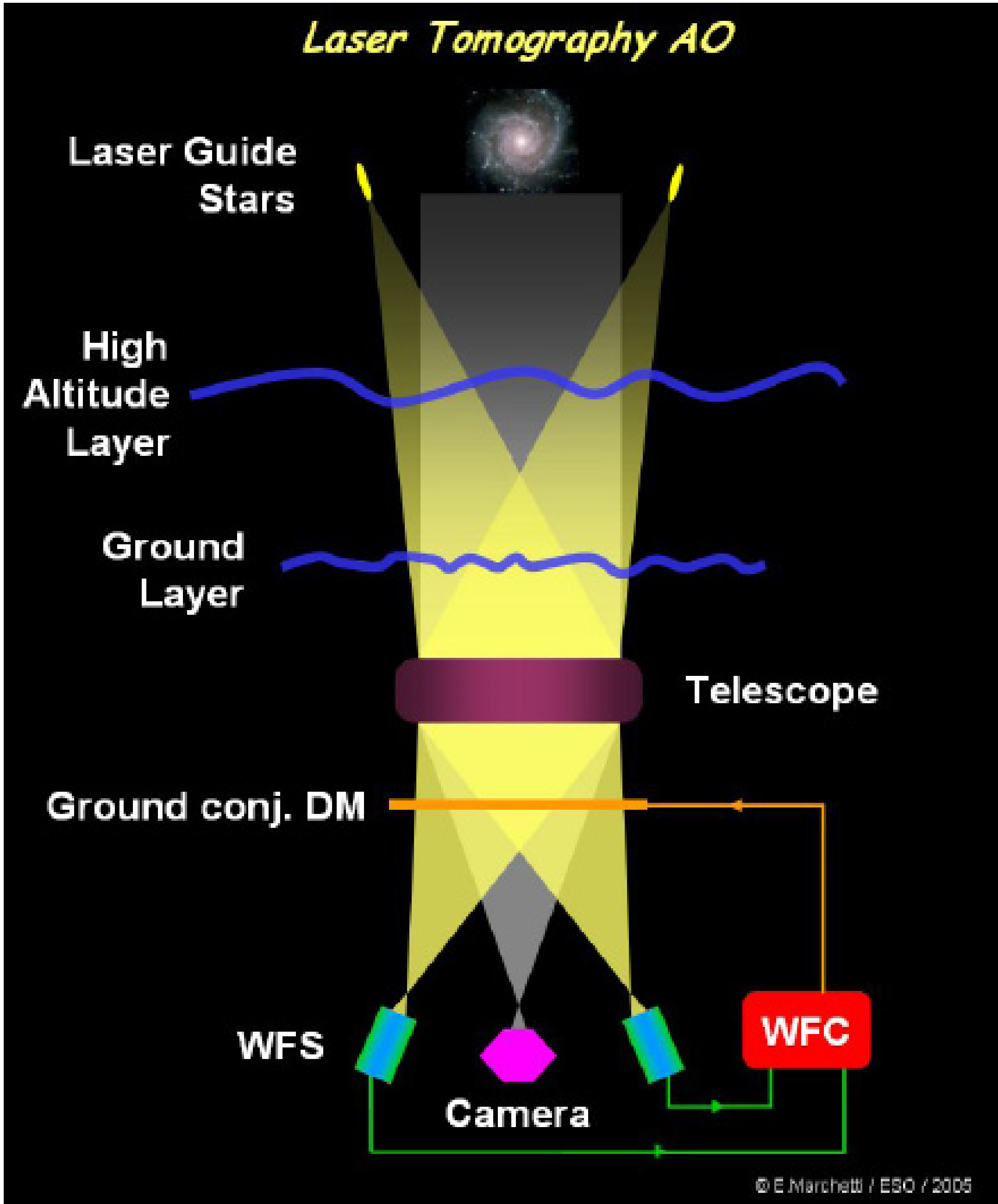
- GLAO is thus a "seeing enhancement" technique.

- Advantage: wider fields and shorter wavelengths



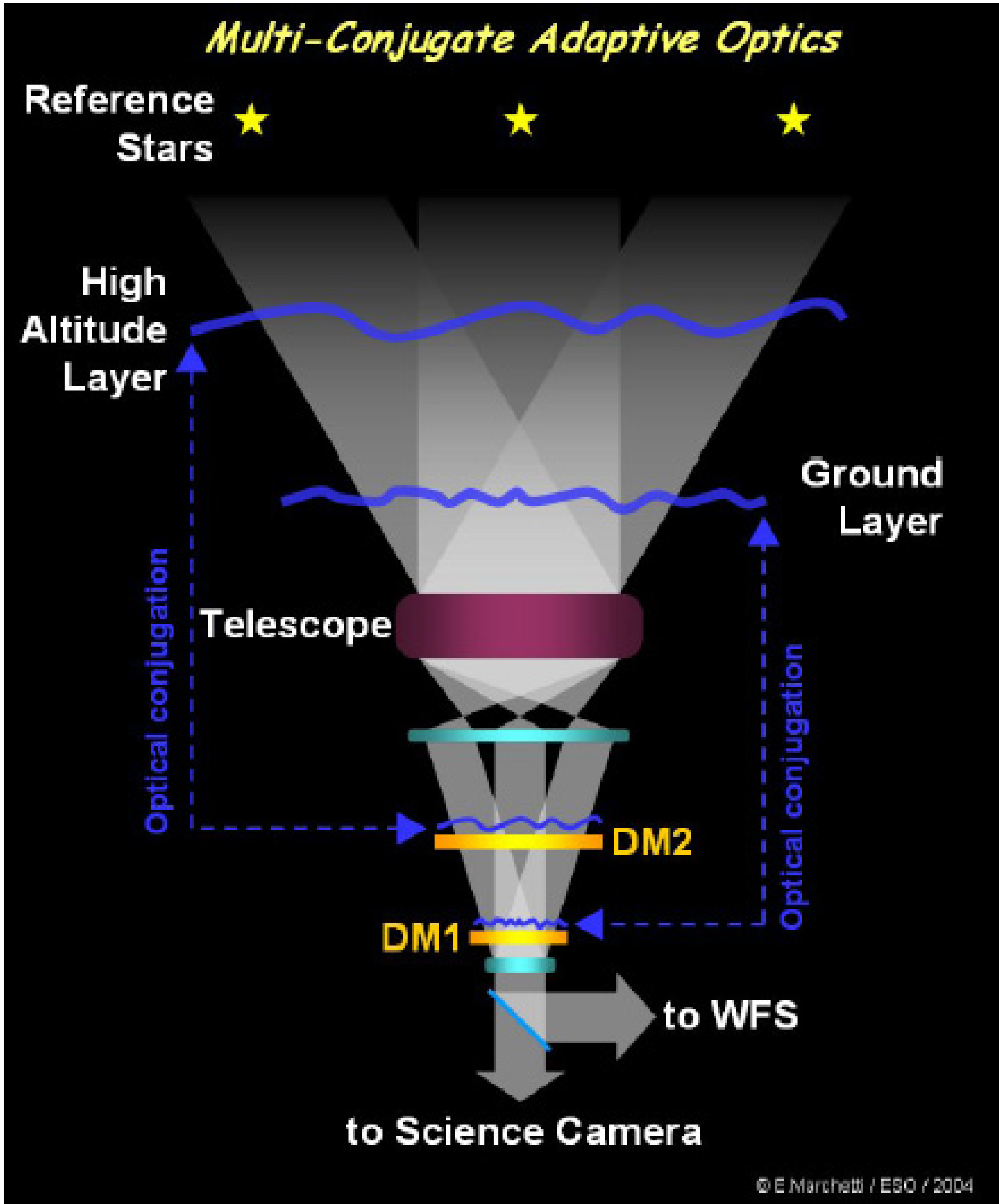
Laser Tomography AO – LTAO

- Uses multipe laser beacons
- each laser has its WFS
- combined information is used to optimize the correction by one DM on-axis.
- reduces the cone effect
- system performance similar to natural guide star AO but at much higher sky coverage.

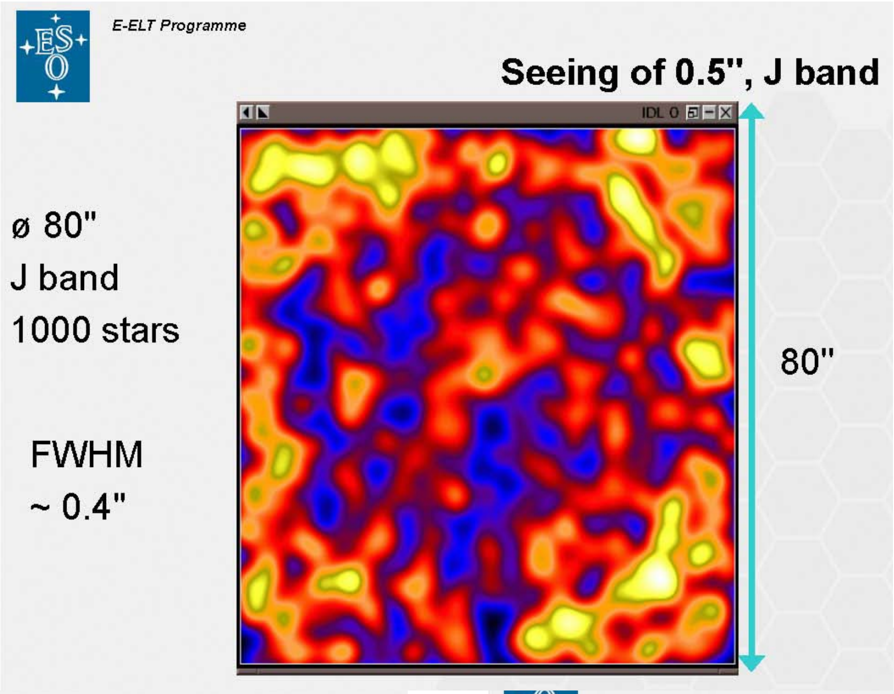


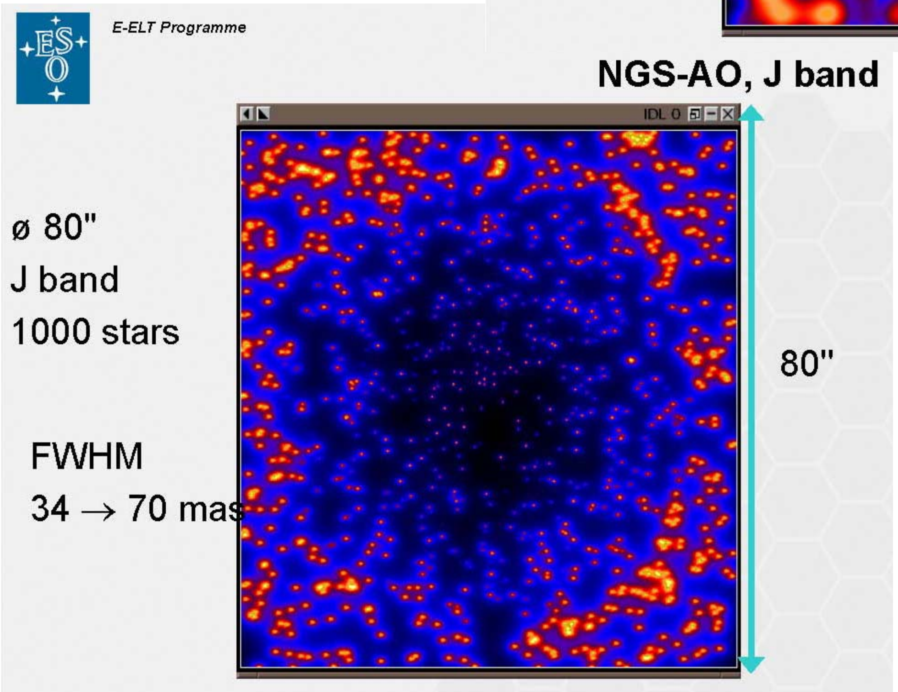
Multi-Conjugate AO – MCAO

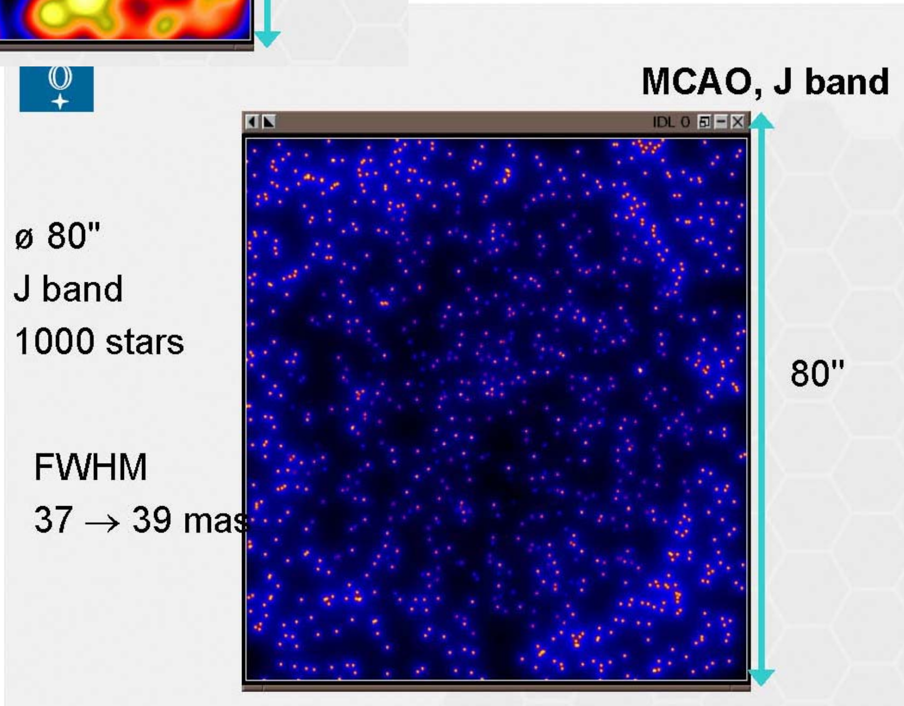
- to overcome anisoplanatism, the basic limitation of single guide star AO.
- MCAO uses multiple NGS or LGS.
- MCAO controls several DMs
- each DM is conjugated to a different atmospheric layer at a different altitude
- at least one DM is conjugated to the ground layer
- best approach to larger corrected FOV.



Side note: MCAO: Performance

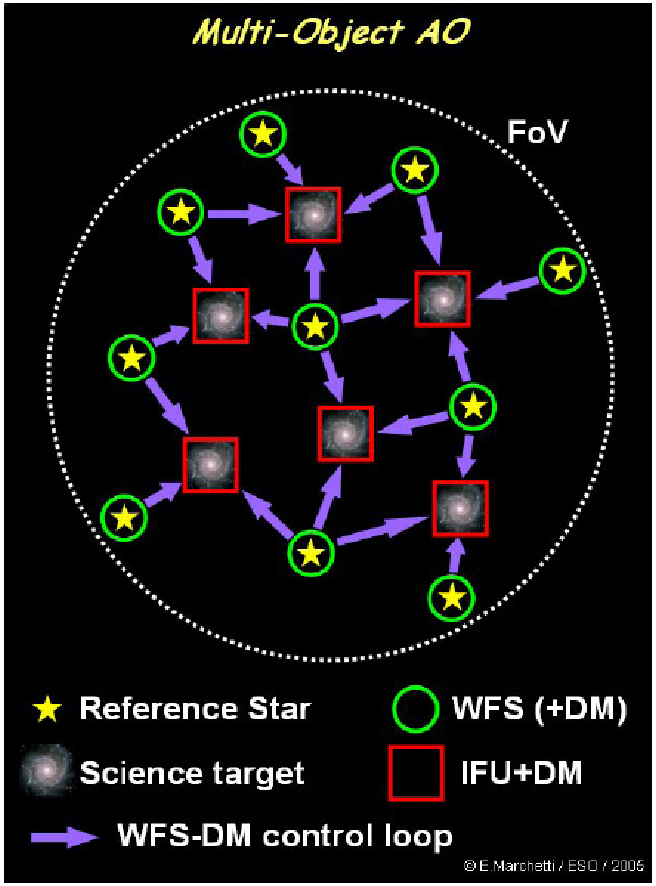


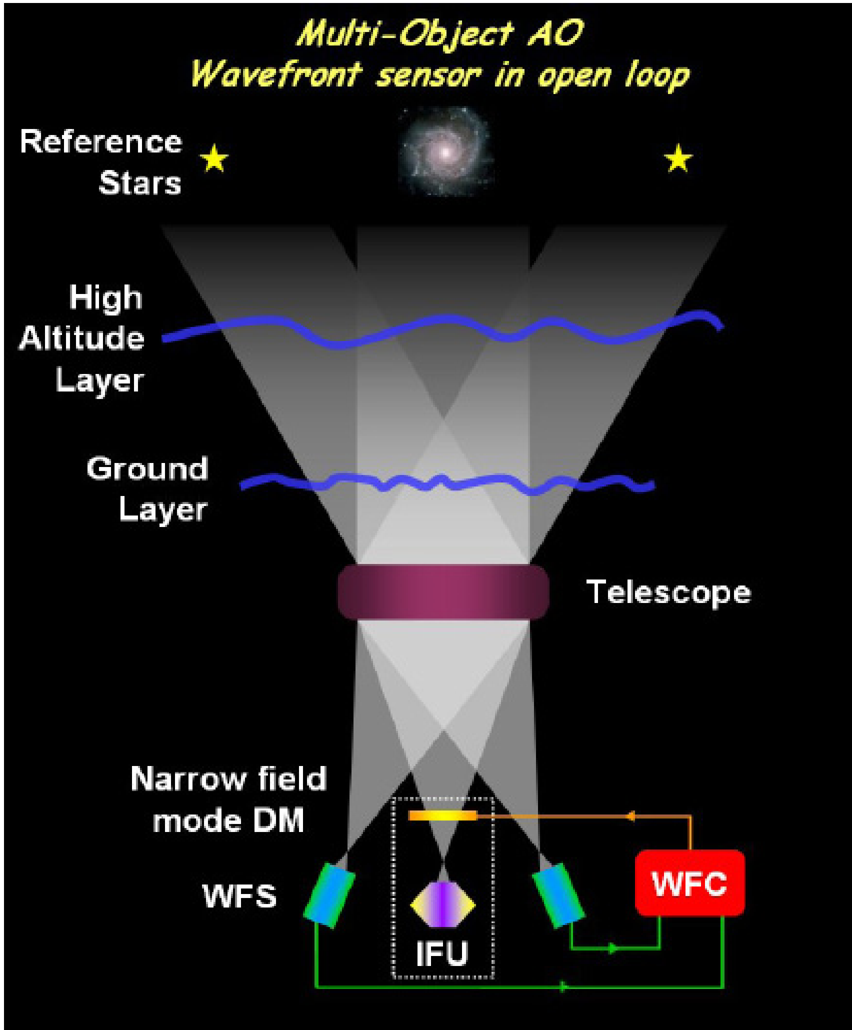




Multi-Object AO – MOAO

- MOAO provides correction not over the entire FOV of several arcmin but only in local areas within several arcmin → multi-object spectroscopy.
- needs (several) guide stars close to each science target.
- picks up the WFS light via small "arms" inserted in the FOV.
- each science target has its DM
- systems work in open loop (!)





Extreme AO - XAO

- XAO is configured similarly than SCAO
- high Strehl on-axis and small corrected FOV
- however, Strehl values in excess of 90%
- requires many thousands of DM actuators
- requires to minimize optical and alignment errors
- main application: search for exoplanets, like

with SPHERE on the VLT →