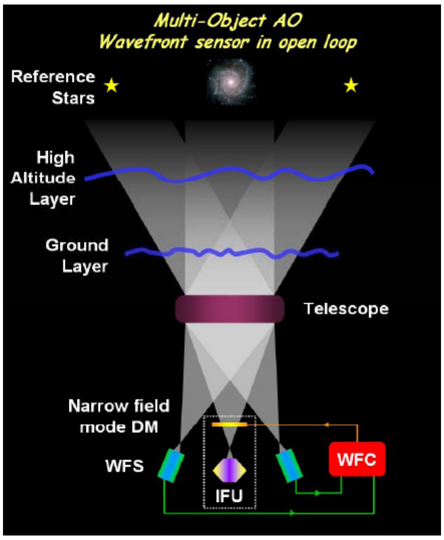
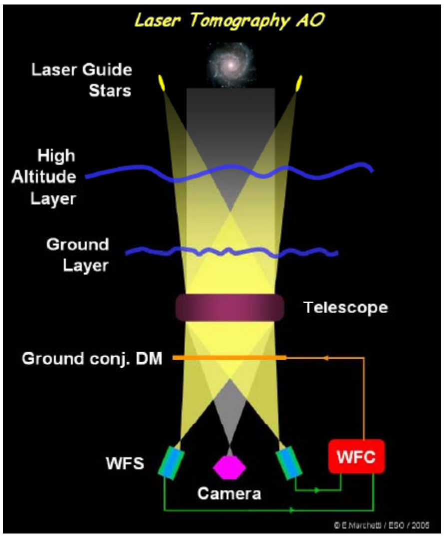
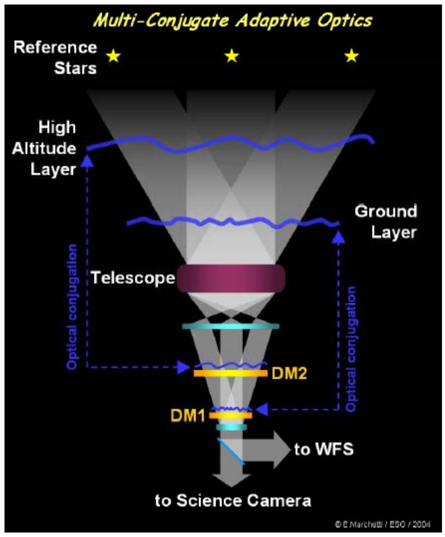
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

12th Lecture: 10 December 2008







Based on:

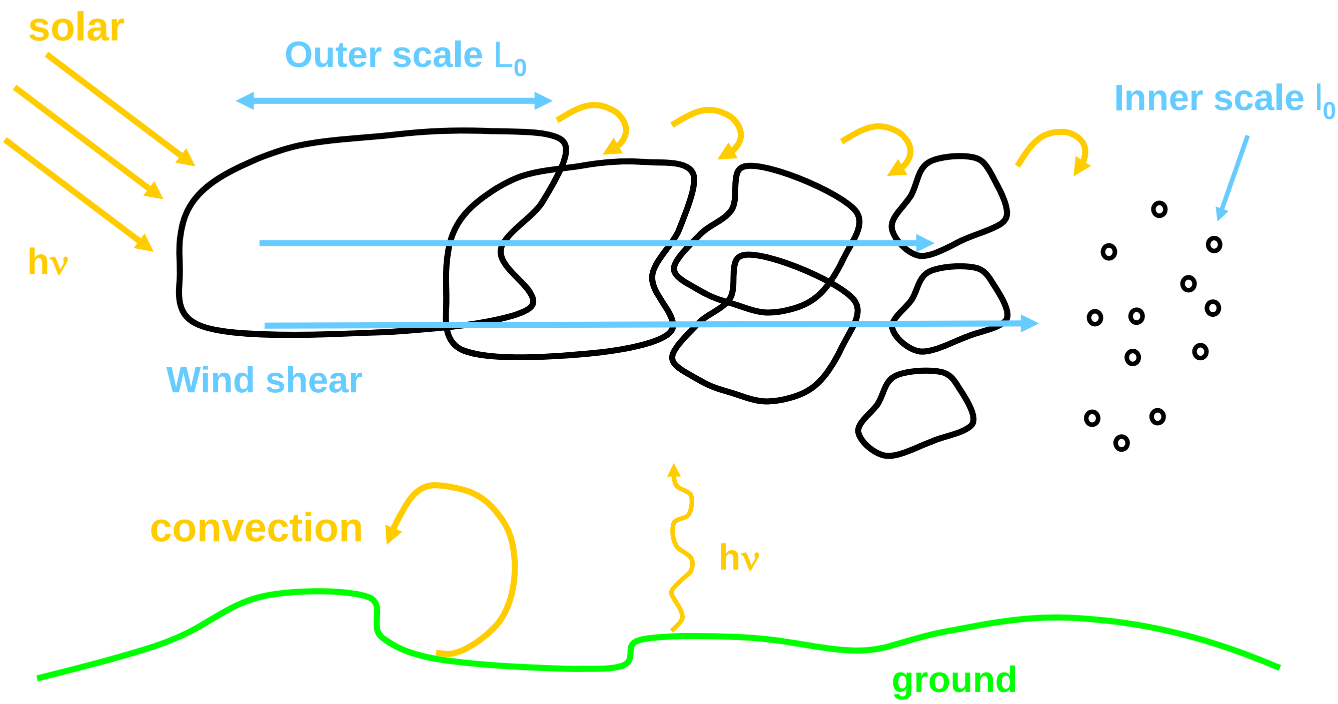
"Adaptive Optics in Astronomy" (Cambridge UP) by F. Roddier (ed.),
Claire Max's lecture course on AO http://www.ucolick.org/~max/289C/
and ESO: http://www.eso.org/projects/aot/DSM/AO_modes.html

Content:

1. Imaging through the atmosphere
2. The Need for AO
3. Basic Principle
4. Key Components
5. Error Terms
6. Laser Guide Stars
7. More Flavours of AO

Reminder: Imaging through the Atmosphere

Reminder: Kolmogorov Turbulence



Reminder: the Main Parameters

The Fried parameter $r_0(\lambda) = 0.185\lambda^{6/5}\left[\int_0^\infty C_n^2(z)dz\right]^{-3/5}$

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

The atmospheric coherence time (or Greenwood delay time) is the maximum time delay for the RMS wavefront error to be less than 1 rad:

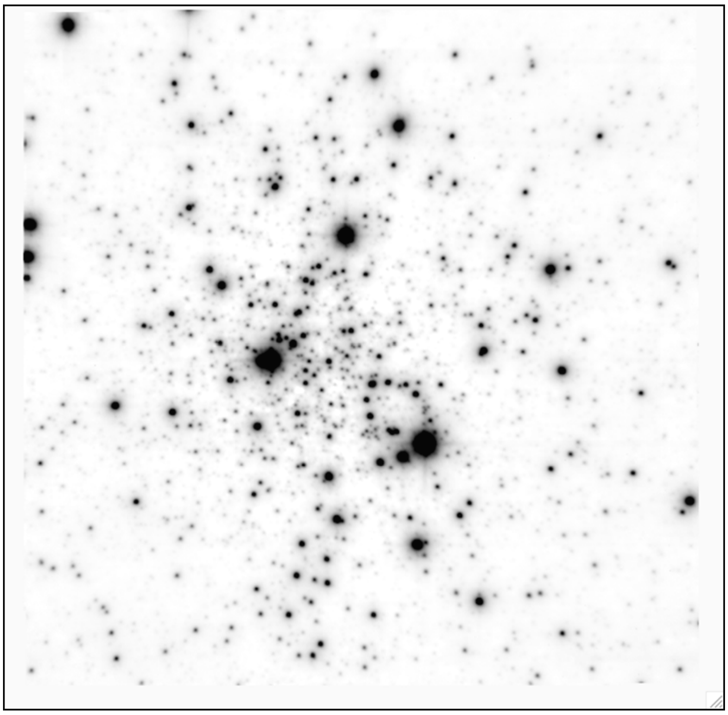
$$\tau_0 = 0.314\frac{r_0}{\bar{v}}$$

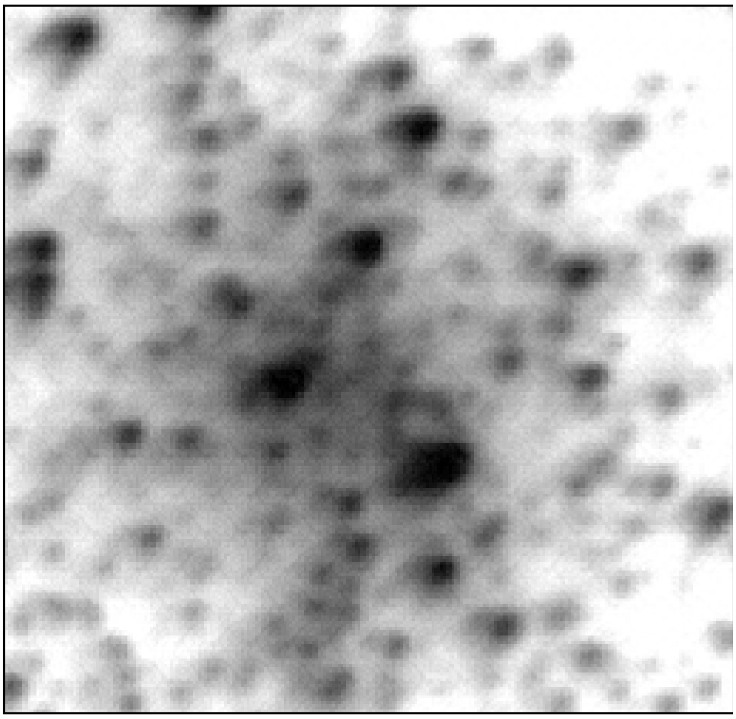
(where v is the mean propagation velocity).

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.

Motivation – or the Need for Adaptive Optics

Example 1

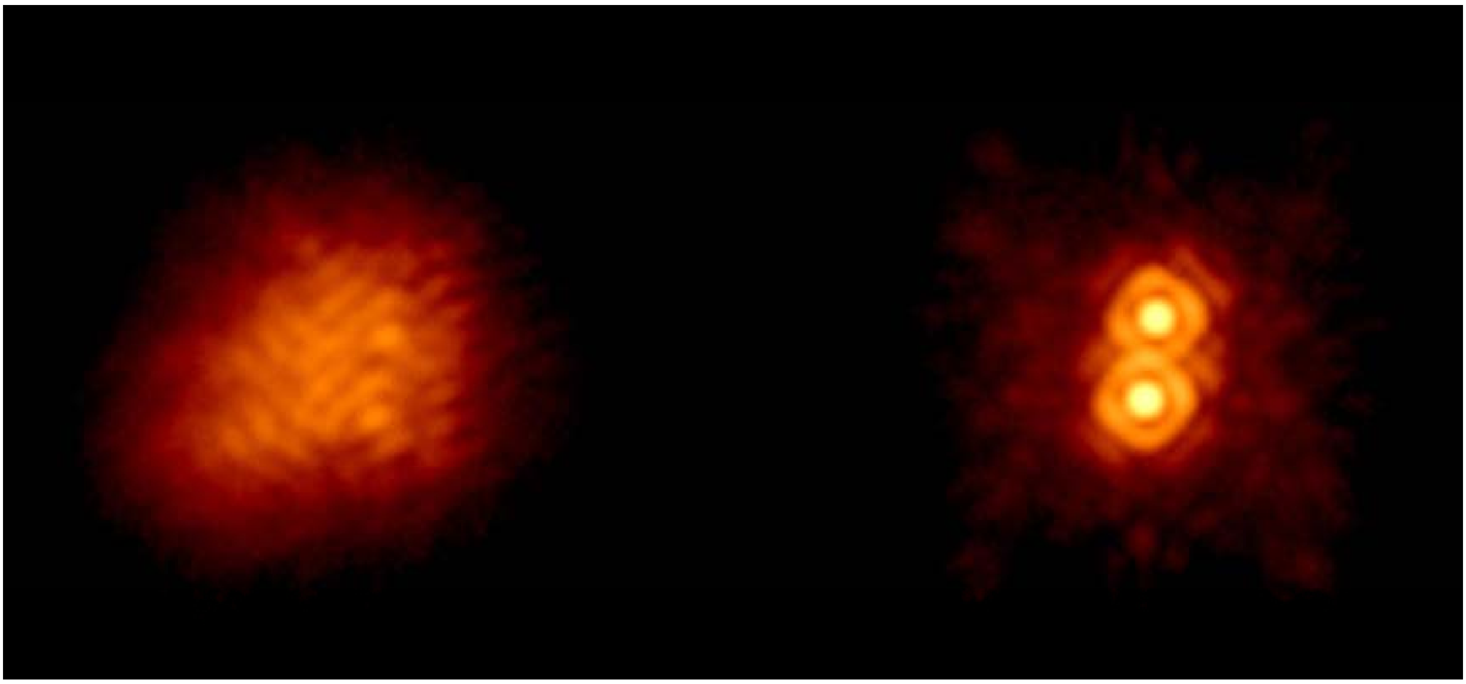




PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM

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

Example 2



Binary star IW Tau with 0.3 arcsecond separation.
(Chas Beichman and Angelle Tanner, JPL)

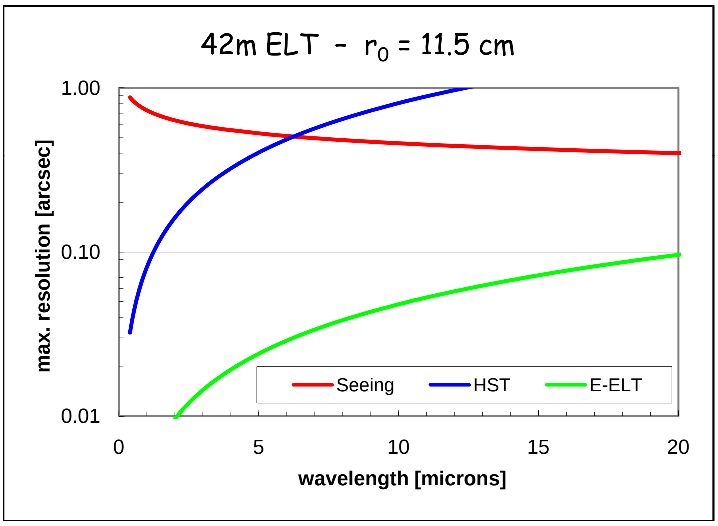
Resolution and Sensitivity

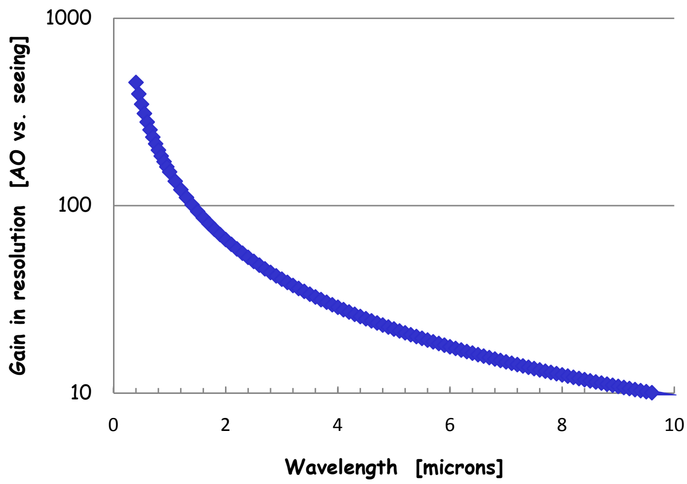
The two main gains of an AO system are:

1. Angular resolution: $\theta = \frac{\lambda}{r_0} \rightarrow \theta = \frac{\lambda}{D}$

2. Sensitivity: $S/N \sim \mathrm{D}^2 \rightarrow t_{\mathrm{int}} \sim \frac{1}{D^4}$

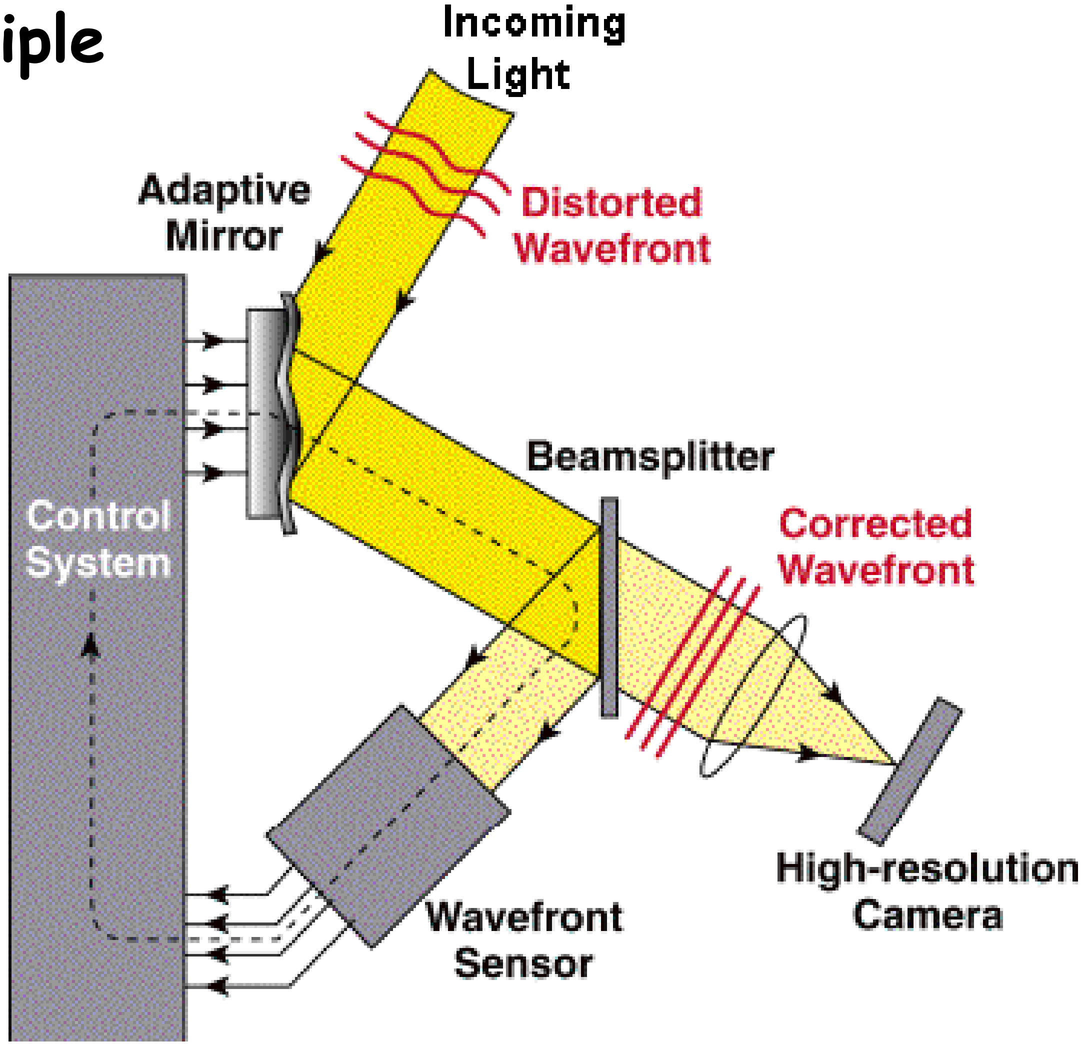
   for diffraction limited sources





Basic Principle

AO Principle



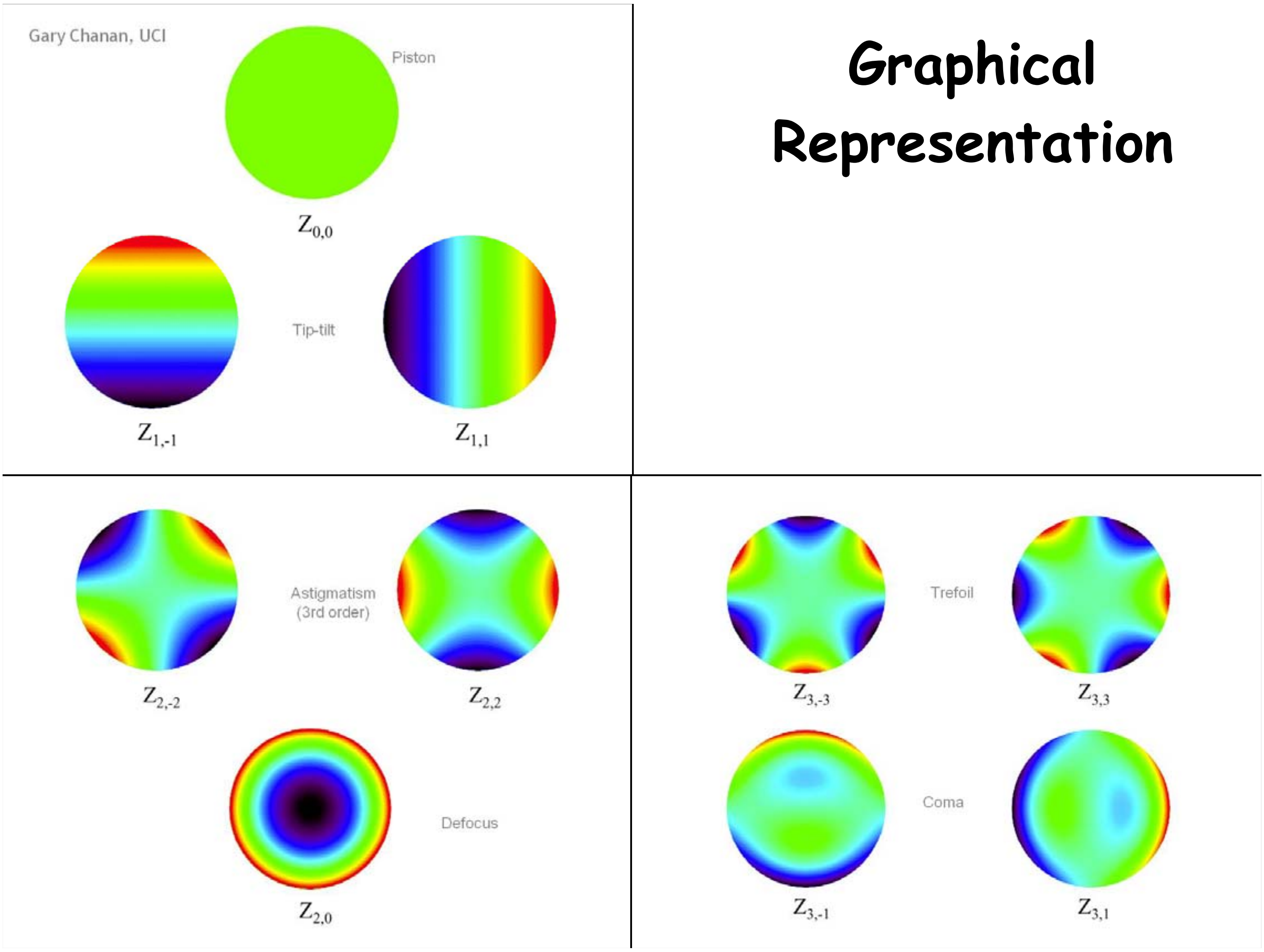
Wavefront Description: Zernike Polynomials

Expansion into a series of orthogonal terms:

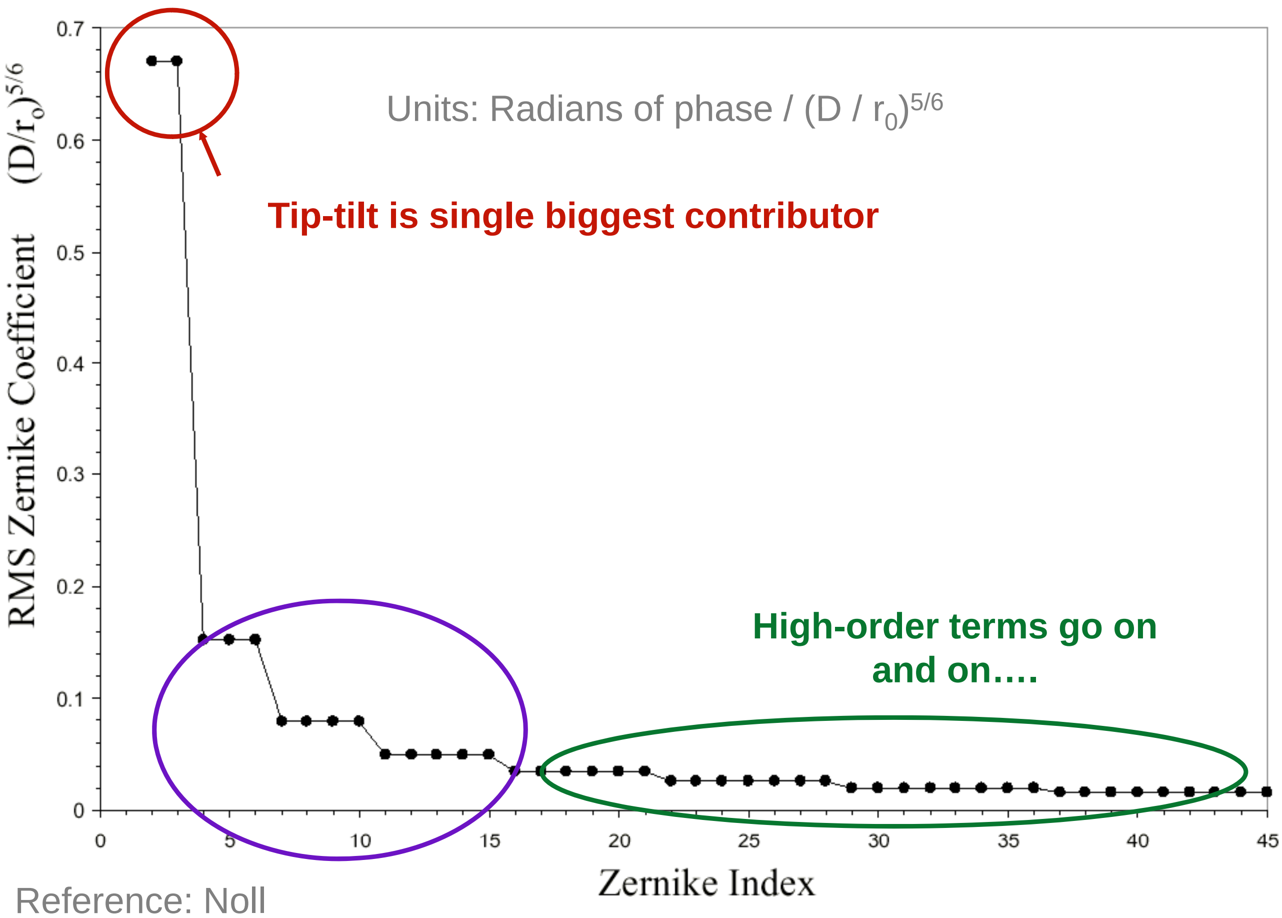
$$\varphi(r,\theta) = \Sigma a_{m,n} Z_{m,n}(r,\theta)$$

$Z_{0,0} = 1$		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

Graphical Representation



Tip-Tilt and higher order Terms (1)



Reference: Noll

Tip-Tilt and higher order Terms (2)

Wavefront error for completely uncompensated images:

$$\sigma^2_{uncomp} = 1.02\left(\frac{D}{r_0}\right)^{5/3}$$

Wavefront error for image motion (tip-tilt) corrected images:

$$\sigma^2_{no\_tiptilt} = 0.134\left(\frac{D}{r_0}\right)^{5/3}$$

Note: for a 40m telescope at 1μm: $\frac{D}{r_0} \sim 80 \;\Rightarrow\; \sigma^2_{no\_tiptilt} \approx 200 >> 1\,\text{rad}$

➔ If D/r_0 >> 1, removing tip-tilt alone will not provide diffraction limited images.

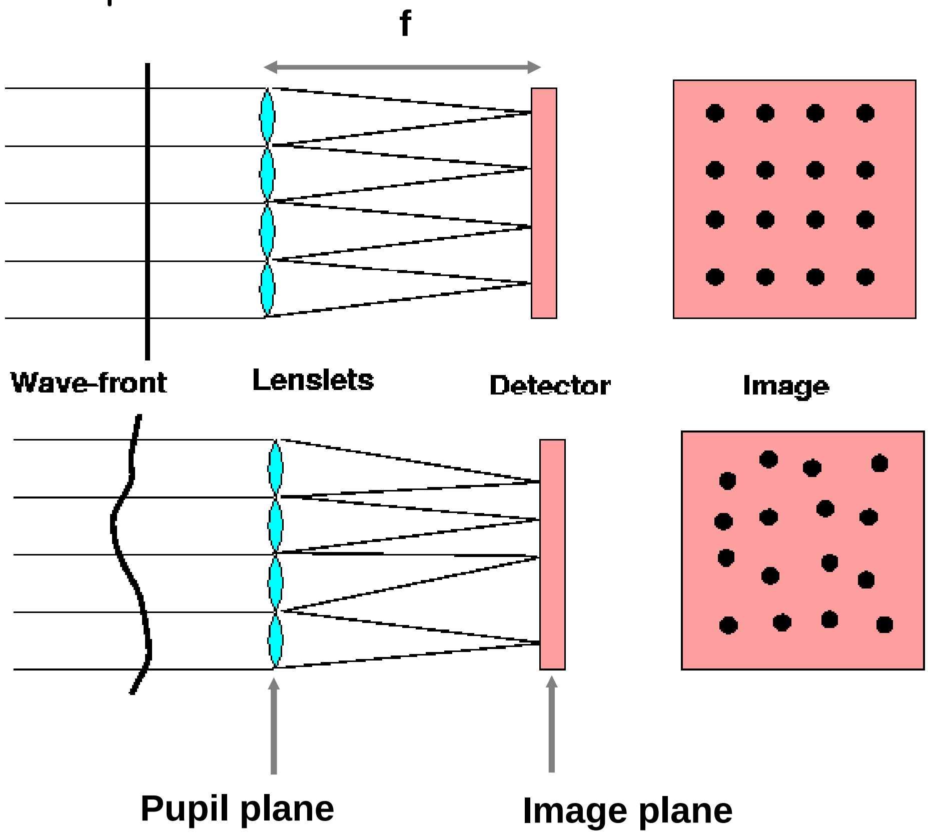
Note that the maximum tilt angle is independent of wavelength:

$$\alpha_{\max} = \pm 1.07 \cdot D^{-1/6}\ \text{rad} \approx 2''$$

AO – Key Components

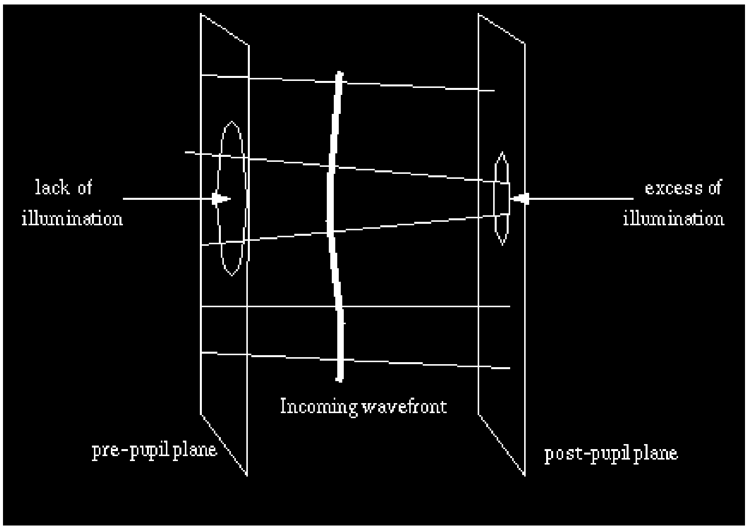
Wavefront Sensors (1)

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



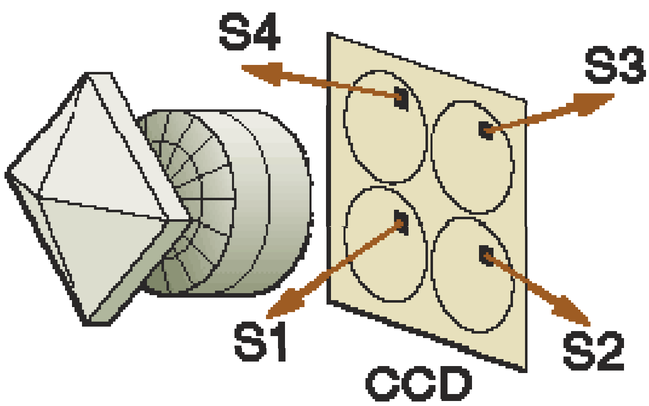
Wavefront Sensors (2)

Other common principles are the



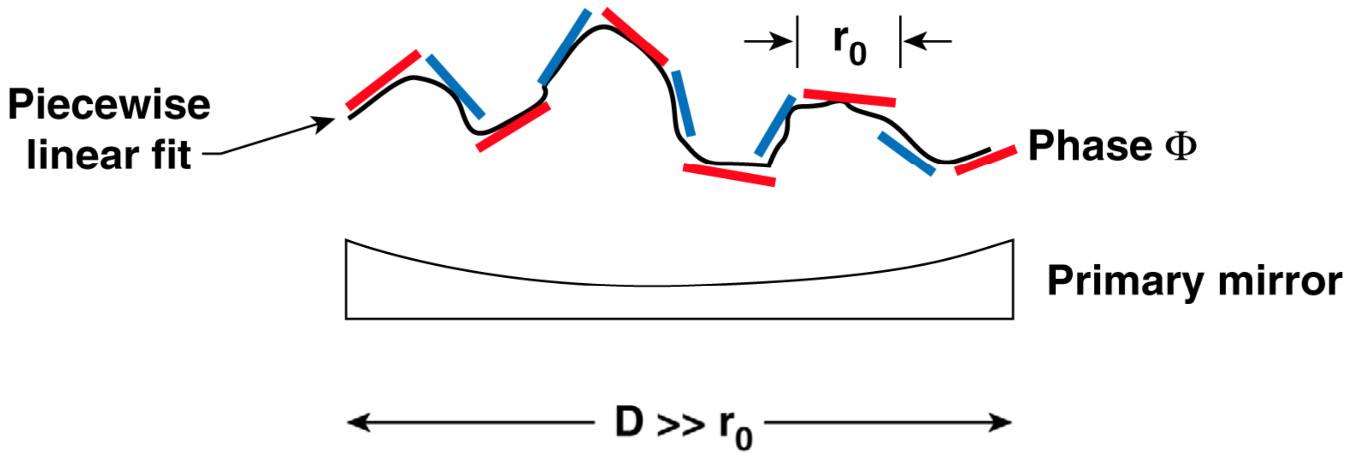
curvature sensor →

and the pyramid sensor →



Deformable Mirrors (1)

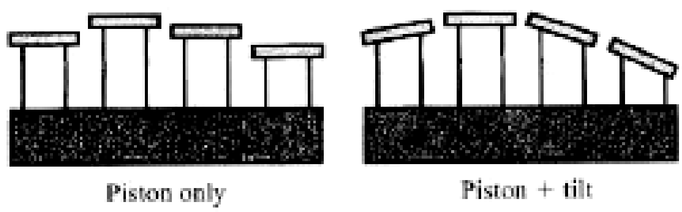
Basic principle: piece-wise linear fit of the mirror surface to the wavefront. r_0 sets the number of degrees of freedom.



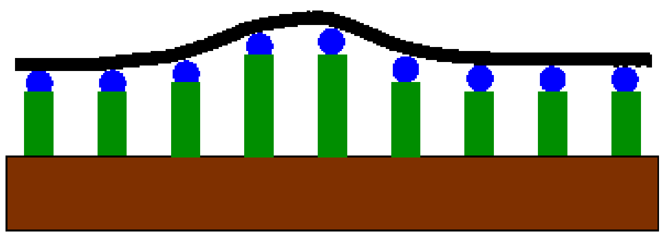
The number of subapertures is $(D/r_0)^2$ at the observing wavelength → can easily require hundreds to thousands of actuators for very large telescopes.

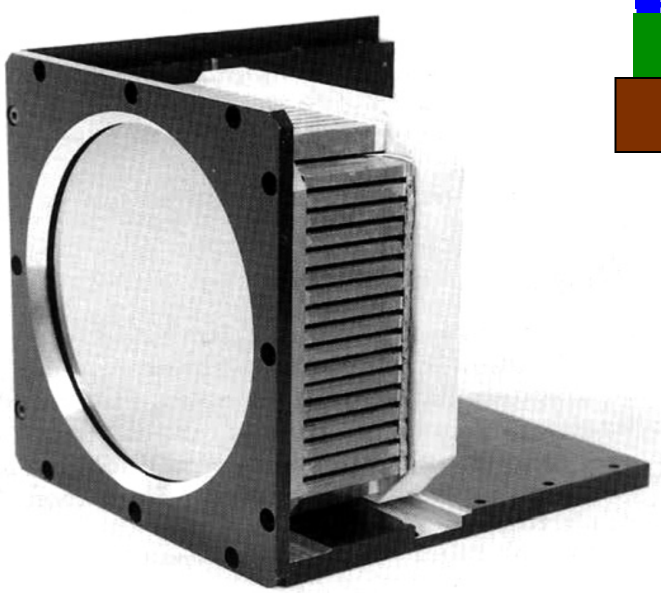
Deformable Mirrors (2)

Two general types: segmented mirrors



and continuous face-sheet mirrors:





A 249 actuator deformable mirror made by CILAS (France)

Note that the (piezo) actuator stroke is typically only a couple of micrometers → cannot correct for tip-tilt → requires separate tip-tilt mirror.

Deformable Mirrors (3)

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

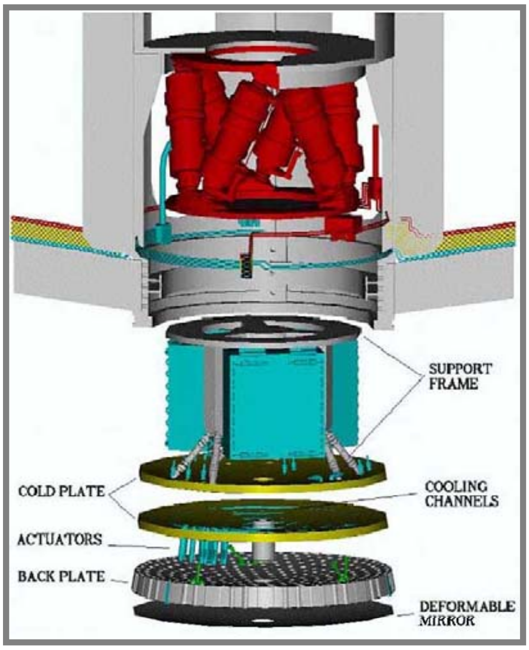
Advantages:

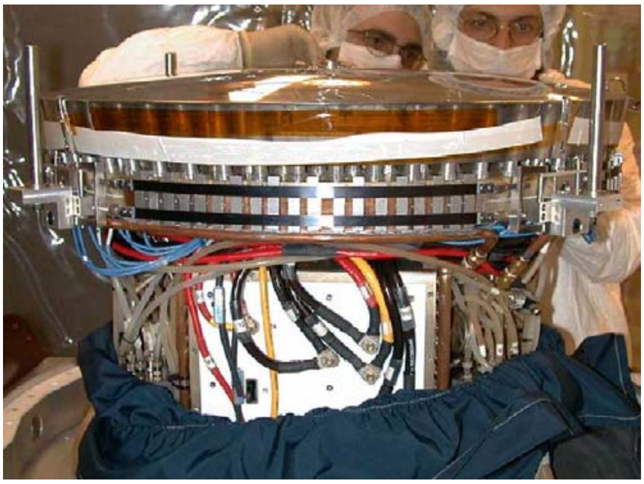
• no additional optical surfaces needed → lower emission, higher throughput

• large surface → high actuator density

• high stroke → no tip-tilt mirror needed

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





DM for MMT Upgrade

AO Correction Error Terms (or: Nothing is Perfect)

Error Terms

Uncorrected wavefront errors may have several causes. Most relevant are:

- 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 (detector noise etc.)
- Calibration errors from aberrations in the non-common path between sensing channel and imaging channel.
- Angular anisoplanatism from sampling different lines of sight through the atmosphere.

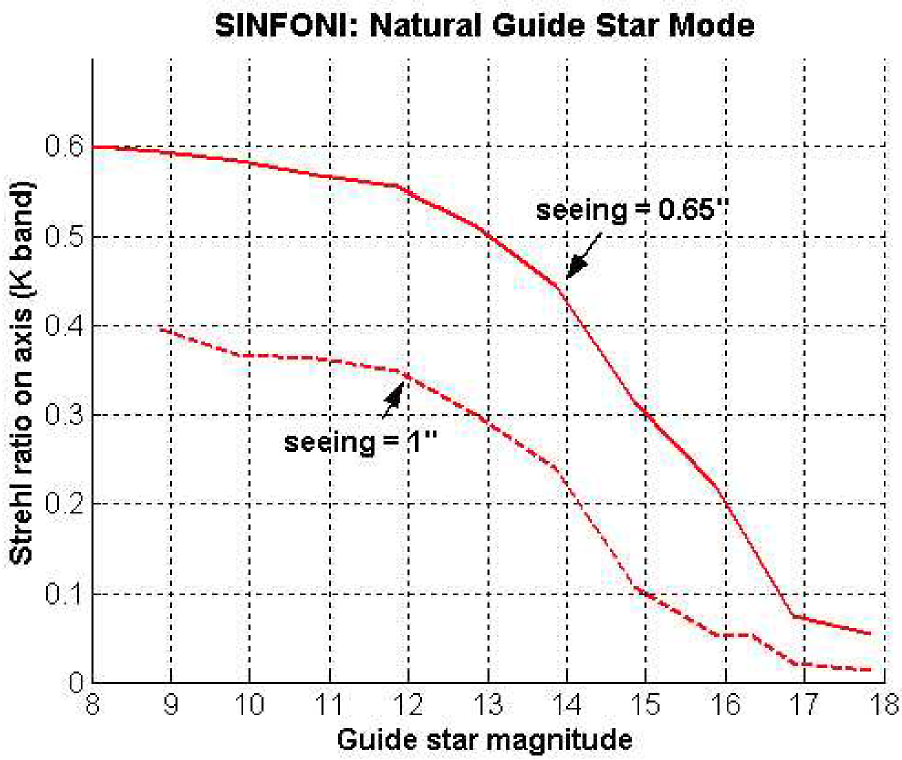
$$\sigma_{aniso}^2 \approx \left(\frac{\theta}{\theta_0}\right)^{5/3}$$

The total variance of the WFE is:

$$\sigma^2 = \sigma_{fit}^2 + \sigma_{temp}^2 + \sigma_{meas}^2 + \sigma_{calib}^2 + \sigma_{aniso}^2 + \ldots$$

Measurement Error

The WFS detector needs a sufficient photon flux per pixel to properly calculate the centroid. Typical frame rates are 100 Hz → need a moderately bright guide star:

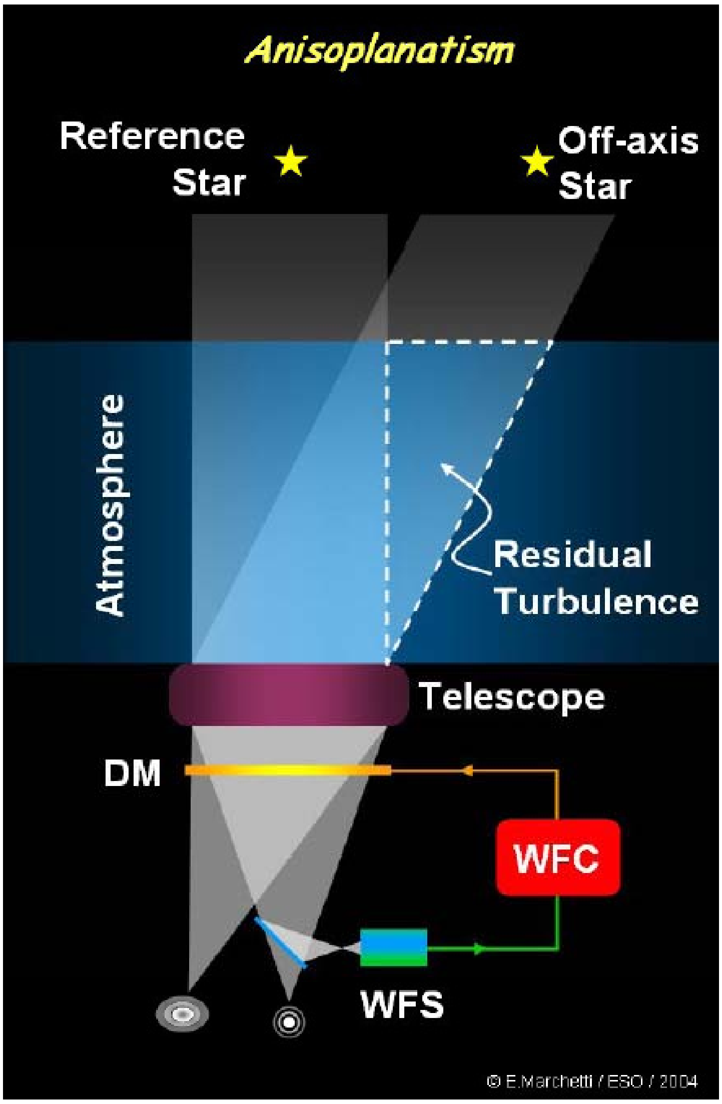


Angular Anisoplanatism

Angular anisoplanatism is a severe limitation to:

• wide-field imaging

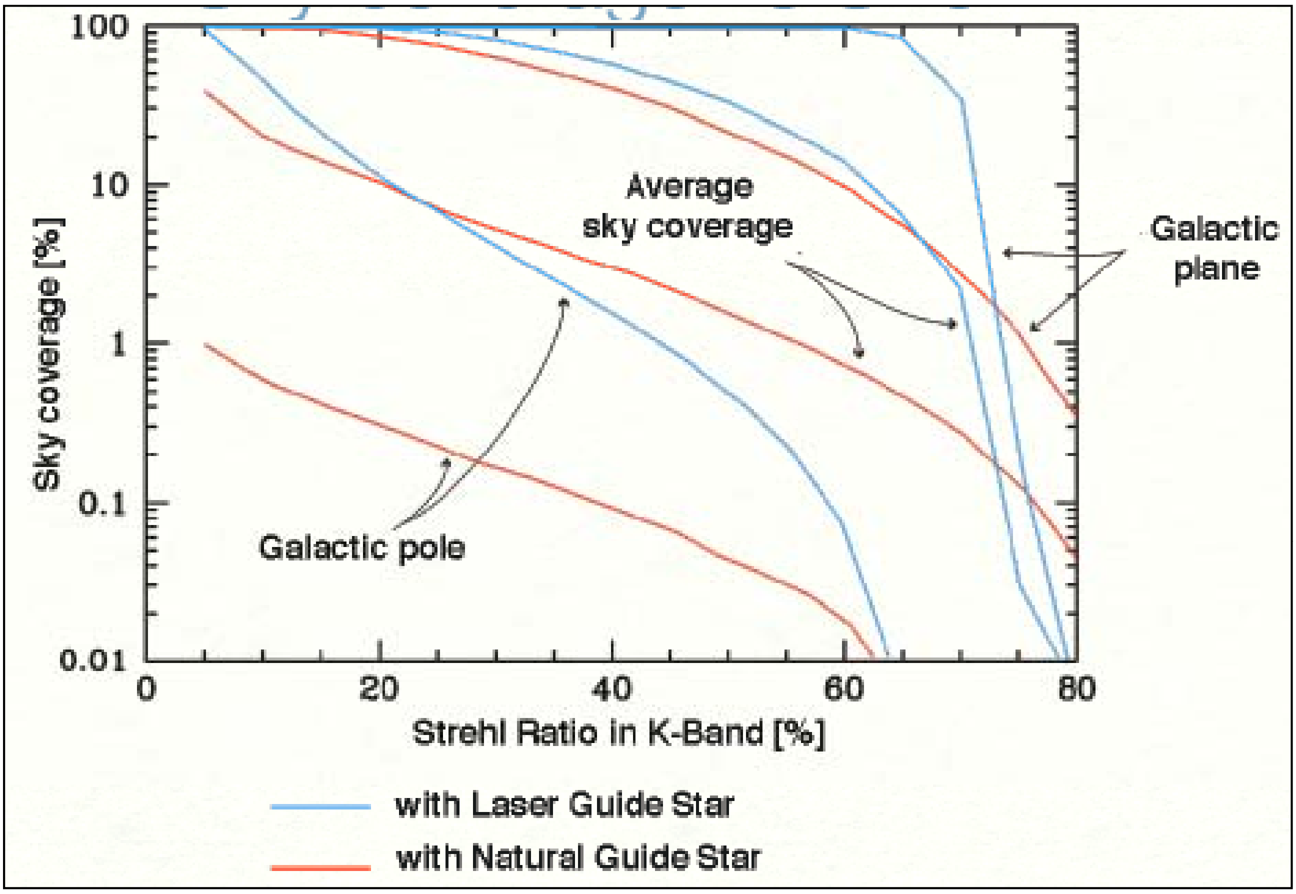
• sky coverage (finding a guide star within the isoplanatic angle)



Laser Guide Stars (Beacons)

Sky Coverage

Problem: need a *bright guide star* (<12mag) within the isoplanatic angle.

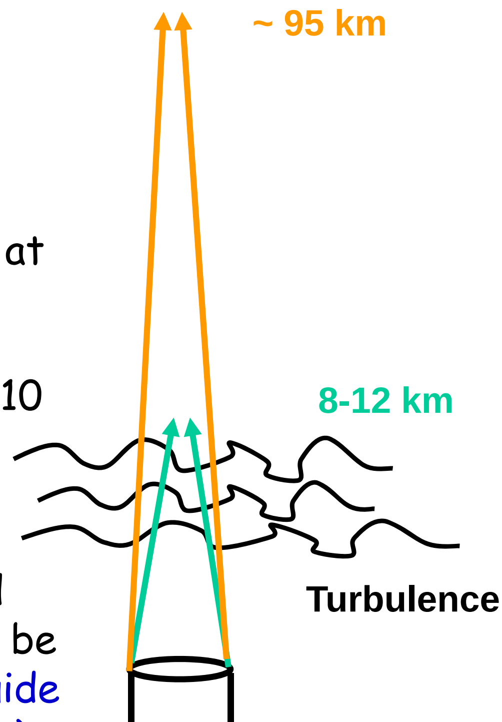


Laser Guide Stars

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

Two principle concepts:

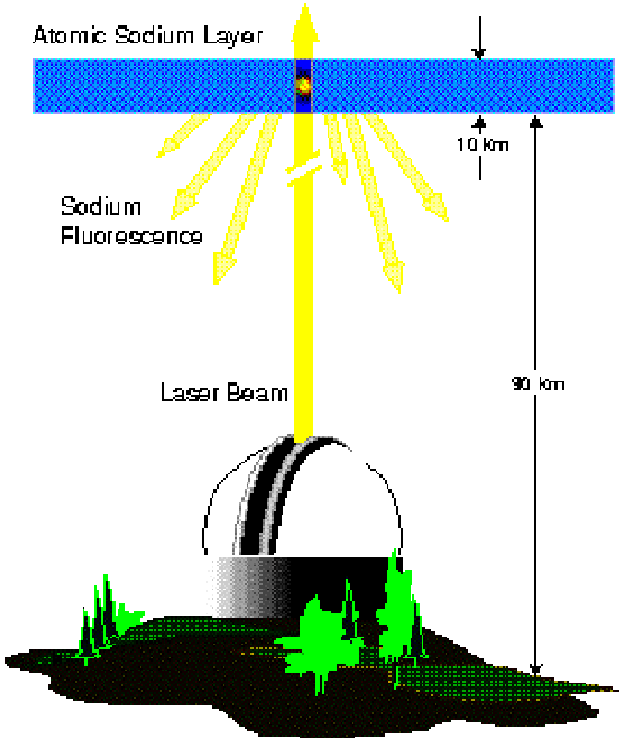
- Sodium LGS – excite atoms in "sodium layer" at altitude of ~ 95 km
- Rayleigh beacon LGS – scattering from air molecules sends light back into telescope, h ~ 10 km



However, 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.

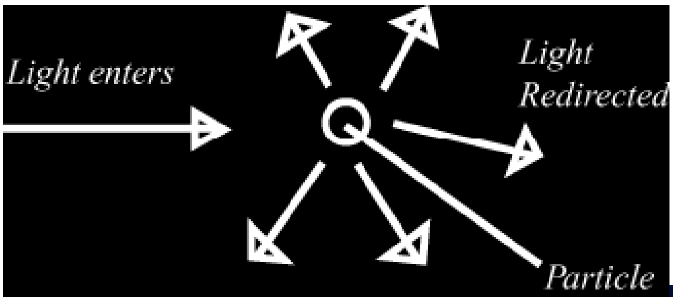
Sodium Beacons

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

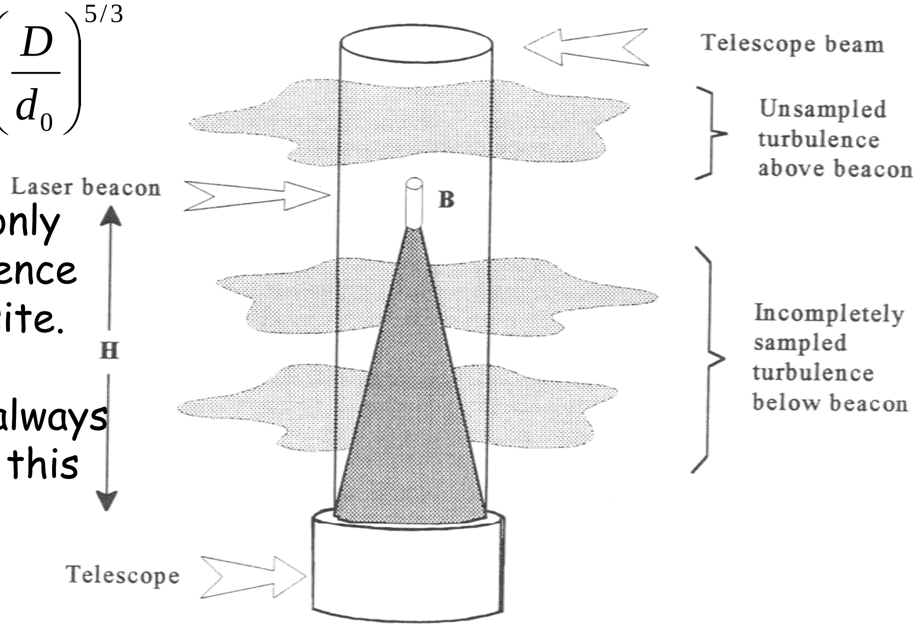
Focus Anisoplanatism

The LGS is at finite distance 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 always need multiple LGS due to this cone effect.



More Flavours of AO

Ground Layer AO – GLAO

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

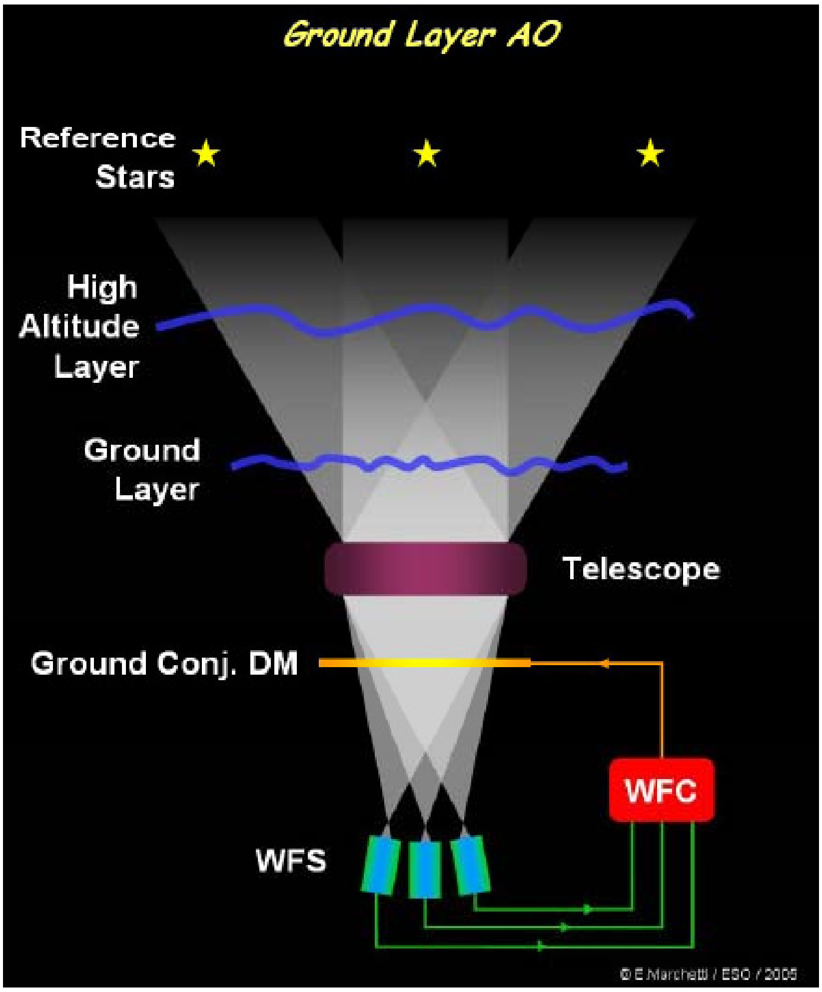
• Uses several WFS and guide stars within a large FOV (several arcmin).

• 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

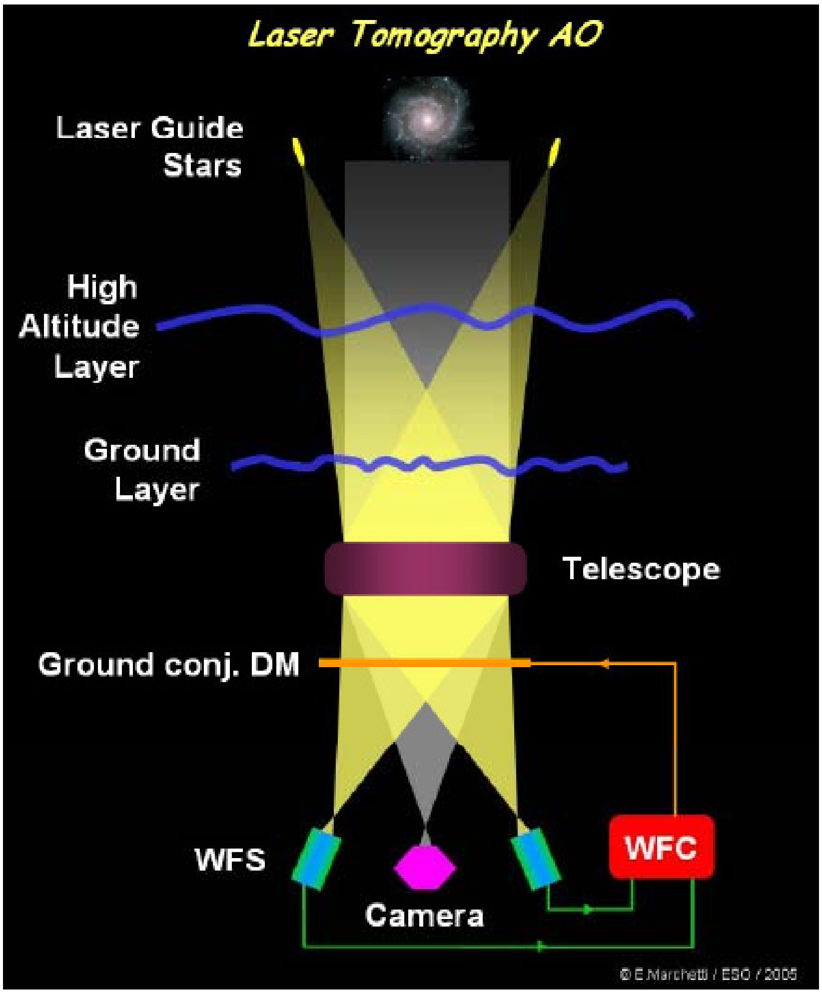
• Uses multipe laser beacons

• each laser has its WFS

• combined information is used to optimize the correction on-axis.

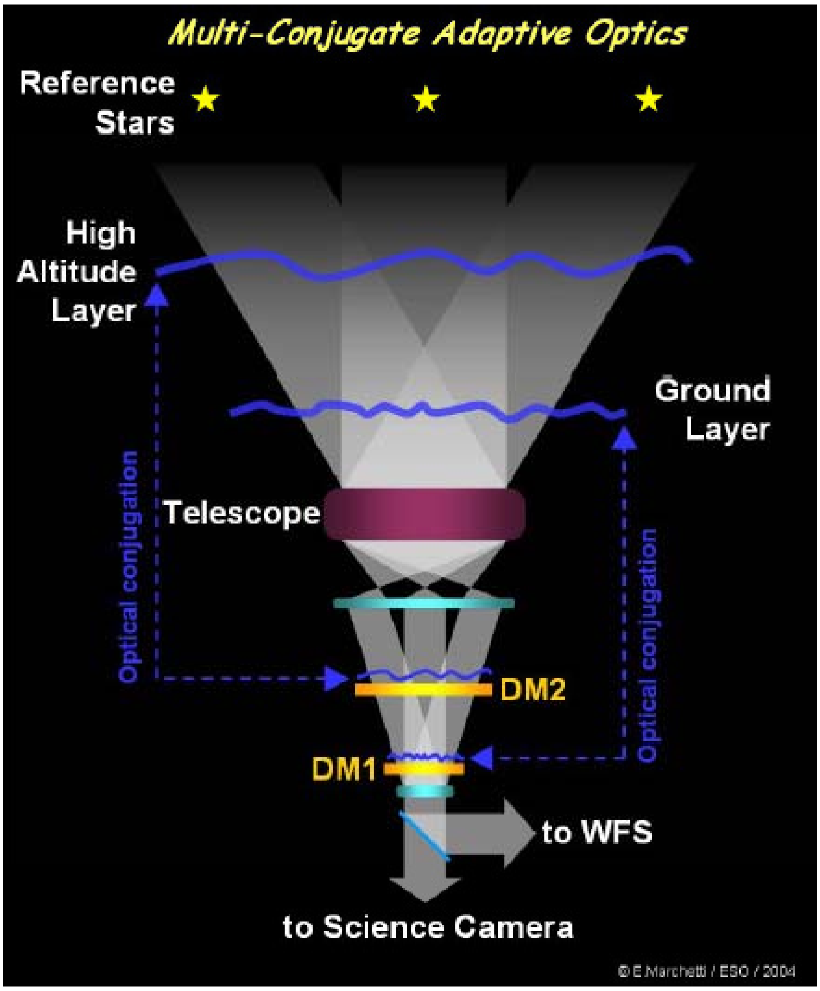
• reduces the cone effect

• system performance similar to natural guide star AO but at much larger sky coverage.



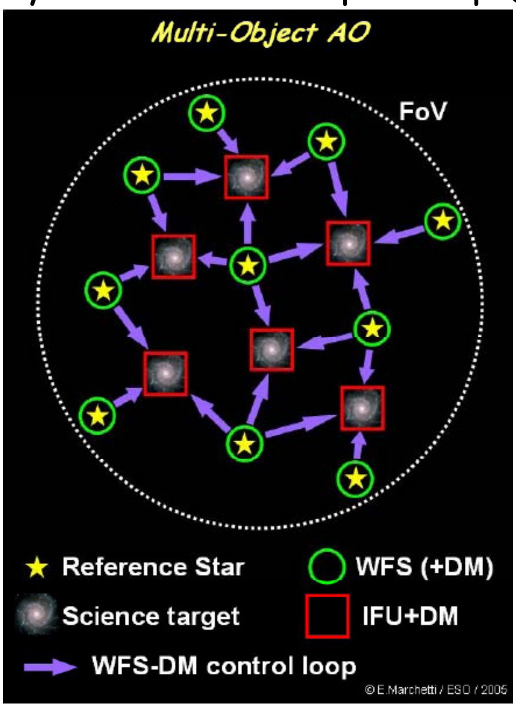
Multi-Conjugate AO – MCAO

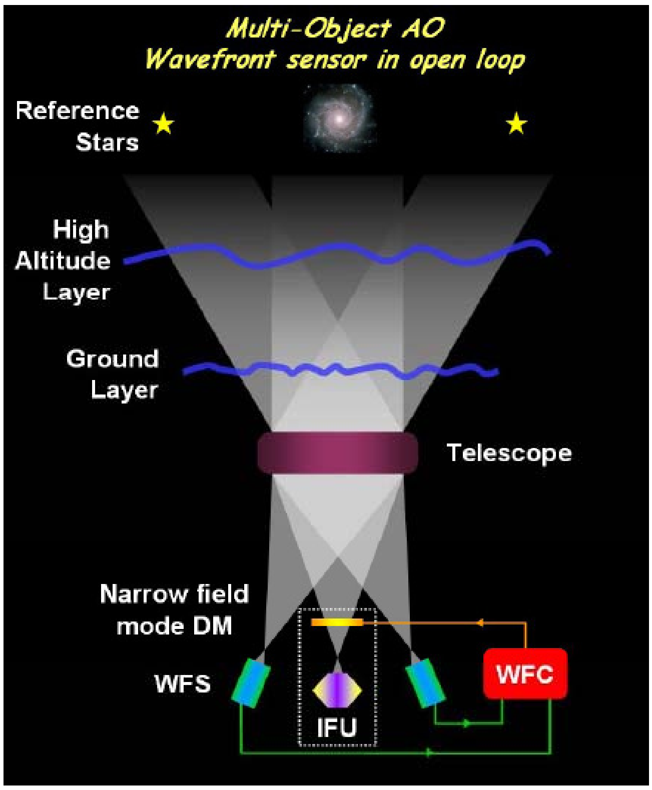
- to overcome anisoplanatism, the basic limitation of single guide star AO.
- MCAO uses multiple NGS or LGS.
- MCAO controlls several DMs
- each DM is conjugated to an atmospheric layer at a different altitude
- at least one DM is conjugated to the ground layer
- best approach to larger corrected FOV.



Multi-Object AO – MOAO

- MOAO provides correction not over the entire FOV of several arcmin but 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 (!)

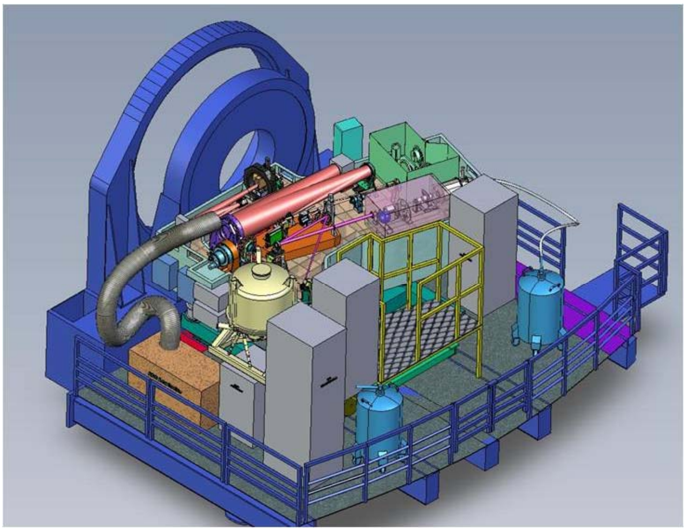




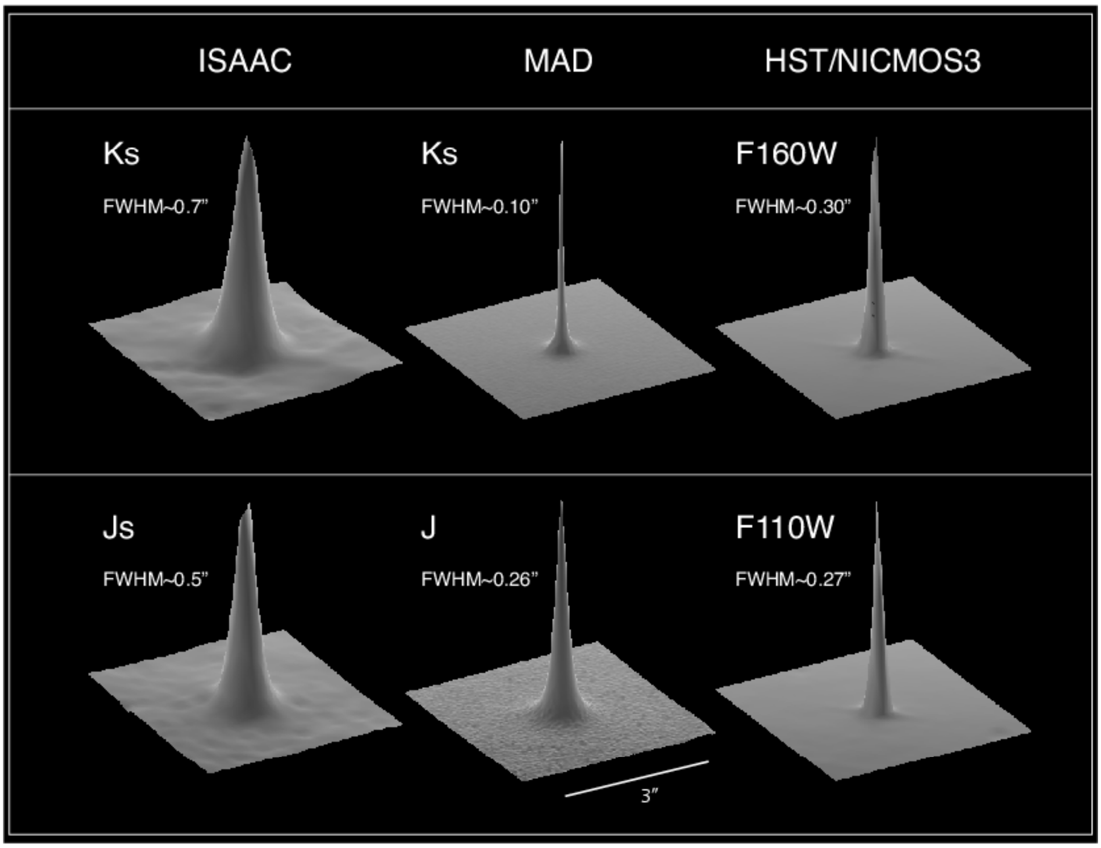
Extreme AO – XAO

- XAO is similarly configured 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 →



High Quality AO-PSFs



Comparison of the PSF of ISAAC (left, J_s and K_s-bands), MAD (center, J and K_s bands), and HST/NICMOS3 (right, F110W and F160W). Bouy et al. (2008) A&A 477, 681-690