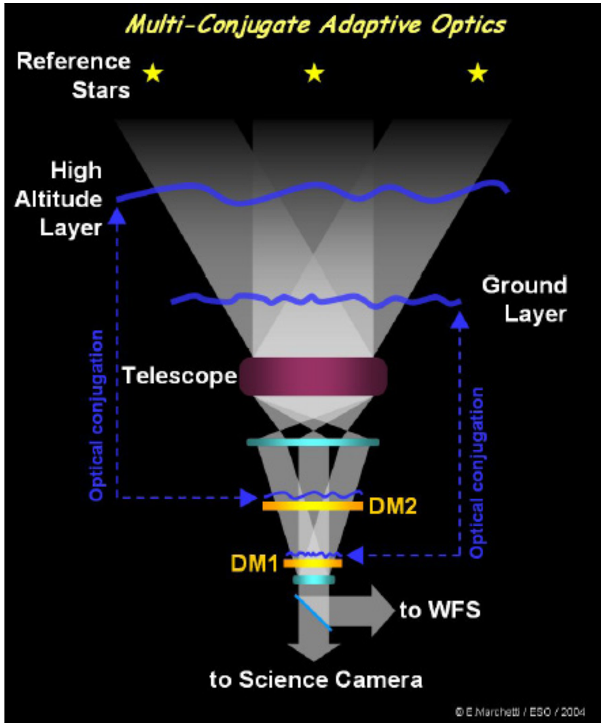
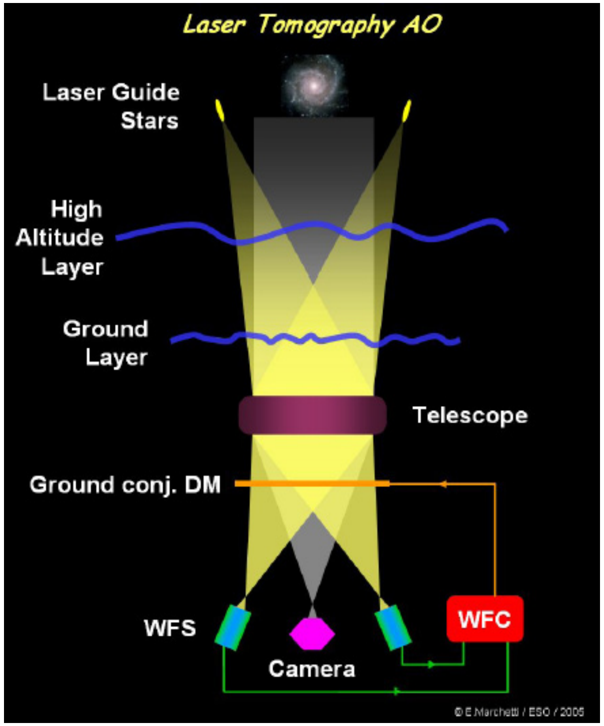
Astronomische Waarneemtechnieken (Astronomical Observing Techniques)

Based on lecture by Bernhard Brandl

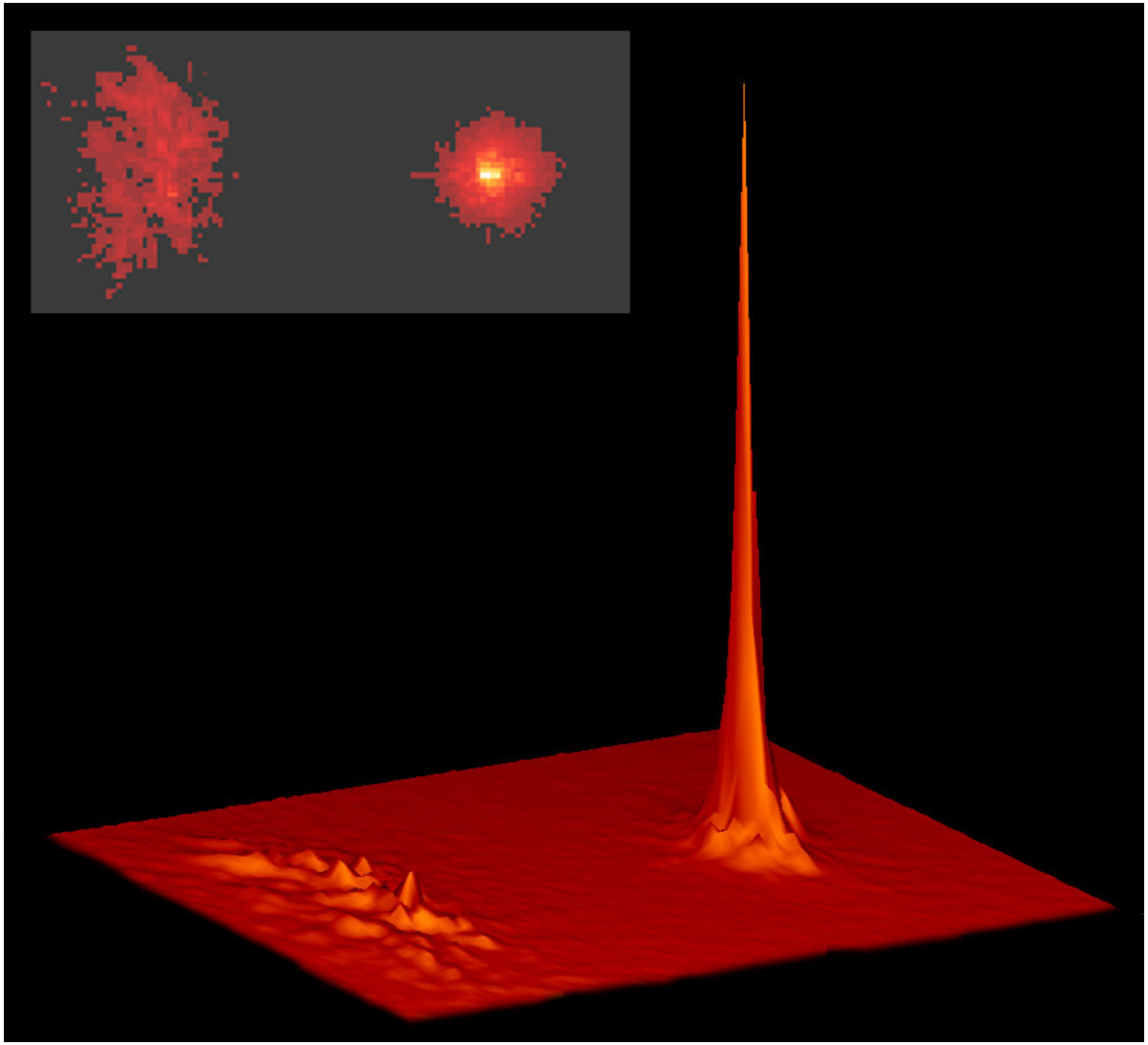




Lecture 13: Adaptive Optics

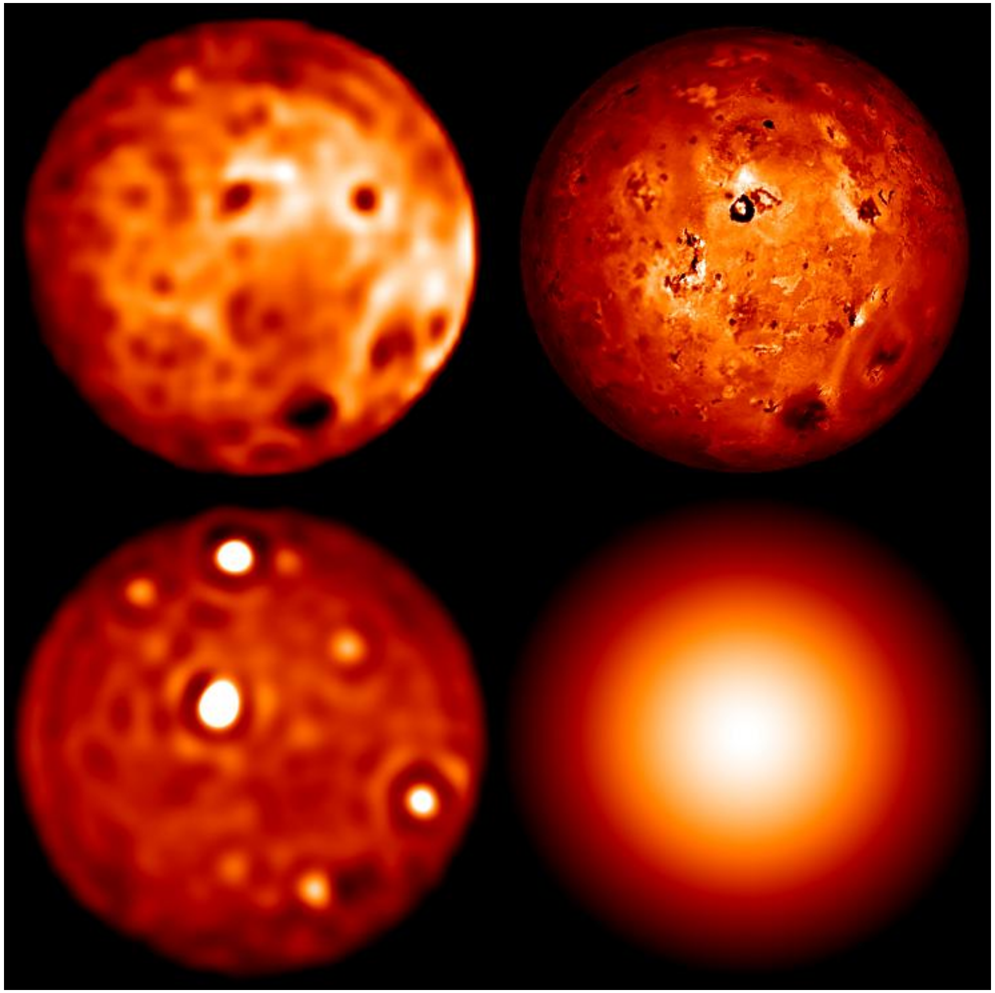
1. Atmospheric Turbulence
2. Why AO?
3. Basic Principle
4. Key Components
5. Error Terms
6. Laser Guide Stars
7. Types of AO Concepts

Star with and without AO



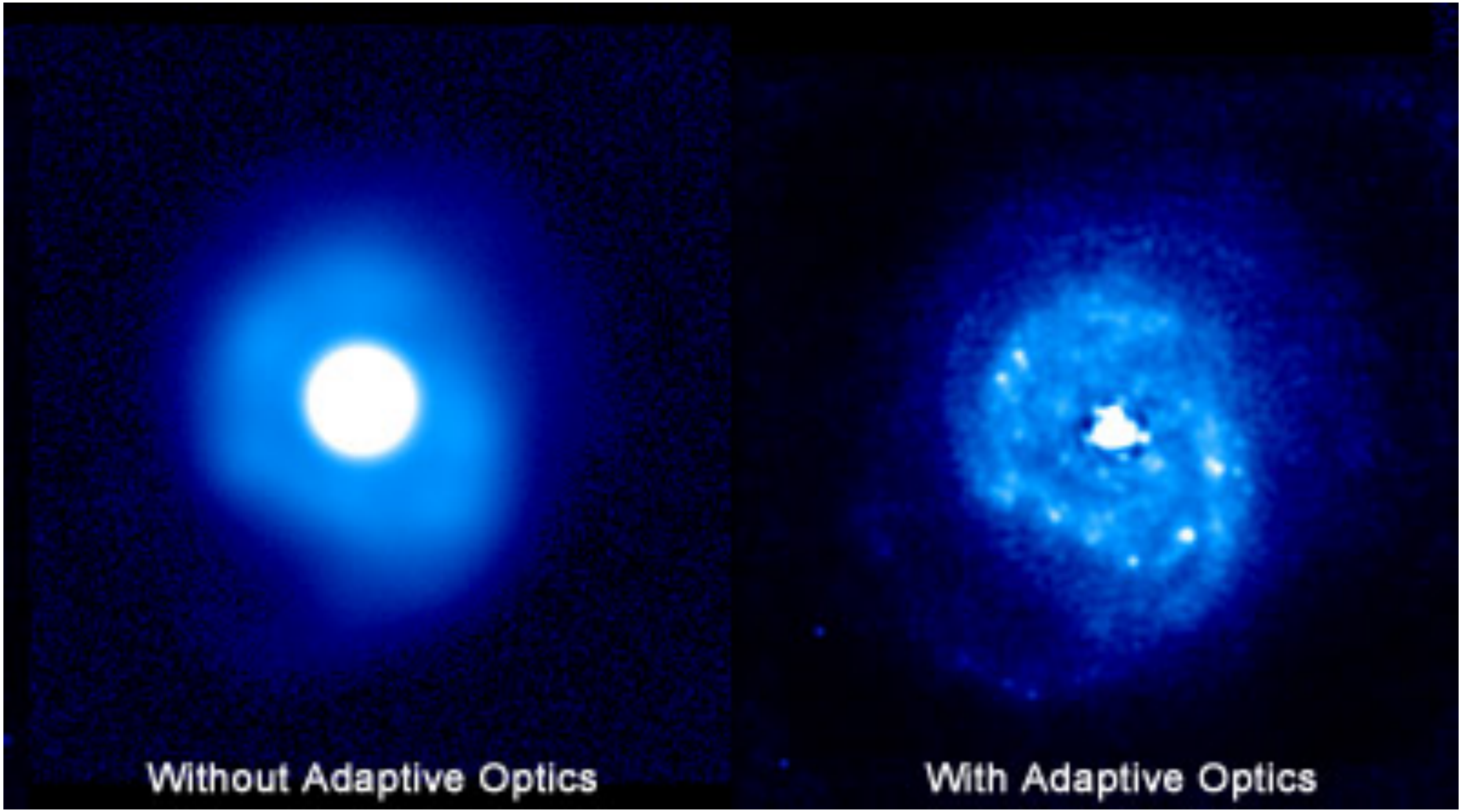
http://cfao.ucolick.org/pgallery/stellar.php

Io with and without AO



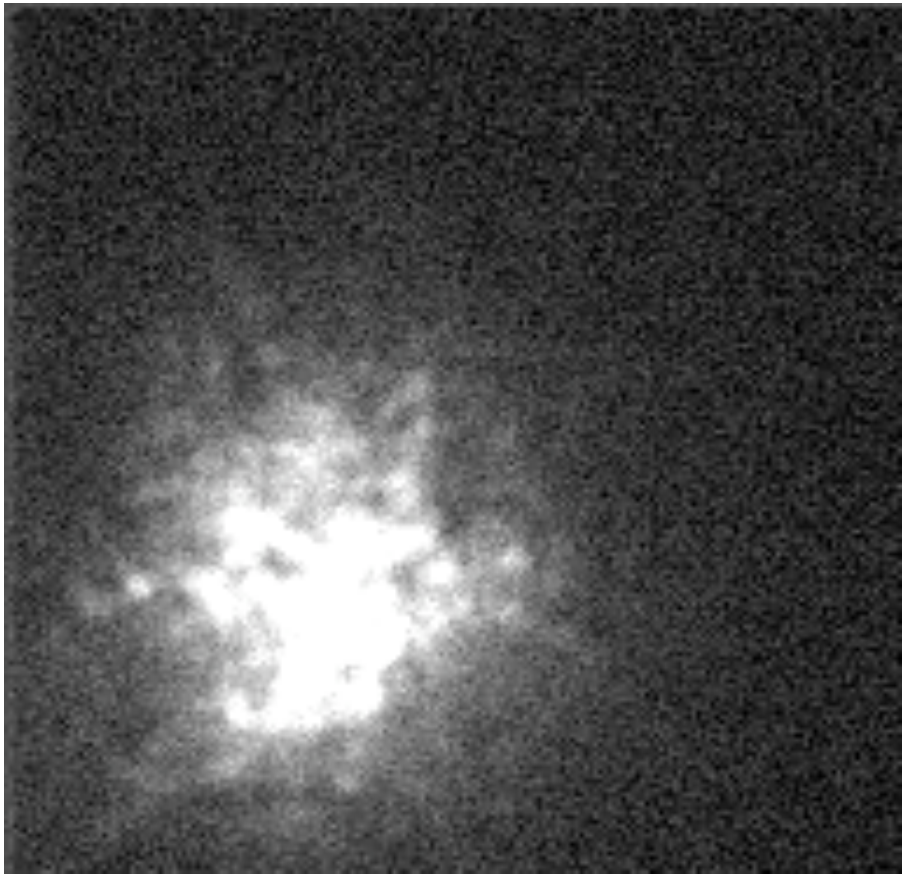
http://cfao.ucolick.org/pgallery/io.php

NGC 7469

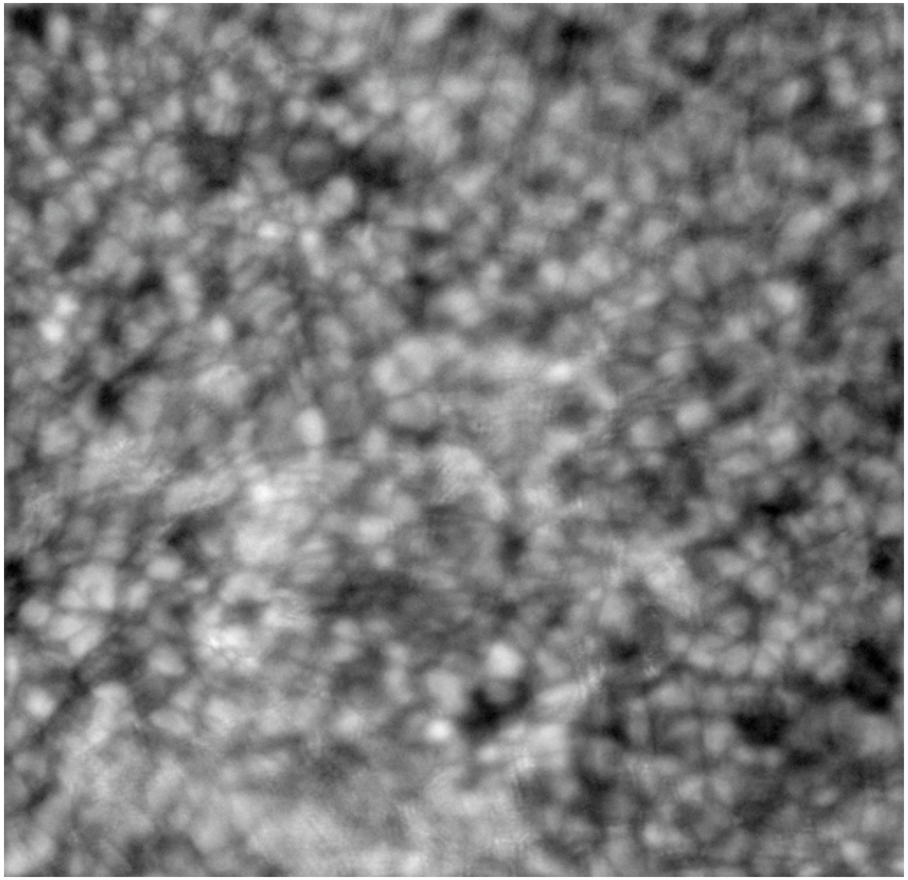


- http://cfao.ucolick.org/ao/why.php

Seeing

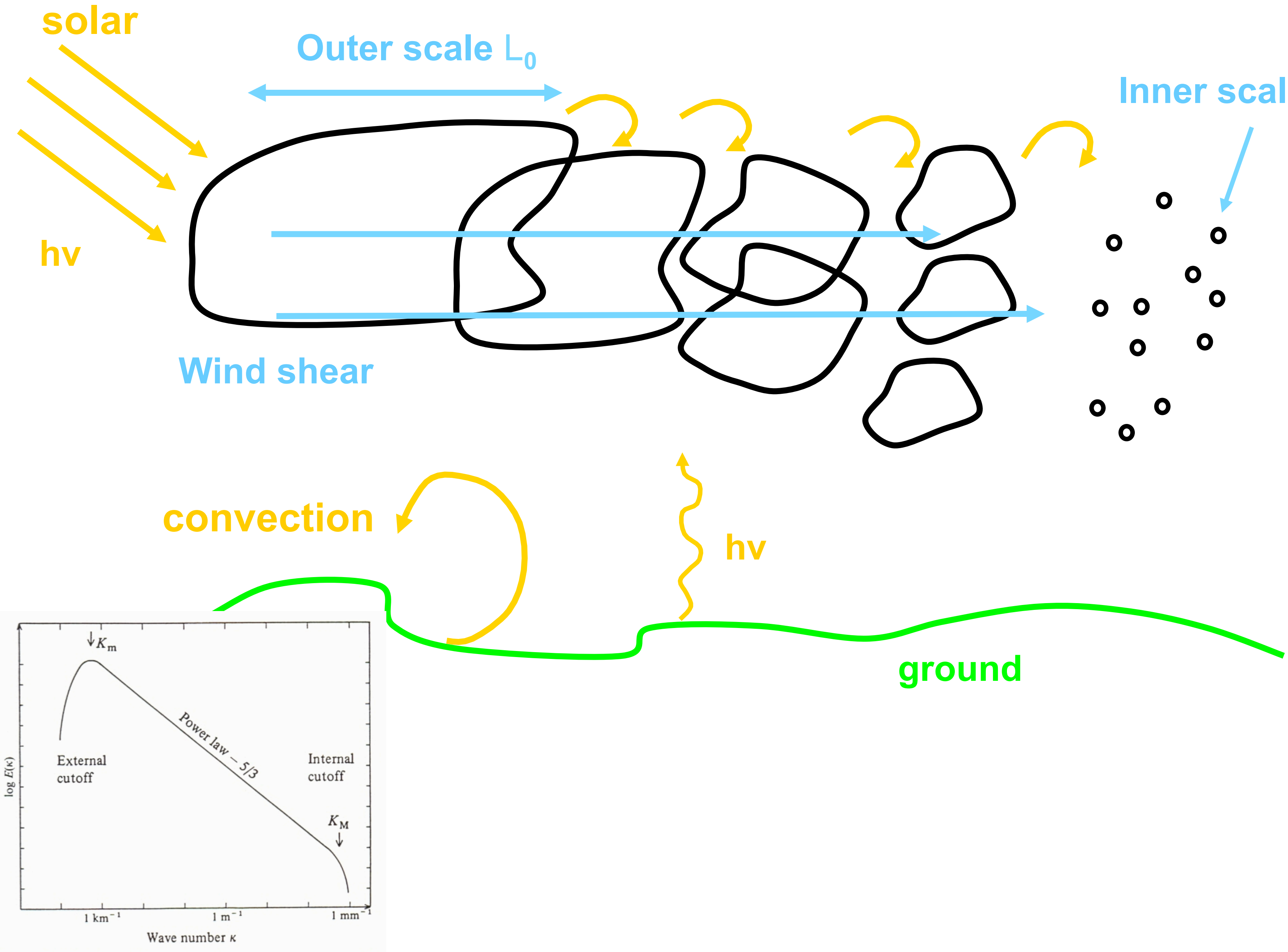


star



solar photosphere

Kolmogorov Turbulence



solar

hv

Outer scale L_0

Inner scale l_0

Wind shear

convection

hv

ground

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.

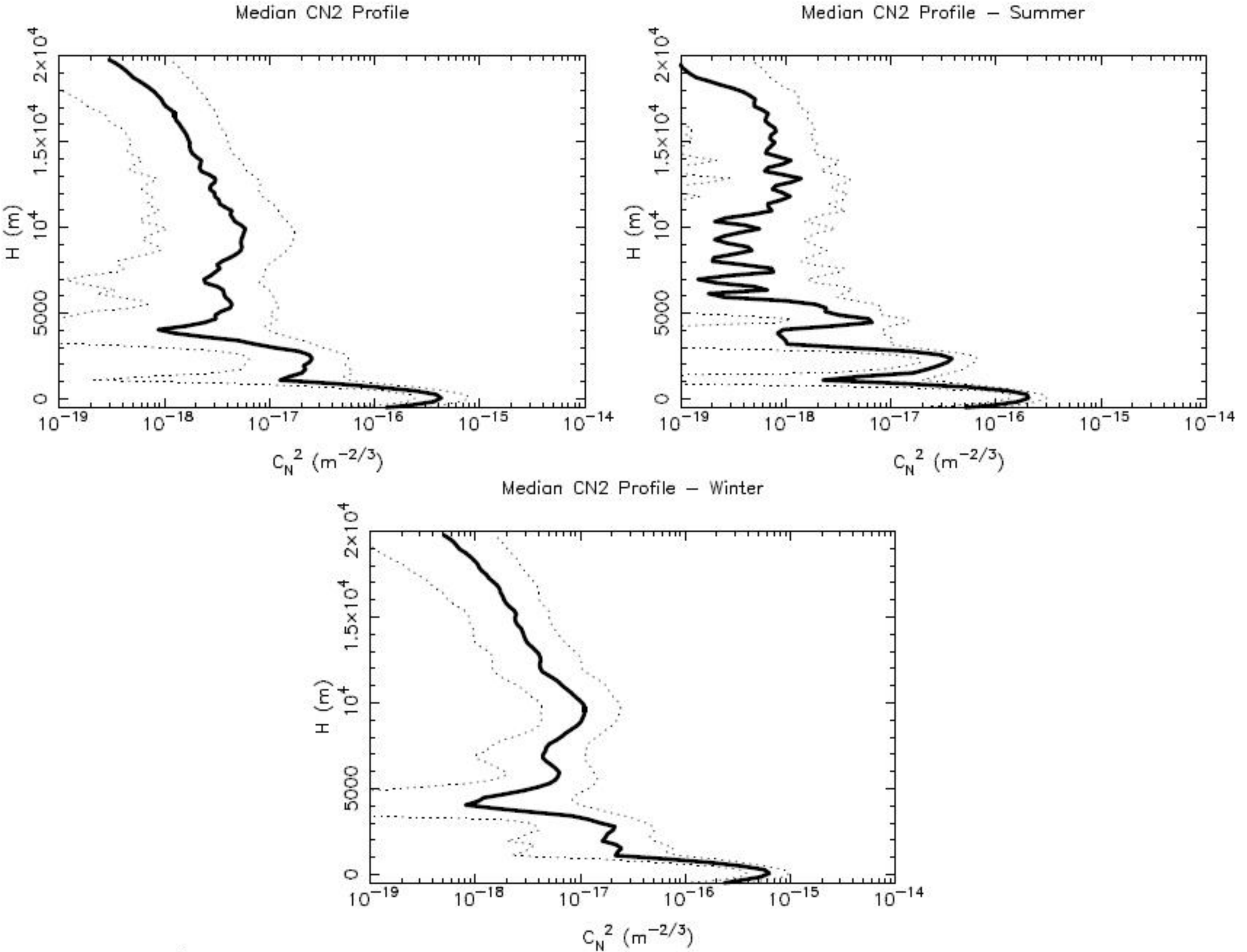
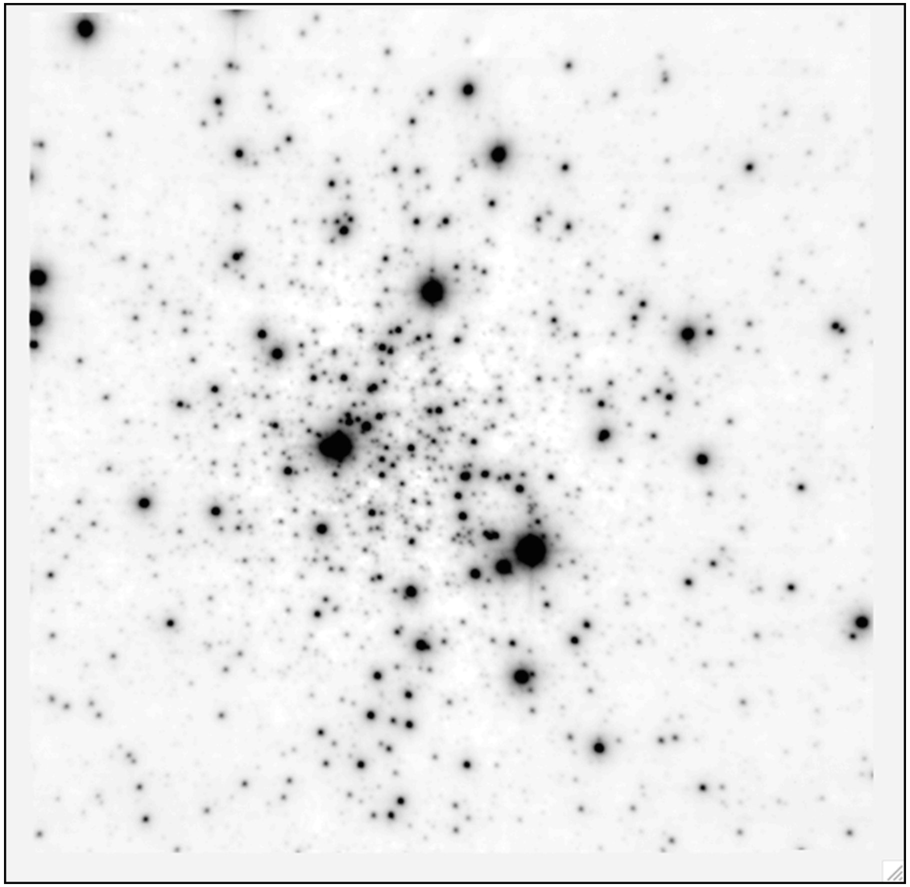


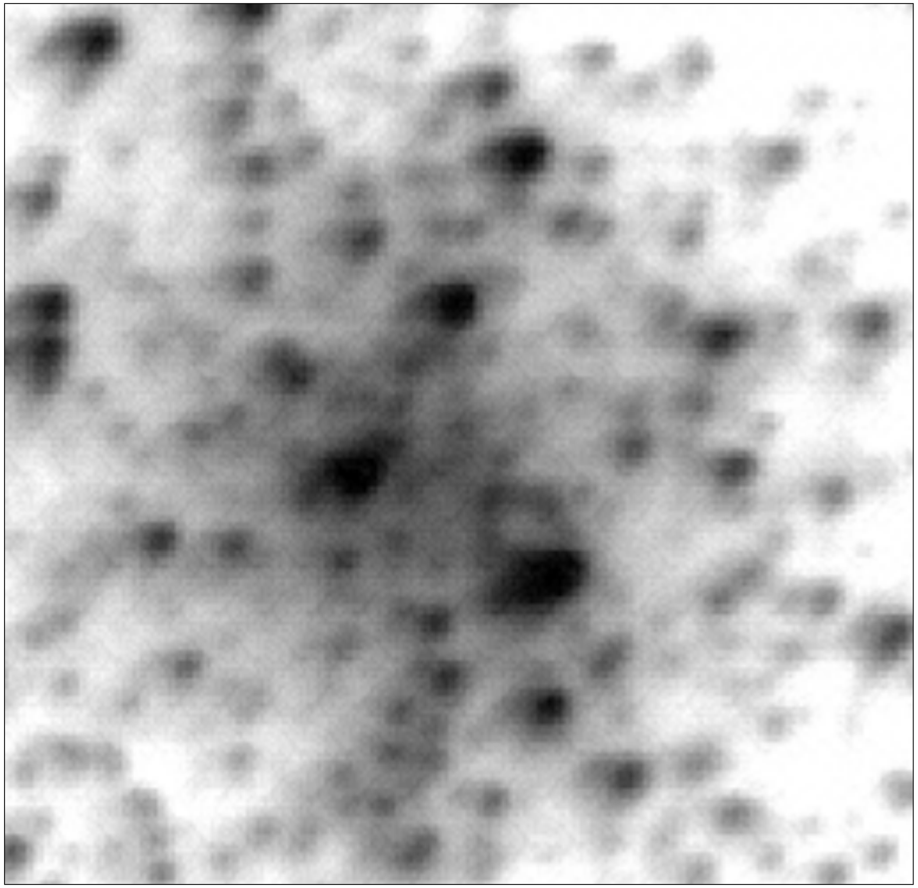
Figure 2. Median C_N^2 profile obtained with the complete sample of 43 nights, the summer [April-June] and winter [October-March] time samples. Results are obtained with the standard GS technique.

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: $S/N \sim \mathrm{D}^2 \quad \Rightarrow \text{gain in } t_{\text{int}} \sim \frac{1}{D^4}$



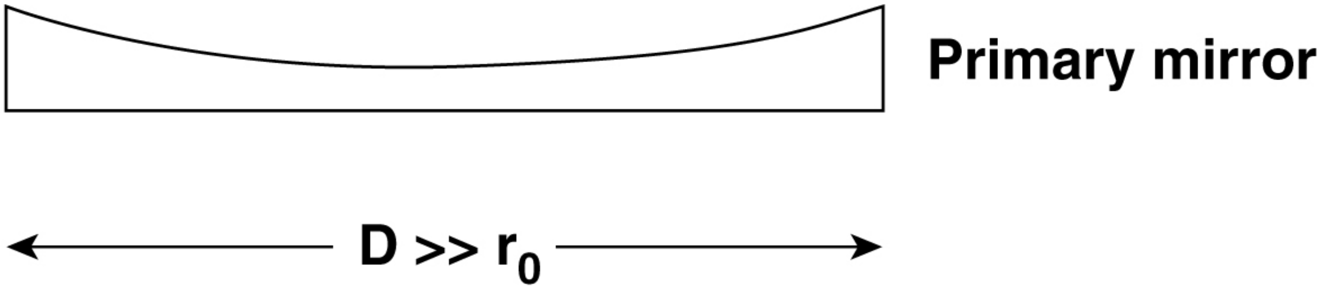
PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM



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

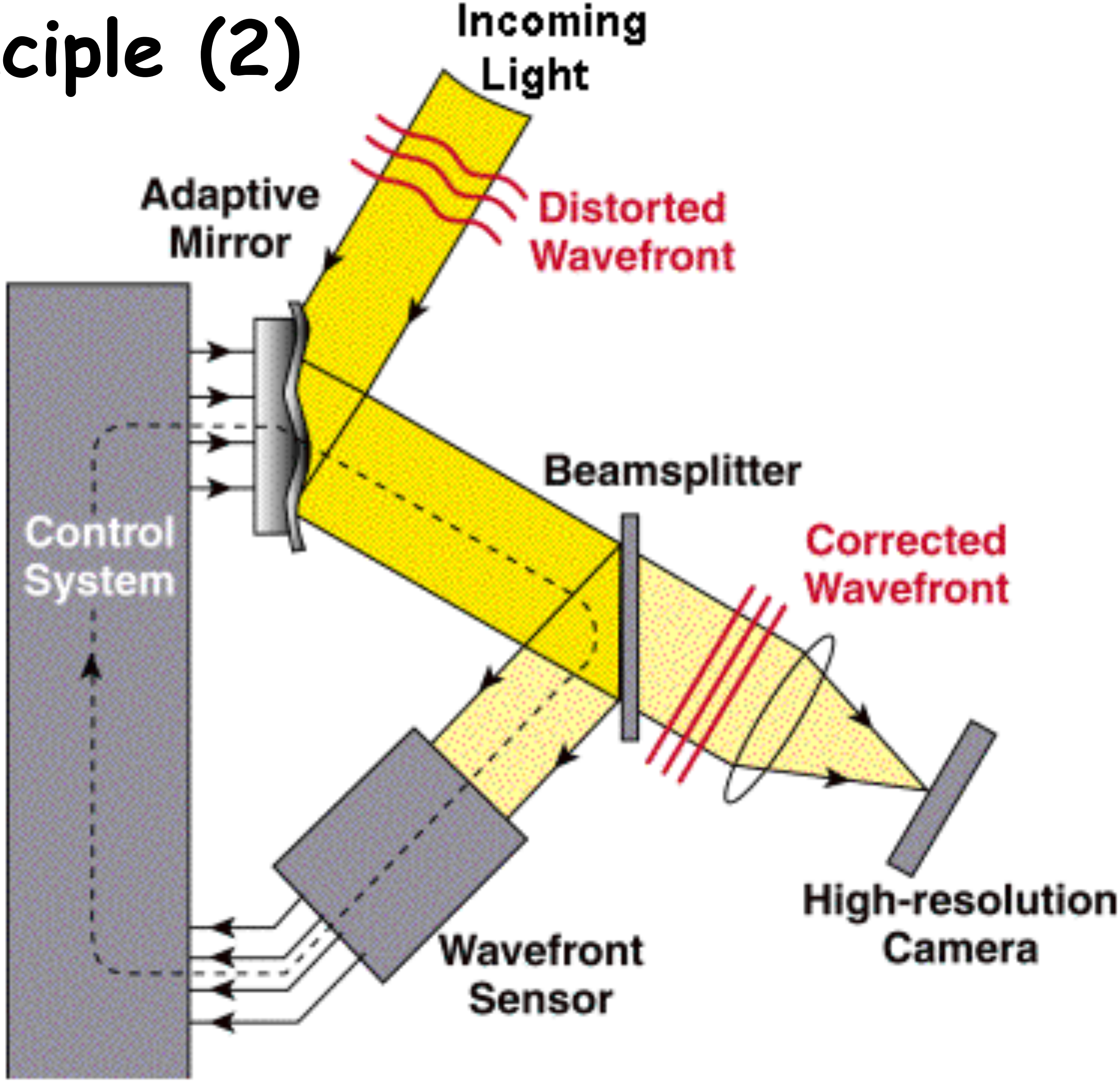
AO Principle

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)

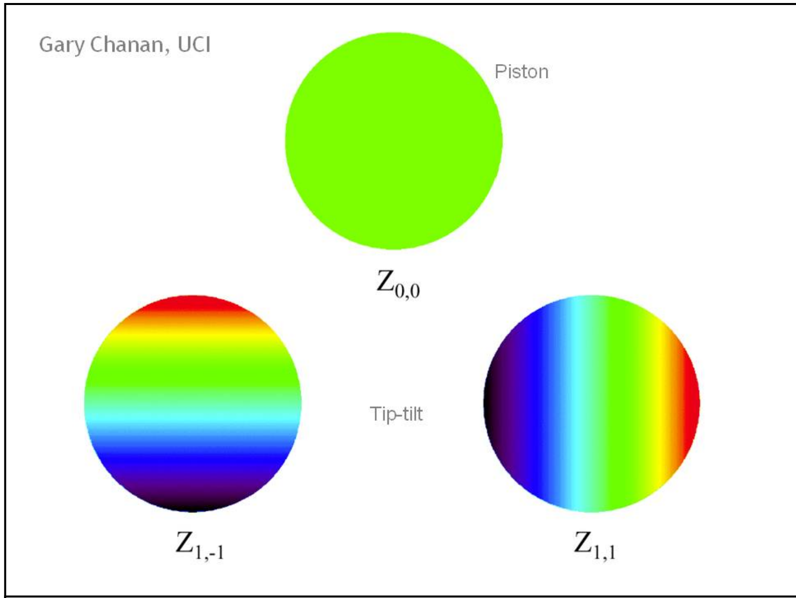


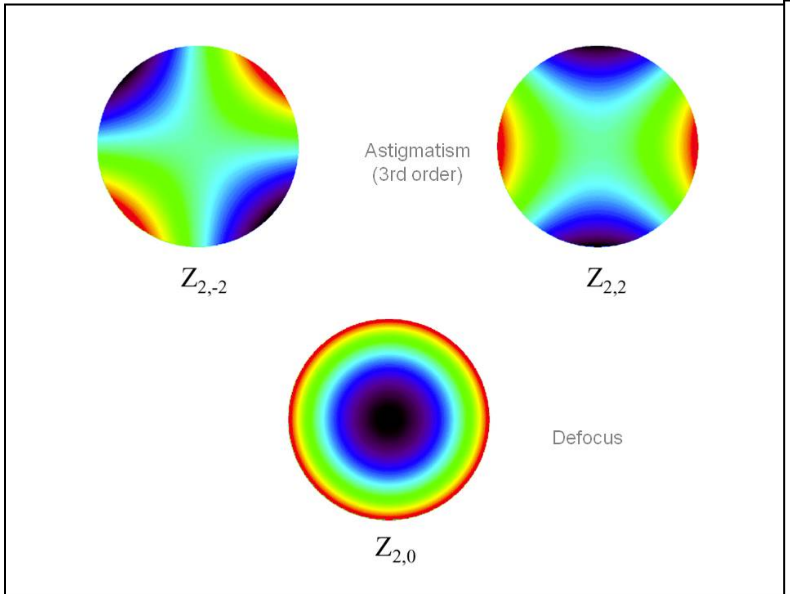
Wavefront Description: Zernike Polynomials

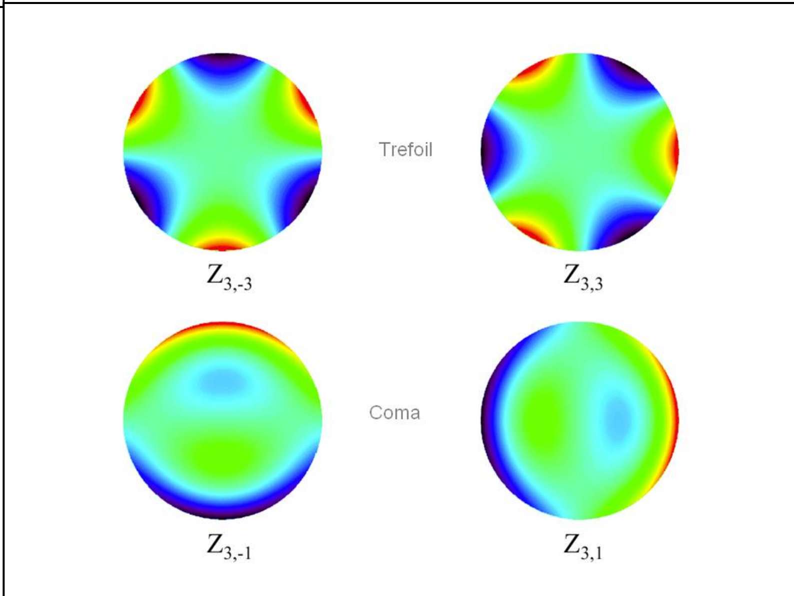
Expansion into a series of orthogonal terms:

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

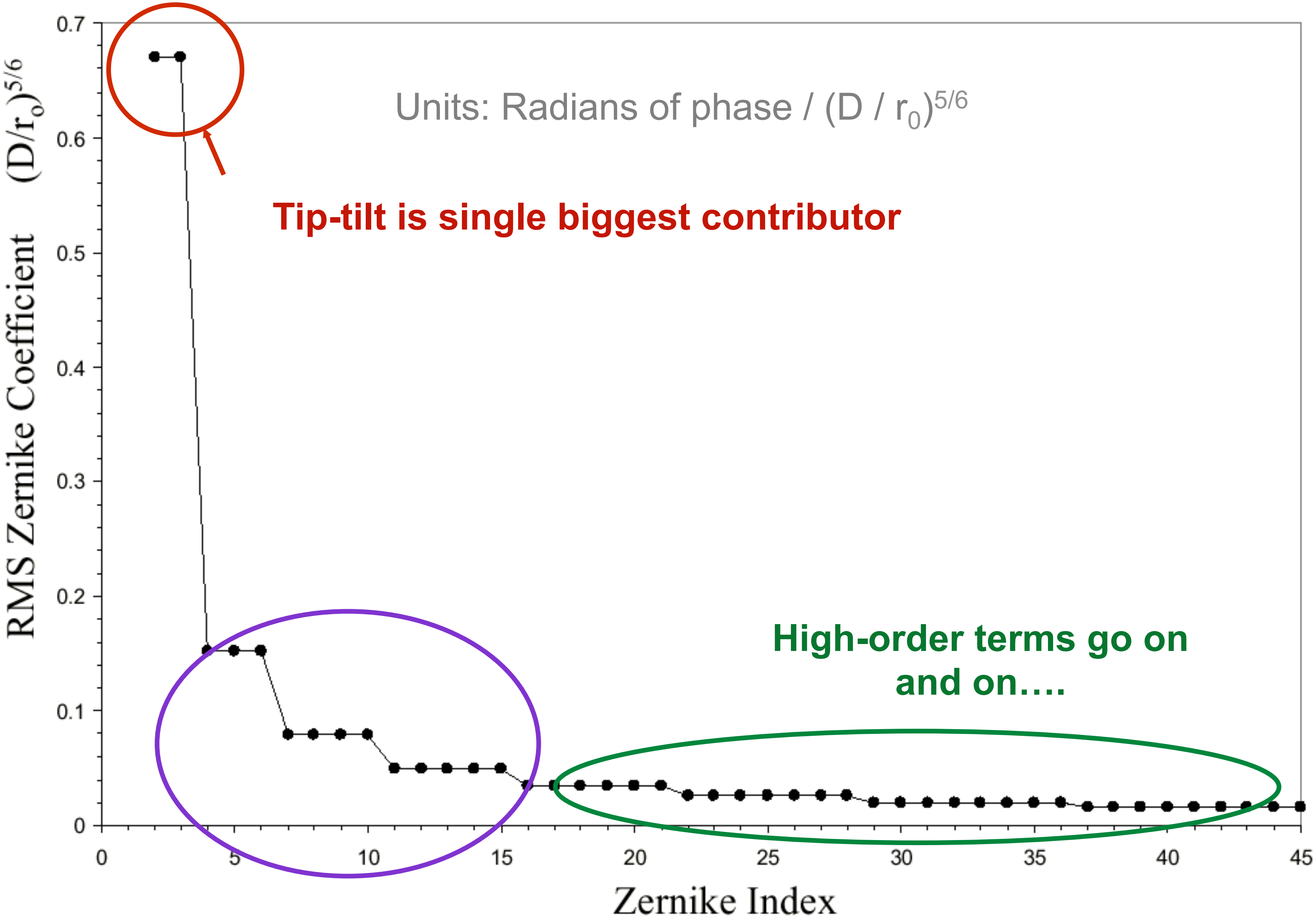
$Z_{0,0} = 1$	piston
$Z_{1,-1} = 2\, r \sin\theta$	tip/tilt
$Z_{1,1} = 2\, r \cos\theta$	
$Z_{2,-2} = \sqrt{6}\, r^2 \sin 2\theta$	astigmatism
$Z_{2,0} = \sqrt{3}\,(2r^2 - 1)$	focus
$Z_{2,2} = \sqrt{6}\, r^2 \cos 2\theta$	astigmatism







Tip-Tilt and higher order Terms (1)



Units: Radians of phase / $(D / r_0)^{5/6}$

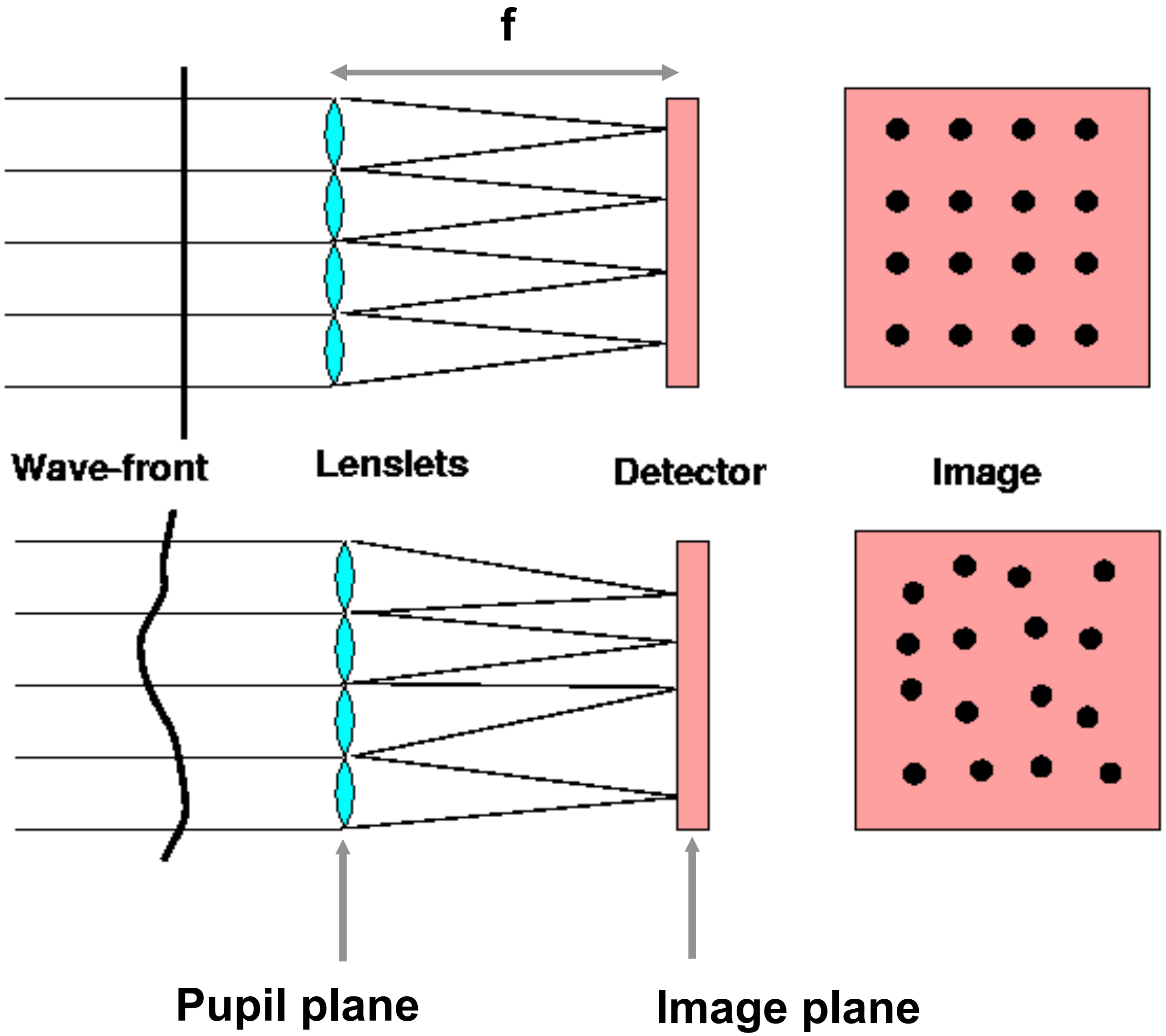
Tip-tilt is single biggest contributor

High-order terms go on and on….

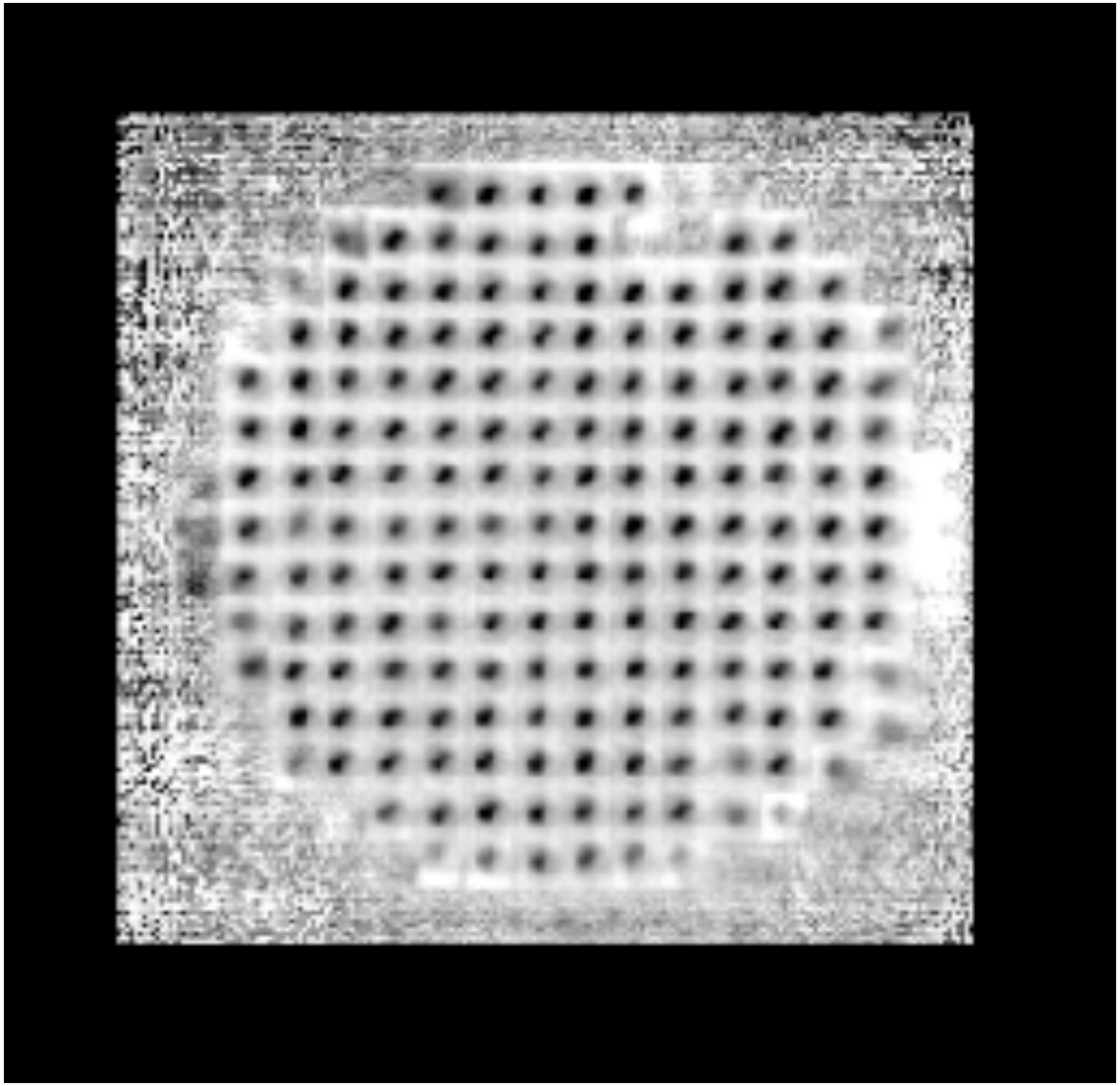
Reference: Noll

Wavefront Sensors – Shack Hartmann

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

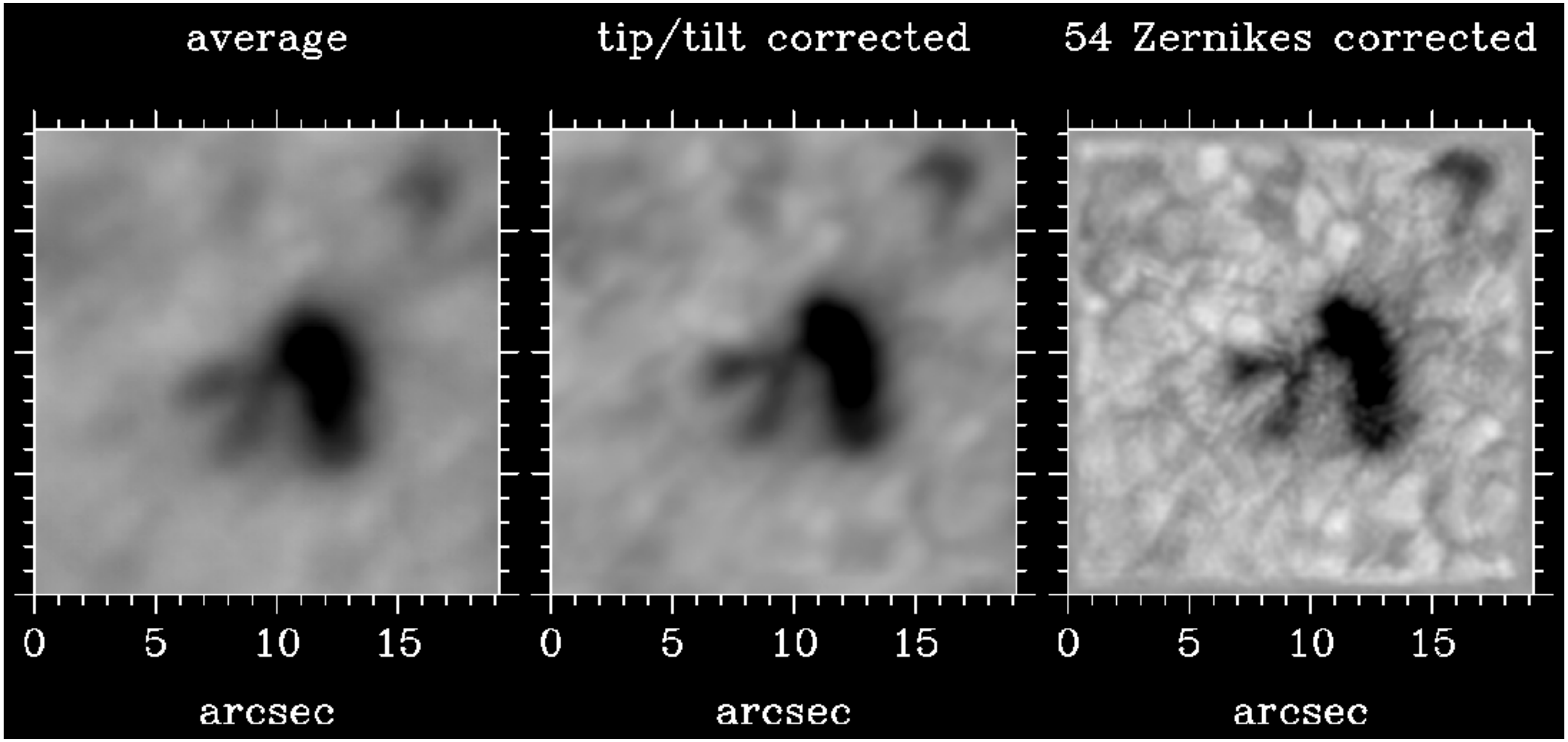


Wavefront Sensing



Sunspot wavefront
sensor images at 955Hz

Deconvolution from Wavefront Sensing

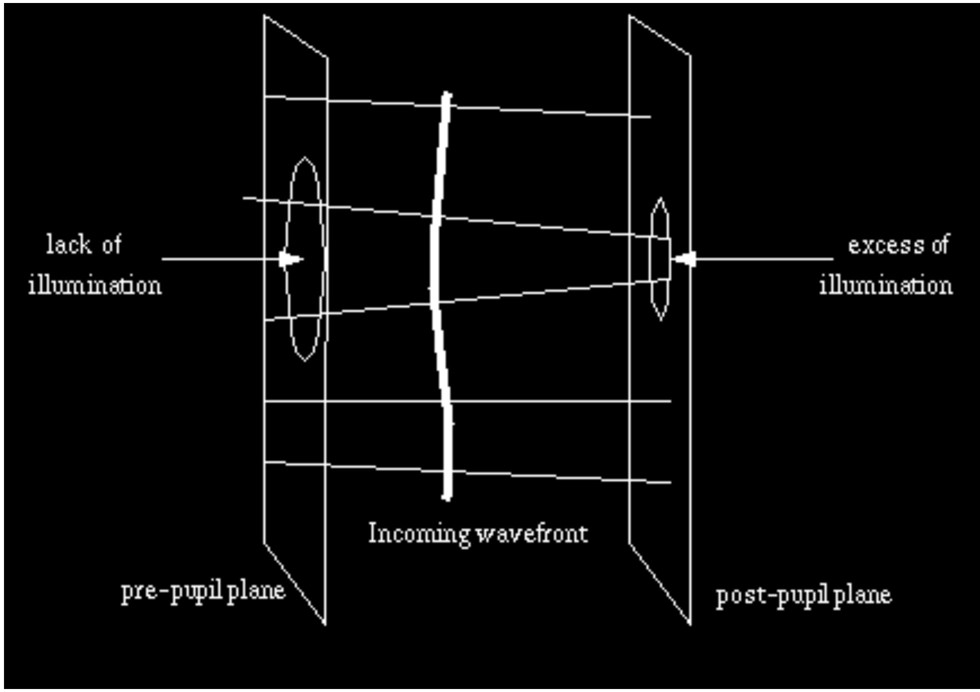


- deconvolution from wavefront sensing provides AO-like results
- 106 subapertures over 1m aperture at 950 nm at McMath-Pierce telescope

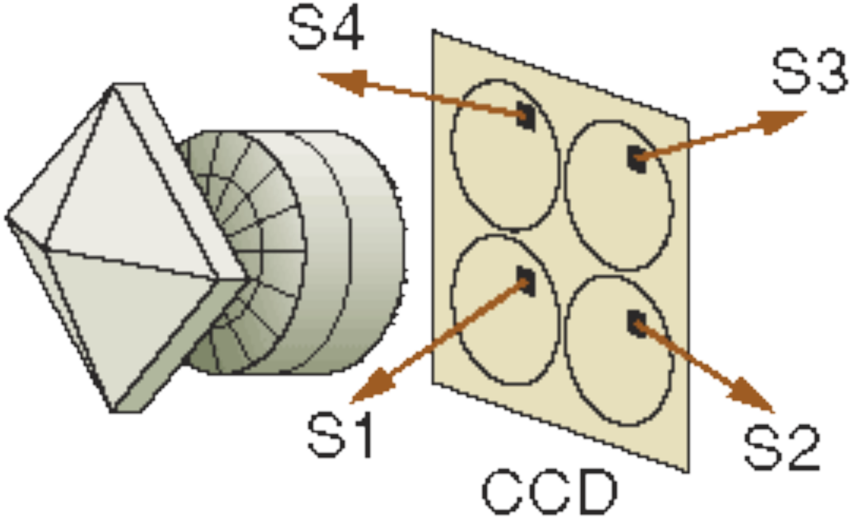
WFs: Curvature and Pyramid Sensors

Other common principles are the

curvature sensor →

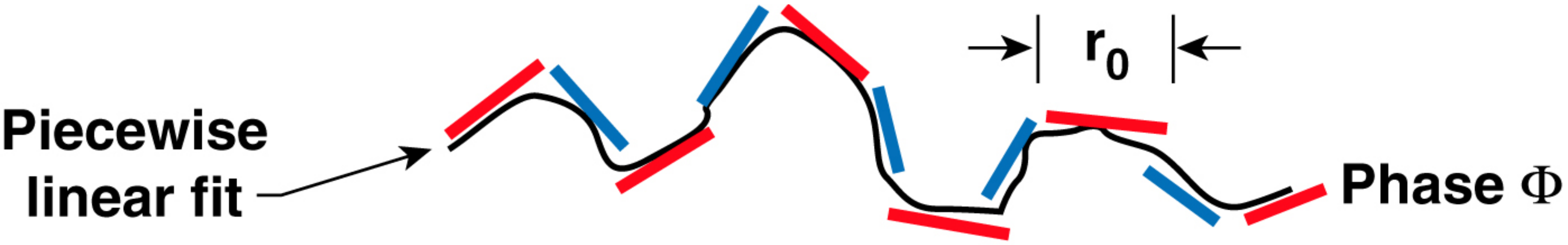


and the pyramid sensor →



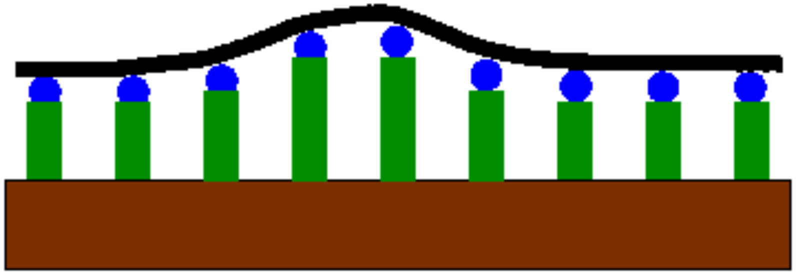
Deformable Mirrors

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:



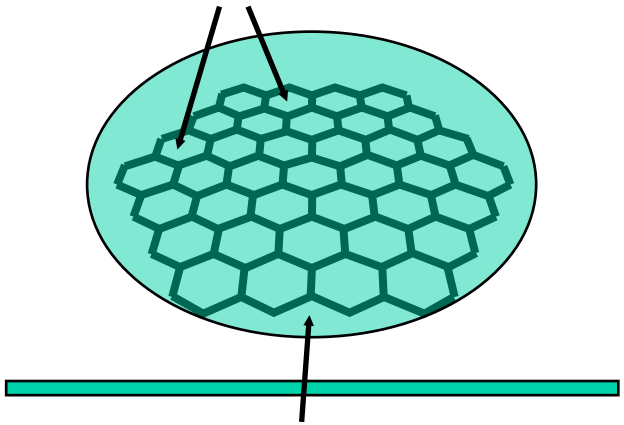
Note that the (piezo) actuator stroke is typically only a couple of micrometers → requires separate tip-tilt mirror.

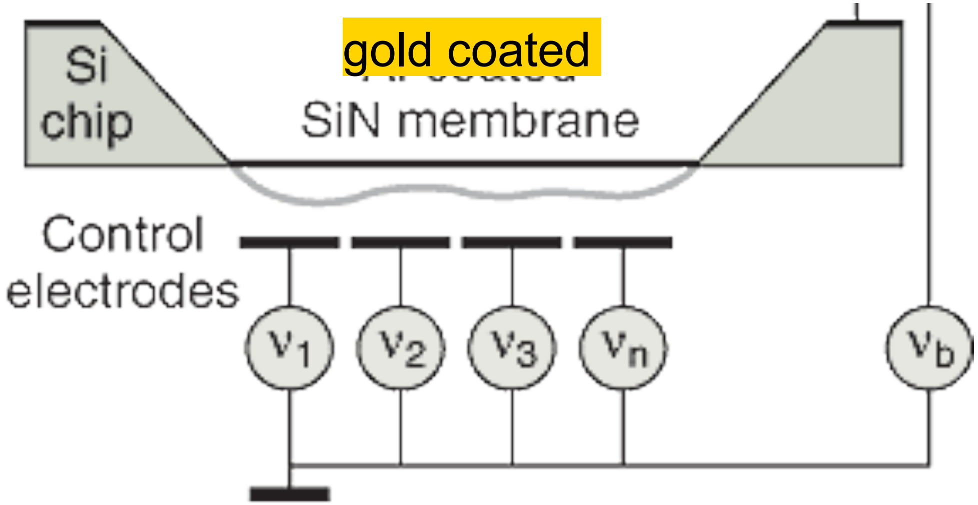
Membrane Deformable Mirror

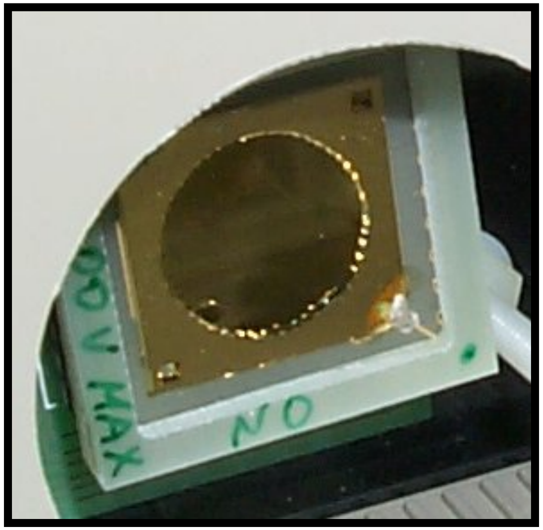
micromachined deformable mirror (OKOtech/Flexible Optics) with 37 actuators

600-nm thick, 15-mm diameter silicon nitride membrane

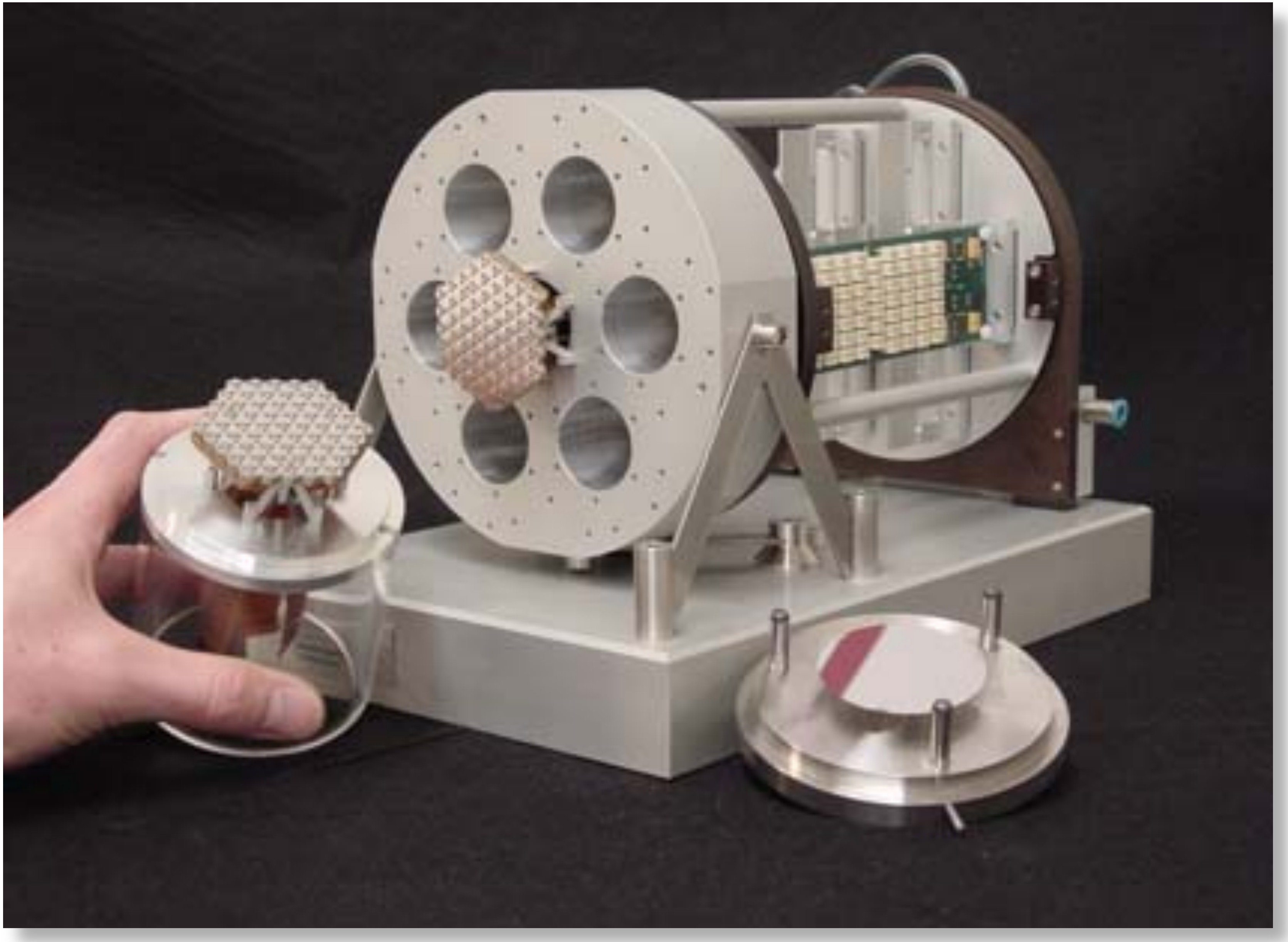
electrostatic actuators







TNO TU/e Deformable Mirror



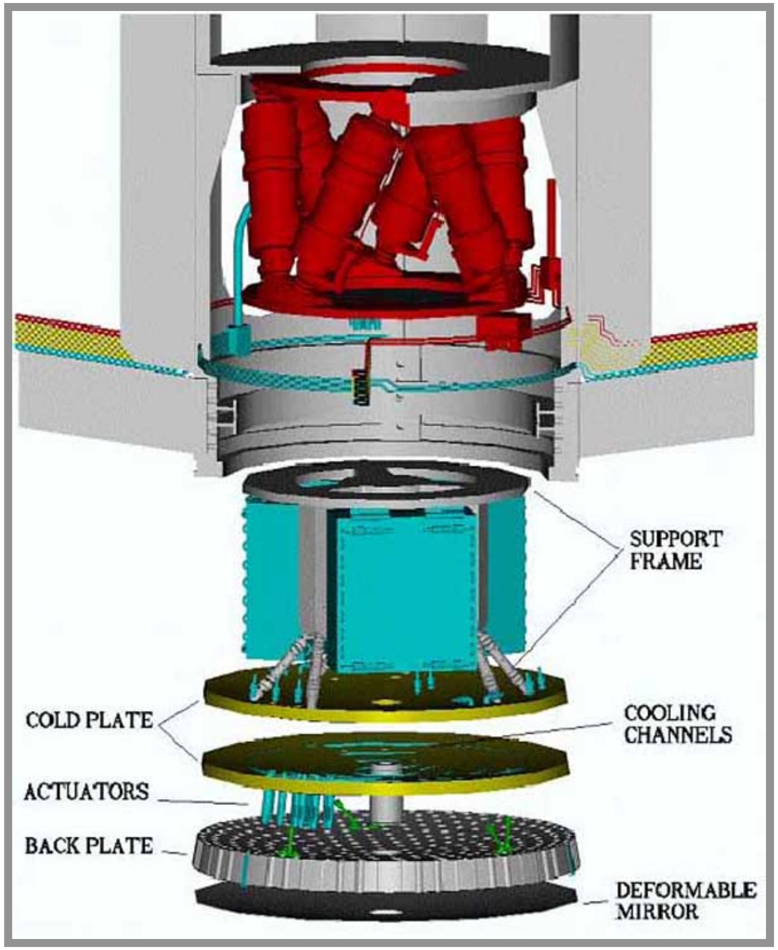
Adaptive Secondary Mirrors

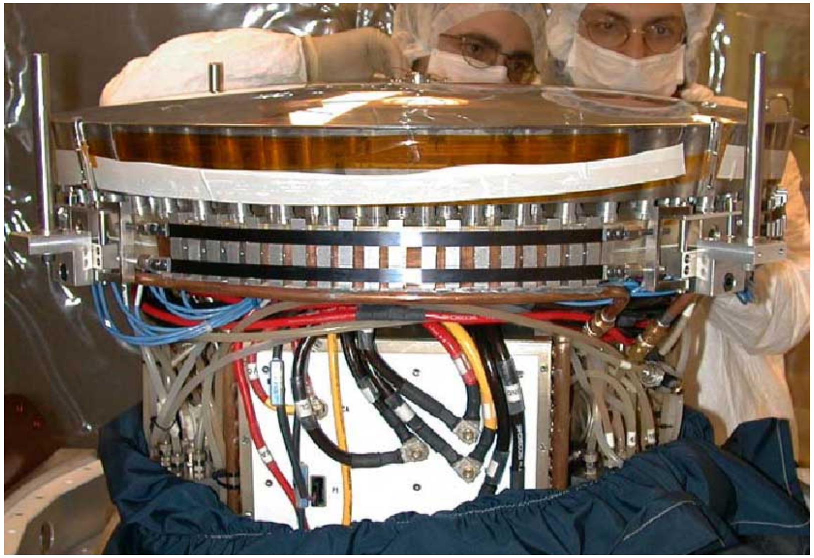
Concept: integrate DM into the telescope → adaptive secondary mirrors.

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.



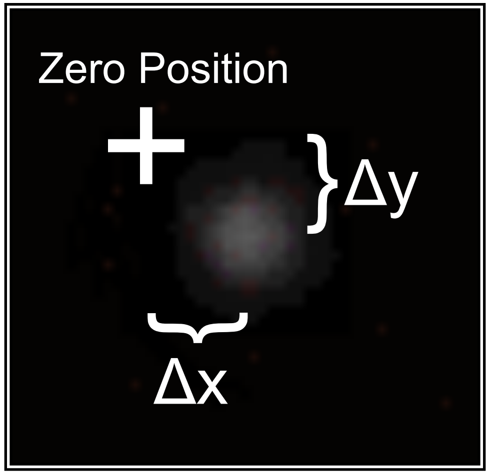


DM for MMT Upgrade

Wavefront Analysis

performs centroid (center of gravity) calculation on each spot:

$$x_{pos} = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j) \cdot i}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)} \qquad y_{pos} = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j) \cdot j}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)}$$



Influence Matrix

- ignore wavefront shape
- slope of mirror surface *and* Shack-Hartman spot offsets are proportional to voltage
- linear relationship between actuator *a* and spot offset *c*:

$$c_n = \sum_{k=1}^{N} a_k b_{nk}$$ (For a single spot — x-offset or y-offset)

- Combine equations for each spot offset *n* in matrix equation:

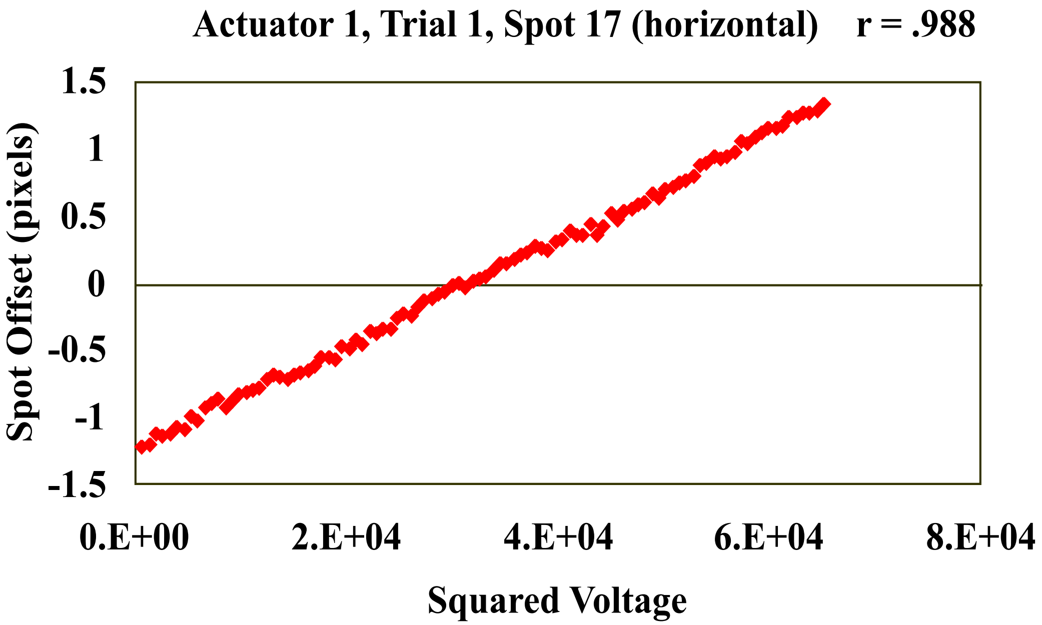
$$C = BA$$

- *C* = spot offsets
- *A* = control vector (voltages)
- B = influence matrix describing influence of specific actuator voltages on spot offsets

Measuring the Influence Matrix

- need to know voltages that will correct wavefront
- solve for A (control vector) given C (spot offsets)
- first find B (influence matrix) through direct measurement
    - Step each actuator k through the possible voltages and measure the spot locations at each step
    - For the kth actuator and the nth spot coordinate, the slope of the best fit line is the element (n, k) of the influence matrix B

- Influence matrix gives the resulting spot offsets when multiplied by a control vector (list of voltages)



Solving for the Control Vector

- Influence matrix B is known and C is given from wavefront sensor
- Find A (control vector) to correct for error in wavefront
- Invert equation C = BA:

$$A = B^{-1}C$$

- Overdetermined system:
  - More spot measurements than actuators
  - No exact solution A exists for any given set of spot offsets
  - No exact B^{-1} exists (B is rectangular)
- Singular Value Decomposition: Generates approximate B^{-1} that won't solve equation, but will represent best solution

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!)

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

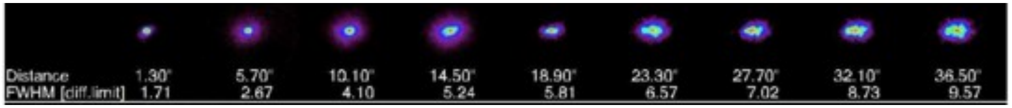
- Calibration errors from aberrations in the non-common path between sensing channel and imaging channel.

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

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

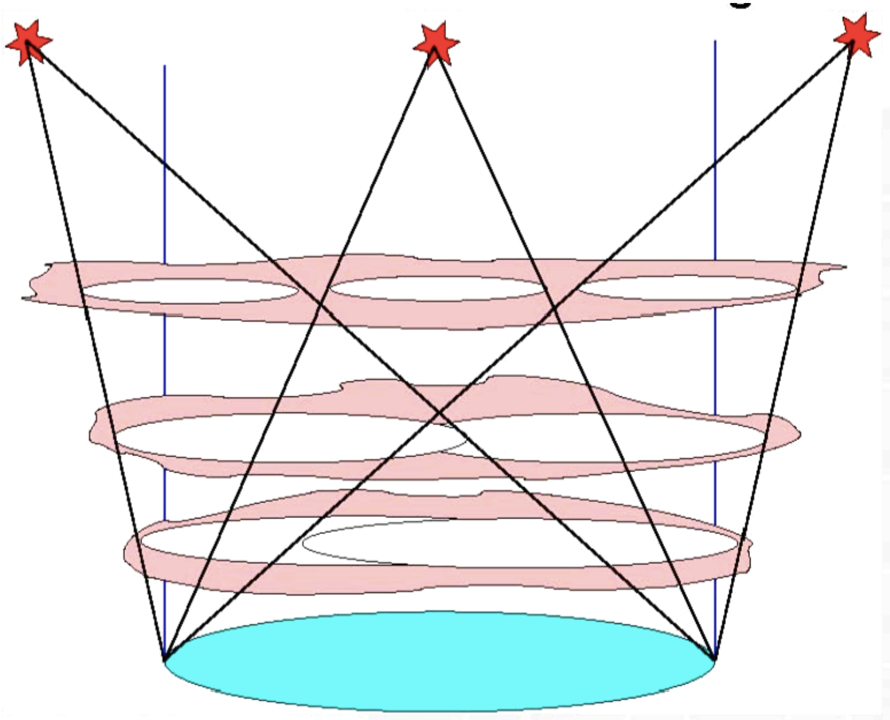
$$\sigma_{aniso}^2 \approx \left(\frac{\theta}{\theta_0}\right)^{5/3}$$

Angular Anisoplanatism

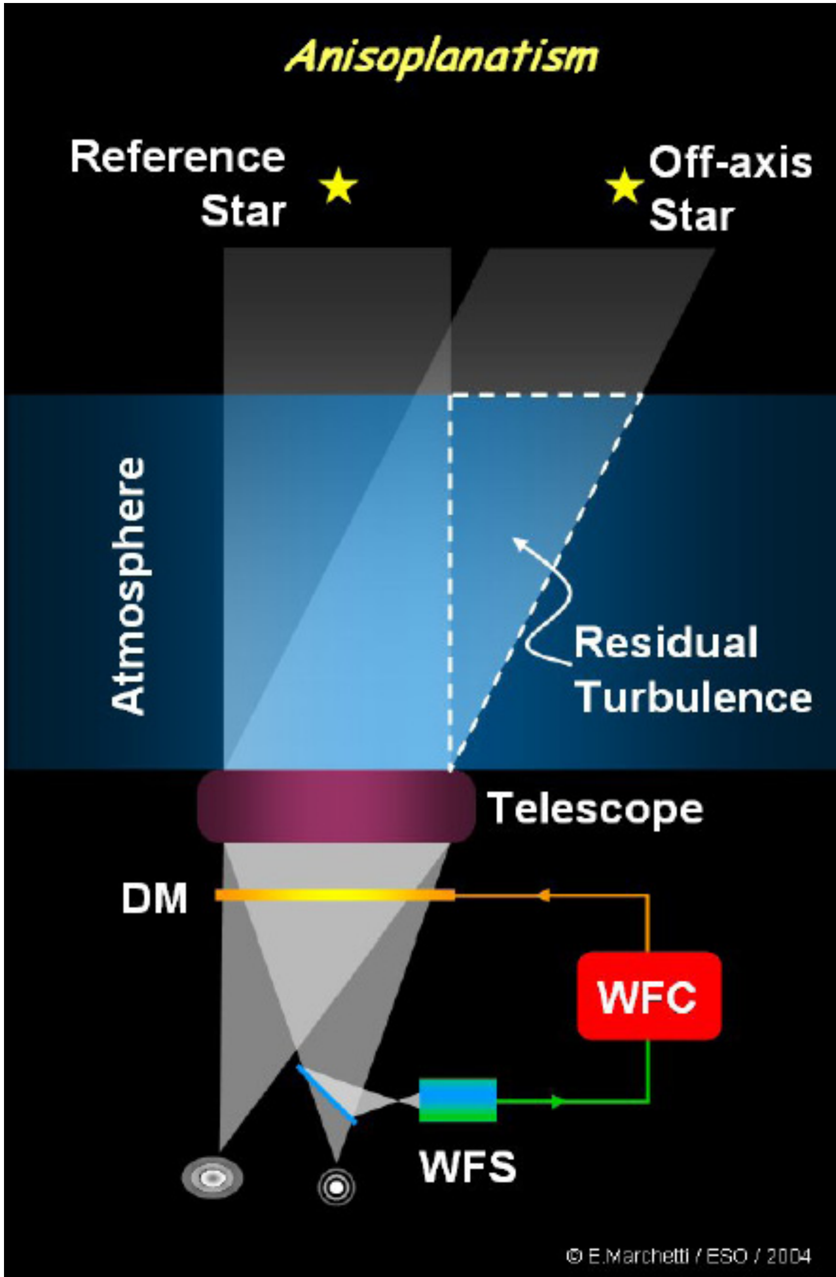


Angular anisoplanatism is a severe limitation to:

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



Multi-LGS allows to fight cone effect AND increase FOV



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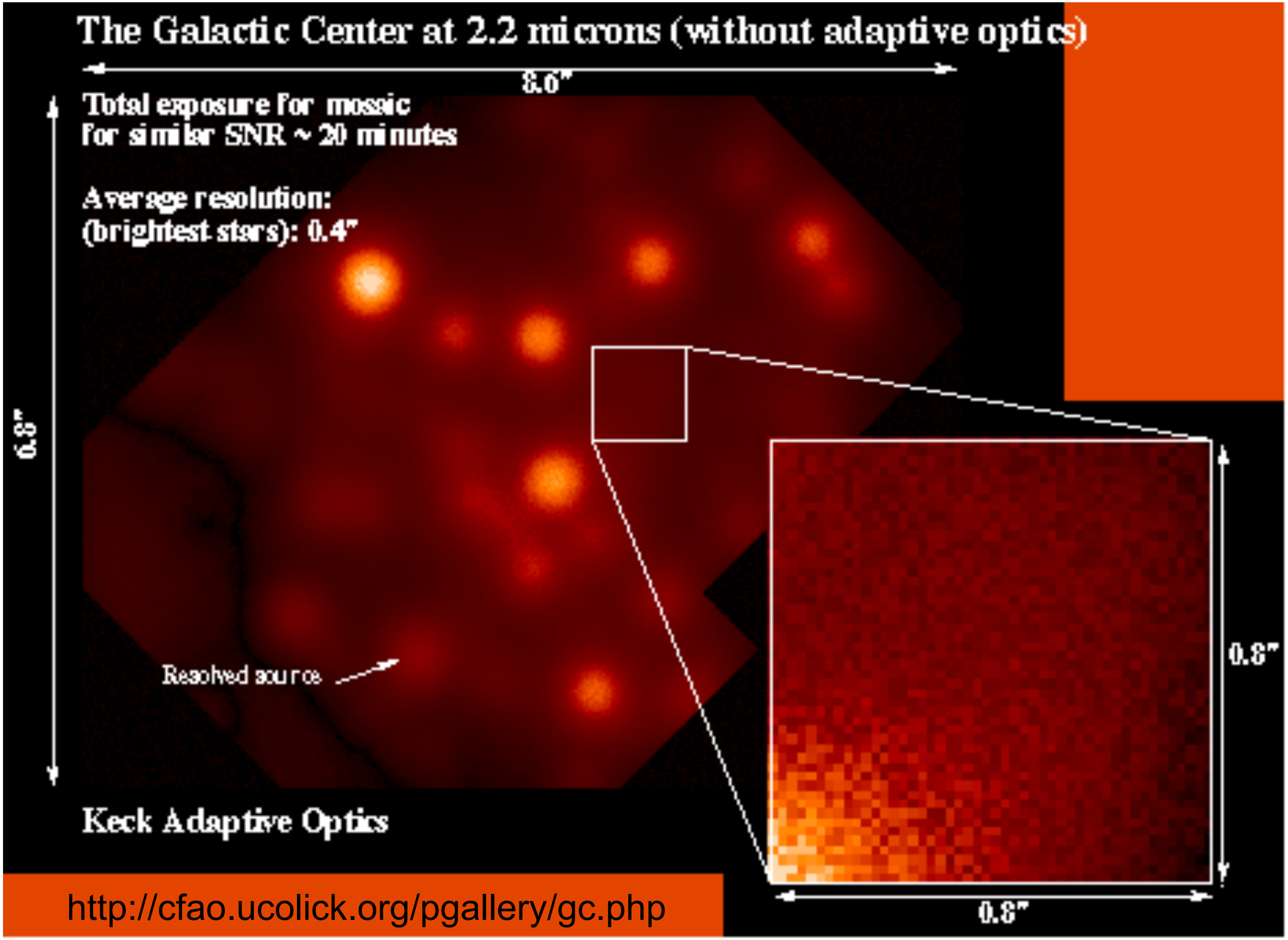
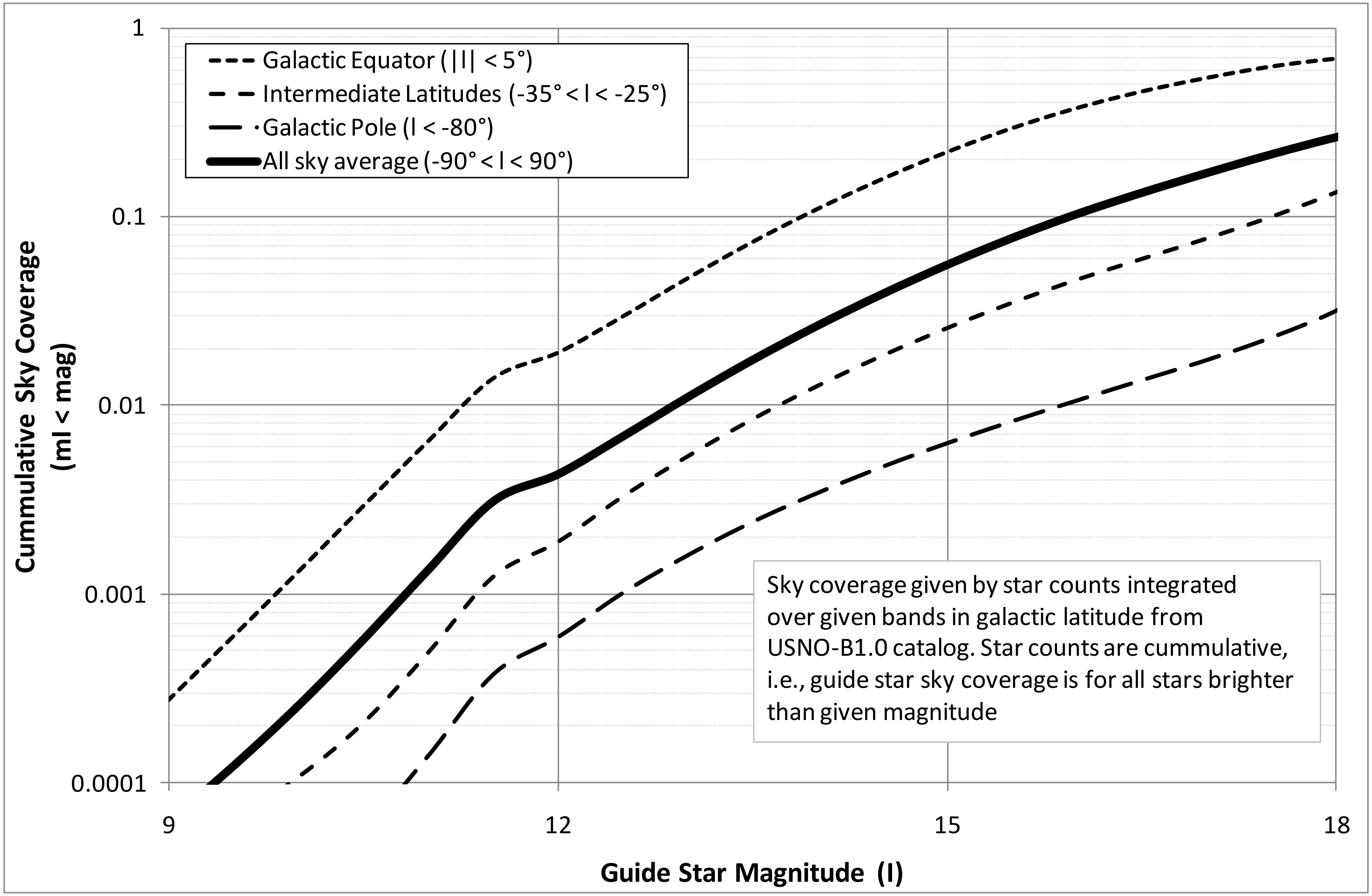
“Typical” Correction and Residuals



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

Sky Coverage

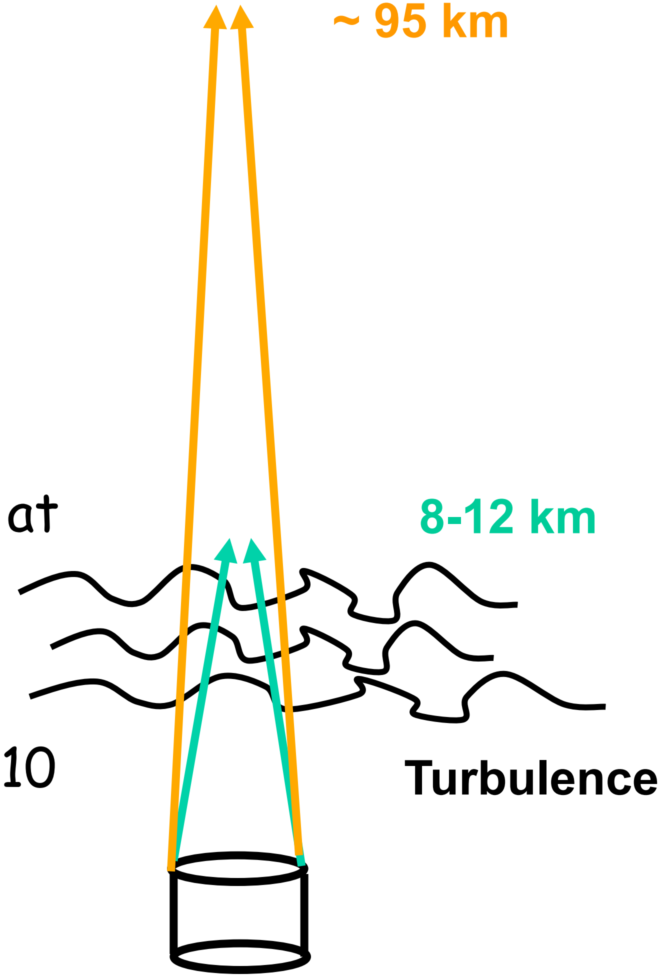
To sense the wavefront one needs a bright reference/guide star within the isoplanatic angle.



Sky coverage given by star counts integrated over given bands in galactic latitude from USNO-B1.0 catalog. Star counts are cummulative, i.e., guide star sky coverage is for all stars brighter than given magnitude

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:

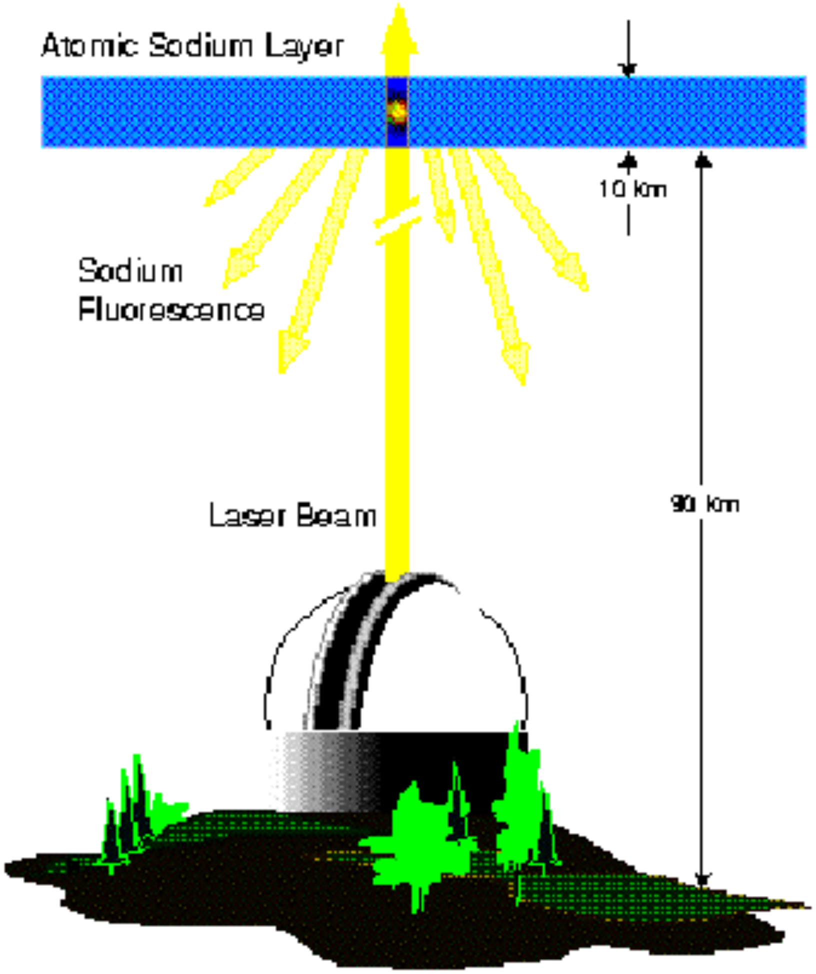
- Sodium LGS – excite atoms in "sodium layer" at altitude of ~ 95 km.

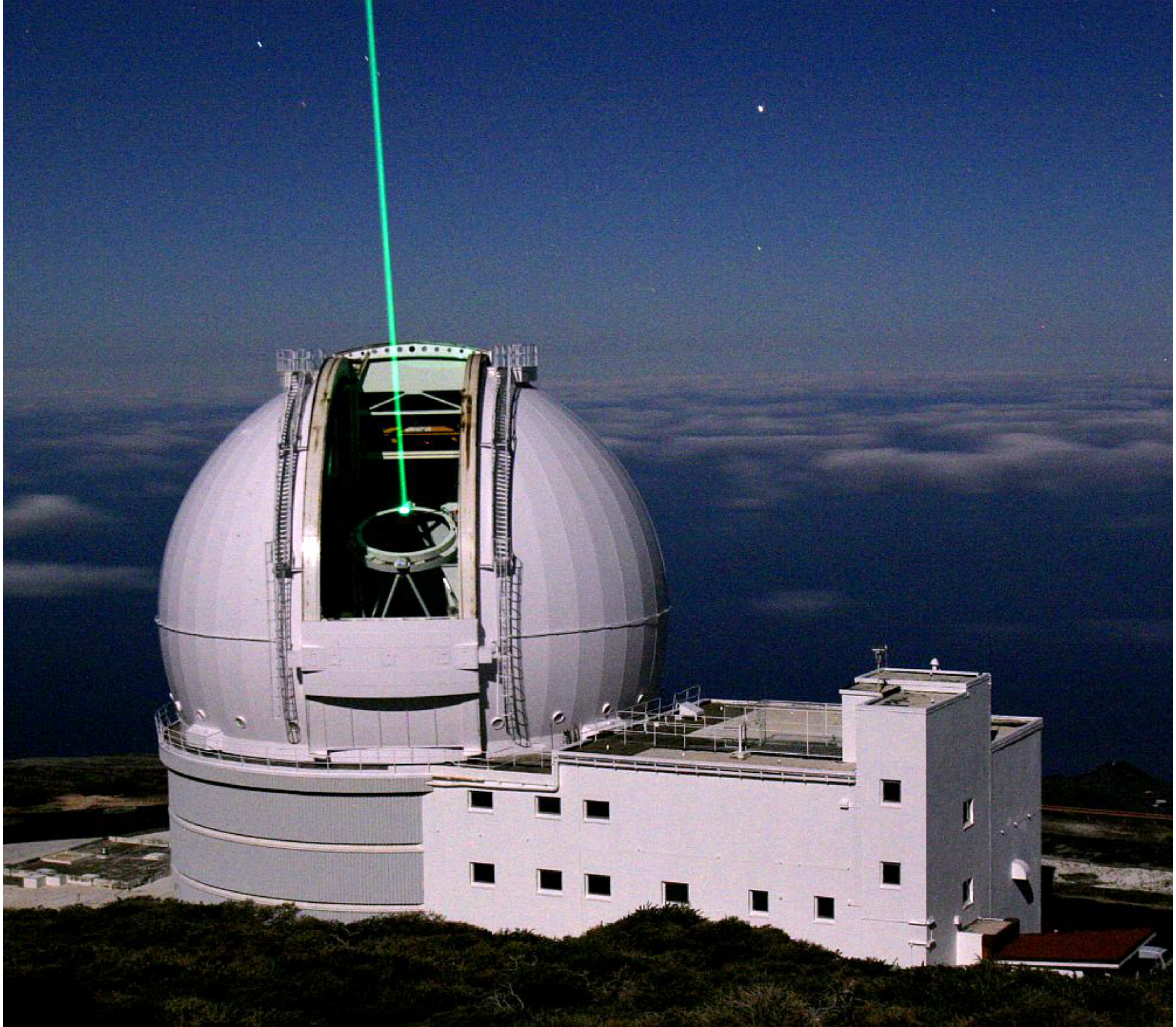
- Rayleigh beacon LGS – scattering from air molecules sends light back into telescope, h ~ 10 km

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

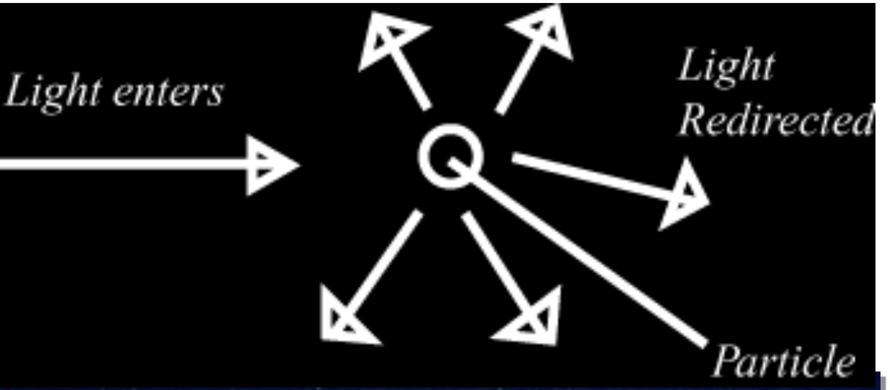
Layer of neutral sodium atoms in mesosphere (height ~ 95 km, thickness ~10km) thought to be deposited as smallest meteorites burn up. Resonant scattering occurs when incident laser is tuned to D2 line of Na at 589 nm.





Rayleigh Beacons

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



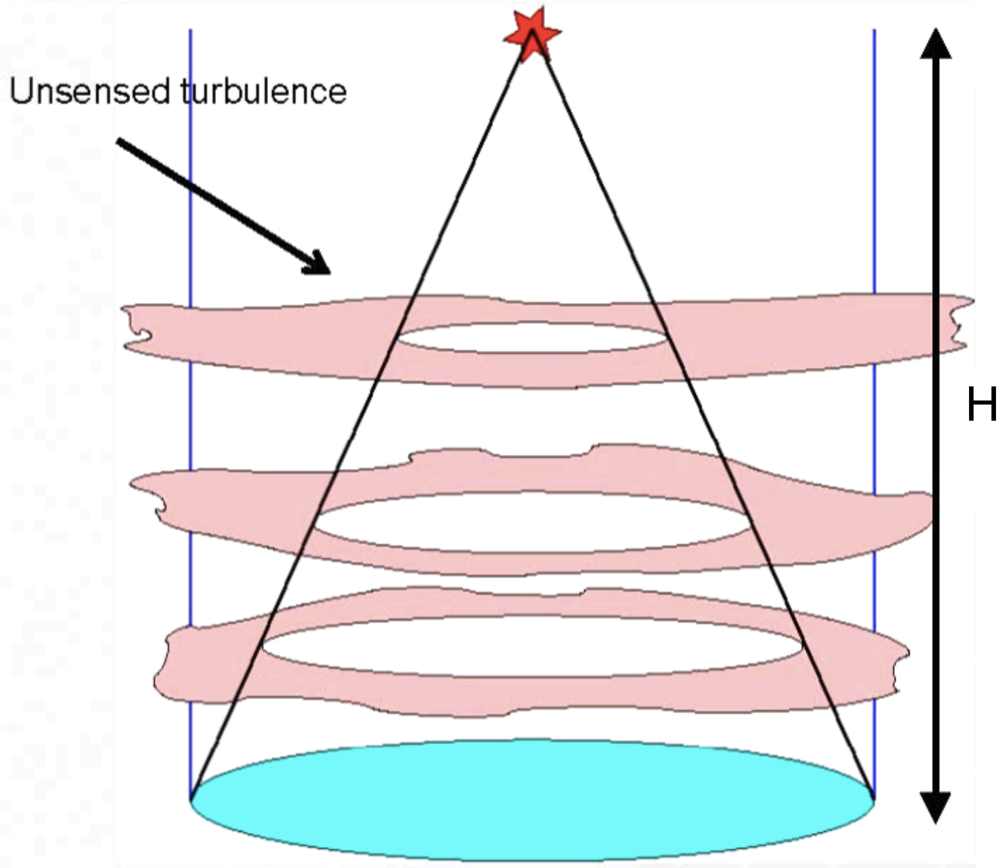
Advantages:
- cheaper and easier to build
- higher power
- independent of Na layer

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.

Ground Layer AO – GLAO

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

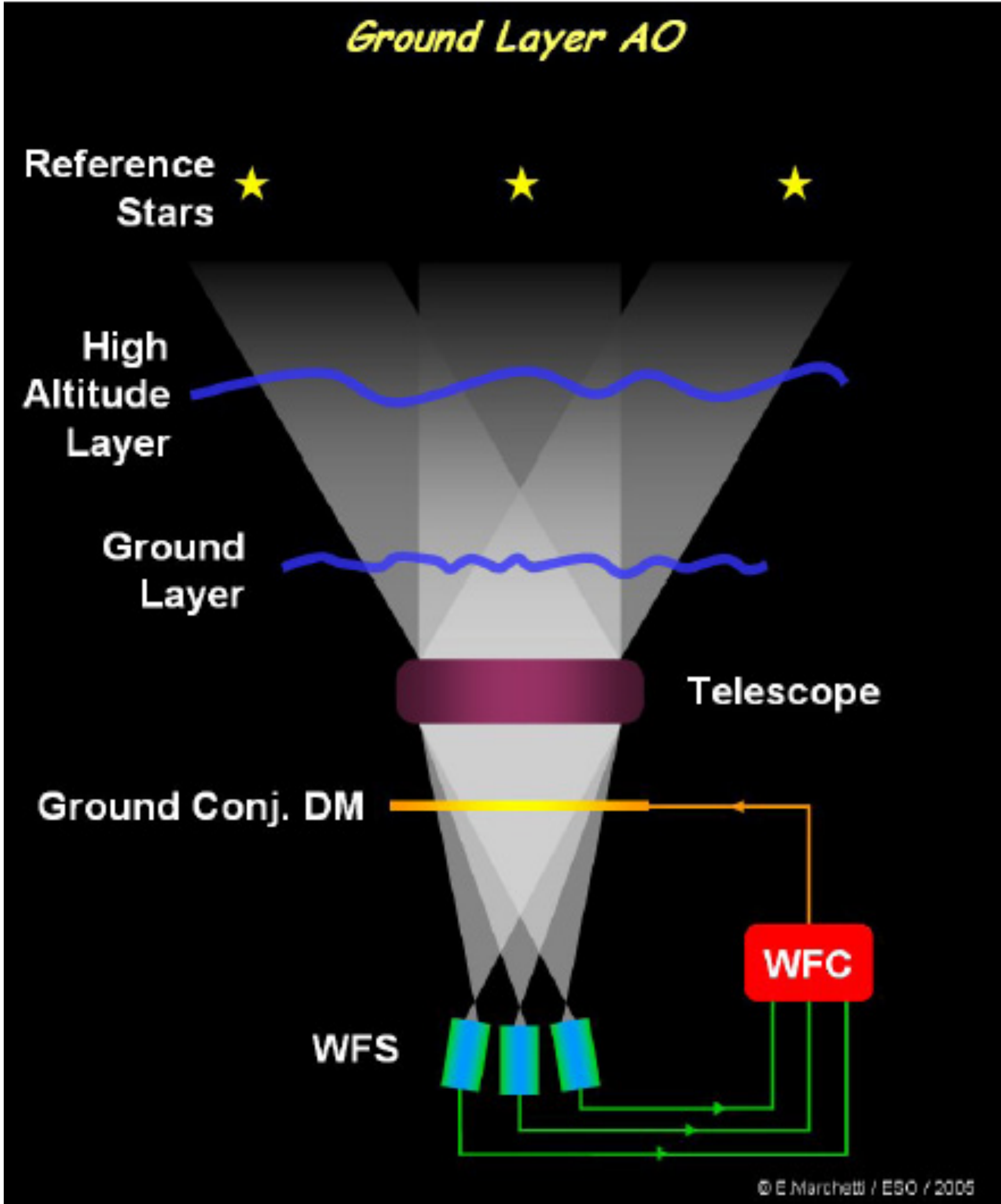
- Uses several WFS and guide stars within a large FOV (several arcmin).

- 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

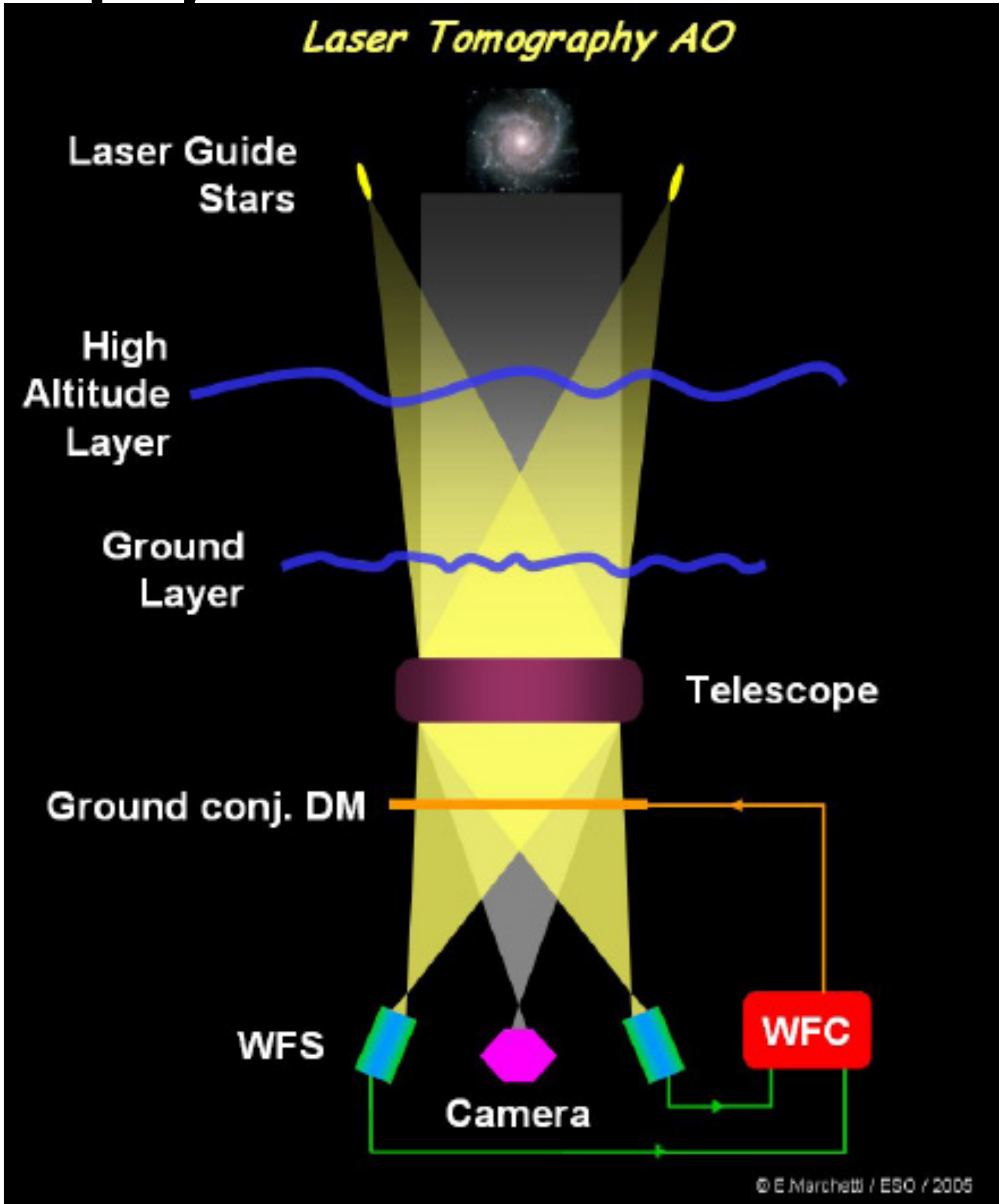
- Uses multipe laser beacons

- 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.



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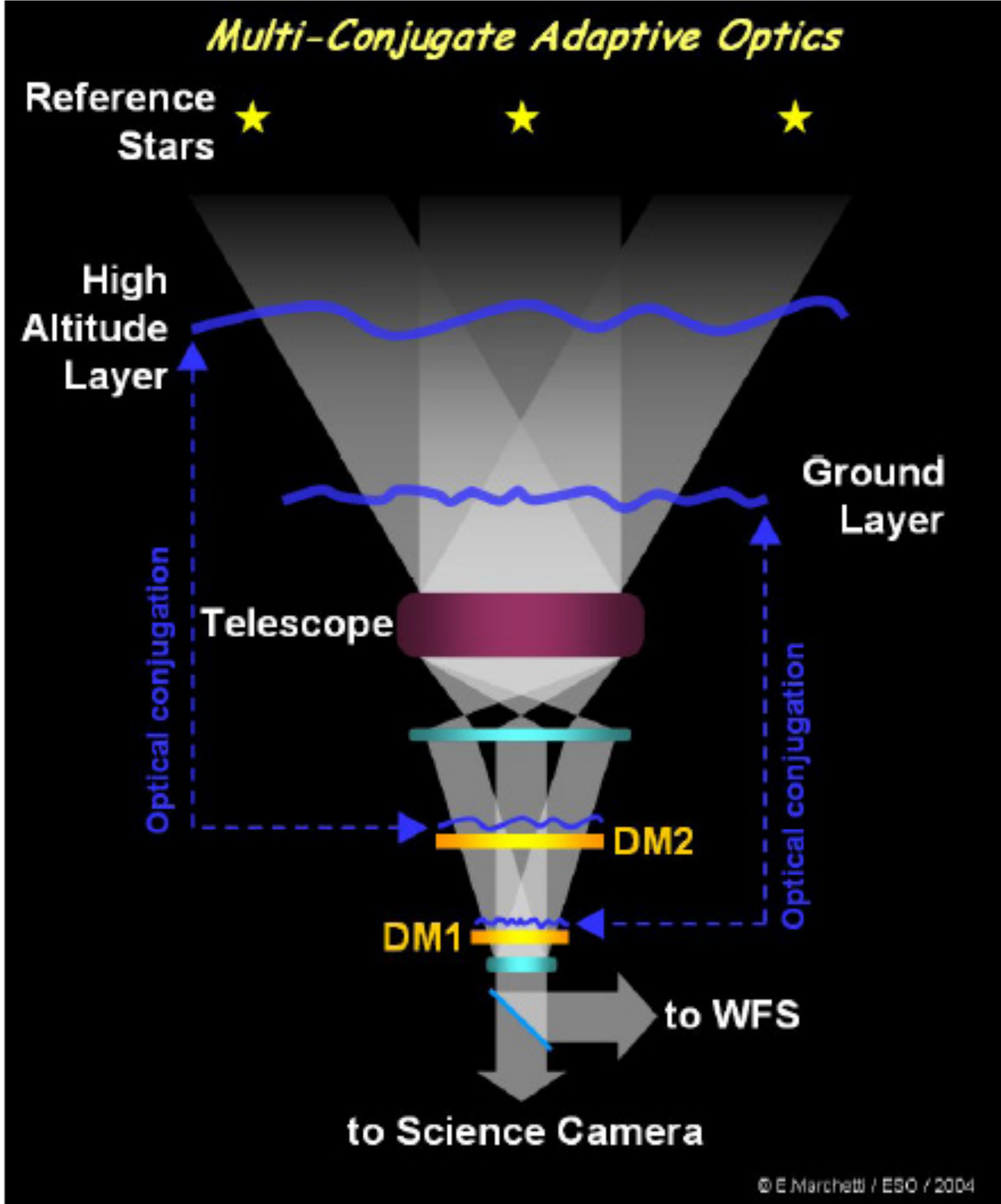
Multi-Conjugate AO – MCAO

- 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.



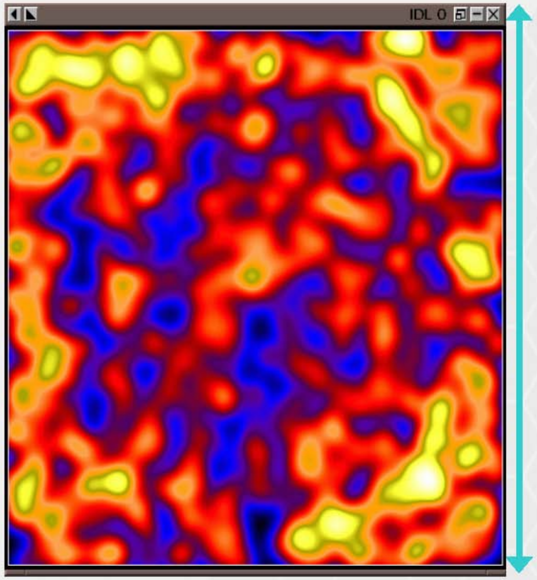
Side note: MCAO: Performance

E-ELT Programme

Seeing of 0.5", J band

ø 80"
J band
1000 stars

FWHM
~ 0.4"

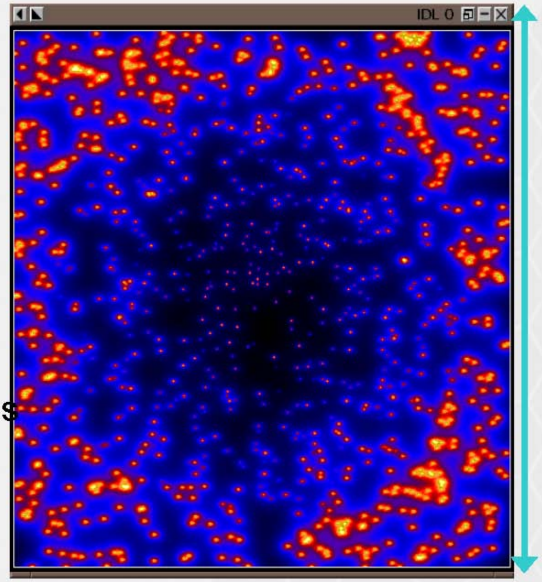


E-ELT Programme

NGS-AO, J band

ø 80"
J band
1000 stars

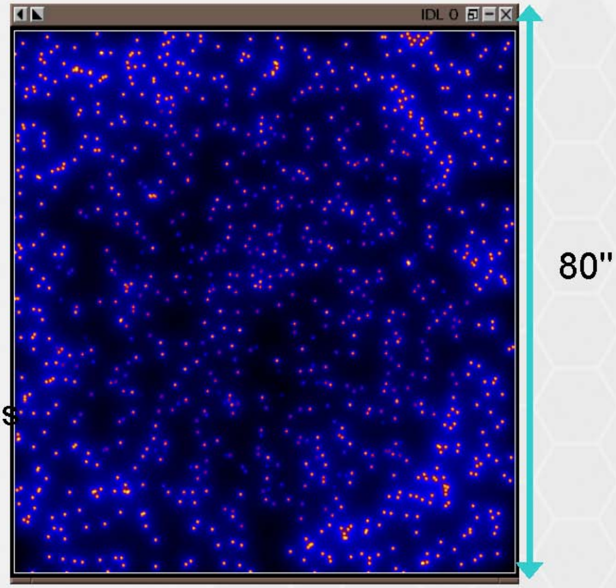
FWHM
34 → 70 mas



MCAO, J band

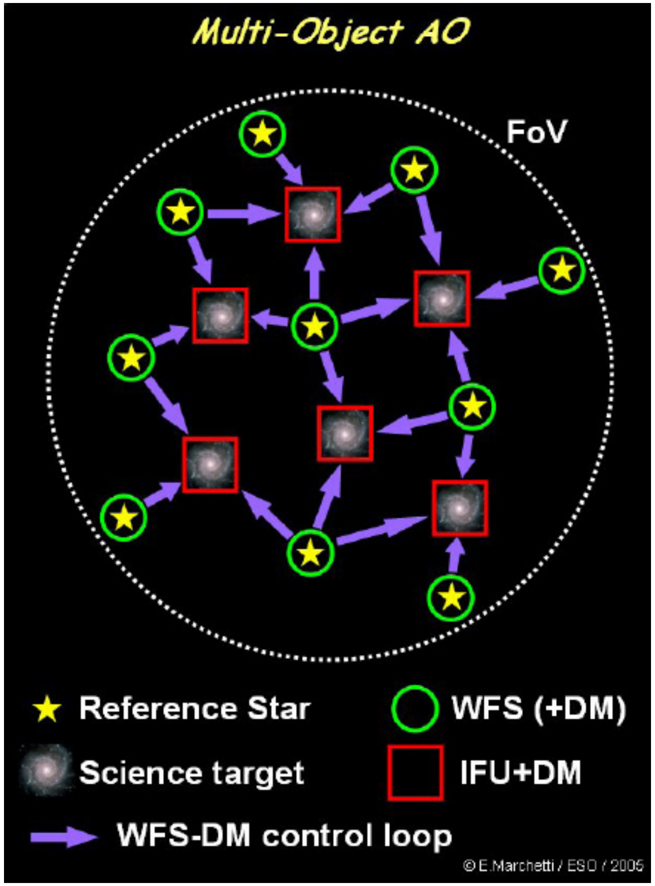
ø 80"
J band
1000 stars

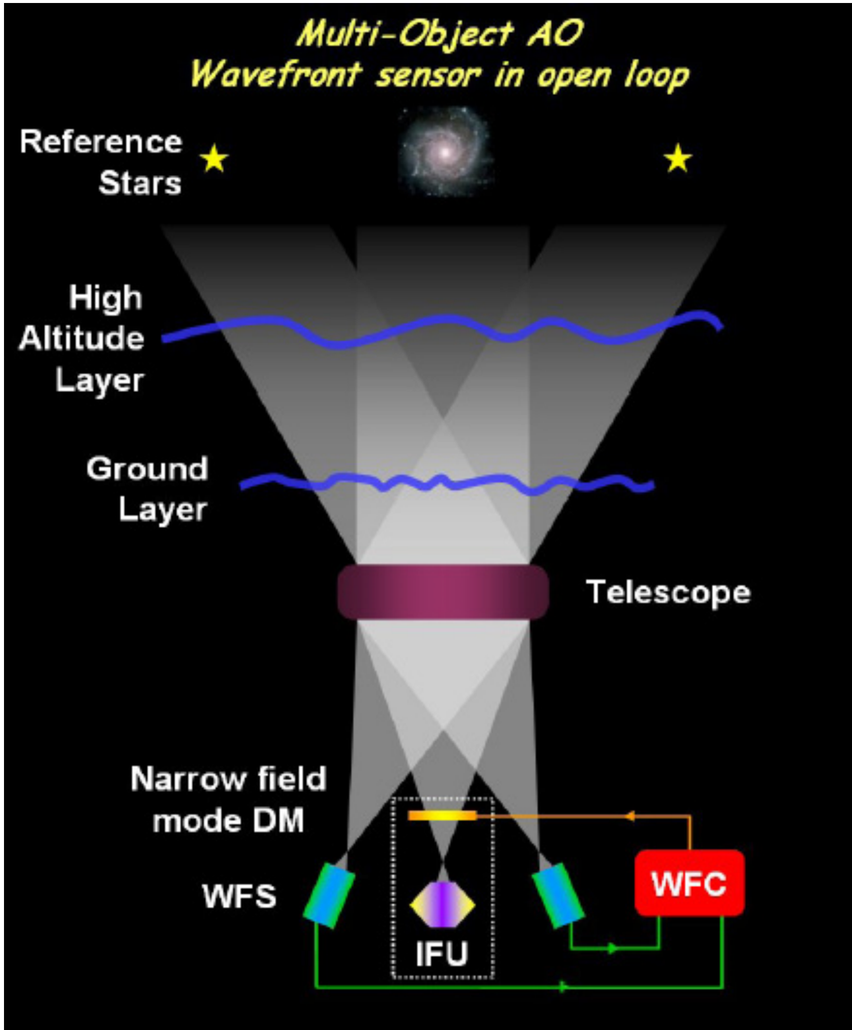
FWHM
37 → 39 mas



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 (!)

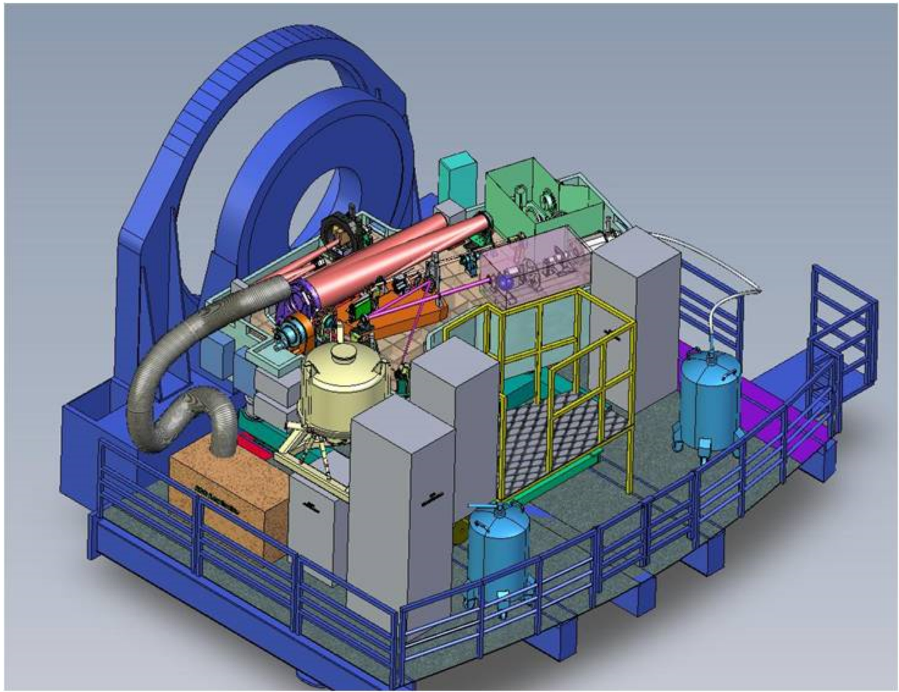




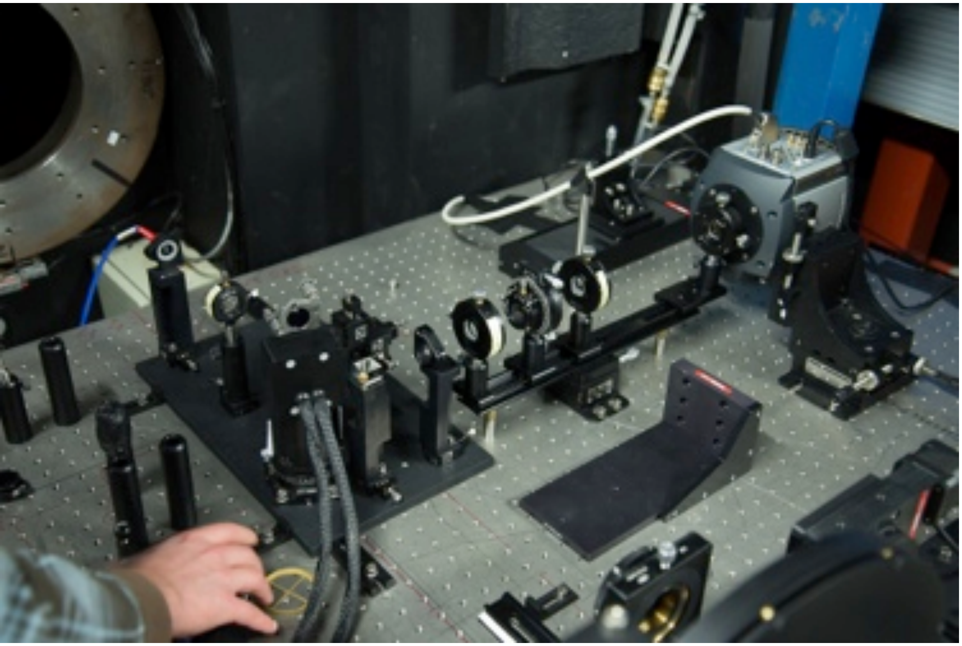
Extreme AO – XAO

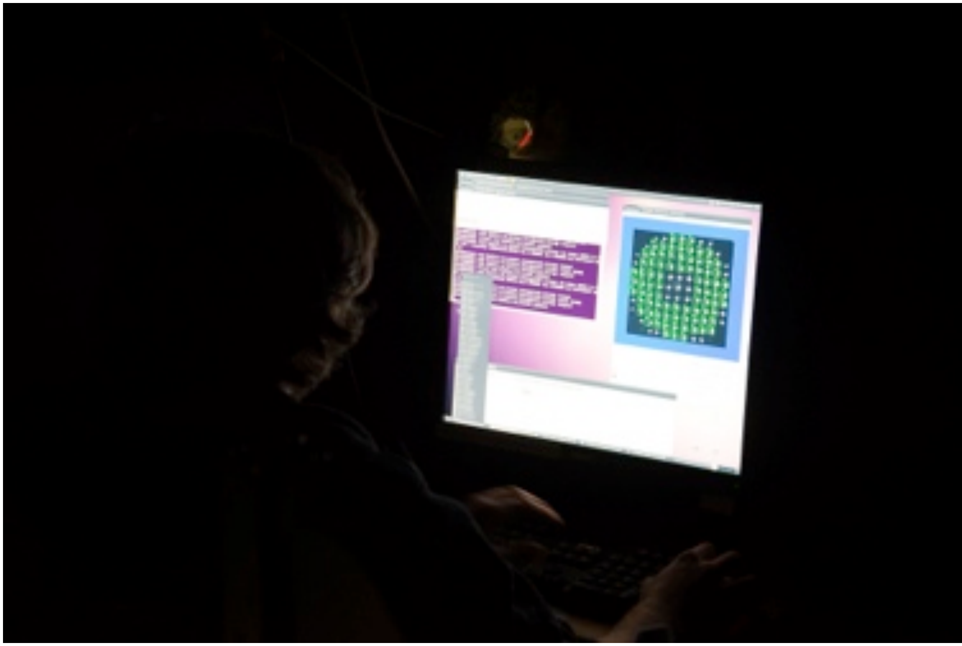
- XAO is similar to SCAO
- high Strehl on-axis and small corrected FOV
- however, Strehl values in excess of 90%
- requires many thousands of DM actuators
- requires minimal optical and alignment errors
- main application: search for exoplanets, like

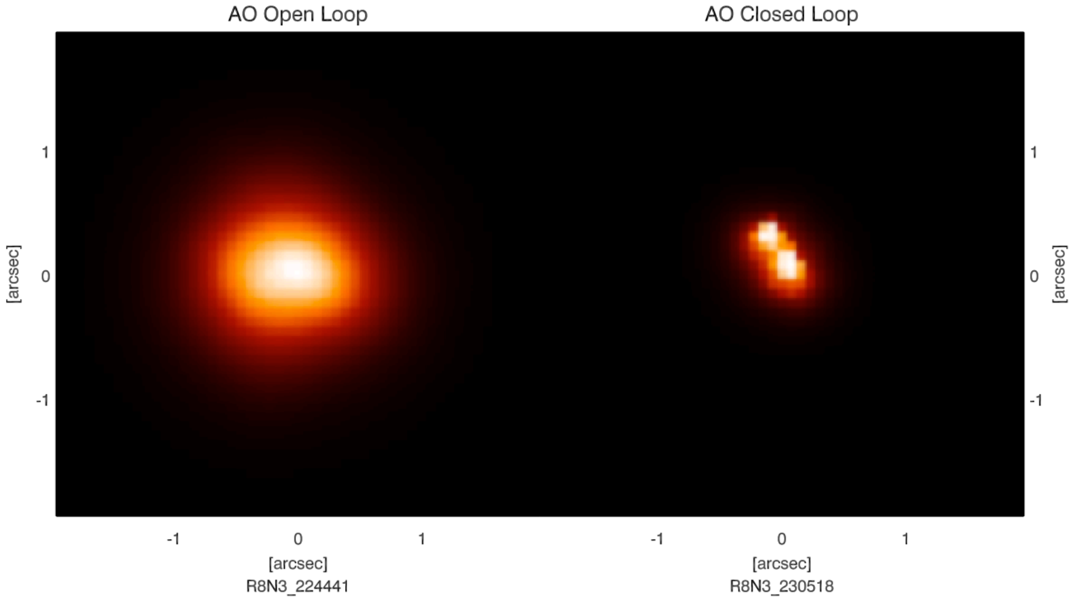
with SPHERE on the VLT →



Student-Built ExPo Adaptive Optics







AO Open Loop

AO Closed Loop

MSc Track in Instrumentation

- new start in fall 2014
- new lectures:
  - Astronomical Telescopes and Instruments
  - Detection of Light (renewed)
  - High Contrast Imaging
  - Astronomical Systems Design
  - Project Management
- option to take courses at TU Delft (not required)
- option for major research thesis in industry