Astronomical Observing Techniques

Lecture 13: Adaptive Optics

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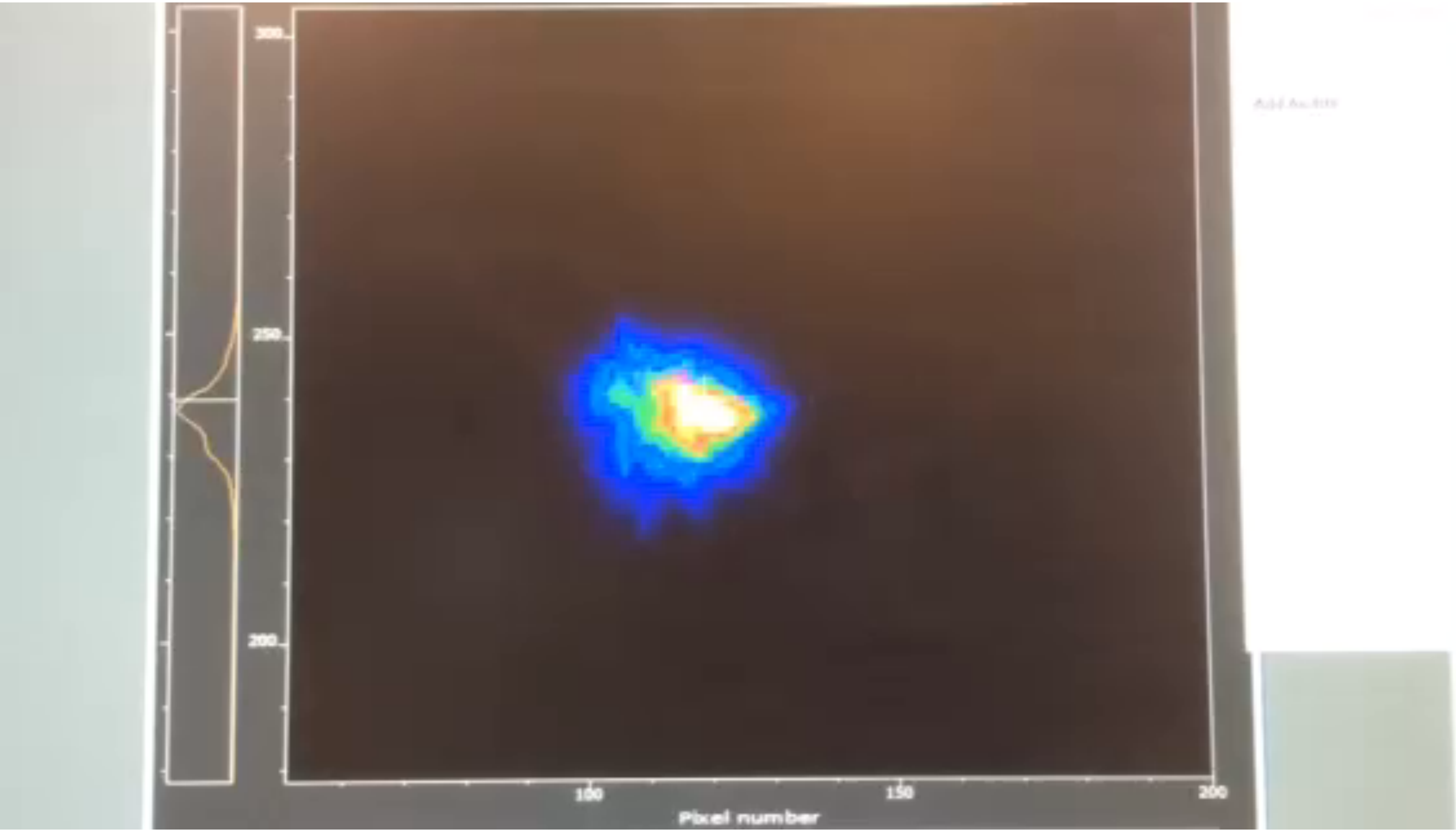
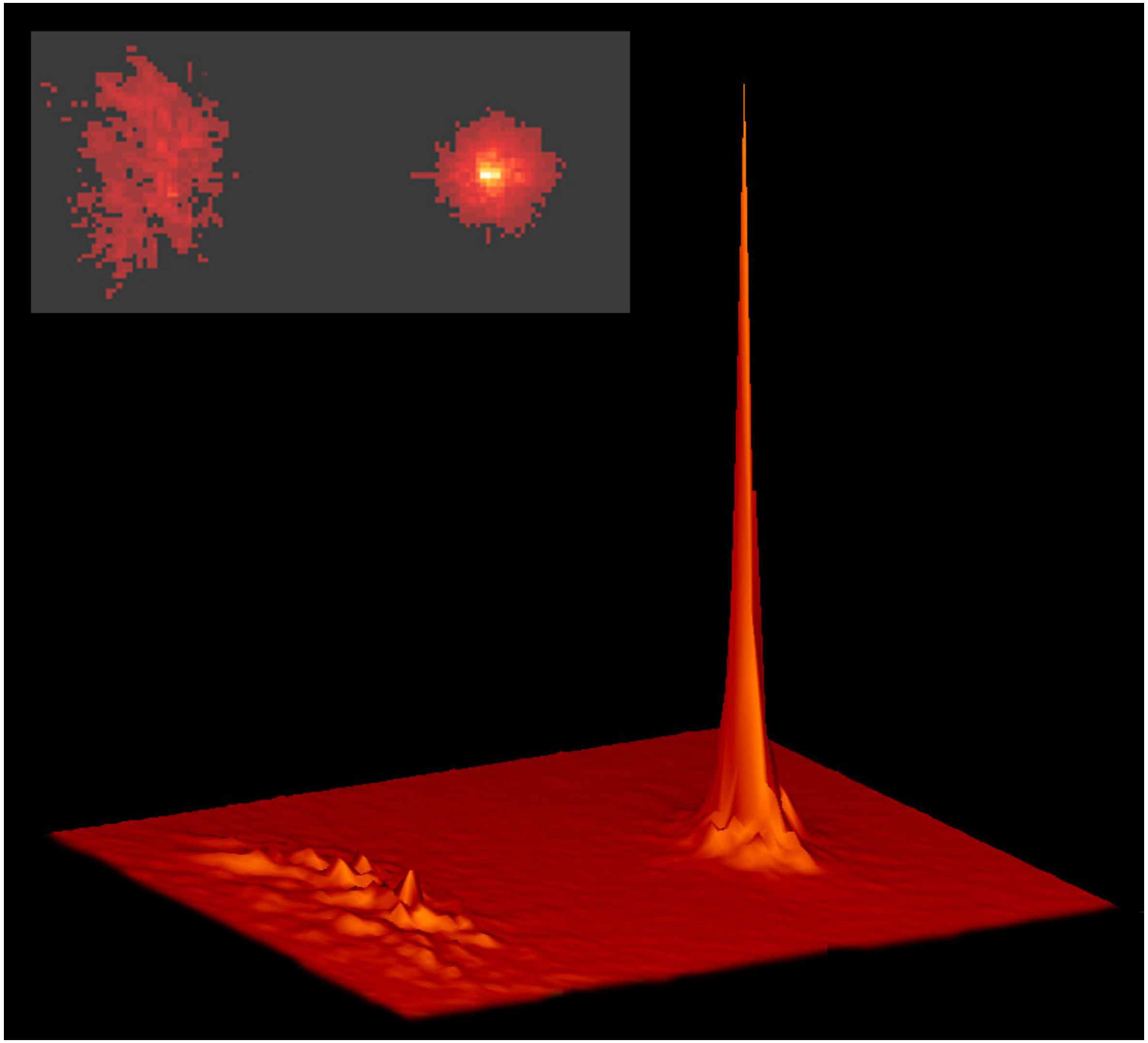
Overview

1. The Power of Adaptive Optics
2. Atmospheric Turbulence
3. Basic Principle
4. Key Components
5. Error Terms
6. Laser Guide Stars
7. Adaptive Optics Operations Modes

ExPo Adaptive Optics at WHT

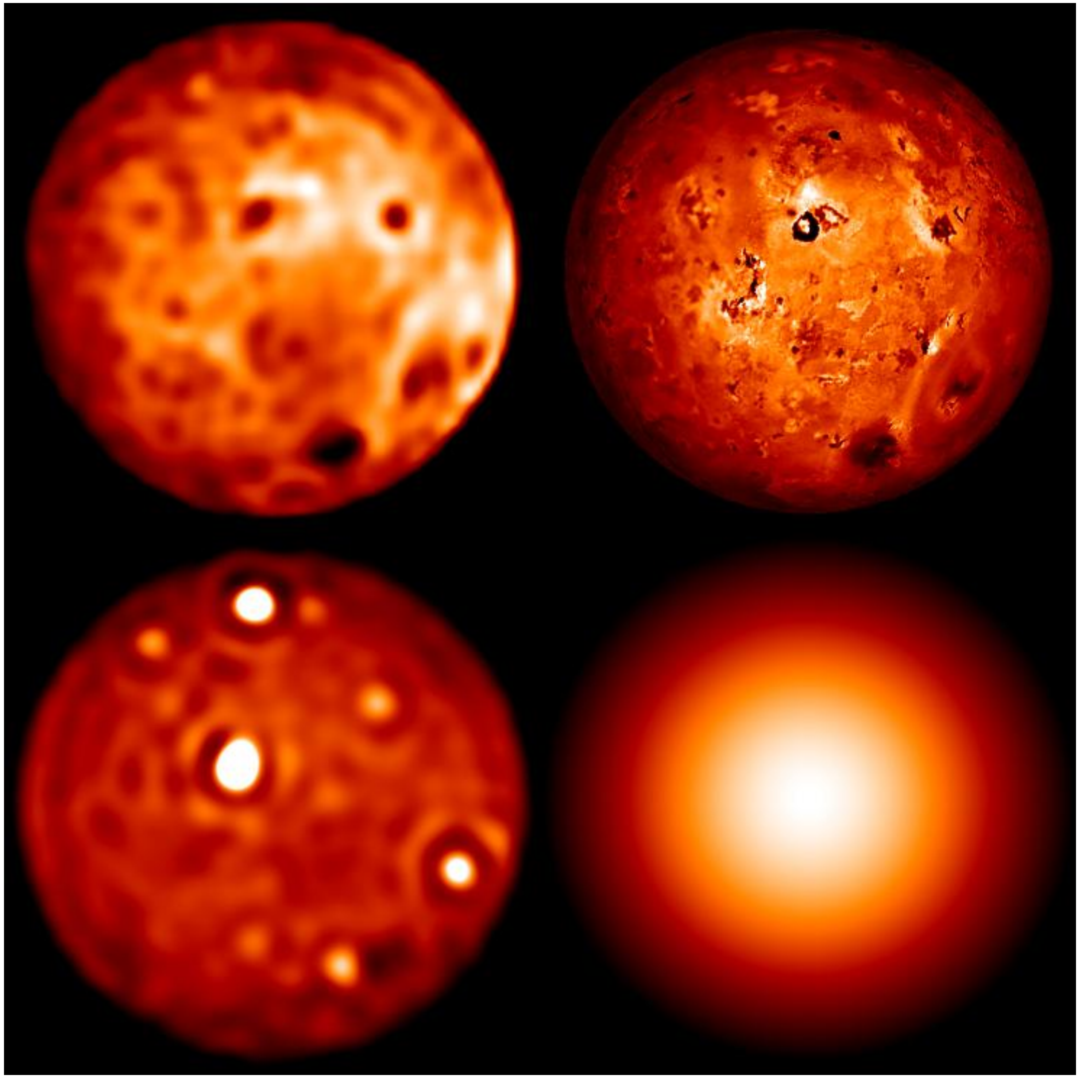


Star with and without AO



cfao.ucolick.org/pgallery/stellar.php

Io with and without AO



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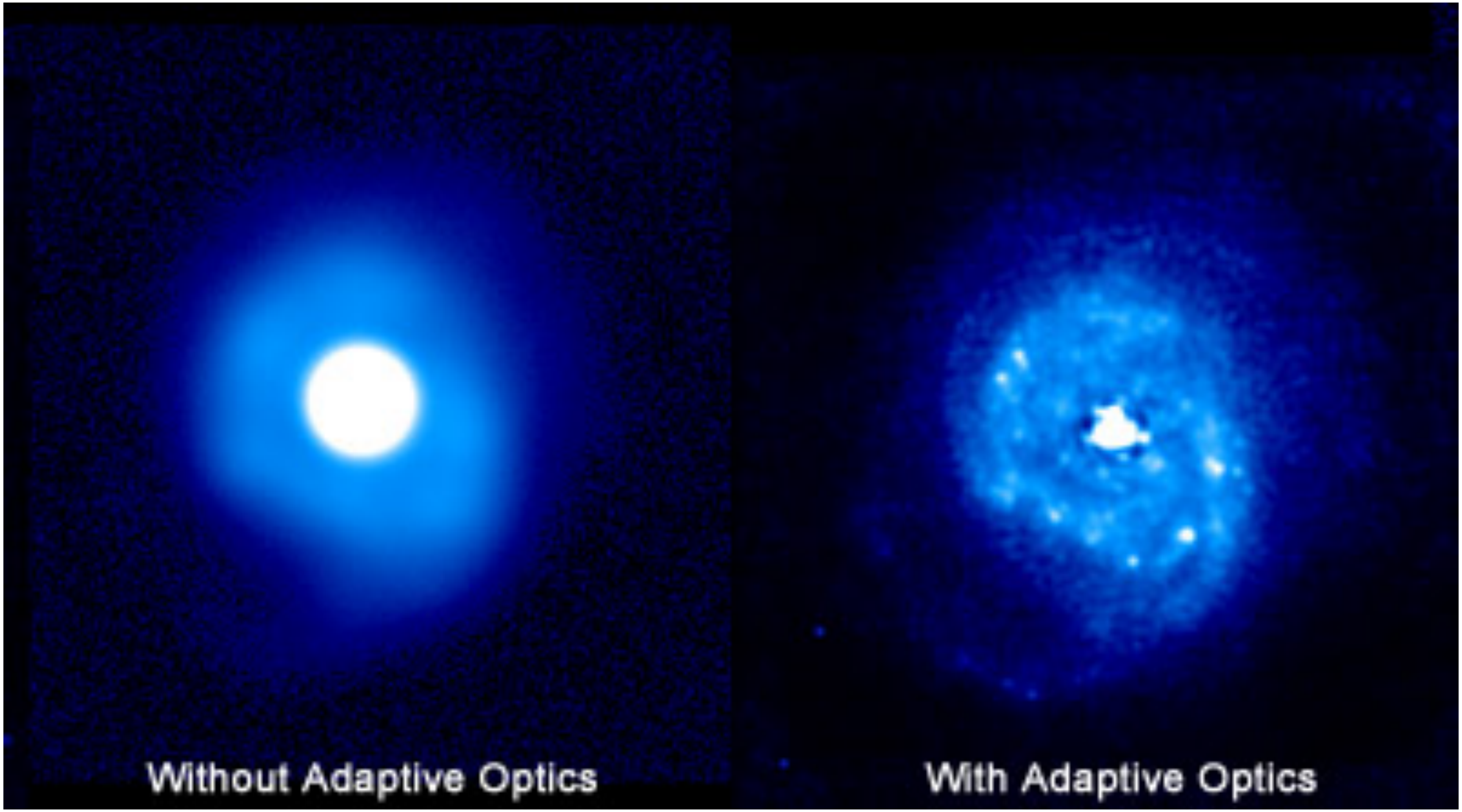
NGC 7469



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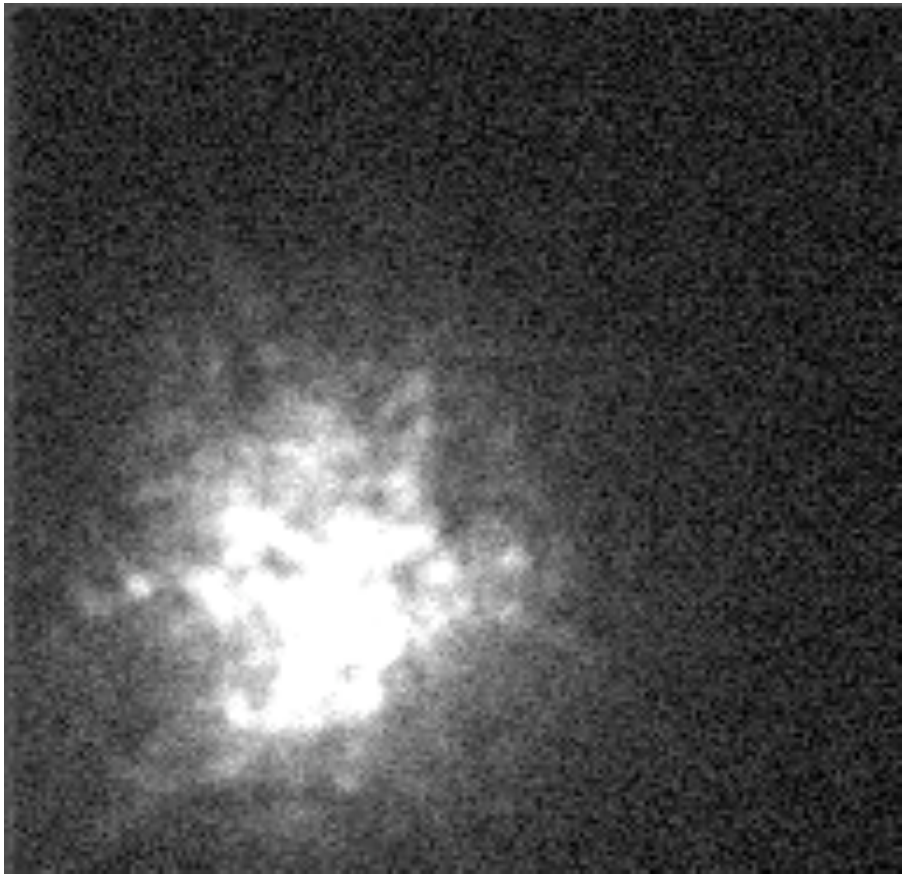
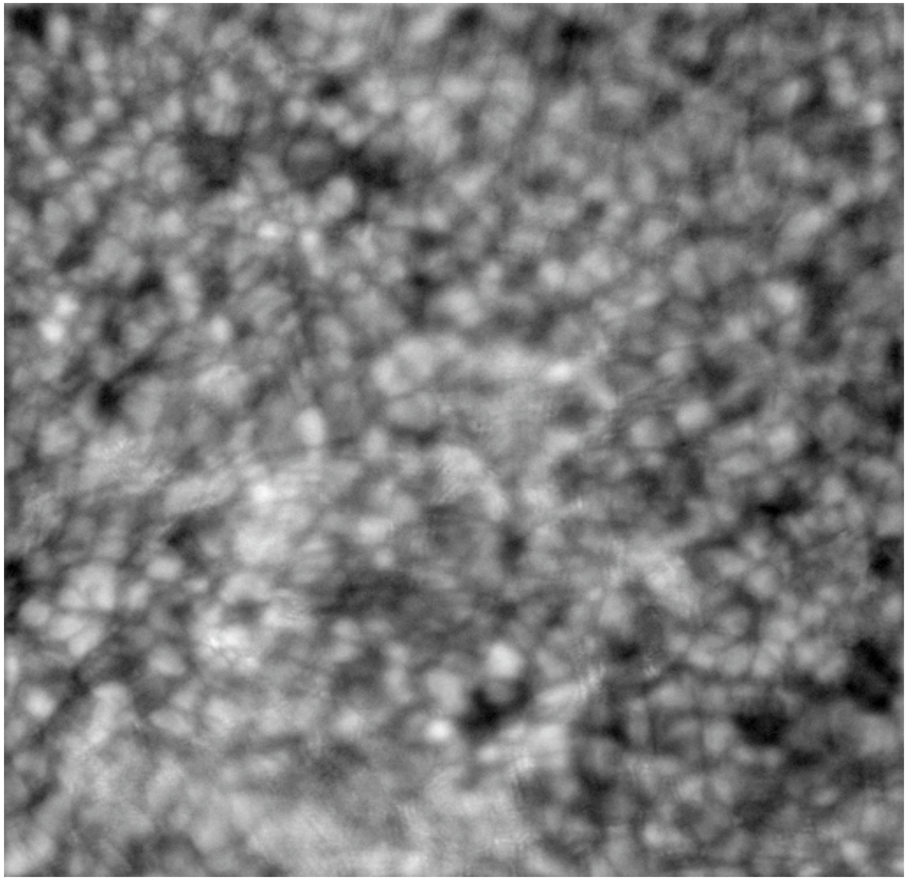
Seeing



star



solar photosphere

Seeing: r_0, τ_0, θ_0 (from Lecture 2)

- Fried parameter r_0: average turbulent scale over which RMS optical phase distortion is 1 rad

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

- r_0 increases as $\lambda^{6/5}$
- Seeing $\Delta\theta$ at good sites at 0.5µm: 10 - 30 cm

$$\Delta\theta = \frac{\lambda}{r_0} \sim \lambda^{-1/5}$$

- atmospheric coherence (or Greenwood delay) time: maximum time delay for RMS wavefront error to be < 1 rad ($\bar{v}$ is mean propagation velocity)

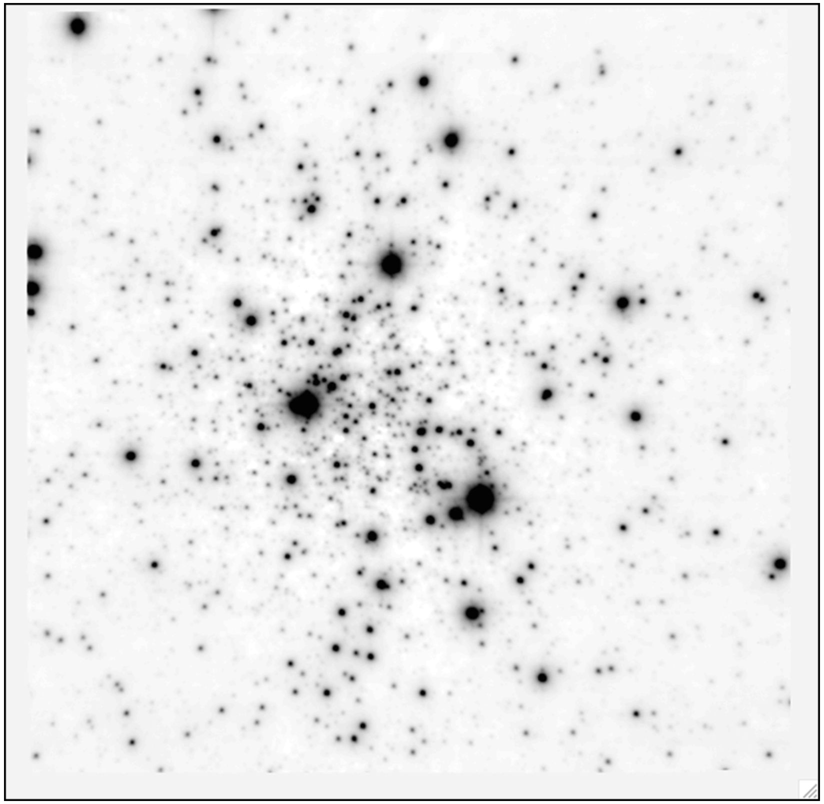
$$\tau_0 = 0.314\frac{r_0}{\bar{v}}$$

- Isoplanatic angle θ_0: angle over which RMS wavefront error is smaller than 1 rad

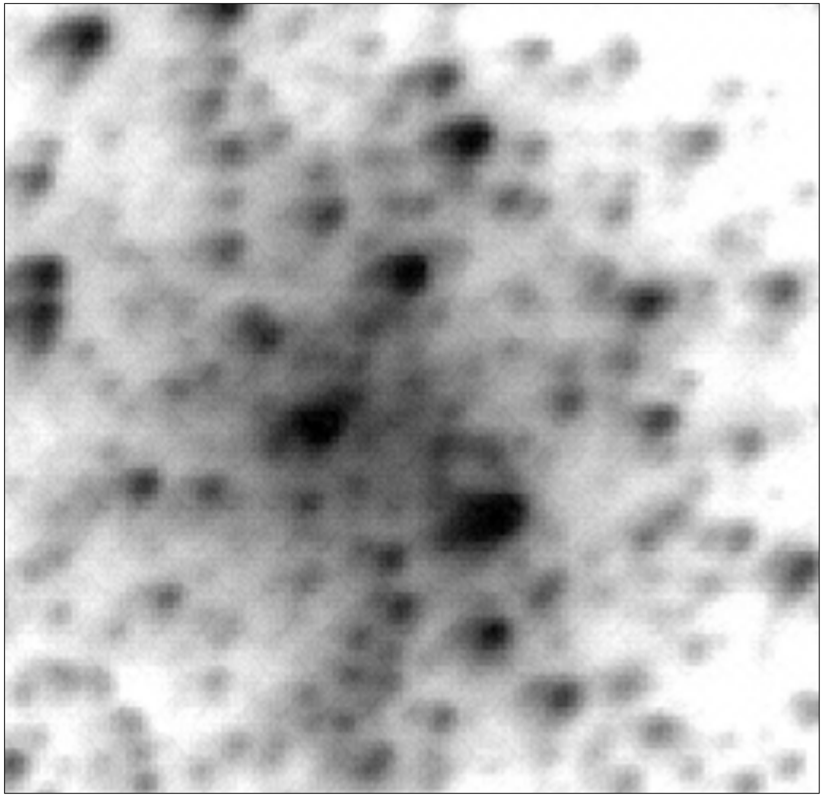
$$\theta_0 = 0.314\cos\zeta\frac{r_0}{\bar{h}}$$

Resolution & Sensitivity Improvement

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



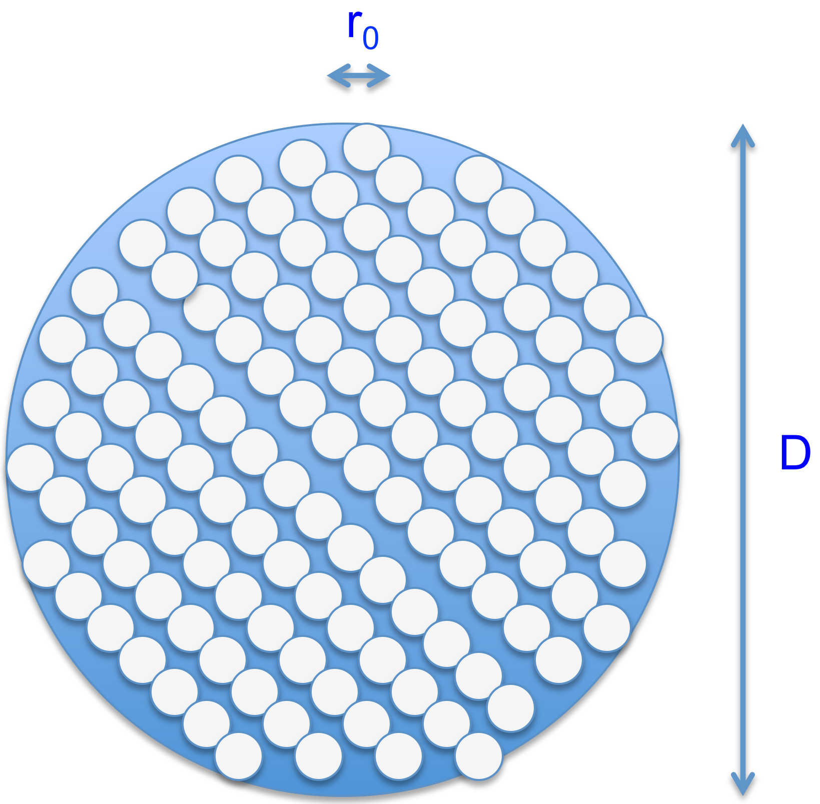
PHARO LGS Ks image
500s integ., 40" FOV, 150 mas FWHM



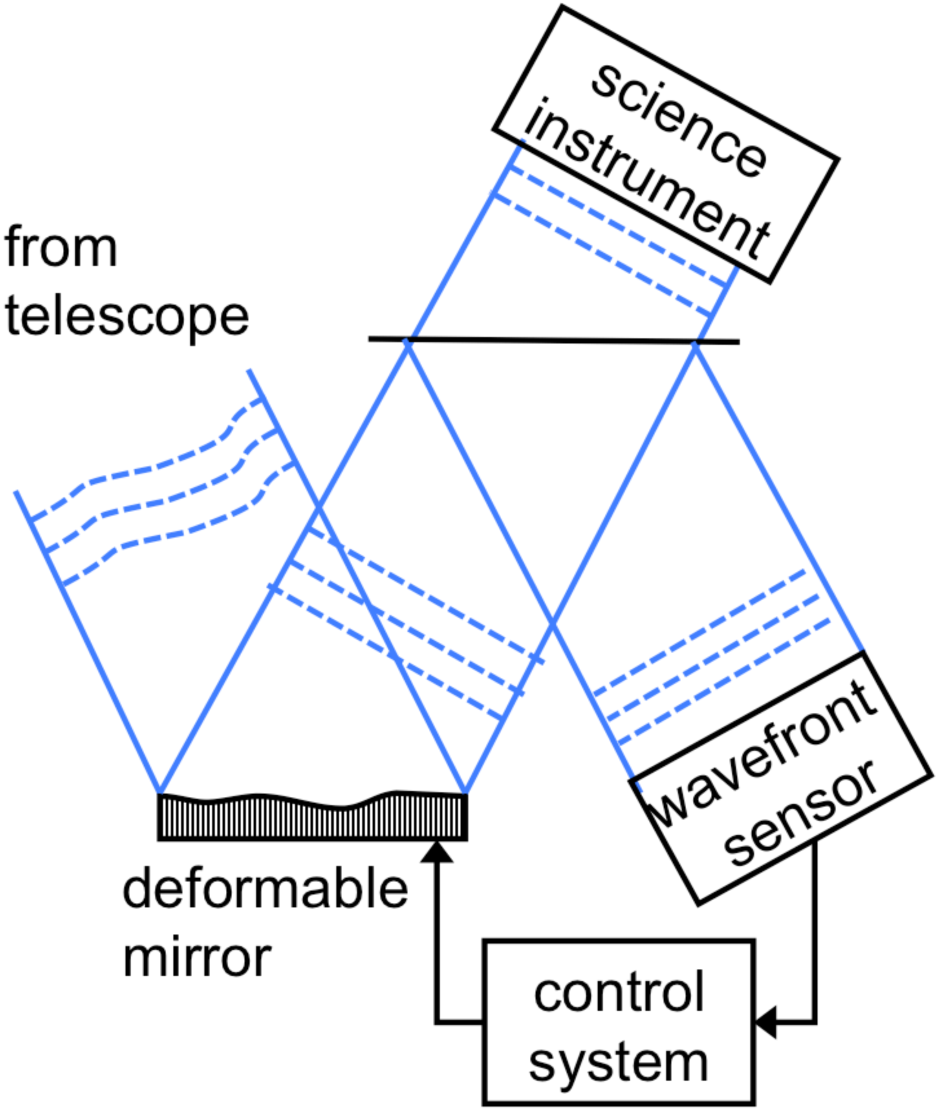
WIRO H image
Kobulnicky et al. 2005, AJ 129, 239-250

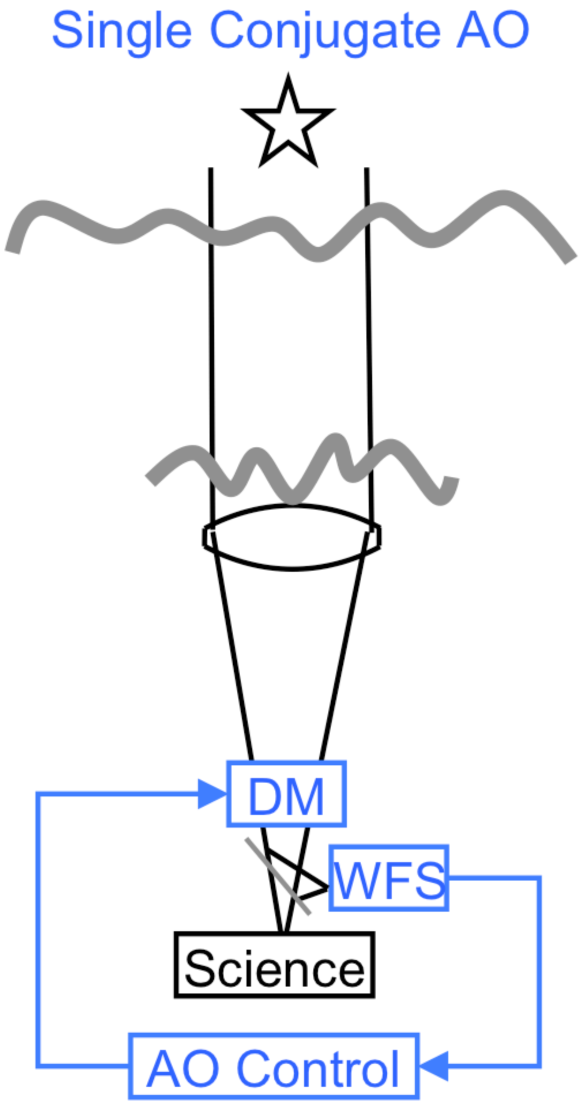
Adaptive Optics Principle

- Maximum scale of tolerated wavefront deformation is r_0 → subdivide telescope into apertures with diameter r_0
- Measure wavefront deformation
- Correct wavefront deformation by "bending back" the patches of size r_0
- Number of subapertures is $(D/r_0)^2$ at observing wavelength → requires hundreds to thousands of actuators for large telescopes



Adaptive Optics Scheme (SCAO)





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

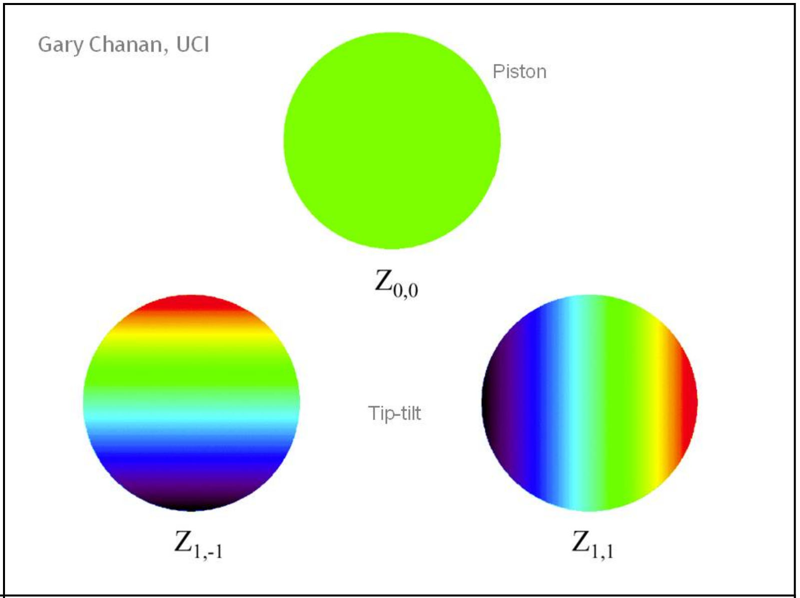
$Z_{1,-1} = 2\,r \sin\theta$ } tip/tilt

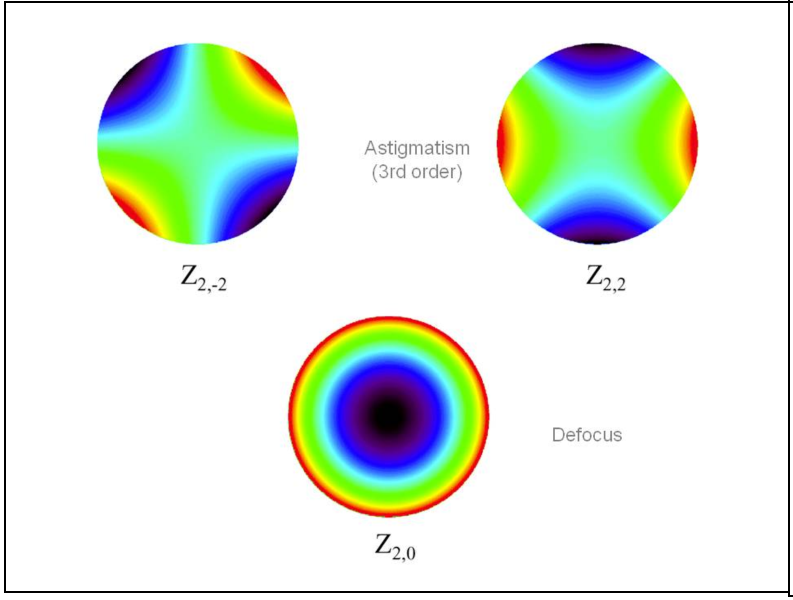
$Z_{1,1} = 2\,r \cos\theta$

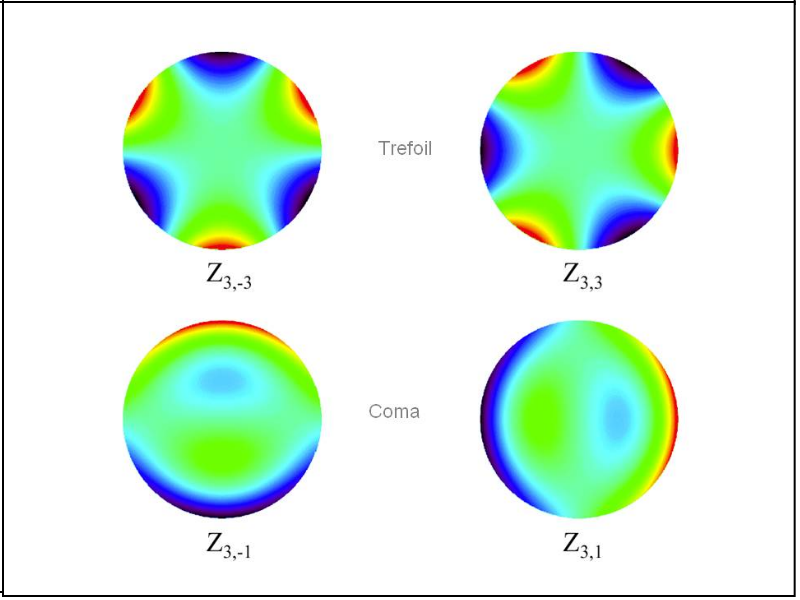
$Z_{2,-2} = \sqrt{6}\, r^2 \sin 2\theta$ astigmatism

$Z_{2,0} = \sqrt{3}\,(2r^2 - 1)$ focus

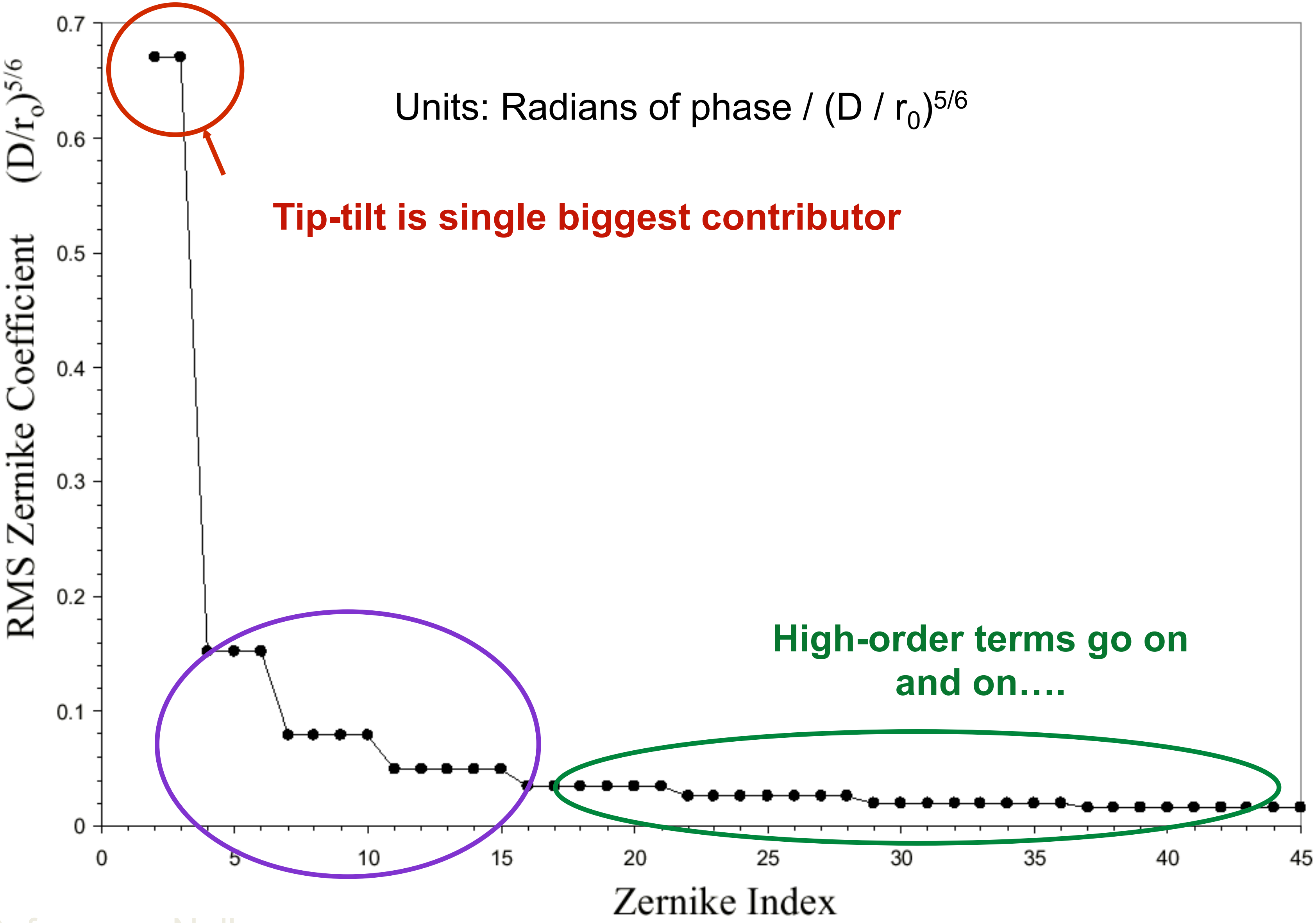
$Z_{2,2} = \sqrt{6}\, r^2 \cos 2\theta$ astigmatism







Zernike Amplitudes for Kolmogorov Turbulence



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

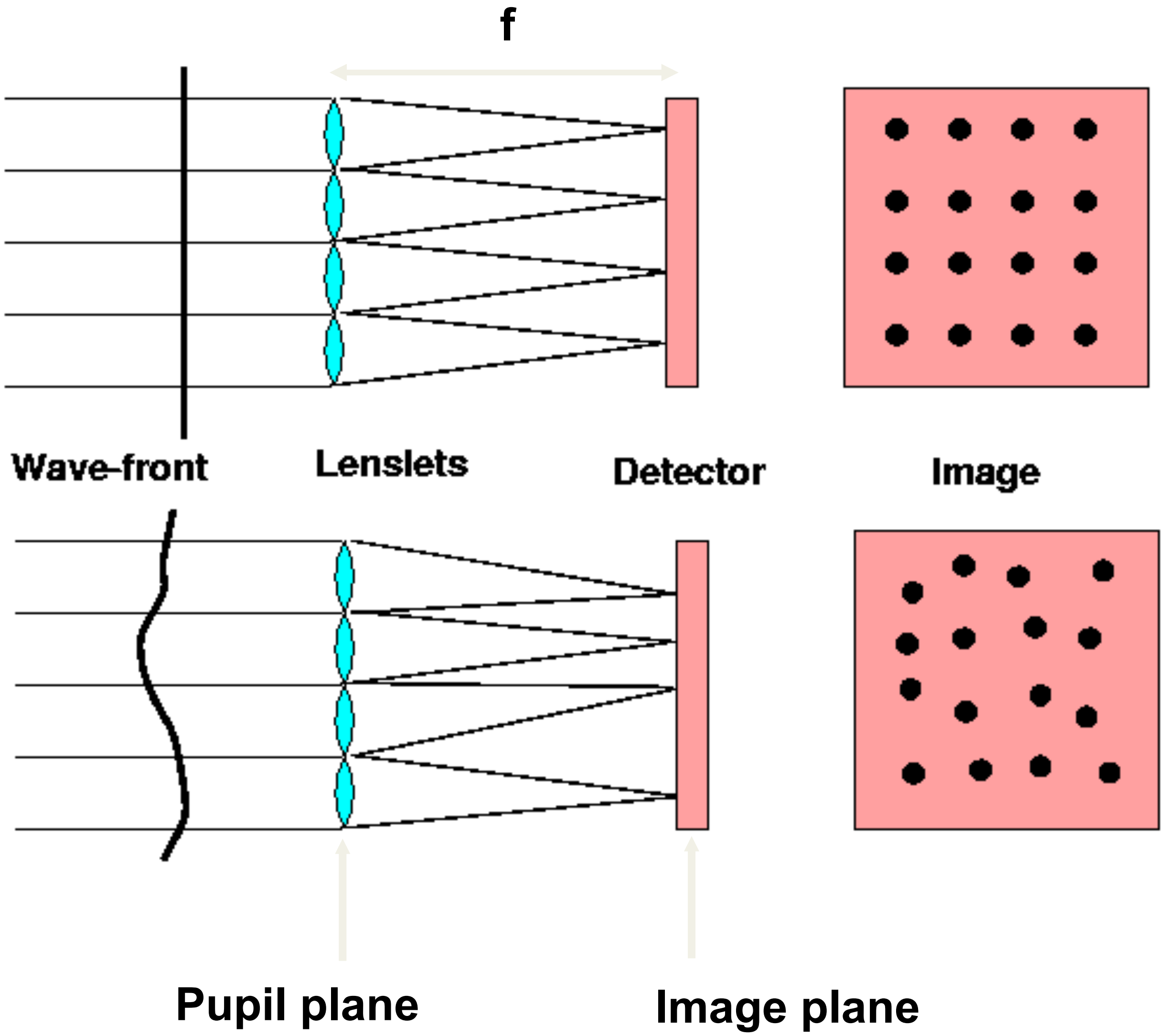
Tip-tilt is single biggest contributor

High-order terms go on and on….

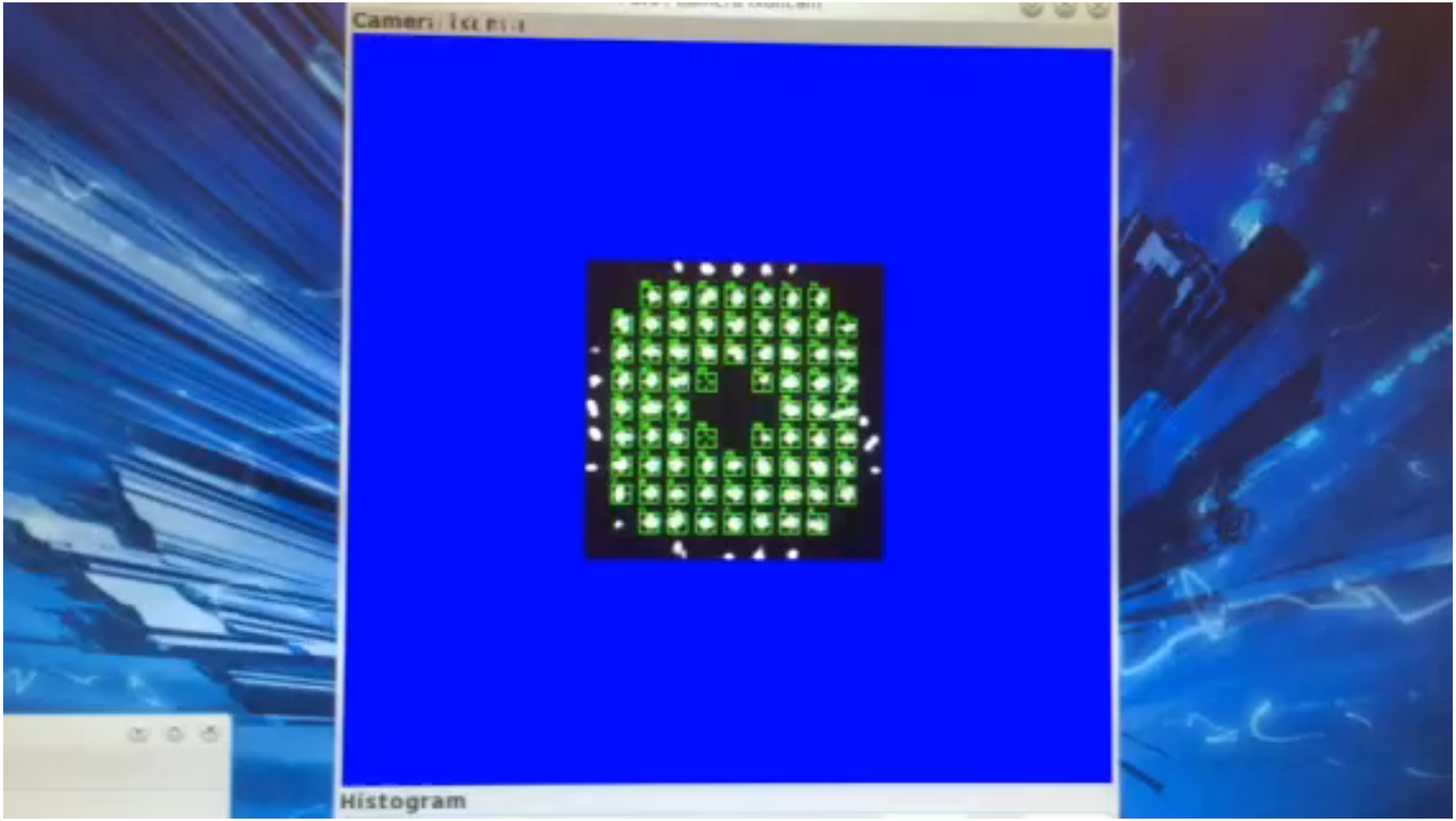
Reference: Noll

Wavefront Sensors – Shack Hartmann

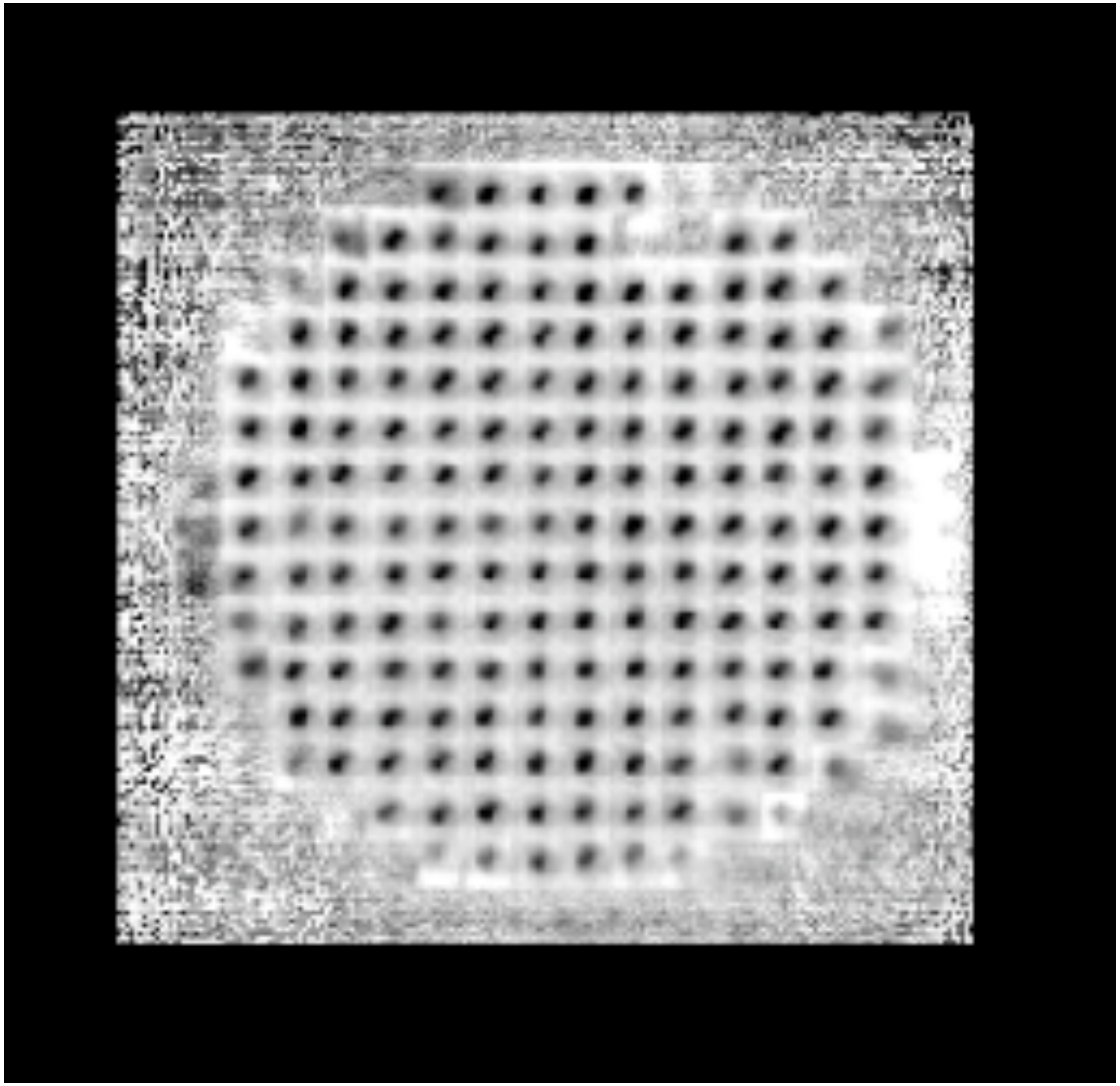
Most common principle is the Shack Hartmann wavefront sensor measuring sub-aperture tilts:



ExPo Wavefront Sensor at WHT

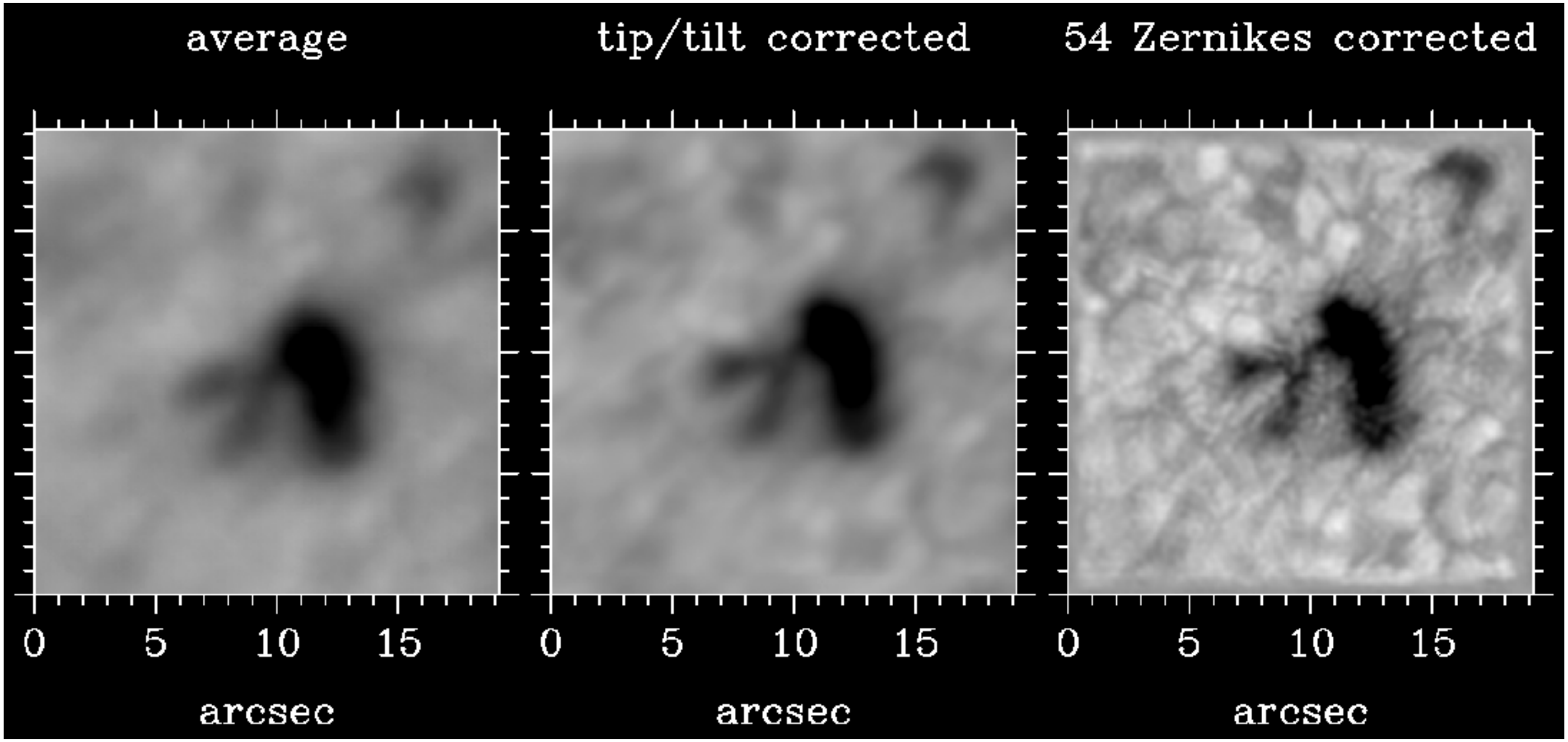


Wavefront Sensing



Sunspot wavefront sensor images at 955Hz

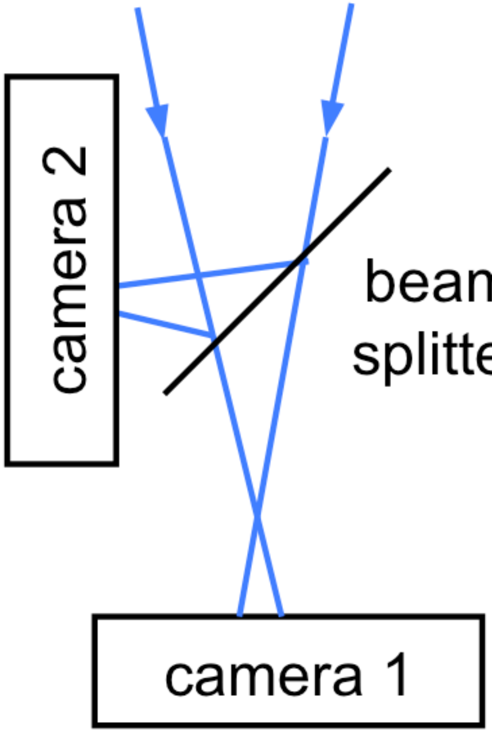
Deconvolution from Wavefront Sensing



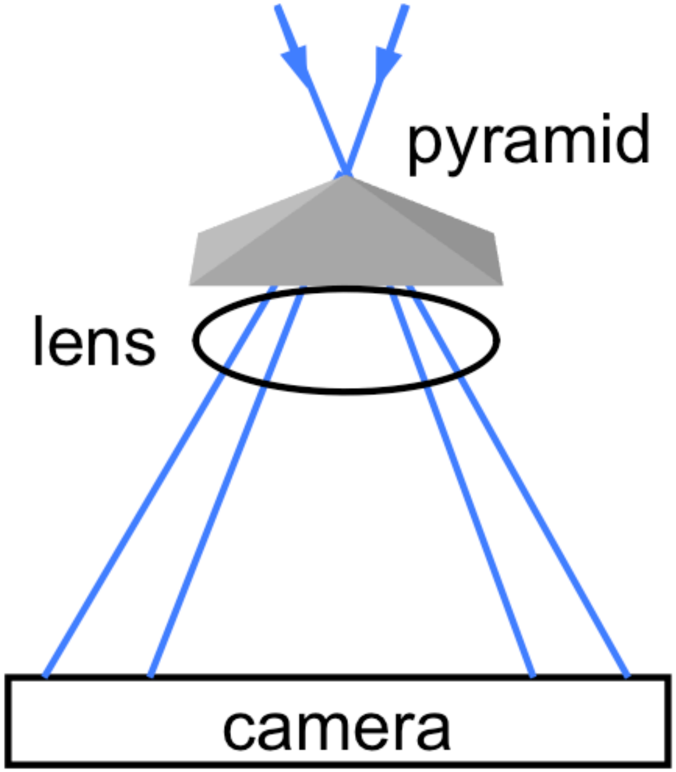
- deconvolution from wavefront sensing provides AO-like results
- 106 subapertures over 1m aperture at 950 nm at McMath-Pierce telescope

WFSs: Curvature and Pyramid Sensors

Curvature Wavefront Sensor

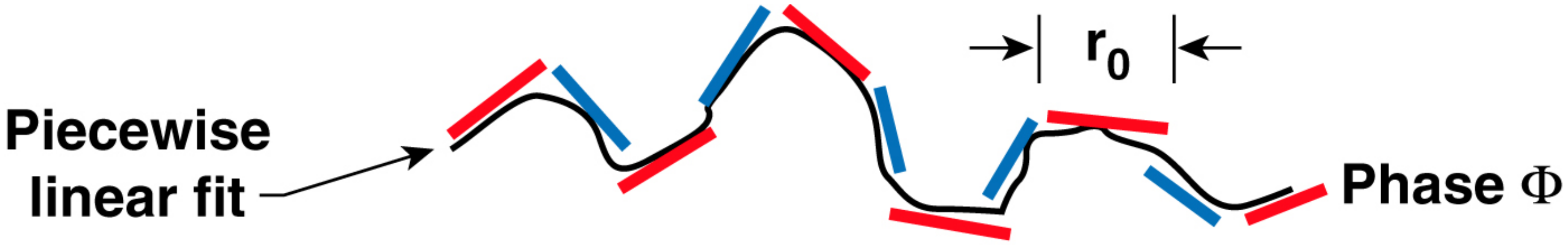


Pyramid Wavefront Sensor



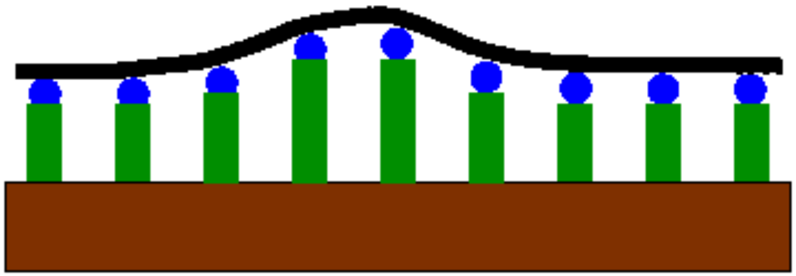
Deformable Mirrors

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

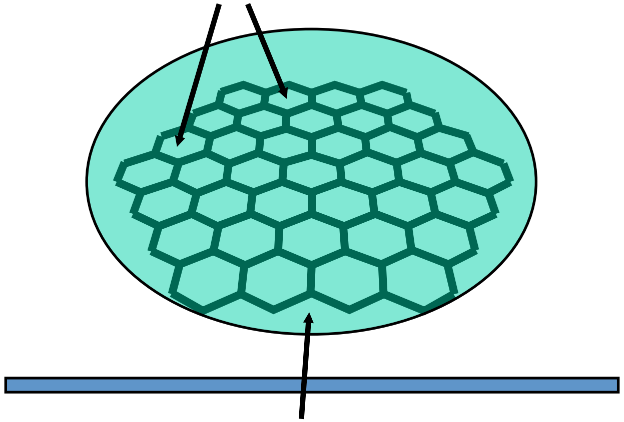
and continuous face-sheet mirrors:

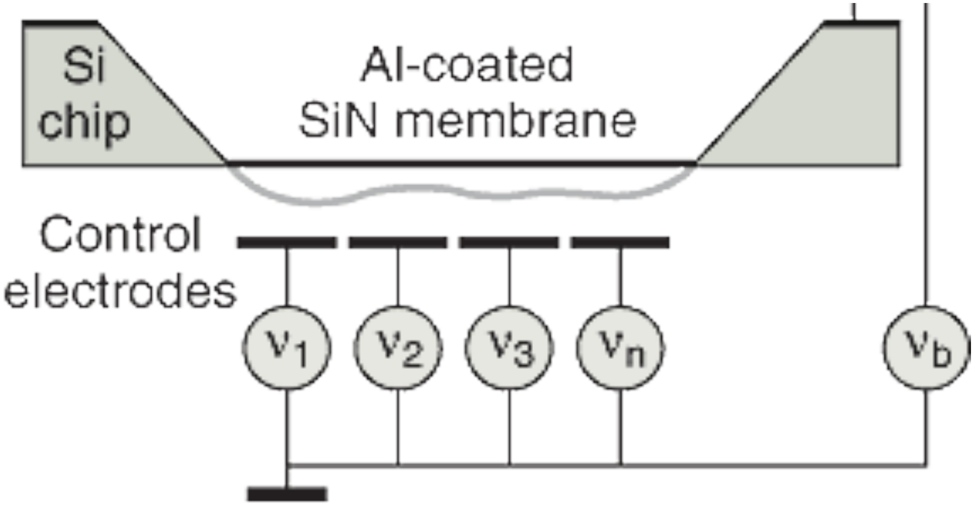


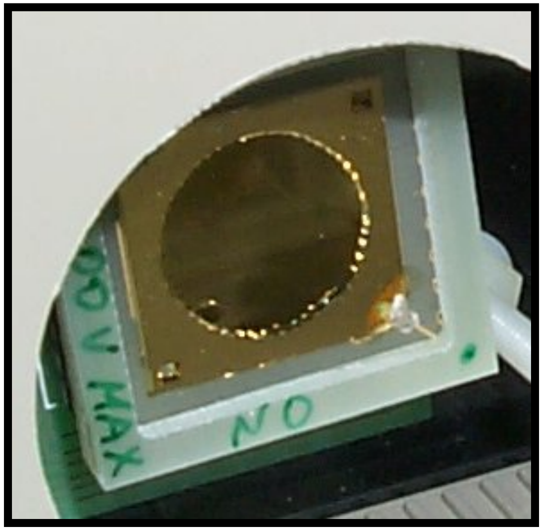
Note that the (piezo) actuator stroke is typically only a couple of micrometers → requires separate tip-tilt mirror.

Membrane Deformable Mirror

- micromachined deformable mirror (OKOtech/Flexible Optics) with 37 actuators
- 600-nm thick, 15-mm diameter silicon nitride membrane
- electrostatic actuators







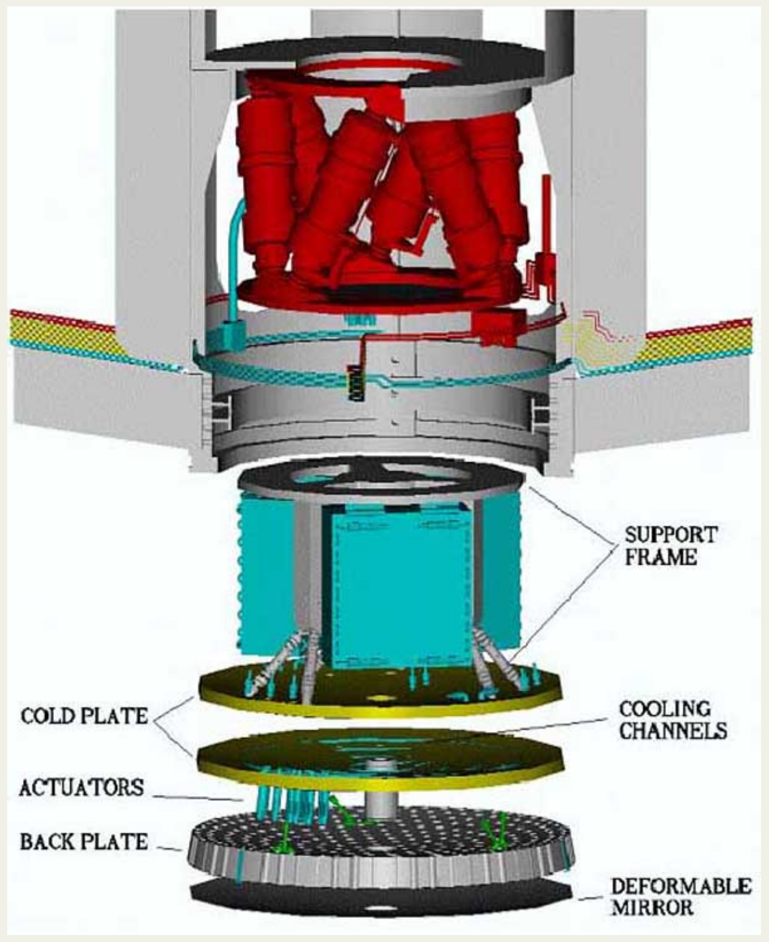
Adaptive Secondary Mirrors

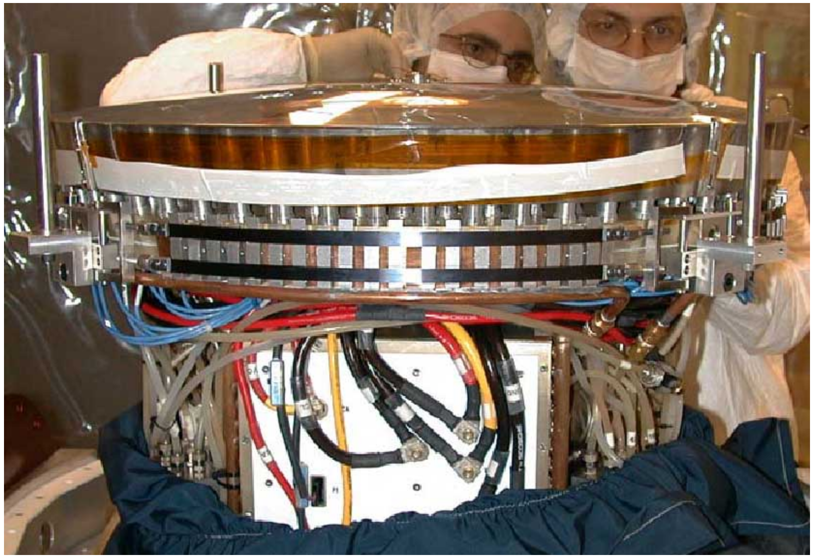
Concept: integrate DM into the telescope → adaptive secondary mirrors

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



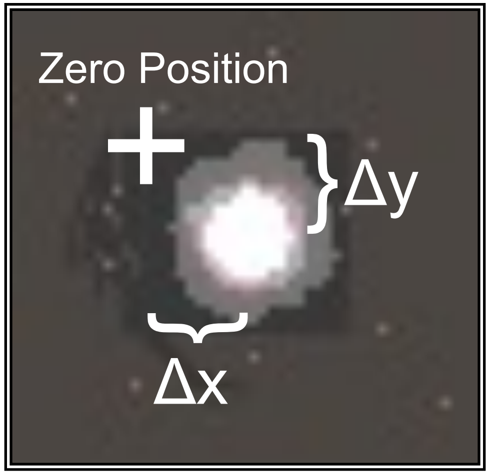


DM for MMT Upgrade

Shack-Hartmann Wavefront Analysis

- centroid (center of gravity) calculation on each subaperture:

$$\Delta x = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j) \cdot i}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)} \qquad \Delta y = \frac{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j) \cdot j}{\sum_{i=i_{\min}}^{i_{\max}} \sum_{j=j_{\min}}^{j_{\max}} I(i,j)}$$



Finding Star Positions

Influence Matrix

- slope of mirror surface *and* Shack-Hartmann star positions are proportional to actuator position
- linear relationship between actuator *a* and star position *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 position *n* into matrix equation:

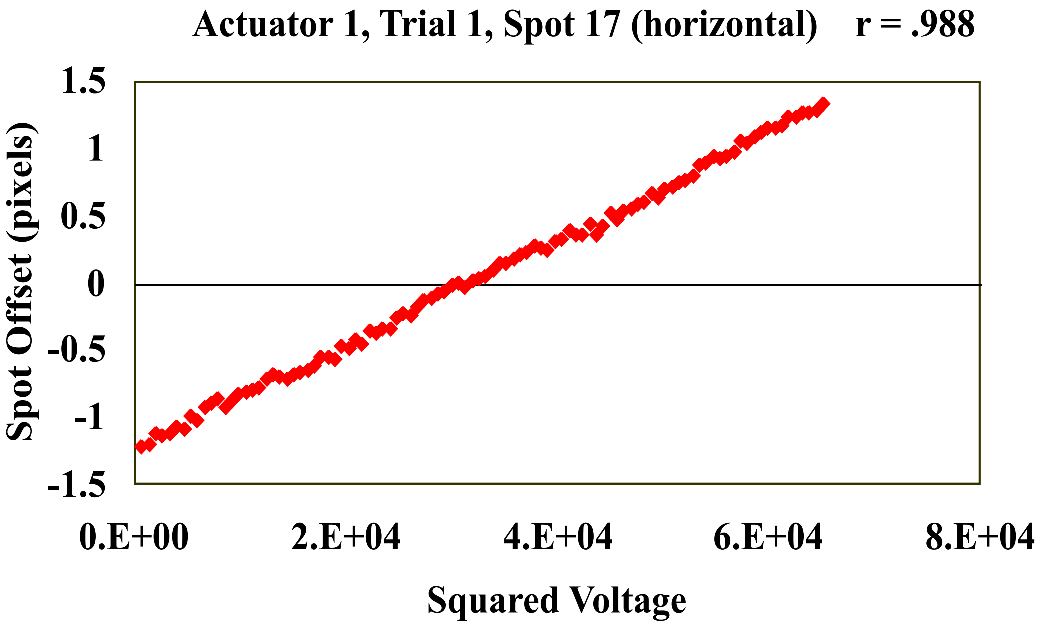
$$C = BA$$

  - C = star positions
  - A = actuator positions
  - B = influence matrix describing influence of specific actuator position on star positions

Measuring the Influence Matrix

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

- Influence matrix gives the resulting star positions when multiplied by a control vector (list of actuator positions)



Solving for the Control Vector

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

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

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

Typical AO Error Terms

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

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

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

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

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

$$\sigma^2_{measure} \sim S/N$$

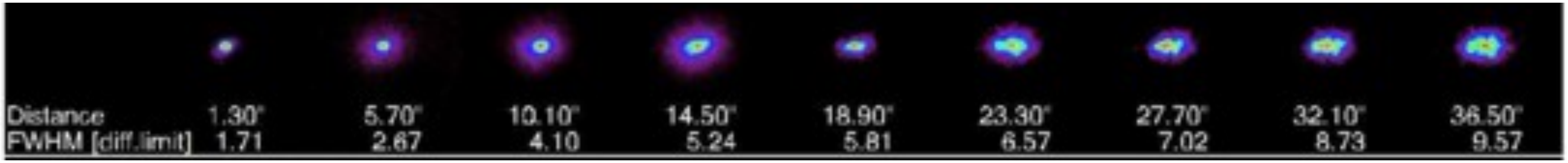
- Calibration errors from aberrations in the non-common path between sensing channel and imaging channel.

$$\sigma^2_{calibration} \sim ???$$

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

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

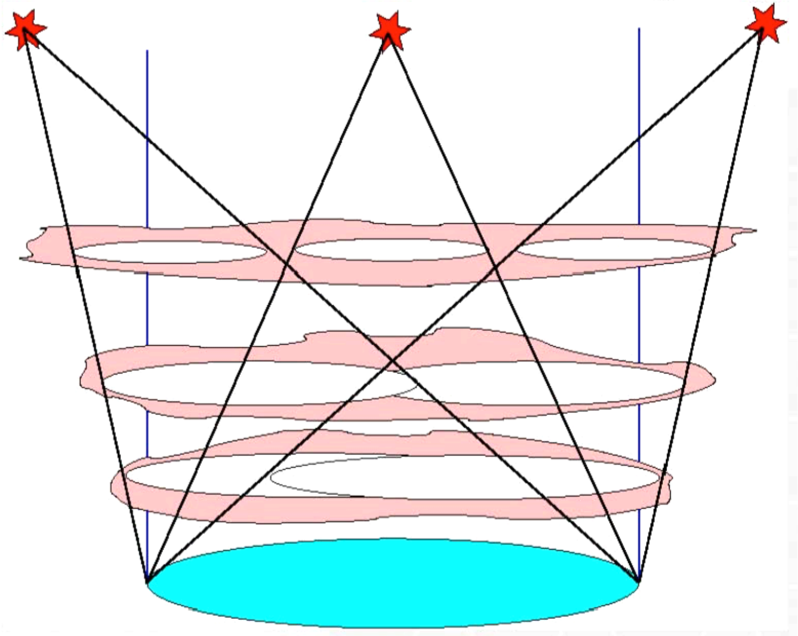
Angular Anisoplanatism



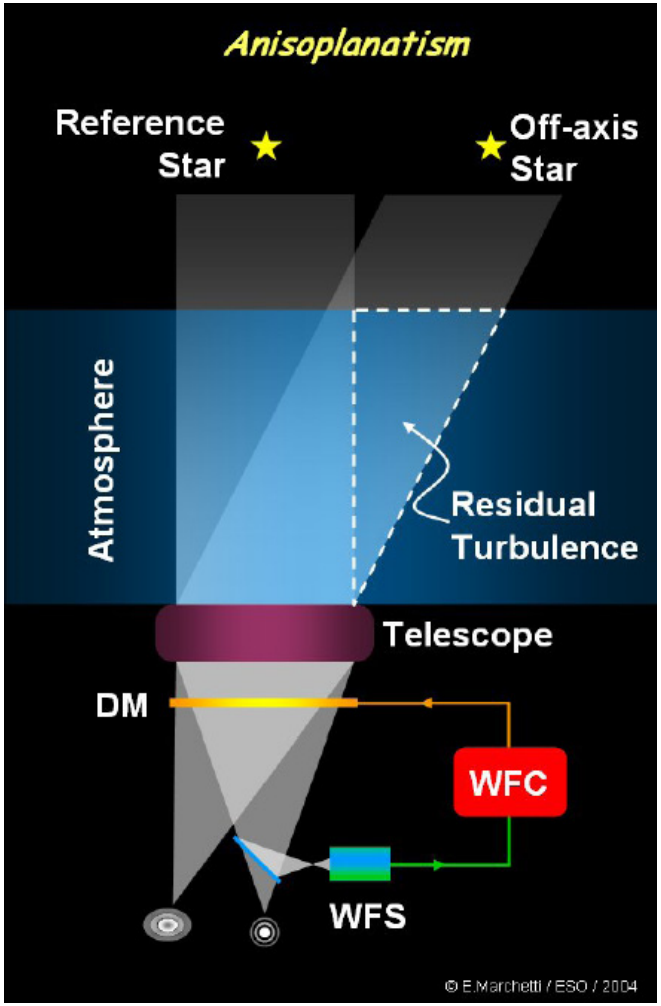
Distance	1.30"	5.70"	10.10"	14.50"	18.90"	23.30"	27.70"	32.10"	36.50"
FWHM [diff.limit]	1.71	2.67	4.10	5.24	5.81	6.57	7.02	8.73	9.57

Angular anisoplanatism severely limits

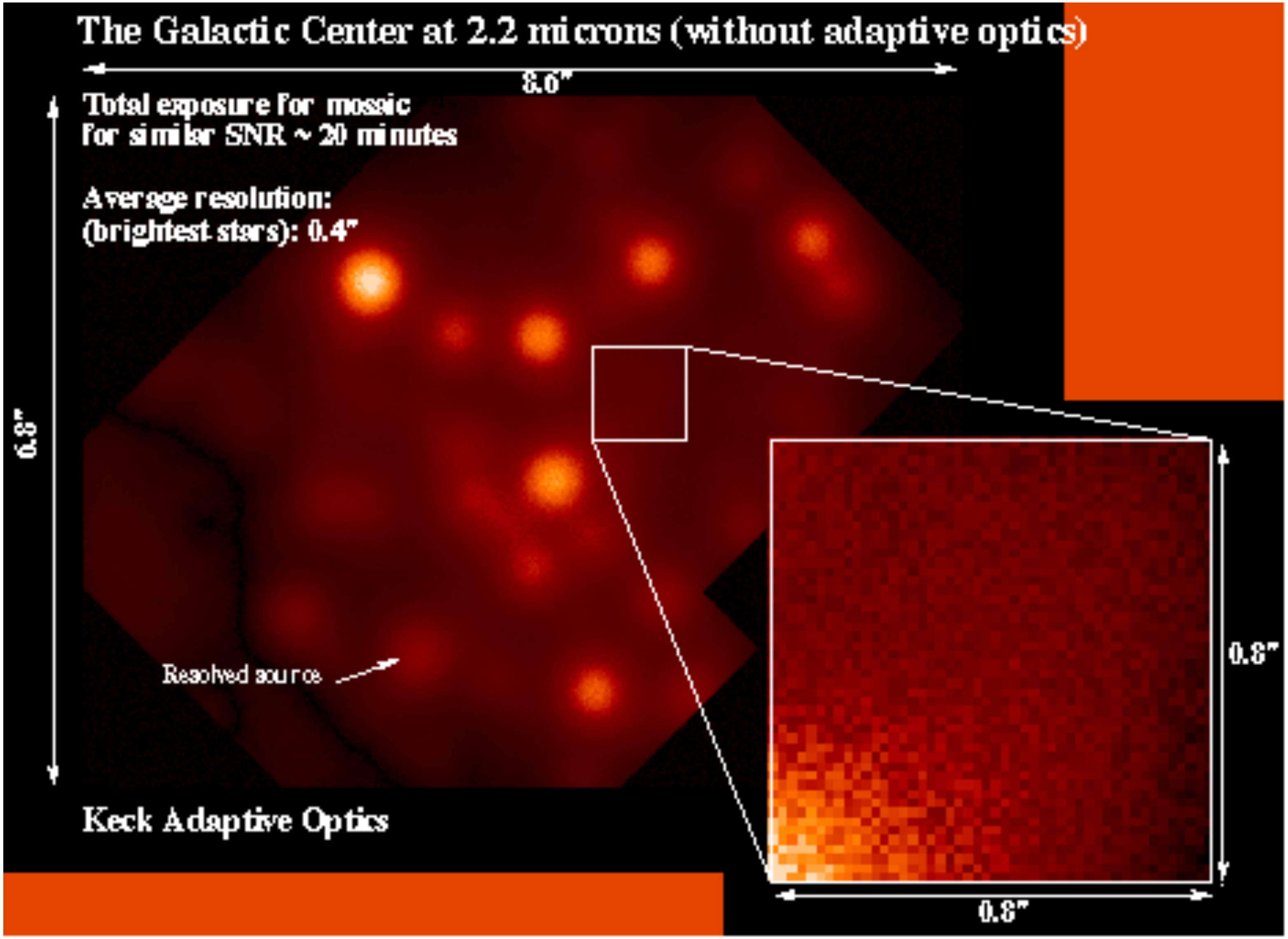
- wide-field imaging
- sky coverage (finding a guide star within the isoplanatic angle)



Multi-LGS allows to fight cone effect AND increase FOV



“Typical” Correction and Residuals



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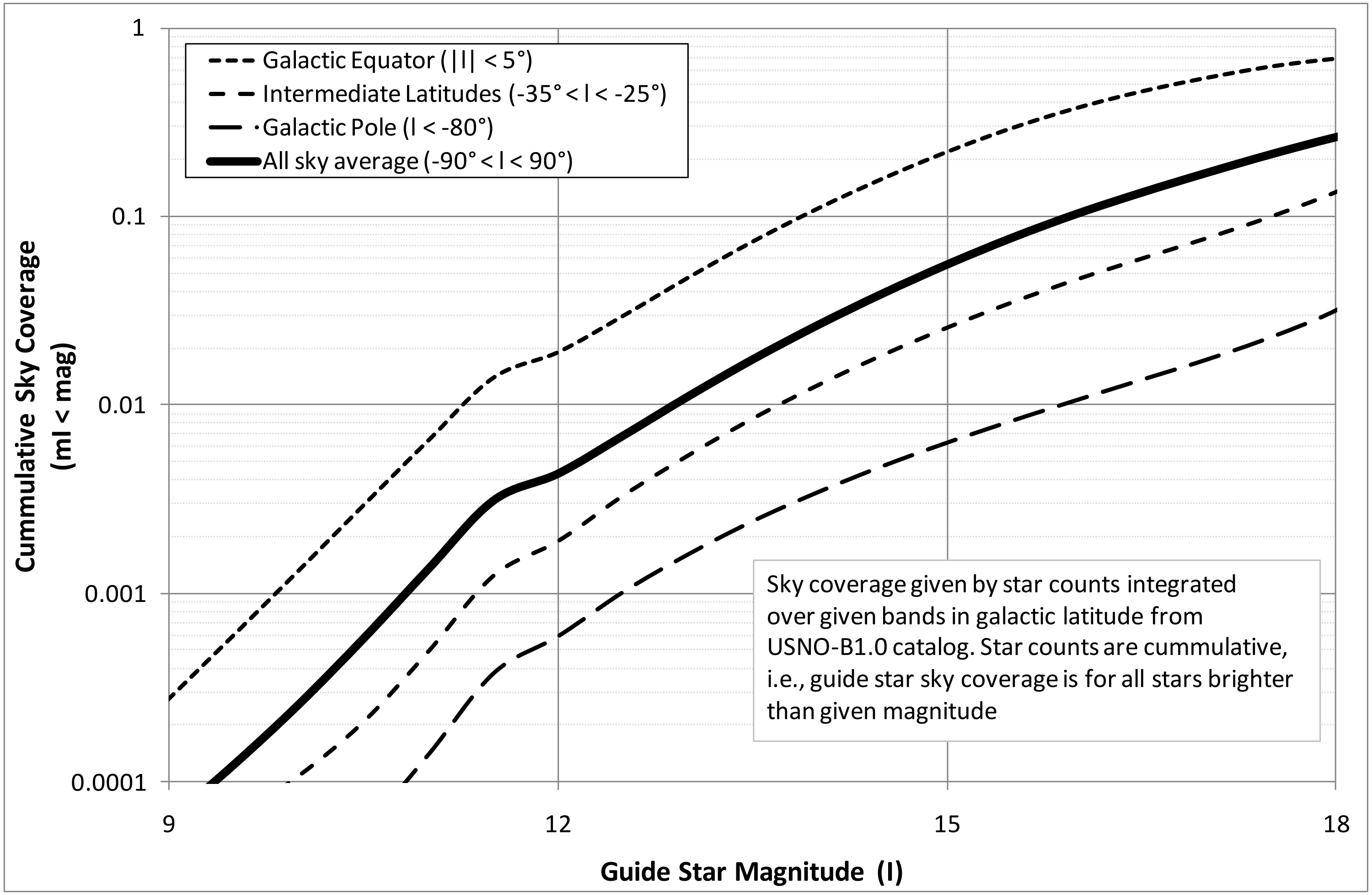
Sky Coverage

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.

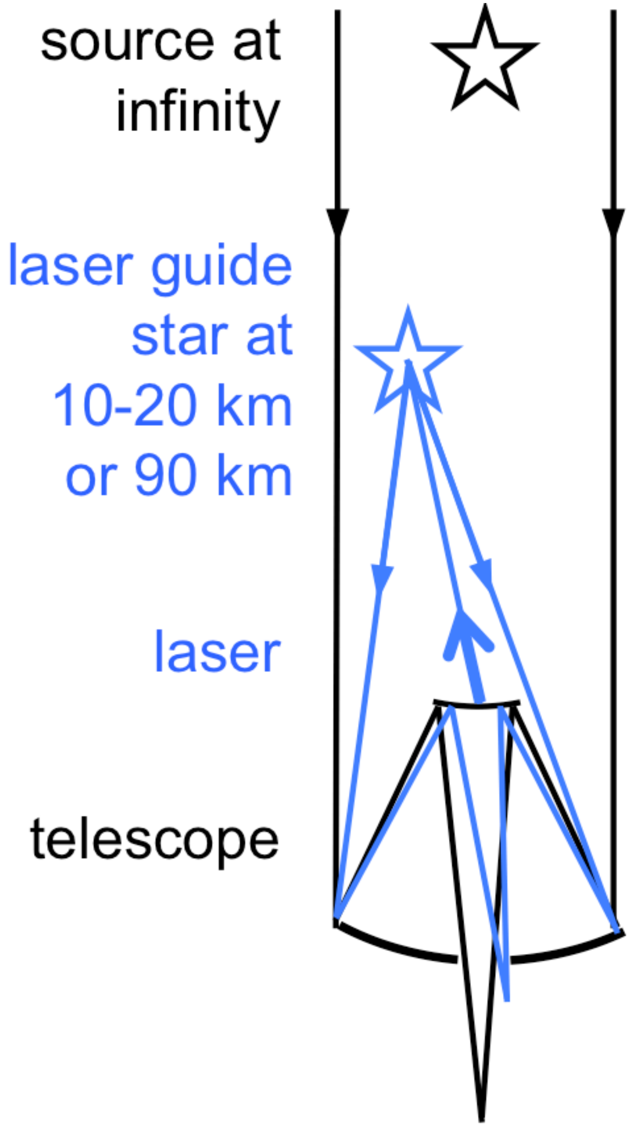
Laser Guide Stars

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

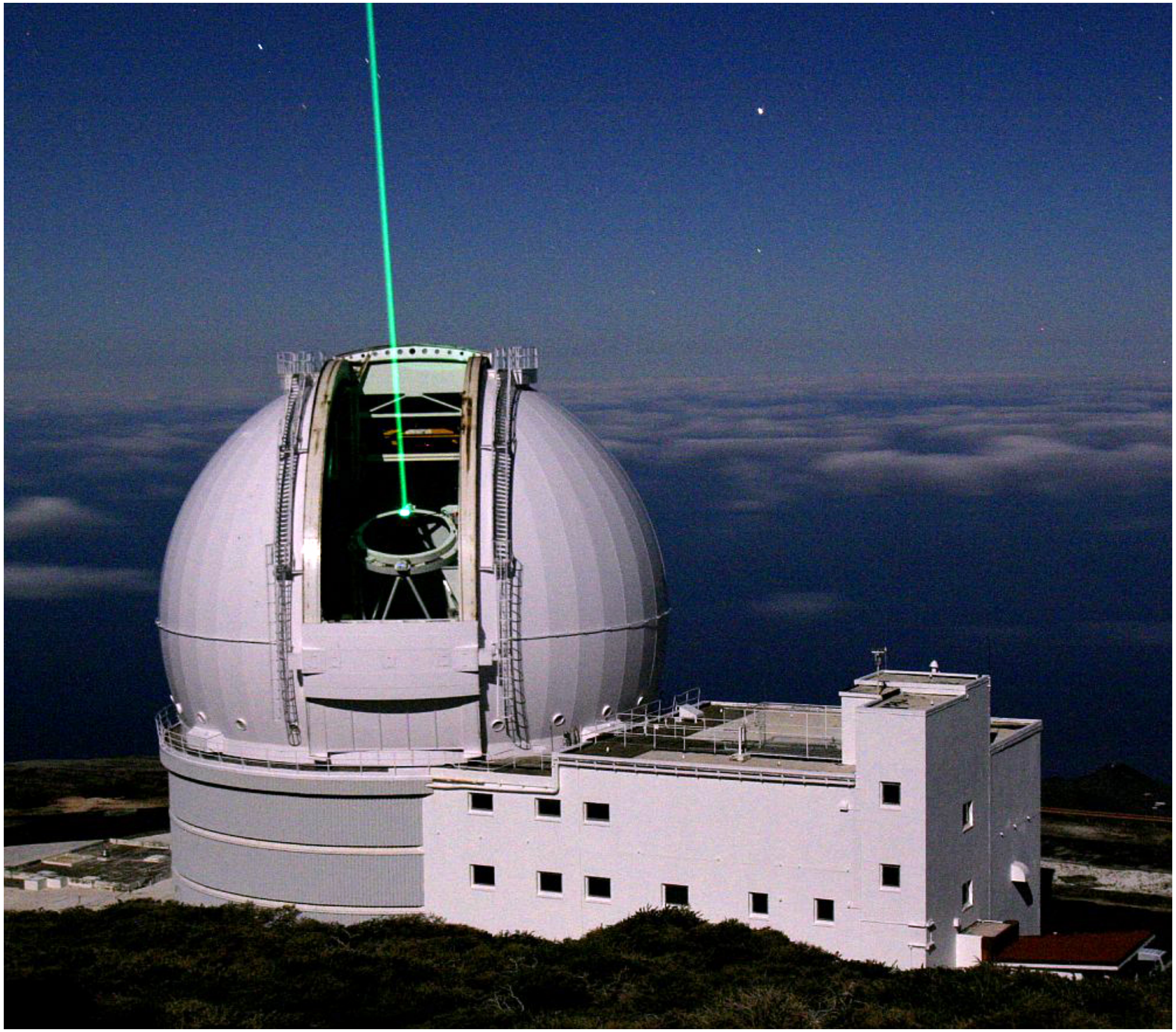
Since the beam travels twice (up and down) through the atmosphere, tip-tilt cannot be corrected → LGS-AO still needs a natural guide star, but this one can be much fainter (~18mag) as it is only needed for tip-tilt sensing.



Sodium Beacons

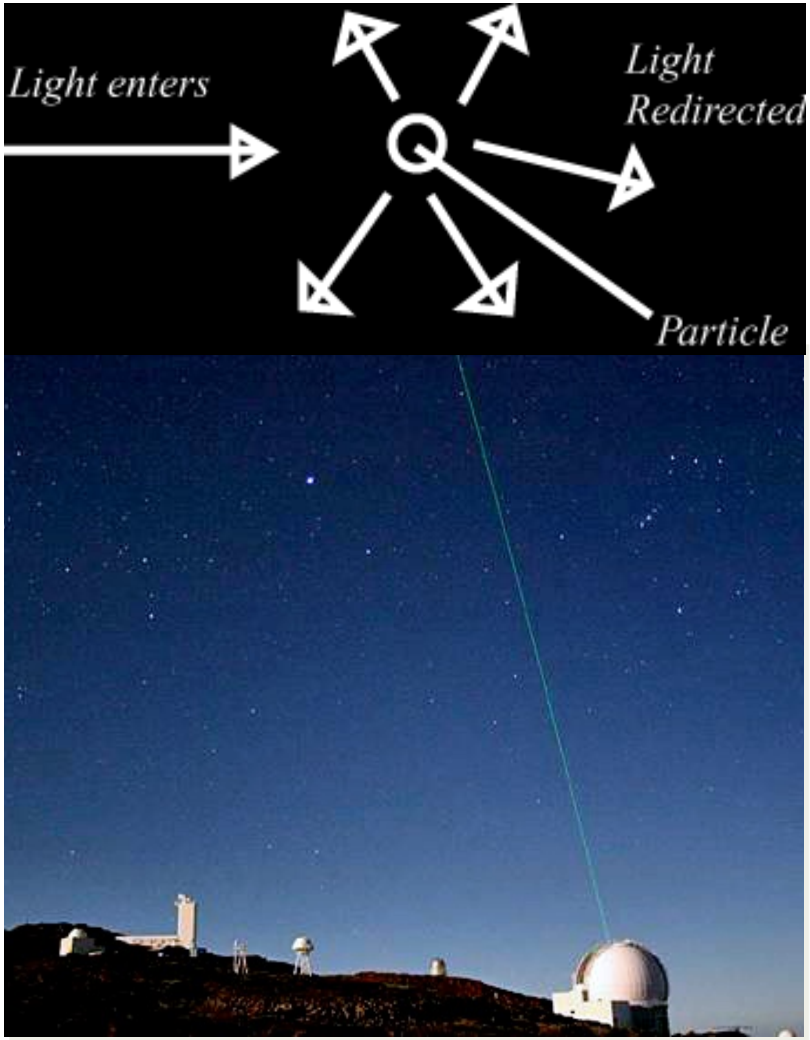
Layer of neutral sodium atoms in mesosphere (height ~ 95 km, thickness ~10km) thought to be deposited as smallest meteorites burn up.
Resonant scattering occurs when incident laser is tuned to D2 line of Na at 589 nm.

WHT Rayleigh Guide Star



Rayleigh Beacons

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



Advantages:

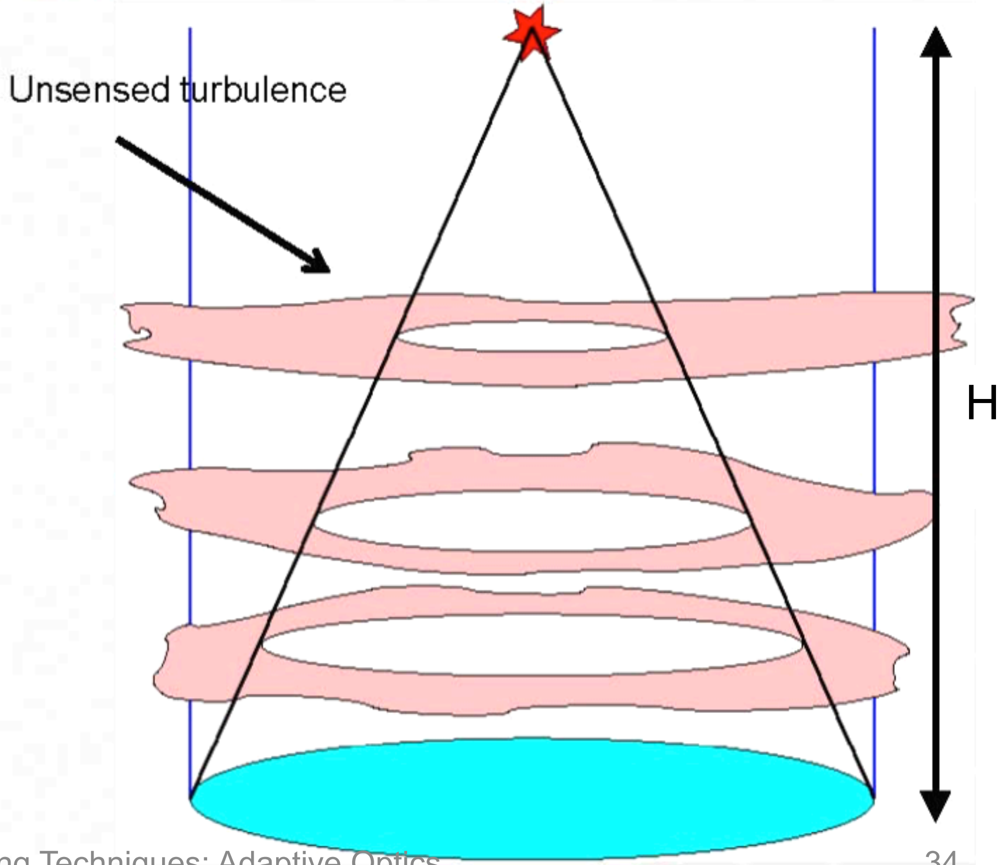
- cheaper and easier to build
- higher power
- independent of Na layer

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"):



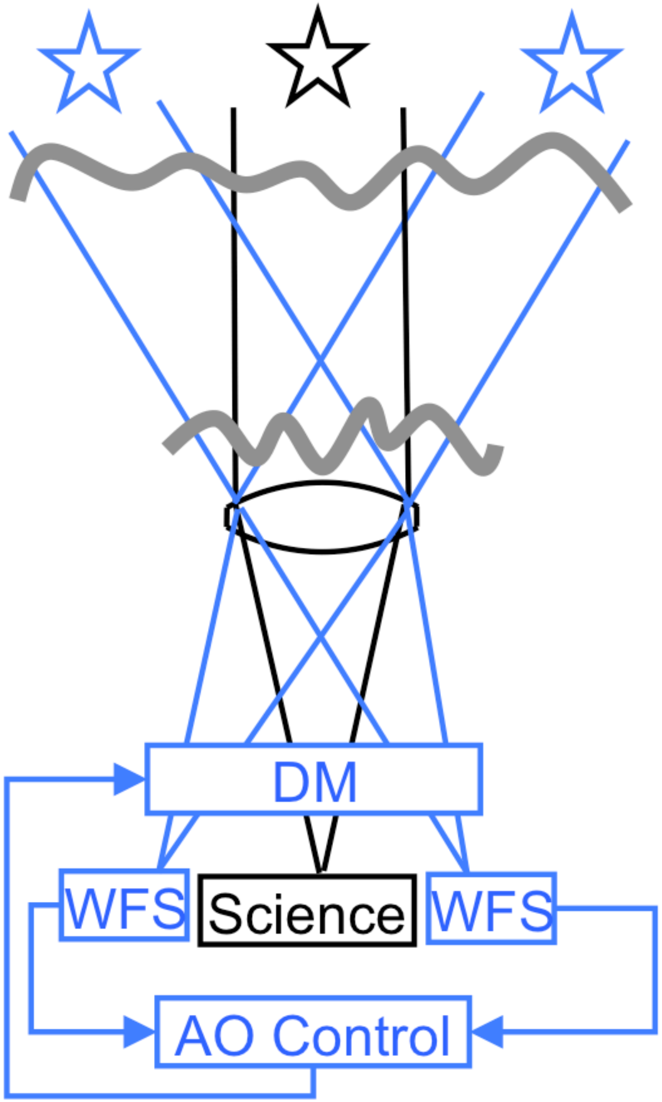
The contribution to the wavefront error contribution from focus anisoplanatism is: $\sigma_{FA}^2 = \left(\frac{D}{d_0}\right)^{5/3}$

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

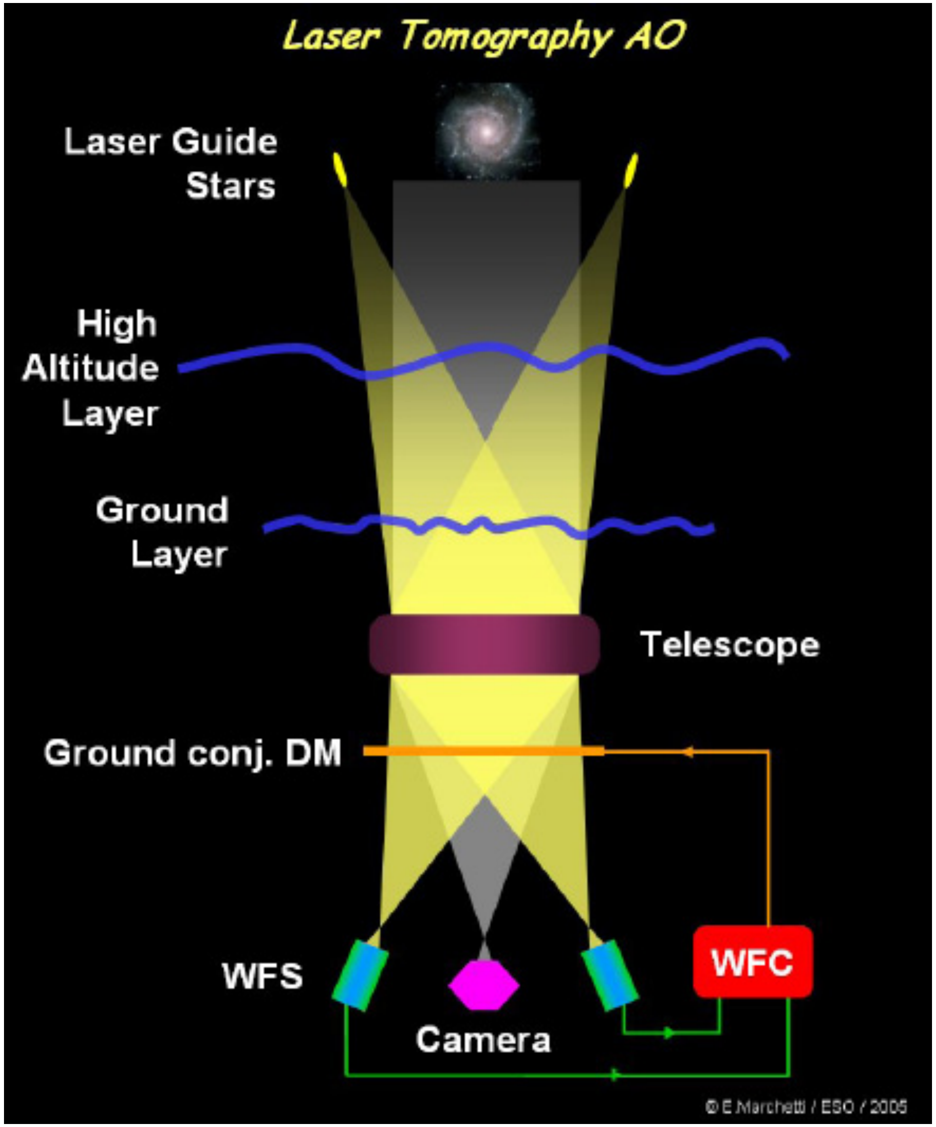
- Uses multipe laser beacons

- each laser has its WFS

- combined information is used to optimize the correction by one DM on-axis.

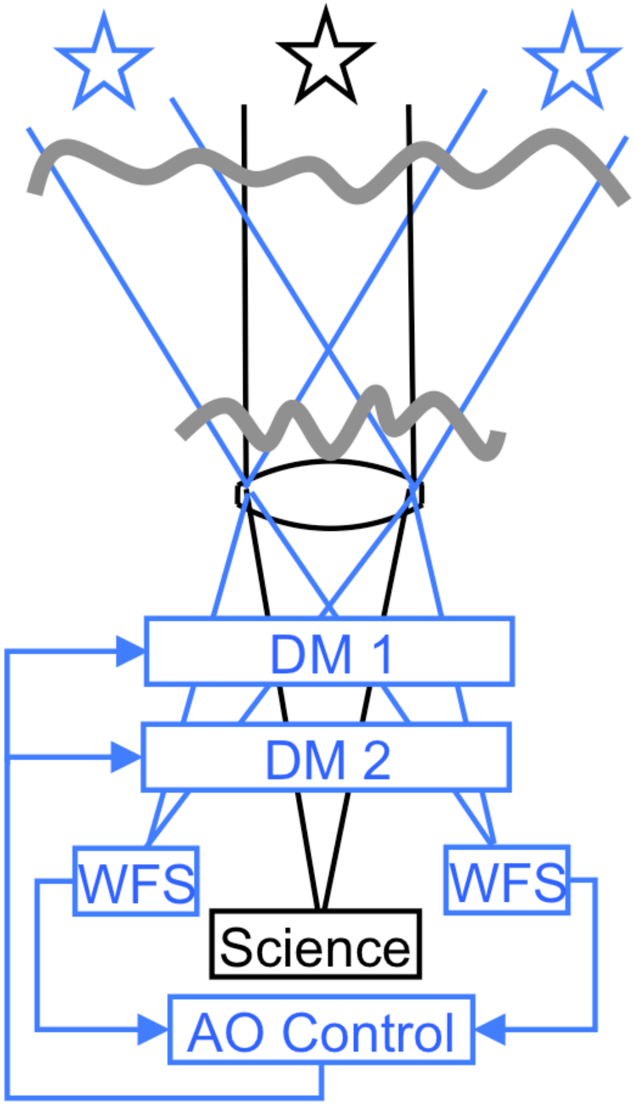
- reduces the cone effect

- system performance similar to natural guide star AO but at much higher sky coverage.

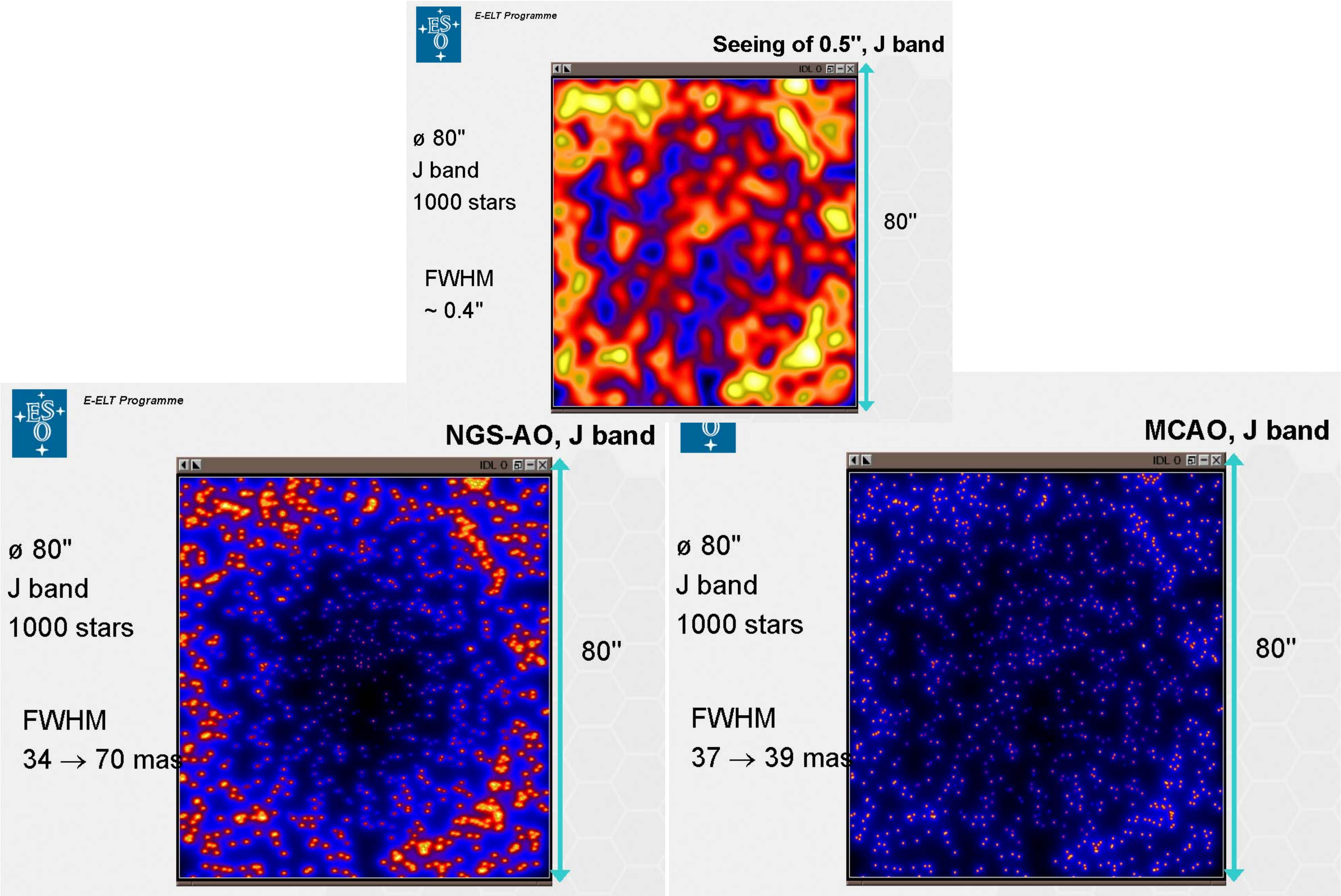


Multi-Conjugate AO – MCAO

- 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"

80"

E-ELT Programme

NGS-AO, J band

ø 80"
J band
1000 stars

FWHM
34 → 70 mas

80"

MCAO, J band

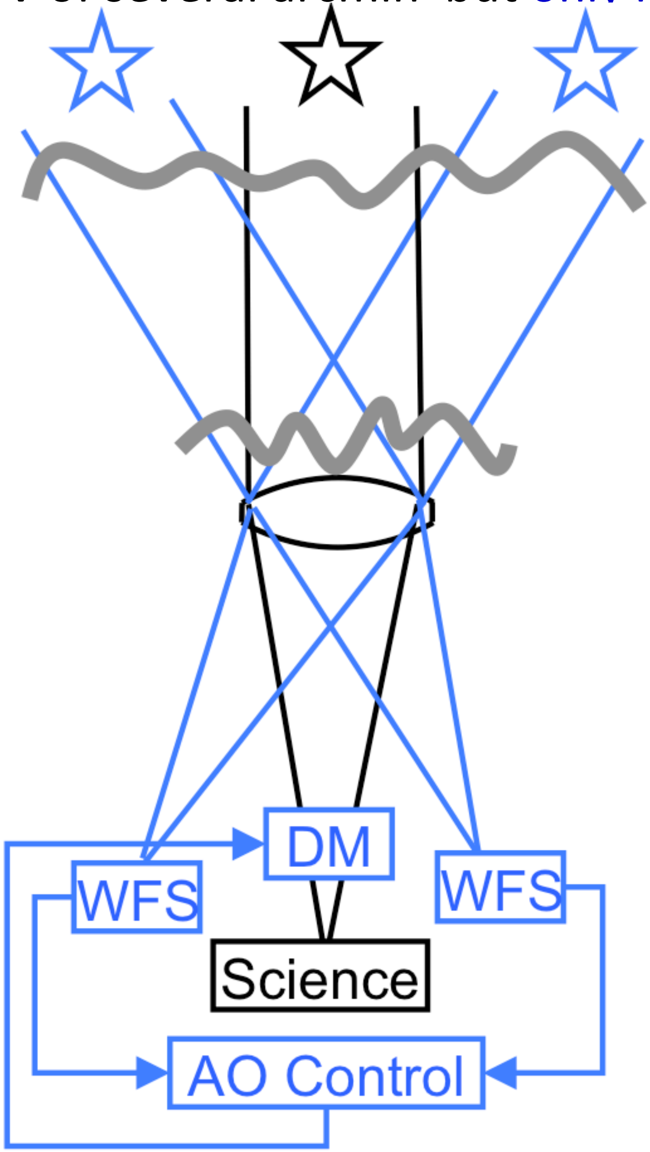
ø 80"
J band
1000 stars

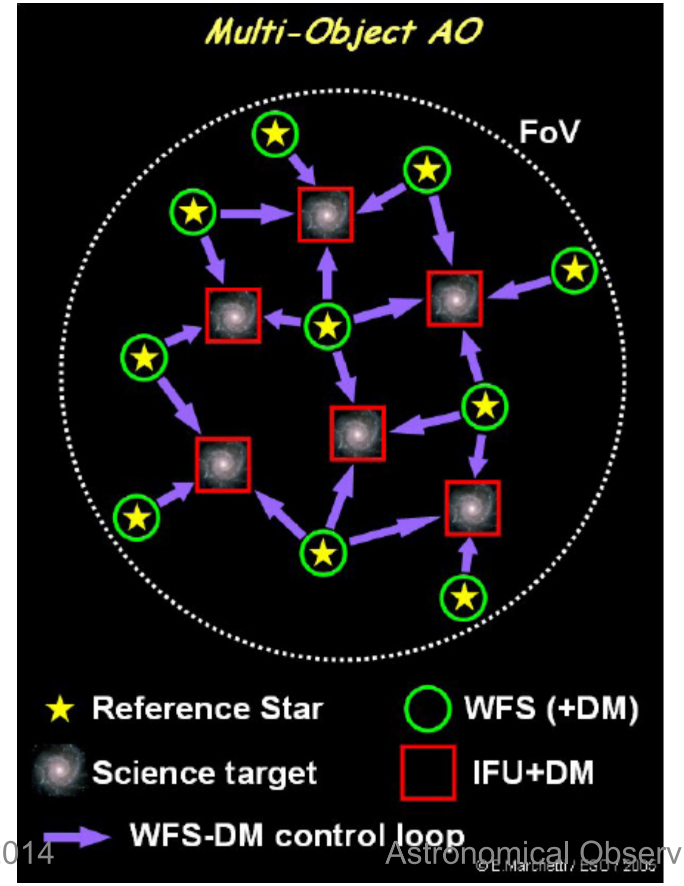
FWHM
37 → 39 mas

80"

Multi-Object AO – MOAO

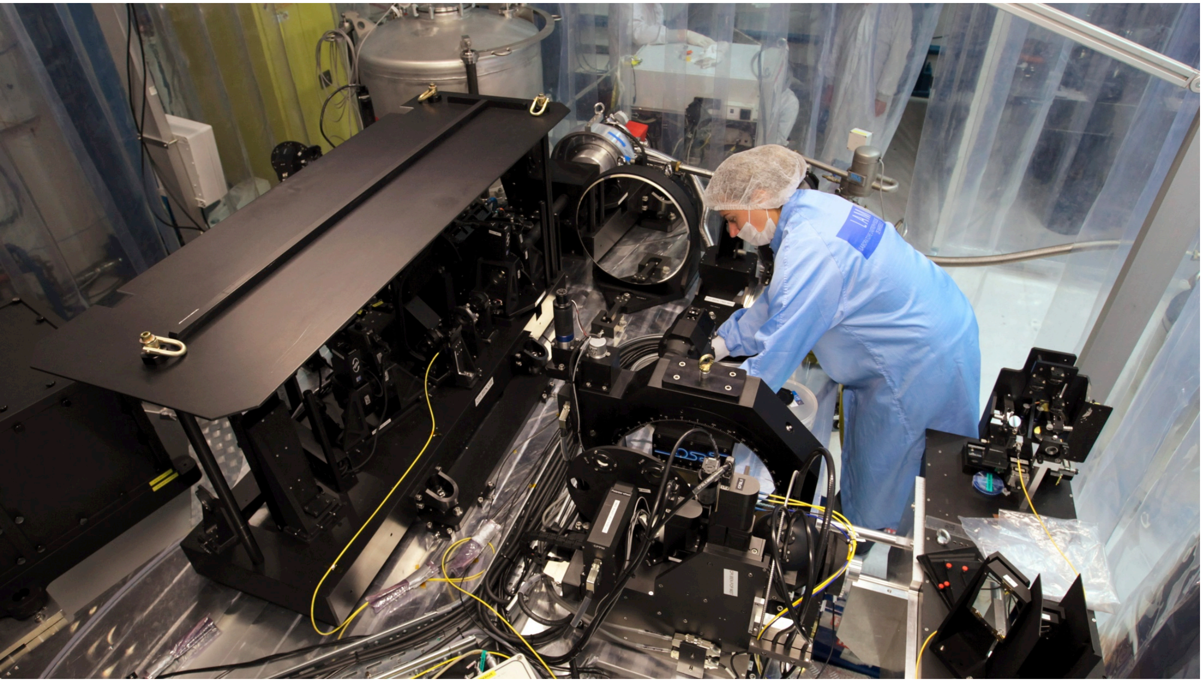
- MOAO provides correction not over the entire FOV of several arcmin but only in local areas within several arcmin → multi-object s
- needs (several) guide stars close to each science
- picks up the WFS light via small "arms“ inserted i
- each science target has its DM
- systems work in open loop (!)

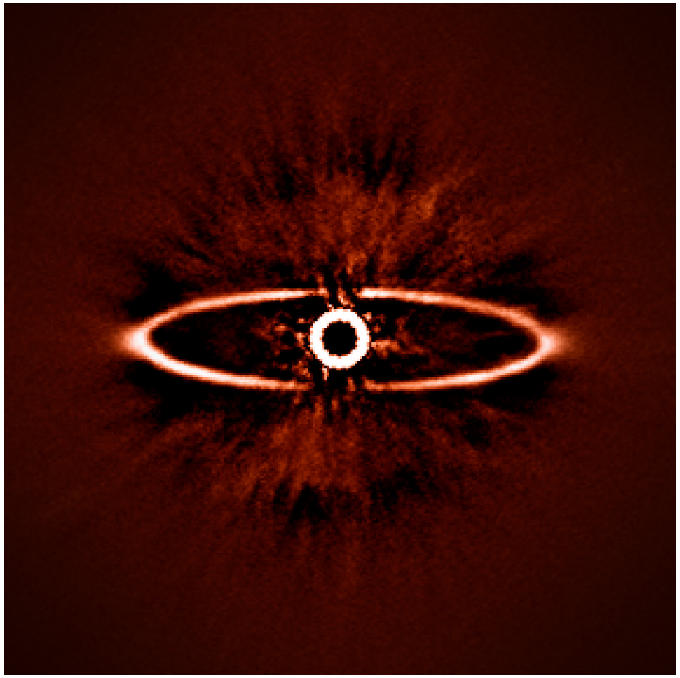




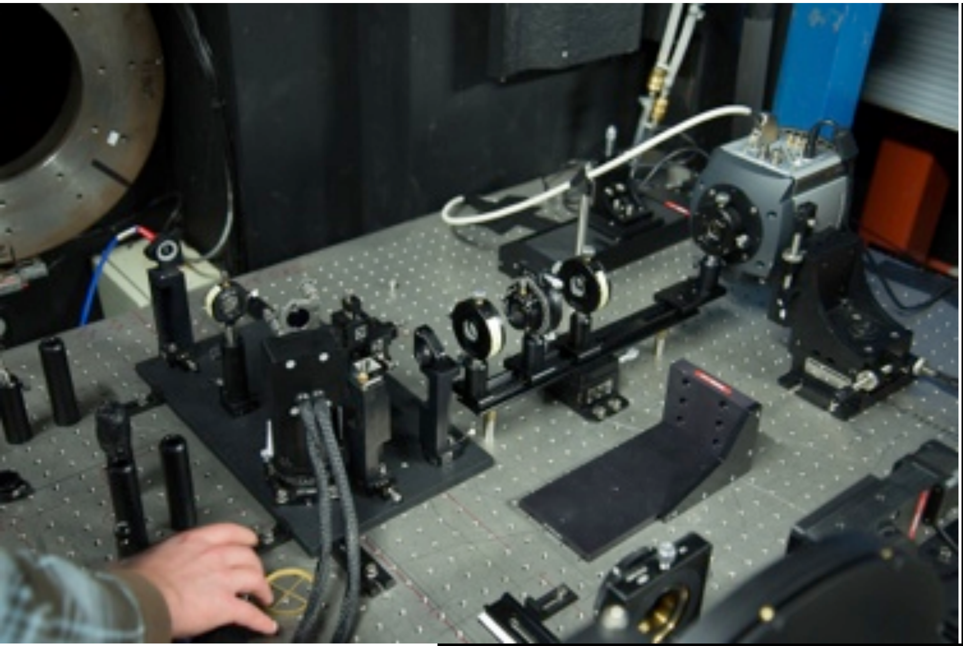
Extreme AO – XAO

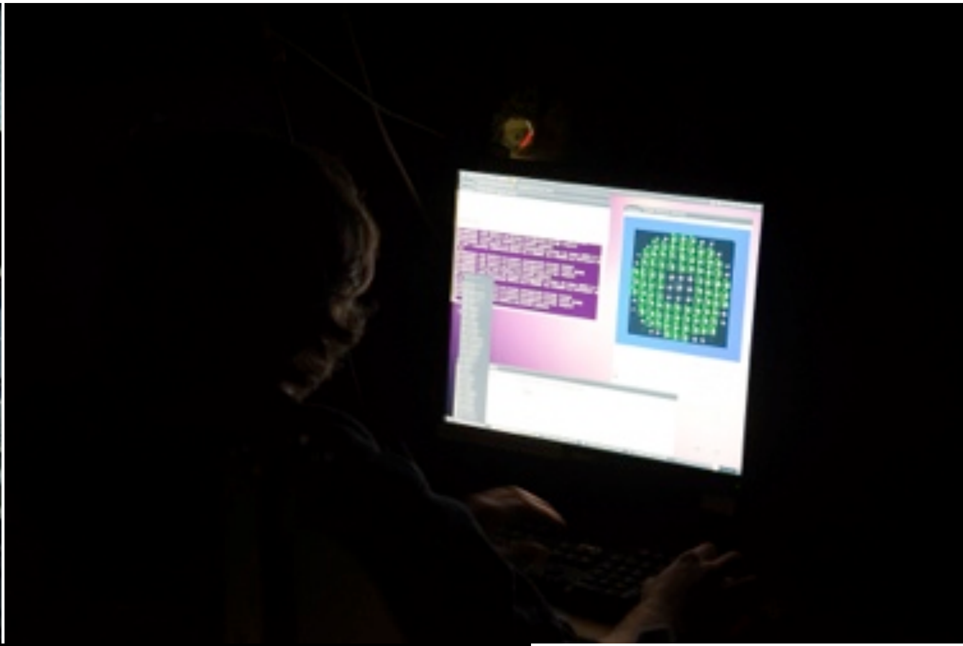
- XAO is similar to SCAO
- high Strehl on-axis and small corrected FOV
- however, Strehl values in excess of 90%
- requires many thousands of DM actuators
- requires minimal optical and alignment errors
- main application: search for exoplanets, SPHERE on VLT

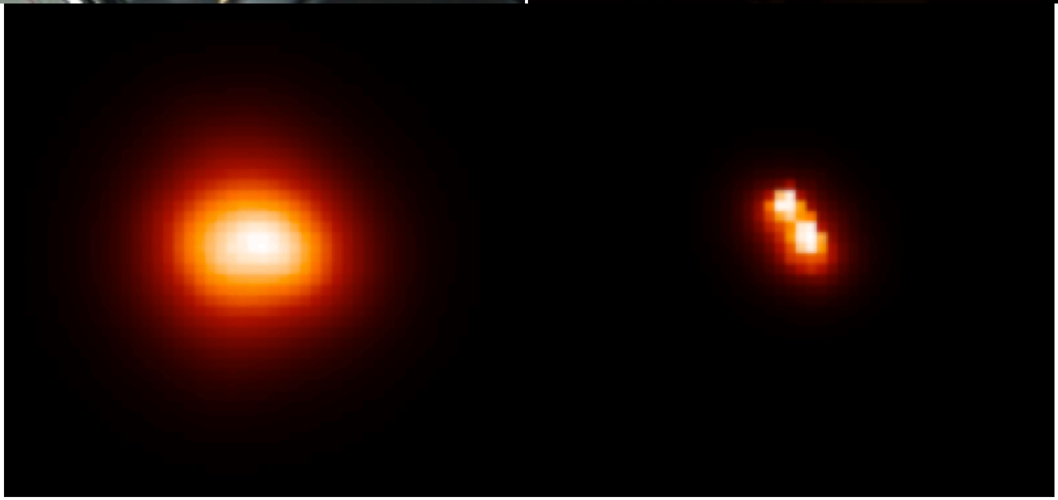




Student-Built ExPo Adaptive Optics







MSc Astronomy & Instrumentation

- 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